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## Spacelab Science Results Study

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# SPACELAB SCIENCE RESULTS STUDY: EXECUTIVE OVERVIEW

**Robert J. Naumann**  
**Study Team Leader**

## **Introduction**

Beginning with OSTA-1 in November of 1981 and ending with Neurolab in March of 1998, thirty-six of NASA's space shuttle missions are considered Spacelab missions because they carried one or more of the Spacelab components, including the Spacelab module, the pallet, the Instrument Pointing System (IPS), or the Mission Peculiar Experiment Support Structure (MPESS). The experiments carried out during these flights included astrophysics, solar physics, plasma physics, atmospheric science, Earth observations, and a wide range of microgravity experiments in life sciences, biotechnology, materials science, and fluid physics, which includes combustion and critical point phenomena. In all, investigators from the United States, Europe, Russia, and Japan conducted over 760 separate experiments. These experiments resulted in several thousand papers published in refereed journals, and thousands more in conference proceedings, as chapters in books, and in other publications. A number of these investigations are considered landmark experiments in that they produced results that set the tone for new vistas to be explored, and subsequently added greatly to our body of knowledge of the universe, the planet on which we live, how our bodies and other biological systems function, and the science involved in materials processing.

The purpose of this Spacelab Science Results Study is to document the contributions made in each of the major research areas by giving a brief synopsis and analysis of the more significant experiments, and provide an extensive list of the resulting publications. We have also endeavored to show how these results impacted the existing body of knowledge, where they have spawned new fields, and, if appropriate, where the knowledge they produced has been applied.

The team members that conducted this study and their areas of responsibility are:

- Dr. Charles A. Lundquist – Astrophysics
- Dr. Einar Tandberg-Hanssen – Solar Physics
- Dr. James L. Horwitz - Space Plasma Physics
- Dr. Glynn A. Germany – Atmospheric Science
- Dr. James F. Cruise – Earth Observations
- Dr. Robert J. Naumann – Microgravity Physical Sciences
- Dr. Marian L. Lewis – Microgravity Life Sciences

The material used in this study came from many sources including the Mission Summary Reports, Mission and/or Investigator Team websites, the Astrophysics Data Facility, the AstroWeb, the International Distributed Experiments Archives (IDEA, which contains both the NASA Microgravity Research Experiments (MICREX) database and the ESA Microgravity Database), the Compendex Web, the NASA Life Sciences Data Archive, the Science Citation Index, the NASA Office of Biological and Physical Research Task Books, various survey papers, conference proceedings, and the open literature publications of the investigators.

Our initial intent was to assess the scientific impact of these various investigations on the basis of the number of publications generated and the citations they received. It soon became apparent that this would not be a fair assessment for the following reasons:

- Often the total number of publications is dominated by a small number of highly productive teams that flew the same investigation on multiple shuttle flights.
- Time and fiscal restraints for the study did not allow for an exhaustive reference search; thus there is the possibility that key documents to a particular experiment may have been missed.
- Investigators often publish papers using data from multiple Spacelab missions or combine data from Spacelab with other flights. Therefore, it is sometimes not possible to ascribe a particular publication to a specific experiment.
- Often the flight data is only a small part of a much larger ground based investigation. It may be difficult to determine which of the ground based papers to include.
- Many of the early ESA microgravity investigators chose to present their results at the series of ESA-sponsored conferences instead of the open literature. Therefore, their results, even though important, are not as widely known to the greater scientific community.
- Many of the Japanese microgravity investigators chose to present their results at NASDA-sponsored conferences instead of the open literature, making them, as with the ESA investigations above, less available to the larger community.
- Many of the more exciting results have come on the more recent flights and, therefore, have not had time to collect many citations.

For these reasons, we thought it prudent to simply document the experiments that produced publishable results (even though some were not published in the open literature) by presenting a brief synopsis of their results in context with the state of knowledge in the field (where appropriate) along with the references we have been able to find. The included bibliography is quite extensive, as may be seen in the table below.

In addition to the listed references in the Astrophysics section, there are a number of other papers listed in the mission websites reporting observations of specific objects. Also, we understand that there are an additional 538 publications resulting from Spacelab J that were not available to us. Therefore it is safe to say that the Spacelab program has generated in excess of 5400 publications, with additional publications expected as the data from later missions such as MSL-1R and Neurolab continues to find its way into the open literature. Of these, we estimate that over half are published in refereed journals, and the remaining are available as chapters in books or in conference proceedings.

Again, time and resources did not permit iteration with investigators as we would have liked. So if we misinterpreted a result, we apologize. Invariably, when dealing with this many experiments in a limited time, we are bound to have left out an important experiment by oversight or because we failed to grasp the significance of the result.

Some of these Spacelab missions were more or less dedicated to specific scientific disciplines, while others carried an eclectic mixture of experiments ranging from astrophysics to the life sciences. However, the experiments can be logically classified into two general categories: those that make use of the Shuttle as an observing platform for external phenomena (including those which use the Shuttle in an interactive mode) and those that use the Shuttle as a microgravity laboratory. Since the resulting study report turned out to be rather unwieldy when all of the references are included, we have broken it down into several sections by discipline. The first section of the Spacelab Science Results study will be devoted to experiments of the first category. The disciplines included are Astrophysics, Solar Physics, Space Plasma Physics, Atmospheric

**Table 1. Total Publications by Discipline**

<b>Discipline</b>	<b>Total Publications</b>
Astrophysics	538
Solar Physics	172
Space Plasma Physics	140
Atmospheric Sciences	220
Earth Observations	117
Fluid Physics	563
Combustion	118
Materials Science	999
Biotechnology	598
<u>Life Sciences</u>	<u>2010</u>
Total Publications	5475

Sciences, and Earth Observations. Because of the large number of microgravity investigations, a second segment will be devoted to the Microgravity Physical Sciences, which includes Fluid Physics, Combustion Science, Materials Science, and Biotechnology, and the third section will be devoted to the Microgravity Life Sciences, which studies the response and adaptability of living organisms to the microgravity environment. In addition, this executive overview of all of the disciplines was prepared (without references) by distilling the inputs from the members of the science team.

## I. ASTROPHYSICS

Astronomy and astrophysics are rapidly moving disciplines. Results that were new and important at the time of their release may be superseded by newer results a few years later. The astronomical observations made from the Spacelab missions must be viewed against this general feature of the science. Nonetheless, some of the pioneering work on Spacelab missions have made direct as well as indirect lasting contributions to our current body of knowledge of the Universe.

Spacelab 1 carried three instruments, a Far Ultraviolet Space Telescope (FAUST), a Very Wide Field Camera (VWFC) and a Gas Scintillation Proportional Counter (GSPC). These instruments were hard mounted to the shuttle structure, so that pointing was accomplished by controlling the attitude of the shuttle. Because this first mission expected to demonstrate diverse uses of Spacelab, the instrumentation represented a broad range of disciplines. The two telescope-camera instruments photographed star fields in the far ultraviolet (FAUST) and ultraviolet (VWFC). As might be expected, a principal result was an improved understanding of how shuttle borne cameras of this class can best be employed. Also, the photographed fields provided surveys of ultraviolet (UV) characteristics of classes of stars that could be selected for future detailed observation and analysis. The GSPC measured X-ray energy spectra in the range 2-80 keV for Cyg X-3, Cen X-3 and the Perseus cluster of galaxies. The first two are well known X-ray sources for which these measurements provided further information.

The astrophysical instruments on Spacelab 2 probed the universe in the infrared (IR), X-ray, and cosmic radiation spectral regions. For the first of these, a small, helium-cooled infrared telescope (IRT) was mounted on the Spacelab Instrument Pointing System (IPS). It was designed to observe diffuse, extended sources of infrared as well as to augment data on discrete infrared sources, many of which were cataloged earlier by the Infrared Astronomical Satellite (IRAS). An operational question addressed was the suitability of the Shuttle as a carrier for infrared telescopes. With respect to this question, the IRT background due to emission of gas from the Shuttle was found to be greater than anticipated. The surveys of the Milky Way Galaxy at two and seven microns were new data, implying that the structure of the Galaxy is broader at these wavelengths than at longer wavelengths.

The objective of the X-ray imaging telescope on Spacelab 2 was to produce images of clusters of galaxies, particularly, and also other extended X-ray sources. A puzzle was the source of the hard X-rays coming from the direction of some clusters of galaxies. Hot gas between the galaxies of the cluster was one hypothesis. From spectrally resolved images of the Virgo cluster, the investigators report that much of the hard X-ray emission previously reported from the cluster actually originates in the single galaxy NGC 4388.

The large lifting capability of the Space Shuttle supported a significant advance in cosmic ray astrophysics by bringing up the 2000 Kg Cosmic Ray Nuclei Experiment (CRNE). An instrument of this extreme size and complexity was required to extend measurements of rare cosmic rays to energies almost 100 times greater than those previously studied by comparable techniques. The investigators conclude that the cosmic ray flux arriving near earth becomes enriched with heavier nuclei, most notably iron, as energy increases. Another analysis presented energy spectra of the cosmic-ray nuclei boron, carbon, nitrogen and oxygen up to energies around 1 Tev, which yield information on the propagation of cosmic rays through the galaxy.

Spacelab 3 carried an instrument, the Ionization Status of Low Energy Cosmic Rays (IONS), to measure low energy "anomalous" cosmic ray ions. The abundances of sub-iron (Sc through Cr) and of iron (Fe) were determined. The investigators conclude that the IONS measurement ratios are probably enhanced inside the earth's magnetosphere due to the degree of ionization of low energy Sc to Cr and Fe ions in galactic cosmic ray, and to the filtering effects of the geomagnetic field. This is the suggested explanation of cosmic ray data previously cited as anomalous.

The Astro-1 and -2 flights, using Spacelab pallets, carried an ensemble of astronomical instruments. Three of these, the Hopkins Ultraviolet Telescope (HUT), the Wisconsin Ultraviolet Photo-Polarimeter Experiment (WUPPE), and the Ultraviolet Imaging Telescope (UIT) operated in ultraviolet wavelengths and were mounted on the IPS.

A Broad-Band X-ray Telescope (BBXRT) with its own pointing system was added to Astro-1 with the initial motivation to observe a 1987 super nova, SN1987A, in a nearby galaxy. However, Astro-1 did not reach orbit until December 1990. The BBXRT was designed to make moderate resolution spectrophotometry of X-ray sources in the 0.3 to 12 keV band. It collected and published data for several astronomical objects, including Xi Pup, the Puppis A supernova remnant, and Cygnus X-2.

The HUT operations, particularly on Astro-2, were similar to that of a major ground based observatory. A list of several hundred observing targets was adopted to provide data to many investigators for diverse analyses. The unique capabilities of this facility were used to make new far-UV observations of virtually every class of objects in the universe, a remarkable achievement! One of the tasks the instrument was designed for was to detect and measure the characteristics of the primordial intergalactic gas. It so happens that the redshifted spectrum of quasar HS 1700 + 64 covered an absorption line of partially ionized helium. Thus by observing this redshifted spectrum, the concentration of intergalactic helium was measured for the first time.

The Wisconsin Ultraviolet Photo-Polarimeter was conceived as a pioneering instrument for exploring polarization and photometry of astronomical objects in the ultraviolet spectrum. It, too, had a long observation target list of many different types of astronomical objects in the universe. During the two Astro missions, WUPPE obtained polarimetry and spectra for 121 objects.

The UIT is a 38-cm Ritchey-Chretien telescope equipped for an ultraviolet filter and grating imagery over a 40 arc minute field of view with a resolution of about 3 arc seconds. It produced ultraviolet (1200 to 3300 angstroms) images of a variety of astronomical objects, particularly extended objects that are recorded on 70 mm film. This instrument produced an atlas of spatially-resolved mid-UV and far-UV images of fifty nearby galaxies. This set includes ellipticals, disk systems and irregular galaxies. Other extended objects studied include the Large and Small Magellanic Clouds and various star clusters.

The Astro missions produced over 167 publications in the astronomical and astrophysical journals. The surveys and catalogs generated from the Spacelab observations in previously unavailable frequency and energy ranges will find continuing utility in identifying individual astronomical objects worthy of future detailed study. This will insure a lasting legacy from Spacelab.

The evolutionary progress of instrumentation design afforded by the Spacelab missions was also an important contribution. While the Shuttle is not the ideal carrier for many astronomical instruments, it was a valuable test-bed for new observation techniques and opportunities. The resulting insights can subsequently be applied to free-flying observatories as the remaining astronomical issues warrant. Presumably, in the future the International Space Station may provide a comparable test-bed for instrument concepts yet to be invented.

There has been a recent revolution in cosmology (see, for example, "Revolution in Cosmology," *Scientific American*, January 1999) that began when two independent groups reported in the journal *Science* evidence that the universe is expanding. A crucial starting point in any cosmological theory is the distribution of

gravitating mass in the universe and a key element to this is the cosmological baryon density. The measurements of singly ionized helium (He II) in the spectrum of the quasar HS 1700+64 with the HUT telescope on Astro-2 contributed directly to estimates of baryonic or ordinary matter generated in the big bang.

Also, the X-ray telescope on Spacelab 2 was a pioneering effort to use the measurements of X-rays from the intergalactic gas to assess the masses of galactic clusters. It demonstrated the usefulness of the technique, which requires spectral imaging of the clusters studied. Of course the duration and scope of observations from Spacelab 2 was limited by the mission length. In 1990, five years after Spacelab 2, the ROSAT (Roentgen Satellite) was launched with X-ray spectral imaging capabilities. Far more comprehensive observations of galactic clusters were obtained and analyzed. These later data, building on the Spacelab 2 experience, currently provide one of the best measurements of observable mass in the universe, since galactic clusters represent a large fraction of the identifiable mass.

The noteworthy point here is that pioneering investigations using Spacelab instrumentation helped move the cosmology discipline to its current exciting state.

## II. SOLAR PHYSICS

The scientific investigations carried out by solar experiments using the Spacelab facility fall into three main categories:

- measurements of the solar irradiance (the solar constant problem)
- abundance determinations (the solar helium problem)
- the dynamic nature of the solar atmosphere.

The solar constant is not really a constant. Small, but persistent variations in the solar input to the Earth's atmosphere, oceans, and land masses can have dramatic effects and can possibly explain a wide range of past climatic changes. To determine the effects of variations in solar input, it is essential to monitor solar irradiance over long intervals and to understand the physical basis for its variations. This task is best carried out on unmanned satellites that can remain in orbit more-or-less indefinitely. The Spacelab missions have been used to test and calibrate new instruments before committing them to unmanned satellites and to provide periodic checks on the calibration of similar instruments already on free fliers. Short duration missions have the distinct advantage of being able to calibrate an instrument just before and just after a flight.

The total solar irradiance was measured using the Active Cavity Radiometer Irradiance Monitor (ACRIM) and the Measurement of the Solar Constant (SOLCON) instruments. SOLCON measures the absolute irradiance integrated over the entire solar spectrum, while the ACRIM measures the absolute irradiance from the ultraviolet to the infrared. ACRIM was first flown on Spacelab 1 and was later flown on the Solar Max satellite. Each of the ATLAS (Atmospheric Laboratory for Applications and Science) missions carried an ACRIM and a SOLCON instrument. SOLCON was also flown on the European Space Agency (ESA) retrievable platform, EURECA (European Retrievable Carrier).

Solar ultraviolet radiation in the wavelength range 120 to 400 nm is absorbed by the Earth's atmosphere between 20 and 120 km and even though this radiation constitutes only a small percentage of the total solar output, it is the main source of energy for the middle atmosphere. This ultraviolet component of sunlight varies considerably more than the visible radiation. During an 11-year cycle of the Sun's activity, changes in ultraviolet radiation bring about corresponding changes in a number of atmospheric conditions and may be responsible for weather and climate changes. This region of the spectrum is monitored by the Solar Ultraviolet Spectral Irradiance Monitor (SUSIM). SUSIM was flown on Spacelab-2 and on each of the ATLAS flights. Measurements from these flights are compared with the same instrument on the Upper Atmosphere Research Satellite (UARS).

The Solar Spectrum (SOLSPEC) instrument measures the solar spectrum from the infrared through the ultraviolet to obtain spectral variations over the entire optical spectrum. This instrument was also flown on each of the ATLAS missions.

The abundance determinations and the dynamic nature of the solar atmosphere were carried out using the Coronal Helium Abundance Spacelab Experiment (CHASE), the Solar Ultraviolet High Resolution Telescope and Spectrograph (HRTS), and the Solar Optical Universal Polarimeter (SOUP). These instruments were flown on Spacelab 2.

### III. SPACE PLASMA PHYSICS

When an object as large as the Shuttle moves through the residual atmosphere at nearly 8 Km/s, it generates many complex interactions with both the neutral and ionized components. Several of the Spacelab flights carried a variety of instruments to probe the responses of the surrounding ionospheric plasma environment to these perturbations. It has also been possible to conduct experiments that actively modified this environment in order to learn more about the dynamics of the Earth's ionosphere.

Visible evidence of such interactions was observed on the very first Shuttle flights when a glow was noticed on the Shuttle surfaces interacting with the atmosphere in the ram direction. It was found that this glow emission had intensities that were comparable to that of the Earth's airglow and to the brightness of stars in TV cameras.

Although most of the Shuttle based space plasma science was oriented towards actively stimulated effects, an electron spectrometer experiment aboard Spacelab 1 was used to measure fluxes of low-energy electron precipitation at low latitudes (below the Van Allen belts). In addition to a low energy component with a power law spectrum, they found a high-energy peak that at times showed temporal flaring with time scales of about 1.5 hours. A likely acceleration mechanism for these electrons has still not been identified.

Spacecraft charging was measured during the STS-3 (OSS-1) mission using instrumentation of the Vehicle Charging and Potential (VCAP) experiment. Charging measurements using thermal plasma probes were obtained during passive events as well as periods when a 100 mA at 1 keV electron beam was emitted. An upper limit of about 1 mF was obtained for the Shuttle's capacitance. Under steady state conditions, the electrical potential typically reached only a few volts, although during some nighttime conditions, potentials of over 40 volts were detected.

The Space Experiments with Particle Accelerators (SEPAC) was a joint endeavor between NASA and the Institute of Space and Aeronautical Sciences (ISAS) in Japan. Its objectives were to investigate beam-atmosphere interactions and beam-plasma interactions in the Earth's upper atmosphere and ionosphere. It was found that the magnetoplasdynamic (MPD) arcjet was effective in maintaining vehicle charge neutralization during electron beam firings, but only for a brief period of 10 ms or so. Therefore, a xenon plasma contactor, which can provide continuous vehicle charge neutralization, was developed for the ATLAS 1 SEPAC experiments.

One of the important investigations from Spacelab 2 was of the creation of "artificial holes" in the F-region ionosphere. These holes are the result of rocket launches as well as shuttle engine burns supplying various contaminants in large amounts to react with the ambient  $O^+$  (oxygen ions), producing a new ion and neutral. The ions subsequently recombine rapidly with electrons to form neutral molecules and airglow. Hence the plasma density is rapidly depleted, creating a hole in the ionosphere. The artificially induced hole resulting from a Shuttle engine firing was observed as a burst in the airglow over New England on July 29, 1985. Another Shuttle engine burn over the Hobart observatory in Australia on August 5, 1985, created a "window" in the ionosphere that allowed much lower than normal frequencies to be observed from the ground observatory. Such observations were described as being useful in permitting much-improved mapping of the galactic radio distribution, particularly at frequencies below 1.6 MHz.

A deployable Plasma Diagnostics Package (PDP) was developed in order to probe the plasma, field and wave environment of the Shuttle. This instrument proved invaluable in the beam-plasma experiments con-

ducted on OSS-1, Spacelab 2, and ATLAS 1 as well as the ionospheric perturbations caused by the Shuttle. From data taken from the PDP it was estimated that the Space Shuttle was producing a water vapor cloud with densities of the order of perhaps  $10^9$  H<sub>2</sub>O (water) molecules/cm<sup>3</sup> at approximately 50 meters from the Shuttle. Additional observations of water and other ions during Spacelab 2 were obtained with a Bennett RF ion mass spectrometer on the PDP. They found that the concentrations of the water ions decreased with distance from the Shuttle in the orbiter wake, and fell below the concentrations of ambient O<sup>+</sup> ions at wake distances of about 30 meters. These and other similar measurements raised serious questions about the viability of making reliable natural or ambient ion measurements in the Shuttle environment.

The plasma environment of the wake of the Space Shuttle for the Spacelab 2 mission was investigated with the PDP. It was found that the plasma densities decrease within the deep wake much faster than the rates predicted by previous theoretical models. The densities were, for some regions, an order of magnitude or more lower than the theoretical predictions.

One of the most exciting opportunities for the space plasma investigations was the creation of artificial auroras by means of electron beam injections fired down upon the atmosphere by SEPAC electron accelerators on the Shuttle orbiter. With the hollow-cathode xenon plasma contactor, beam currents of up to 1.2 amps could be maintained. Some sixty artificial auroras were created over the South Pacific. They were observed from the ground as well as with the Atmospheric Emissions Photograph Imaging (AEPI) instrument onboard ATLAS 1.

Early on, it was recognized that the use of a tether connecting a sub-satellite to the Shuttle could enable some intriguing electrodynamic and space plasma experiments, using a long conducting wire. The Tethered Satellite System (TSS) was a partnership venture between NASA and the Italian Space Agency (ASI). The second flight of the TSS hardware was the TSS-1R mission, which involved the deployment of a 1.6 meter diameter, spherical conducting satellite, connected by a electrically-conducting tether, the tether being insulated from the ionospheric plasma. There were twelve science investigations, several of which were designed to explore space plasma-electrodynamic processes, particularly involving the generation of ionospheric currents. One of the major surprises of the TSS-1R mission was in the current collected by the TSS versus the voltage that exceeded theoretical expectations by factors of 2 to 3.

## IV. ATMOSPHERIC SCIENCE

The study of the troposphere and stratosphere is intimately linked with human activities, and several studies focused on the detection and monitoring of the transport of atmospheric pollutants on a global scale. We now know, for example, that widespread burning of grasslands and forests in South America, Africa, and Australia are major sources of carbon monoxide and ozone in the southern hemisphere, observed to travel between continents and across oceans. Spacelab investigations also tracked the spread of industrial pollutants between continents as well, underscoring the global nature of these problems.

Some of the instruments involved in the study of atmospheric physics from various Spacelab missions and the contributions they made are described in the following.

The ATMOS (Atmospheric Trace Molecules Observed by Spectroscopy) is a Fourier transform infrared spectrometer that is designed to study the chemical composition of the atmosphere by observing the absorption spectra when the atmosphere is between the Sun and the instrument. The primary objective for the ATMOS experiment was to make simultaneous measurements of as many trace atmospheric constituents as possible and to provide height to volume mixing ratio profiles of these gases. It was flown on OSTA 3, Spacelab 3, ATLAS 1, ATLAS 2, and ATLAS 3. Observations of vertical profiles of stratospheric trace gases not previously measured, including  $\text{N}_2\text{O}_5$  (nitrogen oxide),  $\text{ClONO}_2$  (chlorine nitrate),  $\text{HO}_2\text{NO}_2$  (peroxynitric acid),  $\text{CH}_3\text{Cl}$  (methyl chloride),  $\text{COF}_2$  (carbonyl fluoride), and  $\text{SF}_6$  (sulfur hexafluoride), were made by this instrument. The following is a quote from the ATMOS team:

“Today we are aware of some forty different molecular species in the atmospheric inventory, all of which play a role in the chemistry of the atmosphere and in its interaction with the Sun’s radiation. In the past decade, research into many interrelated questions about the Earth’s atmosphere has made scientists aware of the complexity of the processes that affect it, and has drawn attention to the need for more detailed studies in order that these processes can be better understood. This, in turn, has shown the need for a means by which global measurements can be made of the composition and temperature of the atmosphere and their variability.”

The Grille Spectrometer flown on Spacelab 1 and ATLAS 1 works on the same principle as ATMOS. It measures absorption and emission profiles of molecules on a global scale in the stratosphere and mesosphere.

The Imaging Spectrometric Observatory (ISO), flown on Spacelab 1 and Atlas 1, measures thermospheric emissions over a broad wavelength range (extreme ultraviolet to near infrared). ISO studied the chemistry and photochemistry of the mesosphere and thermosphere. It was also used in several studies that helped quantify the initially baffling problem of identifying the source of the ‘shuttle glow’ that interfered with remote sensing investigations from space. The instrument development effort for this investigation led to new instruments, including a compact spectrometer and the Ultraviolet Imager (UVI), currently operational on the GGS POLAR (Global Geosynchronous Science (Wind and Polar Missions)) spacecraft. In the delay following the Space Shuttle Challenger accident, the ISO was used as a ground observatory from McDonald, Texas. ISO obtained the first space based measurement of ground state OH (hydroxyl) in the mesosphere, the first dayglow altitude profiles of  $\text{N}^2\text{P}$  at 346.6 nm (which provided the first examination of photochemical sources and sinks in normal daytime thermosphere uncontaminated by auroral emissions), and the first simultaneously acquired altitude images of nitric oxide (NO) gamma band temperature and intensity in the thermosphere.

The Atmospheric Lyman Alpha Emissions (ALAE) was flown on Spacelab 1 and ATLAS-1. The instrument is a spectrophotometer that measures the absolute intensity of the deuterium (D) emissions. Measurement

of the Lyman  $\alpha$  emission of deuterium atoms offers a new possibility to probe the chemically active region where water (and HDO, known as heavy water) is photodissociated, the D atoms serving as the most appropriate proxy to the H (hydrogen) atoms that cannot be observed directly. The AEPI (Atmospheric Emissions Photograph Imaging) also provided observations of gravity waves, not by building up data, but by two-dimensional imaging of the airglow emissions.

Measurement of Air Pollution from Satellites (MAPS) was flown on OSTA-1, OSTA-3, and SRL-2. The MAPS experiment measures the global distribution of carbon monoxide (CO) mixing ratios in the free troposphere. The MAPS instrument made observations of biomass burning in the South American Amazon Basin and southern cerrados, the African savannahs, and the Australian grasslands and ranches to demonstrate that forest burning in remote locations can contribute to enhanced CO and O<sub>3</sub> (ozone) levels that can be transported large distances from the burn sites. These data were responsible for finding that carbon monoxide concentrations in the troposphere are highly variable around the planet, and that widespread burning is a major source of carbon monoxide in the southern hemisphere and tropical troposphere.

The Millimeter-wave Atmospheric Sounder (MAS), flown on ATLAS-1, -2, and -3, is a shuttle-based, limb-scanning spectrometer. It measures emissions from six mm-wave transitions of four molecular species: O<sub>3</sub>, H<sub>2</sub>O, ClO, and O<sub>2</sub>. From these measurements, abundance profiles and temperatures are deduced. The MAS performed the first measurements of latitudinal variation of mesospheric nighttime O<sub>3</sub> and H<sub>2</sub>O, an accomplishment that is also an example of the next class of observations: observations conducted on an extended scale.

The Shuttle Solar Backscatter Ultraviolet (SSBUV) has been flown on a large number of Shuttle missions, including OSTA-1, OSTA-3, Spacelab-1, Spacelab-2, ATLAS- 1, ATLAS- 2, ATLAS- 3, and USMP-2. The SSBUV flights support the long-term global stratospheric ozone and solar UV monitoring programs by providing repeated checks on the calibrations of UV ozone and solar monitoring instruments flying on domestic and international satellites. The SSBUV's value lies in its ability to provide highly accurate ozone measurements. The instrument is calibrated to a laboratory standard before flight, then is recalibrated during and after flight to ensure its accuracy. These laboratory standards are calibrated routinely at the National Institute of Standards and Technology (NIST). The rigorous calibration has been maintained since the beginning of the SSBUV flight series.

The SSBUV instrument detected and verified a significant decrease in the amounts of total Northern Hemisphere ozone between the ATLAS-1 (March 1992) and ATLAS-2 (March 1993) missions. This depletion also was detected simultaneously by satellites and ground-based observations. Indications are that total ozone decreased during the same period on the order of 10 to 15 percent at mid- latitudes in the Northern Hemisphere. Scientists believe that this significant depletion resulted from the combined residual effects of Mt. Pinatubo aerosols in the stratosphere and cold stratosphere temperatures during the winter of 1992/ 93.

The Cryogenic Infrared Spectrometers and Telescopes for the Atmosphere (CRISTA) with the Middle Atmospheric High Resolution Spectrometric Investigation (MAHRSI) flew on the German Space Shuttle Pallet Atmosphere Satellite (CRISTA/SPAS), as part of the ATLAS-3 mission. CRISTA acquires global maps of temperature and atmospheric trace gases with very high horizontal and vertical resolution. MAHRSI's primary objective is to measure limb intensity profiles of the resonance fluorescent scattering of sunlight by hydroxyl (OH) in the altitude region from 38 to 90 km, and by nitric oxide (NO) in the region from 48 to 160 km. The CRISTA-SPAS platform is deployed using the Shuttle manipulator arm and traveled some 50 to 100 km behind the shuttle. After eight days it was retrieved and returned to Earth.

The ATLAS-3 mission was complemented by the CRISTA/MAHRSI campaign to provide ground truth and other coordinated measurements including monitoring of the atmospheric background by ground based, aircraft, balloon, rocket and satellite experiments. The first campaign took place from October 27 to November 25, 1994 and included over 32 rockets, 56 balloons, and ground based experiments at 42 locations. A second campaign was carried out in support of CRISTA 2 that was deployed from STS-85.

The scientific contributions to atmospheric science from the Spacelab missions can be summarized as:

- A greater understanding of the chemistry and transport of the atmosphere, from the lower troposphere to the upper thermosphere, but with greatest emphasis on stratospheric trace gases and especially stratospheric ozone. The contribution from these investigations can be grouped into four categories: observations made for the first time or of a unique event, observations made over an extended period of time or an extended spatial extent, observations detailed enough to provide heretofore unavailable constraints for model development and investigation, and correlative observations with other investigations.
- Increased knowledge of the impact of human activities on the lower atmosphere. Examples include transport of pollutants (both industrial and from biomass burning) across continents and oceans. This category can also include the studies of the optical glow environment of the space shuttle, since this must be understood and corrected for in any shuttle-based remote sensing investigation.
- Unprecedented opportunities for correlative studies and validations between multiple observing platforms, which are vital for quantitative atmospheric studies.

Do we now view the atmosphere in a fundamentally or revolutionarily different manner because of the Spacelab investigations? In the greater picture, probably not; but in the details, undoubtedly so. Atmospheric models, and our understanding of them, are now constrained to match a new wealth of observations. This is the principal contribution of the Spacelab atmospheric investigations.

## V. EARTH OBSERVATIONS

The dual Spaceborne Imaging Radar-C (SIR-C)/X-band Synthetic Aperture Radar (X-SAR) was flown aboard the Shuttle Endeavor during the April and October 1994 missions, SRL-1 (STS 59) and SRL-2 (STS 68). The SIR-C system records data at both L-band (23.5 cm) and C-band (5.8 cm) with full polarimetric scattering, while the X-SAR is capable of recording data in the X-band (3.1 cm) with copolar polarization only. The integrated system records data simultaneously at incidence angles ranging from 15° to 60° with image resolution varying from 10 to 50 m depending on system configuration. The SIR-C/X-SAR is a considerably more advanced airborne imaging radar compared to satellite mounted instruments such as the European Remote Sensing Satellites (ERS-1 and -2), the Japanese Remote Sensing Satellite (JERS-1), or the Canadian RADARSAT, with more than 1000 times their spatial resolution.

The impact within the remote sensing and earth science communities of the two SIR-C/X-SAR missions was demonstrated early on by the large number of sessions and papers devoted to the subject at the 1995 International Geoscience and Remote Sensing Symposium (IGARSS'95) sponsored by IEEE. Significant interest carried over to the subsequent IGARR Symposia in 1996, 1997 and 1998 as well. Subsequently, three major journals within the earth science and remote sensing communities devoted special issues to presentation of the results of the missions. These issues were *IEEE Transactions on Geoscience and Remote Sensing* (33(4), 1995), *Journal of Geophysical Research* (101(E10), 1996), and *Remote Sensing of Environment* (59(2), 1997). In addition, most of the investigators associated with the missions have published significant articles in journals within their specific disciplines and dozens of other scientists not directly associated with the original missions have incorporated the data into their research and continue to publish results.

The earth science applications associated with SIR-C/X-SAR data can be grouped into six broad categories:

- Oceanography (including wave observations)
- Ecology (forestry, agriculture, wetlands)
- Hydrology
- Geology and geomorphology (including vulcanology)
- Precipitation and climate (including glaciology)
- Surface mapping and topography.

### A. Oceanography

The oceanographic studies associated with the SIR-C/X-SAR missions consisted of investigations of the capability of the system to measure important wave properties such as significant wave height (SWH), wave number and propagation direction; and to observe surface frontal boundaries separating cold and warm water masses. An on-board processor developed at Johns Hopkins University produced real time images of ocean wave spectra from the C-band signal. A primary goal of the wave study was to incorporate these real time observations into a numerical wave model in order to correct and update model predictions in real time.

The principal development of the wave studies appears to be the conclusion that low orbit radar data can sufficiently distinguish important wave properties in real time such that they can be used to improve numerical wave forecast models. Improved wave forecasting would be very valuable in many instances, including severe weather situations such as hurricanes, or in the case of waves generated by tsunamis.

Another result of the ocean studies was that frontal boundaries were identified on the SAR images during the October flight and that these boundaries closely agreed with field observations and data obtained from conventional thermal and infrared satellite sources. Boundary movement was also successfully observed by using images from successive shuttle overpasses. Frontal boundary location and movement can have important consequences in terms of weather occurrence and fisheries productivity as well as on water quality issues such as hypoxia and algal blooms. However, the advantages of observing frontal characteristics from microwave radar measurements in lieu of currently available thermal and infrared instruments are unclear.

## **B. Ecological Investigations**

The ecological studies associated with the SIR-C/X-SAR missions can be grouped into the categories of forestry, wetlands, and forest/nonforest land use classification. The forestry studies consisted primarily of classification and mapping of forest spatial structure, and classification of growth stages and above ground biomass estimation. Forestry studies were focused on both northern latitude hardwoods in Michigan, Maine, Germany, and on the southern rainforests of Brazil. Attempts were also made to combine forest growth models with a radar backscatter model to improve image analysis.

Reported results using the SAR data for forest spatial classification were decidedly mixed. The spatial structure recognized on the SAR images was successfully related to forest management practices such as logging or storm damage. The range of results on classification and spatial mapping of forest types is at least partially due to the different physical and environmental conditions at the various sites. Some sites were in cold regions, others were in southern rainforests; some were in flat terrain while others were in mountainous regions, and in some cases snow covered the canopies while in others it did not. These results appear to show that classification and mapping algorithms for SAR data can accurately distinguish broad classes, but that algorithms that would be generally applicable over a range of conditions may be difficult to develop.

The results for biomass estimation from SIR-C/X-SAR data were fairly consistent even though environmental factors are known to affect these estimates as well. The results appear to show that forest biomass can be predicted with sufficient accuracy over a variety of environmental conditions to allow radar data to be used as a significant forest management tool. Forests cover a substantial portion of the earth's surface and the carbon contained in their biomass is an important component of the global carbon budget. The success of these missions in predicting forest biomass clearly indicates the importance of active microwave measurements in analysis of the global carbon cycle.

Wetland analyses focused on identification of wetland flooding cycles during the dry (April) mission compared to the wet (October) mission over the Yucatan Peninsula. Changes from dry or partially flooded to complete inundation could be easily detected; however, changes from dry to partially flooded could not be detected by any configuration. Based on the radar configurations tested, it was concluded that a combination of ERS-1 and 2, and Radarsat might function to detect seasonal flooding of most wetlands, excluding partial flooding.

Land use classification investigations focused primarily on discrimination between forest and non-forested areas. In all of these analyses, under differing environmental and physical conditions, the SAR data were uniformly successful in separating forest from non-forest areas. Accuracies ranged from 87% to nearly 100%. The ability of active microwave measurements to discriminate forested areas, as well as forest classes, and to accurately estimate forest biomass and carbon storage, makes this technology extremely promising as a tool in global change analysis.

### C. Hydrology

The hydrologic investigations associated with the subject missions dealt with the capability of the SIR-C/X-SAR data to estimate soil moisture under a variety of soil types, surface roughness, and moisture conditions, and to map the spatial structure and estimate equivalent water content of non-glacial snow pack. The estimation of soil moisture content from remote sensing sources has thus far been an intractable problem in hydrology and has become a major focus of research). Most of this research has focused on the use of visible-near infrared (IR) or passive microwave instruments. Problems with this approach include the relatively coarse spatial resolution of these instruments and their ability to only sense the surface moisture. Active microwave instruments do not exhibit these problems and, consequently, their employment in hydrology is one of the most promising developments in recent years. The SIR-C/X-SAR missions offered the first opportunity to use multi-frequency, multi-polarization airborne data to study soil moisture signals over a variety of climates, vegetation and soil types ranging from Manitoba, Canada to Oklahoma, USA, to Orgeval, France. For this reason, it potentially represented a major step in the development of algorithms to relate vertical soil moisture profiles to radar backscatter.

The shuttle missions coincided with major field campaigns to measure soil moisture in Manitoba, Canada, the Little Washita basin in Oklahoma, and the Orgeval watershed in the Brie region of France. Given the ability of the longer wave length radar signals to penetrate the soil surface, active microwave instruments have the potential to measure not only surface soil moisture content, but vertical soil moisture profiles as well. Unfortunately, observed backscatter signals are influenced not only by the soil properties of the surface under investigation, but also by the surface topography, roughness and vegetation characteristics. Past research has focused on the use of these data to estimate moisture profiles primarily on bare soil under relatively smooth surface conditions. Effective algorithms have yet to be developed to correct the radar backscatter signal for variations in surface roughness or vegetation. The two SIR-C/X-SAR missions had the potential to lead to significant improvements in current methodologies; however, this potential does not seem to have been fully realized as of yet. As the data collected during the missions are obviously still available, it is hoped that some of the more important problems associated with remote sensing of soil moisture, for example, vertical profile estimation throughout the active zone and correction for vegetative cover and surface roughness, will continue to be addressed in future research. Until this is done, operational use of remote sensing instruments for soil moisture estimation will not be realized.

The results of the snow pack experiments may have more immediate practical applications than the soil moisture investigations. The ability to map snow cover and to estimate the equivalent water content of snow packs can be a great aid in the estimation of spring snow melt runoff from mountainous regions. Snowmelt provides the essential runoff for replenishment of reservoir stocks in many parts of the world (for instance, the western United States). The ability to accurately estimate the volume of this runoff in advance would be a great benefit to hydrologists, hydropower operators and water supply managers. The SRL-1 and -2 missions demonstrated the ability of multi-frequency, multi-polarization data to accurately discriminate between snow covered and non-snow covered regions in areas of high topographic relief (without the aid of topographic maps) and to estimate equivalent water content of snow cover. Ratio backscattering coefficients at the different frequencies could be adjusted to enhance the images and the estimated wetness values compared well with ground observations over the test site. It was also demonstrated that different frequencies (35 GHz and 5.3 GHz) could be employed to discriminate between layers of snow pack based on temperatures and wetness.

## **D. Geology and Geomorphology**

The geological and geomorphological investigations associated with the missions focused on observation of sand covered features in Arabian deserts, mapping of volcanic lava fields and observations of associated deformations and mapping of alluvial flood plains. The restricted range of wavelengths of the SIR-C/X-SAR instruments (3.1 cm to 23.5 cm) limits the penetration range of the beams and thus restricts the application of the system in subsurface investigations. The L-band copolar (HH) data was used to penetrate up to 4 m of sand in the Arabian Peninsula to reveal older geologic features such as drainage channels. The X-band (VV) data could also penetrate up to 3 m of sand. The C and L-band data were employed in an Egyptian desert overlain with a shallower (2 m) sand layer and produced enhanced images that were able to reveal deeper rock formations and fractures, along with shallow quaternary drainage channels. These results suggest that L-band copolar data at small incidence angles may be able to detect shallow groundwater deposits in arid regions- a potentially valuable contribution.

The volcanology investigations focused on analysis of lava fields and geologic structure and deformation of volcanoes in southern Italy and Kilauea volcano, Hawaii. C and L-band copolar (HH) and cross polar (HV) data revealed lava fields of different ages (5000 years and 10,000 years) and were able to separate lava fields from undisturbed areas. In the Lattari and Picentini mountains, three sets of geologic lithologies were identified and fault lines were clearly evident on the images. The Kilauea volcano studies attempted to measure the deformation that occurred in the time span between the two missions, as well as short term (daily) deformation between successive passes on the same missions. A vertical deformation of up to 14 cm was observed over an area of several km<sup>2</sup> around the volcano in the time between the two flights. Comparisons with GPS field measurements showed that while the maximum deformation agreed to within 2 mm, estimates of the deformation did not correspond to the field measurements at any one point in the field, implying that the radar data can detect general deformation trends over large areas, but not exact geographical values. It was also found that the L-band data was superior to the C-band for vegetated areas for these analyses.

C and L-band multi-polarization data were also used to map areas of flooded forests in the Amazon rainforest and to discriminate between vegetation classes corresponding to water tolerance. This study was part of an ongoing investigation to quantify methane fluxes and production of Amazon rainforests. Vegetation classes corresponding to different rates of methane production were successfully identified.

## **E. Precipitation and Climate**

Precipitation and climate studies focused on the use of multifrequency, multipolarization radar data to estimate rainfall rates and classify precipitation types and to observe glacier dynamics. The shuttle missions afforded the unique opportunity to observe storm dynamics associated with Cyclone Odille (April, 1994) and Typhoon Seth (October, 1994) using a variety of radar frequency/polarization configurations. Quantification of rainfall rates was approached as an inversion problem, for example, estimating the radar parameters most likely to have produced the observed scattering profile. As such, the collected data provided an opportunity to develop and test inversion algorithms to be employed with the Tropical Rainfall Measuring Mission (TRMM) satellite that was launched in 1997. Rainfall profiles were obtained from the C-copolar (VV) and X-copolar (VV) scatterometer data. The inversion algorithm demonstrated that rain rates could be estimated within small error bounds at higher altitudes (> 7 km), but that error increased greatly at lower altitudes and was greatest at heights less than 5 km. Rainfall mechanisms could also be accurately discriminated, as convective rainfall was separated from stratiform dynamics.

There is a relationship between glacier dynamics and long term climate change. Northern latitude glaciers in Austria were studied as well as southern glaciers in Chile. The focus of the studies was to map the extent of the glaciers, estimate ice velocities, observe glacial calving (separation), and attempt to identify areas within the glacier field of accumulation or ablation. In some cases, equivalent water content of glacial snowpack was also estimated. Glacier dynamics are studied by radar interferometry; the phase differences between two images acquired at different passes at the same incidence angle are related to the surface displacement of the glacier. In this case, the L-band and C-band data were acquired on each pass at a spatial resolution of about 30 m, and the interferograms were computed for each band. Image analysis can be employed to determine the direction and rate of ice flow and to identify areas where ice is accumulating or abating. The Moreno Glacier in the southern Patagonia icefield showed a displacement of about 17 cm/d over the period of the October mission to an accuracy of 2 cm/d, and the glacier shows a net annual accumulation of 5540 mm of equivalent water to an accuracy of +/- 500 mm.

## **F. Surface Mapping and Topography**

The surface mapping investigations associated with the April and October 1994 shuttle missions were focused on the development of relationships between measured backscatter from the SIR-C/X-SAR radars and surface roughness and topographic characteristics. A foreground/background inversion scheme was able to separate surface roughness signal from background noise through filtering of the different radar frequencies. However, the signal to noise relationship was a significant function of roughness scale and frequency. Large scale features could be accurately identified as could small scale features to some degree. Intermediate scale features were more difficult to identify. It was possible to identify four levels of surface features from the data; however, it was concluded that a stable algorithm must sacrifice roughness resolution.

## **G. Summary and Conclusions**

Due to the nature of earth science investigations, it is not to be expected that some fundamental breakthrough in understanding of the physical or biological processes under observation could be realized from one or more short term remote sensing missions. The measurements obtained during these missions represent mere snapshots of the processes under the particular set of environmental conditions which prevail at the time of the missions. Thus, fundamental knowledge of the processes must be gained from repeated observations under the full range of conditions which can occur at the test sites, and enough sites must be tested in order to gain sufficient information to make informed inferences. This is necessarily a slow and tedious process. However, progress can be and has been made from discrete missions such as the two SIR-C/X-SAR flights in three categories:

- Clear demonstrations of the capability of active microwave instruments to measure some processes that have important scientific or practical value, and thus provide impetus for further mission or satellite development.
- Development and testing of algorithms that can be employed with current satellites or other instruments to enhance their productivity or usefulness.
- Advance basic algorithm development to use microwave backscatter measurements to observe and understand important physical or biological processes with scientific or practical implications.

It is clear that the SIR-C/X-SAR missions made significant contributions in all three of these areas. Clearly, the most important of these is the very significant progress in the first category. In the areas of forest mapping and biomass estimation, ocean wave observations, rainfall quantification, snow cover mapping and

estimation of water content, glacier observations, and crustal deformation associated with volcanoes and earthquakes the SIR-C/X-SAR results provided convincing evidence of the ability of the instruments to provide accurate measures of quantities associated with these important processes. The results of these missions contributed significantly to the utility of the Tropical Rainfall Measuring Mission (TRMM) satellite launched in 1997 to observe and quantify tropical rainfall and to the decision by NASA to design and launch an active microwave satellite soon. The operation of these satellites has the potential to make tremendous contributions to basic science and may have great practical impact on the lives of the people of the United States and elsewhere.

## VI. MICROGRAVITY PHYSICAL SCIENCES

### A. Microgravity Fluids and Combustion Research

The study of the behavior of fluids in microgravity is fundamental to the understanding of virtually all other microgravity sciences since the suppression of fluid flows resulting from buoyancy effects is the primary reason for most microgravity experiments. (The exceptions being cases in materials science where the hydrostatic head may cause deformations in extremely weak solids or in the life sciences where there is evidence that the unloading of the cytoskeleton may be responsible for altered cellular behavior.) As a result, many of the fluids experiments were aimed at providing information to support the materials science experiments. One of the striking features in much of the research on the behavior of liquids in space is the importance of capillary or interfacial phenomena after buoyancy effects are essentially removed. Clearly these phenomena are present in normal gravity, but are usually neglected because their effects are often masked by buoyancy-driven flows. The ability to uncouple gravity effects from non-gravitational effects, so that the latter can be studied in more detail, has been one of the primary justifications for the study of fluid phenomena in microgravity.

Combustion experiments in microgravity are a special case of fluid experiments in which chemical reaction must be included. However, the motivation for performing this class of experiments in space is basically the same; the need to separate gravity-related from non-gravity related effects and to use the simplifications obtained by effectively eliminating convective transport in order to gain a better understanding of the basic principles involved. It is also important to understand combustion in the virtual absence of gravity to develop design criteria and emergency procedures for dealing with fire safety in the operation of manned laboratories in space.

#### 1. *Capillarity Effects.*

Capillarity effects are responsible for liquids wetting and spreading over surfaces (or failing to wet and spread). Water will rise in a clean glass capillary tube as the surface tension pulls the column of water up the tube until its force is balanced by the weight of the column. Without gravity, the liquid will continue to rise until it fills the tube. However, this can only happen if the water wets the surface. By this, we mean that the presence of the water lowers the surface energy of the glass such that the free energy of the system is reduced. Mercury, for example, does not wet glass, hence a column of mercury is forced downward in a capillary tube.

Atoms or molecules in the interior of a solid or liquid have molecular bonds with their nearest neighbors which lower their energy. (Energy must be added to vaporize the material in order to free these molecules.) All surfaces have an excess of energy (compared to their interior) because some of the bonds are not satisfied owing to the lack of nearest neighbors. In the case of water on clean glass, the water molecules partly satisfy the bonds on the surface of the glass, but there is still an excess of energy, called the interfacial energy, due to the fact that the water-to-glass bond is not as strong as glass molecule bonds. Of course, the water also has a surface energy (which in liquids is called the surface tension), so it costs energy for the liquid to spread over the solid. Under static conditions, in the absence of other forces, the configuration of a drop of liquid on a solid is determined by the balance of the forces associated with these surface energies. The contact angle, which is the interior angle between the liquid and solid, is related to the surfaces energies by Young's equation,  $\gamma_{LV} \cos \theta = \gamma_{SV} - \gamma_{LS}$ , where  $\theta$  is the contact angle,  $\gamma_{LV}$  is the liquid-vapor surface energy or surface tension,  $\gamma_{SV}$  is the solid surface energy and  $\gamma_{LS}$  is the interfacial energy between the liquid

and the solid. One may see that the contact angle will be less than  $90^\circ$  when the liquid-solid interfacial energy is less than the solid-vapor surface energy and we say the liquid wets the solid. If the liquid-solid interfacial energy is greater than the solid-vapor surface energy, as is the case between mercury and glass, the contact angle is greater than  $90^\circ$  and the droplet tends to bead up on the solid surface. (Under certain conditions, in the absence of gravity, the droplet will actually be repelled from the surface.) If the sum of the solid-liquid interfacial energy and the surface tension is equal or less than solid-vapor energy, the contact angle goes to zero and the liquid will spontaneously spread over the solid surface. Such a liquid is said to be perfectly wetting.

In normal gravity, the hydrostatic energy generally overwhelms the capillarity forces; hence their effects are manifested only in the vicinity of the liquid-solid wall contact where they form a meniscus. However, in microgravity capillarity forces determine how a liquid will be distributed in a partially filled container. The situation becomes more complicated under dynamic conditions in which the contact line is required to move. There is a sort of static friction or stiction that tends to restrict the motion of the contact line and this stiction depends on whether the contact line is advancing or receding. It becomes important to understand how these forces operate in order to be able to design fluid systems that will operate predictably in space. Examples include being able to control the distribution of fuel in a tank or designing an anti-spread barrier to restrict the motion of a liquid in an open container.

A variety of experiments were conducted in which the configuration of liquids in partially filled containers was observed as the containers were rotated and shaken. The results were compared against computer models to determine how well such effects could be predicted. One particularly interesting set of experiments involved the behavior of liquids in chambers in which the fluid configuration was mathematically indeterminate (for instance, different configurations had the same configurational energy) in order to see how nature would deal with this situation.

## *2. Floating Zones.*

Microgravity offers the chance to conduct experiments with free liquid surfaces on a scale not possible on Earth. One process of interest to materials scientists is the use of a floating zone for crystal growth. A molten zone is created in a rod of feed material and is traversed along the rod. New feed material enters the advancing zone and a single crystal can be grown at the receding interface. The melt is supported by its surface tension, thus eliminating any wall contact that could contaminate the melt and induce various growth defects. Unfortunately, the size zone that can be supported by surface tension is limited to only a few millimeters in normal gravity.

Of primary interest is the stability of such zones. More than 100 years ago, Lord Rayleigh showed that a cylindrical liquid column would become unstable and break if the length exceeded the circumference. But what happens if the zone is not cylindrical? Or vibrated by mechanical disturbances in the spacecraft? Or if it is rotated, which is sometimes done to even out asymmetries in heating? Many of these questions had been approached theoretically and experimentally using neutrally buoyant immiscible liquids similar to the work carried out by the Belgium physicist, Plateau, over a hundred years ago. But these configurations had never been tested in an actual microgravity situation. As was discovered when an unexpected “jump rope” or C-mode instability showed up in a simple rotating liquid zone experiment on Skylab, the presence of a neutrally buoyant solution in a Plateau tank is a different boundary condition, which can often change the result of an experiment. Using the fluid physics module on SL-1 and D-1, the ability to model the behavior of such zones and to predict various instabilities was confirmed experimentally.

The surface tension of a liquid is also influenced by the presence of electric fields and can play an important part in miniature fluidics systems, which use electrocapillarity effects for pumping and manipulating fluids. Presently, the “leaky dielectric” theory developed by G.I. Taylor in 1966 is the only electrohydrodynamic theory applicable to this phenomenon and this theory had remained largely untested. It was shown on the Life and Microgravity Science (LMS) flight that liquid columns could be stabilized at lengths well beyond the Rayleigh limit by applying strong DC (direct current) fields. However, contrary to the theoretical predictions, AC (alternating current) fields failed to stabilize the liquid columns at frequencies above the free charge relaxation times and a hysteresis effect was seen in the field required to stabilize the zone that depends on whether the field is increasing or decreasing. Now the investigator team is sorting out which aspects of Taylor’s theory are correct and which parts need improvement.

### *3. Surface Tension Driven (Marangoni) Convection.*

In floating zone crystal growth, there will be thermal and compositional variations along the axis of the zone. Since surface tension is a function of both temperature and composition, the unbalanced surface forces will cause flows along the surface that are often referred to as Marangoni flows after the Italian physicist. These return flows in the interior of the zone will tend to mix components, which may or may not be desirable, depending on the experiment. Above a certain Marangoni number, a dimensionless parameter that measures the ratio of heat conducted by the flow to the conducted heat, the flows become unsteady, a situation that must be avoided in a crystal growth experiment. Again the ability to model such flows and to predict the onset of unsteady flows was experimentally confirmed on SL-1 and D-1.

Surface tension-driven flows along planar surface are important in many processes on Earth, such as crystal growth using the Czochralski process and pool burning (these flows may be seen in the wax pool of a burning candle as they bring new fuel up to the wick). In Earth’s gravity, these flows are in competition with buoyancy-driven flows and it is difficult to sort out the two effects. Microgravity offers the chance to study such flows without the influence of gravity, and these flows were the topic of a variety of experiments on a number of missions. One of the controversies in the ability to predict the onset of unsteady flows was the role of surface deformation. This issue was settled on USML-2 when it was shown that a critical Marangoni number alone was not sufficient to predict the onset of instability and that an additional surface parameter must be specified.

### *4. Bubble, Drop, and Particle Interactions.*

The bubble, drop, and particle unit (BDPU) developed by ESA and flown on D-2, IML-2, and LMS, proved to be an excellent workhorse facility for a variety of experiments ranging from the behavior of drops and bubble to pool boiling and even electrohydrodynamics. A drop or bubble in a thermal gradient will have unbalanced interfacial forces along its surface, which will tend to propel it in the direction of lower interfacial energy (usually from cold to hot). In 1959 Young, Goldstein, and Bloch developed a theory (known as the YGB theory) relating the motion of the drop to the Marangoni number. Since they did not have access to a microgravity environment, they tested their theory by balancing the surface tension forces against buoyancy forces on very small bubbles. One of the controversies in their theory was their assumption of a spherical drop and if the drop would be deformed under the combined effects of interfacial tension and Stokes drag. Motion of drops and bubbles in temperature gradients is important in many microgravity processes such as the removal of unwanted bubbles in solidification experiments and in phase separation in systems containing immiscible phases.

A variety of experiments were conducted to test the Young, Goldstein, and Bloch model. It was shown that indeed the drops remain spherical and that they do move in the direction of decreasing interfacial energy, but the model is only correct in the limit of zero Marangoni number (very small size) since the model neglects the heat transfer from the Marangoni flow. Also it was found that bubble motion can be retarded by the presence of certain components such as phenol groups in silicone oil which give rise to a “surface dilatational viscosity”. Similar effects prevented bubble motion in experiments using tetracosane (molten paraffin).

Since the velocity of a drop or bubble depends directly on the radius, larger drops would be expected to overtake and engulf smaller drops. This effect is believed to be one of the mechanisms in the agglomeration of minority phase droplets during the solidification of monotectic alloys. However, it was found that a small drop leading a larger drop can slow the motion of the larger drop. When multiple drops are present, they do not always follow a straight path across the chamber, as single drops did. Instead, they followed a sinuous, helical path around their expected trajectory. Sometimes a larger trailing drop would actually move around and pass the leading drop. It is believed that such effects are caused by thermal wakes left by the moving droplets that perturb the imposed thermal field.

### *5. Pool Boiling.*

It is generally assumed that heat transport in boiling is largely the result of buoyancy driven convective flows. The bubbles that nucleate on the hot surface rise, carrying their latent heat with them. Similarly, the hot liquid near the surface, being less dense, will rise, causing overturning flows, which also carry heat away. The practice of cooling small electronic devices by immersing them in a pool of dielectric liquid with appropriate vapor pressure, such as a Freon, was considered by many not to be feasible in space because it was assumed that vapor would form around the device resulting in inefficient heat transfer. However, this assumption was shown to be incorrect on the LMS flight. Small heaters in the form of copper discs 1 to 3 mm in diameter, representing electronic components, were immersed in Freon 123. Surprisingly, the measured heat transfer coefficients were only slightly less than those measured in unit gravity. Thermocapillary jets were observed which appear to be an effective mode of heat transfer in microgravity and should also be effective in terrestrial boiling. These results may cause the theories of boiling in normal gravity to be revisited and it may be possible to design systems that take advantage of capillarity effects along with buoyancy to improve the efficiency of boilers on Earth.

### *6. Drop Dynamics.*

The ability to suspend and manipulate liquid drops in microgravity provides an opportunity to test a number of classical theories describing the oscillations of liquid spheres. Confirmation of these theories using a tethered drop on Spacelab 1 and the drop physics module on Spacelab 3, USML-1, and USML-2 was crucial to the use of these theories to obtain various thermophysical properties of materials in their undercooled state on MSL-1R. The addition of various detergents to the drops on USML-2 illustrated how materials properties such as dynamic surface tension and shear, as well as dilatational surface viscosities, could be extracted from such measurements.

The drop physics module was also used to test the theory developed by Chandrasekhar describing the bifurcation of rotating drops that transitions from an oblate spheroid to a “dog bone” shape, which then fissions into two droplets. This theory has been applied to double star formation as well as to the liquid drop model describing nuclear fission. Earlier deviations from theory seen on Spacelab 3 were found to have been an effect of drop flattening from the acoustic pressure and the theory was found to be correct in the limit of spherical drops.

Other investigations carried out in the drop physics module elucidated the mechanisms by which core centering takes place in compound drops and liquid shells. Also non-linear effects from large amplitude oscillation, which eventually lead to chaotic behavior, were investigated. The former study has application to the fabrication of target shells for inertially confined fusion experiments, while the latter applies to methods for increasing the evaporation and/or combustion of droplets.

## *7. Critical Point Phenomena.*

A number of peculiar things happen in the vicinity of a second order or critical phase transition such as that which takes place at the terminal point of the coexistence region between a liquid and its vapor. Many of the thermodynamic properties change dramatically near the critical point, for instance, the velocity of sound as well as the thermal diffusivity goes to zero, while the heat capacity and compressibility becomes infinite. Other systems, such as a magnetic system near the Curie point (the temperature at which thermal motion becomes sufficient to destroy the magnetization), or the demixing of a homogeneous liquid into two immiscible liquids at the critical consolute temperature, exhibit similar behavior. The divergence of certain parameters near the critical point in each of these systems shows the same exponential behavior, thus leading to the theory of universal behavior near a critical phase transition, regardless of the system. Ken Wilson was awarded the Nobel Prize in 1982 for applying group renormalization theory to determine the exponential behavior of these diverse systems near a critical point.

Since the compressibility diverges near the liquid-vapor critical point, even the smallest temperature difference can cause very strong convection, thus making it difficult to make measurements near the critical point on the ground which are needed to obtain accurate values of the critical exponent. Several early attempts to measure how the heat capacity diverges near the liquid-vapor critical point on D-1 were frustrated by the very long time it took to approach the critical point because the thermal diffusivity becomes vanishingly small. However, in the process a new method for rapid heating by isentropic expansion, called the “piston effect”, was discovered. Using this technique on D-2, heat capacity measurements were made only 0.9mK away from the critical point, whereas the best ground based measurements could only be made 15 to 20mK away from the critical point. The critical exponential term agreed with the theoretical value to within experimental error.

Another experiment circumvented the problems with the liquid-vapor critical point by choosing to measure the heat capacity associated with the transition of liquid helium to superfluid helium, the so-called lambda transition because the shape of the heat capacity curve resembles the Greek lambda. In microgravity, it was possible measure to within a few nK of the critical point, almost 100 times closer than in normal gravity. This experiment, flown on USMP-1, has provided the most accurate test of Wilson’s theory.

A follow-on experiment on USMP-4 extended the heat capacity measurements near the lambda-point in which the helium (He) is confined to a spacing of 57 microns by carefully machined silicon (Si) discs. The objective is to test scaling predictions for the transition to a lower dimension system. Normally, this transition takes place only when the dimension is on the order of Angstroms, but in semiconductors it can be as large as 0.1 micron, a length being approached by modern electronics. Since the correlation length diverges near a critical point, the distance over which the transition occurs can be greatly magnified. Attempts are now being made to correlate the data from the flight experiment with theory and with other measurements.

## 8. *Geophysical Fluid Flow Studies.*

The geophysical fluid flow cell, flown on SL-3 and again on USML-2, made use of microgravity to study the three-dimensional flow in a rotating hemispherical shell with an electric field providing the gravity-like central force. By varying the rotation rate and heating mode, this facility could simulate flows in planetary atmospheres as well as on the sun or in the Earth's mantle. A variety of interesting flow structures was observed as rotation rates and equator to pole heating was varied. The observed flows were used to check 3-dimensional computational models. Rotation with spherical heating produced banded patterns not seen before in numerical simulations and may provide an alternative view of the mechanisms responsible for the observed structure of the Jovian atmosphere.

In slow rotation experiments, climatic "states" in the form of two distinct convective patterns were found to exist with the same external conditions, differing only by the initial conditions. These patterns are persistent and are insensitive to small changes in the external conditions. Data was obtained on how these states break down under larger changes in operating conditions. The transition from anisotropic north-south "banana convection" to the more isotropic convection was studied. This information may lead to a scaling argument for classifying different planetary atmospheres.

Other experiments with latitudinal heating show evidence of baroclinic wave instabilities and successfully showed how spiral wave convection breaks down into turbulence.

## 9. *Combustion Experiments.*

There are two compelling reasons for the study of combustion in microgravity. One is the issue of fire safety in the design and operation procedures of orbiting laboratories, the other is to take advantage of the weightless state to study certain combustion phenomena in more detail and to test various models in which convection has been ignored in order to be mathematically tractable.

As examples of the first category of experiments, smoldering combustion and wire insulation flammability studies were carried out using the glovebox on USML-1. Smoldering combustion can be extremely dangerous in a space station since it can remain virtually undetected for some time, but the increased temperature, due to the absence of convection to carry the heat away, can greatly increase the amount of toxic fumes generated. The wire flammability studies were carried out both without convection and with forced convection to simulate the behavior of a possible electrical fire in space.

The geometry and behavior of a candle flame was also studied using the glovebox on USML-1. Fiber supported droplet combustion experiments were carried out on USML-2. By tethering the droplets on a silicon fiber, they could be kept in the field of view of the video recorder so that the burning rate and other parameters could be recorded. The objective is to test theories of droplet combustion and soot formation that are of importance to improving the efficiency of internal combustion engines and gas turbine engines, as well as home and industrial oil burning heating systems. Microgravity allows to droplet size to be increased to as much as 5 mm so that the combustion process can be studied in detail. Once the theory is developed, its predictions can then be scaled back to the droplet sizes used in the actual combustion processes.

Soot formation in laminar flames was studied on the MSL-1R mission along with the Structure of Flame Balls at Low Lewis Numbers (SOFBALL) experiment. In the latter experiment, a container was filled with various combustible mixtures near their lean limit of combustion. A flame ball was created by an

electrical spark. A stationary spherical flame front develops as fuel and oxygen diffuse into and heat and combustion products diffuse out of the flame ball. This is the simplest possible geometry in which to study the chemical reactions and the heat and mass transport of lean combustion processes. Over 50 years ago, Zeldovich found that the equations for steady heat and mass conservation had a solution corresponding to a stationary flame front, but he also showed that the solution was unstable. He did, however, consider the possibility that heat loss might be a stabilizing factor, which is apparently the case since some of the flame balls lasted the full 500 seconds until the experiment timed-out. It is expected that these experiments will provide new insight on combustion processes in the lean burning limit, which are important in improving the efficiency of engines and heating systems.

## **B. Materials Science**

Materials science experiments carried out on Spacelab flights ranged from metals to glasses and ceramics, with the bulk of the work focused on alloys and single crystal semiconductors. The alloy solidification experiments generally fall into three general categories:

- (1) Experiments designed to understand how the microstructure evolves during solidification,
- (2) Studies of interfacial effects that control the distribution of second phase particles, and
- (3) Measurements of thermal physical properties.

### *1. Evolution of Microstructure.*

The strength and other properties of an alloy depend on its microstructure, which is characterized by the size, orientation, and composition of the grains that make up the solid. One of the main tasks of a materials scientist is to design solidification processes to produce the microstructure that will give the material the desired properties. With the present computational capability, it is possible to design a complex mold so that the heat and mass flow will produce the desired microstructure throughout the final casting. However, in order to do this, the basic laws governing the development of the microstructure must be known along with the thermophysical properties of the components. Establishing the physical basis for the various laws that describe the solidification process has, over the last half-century, transformed metallurgy from an industrial art based on empiricism to a more exact science. Because of the complicating effects of convection, many of the laws in use today are based on theories that assume no convective flows. We know that they don't apply exactly, but we use them anyway, assuming they are basically correct, and then try to fix them up by adding the effects of convection. But most of these theories have never been tested in the absence of convection so various subtleties may have been overlooked. The ability to experiment in microgravity provides an opportunity to test some of these theories to make sure they are basically correct.

One example is the theory developed in 1968 by Jackson and Hunt that describes the microstructure of a eutectic alloy when it is solidified. When a eutectic alloy solidifies, it separates into two solid phases with different compositions that form parallel lamellas along the direction of solidification. Jackson and Hunt showed that the spacing between these lamella times the square of the solidification velocity is a constant that depends on the diffusion coefficient and other properties of the material involved. Since a eutectic solidifies congruently, that is, a melt of uniform composition is transformed directly into a two-phase solid, there is little chance for convection to act, even in a gravity field and, indeed, the theory seemed to be correct. However, several early flight experiments found a larger spacing in their flight samples than in their ground control samples. This raised some interesting questions. Was there something wrong with the Jackson-Hunt model, or was something else going on in the microgravity environment that might account for the different spacing? One hypothesis was that thermal diffusion, sometimes referred to as the

Soret effect, might shift the composition of the melt at the solidification interface away from the eutectic composition, which could account for the different spacing. Soret diffusion is very difficult to measure on the ground because of convective remixing. Another hypothesis is that microconvection occurs in the melt in the vicinity of the solidification interface that increases the effective diffusion rate that governs the separation of the two phases, resulting in a closer spacing in a gravity field.

A series of eutectic solidification experiments were carried out on Spacelab 1, D-1, and D-2. All but one experiment found increased lamella spacing in the flight samples. Although Soret diffusion may be the dominant effect in some of the systems, there were no apparent compositional shifts in the others, which argues for the microconvection theory. Apparently, the Jackson-Hunt model works in normal gravity because the diffusion coefficient and other properties are not known precisely enough to calculate the constant accurately. (See later discussion concerning the measurement of diffusion coefficients)

In most alloy systems, all components in a melt do not enter the solid lattice at the same rate, resulting in a buildup of the rejected component in the melt ahead of the growing solid. This compositional shift raises the local freezing temperature in the melt ahead of the solidification front. If a uniform composition is required in the final solid, as is usual when growing single crystals of electronic materials, the material must be directionally solidified and a sufficient thermal gradient must be maintained ahead of the solidification front to assure that the temperature is everywhere above the local freezing point. Otherwise, the material becomes constitutionally undercooled, the plane solidification front breaks down and dendritic (fir tree-like) solidification occurs.

The transition from plane front solidification to dendritic solidification has been studied extensively. A simple criterion for the gradient required to stabilize the solidification front was developed in 1953 by Rutter and Chalmers, which is known as the constitutional supercooling or CS theory. Later, Mullins and Sekerka applied linear stability analysis and obtained a more refined theory for interfacial breakdown.

The French developed a sophisticated apparatus for studying the transition from plane front to cellular to dendritic solidification which measures the Seebeck voltage at the melt-solid interface to determine the amount of undercooling required to advance the solidification front and to detect the onset of interfacial breakdown. The official name of the apparatus is Materials for the Study of Interesting Phenomena of Solidification on Earth and in Orbit or MEPHISTO. One of the objectives of the flight on USML-1 was a definitive test of the Mullins-Sekerka theory in faceting as well as non-faceting eutectics. The apparatus was also used to investigate the effect of transient acceleration from a thruster firing on the solidification front.

In metallic systems, a fine grained structure is often preferred and the dendrite arms play an essential role in the evolution of the microstructure. Therefore, it is necessary to know how dendrites grow in order to design a given microstructure in a casting. Dendrites can form when solidification takes place in a medium where the surrounding temperature is lower than the local freezing temperature. This situation can occur either by constitutional undercooling in the case of alloy solidification, or by the fact that a certain amount of undercooling is required to nucleate the solid from either the melt or the vapor. A classic example of the latter is the formation of ice dendrites (snow flakes). Their intricate shapes have fascinated scientists and philosophers alike, and the study of their formation is the confluence of pure physics from the point of view of pattern formation and material science whose interest is in the evolution of microstructure in alloys.

A first attempt to model the growth of a dendrite was made by Ivantsov who approximated the trunk of a dendrite as a paraboloid of revolution and solved the heat flow equation that described the flow of the heat

of solidification into the surrounding medium. He was able to obtain the growth rate  $V$  as a function of tip radius  $R$ . However, there seems to be no fundamental relationship that would select either a specific tip radius or growth rate in a solidification process. The question becomes, how does nature select a unique operating state? Experimental observations of pure systems suggest that  $V R^2$  is either a constant for a specific material, or a weakly varying function of the undercooling. A large body of terrestrial data has been taken on several systems, but convection effects, especially in the crucial region of low undercoolings where the growth rate is comparable to the convective flow velocities, have prevented an adequate test of the selection rules governing this process. This was the motivation behind a set of flight experiments carried out on USMP-2, 3, and 4.

Dendrites were grown in transparent organic metal analogs, succinonitrile, which solidifies in a body centered cubic structure, and pivalic acid, which solidifies in a face centered cubic structure. The use of transparent systems allows direct observation of the growth process, from which growth and other data may be extracted. The measured product of tip radius and growth velocity in microgravity falls much closer to the Ivantsov solution than the terrestrial data. The slight deviations maybe attributed to the formation of side branches on the dendrites, possible wall effects from the growth chamber, and the fact that the observed shape of the dendrite tip is a slightly different shape from the parabola assumed in the Ivantsov solution. Now that the heat transfer away from the growing dendrite is properly accounted for, the physics of shape selection can be approached with reliable data. A large number of highly detailed photographs of dendrites growing under carefully controlled and well documented conditions are now being used to study other aspects of dendrite growth such as the side arm growth rates and spacing.

In the meantime, investigators on D-1 took advantage of the larger dendrites obtained by solidifying an aluminum-copper alloy at low velocities in microgravity. By taking multiple cross sections, they were able to reconstruct, for the first time, an actual dendrite formed in an opaque alloy system of practical interest. The resulting reconstruction provided valuable information on the secondary and tertiary arm spacing and on the ripening of the dendrite arms. On the LMS mission, grain refining inoculants were added to the system order to promote the nucleation of small grains ahead of the solidification front which grow dendritically in all directions, thus forming equiaxed dendrites. This allowed a test of a simple theory proposed by Hunt which relates the transition from columnar to equiaxed dendrites to the undercooling, the thermal gradient, and the number of nuclei, but ignores the effects of convection.

Ostwald ripening is responsible for grain growth and coarsening of the dispersed phase in dispersion hardened alloys. The original theory describing this effect was developed independently by Landau and Slyozov and by Wagner and is known as the LSW theory. But their theory is based on a mean field approximation that ignores the presence of other particles. Several theories have been proposed to correct for finite volume fractions of the dispersed phase but give quite different results. Microgravity experiments have provided data in molten systems without the complicating effects of convection, but are awaiting more accurate thermophysical data in order to properly evaluate the competing theories. It is interesting to note that Ostwald ripening also plays an important role in the development of ice grains that destabilize snowpacks and cause avalanches.

Other aspects of solidification were also studied in order to refine various models that are used to predict the final microstructure. These include liquid phase sintering and the study of order-disorder transitions.

## *2. Interfacial Effects.*

When an advancing solidification interface encounters a second phase object such as a particle or bubble, the object can either be engulfed by the advancing solid or pushed ahead. The critical velocity, above which the particle will be engulfed, depends of the size of the object as well as the thermophysical properties of both the host solid and the second phase object. Being able to predict whether an object is engulfed or pushed is important in the processing of dispersion hardened alloys, forming fiber-reinforced composites, and seemingly unrelated problems such the destruction caused by frost heave. Several theories that predict the critical velocity for simple systems have been tested and verified on five Spacelab missions, but issues still exist when the situation is complicated by a dendritic rather than planar solidification front, or when submicron particles agglomerate. One of the space experiments demonstrated that such agglomeration was not a gravity effect and that the van der Waals forces were not effectively shielded by the melt. These findings convinced one group of investigators that it was not practical to pursue attempts to form dispersion alloys by casting.

One of the first applications considered for microgravity was the formation of hypermonotectic alloys, alloy systems that have a region of liquid phase immiscibility. When solidifying such systems through the immiscible region in normal gravity, the denser liquid immediately settles out, resulting in complete phase separation. It was thought that this separation could be avoided by solidifying in microgravity, thus opening the door for hundreds of alloys that cannot be processed from the melt on Earth. Much to the surprise of the early space experimenters, these alloys also separated in microgravity, but for totally different reasons, many of which had not been considered previously. Such experiments have been carried out on seven Spacelab missions and have produced a wealth of information concerning spinodal decomposition, nucleation and growth of liquid phases, critical wetting and spreading, and Marangoni-driven droplet motion. These experiments also helped develop a terrestrial strip casting technique in which bismuth droplets are suspended in a molten Al-Si (alumina-silica) alloy by balancing gravity forces against Marangoni forces. The resulting solid is used for high performance, self-lubricating bearings.

Another industrially inspired series of experiments explored the use of a thin oxide coating to support the shape of a molten sample in the absence of hydrostatic pressure. The motivation was to eliminate the thermal conductance of the mold during the recrystallization of superalloy gas turbine blades. So called single crystal blades are actually aligned column dendrites interspersed with the last-to-freeze interdendritic fluid. When the very small oxide particles were added for dispersion hardening, they tended to clump together. Without the mold, it was hoped to be able to apply a higher thermal gradient so that plane front solidification could be achieved at high enough speeds to engulf the oxide particles.

Actual turbine blades were coated with thin oxide layers and directionally solidified on D-2. The complex blade shape was maintained even through cross sectional area changes for cast blades without the oxide particles. However, the evolution of trapped gases in the blades prepared using powder metallurgical techniques, where the oxide particles could be added, caused shape distortion and the particles still agglomerated because of other mechanisms. Even though the desired result was not achieved, this is an example of how an industry might use space to determine what the problem is not, which can be a valuable piece of knowledge.

## *3. Crystal Growth from the Melt.*

There are many difficulties in growing bulk single crystals of various electronic and photonic materials for use as windows and substrates for various devices. Since the properties depend on composition, it is

necessary that the composition be as uniform as possible over the wafer the device is to be fabricated on. Since dislocations scatter and trap electrons, the number of dislocations and other electron traps must be as low as possible. Small angle grain boundaries and twins affect device performance and must also be eliminated.

Maintaining a uniform composition is particularly difficult in the growth of multi-component, alloy type crystals such as  $\text{Pb}_{1-x}\text{Sn}_x\text{Te}$  (lead-tin-tellurium) or  $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$  (mercury-cadmium-tellurium) that are used for infrared imaging devices. The bandgap of these systems varies with the composition  $x$ , which allows one to tune the detector to the desired bandwidth, but also requires that  $x$  be uniform over the detection area in order for every element to have the same spectral response. Since the different atoms go into the lattice at different rates, obtaining a uniform composition becomes a difficult task. Usually such systems are grown by directional solidification using the vertical Bridgman method to minimize convection.

If the rejected component is more dense than the bulk melt, as is the rejected Hg-rich component in the case of  $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$ , the system is both thermally and solutally stable. The Hg-rich layer builds up in a diffusion layer in front of the growing crystal until an equilibrium is reached in which the Hg atoms enter the growing crystal at the same composition as they are in the bulk melt. After this transient region of varying composition, equilibrium growth should continue with uniform composition until the diffusion region encounters the end of the bulk melt. However, it is necessary to add heat to the melt through the sides of the growth ampoule and extract it through the growing crystal. This produces small radial thermal gradients in the melt causing the warmer fluid near the walls to rise while the cooler melt near the center falls. This circulation distorts the buildup of the diffusion layer at the growth interface, resulting in radial segregation. It was hoped to be able to avoid these flows in microgravity and grow crystals under diffusion controlled transport conditions.

Macrosegregation becomes a major problem in Bridgman growth of non-dilute or alloy-type systems when the rejected component is less dense than the bulk melt, as is the case in the Sn-rich rejected component of  $\text{Pb}_{1-x}\text{Sn}_x\text{Te}$ . When the diffusion layer builds up to a certain critical point, the lighter fluid will rise and remix with the bulk fluid. If the growth system is turned upside down to prevent this from happening, the system becomes thermally unstable. Thus it becomes impossible to stabilize such a system against overturning convective flows in the presence of gravity. Coriell performed a linear stability analysis on such systems that suggested that they might even be unstable in microgravity. Experiments using the NIZEMI centrifuge showed that Coriell's analysis was overly conservative since it did not include the stabilizing effects of the ampoule walls.

Being able to stabilize Bridgman-type growth systems presents a major challenge to the ability to control the residual acceleration of the spacecraft. When gravity is removed, the favorable density gradient no longer stabilizes the  $\text{HgCdTe}$  system and the slightest transverse acceleration will drive convective flows. The transport from these flows must be less than the diffusive transport if diffusion control is to be achieved. If the liquid diffusion coefficient is small, as it is for most of the systems of interest, the quasi-steady component of the transverse acceleration must be held to less than 0.1 micro-gravity (micro-g or  $\mu\text{g}$ ). Since gravity gradient accelerations are typically on the order of 1.0 micro-g, the axis of the furnace must be aligned nearly along the residual acceleration vector if this condition is to be met.

An attempt was made to align the Crystal Growth Furnace (CGF) along the residual acceleration vector on the USML-1 mission. However, the force from the venting of the flash evaporator system on the Shuttle resulted in an unanticipated 0.5 micro-g transverse acceleration. The  $\text{HgZnTe}$  (mercury-zinc-tellurium)

experiment (similar to HgCdTe) was accidentally terminated just as the growth was reaching steady state, but the effect of the transverse acceleration could clearly be seen in the composition of the sample. HgCdTe was flown on USMP-2 and PbSnTe was flown on USMP-3. However, in neither case was the Shuttle able to provide the necessary attitudes to satisfy the very demanding requirements needed to provide diffusion controlled growth. The major contributions from these experiments lies in the extensive research that went into their preparation in the form of measurements of pertinent thermophysical properties, analytical and computational modeling, and extensive ground based testing with and without strong magnetic fields. The measured redistribution of solute in the flight samples is being compared with the predicted values based on the accelerometer data in order to verify and refine the models that have provided a much deeper appreciation of the importance of convection in Bridgman crystal growth.

The unexpected 0.5 micro-g acceleration on USML-1 caused the melt in a CdZnTe sample to be nudged against one wall and become detached from the opposite wall. The side that solidified as a free surface had a much lower dislocation density than the side in wall contact and no evidence of twin formation was seen. This confirms an earlier observation on a semiconductor sample that had partially detached from a wall on one of the Skylab experiments. The experiment was repeated on USML-2 using a novel ampoule design that would minimize wall contact with the sample. Approximately half the sample grew with no wall contact, while the other half grew with partial wall contact. A second sample had a spring-plunger system that forced the sample to fill the ampoule, thereby assuring wall contact. Preliminary analysis showed that twin formation was virtually zero in the region grown without wall contact; whereas, the sample in the spring-loaded ampoule was highly strained at the exterior and heavily twinned. This experiment verified the contention that wall induced stresses are a major cause of the growth defects in crystals of this type grown on Earth.

The Europeans, using their mirror furnaces on D-1 and D-2, focused primarily on various forms of traveling zone growth. Since only a small portion of the material is molten at any one time, steady state growth conditions with uniform composition can be achieved if the melt is either diffusion controlled or if it is completely mixed, so long as the flows do not fluctuate with time. Therefore, the acceleration requirements for this class of experiments are not as stringent as for Bridgman growth. A number of compound semiconductor systems, including doped compounds such as GaAs (gallium arsenide), CdTe (cadmium telluride), InP (indium phosphide), and GaSb (gallium antimonide), as well as the ternary PbSnTe, were grown by the traveling solvent zone method (a method in which the zone contains an excess of one of the components to lower the melting point). For the most part, the space-grown crystals were free of growth striations and had lower dislocation densities than the ground control counterparts. In many cases, the melt had pulled away from the walls that may account for the fewer defects, thus reinforcing the findings from USML-1 and -2.

Considerable attention was also given to crystal growth using the floating zone technique in this series of missions. Striations were seen on doped-Si samples grown on the first Spacelab flight that closely resembling those seen on the ground control samples. This proved that the origin of these striations was due to unsteady Marangoni convection rather than buoyancy convection. However, it was found on a series of TEXUS suborbital flights and on D-1 that a thin (5 micron) coating of amorphous silica completely suppressed the Marangoni flows.

On the D-2 flight, GaAs crystals as large as 20 mm in diameter were grown. This is more than twice the diameter than can be grown by float zone in normal gravity. A special heater controlled an arsenic source to provide the necessary arsenic overpressure to maintain stoichiometry. As a result, no evidence was seen of

either gallium or arsenic precipitates. The shape of the growth interface could be controlled by controlling the height of the molten zone. When the interface was nearly flat, the dislocation density dropped to  $5 \times 10^3 \text{ cm}^{-2}$ , two orders of magnitude less than typically found in Earth-grown GaAs. Rocking curve width, which measures the internal order of the crystal, was as low as 11.6 arc seconds, comparable to the best quality crystals grown on Earth. Dopant striations were observed, which were attributed to unsteady Marangoni convection. A cobalt-samarium magnet was inserted near the end of several samples to help suppress the Marangoni convection, but the field was too weak to prevent unsteady Marangoni flows.

#### *4. Vapor Crystal Growth.*

For materials that lend themselves to physical or chemical vapor transport, growth from the vapor offers some attractive alternatives to growth from the melt. Growth can take place at temperatures considerably lower than the melting point, thus avoiding some of the higher temperature problems associated with melt growth. Gravity-driven convection will definitely influence the growth process, perhaps in ways that are not yet completely understood or appreciated. However, since diffusion is much more rapid in vapors than in melts, diffusion limited growth conditions can be obtained under far less stringent acceleration conditions than those required for melt growth and, since vapors must fill their containers, there are no free fluid surfaces that can drive Marangoni convection.

Experiments in which  $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$  was grown on (100) CdTe substrates by closed tube chemical vapor transport (CVT) were carried out on USML-1 and USML-2 using  $\text{HgI}_2$  as the transport agent. Considerable improvements in the compositional uniformity and morphology of the films deposited in space were noted. Etch pit densities indicating dislocations were lower by one to two orders of magnitudes and electron mobilities were higher than the ground control by a factor of two (films were doped n-type from the incorporation of the iodine in the transport agent). These improvements were attributed to the sensitivity of the  $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$ - $\text{HgI}_2$  vapor transport system to minute fluid dynamic disturbances that are unavoidable in normal gravity.

Mercuric iodide ( $\text{HgI}_2$ ) forms a layered structure, similar to graphite, in which the A-B planes are bonded by van der Waals forces. Consequently, the crystalline structure is very weak, especially at the growth temperature, and it was thought that the performance of the material as a room temperature nuclear spectrometer might be limited by defects caused by self-deformation during the growth process. Mercuric iodide crystals were grown by physical vapor transport on Spacelab 3. It was possible to increase the growth rate on Spacelab 3 to more than twice the rate on the ground without spurious nucleation. The space-grown crystals exhibited sharp, well-formed facets indicating good internal order. This was confirmed by  $\gamma$ -ray rocking curves that showed a single peak and were approximately one third the width of the multi-peaked curves from the ground control crystals; however there was still evidence of lattice strain in the flight sample. Measurements just after the flight showed that both electron and hole mobility were significantly enhanced in the flight crystal, although, for reasons that are not clear, the values decreased after some time. The experiment was repeated on IML-1 with similar results. It is still not understood whether the improved quality of the flight crystals was due to the elimination of the weight of the crystal during its growth, or to the diffusion-controlled transport conditions that produced a more uniform growth environment.

#### *5. Solution Crystal Growth.*

A novel, cooled sting method for growing crystals from aqueous solutions was used to grow tri-glycine sulfate (TGS) on Spacelab 3 and IML-1. TGS is a long wavelength pyroelectric infrared detector mate-

rial. Methods for the seed preparation were improved for the IML-1 experiment that resulted in an unprecedented success. Although it was possible to grow only a small amount of material in the low-g time available, some very interesting results were obtained. In space it was possible to grow uniformly on the (010) face, whereas on Earth growth on this face is nonuniform and multifaceted. The detectivity ( $D^*$ ) and other parameters measured on the space grown crystals during the IML-1 show a definite improvement over the ground control crystals. For example, the dielectric loss tangent in the space grown crystal was 0.007, which is much lower than the 0.12 to 0.18 measured on the crystals grown by the cooled sting technique on the ground. The TGS crystal grown on the IML-1 mission was examined with high-resolution monochromatic synchrotron X-radiation diffraction imaging using the National Synchrotron Light source at Brookhaven National Laboratory. The images indicate an extraordinary crystal quality as the local acceptance angle for diffraction from an uncut IML-1 flight crystal was found to be 1 to 2 arc seconds. The continuity between the seed and the space grown materials is indistinct. The only inclusions visible in the high resolution X-ray topographs are due to the incorporation of polystyrene particles intentionally inserted in the growth solution to study the fluid motion in low-g.

Zeolites are a class of crystalline aluminosilicate materials that form the backbone of the chemical process industry worldwide. They are used primarily as adsorbents and catalysts. One of their most important roles is that of a “cracking” catalyst in the petroleum industry. New applications for zeolites include selective membranes, chemical sensors, polymer-zeolite composites, and molecular electronics. For these reasons, there is an intensive interest in obtaining a better understanding of how they nucleate and grow with the aim of being able to tailor their structure for specific applications.

Various forms of zeolite crystals, including zeolite-A, X, Beta, and Silicalite were grown on USML-1 and -2 with the aim of getting larger and more uniform crystals. In general, the crystals grown in space with nucleation control grew 10% to 25% larger in linear dimension than their ground controls. The zeolite-X crystals grown on USML-2 were 25% to 50% larger than their ground controls and twice as large as grown on USML-1. For the most part, the flight samples had higher Si/Al ratios than did their control samples and one of the A crystals exhibited the theoretical Si/Al ratio of 1.00, which had not been seen before. Space-grown Beta crystals were free of the line defects that are common in those grown on the ground. X-ray diffraction studies indicated slightly smaller unit cell volumes, which indicates fewer defects. A comparison of the catalytic activity of the space and ground-grown crystals has not yet been published in the open literature.

## *6. Thermophysical Properties.*

One of the most interesting and potentially useful series of experiments had to do with the use of microgravity to measure thermophysical properties of materials in their molten and even supercooled state.

A diffusion experiment on Spacelab 1 not only measured diffusion coefficients that were substantially lower than the values measured on the ground, but the variation with temperature suggested a  $T^2$  dependence rather than the Arrhenius-like dependence seen in most solids. This result prompted a series of liquid-liquid diffusion experiments on Spacelabs D-1, D-2, SL-J, and LMS. Generally the diffusion coefficients were found to be 30 to 50% lower when measured in microgravity and, with one exception, seemed to follow a power law with an exponent close to 2. These findings imply that all of the liquid diffusion measurements made on Earth are probably contaminated to some degree by convection effects, and that the vacancy diffusion model that has been applied successfully to solid diffusion does not apply to liquids. At the present, there is no viable model for the liquid state that predicts a  $T^2$  dependence of the diffusion coefficient. Therefore, these results could provide new insight into the theory of the liquid state.

An impressive number of thermophysical constants can be measured without physical contact from an electromagnetically positioned molten sphere. Surface tension and viscosity can be obtained by exciting vibrational modes and measuring their frequency and damping rate. The heat capacity, thermal conductivity, and total hemisphere emissivity were measured using A.C. calorimetry in which the heating field is modulated at frequencies ranging from 0.05 Hz to 0.2 Hz. The heat capacity is related to a correlation function of modulation frequency, the internal (heat up) relaxation time, and the external (heat loss) relaxation time. Also, thermal expansion and volume change on melting can be determined by direct observation of the suspended drop. A change in electrical resistance with temperature in the sample changes the inductance of the heating coil. Thus by measuring the voltage, current, and phase of the heating current, resistivity can be inferred. Although it is possible to levitate conductive samples in unit gravity, the heating effect from the levitating field makes it difficult to undercool the material. Also the shapes become highly distorted and spherical samples are required to extract much of the thermophysical data.

There is considerable interest in the properties of the undercooled state of the glass-forming metals. In order to estimate the cooling rate required to form a metallic glass, it is necessary to know the difference in the Gibbs free energy between the solid and the liquid state as well as the viscosity and the interfacial energy. The Gibbs free energy is the enthalpy of the liquid less the product of the entropy and temperature. The enthalpy of the liquid can be obtained by integrating over the heat capacity of the undercooled liquid.

The TEMPUS electromagnetic levitator was flown on IML-2, but many of the samples became contaminated before the experiment began in space. The problem was corrected and the instrument was reflowed on MSL-1R, which produced some very interesting results. The heat capacities of the liquid state were found to be considerably higher than the Dulong-Petit limit for solids. The viscosities appeared to follow an Arrhenius law, although the scatter in the data was such that a power law dependence could not be ruled out (see previous discussion on diffusion constants). Surface tensions tended to decline linearly with temperature. The electrical resistivity of  $\text{Co}_{80}\text{Pd}_{20}$  alloy was found to increase linearly with temperature in both the solid and liquid state, but with a higher value and slightly steeper slope in the case of the liquid. Solid  $\text{Co}_{80}\text{Pd}_{20}$  is a good ferromagnet with a Curie temperature of 1250 K. The measured inductance in both solid and in undercooled melt exhibited a dramatic change, beginning when the material was cooled below 1360 K and showing a sharp increase at 1250 K. This increase was interpreted as magnetic ordering. There had been speculation as to whether a ferromagnet could exist in the liquid state. There appears to be no fundamental reason to believe that it could not; it's just that the Curie temperature of every known magnetic material happens to lie below its melting point. This is the first evidence suggesting that ferromagnetism does indeed exist in the liquid state.

In a related experiment, it was possible to deeply undercool samples of Ag-Ge (silver-germanium) and Fe-Ni (iron-nickel) in a  $\text{B}_2\text{O}_3$  (boron III oxide) lined crucible. The  $\text{B}_2\text{O}_3$  acts as a flux, and keeps the metal sample away from the crucible walls, thus denying the metal melt low energy nucleation sites. Two of the FeNi samples actually hypercooled (hypercooling occurs when the enthalpy of the melt becomes lower than the latent heat of fusion, so that the sample cannot return to its melting temperature during recalescence). Therefore, this technique offers an alternative way of making heat capacity measurements in the undercooled state.

## 7. *Glass Formation.*

Microgravity offers a number of potential advantages for the formation of unique glasses, but so far only a few experiments have been conducted to explore these advantages. Lithia-silica and  $\text{Na}_2\text{O-B}_2\text{O}_3\text{-SiO}_2$

glasses formed in a crucible on Spacelab D-2 showed greater homogeneity than the ground control based on variations in refraction analysis and microprobe analysis. The difference was ascribed to the fact that nuclei that formed at the wall were not transported to the remainder of the melt in microgravity.

The Single Axis Acoustic Levitator, originally developed as a suborbital facility, was flown on D-1. A sample of low viscosity gallia-calcia-silica (GaCaSi) was successfully melted and solidified without contact. A glass was formed at a much slower cooling rate (2 to 3 times slower) in space than is possible in a crucible, which reflects the absence of low energy nucleating sites on the levitated sample.

### **C. Biotechnology**

The biotechnology investigations carried out on Spacelab missions include protein crystal growth, electrophoresis, electrofusion, and various cell culturing and plant growth experiments with commercial implications. The vast majority of the experiments were devoted to the growth of protein crystals. Experiments dealing with living organisms, including the remainder of the cell culturing and plant growth experiments, including those performed in the Biorack, will be covered under Life Sciences (Section IV).

#### *1. Biomolecular Crystal Growth.*

Some of the most exciting results from the Spacelab missions have been in the field of biotechnology. Spacelab can legitimately claim to be the genesis for the expanded interest in the growth of protein and other biomolecular crystals, which are necessary for understanding biological function at the molecular level. X-ray diffraction is the only method for obtaining the three-dimensional structure of complex biomolecules that determines their function and crystals of a certain size and perfection are necessary for this analysis. Structure-based drug design is an emerging technology that shows great promise. For example, neuraminidase is an enzyme required by all strains of influenza virus to replicate. Three pharmaceutical houses are using the structure of this enzyme to develop inhibitors which have the potential of treating all strains of influenza.

When Walter Littke reported that he was able to grow larger crystals of lysozyme and beta-galactosidase on Spacelab-1, Charlie Bugg, then the Associate Director of the Comprehensive Cancer Center at the University of Alabama in Birmingham (UAB), immediately recognized the implications of this result and organized molecular biologists, who were having difficulty growing large enough crystals of their materials of interest, to try to exploit the perceived advantage of microgravity for protein crystal growth. After several tries with simple hand-held experiments to work out the details of the growth technique, they were able to clearly demonstrate that it was not only possible to grow larger crystals in microgravity, but also that some of the crystals had better internal order than the best crystals ever grown on Earth.

These results provoked theorists as well as experimentalists, who previously had concentrated on the growth of inorganic small molecule crystals, to ask why should these macromolecular crystals grow better in microgravity? Suddenly, the task of growing biomolecular crystals, that had been simply an obstacle for molecular biologists to overcome, became a science unto itself, receiving funding from NASA as well as from NSF (the National Science Foundation) and NIH (National Institutes of Health). These studies have transformed what had been largely a shotgun-approach to growing biomolecular crystals to a more exact approach by providing solubility data, modeling the transport, assessing the effects of impurities, and examining the dynamics of the growth interface in order to establish the conditions under which growth instabilities might occur. The

insights provided by these studies have suggested ways for improving crystal growth as well as explaining why some growth systems may not perform as well in space as they do on Earth.

Larry Delucas, the Payload Specialist on USML-1, demonstrated the advantage of a trained crystallographer onboard to set up and monitor the crystal growth experiments, intervening when necessary to optimize the growth process, which is different in space than on the ground. For example, he found that mixing of the protein and the precipitating agent in many of the automated experiments that had been set up on the ground was not adequate, especially when a viscous precipitating agent such as polyethylene glycol was required. By mechanically mixing the precipitating agent on orbit, he was able to grow diffraction quality crystals of several proteins that previously had not been successfully grown in space.

In the meantime, the success of the group headed by Bugg, and later by Delucas, inspired other leaders in the field to develop new concepts for growth facilities to be used in space. Alex McPherson and Dan Carter in the US organized teams interested in using the growth facilities they had developed, while ESA (the European Space Agency) developed their advanced protein crystal growth facility that can accommodate a variety of growth methods and provide diagnostics of the growth process.

It should be recognized that many crystals are generally required to obtain sufficient data to solve a structure. However, often one crystal that can provide even a small increase in resolution, when merged with data from other crystals, may be key to either solving the structure for the first time, or for refining a structure so that the active site may be mapped more accurately. Thus far, US sponsored Spacelab experiments have been able to improve the resolution of five different proteins by as much as 0.5 to 1.0 Å, three proteins to between 0.3 and 0.5 Å, and another twenty-five proteins by up to 0.3 Å.

After the structure of a target molecule has been determined to good accuracy, there is still a major task ahead before an effective drug can be designed and selected for clinical trials. Each candidate drug must be complexed with the target molecule and more crystals are required of the complex in order to determine how well the drug fits the active site. After the more promising candidates are selected, there is still the long and torturous procedure required to take it through the Food and Drug Administration's (FDA) approval cycle and bring it to market. Thus it can easily be a number of years before the benefits of many of these space experiments will be seen by the general public.

Some of the more promising drugs under development, in which space played a significant role, include the following.

- Pharmaceutical companies had been searching for ways to control the release of human insulin so that diabetics could take fewer injections and have a more constant supply. One promising binding agent turned out to be toxic to humans. Space grown crystals provided the clue as to what was going on and led to a solution of the problem.
- Factor D is a protein that often stimulates the immune system to overreact from the trauma following open heart surgery. A particularly large crystal of this protein grown on USML-1, when merged with other data, provided the structural information. Drugs to block this protein are in Phase II clinical trials and may be available by 2001.
- Space grown crystals of glyceraldehyde 3-phosphate dehydrogenase (GAPDH), an essential enzyme in the parasite that is responsible for Chagas' disease, were instrumental in refining this protein. Drugs based on the structure of this molecule are in pre-clinical trials.
- NAD-synthetase is a target for a wide spectrum antibiotic under development that pre-clinical trials have shown to be effective against anthrax, pseudomonas, and flesh eating bacteria. Space grown

crystals played a role in obtaining its structure. A crystal grown on STS-95 improved the resolution from 1.6 Å to 0.9 Å. These data should prove useful to help improve knowledge of the active site if it becomes necessary to adjust the design of the drug that is presently being tested.

- The Center for Macromolecular Crystallography, a NASA-created Commercial Space Center (CSC) in Birmingham, Alabama, now employs more than 100 scientists and engineers working on crystal growth, structure determination, and the next generation of flight experiments. They collaborate with thirty-seven universities and have twenty-one industry partners that contribute over \$2 million per year in direct funding. There are now four spin-off companies (BioCryst Pharmaceuticals, Inc., Ibbex Pharmaceuticals, Inc. and Diversified Scientific, Inc., in Birmingham, Alabama, and New Horizons Pharmaceuticals in Huntsville, Alabama) that have been created as a result of the NASA-sponsored work in this area.

## 2. *Electrophoresis.*

Electrophoresis, and its related electrokinetic separation processes such as isoelectrofocussing, are widely used for separation of proteins on an analytical scale. The protein molecules take on a particular surface charge (zeta potential) in a buffer solution. When an electric field is applied, the molecules will be moved under the influence of the applied field. Usually, the proteins are caused to migrate through a gel. The combination of the attraction by the applied field and the drag through the pores of the gel give each protein a specific mobility so that they will become separated spatially as the process is continued. Because this process is limited to microgram quantities, it is used primarily as an analytical tool.

Attempts to scale electrophoresis to a preparative scale by replacing the gel with a continuous flowing sheet of sample plus buffer solution have enjoyed only limited success on the ground, primarily because buoyancy driven convection places severe restrictions on the sample concentration and the thickness of the flowing buffer sheet. These factors limit the throughput of continuous flow electrophoresis (CFE); consequently, it has largely lost popularity to other methods, such as column chromatography, as a preparative separation method. There are certain potential advantages to CFE, however. It is a universal method, as opposed to column chromatography, where the columns have to be designed to separate specific proteins. Also, it can be applied to cell separation without having to tag the cells as is required by various cell sorting techniques.

There are reasons to believe that continuous flow electrophoresis could be carried out more efficiently in space from two points of view. First, the thickness of the flow chamber could be scaled up without encountering the convective distortions that limit the scale on terrestrial machines. Second, it should be possible to increase the sample stream concentration without sedimentation problems. Combining these two factors could theoretically increase the throughput by several hundred over Earth-based machines.

However, increasing the concentration of the sample stream can create additional problems if the conductivity and dielectric constant are different from the buffer fluid. Such differences in electrical properties distort the sample stream and can even lead to flow instabilities. One of the motivations for the series of electrophoresis experiments carried out in the French “Recherche Appliquee sur la Methodes de Separation Electrophorese Spatiale”, or RAMSES, on IML-2 was to examine these electrohydrodynamic effects without the complicating distortions caused by buoyancy. Other experiments used the Japanese Free Flow Electrophoresis Unit (FFEU) to evaluate its ability to carry out various separations. Bubbles in the buffer curtain and various technical problems allowed only limited success in this set of experiments.

### *3. Commercial Biotechnology.*

Two other NASA-sponsored Centers for Space Commercialization conducted biotechnology experiments on USML-1 and -2 in addition to a series of Spacehab flights.

The Wisconsin Center for Space Automation and Robotics (WCSAR), has developed ASTROCULTURE™, a state-of-the-art plant growth chamber for space as well as terrestrial research in which the many variables involved in plant growth can be controlled. One of their goals is to provide the means for on-orbit food production for extended missions. This activity has produced a number of commercially useful spin-offs including a novel system for delivering water and nutrients to plants, an air humidification/dehumidification system that does not need a gas or liquid separator, and an efficient LED lighting system for plant growth that is also finding medical applications. Their work on utilizing microgravity to improve the process of transgenic plant alterations could also have significant societal and economic benefits by producing food crops that mature faster.

The BioServe CSC is carrying out an extensive research program to catalog how various organisms respond to the microgravity environment with the goal of exploiting those characteristics they find useful for commercial purposes. Many of their findings, such as the accelerated growth of certain organisms, enhanced production of cell products, and enhanced enzymatic activity in microgravity are surprising and are not understood from simple fluid modeling of gravity effects in living organisms. Their academic collaborators at the University of Colorado, Boulder, and Kansas State University in Manhattan, Kansas have published a very impressive number of papers on their findings. One of the more promising areas of their research has to do with the effects of microgravity on plant production of lignin. Attempts are being made to understand how this comes about and perhaps use this information to genetically engineer plants on Earth to control the production of lignin. There is significant interest in both the paper industries, which want less lignin in their pulp wood, as well as the timber industry, which wants more.

## VII. LIFE SCIENCES

Life sciences experiments were flown on sixteen of the 36 Spacelab missions between 1981 and 1998. More than 375 separate experiments were designed, developed, and conducted by more than 138 principal investigators and 536 co-investigators. Over a thousand publications and reports were published and results from more recent Spacelab missions, including Neurolab, are just beginning to appear in journals.

Life sciences experiments fall into three major discipline areas that are:

- Gravitational Biology and Ecology,
- Biomedical Research and Countermeasures, and
- Advanced Human Support Technology.

### A. Gravitational Biology and Ecology

#### 1. *Cell and Molecular Biology.*

Cell and molecular biology investigations were conducted on eight of the sixteen Spacelab missions that included Life Sciences experiments, under the discipline category “Gravitational Biology and Ecology”. The experiment specific categories included cell growth and metabolism, organelles and structures, immunology, hematology, bacteria and viruses, yeast, circadian rhythm, and protoplasmic streaming.

In the interpretation of all cell biology experiments flown in space, it is important to understand that differences in growth, metabolism and function can reflect differences in hardware used as well as the particular characteristics of launch, payload location on the Shuttle, and other mission and experiment specific parameters including temperature changes during an experiment, length of the mission, starting and stopping of the 1g in-flight reference centrifuge during sampling, and storage of samples. Significant differences in response to spaceflight are also cell type and culture dependent. Not all cell types respond in the same way to conditions of spaceflight. A number of cell lines flown on the various Spacelab missions showed virtually no response to microgravity. Examples include Murine Friend Leukemia Virus transformed cells and Hamster kidney cells (ATCC CCI 15) grown on Cytodex 3 microcarrier beads. Hybridoma cells flown on Spacelab D-1 showed only a slight change in metabolite production, whereas hybridoma cells of a sub-clone of the cell line 7E3-N showed a decrease in the production of monoclonal antibodies, which seems to argue against the use of microgravity for the production of monoclonal antibodies. Monkey kidney derived cultured cells (JTC-12) flown on SL-J showed evidence of cytoskeletal/membrane interface perturbation induced by spaceflight.

A landmark experiment by Cogoli on the Spacelab 1 mission was the first to show a dramatic, quantitative response to spaceflight at the single cell level. Normal peripheral human T lymphocytes (white blood cells functioning in cellular immunity) were growth stimulated in flight by addition of Con-A (concanavalin-A, a plant protein which binds to cell surface proteins). In microgravity, activation of the cells was 90% less than that of the ground controls. This result was confirmed on D-1. Additional experiments on IML-2 indicated that the first step in T-cell recognition of antigen appears to be significantly compromised in microgravity. In the experiments flown on SLS-1, Cogoli mixed microcarrier beads with the cells as a way to increase cell to cell contact. The results were surprising. Although lymphocytes do not normally attach to substrata, the cells attached to the microcarriers and activation in microgravity in response to Con-A was now double that of ground controls. The cells without microcarrier beads again failed to respond to Con-A thus confirming the SL-1 and D-1 results.

Other experiments on IML-2 demonstrated that cell-cell contacts, necessary for T cell activation, do occur in microgravity. Addition of microcarrier beads promotes activation two-fold higher than ground controls yet without beads, lymphocyte activation in microgravity is almost totally abolished. Reasons for this are not clear. The impact to crew health on long term missions due to impaired cell mediated immunity is not known and remains a significant biomedical area to be investigated.

Previous studies on US biosatellites and Soviet Salyut missions showed an increase in bacterial growth rate. The experiments conducted on Spacelab D-1, D-2, IML-1, and USML-1 confirmed that the growth rate in bacteria as well as some other organisms is increased. In addition, antibiotic sensitivity is reduced and genetic transfer between bacterial cells is different in microgravity compared to ground controls. It was found that the increased growth rate, not the permeability of the cells, is the primary reason for reduced response of bacterial populations to antibiotics during spaceflight.

Yeast cells (*Saccharomyces cerevisiae*) were flown in a miniaturized bioreactor on IML-2. No remarkable differences were found in cell cycle, proliferation, cell volume, ethanol production or glucose consumption and no morphological anomalies were found.

*Paramecium tetaurelia* had been shown in previous flight experiments to increase growth rate and cell volume significantly and decrease cell dry weight and protein content. A comparison of data from microgravity and the 1g in-flight shielded centrifuge on D-1 demonstrated that effects on *Paramecium* growth and volume in space are due to the effect of microgravity and not to cosmic radiation.

The microscope equipped NIZEMI centrifuge on IML-2 was used to determine the threshold for gravitaxis, the locomotive response to gravity, on two species of ciliates, *Paramecium* and *Loxodes*, and on the slime mold *Physarum polycephalum*. *Physarum* does not have a specialized structure for gravity perception, yet it showed a very low threshold (0.1 g) for gravitaxis.

Two different strains of the unicellular green algae, *Chlamydomonas reinhardtii*, were used on D-1 to evaluate circadian rhythm. No differences were found between flight and ground control, thus this organism appears to have an endogenous biological clock. Cell proliferation and survival rates in microgravity were higher and no mutations were found in flown samples.

## 2. Developmental Biology.

Developmental biology experiments were flown on eight Spacelab missions. A total of twenty-eight experiments were conducted and eleven different species were studied including insects, brine shrimp, jellyfish, sea urchins, amphibians (frogs and newts), fish, mice, and quail.

Experiments to determine the effects of spaceflight on the development of fruit flies, *Drosophila melanogaster*, were carried out on Spacelab D-1, IML-1 and IML-2. Oocyte (egg cell) production was significantly increased in microgravity compared to the 1g in-flight centrifuge and ground controls. Embryos continuously exposed to microgravity were larger than controls. Larvae showed thoracic and/or head abnormalities in the microgravity samples. The lifespan of adult males continuously exposed to microgravity was only 75% of normal, while the lifespan of females was unaffected.

The development of graviceptors of a larval form of *Aurelia aurita* (jellyfish) was studied on IML-2 and on SLS-1. There was no difference in morphology between space and ground developed ephyrae but ab-

normalities were found in their pulsing behavior. This suggests an abnormal development of graviceptors or the neuromuscular system, or a defect in the integration of impulses between the systems.

Sea urchin larvae (*Sphaerechinus granularis*) were flown on IML-2 to determine whether mineralization and formation of skeletal structure occur properly and if larvae with skeletons already developed on the ground would lose mineral in microgravity. Significant results were that larvae developed skeleton in flight and no pronounced loss of mineral from already formed skeletons occurred. However, the skeletons that were formed showed some unusual architecture indicating that the process of association and positioning of the cells which determine the size and shape of the skeleton are particularly sensitive to environmental perturbations. Evaluation of calcium and magnesium did not show significant differences between flight and ground samples.

Five of the Spacelab missions, D-1, D-2, IML-1, IML-2 and SL-J, included investigations into the role of gravity and weightlessness on developing amphibian eggs. These experiments used eggs of *Xenopus laevis* (African three-clawed frog) to determine if fertilization occurs in microgravity and if embryo development is initiated. *Xenopus* eggs, fertilized and developed in microgravity, formed normal axis and neural plates, and the tadpoles developed normally. The inner ear of juvenile developing newts flown on IML-2 showed significantly larger saccular otoliths (ear stones) and some differences in assembly of components of the otoconia, the gravity-sensing organ.

Alterations in gravity environment induced somewhat pronounced long-lasting behavioral reactions followed by long-term adaptation to the gravity changes. Changes in brain biochemistry were found in fish and tadpoles subjected to hypergravity (3g) and electron microscopy data showed that after exposure to microgravity energy metabolism was reduced in neurons in the gravity integration center of the brainstem. There were also changes in the gravity-sensitive epithelial cells in the inner ear of fish larvae. The tadpoles swam in narrow somersaults, in circles or floated motionless in random positions. Some of the fish swam in large circles, or darted around randomly or floated motionless. After returning to earth, fish re-adapted and swam normally after about 16 hours but the tadpoles continued to swim in circles, loops or in screw-like patterns for at least six days.

Avian development was evaluated on chicken eggs fertilized before launch on SL-J and quail eggs on a series of Spacelab Mir missions. For chick embryos, all tissues including cartilage and bone formed in seven and ten day old chick embryos during spaceflight. After flight, these chicks continued to develop and hatched normally.

### 3. Plant Biology.

Plant biology experiments were flown on eleven Spacelab missions. More than thirty individual experiments, most with multiple objectives evaluating multiple plant types, were conducted addressing the general areas of plant growth and development, gravity sensing and response, metabolism, lignification and support hardware development.

The results on plant growth and development from experiments performed on a number of plant types (oat, mung bean, *anis* callus cultures, rapeseed protoplasts, wild carrot, *arabidopsis* and its mutants and *hemerocallis*, or daylily, and a fungal species) showed that responses are generally plant type and species specific. In general, seed germination and plant growth progressed well in microgravity. Root orientation is strongly dependent on gravity but starch storage cells (amyloplasts) resting on the endoplasmic reticulum or cytoskeletal elements do not account totally for all gravity-sensing mechanisms in plants and the

full mechanisms are still unclear. The thresholds (minimum g-force required to elicit a response) were surprising low. Use of the NIZEMI centrifuge-microscope allowed visualization of the bending responses of seedling roots. This provided extremely significant information on the influence of gravity related to developing plants on Earth, as well as the effects of microgravity.

Leguminous plants formed nodules in the presence of *Rhizobium* bacteria. This showed that gravity is not necessary for normal co-development of nitrogen-fixing bacteria and leguminous plants and is important information for the future cultivation of legumes on space stations, long-duration missions or Lunar outposts.

Lignification was significantly reduced in microgravity. Without the requirement to grow strong stems to hold plants upright as in 1g, the plants adapted to microgravity by reducing lignin synthesis.

A commercially developed and available plant growth facility, Astroculture™, allowed cultivation of potatoes (1.5 cm diameter in approximately 16 days) in microgravity. Technology developed as a part of this facility is being used for ground-based purposes ranging from treatment of cancer patients to horticulture. Another experiment in the area of plant growth facilities development was the Greenhouse experiment conducted in the Russian/Slovakian-developed plant growth facility called the “Svet”, launched on SL-Mir. Probably one of the most complex plant experiments ever attempted in space, the facility grew plants for 90 days on Mir to allow seed-to-seed growth.

#### 4. Radiation Biology.

Experiments to evaluate radiation levels and their effects on living systems, and to obtain information on levels of radiation within the spacecraft and Spacelab were flown on five Spacelab missions that included Life Sciences payloads. Sixteen radiation experiments were flown, ten of which evaluated effects on life forms including insects, bacteria, mammalian cells, nematodes, yeast, and plants. Five experiments provided information on the levels of radiation in different locations on the Shuttle and in some of the experiment specific hardware including Biorack, the access tunnel, pallet, and the Shuttle middeck. One experiment reported dosimetric information on the crew. Radiation has been a topic of biomedical concern since the beginning of human spaceflight and must be taken into consideration, either as to effect on individual experiments or experiment specific hardware shielding, when any biological experiments are conducted in space.

The primary type of radiation evaluated, HZE, is cosmic radiation produced by heavy, high energy and charge particles (ions) released by the interactions of primary galactic radiation with the Earth's atmosphere. This densely ionizing component of cosmic radiation is the most damaging to cells and tissues. Hits by HZE cause damage to cells from the nuclear disintegration stars produced by protons and neutrons in the irradiated tissue. Another type of radiation that should be considered comes from ionizing components of the radiation field, including photons, electrons, muons, pions and protons.

Radiation surveys on SL-1 and IML-1 concluded that the radiation exposure on astronauts during the mission was higher than the mean annual public exposure but well below the limits defined for spaceflight. Heavy ion flux in different positions within Biorack varied between 0.5/cm and 0.2/cm. Comparison of results from IML-1 and IML-2 showed a higher heavy ion flux variation for the different locations in IML-2 (a factor of more than six compared to a factor of two in IML-1). Thus the conclusion was that the only way to obtain confident information about radiation intensity and type is to measure radiation on each mission in the vicinity of the experiment of interest. Assumptions made that the Biorack facility components shield biological experiments may not be totally valid. A similar measurement of the same general areas

of Biorack on D-1 provided additional information that experimental conditions for biological experiments in space must consider that dosimetric data may not be sufficient for proper assessment of test data. At the cellular level, hits are not evenly distributed and thus averaging of radiation doses in the general area may not provide accurate information for the experiment.

On SL-1 and D-2, experiments were conducted to evaluate the effects on prokaryotes (single cell organisms) of vacuum and solar ultraviolet (UV) radiation, separately and in combination. On D-2, 308 biological samples were exposed to solar UV, vacuum, or a combination of both. As shown on SL-1, reduced survival of *Bacillus subtilis* was more evident in samples exposed to both vacuum and UV-radiation. Survival was affected by the repair capacity of the strains investigated, and injury of the spore DNA, in the form of DNA strand breaks, was assumed to be the mechanism of damage.

Eggs of the stick insect, *Carausius morosus*, have different sensitivities when exposed to cosmic radiation at different developmental stages. Experiments flown on Spacelab D-1 and IML-1 show that the effects of HZE particles from cosmic radiation combined with microgravity are synergistic. Yeast cells irradiated with X-rays before launch were capable of repairing some of the damage, but the repair rate was reduced in the microgravity samples. However, an experiment on IML-2 found no significant differences in the rejoining kinetics of radiation induced double-stand breaks of DNA in *Escherichia coli* PQ37 or in a human primary fibroblast line (fibroblast develop into connective tissue). In human skin fibroblasts the rejoining kinetics were almost identical in microgravity, in the ground control, and in the 1g in-flight centrifuge control. Similarly, the *E. coli* strain PQ37 also repaired its DNA under all gravity conditions. These results were corroborated by another experiment on IML-2 using *Bacillus subtilis*. The spores were irradiated on the ground before flight and allowed to germinated in static microgravity and in the 1g in-flight centrifuge, as well as in ground controls. Results again proved that DNA repair can be initiated and function normally in microgravity.

## **B. Biomedical Research and Countermeasures - Animal Physiology**

Animal physiology studies flew on six of the Spacelab missions. Animal physiology experiment specific areas included bone, muscle, cardiovascular, neurophysiology, renal physiology and endocrinology, immunology, metabolism and nutrition, and chronobiology. There were more than 100 individual animal physiology experiments flown which included species of mouse, fish, and avian, although the rat was the most studied species.

### *1. Bone.*

Skeletal loss in the long bones, primarily weight-bearing bones, is well documented yet the mechanisms of this are not clear. Earlier experiments on the Cosmos unmanned orbiting spacecraft showed that production and mineralization of bone matrix was retarded, contained fewer collagen fibers, and the collagen was less mature in flown versus ground controls. The effect of microgravity on cartilage development and bone formation can result in marked skeletal changes including decrease in bone volume and altered biochemical properties. Loss of bone mass remains one of the most important biomedical concerns to long-duration human habitation of microgravity environments.

Thirteen experiments to investigate effect of microgravity on bone and cartilage formation, mineralization, endocrinology, and metabolism were flown on five of the Spacelab mission. An experiment on SL-3 showed that even during a short spaceflight less matrix is formed and there is less mineralization in rat bones. A follow up to investigate production of collagen by primary mouse bone cells in culture was flown

on IML-1. This experiment addressed the development of cartilage during skeletal development. Endochondrial ossification involves collagen synthesis as well as other factors. Conclusions were that, although chondrocytes could function, proliferation of rough endoplasmic reticulum and production of matrix did not occur in flown cells. An experiment on SLS-1 showed that bone regenerative potentials decreased, thus stimulating the process of osteoporosis.

Metabolic studies on SLS-1 evaluated bones, blood plasma, and endocrine factors that participate in bone metabolism regulation. Limb bones and lumbar vertebrae were evaluated. Results showed decrease secondary spongiosa and increased bone resorption surface in proximal metaphyses of tibiae. These are signs of developing osteoporosis. These changes correlated with biochemical data showing decreased alkaline phosphatase activity and increased activity of tartrate-resistant acid phosphatase (a bone resorption enzyme). There were decreases in bone calcium, phosphorus, sodium and chloride, and depressed function of thyroid C-cells producing calcitonin, which is necessary for normal mineralization of bone matrix. Mineral metabolism changes confirmed previous findings that calcium is higher and phosphorus is lower in the blood of flown animals. Somatotrophic (growth hormone) activity was depressed in the pituitary leading to decreased synthesis and secretion of the growth hormone.

Thirteen experiments investigating muscle physiology in rats were flown on three Spacelab missions. The soleus, a primary weight-bearing muscle sometimes referred to as the antigravity muscle, was the subject of several investigations. As was predicted, the soleus showed the most dramatic changes in response to microgravity. Flexor muscles such as the tibialis anterior, and extensor muscles (extensor digitorum longus) were not significantly affected by gravitational unloading in microgravity.

Spaceflight induced significant fiber shrinkage, or atrophy, and increased expression of fast muscle characteristics (fast myosin) in slow fibers. In addition, muscle damage resulting from muscle atrophy in microgravity that occurred post flight included thrombosis of microcirculation, interstitial and cellular edema, muscle fiber fragmentation, sarcomere disruptions, activation of phagocytic cells, and elevated ubiquitin conjugation suggesting protein breakdown. Accelerated aging-like involution of neuromuscular junctions was found in caged rats, and thus was not just a characteristic of spaceflight. The abductor longus muscle appeared more susceptible to damage, probably due to resumption of activity after flight.

## *2. Cardiovascular Physiology and Hematology.*

Human adaptation to microgravity results in loss of red blood cell (RBC) mass, reduction in plasma volume and decrease in total blood volume. Spaceflight-induced anemia is the subject of a number of investigations to discover the potential mechanisms. Use of rats as a model to investigate space adaptation responses on the Spacelab missions proved an excellent means to investigate space anemia.

Experiments on SL-3 demonstrated a significant increase in hematocrits (ratio of packed cells to whole blood volume), RBC counts, hemoglobins and neutrophils. (The increased cell counts could be due to artificially increased concentrations because the plasma volume was reduced in spaceflight as a result of fluids shifts and loss in microgravity.) Also found was a significant reduction in the percentage of lymphocytes, which confirmed earlier reports that lymphocytes are affected by spaceflight. Bone marrow, spleen and erythropoietin (EPO), the hormone that stimulates RBC precursors in the bone marrow to development into mature RBCs, showed no significant differences between flown and ground animals. Bone marrow cells of flown rats could be induced by EPO to produce erythroid colonies, thus the changes in RBC numbers was apparently not due to faulty cell response to EPO stimulation.

In humans, characteristic adaptation to upper body fluid shifts in space include increased heart rate, blood pressure and total peripheral vascular resistance, and decreased venous pressure. Upon return to Earth, re-adaptation causes severe increase in heart rate and low blood pressure. Results of the study with heart tissue removed from rats after flight on SLS-2 showed that the contractile strength of the heart muscle was decreased.

### *3. Endocrinology.*

Experiments to determine the effects of microgravity on hormone and regulatory peptide synthesis and release have shown that spaceflight has significant effects on animal physiology. Most of the animal endocrinology experiments were flown on the Spacelab-3 mission. One flew on SLS-1 and five endocrinology-related experiments were flown on SLS-2.

Fluid shifts to the upper body during spaceflight are related to changes in the fluid regulating hormones. Atrial natriuretic factor (ANF) is one of the hormones that regulates fluid shifts. ANF is secreted in response to increased pressure in the cardiac atria from increased shift of fluids to the upper body. ANF activates membrane-bound guanylyl cyclase coupled receptors (GC-A receptors). A second type of guanylyl cyclase coupled receptor is an apparent target for a natriuretic peptide in the brain. A third receptor appears to be coupled to adenylyl cyclase. Other hormones, including vasopressin and catecholamines, in addition to ANF, regulate response to fluids shifts and rennin influences blood pressure. Atriopeptin (AP-3) is released when right atrial stretch receptors are stimulated (possibly by fluid shifts in microgravity). The atriopeptins cause excretion of excessive amounts urine (diuresis) and of sodium in the urine (natriuresis) by direct action on the kidney as well as inhibition of aldosterone and vasopressin secretion and dilation of large vessels, resulting in further central pooling of blood.

### *4. Metabolism And Nutrition.*

Nine experiments were flown on three Spacelab missions, SL-3, SLS-1 and SLS-2, to investigate the digestive and metabolic changes that occur during and after spaceflight. Previous experiments with animals have shown that spaceflight significantly affects metabolism.

The Spacelab mission experiments advanced understanding of the qualitative and quantitative changes in lipid metabolism, the interactions between the function of endogenous intestinal microflora and digestive function, and digestive enzyme activity and function during and after spaceflight. Metabolic breakdown of nutrients, medications, and many hormones occurs in the liver, and numerous hepatic enzymes regulate catabolic function. Adaptation to spaceflight includes biochemical changes in the liver to accommodate energy requirements, including glycolysis and lipid peroxidation. A 20-fold higher stored carbohydrate (glucogen) content was seen in flown rats post-flight compared to ground controls on SLS-3. In addition, glucose levels and enzymes of the citric acid cycle were decreased, and glycolysis and ATP synthesis was increased.

Experiments on SLS-1 showed that spaceflight did not significantly affect the antioxidant protection component in liver and other tissues but after return to 1g, readaptation caused changes in antioxidant protection.

Endemic intestinal microflora provide enzymes that work with the host to help digestion in the small intestine. A very important finding was that lipid metabolism was greatly altered by spaceflight. Lipase, which breaks down fats, activity was significantly decreased and short chain fatty acid concentration was significantly increased, indicating a different energy providing metabolism in microgravity. An experiment on SLS-2 suggested that changes in basic metabolism in RBC's and lymphocytes were due to structure and

function of their membranes because lipid and phospholipid composition of the membranes was changed. This can be extremely significant to the understanding of mechanisms responsible for blunted immune cell response to antigen stimulation during spaceflight.

#### *5. Immunology.*

Five experiments were flown on three Spacelab missions, SL-3, SLS-1 and SLS-2, to investigate the immune response of rats exposed to spaceflight. Previous experiments demonstrated that immune system alterations occur in animals and humans as a result of spaceflight. These are detected immediately after flight and, after time, appear to normalize to pre-flight function. The immune changes predominantly manifest as decreases in proliferation and function of T lymphocytes reflected as changes in the activity of natural killer cells and the production of cytokines, the proteins that help activate the immune response.

An experiment on SL-3 sought to determine if weightlessness alters the production of interferon-gamma (IFN-gamma), the protein produced by cells to inhibit viral replication, by the spleen cells of flown rats. It appears that the reduction in T lymphocyte number or function, or stress per se, could be responsible for the observed lack of IFN-gamma production by the spleen cells of flown rats.

In other experiments flown on SLS-1 and SLS-2 the cells from rats dissected immediately after landing did not grow, in contrast to increased growth of cells from rats dissected 14 days post-flight. Activity of spleen natural killer cells was reduced during and after flight, and returned to normal after 14 days at 1g. No significant changes in bone marrow natural killer cell activity were found between flight and controls. Production of interleukin 1 and 2 (which stimulate T-cell growth) and tumor necrosis factors alpha and beta (which destroy tumor cells) in spleen cell cultures of flown rats was reduced. At landing, IFN-alpha and gamma were diminished.

In summary, cell-mediated immunity in rats was significantly suppressed during spaceflight.

#### *6. Neurophysiology.*

Fifteen experiments were flown on four Spacelab missions, SL-3, SLS-1, SL-J, and SLS-2, to investigate the effects of spaceflight on the brain and nervous system and general neurophysiology of animals.

Physiological systems are generally regulated by the nervous system and many of these systems are affected by spaceflight. Temperature regulation, fluid volume and water intake, calcium metabolism and neuromuscular control of movement are all altered in the microgravity environment. Viewed as adaptations to microgravity, these functions are mediated by changes in brain neurotransmitter interactions.

### **C. Biomedical Research and Countermeasures - Human Physiology**

The Spacelab missions contributed significantly to the understanding of human physiological adaptation to the space environment and re-adaptation to 1g post-flight. Experiments addressed the areas of bone, muscle, cardiovascular and pulmonary physiology, hematology, kidney function, endocrinology, immunology, neuro-physiology, and circadian rhythm. A total of more than fifty human physiology experiments were conducted on seven of the Spacelab missions.

## *1. Bone.*

Bone is a dynamic tissue that is continuously undergoing remodeling by the interactions of osteoblasts to build, and osteoclasts to destroy bony tissue. Not only does bone function in support, protection, and movement, and as a reservoir for the stem cells that differentiate into cells of the immune system and blood, but bone is also a storage tissue for fat and minerals. Calcium is involved in a large number of normal cellular processes and maintenance of nervous system homeostasis and when the level of calcium is low in the bloodstream, it is recruited from bone. Deposit and release of bone calcium and minerals goes on almost continuously.

Rapid loss of bone mass occurs under microgravity conditions because of the exit of calcium and other minerals. Loss of bone is one of the most important human health-related concerns to potentially limit future exploration of space. Due to the lack of impact stress, which is normally provided by walking in Earth gravity, bone mass and the levels of hormones that regulate calcium in the body decrease significantly, causing calcium resorption from bone into the bloodstream. The disruption of calcium metabolism and balance, while adaptive in microgravity, causes serious imbalances in the body. Bone resorption appears to begin immediately upon reaching microgravity and the increased calcium levels in the bloodstream cause higher excretion of calcium in urine and decreased absorption by the intestines. Countermeasures are not simple since increased calcium intake in microgravity could cause still more urinary excretion of calcium and increase risk of kidney stones.

Human bone physiology experiments were conducted on six of the Spacelab missions. The experiments addressed bone metabolism, calcium flux and mineral loss, and the hormones related to the maintenance of bone. Objectives were to advance understanding and provide information on causes of bone loss and possible countermeasures to prevent this loss during spaceflight.

Osteocalcin, a non-collagenous protein in bone, is synthesized by bone builder cells (osteoblasts) and its plasma level can be used as a marker for osteoblast activity and bone metabolism. High levels of osteocalcin in the plasma usually indicate fast growing bone. An experiment on Spacelab D-1 designed to evaluate osteocalcin in plasma from blood drawn before launch, in-flight and after landing did not show significant differences in osteocalcin levels that could be attributed to flight. On SLS-1 it was found that serum ionized calcium, the metabolically active calcium, increased dramatically on flight day 2 to levels 40% above control in all crewmembers tested. This level is considered to be severe hypercalcemia. At day eight, serum ionized calcium levels remained high, 35% above normal, indicating that clinically significant hypercalcemia was maintained throughout the flight. Parathyroid hormone (PTH), released when blood levels of ionized calcium decline, decreased to about 50% of control throughout the flight. (PTH causes calcium to release from the bone matrix by stimulating osteoclast, or bone reducer cell, activity and bone resorption). The finding that PTH was decreased, biologically validated the increase in serum ionized calcium and negated the possibility that the PTH caused the hypercalcemia.

## *2. Muscle.*

Humans were the subjects for a number of Spacelab mission investigations on muscle physiology and adaptation to microgravity. Experiments were flown on five of the missions.

The muscular system and neural control components of the neuromuscular system are significantly affected by spaceflight. Just after launch, very rapid adaptation in motor control to hypergravity and then to microgravity must occur. The degradation in skeletal muscle function after time in space may be, in part,

an outcome of altered motor functions or how humans move in microgravity. In addition, impaired musculoskeletal function has been noted in astronauts after spaceflight. Muscle atrophy, neuromuscular control and the contractile force of individual muscle fibers may contribute to decreased muscle strength. Data from animals flown on Spacelab-3 and Cosmos 1887 indicated that skeletal muscle atrophy predominantly affects the slow-twitch fibers in muscles of animals. In humans, the responses may be different. Experiments on Shuttle missions have shown a greater atrophy of fast-twitch fibers.

### *3. Cardiovascular Function.*

Cardiovascular adaptation in microgravity occurs rapidly and is characterized by a shift of as much as 2000 ml of fluid toward the upper body. The experiments on human subjects to evaluate cardiovascular response in microgravity were generally involved with fluid shifts, heart function and orthostatic intolerance upon return to 1g. Investigations were conducted on seven Spacelab missions and included more than twenty experiments with multiple sub-investigations.

Astronauts generally experience decreased performance, facial edema, overswelling of the veins, and stiffness in movement early in the mission. While cardiovascular adaptation in microgravity is rapid and effective, the difficulty in standing upright, known as orthostatic intolerance, that occurs after spaceflight is associated with significant dysfunction and clinically apparent orthostatic intolerance. Characteristically, some astronauts feel faint and exhibit varying degrees of disability in standing. On D-2, it was found that maximal cardiac pump performance was maintained in space. In the upright position after flight stroke volume was reduced by about 25% and heart rate increased 35% with a parallel increase in peripheral resistance. This confirmed SLS-1 data which showed standing heart rate after flight increased from 82 beats per minute preflight to 98 post flight, and the stroke volumes were decreased from 52 ml preflight to 42 ml post flight.

An experiment on D-2 to evaluate fluid shifts within superficial tissues of the upper and lower parts of the body found that tissue thickness decreased about 16% around the tibia and increased by 7% in the forehead. It is estimated that about 410 ml of fluid leaves the lower limbs and about 40 ml accumulates in the superficial tissues of the head. Swelling of the head decreases within three to five days in space but does not disappear until after landing.

The intraocular pressure preflight measured about 10 mm Hg whereas immediately after entering microgravity this pressure increased by about 100%. After four to five days on orbit, pressure declined to preflight values. Twenty minutes after landing, intraocular pressure decreased to about 30% less than preflight values.

Experiments on SL-Mir showed that long duration spaceflight effects are similar to short-term exposure. Most autonomic cardiovascular adaptations occur within the first days of spaceflight. On Mir, these changes persisted for at least four months in flight. Conclusions from the SL-Mir experiments were that long-duration spaceflight did not cause higher incidence of orthostatic problems compared to shorter duration Shuttle flights. This should be confirmed with a larger test subject pool in the future flight experiences. Heart rate and blood pressure during re-entry showed a lower than expected (small) increase over values seen during normal preflight and intravehicular activities.

### *4. Hematology.*

Hematology experiments were flown on SLS-1 and SLS-2 and SL-Mir. A consistent finding after spaceflight has been a significant reduction on red blood cell (RBC) mass. Experiments on SL-Mir again showed a

rapid decrease in total blood volume (12%) within 24 hours. This decrease in plasma volume caused an apparent increase in RBC blood volume (hematocrit) compared to preflight values. Erythropoietin levels in the serum were reduced also. The release of newly produced RBCs, which is under the control of erythropoietin, was terminated immediately after entering microgravity. It was concluded that down-regulation of RBC production during spaceflight is due to ineffective erythropoiesis resulting from decreased erythropoietin release into the serum. Additional studies on Mir 18 over a longer time will be very useful. The microgravity adaptation process, with regard to RBC mass and survival, represents a state of anemia which can be used to gain understanding of the mechanisms of erythropoiesis during spaceflight.

## *5. Immunology.*

Changes in immune response have been consistently found in astronauts and cosmonauts, yet the mechanisms are not clearly understood, and the impact on human health and productivity in flying long-duration missions has not been determined. The immune system involves both cell-mediated response of T-lymphocytes and the production of antibodies (humoral or blood-borne) by B-cells. B-cells are specialized white blood cells that release antibodies into the bloodstream when stimulated by infectious organisms, while T-cells rid the body of cells infected with bacteria, viruses, fungi and parasites. Maintenance of immunity in the body occurs by a very complex cascade of molecular and cellular events involving differentiation of cells and secretion of cytokines (immune cell messenger molecules) and production of immunoglobulins (chemical antibodies). One experiment on SL-Mir was designed to investigate whether antibodies are produced in response to antigen introduced by vaccination and to determine the time course of the response. This experiment is long-term beginning with STS-71 in 1995 and continuing on Shuttle-Mir missions for several years. The second experiment series was designed to determine the phenotypic alterations in circulating immune cell subpopulations during spaceflight compared to populations observed immediately after flight and to assess functional changes in the peripheral immune cells. The roles of specific cytokines, including interleukin 1, interleukin 1 receptor antagonist, and interleukins 2, 6, and 10, tumor necrosis factor alpha, granulocyte/macrophage colony stimulating factor and immunoregulatory factors such as prostaglandin E2 are being evaluated to assess spaceflight-induced immune suppression.

## *6. Pulmonary Function.*

The human lung is very sensitive to gravity; on Earth there are large differences in gas flow, blood flow and gas exchange between upper and lower portions of the lung. On Earth, pulmonary blood flow (perfusion) is greater near the bottom of the lung and becomes smaller toward the top. Gas flow (ventilation) is distributed throughout, though there are still large differences. Generally it is believed that these differences are primarily due to the pull of gravity. Comprehensive studies of pulmonary function on the SLS-1, SLS-2 and D-2 missions showed, however, that much of the imbalance in lung ventilation and perfusion is maintained in microgravity.

## *7. Kidney Function.*

Early in the flights, astronauts loose two to four Kg of body mass, mostly due to extracellular fluid volume loss. The objective of experiments flown on SLS-1 and SLS-2 was to gain further understanding of adaptive changes that alter fluid, electrolyte, renal and circulatory status of humans in microgravity. Preliminary results indicate that glomerular filtration rate was elevated in-flight, especially on flight day eight. Plasma volume was 22% lower than preflight and extracellular fluid volume was 15% below preflight value, and was still low at day eight. Fluid intake and urine volume decreased sharply, and mean intake remained at least 20% below preflight values throughout the mission.

Data from SL-M showed that extracellular fluid was reduced from 19.5 to 15.6 liters. These values are similar to those from a 14 day Shuttle mission. Conclusions are that changes in fluid volume that occur early in a flight, remain throughout long-term missions. Levels of two hormones important for fluid and electrolyte homeostasis (antidiuretic hormone and atrial natriuretic peptide) were reduced after 110 days of spaceflight.

Factors predisposing humans to increased risk of renal stones include excretion and negative calcium balance as a result of bone mineral loss, decreased urinary output after the first few days in microgravity, urinary pH changes, magnesium and citrate concentrations, and increased urinary phosphate. These changes can all increase urinary supersaturation of stone-forming salts. Seventy percent of the renal stones in humans on Earth are composed of calcium oxalate and the remaining 39% are uric acid, struvite and cystine stones. Studies from Shuttle missions of 4 to 14 days on a total of 150 astronauts showed that immediately after flight, the urine of most crewmembers is saturated with stone-forming salts, placing them at risk of developing calcium oxalate and uric acid stones. There was also a difference in stone-forming salt concentrations between the short-and long-duration missions. Studies on SL-M and continuing long-term on Mir are designed to further investigate the effect of long-term habitation in microgravity on the risk of development of kidney stones.

#### *8. Neurophysiology.*

Space motion sickness affects approximately 50% to 75% of Shuttle crewmembers in gradations of severity and presents a problem early in short-duration missions especially when the workload is heavy. It is important to understand the threshold for perception of vestibular inputs in order to improve methods for prevention, prediction and treatment of space motion sickness. Neurophysiology experiments were flown on eight Spacelab missions and more than thirty-five individual experiments have been conducted.

Some of the findings are generalized as follows.

- After flight all subjects showed an increase in postural instability and a strong tendency to sway when the visual field rotated.
- No consistent vestibulo-ocular reflex changes were noted on orbit.
- Pointing accuracy was very poor. The bias was toward pointing low. Performance was always better with eyes closed only while pointing. In this case results were similar to ground. Recovery to preflight accuracy returned by 7 days post flight. This shows that primary adaptation in microgravity is loss of the external spatial map and complete recovery requires several days after flight.
- Muscle fatigue showed that isometric muscle strength was reduced by 10% to 50% post flight in ankle plantarflexion and unchanged in dorsiflexion. The fatigability did not return to baseline by day seven, post flight.
- The threshold for perception of direction of linear acceleration was not significantly changed.
- Susceptibility to space motion sickness (SMS) was not predictable based on ground tests. After day 3, SMS dropped and remained low thereafter. Postural bias was negatively correlated with discomfort. (Crewmembers became sick without regard to position of the body in the spacecraft).
- Sensations of trunk tilt and respective concomitant reflexes are missing in microgravity when the head is tilted with respect to the trunk.

The effect of autogenic feedback (motion tolerance, autonomic control) was investigated as a countermeasure for space motion sickness. It was found to be effective in some but not all crewmembers. Individual autonomic response to spaceflight was different from ground simulation tests.

## **D. Advanced Human Support Technology - Human Factors**

Human factors include all of the factors across the disciplines that impinge on the health, performance, safety, and well-being of humans in orbiting spacecraft, planetary bases and space stations.

### *1. Environmental Contaminants.*

Microbial evaluation of the crew, air, surfaces and water on the Mir Station is critical to understanding the ecology of microbial organisms that inhabit crew living areas. Based on findings over the past 25 years it is evident that microbial ecology on spacecraft under go quantitative and qualitative changes. Investigations on microbial biota from SL-Mir provide information on incidence and mechanisms of microbial transmission between crewmembers and work station/crew transmissions. Isolations of organisms from air, water and surfaces were shown to be within the International Space Station acceptability limits.

The environment of spacecraft contain chemical contaminants that can be potential threats to crew health and safety especially on long-duration missions. These airborne pollutants must be identified and controlled and air must be scrubbed and rendered compliant with safe levels. Evaluations of air quality are a significant part of the human factors considerations.

On Mir, approximately 50% of the potable water supplied to crewmembers is produced by direct recycling of water from humidity condensate. The other primary source is from potable water delivered by re-supply spacecraft from the ground or from fuel cell water that is transferred from the Shuttle. Experiments to assess the reliability of the water supply system are done to support water requirements for the International Space Station needs based on information from Mir. Water samples collected on the Mir 18 and STS-71 SL-Mir Shuttle missions were analyzed and considered to be of general potable water quality although it exceeded water quality standards for total organic carbon (TOC). Ground supplied water was considered of general potable water quality although it exceeded standards for TOC, turbidity and chloroform. These investigations are ongoing and modifications are being considered for future flights.

### *2. Microgravity Environment Effects on Cognitive Performance of Humans.*

Space travelers are subjected to a number of stresses during spaceflight. These include physical isolation, confinement, a lack of privacy, fatigue and changing work/rest cycles. Studies on Earth have shown that changing work/rest cycles can degrade cognitive performance and productivity. A battery of cognitive tests was administered on IML-2 and LMS to determine the effect of microgravity on cognitive skills critical to the success of operational tasks in space. The tests included a number of cognitive, mood, fatigue, memory and performance tests. No general conclusions can be drawn at this time, based on the limited number of subjects.

## ACRONYMS AND ABBREVIATIONS

AADSF	advanced automated directional solidification furnace
AC	alternating current
ACRIM	active cavity radiometer irradiance monitor
ADVASC	advanced Astroculture unit
AEPI	atmospheric emissions photograph imaging
AFM	atomic force microscope
AGHF	advanced gradient heating facility
ALAE	atmospheric Lyman alpha emissions
AMU	atomic mass unit
ANF	atrial natriuretic factor
AO	Announcement of Opportunity
APCF	advanced protein crystallization facility
ASC	Astroculture
ASI	Agenzia Spaziale Italiana (Italian Space Agency)
ASTRO	Ultraviolet Astronomy Mission
ATLAS	Atmospheric Laboratory for Applications and Science
ATMOS	atmospheric trace molecules observed by spectroscopy
ATP	adenosine triphosphate
ATV	automated transfer vehicle
AVHRR	advanced very high-resolution radiometer
BDPU	bubble, drop, and particle unit
BFD	bulk fluid dynamics
BIMDA	Bioserve/ITA materials dispersion apparatus

## ACRONYMS AND ABBREVIATIONS (Continued)

BMFT	German Ministry for Research and Technology
BPL	BioServe pilot lab
BSA	bovine serum albumin
BTB	bulk thermal dynamics
BTS	breedable transformed seed
CAAMP	Center for Advanced Microgravity Materials Processing
CBSE	Center for Biophysical Sciences and Engineering
CCD	checkout command decoder constants change display configuration control document charge coupled device
CEA	French Atomic Energy Agency
CEBAS	closed equilibrated biological aquatic system
CFC	chlorofluorocarbon
CFE	continuous flow electrophoresis
CGBA	commercial generic bioprocessing apparatus
CGF	crystal growth furnace
CHASE	Coronal Helium Abundance Spacelab Experiment
CIDR	critical intermediate design review
CITE	cargo integration test equipment
CIV	critical ionization velocity
CNES	Centre National d'Etudes Spatiales (French Space Agency)
CNRS	Centre National de la Recherche Scientifique (National Center for Scientific Research, National College of France)
COF	construction of facilities Columbus orbiting facility
COSMOS	early European space consortia

## ACRONYMS AND ABBREVIATIONS (Continued)

CPBF	commercial plant biotechnology facility
CPF	critical point facility
CPL	capillary pumped loop
CPU	central processor unit
CR/IM	commercial refrigerator/incubator module
CRISTA	cryogenic infrared spectrometers and telescopes for the atmosphere
CRNE	Cosmic Ray Nuclei Experiment
CS	constitutional supercooling
CSA	Canadian Space Agency
CSC	Commercial Space Center
CT	crawler transporter current transformer
CTC	constant temperature configuration
CVP	central venous pressure
CVT	closed vapor transport
DARA	Deutsche Agentur für Raumfahrtangelegenheiten (German Space Agency)
DARPA	Defense Advanced Research Projects Agency
DASA	DaimlerChrysler Aerospace (present day)
DC	direct current
DCAM	diffusion controlled crystallization apparatus for microgravity
DCCA	dynamic cell culture system
DE	dynamics explorer satellite
DFVLR	Federal German Aerospace Research Establishment (precursor to DLR)
DIFP	differential ion probe
DLR	Deutsches Zentrum für Luft-und Raumfahrt e.V. (German Research Aerospace Establishment)

## ACRONYMS AND ABBREVIATIONS (Continued)

DNA	deoxyribonucleic acid
DOD	Department of Defense
DSR	database support request
ECLS	environmental control and life support
ECG	electrocardiogram
EGA	electron gun assembly
EGSE	electrical ground-support equipment
ELDO	European Launcher Development Organization
ELLI	elliptical mirror furnace
EMC	electromagnetic compatibility
EMI	electromagnetic interference
EPM	European physiology modules
EPO	erythropoietin
EPS	elite parent seed
ER	early release explanation report
ERS	European remote sensing
ESA	European Space Agency
ESRO	European Space Research Organization
ESTEC	European Space Research and Technology Centre
EURECA	European retrievable carrier
EVA	extravehicular activity
FAUST	far ultraviolet space telescope
FCC	face-centered cubic structure
FFEU	Japanese free-flow electrophoresis unit
FFFT	forced-flow flame spread test

## ACRONYMS AND ABBREVIATIONS (Continued)

FFT	fast Fourier transformations
FGBA	fluids generic bioprocessing apparatus
FNDS	fluid and nutrient delivery system
FPA	fluids processing apparatus
FPEG	fast-pulsed electron generator
FPM	fluid physics module
FSL	Fluid Science Laboratory
GAP	group activation pack
GAS Can	getaway special canister
GBA	generic bioprocessing apparatus
GEFA	gas exchange fermentation apparatus
GGFC	geophysical fluid flow cell
GGs	global geosynchronous science
GHF	gradient heating facility
GHz	gigahertz
GPRF	general-purpose rocket furnace
GSE	ground-support equipment
GSFC	Goddard Space Flight Center
GSPC	gas scintillation proportional counter
HCL	horizontal centerline
HEWL	hen egg white lysozyme
HF	high frequency horizontal flight hot firing hydrogen fill hyperfiltration hard failure
HHDTC	hand held diffusion test cell

## ACRONYMS AND ABBREVIATIONS (Continued)

HIP	hot isostatic pressing
HOLOP	holographical optical laboratory
HPLC	high-performance liquid chromatography
HRTS	solar ultraviolet high-resolution telescope and spectrograph
HUT	Hopkins ultraviolet telescope
HZE	high-energy cosmic rays
ICD	interface control document
ICF	inertially confined fusion experiment
ICM	isothermal containment module
IDEA	International Distributed Experiment archive
IDGE	Isothermal Dendritic Growth Experiment
IFN	interferon
IGA	InterGovernmental Agreement
IGARRS	International Geoscience and Remote Sensing Symposium
IML	International Microgravity Laboratory (IML-1 and IML-2)
IMSPG	international microgravity strategic planning group
IMU	inertial measurement unit
IONS	Ionization Status of Low Energy Cosmic Rays Experiment
IPMP	integrated payload mission planning
IPS	instrument pointing systems
IR	infrared
IRAS	infrared astronomical satellite
IRT	infrared telescope
ISAS	The Institute of Space and Astronautical Science
ISIS	international satellite for ionospheric studies

## ACRONYMS AND ABBREVIATIONS (Continued)

ISLSWG	international space life sciences working group
ISO	imaging spectrometric observatory
ISPR	international standard payload rack
ISS	International Space Station
JASEM	Journal of Aerospace and Environmental Medicine
JASMA	Japan Society of Microgravity Application
JERS-1	Japanese remote sensing satellite
JPL	Jet Propulsion Laboratory
JSAEM	Japan Society of Aerospace and Environmental Medicine
JSBBS	Japanese Society of Breeding: Breeding Science
JSC	Johnson Space Center
JSLWG	joint Spacelab working group
JSSS	Japanese Society of Sericultural Science
JURG	joint user requirements group
KSC	Kennedy Space Center
LED	light-emitting diode
LEPEDEA	low-energy proton and electron differential energy analyzer
LIDAR	light intensification direction and ranging
LIF	large isothermal furnace
LITE	LIDAR In-Space Technology Experiment
LMS	Life and Microgravity Spacelab

## ACRONYMS AND ABBREVIATIONS (Continued)

LP	Langmuir probe
LSW	Landau, Slyozov, and Wagner theory explaining Ostwald ripening
LSDA	life sciences data archive
LYL	Lynn Lake, Manitoba, Canada, ground observation site
MAHRSI	middle atmospheric high-resolution spectrometric investigation
MAPS	measurements of air pollution from satellites
MARES	muscle atrophy research and exercise system
MAS	millimeter-wave atmospheric sounder
MAUS	Messenschafteliche Autonome Experiment Unter Scherewereelosigkeit
MBB	Messerschmitt-Bölkow-Blohm(German company now part of DASA)
MCS	modular cultivation system
MDMs	modulator-demodulator
MDMs	multiplexer-demultiplexer
MEPHISTO	Matériel pour l'Étude des Phenomènes Intéressants de la Solidification sur Terre et en Orbite ("Apparatus for the Study of Interesting Phenomena of Solidification on Earth and in Orbit" also known as "Materials for the Study of Interesting Phenomena of Solidification on Earth and in Orbit")
MESH	Early European Space Consortia
mg	microgravity
MMA	microgravity measurement assembly
MOCVD	metal organic chemical vapor deposition technique
MOMS	modular optoelectronic multispectral scanner
MOU	Memorandum of Understanding
MPD	magnetoplasmadynamic
MPLM	mini pressurized logistics module
MSDR	materials science double rack

## ACRONYMS AND ABBREVIATIONS (Continued)

MSFC	Marshall Space Flight Center
MSL	Materials Sciences Laboratory (MSL–1 and MSL–2)
NACA	National Advisory Committee for Aeronautics (Predecessor of NASA)
NASDA	National Space Development Agency of Japan
NIH	National Institutes of Health
NIST	National Institute of Standards and Technology
NIZEMI	Japanese Space Agency spaceflight centrifuge
NRA	NASA Research Announcement
NRC	National Research Council
NSF	National Science Foundation
O&C	operations and checkout building (KSC)
OD	optical density
OLMSA	Office of Life and Microgravity Science and Applications
ONR	Office of Naval Research
OPF	orbiter processing facility (KSC)
OSS–1	Office of Space Science Spacelab Flight (STS–3)
OSTA	Office of Space and Terrestrial Applications
OTFE	Oscillatory Thermocapillary Flow Experiment
PACE	physics and chemistry experiments
PAH	polyaromatic hydrocarbons
PAO	Public Affairs Office
PCAM	protein crystallization apparatus for microgravity
PCDF	protein crystallization diagnostics facility
PCF	protein crystallization facility
PD	payload developer

## ACRONYMS AND ABBREVIATIONS (Continued)

PDP	plasma diagnostics package
PEG	polyethyleneglycol
PEMS	percutaneous electrical muscle stimulator
PGBA	plant generic bioprocessing apparatus
PIs	Principal Investigators
PICPAB	phenomena induced by charged particle beams
PKC	protein kinase C
PL	payload
PMMA	polymethylacrylate
POCC	Payload Operations Control Center
PR	public relations
PSG	payload support group
PTCU	passive thermal conditioning unit
PTH	parathyroid hormone
QINMS	quadruple ion-neutral mass spectrometer
QSW	Quantized Surface Wave Experiment
RAMSES	Recherche Applique sur la Methodes do Separation Electrophorese Spatiale
RBC	red blood cells
RETE	research on electrodynamic tether effects
RG	renormalization group
RHCP	random hexagonal close-packed structures
R/IM	refrigerator/incubator module
RMS	remote manipulator system
ROPE	research on orbital plasma electrodynamic
ROSAT	Roentgen satellite

## ACRONYMS AND ABBREVIATIONS (Continued)

ROTEX	Robotic Technology Experiment
RPI	Rensselaer Polytechnic Institute
SAAL	single-axis acoustic levitator
SAR	synthetic aperture radar
SCE	Smoldering Combustion Experiment
SEPAC	space experiments with particle accelerators
SIR	spaceborne imaging radar (versions A, B, and C)
SIRTF	space infrared telescope facility
SMURRF	shared multiuser remote robotic facility
SOFBALL	structure of flame balls at low-Lewis numbers
SOLCON	Measurement of the Solar Constant Experiment
SOLAPEC	solar spectrum instrument
SOUP	solar optical universal polarimeter
SMM	solar maximum mission
SMS	space motion sickness
SPAS	Shuttle pallet satellite
SPES	soft particle electrostatic spectrometer
SPICE	Spacelab Payload Integration Center in Europe
SPOT	Spot Image is a member of the ERS consortium appointed by the ESA to ensure the commercial distribution of ERS products.
SPP	science and power platform
SPRA	spherical retarding potential analyzer
SPRAG	STS payloads requirements and analysis group
SPREE	Shuttle Potential and Return Electron Experiment
SQUID	superconducting quantum interference devices
SRB	solid rocket booster

## ACRONYMS AND ABBREVIATIONS (Continued)

SSBUV	Shuttle solar backscatter ultraviolet
SSCE	Solid Surface Combustion Experiment
SSPPSG	Space Shuttle Payload Planning Steering Group
STAR	early European space consortia
STDCE	Surface Tension Driven Convection Experiment
STES	single-locker thermal enclosure system
STS	Shuttle transport system
SUSIM	solar ultraviolet spectral irradiance monitor
TDRSS	tracking and data relay satellite system
TEM	tunneling electron microscopy
TEMAG	Magnetic Field Experiment for TSS missions
TEMPUS	Tiegelfreies Elektromagnetisches Prozessieren Unter Schwerelosigkeit (electromagnetic containerless processing facility)
TES	thermal enclosure system
TTF–TCNQ	tetrathiafulvalene-tetracyanoquinodimethane
TGS	triglycine sulphate
THM	traveling heater method
TMS	The Minerals, Metals, and Materials Society
TOC	total organic carbon
TRMM	tropical rainfall measuring mission
TSS	tethered satellite system
TVD	torque velocity dynamometer
UAB	University of Alabama at Birmingham
UAH	University of Alabama in Huntsville
UARS	upper atmosphere research satellite

## ACRONYMS AND ABBREVIATIONS (Continued)

UIT	ultraviolet imaging telescope
USDA	U. S. Department of Agriculture
USML	U. S. microgravity laboratory (USML–1 and –2)
USMP	U. S. microgravity payload (USMP–1, –2, –3, –4)
UVI	ultraviolet imager
VAFB	Vandenberg Air Force Base
VCAP	Vehicle Charging and Potential Experiment
VDA	vapor diffusion apparatus
VLF	very low frequency
VVIS	visual and vestibular investigation system
VWFC	very wide field camera
WCSAR	Wisconsin Center for Space Automation and Robotics
WIFE	Wire Insulation Flammability Experiment
WUPPE	Wisconsin Ultraviolet Photo Polarimeter Experiment
X–SAR	x-band synthetic aperture radar
YGB Theory	Young, Goldstein, Bloch relating drop motion to Marangoni number

# **SPACELAB SCIENCE RESULTS STUDY: EXTERNAL OBSERVATIONS**

**Robert J. Naumann, Compiler**

## **Introduction**

Some of the thirty-six Spacelab missions were more or less dedicated to specific scientific disciplines, while other carried an eclectic mixture of experiments ranging from astrophysics to life sciences. The variety of disciplines accommodated by the Spacelab flights logically group into three distinct categories.

1. External Observations in which the Shuttle/Spacelab is used as an observing platform,
2. Microgravity Physical Sciences that make use of the microgravity environment to further the studies of Fluid Physics, Combustion Science, Materials Science, and Biotechnology, and
3. Microgravity Life Sciences that study the response and adaptability of living organisms to the microgravity environment.

This first part of the Spacelab Science Results study will be devoted to experiments of the first category. The disciplines included are Astrophysics, Solar Physics, Space Plasma Physics, Atmospheric Sciences, and Earth Observations.

The team members that contributed to this section and their areas of responsibility are:

- Dr. Charles A. Lundquist – Astrophysics
- Dr. Einar Tandberg-Hanssen – Solar Physics
- Dr. James L. Horwitz - Space Plasma Physics
- Dr. Glynn A. Germany – Atmospheric Science
- Dr. James F. Cruise – Earth Observations

The purpose of this Spacelab Science Results Study is to document the contributions made in each of the major research areas by giving a brief synopsis and analysis of the more significant experiments, and an extensive list of the publications produced by the various investigators and teams. We have also endeavored to show how these results impacted the existing body of knowledge, where they have spawned new fields, and, if appropriate, where the knowledge they produced has been applied. Since a new generation of young researchers will make up the cadre of investigators that utilize the International Space Station (ISS), we feel it is important to leave a legacy of the results, some positive, some negative, of the previous experiments that have been performed. Hopefully, the new generation will build on the successes and learn from the failures of the past.

The material used in this part of the study came from many sources including the Mission Summary Reports, Mission and/or Investigator Team websites, the Astrophysics Data Facility, the Compendex\*Web, the Science Citation Index, the AstroWeb, various survey papers, conference proceedings, and the open literature publications of the investigators.

The bibliography is rather extensive and includes papers generated by the various investigators during the course of the development of their experiments as well as the results and applications of the results. There is, perhaps, a lack of uniformity in the number of documents listed since some investigators left a much more extensive document trail than others. Also, several of the investigators had spent a good fraction of their careers in the development of their experiments. Even though this study was restricted to the experiments

actually performed on Spacelab missions, in several cases experiments performed on suborbital rockets or on non-Spacelab Shuttle flights went into the development of the Spacelab experiment. Therefore, the results from these flights were also included.

The number of publications generated by this research is summarized in Table I-1.

**Table I-1. Publications from experiments using external observations, by discipline.**

Discipline	Publications
Astrophysics	538
Solar Physics	172
Space Plasma Physics	140
Atmospheric Science	220
Earth Resources	117
Total	1187

We regret that time and resources did not permit iteration with the investigators as we would have liked. If a result is misinterpreted or if references were missed, we apologize. We tried to include every relevant experiment that was flown on a Spacelab mission, but invariably when dealing with this many experiments in a limited time, an important experiment or result is bound to be missed. It is our hope that with the bibliography and other reference material included, interested parties can locate any information we were unable to provide.

## I. ASTROPHYSICS

Charles A. Lundquist

### A. Introduction and Background

Of the scientific disciplines represented on the several Spacelab missions, the astronomical discipline is one of the most mature. Thus the accomplishments from the astronomical instruments must be viewed against a large body of knowledge from many years of prior investigations. In some cases this means that very specific or detailed questions were posed and answered. In other cases it means that astronomical observing technology was extended into difficult wavelengths or modes not previously used. The most significant data fall into such cases, and will be identified as such in subsequent discussions. There are also, of course, instances in which the Spacelab instrumentation produced observations of individual stars or objects that add incrementally to the general astronomical data base. These data are valuable, but cannot be addressed in any depth here.

Because the Spacelab missions spanned many years, a further factor in reviewing astronomical results is timeliness. Astronomy is a rapidly moving discipline. Results that were new and important at the time of their release may be superseded by newer results a few years later. This is a general feature of astronomy that must be recognized when discussing any individual achievement.

The Spacelab astronomical-astrophysical observations were performed with the instruments on the missions listed in Table I-2. Also listed are the Principal Investigators. The co-investigators and guest investigators are numerous and generally are represented as co-authors in the cited references (see Appendix B: References).

<b>Table I-2. Astronomical-astrophysical observations.</b>	
Mission and Launch Date	Principal Investigator
Spacelab 1, November 1983	
Far Ultraviolet Space Telescope (Faust)	C. S. Bowyer
Very Wide Field Camera (VWFC)	G. Courtes
Gas Scintillation Proportional Counter (GSPC)	R. Andresen
Spacelab 2, July 1985	
InfraRed Telescope (IRT)	G. Fazio
Cosmic Ray Nuclei Experiment (CRNE)	P. Meyer
X-Ray Telescope (XRT)	A. P. Willmore
Spacelab 3, April 1985	
Ionization Status of Low Energy Cosmic Rays (IONS)	S. Biswas
Astro 1, December 1990	
Hopkins Ultraviolet Telescope (HUT)	A. F. Davidson
Wisconsin Ultraviolet Photo-Polarimeter Experiment (WUPPE)	A. D. Code
Ultraviolet Imaging Telescope (UIT)	T. Stecher
Broad-Band X-Ray Telescope (BBXRT)	P. Serlemitsos
Astro 2, March 1995	
Hopkins Ultraviolet Telescope (HUT)	A. F. Davidson
Wisconsin Ultraviolet Photo-Polarimeter Experiment (WUPPE)	A. D. Code
Ultraviolet Imaging Telescope (UIT)	T. Stecher

## **B. Spacelab 1**

Spacelab 1 carried an eclectic ensemble of instruments and experiments. Because this first mission expected to demonstrate diverse uses of Spacelab, the instrumentation represented a broad range of disciplines, including the three astronomical instruments in Table II-2. These three instruments were hard mounted to the Shuttle structure, so that pointing was accomplished by controlling the attitude of the Shuttle.

The two telescope-camera instruments photographed star fields in the far ultraviolet<sup>1</sup> (Faust, the Far Ultraviolet Space Telescope) and ultraviolet<sup>2</sup> (VWFC, or Very Wide Field Camera). As might be expected, one principal result was an improved understanding of how Shuttle borne cameras of this class can best be employed. Also, the photographed fields provided surveys of ultraviolet (UV) characteristics of classes of stars that could be selected for future detailed observation and analysis.

The Gas Scintillation Proportional Counter (GSPC) measured X-ray energy spectra in the range of 2 to 80 keV for Cyg X-3, Cen X-3 and the Perseus cluster of galaxies<sup>3,4</sup>. The first two are well known X-ray sources for which these measurements provided further information.

## **C. Spacelab 2**

The astrophysical instruments on Spacelab 2 used three distinct signals to probe the universe: infrared (IR) radiation, X-rays and cosmic rays.

For the first of these, Spacelab 2 carried a small, helium-cooled infrared telescope (IRT). It was designed to observe diffuse, extended sources of infrared as well as to augment data on discrete infrared sources, many of which were cataloged earlier by the Infrared Astronomical Satellite (IRAS). An operational question addressed was the suitability of the Shuttle as a carrier for infrared telescopes. With respect to this question, the IRT background due to emission of gas from the Shuttle was found to be greater than anticipated.

The surveys of the Milky Way Galaxy at two and seven microns were new data, implying that the structure of the galaxy is broader at these wavelengths than at longer wavelengths<sup>5,6,7</sup>.

As compared to other instruments carried by Spacelab, the Cosmic Ray Nuclei Experiment (CRNE) was massive, nearly 2,000 kilograms (kg). An instrument of this extreme size and complexity was required to extend measurements of rare cosmic rays to energies almost one hundred times greater than those previously studied by comparable techniques.

The measurements were successful and extend to energies beyond 1 TeV per atomic mass unit (amu). The investigators conclude that the cosmic ray flux arriving near earth becomes enriched with heavier nuclei, most notably iron, as energy increases<sup>8,9</sup>. Another analysis presented energy spectra of the cosmic-ray nuclei boron, carbon, nitrogen and oxygen up to energies around 1 TeV<sup>10</sup>, which yielded information on the propagation of cosmic rays through the galaxy. Thus the large carrying power of the space Shuttle supported a significant advance in cosmic ray astrophysics.

The hard X-ray imaging capability on Spacelab 2 was the result of two associated instruments operating approximately in the 2 to 20 keV energy range but with different resolutions, respectively 12 x 12 arc minutes

and 3 x 3 arc minutes. Both of the instruments used a coded, X-ray absorbing mask having many small holes in random locations that produced a shadow pattern on a position sensitive multiwire proportional counter. From the resulting data, an X-ray image was constructed<sup>11,12</sup>.

The objective was to produce images of clusters of galaxies, particularly, and also other extended X-ray sources. A puzzle was the source of the hard X-rays coming from the direction of clusters of galaxies. Measurement of hot gas between the galaxies of the cluster was an objective (see G. An Exercise in the Implication of Spacelab Results). Spectrally resolved images of the Virgo cluster were obtained in the 2 to 32keV energy range<sup>13</sup>. The investigators report that much of the hard X-ray emission previously reported from the cluster actually originates in the single galaxy NGC 4388.

#### **D. Spacelab 3**

Spacelab 3 carried an instrument (IONS) developed in India to measure low energy (30 to 300 MeV per amu) “anomalous” cosmic ray ions (ACR). The detector used two sets of nuclear track plates (mostly CR-39) slowly rotating relative to each other. Thus arrival time of a given cosmic ray can be obtained from relative track displacement. That time when combined with Shuttle position and attitude at the same time yields arrival direction.

These low energy cosmic rays may not have all the electrons stripped from their respective nuclei. The low energy cosmic rays have trajectories that are bent more strongly by the magnetic fields in space, particularly the geomagnetic field. The results of magnetic field interaction and therefore arrival direction depend on the charge of the particle and hence on whether or not all the electrons are stripped.

From the IONS instrument data, the abundances of sub-iron (Sc-Cr) and of iron (Fe) particles in the low energy interval of 30 to 300 MeV per amu were determined<sup>14,15,16,17,18</sup>. The sub-iron to iron abundance ratios were 0.8 to 1.2. These ratios are enhanced by a factor of two compared to interplanetary (high energy) ratios of about 0.5. The investigators concluded that the IONS measurement ratios are probably enhanced inside the earth’s magnetosphere due to the degree of ionization of low energy Sc to Cr and Fe ions in galactic cosmic rays and to the filtering effects of the geomagnetic field. This is the suggested explanation of cosmic ray data previously cited as anomalous.

#### **E. Astro 1 and 2**

As the mission names imply, the Astro 1 and 2 flights, using Spacelab pallets, carried an ensemble of astronomical instruments. Three of these, HUT, WUPPE and UIT operated in ultraviolet wavelengths and were on a common Instrument Pointing System (IPS). These three were carried on both Astro 1 and 2.

A Broad-Band X-ray Telescope (BBXRT) with its own pointing system was added to Astro 1 only<sup>19</sup>, with the initial motivation to observe a 1987 super nova, SN1987A, in a nearby galaxy. However, Astro 1 did not reach orbit until December 1990. The BBXRT was designed to make moderate resolution spectrophotometry of X-ray sources in the 0.3 to 12 keV band. It consisted of a pair of coaligned conical foil telescopes, with cryogenically cooled Si(Li) (silicon(lithium)) spectrometers as focal detectors.

The BBXRT collected and published data for several astronomical objects including Xi Pup, the Puppis A supernova remnant and Cygnus X-2<sup>20,21,22</sup>.

The Hopkins Ultraviolet Telescope (HUT) was the largest of the three instruments assembled on the Instrument Pointing System for both Astro 1 and 2. HUT was a 0.9 meter telescope designed to perform moderate resolution spectroscopy in the 850 to 1850 Ångstrom region of the far-UV. This spectral range goes farther into the UV than the spectrography on the Hubble telescope, which cuts off sharply at wavelengths below 1200 Ångstroms.

The HUT operations, particularly on Astro 2, were similar to that of a major ground based observatory. A list of several hundred observing targets was adopted to provide data to many investigators for diverse analyses. These, of course, employed in crucial ways the unique far-UV capabilities of HUT. Hence, it is quite impractical here to even enumerate the results, other than to note that new far-UV observations were obtained for virtually every class of objects in the universe, a remarkable achievement!<sup>23</sup>

The astronomers who conceived and built HUT identified what they felt were particularly important or interesting key objectives for the instrument. One of these was to detect and measure the characteristics of the primordial intergalactic gas. Hydrogen (H), the most abundant element in the universe should dominate the intergalactic medium. Helium (He) should be the next most abundant residual component from the Big Bang and the subsequent condensation of stars and galaxies.

The plan was to observe a very distant quasar in its far ultraviolet spectrum and look for absorption lines due to its light passing through the intervening intergalactic gas. For this purpose, HUT was programmed to observe quasar HS 1700 + 64. By good fortune, the redshifted spectrum of this quasar covered an absorption line of partially ionized helium. This was detected and analyzed successfully<sup>24</sup>. (See also G. An Exercise in the Implication of Spacelab Results.)

A second instrument on the Instrument Pointing System was the Wisconsin Ultraviolet Photo-Polarimeter (WUPPE). It was conceived as a pioneering effort to explore polarization and photometry of astronomical objects in the ultraviolet spectrum. As did HUT, WUPPE had a long observation target list of many different types of astronomical objects in the universe.

During the two Astro missions, WUPPE obtained polarimetry and spectra for one hundred and twenty-one objects. Most of the observations were unique in extending polarimetry into areas of the UV spectral range not possible from the ground<sup>25,26,27,28,29,30,31,32,33,34,35</sup>.

The third instrument on the Instrument Pointing System was the Ultraviolet Imaging Telescope (UIT). It was a 38 cm Ritchey-Chretien telescope equipped for ultraviolet filter and grating imagery over a 40 arc minute field of view with a resolution of about 3 arcsec. It produced ultraviolet (1200 to 3300 Ångstroms) images of a variety of astronomical objects, particularly extended objects, recorded on 70 mm film<sup>36,37,38</sup>.

One product of the Astro missions that is of general utility to the entire astronomical community is an atlas of spatially-resolved far-UV (1500 Ångstroms) and mid-UV (2500 Ångstroms) images of fifty nearby galaxies. This set includes ellipticals, disk systems and irregular galaxies. Other extended objects studied include the Large and Small Magellanic Clouds and various star clusters were likewise recorded<sup>40,41,42,43,44</sup>.

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## **F. Summary**

The sequence of astronomical instruments on the Spacelab missions evolved over the years from exploratory, pioneering devices to more mature, multi-purpose instruments and operations. The very productive and successful Astro 2 mission is the prime example of the latter situation.

The evolutionary progress of instrumentation design afforded by the Spacelab missions is probably as important as the observations obtained. While the space Shuttle is not the ideal carrier for many astronomical instruments, it was a valuable test-bed for new observation techniques and opportunities. The resulting insights can eventually be applied to other free-flying observatories if the remaining astronomical issues warrant, a circumstance illustrated in the following section. Presumably, in the future, the International Space Station (ISS) may provide a comparable test-bed for instrument concepts yet to be invented.

The surveys and catalogs generated from the Spacelab observations in previously unused frequency and energy ranges will find continuing utility in identifying individual astronomical objects worthy of future detailed study. This in and of itself will insure a lasting legacy from Spacelab.

## **G. An Exercise in the Implication of Spacelab Results**

It has been noted that astronomical and astrophysical observations build on earlier results and subsequently motivate still further observations. The observations from the instruments on Spacelab have a place in this ever-growing fabric of astronomical knowledge.

Occasionally a notable milestone is reached in this process. Such was the case in 1998 when the magazine Science designated the findings by two groups that the general expansion of the universe is accelerating as the science breakthrough of the year <sup>1, 2, 3</sup>. This is a remarkable discovery because it has profound implications for cosmology when combined with other information.

In a parallel treatment, Scientific American, in its January 1999 issue, carried a special report on the "Revolution in Cosmology"<sup>4, 5, 6</sup>. This three-article series also emphasized the reported accelerated expansion of the universe and its cosmological implications, which depended on many observational facts about the universe.

Still further, the American Physical Society held its Centennial Meeting in March 1999. This Centennial Celebration was the largest meeting of physicists ever. One well-attended session of invited papers on the Cosmological Constants<sup>7</sup> covered similar topics to those in Science and Scientific American.

Cosmology usually does not receive such notoriety. Hence it is particularly timely to ask whether, or how, the earlier Spacelab results contributed to the excitement of these discoveries. An attempt to answer this question is undertaken as an instructive exercise to illustrate the process.

In brief, the current view of the universe envisions that some 70% of the energy of the universe is represented by a cosmological constant in the general theory of relativity. This energy of the cosmological constant, or the vacuum, is responsible for an accelerated expansion of the universe. About 30% of the energy of the universe is in the form of gravitating matter. Of this 30%, some 5% is in baryon matter and 25% or so in cold dark matter. However, the sum of the cosmological constant energy and matter energy is just sufficient to produce a flat universe in the sense of the general theory of relativity. This is a dramatic revision of the view of the universe held only a few years ago.

The accelerated expansion of the universe is supported by observations of Type Ia supernovae in distant galaxies<sup>2,3</sup>. Large numbers of such galaxies are monitored from the ground at intervals of a few days to detect promptly any changes in brightness caused by a rare supernova in some distant galaxy. When such an event is detected, large ground telescopes and/or the Hubble Space Telescope are mobilized to measure first the increasing and then the decreasing luminosity of the supernova over several days or weeks. From the time history of this measured luminosity, the absolute peak luminosity from the supernova can be determined using established models. The absolute and observed luminosity provides a reliable measurement of the distance to the supernova and its galaxy. Also the redshift of the galaxy provides evidence of its expansion rate. From analysis of several such events, a plot of relative distance versus redshift can be produced for the distant galaxies involved. This yields the basic finding that the expansion of the universe, as determined from redshifts of galaxies at known distances, is accelerating.

Previously, a deceleration had been expected due to mutual gravitation of the galaxies and other massive constituents of the universe. The apparent issue had been whether there was enough mass in the universe to eventually halt the expansion or whether the expansion would continue forever. The recent assessment is that the expansion is instead accelerating, because of some other factors such as a cosmological constant, and there is too little gravitating matter to produce deceleration.

In as much as Type Ia supernovae are rare events in distant galaxies and they require dedicated and specialized techniques for their observation, the Spacelab instruments contributed nothing directly to these recent findings, although Spacelab did add to the general understanding of supernovae. However, the instruments did have a role in measuring massive constituents of the universe. Lawrence M. Krauss, for example, has discussed this issue<sup>5,8</sup>.

The standard theory of nucleosynthesis in the Big Bang predicts that measurement of the production ratios of the lightest isotopes gives a sensitive constraint on the cosmological baryon-to-photon ratio. The cosmic microwave background gives a measure of the photon density at the Big Bang, which, with the baryon to photon ratio, yields the cosmological baryon density<sup>9</sup>.

The deuterium to hydrogen ratio (D/H) in the intergalactic gas has been determined by observing absorption lines in the light from distant quasars<sup>9, 10</sup>. These D/H measurements can be done from the ground, but the corresponding measurement of helium absorption is best measured in ultraviolet wavelengths, which must be done in space. This circumstance motivated Davidson, Kriss and Zheng<sup>11</sup> to use the HUT telescope on Astro 2 to measure the absorption from singly ionized helium (He II) in the spectrum of the quasar HS 1700+64.

Since the intergalactic clouds have been negligibly affected by nucleosynthesis in stars, measurements of the light isotope abundance ratios in intergalactic space implies the ratios from the Big Bang. Thus the HUT measurements contribute to estimates of baryonic or ordinary matter generated in the Big Bang, as cited above.

Another way to obtain information on masses in the universe is to deduce the mass in large clusters of galaxies. These are currently the largest objects in the universe for which total masses can be estimated directly<sup>12, 13, 14</sup>. The measurement technique depends on the notion that most of the luminous mass of a large galaxy cluster is in hot intergalactic gas which emits X-rays. The assumption is used, and justified, because the gas is in hydrostatic equilibrium, that is, the gas pressure gradients and gravity are in balance. For a massive galaxy cluster, this requires that the gas be so hot that it emits X-rays. Appropriate theory provides equations from which the mass of a galactic cluster can be determined from measurements of the X-rays from its intergalactic gas.

The X-ray telescope on Spacelab 2 was a pioneering effort to use this technique to assess the masses of galactic clusters<sup>12</sup>. It demonstrated the usefulness of the technique, which requires spectral imaging of the clusters studied, even within the limitations of space Shuttle mission parameters.

In 1990, five years after Spacelab 2, the ROSAT (Roentgen Satellite) was launched with X-ray spectral imaging capabilities, and with mission parameters allowing for far more comprehensive observations and analyses of galactic clusters<sup>13, 14</sup>. These later data, building on the Spacelab 2 experience, currently provide one of the best measurements of observable mass in the universe, since galactic clusters represent a large fraction of identifiable mass.

The galactic cluster mass data are cited, with the previously noted results from light element nucleosynthesis, as the most important available information on the matter content in the universe. This information is central to the present “Revolution in Cosmology”. The noteworthy point to this exercise is that pioneering investigations using Spacelab instrumentation helped move the cosmology discipline to its current exciting state, providing critical steps in our pathways of discovery.

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<sup>2</sup>S. Perlmutter et al, Discovery of a supernova explosion at half the age of the Universe, Nature 391, p. 51-54, 1998 Jan. 1.

<sup>3</sup>Adam G. Riess et al., Observational Evidence from Supernovae for an Accelerating Universe and a Cosmological Constant, Astronomical Journal 116, p. 1009-1038, 1998 Sept.

<sup>4</sup>Craig J. Hogan et al., Surveying Space-time with Supernovae, Scientific American, p. 53-59, 1999 Jan.

<sup>5</sup>Lawrence M. Krauss, Cosmological Antigravity, Scientific American, p. 53-59, 1999 Jan.

<sup>6</sup>Martin A. Bucher and David N. Spergel, Inflation in a Low-Density Universe, Scientific American, p. 62-69, 1999 Jan.

<sup>7</sup>Session EB 22, The Cosmological Constants, p. 182-183, Bulletin of the American Physical Society, Vol. 44, No. 1, March 20-26, 1999.

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- <sup>9</sup>Scott Burles and David Tytler, The Deuterium Abundance Toward Q 1937-1009, The Astrophysical Journal, 499, p. 699-712, 1998 June 1.
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## II. SOLAR PHYSICS

Einar Tandberg-Hanssen

### A. Spacelab Solar Physics Experiment Descriptions

Seven different solar physics experiments have been flown on the Spacelab facility. Three of these Spacelab experiments have also been flown on non-Spacelab missions. A list of experiments, principal investigators and their missions is given in Table I-3.

**Table I-3. Solar physics experiments by principal investigator and mission.**

G. E. Brueckner	Naval Research Laboratory, Washington DC, USA, (SUSIM: ATLAS-1, ATLAS-2, ATLAS-3; HRTS: Spacelab-2; OSS-1 (Office of Space Science-1), 1982, and on UARS (Upper Atmosphere Research Satellite), 1992.)
D. A. Crommelynck	Institut Royal Meteorologique de Belgique, Brussels Belgium, (SOLCON: Spacelab-1, ATLAS-1, ATLAS-2, ATLAS-3; EURECA (European Space Agency's European Retrievable Carrier), 1992.)
J. A. Culhane	University College London, UK (CHASE: Spacelab-2)
A. H. Gabriel	Rutherford and Appleton Laboratory, Chilton, UK, (CHASE: (Spacelab-2).
G. O. Thuillier	Service d'Aeronomie du Centre National de la Recherche Scientifique, Verrieres-le-Buisson, France, (SOLSPEC: Spacelab-1, ATLAS-1, ATLAS-2, ATLAS-3)
A. M. Title	Lockheed Solar Observatory, Palo Alto, CA. USA (SOUP: Spacelab-2).
R. C. Willson	Jet Propulsion Laboratory, Pasadena, CA. USA, (ACRIM: Spacelab-1, ATLAS-1, ATLAS-2, ATLAS-3, SMM (Solar Maximum Mission 1980-1989)).

#### 1. Active Cavity Radiometer Irradiance Monitor (ACRIM).

a. Purpose. The primary objective of this instrument was to determine the degree and direction of possible fluctuations in the Sun's total output of optical energy (X-rays to microwave wavelengths) by measuring the total solar optical irradiance outside the Earth's atmosphere.

b. Physical Characteristics. These included the following.

Spectral coverage: 180 to 3200 nm

Effective cavity absorptance: 0.999980 +/- 0.000020

Single sample irradiance precision: +/- 0.012 %

Length of single measurement cycle: ~2 min

Uncertainty for single shutter cycle: less than +/- 50 ppm

Data rate: 256 b/s

Mass 35 kg

c. Instrument Operation. The ACRIM contains four cylindrical bays, three of which house independent heat detectors, pyrheliometers. The pyrheliometers are independently shuttered, self-calibrating and automatically controlled. Each pyrheliometer consists of two cavities, and the temperature difference between the two is used to determine the solar flux. One cavity is maintained at a constant reference temperature, while the other is heated 0.5 K higher than the reference cavity and is periodically exposed to the Sun. When the shutter covering the second cavity is open, sunlight enters and creates an even greater difference in cavity temperatures. The power supplied to the second cavity by the ACRIM electronics decreases

automatically to maintain the 0.5 K temperature difference between the two cavities, and this decrease is proportional to the solar irradiance entering the cavity. The fourth bay contains a sensor that measures the relative angle between the instrument and the Sun. The cavities have mirror-like black surfaces that reflect light toward the apex of the cavity, where 99.99998 % of the Sun's incoming energy in the 180 to 3200 nm wavelength range is absorbed.

## *2. Solar Ultraviolet Spectral Irradiance Monitor (SUSIM).*

a. Purpose. The objective of this instrument is to determine both long-term and short-term variations of the total ultraviolet flux emitted by the Sun.

b. Physical Characteristics. These included the following.

Spectral coverage: 110 to 410 nm

Spectral resolution: 5 nm, 0,15 nm

Accuracy: 5 % absolute.

Inflight calibration source: deuterium lamp

Data rate: 156 b/s

Mass: 69 kg

Power consumption: 53 W

c. Instrument Operation. The instrument is composed of two precision ultraviolet spectrometers with two sets of optics and an inflight calibration deuterium lamp. This assembly provides an accurate recording of the solar spectral irradiance from 110 to 410 nm, and is capable of tracking any change in ultraviolet sensitivity. The instrument has seven detectors that allow cross-checks of possible detector changes. One spectrometer operates as the primary unit and makes the solar spectral measurements. The other spectrometer gathers data from the deuterium lamp used to calibrate both this unit as well as the primary unit. Since the second spectrometer is not exposed to solar radiation, its readings can be used as reference information to track any degradation in the first spectrometer.

## *3. Measurement of the Solar Constant (SOLCON).*

a. Purpose. SOLCON's purposes are to measure the absolute value of the total solar irradiance and to detect and measure long-term variations that may exist in its absolute value.

b. Physical Characteristics. These included the following.

Spectral coverage: integrated over the full wavelength range

Absolute accuracy: better than 0.1 %

Precision: better than +/- 0.01 %

Sensitivity: better than 0.05 %

Field of view: 9 deg

Data rate: 46 b/s

Digital resolution: 22 b

Mass: 13 kg.

c. Instrument Operation. The instrument is a true differential, absolute radiometer with a digital processing/converter unit. Because its electrical, optical, mechanical, and thermal characteristics are known, no radiative calibration source is required. Two openings admit sunlight into two cavities, which are painted black. Each cavity has an independently controlled shutter at the front to block sunlight and a thermopile to measure the heat that is generated electrically as well as by absorbed sunlight. The actual measurements were made by pointing the radiometer towards the Sun's center and opening the shutter of one cavity, while the other cavity remained closed. The closed cavity is heated electrically until its heatflux to the heatsink

matches the heatflux of the open cavity. The energy required is proportional to the incoming sunlight, and the difference in power applied with the shutter opened and closed is a measure of the solar radiation flux. In an alternative mode of operation a constant electrical power is supplied to the closed cavity, and the heatflux balance is re-established by heating the open cavity.

#### 4. *Solar Spectrum Measurement from 180 to 3200 Nanometers (SOLSPEC).*

a. Purpose. The objective of this instrument is to measure the solar energy in the ultraviolet, visible and infrared parts of the spectrum, and to determine the amounts of energies in this spectral irradiance, and how they change with time.

b. Physical Characteristics. These included the following.

Spectral coverage: 180 to 3200 nm

Bandpass in ultraviolet and visible: 1 nm

Bandpass in infrared: 20 nm

Total number of bandpasses: 1950

Precision of individual bandpass: 0.01 nm

Photometric accuracy: 5 % in ultraviolet, 1 % in infrared and visible

Time to record solar spectrum: 13 min

Number of spectra per orbit: 3

Data rate: 500 b/s

Mass: 32 kg.

c. Instrument Operation. The instrument is a double-monochromator using two holographic gratings as dispersive elements. It has three spectrometers (one each for the ultraviolet, visible, and near-infrared portions of the spectrum), scanning at 650 different positions. Each position corresponds to a 1 nm bandpass in the ultraviolet and visible ranges, and to a 20 nm bandpass in the infrared, producing a total of 1950 bands. A hollow cathode lamp measures the wavelength scale of the spectrometers. Accuracy in flight is assured by four calibration lamps (two deuterium and two tungsten ribbon lamps). Their light follows the same optical path as the Sun's light. During operation, observations of the Sun alternate with observations of the calibration lamps at fifteen minute intervals.

#### 5. *Solar Optical Universal Polarimeter (SOUP).*

a. Purpose. The objectives of the experiment are:

i. measure magnetic and velocity fields in the solar atmosphere with high spatial resolution and to deduce the small-scale structure and evolution of these fields on the 10- to 20-minute time scale of solar granulation;

ii. follow the evolution of solar magnetic structures over periods of several days to determine how magnetic elements couple to the supergranule velocity patterns and by what mechanisms field diffusion and disappearance occur;

iii. study with high temporal and spatial resolution the magnetic field changes associated with transient events, like flares, and to isolate and follow the birth of sunspots, pores, and ephemeral regions;

iv. provide a test of the pointing accuracy and stability of the Instrument Pointing System (IPS) to sub-arc second accuracy.

b. Physical Characteristics. These included the following.

Dimension (cm): Telescope and focal- plane structure: 40x40x205

Processor: 56x48x36

Total mass: 248 kg  
Average power: 150 W at 28 Vdc  
Total energy: 22 kWh  
Data: Digital: 1.4 Mbps  
Film : Type SO-115  
TV: 4.2 MHz.

c. Instrument Operation. The experiment consists of a Solar Optical Universal Polarimeter (SOUP) mounted on the IPS, using a 30 cm Cassegrain telescope designed for diffraction-limited performance in the wavelength region 480 to 700 nm. A gimbal system and a solar limb tracker allow the observation of any point on the solar disk when the IPS is directed within several degrees of the Sun. Two independent focal-plane systems are used, the first being a white-light system which records granulation and pointing data onto film. The other, a tunable filter system, consists of a birefringent filter with selectable bandpass of 30 mÅ or 70 mÅ, and associated blocking and polarizing filters to produce monochromatic images in a known state of circular or linear polarization. The wavelength of the resulting image is selectable to within  $\pm 4$  Å of any of nine predesigned spectral lines. The resulting filtergrams are recorded on SO-115 film and with a diode array camera. The diode array output is fed into the video processor, which is capable of image storage and also of adding, subtracting, multiplying and dividing images into any or all of its six internal image memories. In this manner, magnetograms and velocitygrams are made in real time.

#### 6. Coronal Helium Abundance Spacelab Experiment (CHASE).

a. Purpose. The goal of this experiment is to determine accurately the helium abundance of the Sun. In addition, the temperature, density and composition of coronal gases can be derived from measurements of the intensities of ultraviolet emissions.

b. Physical Characteristics. These included the following.

Dimension (cm): Instrument: 56x44x115

Microprocessor: 37x36x30

Power supply: 35x33x30

Total mass: 114 kg

Average Power: 72 W at 28 Vdc

Total energy: 11.7 kWh

Data: 8.2 kbps

c. Instrument Operation. The experiment utilizes a 1 m grazing-incidence spectrometer with a 1200 lines/mm concave grating. The image of the Sun is focused onto the entrance-slit plane by means of a 28 cm focal length grazing incidence Wolter-type I telescope. Eleven channel-electron multipliers are placed behind individual exit slits that are positioned on the Rowland cycle to accept pre-selected wavelengths. Two such detectors monitor the hydrogen Lyman alpha and the He II, 304 Å lines. The other detectors monitor ionized lines of Fe (iron), S (sulfur), C (carbon), and O (oxygen), for temperature and density determinations.

#### 7. Solar Ultraviolet High Resolution Telescope and Spectrograph (HRTS).

a. Purpose. The major objectives of the experiment are:

- i. investigate the energy transport and mass balance of the temperature minimum, chromosphere, transition zone, and corona in the quiet Sun as well as in plages, flares and sunspots;
- ii. study the velocity field of the lower corona in order to investigate the origin of the solar wind;

- iii. investigate the structure of spicules and superspicules;
- iv. investigate the structure and dynamics of prominences;
- v. study the preflare and flare phenomena.

b. Physical Characteristics. These included the following.

Dimension (cm): Instrument: Diam. 49x365

Electronics: 49x60

Total mass: 326 kg

Average power: 340 W at 28 Vdc

Total energy: 48.6 kWh

Data: Digital: 3.2 kbps

Film: Type S0-652 and Type S0-410

TV: 4.2 MHz.

c. Instrument Operation. The instrument consists of a telescope, an ultraviolet spectrograph, an ultraviolet spectroheliograph, and an H-alpha slit-display system, all housed in a thermally controlled canister. The telescope is a concentric Gregorian with a 30 cm primary paraboloid of 90 cm focal length. An occulting mirror at the primary focus reflects away all but a 7x15 arc minute portion of the solar image. This portion passes through an aperture in the occulting mirror and strikes the secondary mirror that re-images it at the slit plane of the ultraviolet spectrograph. The telescope resolution is diffraction limited at 0.5 arc second. The ultraviolet spectrograph of the symmetric tandem Wadsworth type uses two concave diffraction gratings. A stigmatic spectrum with spectral resolution of 50 mÅ and a spatial resolution of 0.5 arc second is formed at the film camera. The ultraviolet spectroheliograph photographs the solar image reflected from the front surface of the spectrograph slit-plate. It is tuned to observe the C IV, 1550 Å emission line. This instrument is a reversed tandem Wadsworth arrangement with two concave gratings that form a zero-dispersion image at the camera focal plane. The H-alpha filter consists of two tandem Fabry-Perot interference filters with half-width of 0.5 Å. The slit-display system forms a photographic and a video image of the solar image reflected from the front surface of the spectrograph slit-plate.

## B. Major Scientific Results from Solar Spacelab Missions.

The scientific investigations carried out by solar experiments using the Spacelab facility (see Table I-4) fall into three main categories.

1. Measurements of the solar irradiance (the solar constant problem);
2. Abundance determinations (the solar helium problem);
3. The dynamic nature of the solar atmosphere.

The ACRIM, SOLSPEC, SOLCON, and SUSIM experiments all addressed the solar constant problem, while CHASE was used to investigate the helium abundance problem. The multifaceted aspect of the nature of the dynamic solar atmosphere was studied in great detail by the SOUP and HRTS experiments.

**Table I-4. Spacelab Missions with Solar Experiments.**

Spacelab-1	1983	SOLSPEC ACRIM SOLCON	ATLAS-2	1993	SUSIM ACRIM SOLCON
Spacelab-2	1985	SOUP CHASE HRTS SUSIM	ATLAS-3	1994	SOLSPEC SUSIM ACRIM SOLCON
ATLAS-1	1992	SOLSPEC SUSIM ACRIM SOLCON SOLSPEC			

### *1. Measurements of solar irradiance.*

The total solar irradiance is the total radiant energy of the Sun received by the Earth at a distance of one astronomical unit. The absolute value of the solar irradiance is one of the critical factors that determines Earth's absorption and reflection of radiation, the energy balance that governs atmospheric circulation. Solar ultraviolet radiation in the wavelength range 120 to 400 nm is absorbed by the Earth's atmosphere between 20 and 120 km, and even though this radiation constitutes only a small percentage of the total solar output, it is the main source of energy for the middle atmosphere. This ultraviolet component of sunlight varies considerably more than the visible radiation. During an eleven-year cycle of the Sun's activity, changes in ultraviolet radiation bring about corresponding changes in a number of atmospheric conditions, and may be responsible for weather and climate changes.

Already, on the pre-Spacelab Solar Maximum Mission (SMM), the ACRIM experiment had discovered that the models used to estimate the irradiance underestimate the observed irradiance values at the time of solar activity maximum and at the beginning of the declining phase of solar cycle twenty-two. Furthermore, the nine-year long series of measurements carried out by ACRIM on the SMM revealed both a long-term and a day-to-day variation in the value of the irradiance, variations that could be related to the presence of sunspots on the solar disk. According to Willson and Hudson, the experiment detected an eleven-year

cycle in the bolometric radiation with 0.1% amplitude. Note that several, more or less identical, versions of the ACRIM experiment flew, sometimes simultaneously, on different missions. In particular, during the Spacelab 1 and Spacelab 2 missions Willson flew the first ACRIM on the much longer lasting SMM. Many of the ACRIM experiment descriptions and scientific results from the Spacelab missions can be studied in the appropriate literature from the SMM. A comparison of data obtained by the SMM, Spacelab 1, UARS and ATLAS missions was given by Willson, and Woods et al made a comparison of the UARS irradiance measurements with the ATLAS 1 and ATLAS 2 data, showing the basic consistency among them.

SOLCON results from the Spacelab 1 mission determined the value of the solar constant at the time to be  $1361.5 \pm 2.3$  Watts/m<sup>2</sup>, as noted by Crommelynck et al, who published the first SOLCON results from the ATLAS-1 mission. Also from the ATLAS-1 mission, SOLCON results indicated a correlation between the number of sunspots and the fluctuation of the values of the solar irradiance. Hence, both the ACRIM and the SOLCON experiments established the important link between the occurrence of sunspots and the value of the solar constant. Crommelynck et al described in some detail the observations from the ATLAS-1 and the ATLAS-2 missions, and Mecherikunnel compared the irradiance measurements from SOLCON on the ATLAS missions with the ACRIM data from UARS.

Labs et al measured the solar spectrum on the SOLSPEC experiment on Spacelab 1, and it was again measured by the SUSIM experiment on Spacelab 2; the spectra obtained agreed within three percent in the 200 to 3500 nm range. The SOLSPEC data showed that the solar irradiance is spectrally similar to sun-like stars down to at least 240 nm. The experiments showed that while the differential irradiance at 200 nm is less than 10 mW/m<sup>2</sup>nm, it increases strongly toward longer ultraviolet wavelengths, and reaches 1000 mW/m<sup>2</sup> nm at 3500 nm. These results are of prime importance for the study of the influence of solar radiation on the Earth's atmosphere. Already Doschek, working on the SMM, discovered with the SOLSPEC X-ray data a time-dependent line broadening that was to be further studied in later missions.

## *2. Helium abundance determination.*

Helium is a major contributor to opacities and radiative loss effects, and its abundance is important to all aspects of stellar evolution and stellar modeling. In the Sun helium contributes about 10 percent to the mass and therefore plays a crucial role in models of the solar interior.

However, because of their high excitation potential, He I lines are formed in the Sun at high temperatures in the chromosphere where the situation is complicated due to inhomogeneities associated with the chromospheric network and spicules. As a consequence, normal methods of determining abundances from photospheric absorption lines cannot be applied. Instead the CHASE experiment observed the hydrogen (1216 Å) and the ionized helium (304 Å) resonance lines formed by photoexcitation of the coronal plasma, i.e. in a region where the hydrogen and helium line emissions are due mainly to the resonance scattering of the intense chromospheric emission. The experiment observed both the light source (solar disk) and the scattering region (corona above solar limb), and since the two principal lines are common in both cases, the results are independent of instrument intensity calibration.

No comprehensive report concerning scientific data obtained by CHASE on the Spacelab 2 mission seems to have been published in any of the major astronomical journals.

### *3. The dynamic nature of the solar atmosphere.*

The SOUP and HRTS instruments have provided a host of new results concerning the nature of the solar atmosphere. From observations with the Skylab and the SMM we know that solar magnetic fields play the crucial role in determining the state and development of the ionized solar atmosphere, but many aspects of the physics involved have been clarified by the SOUP and HRTS investigations, and new discoveries have been made.

a. Results from the SOUP experiment. In-depth studies of both solar granulation and super-granulation have been made using SOUP data from Spacelab 2. In particular, the horizontal flow field in the solar atmosphere was observed and analyzed by Title, and Simon investigated the statistical properties of the granulation and modeled the supergranulation diffusion (from the observed horizontal flow pattern), and Simon, Weiss and others produced models of exploding granules.

The important transport of magnetic fields in the horizontal flows was treated by Simon, while the general properties of the horizontal velocities were delineated by Tarbell. Interesting results from the SOUP measurements also were the discoveries by November's team of a 600 to 1000 m/s outflow from the penumbra of sunspots, and the reduced horizontal flow in regions with many magnetic pores.

b. Results from the HRTS experiment. The spectroscopic investigations using the HRTS experiment on Spacelab 2 furnished high-resolution (1 arcsec spatial, 0.05 Å spectral) spectra of the 1170 to 1710 Å region in the quiet, as well as in the active, solar atmosphere. In particular, Sundlin and colleagues identified several new lines.

Brueckner's team and Kjeldseth-Moe, using the HRTS spectra, further revealed some up- but mainly strong down-flows over sunspots in the transition region between the chromosphere and the corona. The down-flows cover most of the sunspot area and are supersonic in nature, with velocities, for the C IV, 1548 Å line, of 40 to 80 km/s. Brueckner and Cook both noted that the C IV line also reveals large non-thermal line-broadening in areas of emerging magnetic flux. Detailed studies by Kjeldseth-Moe and colleagues of the transition region revealed a multiple-flow regime around sunspots, some of the flows being supersonic in nature. Furthermore, Dere's team on Spacelab 2 used the HRTS experiment to discover macrospicules inside a polar coronal hole, and other Spacelab 2 data have been used to check theoretical calculations. In particular, Keenan calibrated the effect of non-Maxwellian electron-distribution functions on S III line ratios against HRTS observations.

### III. SPACE PLASMA PHYSICS

**James L. Horwitz**

In this report, we attempt to provide a perspective and summary of published science accomplishments in the areas of Shuttle-based studies of space plasmas, having at least to some connection with the charged particle environment. We have chosen to employ a mixed grouping of the science accomplishments, in some cases based on the scientific nature of the effort or the phenomenon, in other cases based on the technique or experimental method, and in one case based on the science accomplishments for a particular mission.

#### **A. Measurements of Natural Energetic Particles from the Shuttle**

Although most of the Shuttle based space plasma science was oriented towards actively stimulated effects, Lieu et al<sup>1</sup> used an electron spectrometer experiment aboard Spacelab 1 to measure fluxes of low-energy (0.1 to 12.5 keV) electron precipitation at low latitudes,  $\pm 30^\circ$ . They found generally two components: a low-energy component in the range 0.1 to 1 keV which had a power law spectrum, and a high-energy component showing a tail “flattening” at higher energies. This latter spectral component occasionally showed a peak in the spectrum, and at times showed temporal flaring with time scales of about 1.5 hours. This higher-energy (1 to 12.5 keV) component in some cases exhibited very large fluxes, for example,  $> 3 \times 10^5$  el  $\text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$ , and also showed peaks straddling the equator, where a flux minimum was observed. Lieu et al<sup>1</sup> were unable to adequately determine the likely acceleration mechanism for these electrons.

#### **B. The Shuttle-Based Creation and Use of “Ionospheric Holes”**

One of the important investigations from Spacelab 2 was of the creation of “artificial holes” in the F-region ionosphere, which earlier theoretical and precursor experiments, such as those of Mendillo and Forbes<sup>2</sup>, Bernhardt et al<sup>3</sup>, and Mendillo et al<sup>4</sup>, had suggested.

A review of the theory and experimental results for ionospheric holes was given by Mendillo<sup>5</sup>. Mendillo discussed the effects of rocket launches as well as Shuttle engine burns supplying various contaminants in large amounts to react with the ambient  $\text{O}^+$ , producing a new ion and neutral in this reaction, and the ions subsequently rapidly recombining with electrons to form neutral molecules and airglow. Hence the plasma density is rapidly depleted, creating a hole in the ionosphere.

In this schematic presentation of the ionospheric hole creation process, some of the potential consequences noted in various simulations would include: triggering equatorial plasma instabilities, enhancing photo-electron escape to the conjugate ionosphere, plasma flow into depletion region, overall plasmaspheric flux tube depletion, airglow excitation by thermal electrons, and thermal expansion. The artificially induced airglow burst in the  $\text{O}^+$  line 630 nm was observed over New England on July 29, 1985 and described by Mendillo<sup>5</sup>.

These artificially created holes also enabled radio astronomy observations by Ellis et al<sup>6</sup> due to the reduced plasma frequency cutoff of radio emissions during such hole events. Ellis and colleagues were able to make observations of the galactic radio background emission at a number of frequencies between 0.51 MHz and 2.75 MHz. The observations were conducted at a time when the ambient F-region peak electron density

corresponded to an foF2 plasma frequency cutoff of 1.99 MHz, meaning that no astrophysical emissions below that frequency should have been observable (foF2 is the highest frequency which the ionosphere will reflect vertically). However, on this flight over the Hobart observatory in Australia on August 5, 1985, during the Spacelab-2 mission, the Shuttle engine burn, which produced rapid recombination and depletion of the plasma density, resulted in a dramatic drop in the foF2, creating a “window” which allowed much lower than normal frequencies to be observed from the ground observatory. Such observations were described as being useful in permitting greatly improved mapping of the galactic radio distribution, particularly at frequencies below 1.6 MHz. A survey of the galactic background radio emission derived from the radio studies provided by these burns was presented by Ellis and Mendillo<sup>7</sup>. Mendillo et al<sup>8</sup> also discussed these Spacelab-2 burn/depletion experiments and the associated ionospheric and radio astronomy investigations.

### **C. Shuttle Glow**

Another area of important space plasma investigations was of the so-called “Shuttle glow”. Observations from the third launch of the space Shuttle (STS-3, OSS-1) published by Banks et al<sup>9,10</sup> reported diffuse optical emissions surrounding the Shuttle surfaces interacting with the atmosphere in the ram direction. It was found that this glow emission had an intensity comparable to that of the Earth’s airglow, and also comparable to the brightness of stars in TV cameras. Banks et al estimated that the layer where the glow emission was occurring around the Shuttle was probably in the range of 5 to 10 cm thick. These glows appeared to have generally similar features to the glow observed on the Atmospheric Explorer-C spacecraft by Torr<sup>11</sup>. Mende et al<sup>12</sup> also reported Shuttle glow from STS-4 observations, and estimated the total glow intensity in their observational range to be 100 to 300 Rayleighs, which was much less than the glow estimated for the STS-3 flight, perhaps because STS-4 was at a higher altitude with less atmospheric density and a more oblique angle of interaction. Mende et al<sup>13</sup> distilled some of the observed consistent properties of the Shuttle glow from observations on the STS-3, STS-4, and STS-5 missions.

Slanger<sup>14</sup> suggested that the glow was generated by the Shuttle surface interaction with 5 eV O(<sup>3</sup>P) atoms (ozone) at the high altitudes of the Shuttle. Alternatively, Papadopoulos<sup>15</sup> suggested that the Critical Ionization Velocity (CIV) phenomenon could be involved. In this concept, although the Shuttle velocity was nominally too low (8 km/s compared to the CIV velocity for oxygen, which is 12.7 km/s), Papadopoulos suggested that specular reflection of a small fraction of the ion population would give a relative ion-neutral velocity of 16 km/s, which could excite the CIV effect, which in turn could provide the Shuttle glow effect.

### **D. Use of the Plasma Diagnostics Package for Space Plasma Investigations**

A special feature of Spacelab 2 was that the Shuttle released a separate satellite, the Plasma Diagnostics Package (PDP) in order to probe the plasma, field and wave environment of the Shuttle (for example, the experiments of Shawhan et al<sup>16,17,18</sup>, Reasoner et al<sup>19</sup>, and Kurth and Frank<sup>20</sup>). The instrumentation on this PDP satellite included an electron/ion plasma analyzer, known as a LEPDEA (the Low-Energy Proton and Electron Differential Energy Analyzer used by Frank et al<sup>21</sup>), a Langmuir probe, an ion mass spectrometer, a retarding potential analyzer, a differential ion flux probe that Stone<sup>22</sup> and colleagues made use of, a plasma wave receiver and electric field detector suite, an electrometer, a neutral pressure gauge, and radio receivers. Further discussion of the PDP and the associated instrumentation can be found in the publications of the researchers<sup>16,17,18,19,20</sup>, with the Kurth and Frank<sup>20</sup> providing also a brief review of some of the results.

The first active beam-plasma experiments with the Shuttle were performed during March 1982 on OSS-1, and the properties of waves generated by continuous and modulated electron beams were described by Shawhan et al<sup>18</sup> making the use of the Plasma Diagnostic Package. It was found that during the continuous beam experiments the waves were dominantly electrostatic, unpolarized, and had peaks of the order  $4 \times 10^{-3} \text{V}^2 \text{m}^{-2} \text{Hz}^{-1}$  in the 300 to 500 Hz range. With modulated beams, strong emissions near the electron gyrofrequency and plasma frequency were observed at times, and the emissions near the modulation frequency had more of an electromagnetic character, with electric field strengths sometimes attaining levels up to 1 V/m.

Aspects of electron velocity distributions and the associated plasma waves were also investigated by Frank et al<sup>23</sup> based on Spacelab 2 observations with the PDP. They observed a magnetically aligned “sheet” of electrons returning back opposite to the direction of the injected electrons from behind the Shuttle with a particle spectrometer on the PDP. The thickness of the electrons was estimated to be about 20 meters. They also observed concomitant intensifications of electrostatic noise within the electron sheet, which they attribute to an ion acoustic instability, which they suggested might also be responsible for the returning electrons through the process of quasi-linear diffusion. Spacelab proved to be an excellent laboratory for investigating controlled generation of wave emissions in dilute large-scale plasmas that were not possible to study on confined terrestrial plasma laboratories.

An interesting phenomenon observed by the PDP was whistler mode radiation detected during periods when the PDP and the Shuttle were magnetically connected, and an electron generator injected a 1-keV, 50 milliAmpere (mA) electron beam into the environment. As reported by Gurnett et al<sup>24</sup> and by Farrell et al<sup>25,26</sup>, the generated whistler radiation had some interesting characteristics: the evidence suggested that it was quasi-electrostatic, with little magnetic component of the waves, and that the wave power was “funnel-shaped” when presented on a gray-scale frequency-time spectrogram. From natural auroral region emissions studies it is known that such a shape results from a propagation effect of the whistler waves having normal angles near the resonance cone.

The power in the detected whistler waves was estimated by Farrell et al<sup>25</sup> to be about  $2 \times 10^{-5}$  of the electron beam’s total power. Although this fraction is seemingly low, it was determined by Farrell’s group that a process of *incoherent* Cerenkov radiation should produce radiation that is even lower, about  $10^7$  too small, to explain the detected radiation. These authors then turned their attention toward *coherent* Cerenkov radiation<sup>25,26</sup>. In this framework, the injected beam becomes modulated by a beam-plasma electric field wave instability that causes the beam electrons to bunch up into periodically spaced density perturbations that allow coherent, and thus much stronger, radiation to occur. In a detailed model of the process, they showed that a one-dimensional line source beam/wave radiator was calculated to be expected to produce more than enough power (40 times as much, in fact) to explain the observed waves<sup>26</sup>. It was concluded that the PDP was indeed probably observing coherent Cerenkov radiation during these electron beam injections, and that the actual smaller power was probably associated with the finite spread of the beam and other complicating factors not included in their simulation.

During the OSS-1/STS-3 mission, the PDP was also employed by Stone’s team<sup>27</sup> to investigate the plasma-electrodynamics interactions around the space Shuttle. The PDP included the instruments noted above, as well as a Differential Ion Probe (DIFP) for measuring and deconvolving multiple ion streams and directions<sup>28</sup>. They found that the measured ion flow directions and energies indicated that the interaction region

between the Shuttle orbiter and the ionospheric plasma is confined to 10 m in thickness in the forward/ram direction, with a boundary layer thickness of about 2 m<sup>27</sup>. Stone et al<sup>27</sup> also indicated a close correlation between the ion and neutral gas densities, and that the interactions between secondary ion streams at high inclinations to the basic flow direction of the ambient plasma probably generate the broad-band electrostatic noise found by the PDP wave instruments. Siskind et al<sup>29</sup> examined forward/ram conditions around the space Shuttle from the same STS-3 flight chiefly using a Spherical Retarding Potential Analyzer (SPRA) and Langmuir probe (LP) on the orbiter itself (not the PDP measurements in this case). They found a larger than expected plasma turbulence, with a strong component at 2.2 kHz. They also detected unusually large densities of molecular ions, with masses of 30 to 32 amu, and elevated ion temperatures in the range 2000 to 3000 K, and coincident with even higher electron temperatures of about 5000 K. They also discussed these measurements as evidence for a plasma instability associated with outgasses from the moving Shuttle interacting with the ionosphere. Raitt et al<sup>30</sup> discussed the results from these thermal plasma environment measurements on STS-3 further in their publications.

Paterson and Frank<sup>31</sup> also observed substantial densities of hot ions with the PDP on the Spacelab 2 mission; these ions had energy spectra in the PDP frame showing characteristic peaks near 18 eV, and substantial fluxes of such ions out to about 60 eV. These ions also exhibited “pancake-shaped” velocity distributions, in which the ion distribution was peaked around velocities directed perpendicular to the magnetic field. The PDP detected such ions as far away as 280 km from the Shuttle.

The analysis of these ions by Paterson and Frank<sup>31</sup> determined that they were mainly molecular ions including H<sub>2</sub>O<sup>+</sup> (water), H<sub>3</sub>O<sup>+</sup> (heavy water), CO<sup>+</sup> (carbon monoxide), CO<sub>2</sub><sup>+</sup> (carbon dioxide), and others. The dominant species was the molecular water, ranging from densities of 30 to 10<sup>4</sup> H<sub>2</sub>O<sup>+</sup> ions/cm<sup>3</sup>. These were concluded to have characteristic energies of 18 eV, which was twice the energy associated the relative motion between the spacecraft and the ambient atmosphere. Paterson and Frank<sup>31</sup> constructed a model in which water and other vapor molecules from the Shuttle surrounded the orbiter and charge-exchanged with the ambient ionospheric O<sup>+</sup> ions. By a “pickup ion” process similar to processes occurring in cometary comas, the Io torus, and other settings involving relative motion between neutral gases and magnetized plasmas, the ions were concluded to have been trapped in gyration orbits immediately after the charge-exchange formation by the magnetic field, with twice the relative motion velocity contained in the gyration speed. It was further shown that such ions exhibited a strong diurnal variation in their densities, being large in the daytime and small at night, which is consistent with the controlling factor in their formation being the similarly varying ambient ionospheric O<sup>+</sup> ions which the originally neutral water molecules would charge-exchange with. Paterson and Frank estimated that the space Shuttle was producing a water vapor cloud with densities on the order of perhaps 10<sup>9</sup> H<sub>2</sub>O molecules/cm<sup>3</sup> at approximately 50 m from the Shuttle.

Additional observations of water and other ions during Spacelab 2 were obtained by Grebowsky et al<sup>32,33</sup> with a Bennett RF ion mass spectrometer on the PDP. They found that the concentrations of the water ions decreased with distance from the Shuttle in the orbiter wake, and fell below the concentrations of ambient O<sup>+</sup> ions at wake distances of about 30 m. These and other similar measurements raised serious questions about the viability of making reliable natural or ambient ion measurements in the Shuttle environment. These water molecules can be the result of specific water releases that are needed to eject the excess water produced by fuel cells or other types of wastewater production by the Shuttle. Pickett et al<sup>34</sup> examined observations by the PDP Langmuir probe of plasma density fluctuations, which showed that that such fluctuations and turbulence increased markedly during these water dumps as a consequence of the pres-

ence of such ions. They found that these water dump-associated plasma density fluctuations occurred over a frequency range from the lowest detectable, a few Hertz, up to the local lower hybrid frequency. They concluded that such would be produced by the interaction of the aforementioned charge-exchange produced water ions with the ambient ionospheric plasma. Two mechanisms for producing the waves were considered by Pickett et al<sup>34</sup>: one in which the “free energy” in the relative motion between the water ions and the oxygen ions of the ionosphere would initiate a beam-plasma interaction, or one in which the ring-shaped velocity distribution of the water ions would itself be unstable and thus contain free energy for the excitation of the waves.

Murphy et al<sup>35</sup> also used the above Langmuir probe for the PDP on the STS-3 flight to determine electron densities, temperatures and the plasma potential surrounding the Shuttle. As consistent with other observations, they find similar wake effects as for small satellites and laboratory experiments, but note that these effects are exaggerated in the case of the Shuttle, with orders of magnitude decreases in density and factor of five temperature enhancements. They also observed strong turbulence, with strong power up to and through the lower hybrid frequency. Similar Langmuir probe measurements of the Shuttle orbiter wake were obtained with the PDP during Spacelab 2 by Murphy et al<sup>36</sup>.

Shawhan et al<sup>18</sup> used experiments on the Plasma Diagnostics Package (PDP) to measure the plasma environment of the Shuttle orbiter. Occasionally, somewhat energetic ions and electrons were observed with energies of 10's of eV. It was also found that the Shuttle primary and vernier thrusters usually induce a temporary enhancement of the electron density.

Intense broadband waves around the Shuttle as observed by the PDP were also reported from both the OSS-1 and Spacelab 2 missions by Cairns and Gurnett<sup>37,38</sup>. In their characterization of these waves, they found it useful to view the waves in terms of three relatively distinct components below 10 kHz, together with a high-frequency tail of the power that declined with frequency about 10 kHz. The first component could be characterized as a quasi-uniform, relatively intense level of waves extending over 31 to 10,000 Hz range. On top of this broad spectrum are two components that have about twice the primary's electric field values. One of them has a low-frequency peak in the frequency range 100 to 178 Hz, while the other occurs near the local lower hybrid frequency

One of the most interesting findings by Cairns and Gurnett<sup>37,38</sup> was that the observed waves were strongly modulated in both amplitude and frequency location by the angle between the magnetic field and the Shuttle's velocity vector, which they characterized in terms of  $V_{\parallel}/V_T$ , where  $V_T$  is the total Shuttle speed and  $V_{\parallel}$  is the component parallel to the magnetic field. They found that as the Shuttle moves to regions where it is moving close to parallel to the magnetic field ( $V_{\parallel}/V_T \sim 1$ ), the wave amplitudes and frequency spreads become very small. Because of this directional dependence, Cairns and Gurnett<sup>37,38</sup> concluded that waves were most likely driven by water pickup ions. They also suggested that their findings have important consequences for trying to observe waves from the Shuttle, namely, that the preferred Shuttle orbits should have directions close to the magnetic field (that is,  $V_{\parallel}/V_T > 0.7$ ) so as to inhibit waves of Shuttle origin for experiments designed to probe naturally-occurring waves and waves produced by active perturbations. Such comments imply a preference for polar orbits and against equatorial orbits.

Also from the Spacelab 2 mission and making use of the PDP capabilities were the findings of Reeves et al<sup>39,40,41</sup>, who studied the VLF (very low frequency) wave emissions produced during both pulsed and DC

(direct current) electron beam injections. The electron beam injections were done with the Vehicle Charging and Potential (VCAP) experiment by Banks et al<sup>42</sup>. This experiment included a Fast Pulsed Electron Generator (FPEG) that could inject an electron beam of 50 or 100 mA of current in 1 keV electrons. Additional discussion of the waves and the return currents for these experiments was presented by Neubert et al<sup>43</sup>.

During these experiments, it was found that the injection of a continuous or DC or square-wave modulated beam elicited a broadband electromagnetic spectrum of waves, whereas pulsed beams produced narrowband emissions. Owing to the maneuvering of the PDP, it was possible to probe the wave amplitudes and frequency ranges variation as a function of distance from the center of the beam and Reeves et al<sup>39,40,41</sup> found that the waves amplitudes and frequency extents declined with such increasing perpendicular distance to the beam. Many of the properties of the narrowband waves were found to be consistent with the linear theory of Harker and Banks<sup>44</sup>, and are consistent with Cerenkov radiation for certain wave normal angles. Harker and Banks<sup>45</sup> performed other relevant calculations to the radiation from pulsed electron beam trains in space plasmas for both short and long pulse trains.

Steinberg et al<sup>46</sup> attempted to use a double-probe potential experiment onboard the PDP for Spacelab 2 to measure the electric fields in the vicinity of electron beams injected. Although they observed large differential voltages between the two probes, they concluded that these measurables were not due to ambient electric fields, but rather due to other effects, including shadowing of the probes from streaming electrons by the PDP chassis. One conclusion Steinberg et al<sup>46</sup> did come to was that at greater than 80 meters downstream from the electron beam injection location, the energetic electron flux is opposite to the injection direction, as would be expected if those energetic electrons were basically a secondary return electron caused by scattering of the primary beam electrons.

A further electrostatic potential-related observation made by Tribble et al<sup>47</sup> on the Spacelab 2 mission with the PDP was the observation of large changes in the electrostatic potential on the PDP satellite when a pulsed, high-voltage source is operated, with the magnitude of the PDP voltage variations being dependent on the high-voltage source orientation relative to the plasma flow, among other effects.

## **E. Investigations of the Near Shuttle Environment**

Raitt et al<sup>30</sup> investigated the plasma environment of the wake of the space Shuttle for Spacelab 2 mission. This was an opportunity to examine the plasma structure in the wake of a very large spacecraft, after previous investigations of the wakes of small spacecraft. Raitt et al<sup>30</sup> used the Spherical Retarding Potential Analyzer (SRPA) for ion measurements together with a Langmuir probe for electron measurements to determine plasma properties. They found that the plasma densities decrease within the deep wake much faster than the rates predicted by previous theoretical models. The densities were, for some regions, an order of magnitude or more lower than the theoretical predictions. They also found that in certain angular ranges and periods, two wake electron populations can be deduced. They concluded that one of these electron populations was the electrical filtering of the high-energy tail of the ionospheric population, while the other was from photo-electrons ejected from the payload bay surface during certain daytime periods when that surface was illuminated by the Sun.

Hunton and Cato<sup>48</sup> detected large fluxes of such ions as  $O^+$ ,  $H_2O^+$  and  $H_3O^+$  in the vicinity of the Shuttle using the quadrupole ion-neutral mass spectrometer (QINMS) on Shuttle flight STS-4 in June and July of

1982. The energies for these ions were generally below 1.5 eV relative to the orbiter. Hunton and Cato<sup>48</sup> identified the outgassing neutral flux from the Shuttle surfaces interacting with the ambient ionosphere through ion-molecule reactions and non-reactive scattering processes as the main sources for the observed ions. The reactions include the charge-transfer process  $O^+ + H_2O \rightarrow H_2O^+ + O$ , and the possible subsequent reaction  $H_2O^+ + H_2O \rightarrow H_3O^+ + OH$ .

### **F. Shuttle Charging Effects**

Shuttle charging in association with electron beam injections was investigated with Spacelab 1 measurements by Myers et al<sup>49</sup>, and Watermann et al<sup>50,51</sup> used several experiments on the Spacelab 1 mission to investigate effects such as Shuttle charging during electron beam injections. During these injections, the SEPAC (Space Experiment with Particle Accelerators) experiment fired electron beams of currents up to 280 mA and maximum energies of 5 keV, and the electron spectrometer 1ES019A observed electron fluxes in the energy range 0.1 to 12.5 keV. Watermann et al<sup>50</sup> suggested that for beam injection intensities above 100 mA, there must be beam-plasma discharge phenomena operating, and argued that high-charging events during the electron beam injections were not supported by their observations. Further aspects of the suprathermal electron return flux seen during these Spacelab 1 experiments was discussed in Watterman et al<sup>51</sup> and Wilhelm et al<sup>52</sup>.

Banks et al<sup>42</sup> reported charging of the Shuttle during the STS-3 mission using instrumentation of the Vehicle Charging and Potential (VCAP) experiment. Charging measurements using thermal plasma probes were obtained during passive events as well as periods when a 100 mA/1 keV electron beam was emitted. Banks et al<sup>42</sup> found that during the short pulsed charging events an upper limit of about 1 mF was obtained for the Shuttle's capacitance. For steady-state charging events the electrical potential only reached a few volts ordinarily, although during some nighttime conditions, potentials of over 40 Volts were detected.

### **G. Attempted Remote Detection of Shuttle-Generated Waves**

An attempt was made by Inan et al<sup>53</sup> to detect whistler radiation possibly generated by the electron beams injected with the FPEG experiment on Shuttle flight STS-3 during the latter part of March 1982. This was done remotely out along the field lines threading the plasmasphere, with wave detectors on the Dynamics Explorer-1 satellite. No evidence of such propagation of radiation from the FPEG to the DE-1 satellite was seen, although it was noted that the geometric conditions of the Shuttle were such that either the electrons emitted by FPEG struck the Shuttle main body or the possible wave propagation was otherwise blocked from reaching the DE-1 satellite.

### **H. Uses of the SEPAC and PICPAB Experiments**

Waves generated by the artificially-injected electron beams during Spacelab 1 were reported by Neubert et al<sup>54</sup>, who utilized the SEPAC (Space Experiments with Particle Accelerators) experiment, which injected electrons with current levels of up to 300 mA and energies of 5 keV. Neubert et al<sup>54</sup> found that during these electron beam injections the waves in the VLF range, 0.75 to 10 kHz range have basically power-frequency relation that follows a power law,  $f^{-n}$ . The strongest emissions are observed when the beams are injected parallel to the magnetic field. The observed waves were interpreted as being driven by a drift-wave instability. Further discussion of the waves, wave-particle interactions, and electron energization, as well as a fairly complete discussion of the SEPAC experiment, was given by Taylor et al<sup>55</sup>.

An additional feature of interest from the SEPAC on Spacelab 1 was Sasaki<sup>56,57</sup> and team's initiation of a beam-plasma discharge by the injection of a strong electron beam into a planned release of a dense nitrogen gas plume or cloud, which also made use of the Phenomena Induced by Charged Particle Beams (PICPAB) experiment as reported by Beghin et al<sup>58</sup>. In these experiments, a gas cloud of about  $10^{23}$  N<sub>2</sub> molecules was released over a 100 ms interval, and then an electron beam of 8 keV of energy, 10 or 100 mA of current, was injected for periods of 20 or 40 milliseconds. These experiments were conducted at an altitude of 245 km at night. Making use of video observations, as well as plasma-field diagnostics from a Langmuir probe and VLF/HF receivers, Sasaki et al<sup>56,57</sup> concluded that plasma was produced outside the beam as well as inside it, and that there was an optimum range of gas density for this outside plasma production. They found that the rate of plasma production was greater than expected from the simple beam-neutral gas ionization effects, and that there must have existed suprathermal electrons outside the beam, so as to excite the observed 3914 Ångstrom light emissions. Kawashima<sup>59</sup> reviewed the results of various electron beam experiments conducted with SEPAC, and discussed problems and future possibilities.

Pulsed electron beam experiments by Torkar et al<sup>60</sup> using PICPAB on Spacelab 1 showed return electron fluxes within 1ms of the beam injection. The electron beams had energies of 8 keV, 10 to 100 mA, and durations of 20 to 40 ms, and the electron flux measurements were for the energy range 0.1 to 12.5 keV, using Wilhelm's experiment (1ES019A). Although much of the return flux was found at the lower energy ranges, the return flux spectrum did extend up to the beam energy. Beghin et al<sup>58</sup> also investigated the strong wave emissions in the electron gyrofrequency and plasma frequency ranges produced by these electron beams with PICPAB, finding electromagnetic components that could be used for mode identification

Sasaki et al<sup>61,62,63</sup> also used the SEPAC facility to investigate the effects of injection of high speed plasma into the atmosphere. In this experiment, an argon gas of about  $10^{19}$  atoms was ionized by a chamber with discharging electrodes, creating plasma of about  $10^{19}$  electron-ion pairs. This plasma was then accelerated and ejected into space with a velocity in the range 18 to 28 km/sec. Such fast plasma will have a large flow velocity relative to the neutral gas around the Shuttle. It was found that this surrounding neutral gas was ionized for several tens of ms after the injection. Also observed were waves in the lower hybrid frequency range. Sasaki et al<sup>61,62,63</sup> concluded that they were observing the so-called Critical Ionization Velocity (CIV) effect first proposed by Alfvén<sup>64</sup>, who suggested that if the energy of relative motion between a neutral gas and ions exceeded the ionization energy for this gas, it might be ionized. Papadopoulos<sup>15</sup> and several others have suggested that this process operates indirectly by first driving lower hybrid waves in the initial plasma which heat electrons which can then in turn further ionize the neutral gas. SEPAC was also used on the ATLAS-1 mission to conduct experiments on the Critical Ionization Velocity (CIV) effect by Marshall et al<sup>65</sup>, also finding evidence for CIV occurrence during high-speed plasma injections. In the ATLAS-1 experiments, the plasma injection at supersonic speeds of about 20 km/s was accomplished by using the xenon plasma contactor, hence using the gas originally proposed for the Shuttle experiments. A brief review of experiments on the production of artificial auroras and the CIV experiment with SEPAC was given by Burch et al<sup>66</sup>.

Another related experiment conducted on Spacelab 1 with the SEPAC experiment was the injection of a plume of neutral nitrogen gas into space, which led to a large amount of plasma being detected by Sasaki et al<sup>56,57</sup>. This plasma was above the ambient plasma density level, and the plasma density was strongly influenced by the orbiter attitude. Sasaki et al<sup>56,57</sup> suggested that this was not a CIV effect, because the supplied orbiter/neutral velocity was too low (7.5 km/sec) compared to the relative ion-neutral speed nominally needed for CIV ionization, about 10.4 km/sec for nitrogen. Instead, Sasaki et al<sup>56,57</sup> considered

that the enhanced neutral densities performed the role of collisionally scattering ionospheric ions into the wake region where the measurements were taken.

Sasaki et al<sup>61,62</sup> investigated positive charging of the Shuttle during electron beam injections with SEPAC on the Spacelab 1 mission. The charging levels were detected by means of data from a Langmuir probe, a floating probe, an electron energy analyzer and a low-light-level TV camera. It was found that the level of charging was highly dependent upon the attitude of the Shuttle. Sasaki et al<sup>61,62</sup> found that whenever the beam accelerating potential exceeded 1 kV, the Shuttle's potential attained that level as well, as it did whenever the conducting portions of the orbiter lay within the thicker part of the Shuttle's wake; the beam accelerating potential stayed well below 1 kV when the orbiter was in the thinner part of the sheath.

Still another related experiment, in this case involving plasma injection to neutralize a electron-emitting Shuttle, was performed by Sasaki et al<sup>67</sup> using the SEPAC experiment on Spacelab 1. In these experiments, electron beams were injected with as much as 5 keV of beam energy and 300 mA of current. The electron beam injection of course charges the Shuttle positive. However, it was found that when a plasma of  $10^{19}$  argon ion-electron was subsequently injected, the potential decreased and had attained nearly zero potential by 6 to 20 ms following this injection. It then recovered to the initial high level of charging over a period of 10 to 100 ms. Sasaki et al<sup>67</sup> discussed this relatively long charging recovery time in terms of a model of cold plasma, produced in the charge exchange between neutral argon atoms and energetic argon ions during plasma injection, and then diffusion away from the orbiter.

## **I. Artificial Auroras**

Artificial aurora observations by high-resolution TV imaging of electron beam firings onto the upper atmosphere were conducted by Burch et al<sup>68</sup> on the basis of ATLAS 1 experiments.

The ATLAS-1 mission was conducted between March 24 and April 2, 1992. A brief summary of the scientific objectives of this mission and a tabular description of the experiments onboard is given by Torr<sup>69</sup>. Although the focus of the scientific mission was toward the atmosphere, there were also significant space plasma physics experiments conducted.

Since the dawning of the space Shuttle age, one of the space plasma experiments most discussed has been the creation of artificial auroras by means of electron beam injections fired down upon the atmosphere by electron accelerators on the Shuttle orbiter. Burch et al<sup>68</sup> described the production of artificial auroras via the SEPAC experiment, which was also carried on ATLAS-1. In this case, in order to neutralize the spacecraft in order to allow the beam to leave the spacecraft sheath and not be reflected back, SEPAC utilized three conducting spheres for charge collection, and a hollow-cathode xenon plasma contactor. This permitted the injection of electron beams at high currents of up to 1.2 Amps. It was found that without the operation of the charge collection by these spheres as well as the plasma contactor, as was the case on Spacelab 1, the Shuttle was charged to the beam potential for beam currents above 100 mA.

Mende et al<sup>93</sup> imaged the auroras created by the injection of these beams toward the atmosphere below the Shuttle on ATLAS-1 using the Atmospheric Emissions Photograph Imaging (AEPI) instrument. The emissions were in white light images as well as in a narrow wavelength band centered around 427.8 nm, which corresponds to the first negative band of the ionized diatomic molecule,  $N_2^+$  (nitrogen). Owing to

an extended tail in the imaged distribution together with the very short lifetime of this band, it was concluded that the emissions produced were coming from both high and low altitudes below the orbiter. The peak intensity of the emissions was about 5 kiloRayleighs.

## **J. The Tether Mission TSS-1R**

Early on, Banks<sup>71,72,73</sup> recognized that the use of a tether connecting a sub-satellite to the Shuttle could enable some intriguing electrodynamic and space plasma experiments, using a long conducting wire. The Tethered Satellite System (TSS) was a partnership venture between NASA and the Italian Space Agency (ASI). The second flight of the TSS hardware was the TSS-1R mission, which was launched February 22, 1996 into a 300-km circular orbit with 28.5 ° inclination. This mission involved the deployment of a 1.6 m diameter spherical, conducting satellite, connected by an electrically conducting tether which was insulated from the ionospheric plasma. As described by Stone and Bonifazi<sup>74</sup>, there were twelve science investigations, several of which were designed to explore space plasma-electrodynamic processes, particularly those involved in the generation of ionospheric currents. A major source of potential in this system is the electromotive force  $\phi_{emf} = \mathbf{v} \times \mathbf{B} \cdot \mathbf{L}$ , where  $\mathbf{v}$  is the velocity of the tether relative to the plasma,  $\mathbf{B}$  is the geomagnetic field, and  $\mathbf{L}$  is the displacement from the orbiter to the satellite.

One of the major surprises of the TSS-1R mission was in the parameters of the current collected by the TSS versus the voltage and the ionospheric plasma, which Thompson et al<sup>75</sup> found to exceed those from previous theoretical expectations by factors of 2 to 3. It was determined that the collected current varies approximately with the square root of the voltage over the range 10 to 1200 V. In these experiments, Bonifazi et al<sup>76</sup> controlled the tether current by the ASI Electron Gun Assembly (EGA). Oberhardt et al<sup>77</sup> measured the orbiter potential using the Shuttle Potential and Return Electron Experiment (SPREE). The fact that the currents were significantly larger than expected pointed to the need for developing new and more sophisticated models of three-dimensional plasma behavior under such conditions.

For the TSS-1R mission, the relative energy of the ambient  $O^+$  ions to the orbiter was 5 eV. Wright et al<sup>78</sup> investigated the behavior of ions on the front hemisphere of the TSS satellite while that satellite's potential was changed from below to above 5 Volts. Stone et al<sup>79</sup> used the Research on Orbital Plasma Electrodynamics (ROPE) experiment as the primary instrument in this investigation. It was found that for satellite potentials < 5 V, no ions were observed on the ram side of the satellite. However, when the satellite potential was raised to be greater than 5 V, ions were seen to be flowing from the forward portion of the satellite. The reflected ions were observed to have larger temperatures than those of the ambient ionosphere.

Significant currents through plasma such as the ionosphere can often be sources of free energy that can produce plasma instabilities and waves. Since TSS produced large currents through the ionospheric plasma, it was natural to expect plasma wave activity as a result. Iess et al<sup>80</sup> used the wave sensors of the Research on Electrodynamic Tether Effects (RETE) to measure electromagnetic wave power spectra in the frequency range 180 Hz to 12 MHz. Iess et al examined the wave activity during three intervals in which the currents were at 50, 190 and 55 mA, which corresponded to periods of positive satellite potentials of 9, 200 and 2 V. They found that large power waves occurred between 2 and 4 kHz, which was close to the lower hybrid frequency, and that the electric field amplitudes were extremely large, at times up to 12 V/m. For this particular range of frequencies, the waves observed were determined to be electrostatic and circularly polarized.

Winningham et al<sup>81</sup> used the Soft Particle Electrostatic Spectrometer (SPES) onboard the TSS-1R satellite to measure charged particles with energies up to 27 keV. Since the TSS satellite developed a positive potential owing to the  $\mathbf{v} \times \mathbf{B}$  Lorentz force with the tether, it was expected that ambient electrons would be accelerated to the satellite-borne detectors, and thus the measurements could be used to determine the satellite's potential, as well as the current. However, it was observed that the cold ionospheric electrons were only observed when they were accelerated to less than about 70 eV. For these cases, the accelerated energies agreed with the satellite potentials as observed by other independent techniques. However, when higher satellite potentials were observed, sometimes as high as 1.5 kV, with such other diagnostics, the expected accelerated ionospheric electrons were not observed. At the same time as these expected accelerated cold ionospheric electrons were not observed, it was found that there was a separate population of suprathermal electrons whose flux increased. Winningham et al<sup>81</sup> tentatively concluded that the accelerated ionospheric cold electrons were still present, but that the observation of them was made impossible by the dominating presence of these suprathermal electron fluxes.

These suprathermal electrons had energies typically centered around 200 eV, and their fluxes jumped by four orders of magnitude when the satellite potential exceeded the satellite ram energy. Iess<sup>80</sup> suggested that the origin of these suprathermal electrons was a wave-driven acceleration of the ionospheric electrons, in which the electron-energizing waves might be the observed lower hybrid waves, which in turn could be driven by an ion stream-stream instability associated with the forward reflected ions seen by Wright<sup>78</sup> when the satellite potential exceeds the ram energy, or alternatively with an electron-ion stream instability.

Magnetic fields associated with the intense currents through the tether wire system were measured by Mariani<sup>82</sup> with the TEMAG instrument on TSS-1R. With TEMAG, magnetic field components were observed parallel to the short satellite boom and to the spin axis, having a strong peak when the boom pointing direction was near the ram direction. Part of the explanation of the observed magnetic field signatures is in a toroidal current flowing on the ram side of the plasma sheath.

TSS-1R was apparently the first Shuttle mission to encounter strong negative Shuttle charging as noted by Gentile et al<sup>83</sup>. These negative Shuttle charging events were detected by the SPREE experiment, which measured ion spectral peaks indicative of strongly accelerated ionospheric ions into the Shuttle. These occurred when a 15  $\Omega$  and 25 k $\Omega$  resistors were arranged to connect the tether to the Shuttle ground. It was found during operations with the 15  $\Omega$  shunt that the potential changed from -17 to -245 Volts as the tether extended to 2.6 km, and that the current density detected was controlled also by the ionospheric density. Using the 25 k $\Omega$  resistor, it was found that the potential could go to -300 Volts in the night time ionosphere with the tether at 5.1 km, and could get to -600 Volts near the dawn terminator, with and without thruster firings.

Near the time of the tether breaking on TSS-1R, very large electric currents on the tether were detected by Gilchrist et al<sup>84</sup>. This happened with 19.7 km of the tether deployed at an electromotive force (emf) of 3482 Volts. Approximately 0.97 Amps went through the tether to the Shuttle electrical ground, which, in turn maintained electrical contact with the ionosphere via its main engine surfaces. It was found that as the broken end of the tether was in the ambient ionospheric plasma, the current was enhanced to 1.1 A and stayed high for 75 seconds after the break. It was concluded that the enhancement was due to a gas-enhanced electrical discharge that must have provided an electrical emission source.

Gough et al<sup>85</sup> also used the SPREE to measure plasma responses to electron beams being emitted from the Shuttle with 1 keV energy and 100 mA currents, at magnetic pitch angles of 90°. They measured resulting time-modulations of the electron fluxes in the MHz range that could be considered within two types. One of these was a narrow band near the electron gyrofrequency and its harmonics, while the other was at frequencies between the harmonics, and the modulation frequencies varied with electron energy. Gough et al<sup>85</sup> concluded that strong plasma interactions near the emission aperture caused large time-varying electric fields to modulate the electrons, and suggested an analogy with the electron cyclotron maser process thought to be involved in auroral kilometric radiation.

Williams<sup>86</sup> used the TSS-1R tether system as an electrodynamic double probe to measure vertical ionospheric electric fields. These measurements were conducted in the mid to low-latitude F-region ionosphere, and were consistent with other measurements of such ionospheric electric fields in those regions, and suggested that the scales of such electric fields can be at least 20 km.

## K. Conclusions

Clearly, through the uses of various active experiments as described here, it has been possible to probe the responses of the surrounding ionospheric plasma environment to these perturbations. It has also been possible to probe the physics of the Shuttle's interaction with this environment, and enable experiments not ordinarily feasible by actively modifying this environment, for example, the ionospheric hole experiments which permitted radio astronomy studies at lower frequencies.

Reliable passive studies of the space plasma environment have been much more limited to date. However, one obvious area where Shuttle-based studies should lead to advances in our understanding of the ionosphere, as well as the upper atmosphere, is in the deployment of tethered probes both upward and downward from the nominal Shuttle orbital altitude. For example, if it is possible to troll a probe below the Shuttle down toward the E-region, say 120 km or lower, we will be able to investigate a region which remains explored only by remote radars and rapidly moving rockets at this time. It would permit advanced exploration of a region where important currents flow and unique instabilities and wave-particle interactions occur. Such experiments would be very exciting future uses of the Shuttle for space plasma studies.

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## IV. ATMOSPHERIC SCIENCE

G. A. Germany

### A. Introduction

The principal scientific contributions to atmospheric science from the Spacelab missions are:

1. a greater understanding of the chemistry and transport of the atmosphere, from the lower troposphere to the upper thermosphere, but with greatest emphasis on stratospheric trace gases and especially stratospheric ozone;
2. increased knowledge of the impact of human activities on the lower atmosphere, examples of which include transport of pollutants (both industrial and from biomass burning) across continents and oceans, and the studies of the optical glow environment of the space Shuttle, since this must be understood and corrected for in any Shuttle-based remote sensing investigation;
3. unprecedented opportunities for correlative studies and validations between multiple observing platforms, which are vital for quantitative atmospheric studies.

The contribution from the first set of investigations can be grouped into four categories:

1. observations made for the first time or of a unique event,
2. observations made over an extended period of time or an extended spatial extent,
3. observations detailed enough to provide heretofore unavailable constraints for model development and investigation, and
4. correlative observations with other investigations.

Based on the number of papers published, five Spacelab missions (Spacelab-1 and -3, and ATLAS-1, -2, and -3) have made significant contributions to atmospheric science. Two additional missions (OSTA-1 and -3) have made smaller contributions. A summary of these missions and their relative contribution is given in Table I-5. With the exception of ATLAS-2, there is no significant difference in productivity between the Spacelab-1, -3, and ATLAS missions. The lower publication rate from ATLAS-2 is probably due to its being scheduled between the ATLAS-1 and ATLAS-3 missions with approximately one year between successive launches. It is possible that the ATLAS-2 data was published in conjunction with ATLAS-1 and ATLAS-3 data and not properly allocated by mission in this study. (See B.2. Caveats and methodology below).

**Table I-5. Summary of the most productive Spacelab missions in atmospheric science.**

Year	Mission	Papers
1981	OSTA-1	4
1983	Spacelab 1	50
1984	OSTA-3	9
1985	Spacelab 3	49
1992	ATLAS-1	37
1993	ATLAS-2	14
1994	ATLAS-3	36

The majority of all of the types of investigations (six of ten in Table I-8 below) have focused on the lower atmosphere (troposphere to mesosphere). Only four investigations have focused on the middle to upper

atmosphere (mesosphere to thermosphere). Virtually all investigations (nine of ten in Table I-8) are spectrometers/spectrophotometers. The lone exception in Table I-8 is AEPI, a two-dimensional imager. Also, some lightning surveys were conducted with television cameras.

When individual investigations are examined a clear difference in productivity is found. The two most productive missions, both in total papers and papers per flight, are ATMOS and ISO. Other principal missions are listed in Table I-6, where the investigations are ranked by the number of published papers per Shuttle flight. The paper count for several missions includes initial calibrations and orbital calibrations between other instruments and missions. About 20% of the ATMOS papers and 70% of the SSBUV papers fall into this category.

**Table I-6. Summary of the most productive Spacelab investigations in atmospheric science.**

Team	Papers	Flights	Papers per Flight
ATMOS	102	4	25.5
ISO	36	2	18
CRISTA	11	1	11
GRILLE	16	2	8
MAPS	11	2	5.5
MAHRSI	5	1	5
MAS	12	3	4
AEPI	6	2	3
SSBUV	24	8	3
ALAE	5	2	2.5

Both the Spacelab-1 and Spacelab-3 missions had periods of productivity that lasted about 8 years from mission launch. (See Table I-10 below.) OSTA-1, and OSTA-3 also seemed to follow this pattern, though it was not as apparent due to the lower number of publications.

## **B. Introduction to the Study**

### *1. Questions to be addressed.*

The question of assessing the scientific impact of the Spacelab series of Shuttle missions is necessarily a subjective one. For the purposes of this discussion, we will attempt to quantify this question in terms of the impact of scientific issues addressed as well as the relative significance of individual Spacelab missions and individual investigations.

a. What scientific questions are addressed? The ultimate judgment of scientific impact is not given by the number of Shuttle mission flown, by the number of papers published, or even by the total number of citations to published work. Rather, the scientific impact is judged by how a single investigation or mission changed our understanding of the subject, in this case, the atmosphere. Therefore, this measure of significance is addressed below.

b. What is the relative significance of individual Spacelab missions? The Spacelab missions had varying scientific goals that impacted the relative importance of each mission to studies of the atmosphere. For example, a mission devoted to life sciences or microgravity experiments would not be expected to yield much new insight into atmospheric processes. Therefore the first approach is simply to determine which missions produced the most publications related to atmospheric studies. Unfortunately this is not as straightforward as it may seem, since published papers may combine data from multiple Spacelab missions. Nevertheless, an attempt is made to assess relative importance on a mission-by-mission basis.

c. What is the relative significance of individual investigations? On examination of the Spacelab atmospheric publications, we find that the total number of publications is dominated by a small number of highly productive teams that flew the same investigation on multiple Shuttle flights. Therefore, the publications by instrument team are also presented.

## *2. Caveats and methodology.*

a. Caveats. Scientific productivity, as presented here, is most easily quantified by the number of papers published and by an examination of the published studies. The author is keenly aware that failure to properly locate published material will adversely affect the conclusions of this study. Unfortunately, resources did not allow a more complete review of the publications. However, it is felt that the results presented here, while not necessarily as comprehensive as desired, are representative of the scientific productivity trying to be assessed.

Because this study is limited to Spacelab contributions only, the tables of publications (Table I-8) cannot be used to judge an investigator's total scientific productivity. Some investigators with an otherwise significant and active publication record have published few papers with Spacelab data and are listed among the less productive Spacelab investigations. This is not intended to reflect on their overall scientific contribution.

A potential bias in the results of this study is the difficulty of tracking publications of an individual researcher as compared to those of a team of researchers. An individual may work with multiple data sets from multiple missions, making it difficult to find all publications and properly associate them with single missions. A team of researchers, on the other hand, will typically be identified by an acronym that is included in paper titles and abstracts. This makes finding publications much easier. Teams also tend to maintain web sites with online listings of publications.

Resources did not allow a detailed investigation of all publications from all investigators. Mission identification was made from paper titles, paper abstracts, previous reviews (especially M. Torr, [1995]; see below), and a review of selected papers.

Investigators often publish papers using data from multiple Spacelab missions. For the results of Table I-8, estimates of the mission data used were made from paper title, abstract, and previous reviews. In cases where multiple mission data was used each mission was credited with a publication. If it was not clear which mission data was used then no credit was given in Table I-8. Consequently, the total number of papers in Tables I-7 and I-8 will not agree with each other or with the bibliography given for each mission.

b. Investigations. Only investigations and publications relating to the Earth's atmosphere are included in this study. The investigations in Table I-9 were provided by Dr. Robert Naumann (study team lead) as relevant investigations and were the basis of all publications searches. Where appropriate, additional investigations were added to the survey. Earth observations, such as radar mapping, were not included nor were studies of the Earth's radiation budget since this topic is so closely related to solar studies. Also, auroral studies that do not directly relate to atmospheric studies are omitted.

c. Sources. The following journals and technical reports were used, in part, to identify investigators and their contributions.

- i. Torr, M., The Spacelab scientific missions: A comprehensive bibliography of scientific publications, NASA Technical Memorandum 108487, Marshall Space Flight Center, April 1995.
- ii. Craven, P. D. Spacelab Mission 1 experiment descriptions, NASA Technical Memorandum 82537, Marshall Space Flight Center, July 1978.
- iii. Craven, P. D., and M. R. Torr, Atmospheric Laboratory for Applications and Science Mission 1, NASA Technical Memorandum 4101, Marshall Space Flight Center, October 1988.
- iv. Kaye, J. A., and T. L. Miller, The ATLAS series of Shuttle missions, *Geophysical Research Letters*, 23, 2285, 1996.
- v. Torr, M. R., The scientific objectives of the ATLAS-1 Shuttle mission, *Geophysical Research Letters*, 20, 487, 1993.

Only publications in peer-reviewed publications are considered. Technical reports and meeting proceedings are not included in this study. Scientific impact is gauged by total number of publications and by the nature of the investigation topics.

## **C. Detailed Descriptions**

### *1. Investigations.*

Table I-7 lists the principal investigations examined for this study. Of these investigations, the more productive ones are discussed in more detail below. The investigations are ranked in the order given in Table I-8, that is by the number of published papers per mission. Where possible, instrument descriptions and objectives have been taken from documents prepared by the investigators, many of which are available on investigator or experiment websites, listed in Appendix D.

Published papers are grouped, somewhat arbitrarily, into three categories: science, technical, and general/programmatic. The general category includes descriptions of investigation objectives, of instrument design, and surveys intended for the community at large. Technical papers include details of instrument design, operation, and calibration, as well as data analysis techniques. This category also includes calibration/validation of other instruments via coincident observations. Papers not included in the general or technical are counted as science papers. The designations were made from examination of the paper title and, when available, the paper abstract.

**Table I-7. Principal Spacelab atmospheric science investigations.**

Acronym	Mission	Principal Investigator	Description and Title
ALAE	SL-1, ATLAS-1	J. Bertaux	Investigation of Atmospheric H and D through the Measurement of their Lyman- $\alpha$ Emissions.
ATMOS	OSTA-3 SL-3, ATLAS-1,2,3	C. Farmer, M. Gunson	Atmospheric Trace Molecule Spectroscopy – absorption profiles of molecular species in the stratosphere and mesosphere.
CRISTA	ATLAS-3	K. Grossman	Cryogenic Infrared Spectrometers and Telescopes for the Atmosphere – middle atmospheric IR emissions.
GRILLE	SL-1, ATLAS-1	M. Ackerman	Grille Spectrometer – absorption and emission profiles of molecular species in the stratosphere and mesosphere.
ISO	SL-1, ATLAS-1	M. Torr	Imaging Spectrometric Observatory – emission profiles of atomic and molecular, ion and neutral species in the mesosphere and thermosphere.
MAHRSI	ATLAS-3	R. Conway	Middle Atmosphere High Resolution Spectrometric Investigation – middle atmosphere OH and NO UV solar fluorescence.
MAPS	OSTA-1,3	H. Reichle	Measurement of Air Pollution from Satellites
MAS	ATLAS-1,2,3	G. Hartmann	Millimeter-Wave Atmospheric Sounder – limb profiles of temperature, pressure, and selected molecules in the stratosphere and mesosphere.
SSBUV	ATLAS-1,2,3		Shuttle Solar Backscatter Ultraviolet – calibrated ozone profiles and solar UV
	OSTA-1	B. Vonnegut	“Optical Survey of Lightning”
	SL-1	M. Herse	“Waves in the OH Emissive Layer”
	SL-1	G. Dieterle	“Microwave Remote Sensing”
	OSTA-3	T. Hallinan	“Auroral Imaging Experiment”
	SL-2	G. Brueckner	“Atmospheric Physics”

## 2. Descriptions.

- a. Atmospheric Trace Molecule Spectroscopy Experiment (ATMOS)
  - i. Missions: Spacelab 3, ATLAS 1, ATLAS 2, ATLAS 3
  - ii. Investigators: M. R. Gunson, PI
  - iii. Objective of experiment(s): “The primary objective for the ATMOS experiment is to make simultaneous measurements of as many trace atmospheric constituents as possible, providing height-volume mixing ratio profiles of these gases... under all seasonal and global conditions.... [A] secondary goal was to obtain a set of reference spectra characterizing the background infrared response of the upper atmosphere” — ‘An overview of the relevant results from the ATMOS missions of 1985 and 1992’, by M. R. Gunson and R. Zander, in NATO ASI Series ‘The role of the Stratosphere in Global Change’, M.-L. Chanin, ed. (Springer-Verlag 1993).
  - iv. Techniques: “ATMOS is an infrared spectrometer (a Fourier transform interferometer) that is

designed to study the chemical composition of the atmosphere. Since the molecules of interest to the ATMOS investigation must be measured remotely (i.e., from outside the atmosphere itself), solar spectroscopy was the method of choice for making the measurements, using those periods during each orbit of the spacecraft when the atmosphere is between the Sun and the instrument (i. e., at sunrise and sunset as seen from the spacecraft). During sunset, for example, the tangent point of the ray path to the instrument penetrates deeper and deeper into the atmosphere until it is blocked by the surface of the Earth (or clouds); as seen from a typical Shuttle orbit, the height of the tangent point changes at about 2 kilometers per second so that, to be able to distinguish changes in the composition with altitude, successive measurements of the spectrum must be made very rapidly. By analyzing the absorptions due to a given molecule in each successive spectrum, the variations in its concentration with altitude can be determined. “ – ATMOS website

- v. Observations: Absorption profiles of molecular species in the stratosphere and mesosphere.
  - vi. Significance: “Today we are aware of some 40 different molecular species in the atmospheric inventory, all of which play a role in the chemistry of the atmosphere and in its interaction with the Sun’s radiation. Some of these gases are present only as a result of our activities and are a sensitive indicator of the extent to which the environment is being perturbed. The fact that these gases have the potential for seriously changing the conditions at the surface of our planet, reinforces the realization that we can no longer view humanity and its environment as separate entities. While our primary concern in the past may well have been to protect ourselves from the environment, today we must also be concerned with protecting the environment from the detrimental effects of our own activities.
  - vii. In the past decade, research into many interrelated questions about the Earth’s atmosphere has made scientists aware of the complexity of the processes that affect it, and has drawn attention to the need for more detailed studies in order that these processes can be better understood. This, in turn, has shown the need for a means by which global measurements can be made of the composition and temperature of the atmosphere and their variability. “ –ATMOS website
  - viii. Notes: ATMOS studied chemistry and transport of stratospheric trace gases, including ozone. Observations were made in and near both the Arctic and Antarctic polar vortices. Studies of long-term trends were performed as well as effects of atmospheric perturbations such as the eruption of Mt. Pinatubo. Many correlative and validation experiments were performed with other instruments.
  - ix. Publication Summary: Total papers: 102 (82 Science, 19 Technical, 1 General/Programmatic)
- b. Imaging Spectrometric Observatory (ISO)
- i. Missions: Spacelab 1, ATLAS 1
  - ii. Investigators: M. R. Torr, D. G. Torr
  - iii. Objective of experiment(s): Measure thermospheric emissions over a broad wavelength range (extreme ultraviolet to near infrared).
  - iv. Techniques: “[The instrument] is comprised of an array of five half-meter grating spectrometers which utilize two-dimensional intensified CCD array detectors to simultaneously record spectral and spatial information. Altitude is imaged in the dimension parallel to the

- slit when placed perpendicular to the horizon, and spectral information normal to the slit. In addition, the instrument has a front scan mirror.” —Geophys. Res. Lett. 20, 515, 1993.
- v. Observations: Emission profiles of atomic and molecular, ion and neutral species in the mesosphere and thermosphere.
  - vi. Significance: “[ISO obtained] the first spectra of dayglow over several thousand angstroms, but it obtained these spectra as a function of altitude, providing valuable data for comparison with models of the source and sink functions. By obtaining a large number of emissions simultaneously, a diverse set of production and loss mechanisms can be tested, providing valuable multiple constraints on the theory.” Geophys. Res. Lett. 20, 519, 1993.
  - vii. Notes: ISO studied the chemistry/photochemistry of the mesosphere and thermosphere. It was also used in several studies that helped quantify the initially baffling problem of identifying the source of the ‘Shuttle glow’ that interfered with remote sensing investigations from space. The instrument development effort for this investigation led to new instruments, including a compact spectrometer and the Ultraviolet Imager (UVI), currently operational on the GGS POLAR spacecraft. In the delay following the Space Shuttle Challenger accident, the ISO was used as a ground observatory from McDonald, Texas. The ISO science and development team disbanded shortly after the ATLAS 1 mission, which limited the study and dissemination of the ISO ATLAS 1 data. The author was a member of the ISO science team and has recently been funded by NASA to restore the ISO ATLAS-1 data and make it available to the science community. This work should be completed within two years.
  - viii. Publication Summary: Total papers: 36 (27 Science, 8 Technical, 1 General/Programmatic)
- c. Cryogenic Infrared Spectrometers and Telescopes for the Atmosphere (CRISTA)
- i. Missions: ATLAS 3
  - ii. Investigators: D. Offermann, K. Grossmann
  - iii. Objective of experiment(s): “Prime CRISTA science objective is the study of small scale dynamical structures seen in the global trace gas distributions. The data are also used to test 3-D chemical-dynamical model predictions.” CRISTA website
  - iv. Techniques: “CRISTA... is a limb scanning satellite experiment, designed and developed by the University of Wuppertal to measure infrared emissions of the Earth’s atmosphere. Equipped with three telescopes and four spectrometers and cooled with liquid helium, CRISTA acquires global maps of temperature and atmospheric trace gases with very high horizontal and vertical resolution. The design enables the observation of small scale dynamical structures in the 15-150 km altitude region. CRISTA is mounted on the free flying ASTRO-SPAS satellite by Daimler-Benz Aerospace which is named then CRISTA-SPAS, together with MAHRSI, an ultraviolet spectrograph from Naval Research Laboratory in Washington, DC. The CRISTA-SPAS platform is launched with the U.S. space Shuttle. In orbit it is released from the cargo bay by the manipulator arm and retrieved at the end of the mission.” — CRISTA website
  - v. Observations: Global maps of temperature and trace gases in the stratosphere and mesosphere.
  - vi. Significance: “CRISTA-SPAS has now successfully completed two missions: CRISTA 1 was launched on November 3, 1994 with STS-66 Atlantis. Atmospheric measurements were obtained in the free flying phase from November 4-12, 1994, travelling 50-100 km behind

the Shuttle. On November 12 the satellite was retrieved and two days later returned to Earth. The STS-66 payload also included the SSBUV experiment and the ATLAS-3 instrument package. CRISTA 2 was launched on August 7, 1997 with STS-85 Discovery. Atmospheric measurements were made between August 8, 05:21 UT and August 16, 09:30 UT. The space Shuttle landed on August 19, 11:08 UT at NASA Kennedy Space Center, Florida. The CRISTA/MAHRSI Campaign encompasses the mission and complements it with ground truth and other coordinated measurements including monitoring of the atmospheric background by ground based, aircraft, balloon, rocket and satellite experiments. The first campaign took place from October 27 - November 25, 1994 and included over 32 rockets, 56 balloons, and ground based experiments at 42 locations. The second CRISTA/MAHRSI Campaign was from July 31 until August 30, 1997. “ — CRISTA website

- vii. Notes: Like ATMOS, CRISTA monitors trace gases and ozone, but it has the capability of extending its observations from the mesosphere into the lower thermosphere. Note that CRISTA is a part of a free-flying satellite that is launched and then retrieved by the Shuttle. CRISTA is one of the most recent investigations.

viii. Publication Summary: Total papers: 11 (8 Science, 1 Technical, 2 General/ Programmatic)

#### d. GRILLE Spectrometer

- i. Missions: Spacelab 1, ATLAS 1
- ii. Investigators: M. Ackerman
- iii. Objective of experiment(s): Study on a global scale atmospheric parameters between 15 and 150 km altitude.
- iv. Techniques: Infrared absorption spectrometry during sunrise or sunset periods, with the sun as the source of light
- v. Observations: Absorption and emission profiles of molecules in the stratosphere and mesosphere.
- vi. Significance:
- vii. Notes: GRILLE was also capable of emission spectrometry, but this observing mode was canceled on ATLAS-1 and possibly on Spacelab 1, as well.

viii. Publication Summary: Total papers: 16 (8 Science, 7 Technical, 1 General/Programmatic)

#### e. Measurement of Air Pollution from Satellites (MAPS)

- i. Missions: OSTA 1, OSTA 3, Earth-Observing space Shuttle mission (1994)
- ii. Investigators: H. G. Reichle, Jr., V. Conners
- iii. Objective of experiment(s): The MAPS experiment measures the global distribution of carbon monoxide (CO) mixing ratios in the free troposphere.
- iv. Techniques: “The MAPS instrument is based on a technique called gas filter radiometry. Thermal energy from the Earth passes through the atmosphere and enters the viewport of the downlooking MAPS instrument. Carbon monoxide and nitrous oxide (N<sub>2</sub>O) in the atmosphere produce unique absorption lines in the transmitted energy. The energy entering the MAPS instrument is split into three beams. One beam passes through a cell containing CO and falls onto a detector. This CO gas cell acts as a filter for the effects of CO present in the middle troposphere. A second beam falls directly onto a detector without passing through any gas filter. The difference in the voltage of the signals from these two detectors can be used to determine the amount of CO present in the atmosphere at an altitude of 7-8 km. A third beam of the incident energy

- passes through a cell containing N<sub>2</sub>O and falls onto a detector. This N<sub>2</sub>O gas cell acts as a filter for the effects of N<sub>2</sub>O present in the atmosphere. The global distribution of N<sub>2</sub>O is well known, so the N<sub>2</sub>O signal can be used to detect the presence of clouds in the field of view and to correct the simultaneous CO measurement for systematic errors in the data. “—MAPS website
- v. Observations: Distribution of middle tropospheric carbon monoxide.
  - vi. Significance: “Because of MAPS’ previous flights on board the space Shuttle, Earth system scientists now know that carbon monoxide concentrations in the troposphere are highly variable around the planet, and that widespread burning in the South American Amazon Basin and southern cerrados, the African savannahs, and the Australian grasslands and ranches are major sources of carbon monoxide in the southern hemisphere and tropical troposphere.” — MAPS website
  - vii. Notes: Of all the investigations surveyed here, MAPS most closely monitors the results of human activity via industrial and biomass pollutants.
  - viii. Publication Summary: Total papers: 11 (8 Science, 2 Technical, 1 General/Programmatic)
- f. Middle High Resolution Spectrograph Investigation (MAHRSI)
- i. Missions: ATLAS 3
  - ii. Investigators: R. R. Conway, PI
  - iii. Objective of experiment(s): MAHRSI’s primary objective is to measure limb intensity profiles of the resonance fluorescent scattering of sunlight by hydroxyl (OH) in the altitude region from 38 to 90 km, and by Nitric Oxide (NO) in the region from 48 to 160 km.
  - iv. Techniques: MAHRSI is a high spectral resolution (0.018 nm) imaging spectrometer sensitive in the wavelength region from 190 nm to 320 nm.
  - v. Observations: “From these intensity profiles, global vertical density profiles of OH and NO with a vertical resolution of 2 km and a downtrack resolution of 8 - 12 degrees are inferred. By measuring Rayleigh scattering intensity profiles, the experiment also provides precise knowledge of the neutral density and temperature in the mesosphere” —MAHRSI website
  - vi. Significance: “MAHRSI was designed and developed by the Upper Atmospheric Physics Branch UAP, within the Space Science Division of the U.S. Naval Research Laboratory (NRL). MAHRSI flew in November 1994 on the German Space Agency’s Cryogenic Infrared Spectrometers and Telescopes for the Atmosphere/Shuttle Pallet Atmosphere Satellite (CRISTA/SPAS), as part of NASA’s flight of the Atmospheric Laboratory for Applications and Science ATLAS-3. The CRISTA/SPAS satellite was deployed from the Space Shuttle Atlantis STS-66 on November 4, 1994 for 8 days of free flight. During these 8 days the MAHRSI instrument observed latitudes from 53° S to 63° N, and acquired 80 orbits of OH profiles, composing nearly 5 global maps, and 24 orbits of NO profiles. MAHRSI flew again successfully on Space Shuttle Discovery STS-85 in August of 1997.” — MAHRSI website
  - vii. Publication Summary: Total papers: 5 (4 Science, 0 Technical, 1 General/Programmatic)
- g. Millimeter-wave Atmospheric Sounder (MAS)
- i. Missions: ATLAS 1, ATLAS 2, ATLAS 3
  - ii. Investigators: G. Hartmann
  - iii. Objective of experiment(s): Measure emissions from six mm-wave transitions of four mo-

- iv. Techniques: MAS is a Shuttle-based, limb-scanning spectrometer. From these measurements are deduced abundance profiles and temperature.
- v. Observations: Limb profiles of temperature, pressure, and selected molecules in the stratosphere and mesosphere
- vi. Significance:
- vii. Publication Summary: Total papers: 12 (9 Science, 2 Technical, 1 General/ Programmatic)

- i. Missions: Spacelab 1, ATLAS 1
- ii. Investigators: S. Mende
- iii. Objective of experiment(s): To provide two-dimensional imaging in support of magnetospheric electron bounce experiments by the SEPAC investigation and to study natural auroras.
- iv. Techniques: Dual channel UV/visible video with filter wheels mounted on two-axis gimbal for pointing.
- v. Observations: Observed E and F region Mg<sup>+</sup>, lower thermospheric O(<sup>1</sup>S) and O<sub>2</sub> airglow, and topside images of gravity waves in airglow
- vi. Significance:
- vii. Notes: AEPI was able to conduct only limited observations (~4 hours on Spacelab 1) and was viewed primarily as a companion to SEPAC, a space plasma investigation. Consequently, its contribution to atmospheric science was limited. At least two papers on auroral imaging are not included in this survey. AEPI is the only non-spectrometric instrument included in this survey.
- viii. Publication Summary: Total papers: 6 (4 Science, 0 Technical, 2 General/Programmatic)

- i. Missions: STS-32, -41, -43, -72, ATLAS 1, ATLAS 2, ATLAS 3, USMP-2
- ii. Investigators: E. Hilsenrath, PI
- iii. Objective of experiment(s): “The primary objective of the [ATLAS 1] SSBUV instrument was to transfer accurate absolute calibrations to the SBUV/2 instrument on the NOAA operational satellite used for global ozone measurement.” —Geophys. Res. Lett., 20, 487, 1993.  
“SSBUV supports the long-term global stratospheric ozone and solar UV monitoring programs by providing repeated checks on the calibrations of UV ozone and solar monitoring instruments flying on US and international satellites.” —Geophys. Res. Lett., 23, 2289, 1996.
- iv. Techniques: “The theoretical basis for backscattered ultraviolet (buv) measurements of stratospheric ozone was developed in the late 1960’s, and buv-type instruments have made regular observations from satellites since 1970. The basic instrument design is a nadir-viewing Ebert-Fastie spectrometer, which measures the terrestrial radiance at 12 discrete channels between 250-340 nm with ~1.1 nm resolution. These instruments are flown in Sun-synchronous orbits, so that a diffuser plate can be deployed as the satellite crosses the terminator in order to make solar irradiance measurements at the same wavelengths that are used to measure the backscattered terrestrial radiance. The spectral albedo of the Earth, derived from the ratio of these two measurements, is then inverted to calculate the total column amount of ozone and the distribution of ozone with altitude in the stratosphere.” —SSBUV website
- v. Observations: Calibrated ozone profiles and solar UV from 180 to 405 nm

vi. Significance: “SSBUV’s value lies in its ability to provide highly accurate ozone measurements. The instrument is calibrated to a laboratory standard before flight, then is recalibrated during and after flight to ensure its accuracy. These laboratory standards are calibrated routinely at the National Institute of Standards and Technology. The rigorous calibration has been maintained since the beginning of the SSBUV flight series. SSBUV’s impact on NASA’s ability to detect ozone trends accurately was realized after approximately four flights. Data from the first flight with an earlier satellite already have been used to estimate ozone trends in the upper stratosphere since 1980. These results show a depletion of about 8 percent over 10 years, which is consistent with predictions of ozone depletion. SSBUV has achieved one of its primary objectives using data from the first three flights, flown in 1989, 1990 and 1991. These data have been used to update the calibration of the NOAA-11 SBUV/2 ozone instrument which has been in orbit since late 1988. The NOAA ozone data have been reprocessed with a refined algorithm and new calibration factors based on SSBUV and SBUV/2 in-flight calibration data, which were provided by NASA. The latest reprocessing covers the period 1989 to 1995. The reprocessed data have been checked against ground-based ozone observations, and these comparisons show very good agreement. There is also now excellent consistency between the refined NOAA-11 SBUV/2 data and the Nimbus-7 SBUV/TOMS data set, which goes back to 1978. The combined 15-year data set represents an excellent resource for ozone climate and trend studies. SSBUV detected and verified a significant decrease in the amounts of total Northern Hemisphere between the STS-45/ATLAS-1 (March 1992) and STS-56/ATLAS-2 (March 1993) missions. This depletion also was detected simultaneously by satellites and ground-based observations. Indications are that total ozone decreased during the same period on the order of 10 to 15 percent at mid-latitudes in the Northern Hemisphere. Scientists believe that this significant depletion resulted from the combined residual effects of Mt. Pinatubo aerosols in the stratosphere and cold stratosphere temperatures during the winter of 1992/93.” — SSBUV website

vii. Publication Summary: Total papers: 24 (8 Science, 16 Technical, 0 General/ Programmatic)

j. Atmospheric Lyman Alpha Emissions (ALAE)

i. Missions: Spacelab 1, ATLAS 1

ii. Investigators: J. Bertaux

iii. Objective of experiment(s): To study various sources of Lyman-alpha emission in the atmosphere.

iv. Techniques: The instrument is a spectrophotometer with two absorption cells, one filled with hydrogen, the other with deuterium. Either cell, when in use, absorbs the associated radiation. By modulating the cells the absolute intensity of the deuterium emissions can be determined.

v. Observations: Spacelab 1: Lyman alpha deuterium emission was observed for the first time along long slant path distances on the limb. Nadir viewing was not possible due to the limited sensitivity of the detector.

ATLAS 1: Nadir emission detected from the mesosphere.

vi. Significance: “...measuring the nadir Lyman alpha emission of deuterium atoms offers a new possibility to sound the chemically very active region where H<sub>2</sub>O (and HDO) is photodissociated, the D atoms serving as the most appropriate proxy to the H atoms which cannot

be observed themselves directly.” *Geophys. Res. Lett.* 20, 507, 1993.

vii. Notes: Bertaux published several (non atmospheric) papers on interplanetary Lyman alpha and solar physics (with the Prognoz instrument), but no more on atmospheric studies with the ALAE instrument.

viii. Publication Summary: Total papers: 5 (5 Science, 0 Technical, 0 General/Programmatic)

## **D. Science Impact**

### *1. Summary of Scientific Contributions.*

The nature of atmospheric science contributions from Spacelab missions can be placed in context with a quote from the ATMOS team:

“Today we are aware of some 40 different molecular species in the atmospheric inventory, all of which play a role in the chemistry of the atmosphere and in its interaction with the Sun’s radiation.... In the past decade, research into many interrelated questions about the Earth’s atmosphere has made scientists aware of the complexity of the processes that affect it, and has drawn attention to the need for more detailed studies in order that these processes can be better understood. This, in turn, has shown the need for a means by which global measurements can be made of the composition and temperature of the atmosphere and their variability. “ —ATMOS website

This need for additional studies and global measurements has been at the core of the investigations surveyed here. The contribution from these investigations can be grouped into four categories: observations made for the first time or of a unique event, observations made over an extended period of time or an extended spatial extent, observations detailed enough to provide heretofore unavailable constraints for model development and investigation, and correlative observations with other investigations.

a. Observational ‘firsts’. The number of observational ‘firsts’ that have been accomplished during the Spacelab missions is staggering and every investigation can rightly cite examples from their work. A few examples (not comprehensive) can be listed. They include the observations of vertical profiles of stratospheric trace gases not previously measured, including  $\text{N}_2\text{O}$ ,  $\text{ClONO}_2$ ,  $\text{HO}_2\text{NO}_2$ ,  $\text{CH}_3\text{Cl}$ ,  $\text{COF}_2$ , and  $\text{SF}_6$  by ATMOS. In the thermosphere, ISO obtained the first spacebased measurement of ground state OH in the mesosphere, the first dayglow altitude profiles of  $\text{N}(\text{P})$  at 346.6 nm (which provided the first examination of photochemical sources and sinks in normal daytime thermosphere uncontaminated by auroral emissions), and the first simultaneously acquired altitude images of NO gamma band temperature and intensity in the thermosphere. In addition to observing new emissions, old emissions were examined in new ways as well. For example, MAS performed the first measurements of latitudinal variation of mesospheric nighttime  $\text{O}_3$  and  $\text{H}_2\text{O}$ , an accomplishment that is also an example of the next class of observations: observations conducted on an extended scale.

b. Extended observations. Investigations that were included in multiple missions had the opportunity to make observations over extended geographical ranges or to monitor temporal trends between missions. ATMOS, with 4 missions, for example, made observations throughout the tropics and mid-latitudes, in both hemispheres and over two seasons, and both inside and outside the Arctic and Antarctic polar vorti-

ces. Between missions ATMOS was able to study trends in trace gases between 1985 and 1994 as well as the effects of stratospheric aerosol injection from the Mt. Pinatubo eruption in 1991. Similarly, SSBUV reported a 12% ozone decrease between successive flights in 1992 and 1993.

MAPS made observations of biomass burning to demonstrate that forest burning in remote locations can contribute to enhanced CO and O<sub>3</sub> levels that can be transported large distances from the burn sites. As noted above, MAS produced latitudinal maps of O<sub>3</sub> and H<sub>2</sub>O, as well as ClO. CRISTA similarly obtained high resolution global maps of temperature and atmospheric trace gases. AEPI also provide observations of gravity waves, not by building up data, but by two-dimensional imaging of the airglow emissions.

c. Detailed observations. With the exception of AEPI, every investigation surveyed here employs some type of spectrometer to return spectral information about the atmosphere. (MAPS and ALAE use spectrophotometers, which can be viewed as a limited form of spectrometer.) This emphasis on spectral information is significant and underscores the high information content available from spectral observations. Such observations provide multiple simultaneous constraints on atmospheric models.

d. Correlative studies. A significant component of all the Spacelab missions was the large number of correlative studies based on simultaneous observations from multiple observing platforms. A brief survey of the papers listed in the appendix lists the following illustrative studies: ATMOS/MAS, ATMOS/UARS, ATMOS/ER-2 aircraft, ATMOS/MAS/SSBUV, MAS/UARS, MAS/MLS, MAPS/TOMS. Studies such as these enable examination of different aspects of common atmospheric features, as well as calibration/validation of observations. This latter accomplishment is especially important, in view of the low level, long term changes that are often the subject of quantitative study.

## *2. Scientific Publications.*

Table I-8 lists the number of publications from selected Spacelab missions from 1980 through 1997. Missions with no significant publication history are not included in the table. Boxes indicate mission launch, before which publications are not generally expected. The only exception to this would be publications detailing instrument development or general papers describing a mission or investigation.

The publications for each mission are divided into three categories, labeled at the bottom of the table as 'T', 'S', and 'G', representing papers devoted to instrument development, observing, or analysis techniques (T), scientific papers (S), and programmatic or review papers (G).

Beginning in 1995, it becomes increasingly difficult to associate publications with single missions, as studies combined data from multiple investigations and missions. Best estimates were made as described in the Caveats and Methodology section (B.2).

Table I-9 lists publications by investigation. The nomenclature used is the same as that in Table II-8, with publications identified with the labels 'T', 'S', and 'G'. Shuttle missions are noted with a border and principal Spacelab missions are noted at the top of the table.

**Table I-8. Atmospheric science publications by Spacelab mission.**

	AT1	AT2	AT3	SL1	SL3	OSTA1	OSTA3
1980							
1981							
1982				5			
1983				2 1 1		1	
1984				3 6 2			1 1
1985				3 7	1		
1986				2 4	5		2
1987				3	1 6		
1988				3	1 2	1	1
1989				2	6	1	
1990				1 2	6		2
1991				1	3 7		1
1992	1 2			1	4		1
1993	1 1				1		
1994	1 5	1 1					
1995	2			1			
1996	1 11 1	1 10 1	24 2		5 1		
1997	2		1 8				
TOTAL	2 32 3	2 11 1	1 32 3	16 31 3	5 43 1	1 3 0	2 7 0
	T S G	T S G	T S G	T S G	T S G	T S G	T S G

### 3. Scientific Citations.

A classic method of measuring scientific productivity is by measuring the total number of citations to an investigation's work, rather than the total number of publications. This has the advantage of allowing the scientific community assess the importance of the work being done and is not easily skewed by publication choices made by the investigation team. To be of most use, however, a citation search must guard against bias from such sources as self-citation by authors or participants in correlative studies. Also, citation sources are best used to measure the impact of a single study or publication by a single author. Unfortunately, the nature of the investigations surveyed here make an meaningful citation source difficult.

The first difficulty is the total number of papers to be surveyed. The ATMOS, ISO, and SSBUV teams produced 159 publications included in this survey, none of which can easily be labeled as a seminal paper that would be a potential target for a citation search. The second difficulty is the number of potential authors. The most productive investigations were conducted by teams of scientists. For teams like ATMOS, that were active for long periods, the team composition changed with time. Finally, the caveats discussed above about the dangers of missing publications are greatly amplified in a citation search under these conditions. For these reasons, it was decided that current resources did not permit a comprehensive citation search to be performed.

## E. Conclusions

So we now return to the central questions this study was designed to answer. What has been the impact of the Spacelab Shuttle missions on atmospheric science? How do we view the atmosphere differently now

**Table I-9. Atmospheric science publications by investigation.**

OST1	81	82	83	SL1	OST3	84	85	SL3	86	87	88	89	90	91	AT1	AT2	AT3	94	95	96	97	98	Total	Altitude	Notes		
							S(1)	S(1)	S(5)	T(1) S(6)	T(1) S(2)	S(6)	S(6)	T(3) S(8)	S(5)	S(3)	T(1) S(7)	S(6)	T(13) S(25) G(1)	T(13) S(25) G(1)	S(1)	S(1)	T(19) S(82) G(1)	102	20-80	ATMOS	
											T(1)	T(1)	T(2)	T(1)	S(1)			S(2)	S(2) S(3)	T(4) S(3)	T(2) S(2)		T(15) S(9)	24	20-100	1	SSBUV
																		S(1)	G(1)	S(2) G(1)	T(1) S(6)		T(1) S(8)	11	15-180		CRISTA
																			T(1)	S(8)			T(2) S(9) G(1)	12	20-90		MAS
																					</						

1 SSBUV flew twice in 1994

2 MAPS flew in 1994, but not on AT3

in light of the Spacelab missions? What conclusions, if any, can we draw about the relative success of the different missions and investigations?

When viewed as a whole, we can see that the Spacelab missions and their associated investigations studied virtually the entire atmosphere, from the troposphere near the Earth's surface to the thermosphere in which the space Shuttle orbited. These observations included mesospheric studies which are very difficult to conduct from the ground and for which, consequently, there is a general dearth of data and concomitant understanding. This does not mean that the entire atmospheric range was covered in equal detail. In fact, the stratospheric regions received by far the most attention while the thermospheric regions received much less. It is in the stratosphere, of course, that the Earth's ozone layer resides, along with all its attendant questions about its impact on human activities, and vice versa. These questions were addressed by focusing on the details, studying the chemistry and transport of over 40 trace gases previously unstudied, or studied only in a cursory fashion. These were quantitative studies which required careful calibrations of the sensors and assurance that the rigors of spaceflight did not seriously degrade those same sensors. This assurance was obtained by correlative studies involving simultaneous observations from the ground, aircraft, and other spacebased detectors. A large percentage of the papers published during this period fall into this category, which underscores the importance the atmospheric community places on correlative studies. This emphasis is necessary because the climatological effects examined are quite small.

The study of the troposphere and stratosphere is intimately linked with human activities, and several studies focused on the detection of and monitoring of transport of atmospheric pollutants on a global scale. We now know, for example, that widespread burning of grasslands and forests in South America, Africa, and Australia are major sources of carbon monoxide and ozone in the southern hemisphere, observed to travel between continents and across oceans. Spacelab investigations also tracked the spread of industrial pollutants between continents as well, underscoring the global nature of these problems.

Do we now view the atmosphere in a fundamentally, or revolutionarily different manner because of the Spacelab investigations? In the large picture, probably not much. But in the details, undoubtedly so. Atmospheric models, and our understanding, are now constrained to match a new wealth of observations. This is the principal contribution of the Spacelab atmospheric investigations.

#### *1. Which of the missions was most important?*

This is a question that is dependent on many variables and is only addressed obliquely here, because of the caveats cited above about the publication searches associated with this survey. What can be said without hesitation is that most of the contributions to atmospheric science came from five missions: Spacelab 1, Spacelab 3, and the three ATLAS missions. To a lesser extent, the OSTA1 and OSTA3 missions also made significant contributions. Spacelab 1 and 3 produced more total papers than did the ATLAS missions, but they flew earlier and have had more time for publications. Both of these missions had a period of productivity that lasted roughly eight years. The first ATLAS mission flew seven years before this date of this report. This survey reports that ATLAS 2 had about half the publications of the other ATLAS missions but, as discussed above, this is probably a shortcoming of the survey methodology.

## 2. *Which of the investigations was most important?*

This is a question the author is manifestly unwilling to address, due to the dangers of an incomplete literature search compounded by the fact that the author is experienced in thermospheric studies while the emphasis on tropospheric and stratospheric studies in the Spacelab era has already been noted. Despite this reluctance, a number of conclusions can be made. First of all, the ATMOS team is clearly in a class by itself. No other investigation comes close to matching their total number of papers or the number of papers per mission. It is highly unlikely that a more comprehensive literature search would change this fact. ISO and SSBUV represent a 'second tier' of productivity, after ATMOS, when total number of papers are considered. If the criterion is switched to number of papers per flight, then the second tier is composed of ISO and CRISTA. It is interesting to speculate on what the ISO publication level would have been had the instrument team not disbanded, or what effect the upcoming rerelease of the instrument data to the science community will have. While the status of these first and second tier investigations would probably be unchanged by a more comprehensive literature search, that is clearly not the case for the remainder of the investigations. Take, for example, the investigation entitled "Optical Survey of Lightning" on Spacelab 1 by B. Vonnegut. Only three publications are cited in Table 5, a considerably low value. The literature search, however, turned up multiple references to lightning studies by Vonnegut but only three of them using the Spacelab data. It appears that the Spacelab 1 flight served as a prototype development for instruments that have found wide use on non-Spacelab missions. Once again the caveats of relative comparisons based on this survey must be emphasized.

In summary, the principal scientific contributions to atmospheric science from the Spacelab missions are:

- a greater understanding of the chemistry and transport of the atmosphere, from the lower troposphere to the upper thermosphere, but with greatest emphasis on stratospheric trace gases and especially stratospheric ozone. The contribution from these investigations can be grouped into four categories: observations made for the first time or of a unique event, observations made over an extended period of time or an extended spatial extent, observations detailed enough to provide heretofore unavailable constraints for model development and investigation, and correlative observations with other investigations.
- increased knowledge of the impact of human activities on the lower atmosphere. Examples include transport of pollutants (both industrial and from biomass burning) across continents and oceans. This category can also include the studies of the optical glow environment of the space Shuttle, since this must be understood and corrected for in any Shuttle-based remote sensing investigation.
- unprecedented opportunities for correlative studies and validations between multiple observing platforms, which are vital for quantitative atmospheric studies.

## V. EARTH OBSERVATIONS

James F. Cruise

### A. Introduction

The dual Spaceborne Imaging Radar-C (SIR-C)/X-band Synthetic Aperture Radar (X-SAR) was flown aboard the Shuttle Endeavour during the April and October 1994 missions (STS 59 and STS 68). The SIR-C system records data at both L (23.5 cm) and C (5.8 cm) wavelengths (1.25 GHz and 5.3 GHz frequencies, respectively) with full polarimetric scattering; while the X-SAR is capable of recording data in the X-band (3.1 cm, 10 GHz) with copolar polarization only. The integrated system records data simultaneously at incidence angles ranging from 15 ° to 60° with image resolution varying from 10 to 50 m depending on system configuration. The SIR-C/X-SAR is the most advanced airborne imaging radar system ever flown in earth orbit in comparison to satellite mounted instruments such as the European Remote Sensing Satellites (ERS-1 and 2), the Japanese Remote Sensing Satellite (JERS-1) or the Canadian RADARSAT. Current satellite systems are limited in number of channels, polarization, incidence angle and spatial resolution. For example, the ERS-1, launched in 1991, records data in the C-band, copolar (VV) configuration only with a spatial resolution of 50 km and an incidence angle of 23°, while the JERS-1 records observations in the L-band copolar (HH) configuration at an incidence angle of 35° and a spatial resolution of 80 km. In contrast, the SIR-C/X-SAR is capable of numerous combinations of frequency/polarization configurations over a range of incidence angles and thus can produce enhanced images for a wide variety of earth science applications.

The impact within the remote sensing and earth science communities of the two SIR-C/X-SAR missions was demonstrated early on by the large number of sessions and papers devoted to the subject at the 1995 International Geoscience and Remote Sensing Symposium (IGARSS'95) sponsored by IEEE. Significant interest carried over to the subsequent IGARR Symposia in 1996, 1997 and 1998 as well. Subsequently, three major journals within the earth science and remote sensing communities devoted special issues to presenting the results of the missions. These issues were *IEEE Transactions on Geoscience and Remote Sensing*, 33(4), 1995; *Journal of Geophysical Research*, 101(E10), 1996; and *Remote Sensing of Environment*, 59(2), 1997. In addition, most of the investigators associated with the missions have published significant articles in journals within their specific disciplines and dozens of other scientists not directly associated with the original missions have incorporated the data into their research and continue to publish results (see bibliographic listing in Appendix B).

Following the flights of the SIR-C/X-SAR in 1994, NASA requested the Space Studies Board of the National Research Council (NRC) to evaluate the utility of a third SIR-C/X-SAR mission and to provide guidance in developing a strategy for a space-based, science-oriented interferometric small SAR. The NRC report has been summarized by Kasischke *et al* (1997). Thus, the parametric design standards and mission goals of future missions will build directly on the results of the SIR-C/X-SAR investigations.

The earth science applications associated with SIR-C/X-SAR data can be grouped into six broad categories:

- 1) Oceanography (including wave observations);
- 2) Ecology (forestry, agriculture, wetlands);
- 3) Hydrology;

- 4) Geology and geomorphology (including volcanology);
- 5) Precipitation and climate (including glaciology); and
- 6) Surface mapping and topography.

Some studies may combine elements of two or more categories. In the following sections, the contributions made in each of these areas by the investigators associated with these missions will be discussed in detail.

## **B. Oceanography**

The oceanographic studies associated with the SIR-C/X-SAR missions consisted of investigations by Monaldo and Beal, Keyte, *et al*, Plaut and Flament of the capability of the system to measure important wave properties such as significant wave height (SWH) and wave number and propagation direction, and to observe surface frontal boundaries separating cold and warm water masses. Monaldo and Beal used an on-board processor developed at Johns Hopkins University to produce real time images of ocean wave spectra from the C-band signal. A primary goal of the wave study was to incorporate these real time observations into a numerical wave model in order to correct and update model predictions in real time. Radar observations by Keyte *et al* were also compared to surface measurements provided by buoy observations. Another important goal of this study was to compare the C-band images from the SIR-C radar to those from the ERS-1 in order to develop relationships for Doppler smearing that might be employed in future analysis of ERS-1 images. Frequency-polarization combinations were also studied in order to determine optimal configurations for future satellite systems.

The results of these studies appear to be promising in some cases. The wave properties obtained from the radar data agree fairly closely with predictions from the model and with the buoy measurements. The raw radar-estimated times agreed to  $\pm 3$  hours to model predicted times while location agreed to  $\pm 2^\circ$  latitude/longitude. These estimates were further corrected using polynomial interpolation of SAR values. Correlation between radar-derived wave direction and model predicted direction was 0.74, with the largest mean difference of  $-1^\circ$ . The on-board processor made these data available in real time and they were successfully incorporated into the wave forecasting model. However, in terms of longer range benefits, the results were not as favorable. Comparison with satellite images revealed that the currently available satellite data could probably not be sufficiently corrected with the airborne data, and it was found that the dependence of wave images on radar frequency-polarization configurations is probably too subtle to finalize development of satellite configurations at this time. The principal development of the wave studies appears to be the conclusion that low orbit radar data can sufficiently distinguish important wave properties in real time such that they can be used to improve numerical wave forecast models. Improved wave forecasting would be valuable in many instances, including severe weather situations such as hurricanes or in cases of waves generated by tsunamis.

Another result of the ocean studies, reported by Flament, was that frontal boundaries were identified on the SAR images during the October flight and that these boundaries closely agreed with field observations and data obtained from conventional thermal and infrared satellite sources. Boundary movement was also successfully observed by using images from successive Shuttle overpasses. Frontal boundary location and movement can have important consequences in terms of weather occurrence and fisheries productivity as well as on water quality issues such as hypoxia and algal blooms. However, the advantages of observing frontal characteristics from microwave radar measurements in lieu of currently available thermal and infrared instruments are unclear.

### C. Ecological Investigations

The ecological studies associated with the SIR-C/X-SAR missions can be grouped into three categories: forestry, wetlands, and forest/nonforest land use classification. The forestry studies consisted primarily of classification and mapping forest spatial structure, as reported by Sun and Ranson, Keil *et al*, and Souyris *et al*; classification of growth stages as reported by Yanasse *et al*, and Soares *et al*; and above ground biomass estimation as reported by Souyris *et al*, Ranson and Sun, and Dobson *et al*. Forestry studies were focused on both northern latitude hardwoods in Michigan (reported by Dobson *et al*), Maine (reported by Ranson *et al*), and Germany (reported by Keil *et al*) as well as southern rainforests of Brazil (reported by Saatchi *et al*). Attempts were also made to combine forest growth models with a radar backscatter model to improve image analysis by Floury *et al*, Ranson, and Wang *et al*.

Reported results using the SAR data for forest spatial classification were decidedly mixed. One investigating team was able to distinguish forest classes with accuracy ranging from 70% (hardwoods) down to only 50% (mixed classes). In a more general classification scheme, Keil *et al* used L-HH and L-VV polarizations to distinguish between deciduous and coniferous classes in the Harz mountains of Germany. Souyris *et al* used C-band data with unsupervised classifications to distinguish forest stands lower than 33 ton/hectare with accuracy greater than 85%. Pierce *et al* used multiple frequency-polarization combinations to classify hardwood forests to accuracies of 97% for short vegetation (few large trees) and 98% for tall vegetation. Saatchi *et al* employed copolar and cross polarized L- and C-band data to distinguish primary forest, agriculture and disturbed forest areas to an accuracy of 92%. Combinations of L-, C-, and X-band data allows for the differentiation of spatial features down to areas as small as 10 km<sup>2</sup>, which would not be possible with the resolution of satellite SAR data. Fractal dimensions were used to examine the spatial patterns of forest growth stands with the ability to discriminate between forest patch perimeters by Sun and Ranson. The spatial structure recognized on the SAR images was successfully related to forest management practices such as logging and storm damage. The range of results on classification and spatial mapping of forest types is at least partially due to the different physical and environmental conditions at the various sites according to Dobson *et al* and Bergen *et al*. Some sites were in cold regions, while others were in southern rainforests; some were in flat terrain while others were in mountainous regions. In some cases snow covered the canopies while in others it did not. These results appear to show that classification and mapping algorithms for SAR data can accurately distinguish broad classes, but that algorithms that would be generally applicable over a range of conditions may be difficult to develop.

Growth stage classification for both forest and agricultural areas was performed by Soares *et al* and Yanasse *et al*. Soares, *et al* employed L- and C-band data (both copolar and cross polar) to discriminate fifteen agricultural texture measures as an aid in the classification of seven agricultural land classes. A kappa verification statistic of 0.90 was obtained in this effort. Yanasse *et al* found that L-band cross polar data could be used to distinguish second growth and successional stages of canopy in the Amazon rainforest. However, large samples were necessary in order to obtain suitable statistics, that is, the algorithm must be applied over large spatial areas. Using mean statistics, differences in class means of 5 dB were observed between successional growth stages.

The results for biomass estimation from SIR-C/X-SAR data were fairly consistent even though environmental factors are known to affect these estimates as well. Biomass estimates are obtained by developing regression equations relating plant biomass to the L-band backscatter or the L/C ratios. In these studies,

the regression equations generally explained a fairly high degree of the variance in biomass. Ranson *et al* obtained  $r^2$  of around 0.7 in relating L-HV/ C-HV ratios to biomass in northern hardwood forests. Dobson *et al* related L-band backscatter to biomass estimates for five different vegetation stand heights with  $r^2$  values up to 0.95 with relatively small root mean square error. These results appear to show that forest biomass can be predicted using SAR data (particularly L-band) with sufficient accuracy over a variety of environmental conditions to allow radar data to be used as a significant forest management tool. Forests cover a substantial portion of the earth's surface and the carbon contained in their biomass is an important component of the global carbon budget. The success of the SIR-C/X-SAR mission in predicting forest biomass clearly indicates the importance of active microwave measurements in analysis of the global carbon cycle.

Radar backscatter models were incorporated with forest canopy models by Floury *et al*, Ranson, and Wang *et al*. The purpose of these integrated models is to allow a theoretical model of tree growth to be incorporated with the radar backscatter model in order to enhance the backscatter image and thus strengthen the relationship between forest biophysical parameters and radar backscatter. In all cases, integration of the models was successful to some degree when compared to the observed SAR data. Wang *et al* were able to discriminate between total canopy scattering relationships using L- and C- band copolar scattering models ( $< 0.5$  dB) and cross polar scattering models (1.7 to 2.3 dB for L-HV and 2.9 to 3.4 dB for C-HV).

Wetland analyses were carried out by only one investigative team, Pope *et al*. The research focused on identification of wetland flooding cycles during the dry (April) mission compared to the wet (October) mission over the Yucatan Peninsula. The L- and C- band SIR-C data were used with various frequency-polarization combinations to determine which combination would be more appropriate under the two sets of antecedent conditions. Another objective of the experiment was to determine if some combinations of existing satellite data might also be used to detect seasonal flooding of wetlands. It was found that C-band phase differences (H-V) were most effective in detecting increased wetland flooding. Changes from dry or partially flooded to complete inundation could be easily detected; however, changes from dry to partially flooded could not be detected by any configuration. Based on the radar configurations tested, it was concluded that a combination of ERS-1 and -2, and Radarsat might function to detect seasonal flooding of most wetlands, excluding partial flooding.

Land use classification investigations by Saatchi *et al*, Souyris *et al*, Ranson and Sun, and Pierce, *et al* focused primarily on discrimination between forest and non-forest areas. In all of these analyses, under differing environmental and physical conditions, the SAR data were uniformly successful in separating forest from non-forest areas, with accuracies ranging from 87 % to nearly 100%. The ability of active microwave measurements to discriminate forested areas, as well as forest classes, and to accurately estimate forest biomass and carbon storage, makes this technology extremely promising as a tool in global change analysis.

#### **D. Hydrology**

The hydrologic investigations associated with the subject missions dealt with the capability of the SIR-C/X-SAR data to estimate soil moisture under a variety of soil types, surface roughness, and moisture conditions as reported by Pultz *et al*, Wang *et al*, and Taconet *et al*, and to map the spatial structure and estimate equivalent water content of non-glacial snow pack, as reported by Shi and Dozier, and Matzler *et al*. The

estimation of soil moisture content from remote sensing sources has thus far been an intractable problem in hydrology and has become a major focus of research according to Jackson *et al.* Most of this research has focused on the use of visible-near IR or passive microwave instruments. Problems with this approach include the ability of these instruments to only sense the surface moisture and their relatively coarse spatial resolution. Active microwave instruments do not exhibit these problems, and consequently, their employment in hydrology is one of the most promising developments in recent years according to Mattikalli *et al.* The SIR-C/X-SAR missions offered the first opportunity to use multi-frequency, multi-polarization airborne data to study soil moisture signals over a variety of climates, vegetation and soil types ranging from Manitoba, Canada, to Oklahoma, USA, to Orgeval, France. For this reason, it potentially represented a major step in the development of algorithms to relate vertical soil moisture profiles to radar backscatter.

The Shuttle missions coincided with major field campaigns to measure soil moisture in Manitoba, Canada by Pultz *et al.*, the Little Washita basin in Oklahoma by Wang *et al.*, and the Orgeval watershed in the Brie region of France by Taconet's and Zribi's groups. Given the ability of the longer wavelength radar signals to penetrate the soil surface, active microwave instruments have the potential to measure not only surface soil moisture content, but vertical soil moisture profiles as well. Unfortunately, observed backscatter signals are influenced not only by the soil properties of the surface under investigation, but also by the surface topography, roughness and vegetation characteristics. Past research has focused on the use of these data to estimate moisture profiles primarily on bare soil under relatively smooth surface conditions. Effective algorithms have yet to be developed to correct the radar backscatter signal for variations in surface roughness or vegetation.

The two SIR-C/X-SAR missions had the potential to lead to significant improvements in current methodologies; however, this potential has not yet been fully realized. Two investigating teams (Pultz *et al.* and Zribi *et al.*) studied the effect of surface roughness and moisture content on the backscatter at different frequencies in an attempt to possibly account for the roughness effects. However, the study reported by Pultz *et al.* again concerned only bare soil conditions. The French study teams (Taconet and Zribi) did investigate both roughness and vegetation effects; however, only the surface moisture content was obtained. The American team, as reported by Dubois *et al.* and Wang *et al.* focused entirely on the near surface (5 cm) of bare soil conditions with no attempt to account for either roughness or vegetation effects.

In all of these efforts, considerable success was realized within the narrow confines of the objectives. Pultz *et al.* were able to obtain relationships between backscatter at both the C- and L-band copolar (HH) configurations and moisture profile to a depth of 15 cm over bare soils at the Manitoba test site. The  $r^2$  values of these expressions ranged from 0.84 for the top 2.5 cm layer to 0.77 for the 15 cm layer. The relationships worked well for both spring (April) and fall (October) environmental conditions and the authors found that surface roughness and soil texture do not play significant roles in measuring short term soil moisture. Likewise, Wang *et al.* found that two inversion algorithms currently used to relate radar backscatter to soil moisture in the top 5 cm of bare soil columns worked well with the C- and L-band data (standard error =  $0.05 \text{ cm}^3/\text{cm}$ ). However, in both cases, the algorithms completely failed to capture soil moisture in vegetated environments. A further weakness of both algorithms was that they failed to converge to a solution for a significant number of pixels.

Limited success was also realized over vegetated environments by Taconet *et al.* who were able to estimate surface soil moisture from the C-band measurements to a precision on the order of  $0.05 \text{ cm}^3/\text{cm}$  when

the soil column was overlain with a wheat canopy. A correction was applied to the soil moisture inversion algorithm to correct for the vegetation effects on the radar backscatter measurements. The authors demonstrated that even single band satellite data (ERS-1) could be employed for this purpose. As the data collected during the missions are obviously still available, it is hoped that some of the more important problems associated with remote sensing of soil moisture, for instance the vertical profile estimation throughout the active zone and correction for vegetative cover and surface roughness, will continue to be addressed in future research. Until this is done, operational use of remote sensing instruments for soil moisture estimation will not be realized.

The results of the snow pack experiments reported by Shi and Dozier, and Matzler *et al*, may have more immediate practical applications than do the soil moisture investigations. The ability to map snow cover and to estimate the equivalent water content of snow packs can be a great aid in the estimation of spring snow melt runoff from mountainous regions. Snow melt provides the essential runoff for replenishment of reservoir stocks in many parts of the world (for example, the western United States). The ability to accurately estimate the volume of this runoff in advance would be a great benefit to hydrologists, hydro-power operators and water supply managers. The authors demonstrated the ability of multi-frequency, multi-polarization data to accurately discriminate between snow covered and non-snow covered regions in areas of high topographic relief (without the aid of topographic maps) and to estimate equivalent water content of snow cover. Ratio backscattering coefficients at the different frequencies could be adjusted to enhance the images and the estimated wetness values compared well with ground observations over the test site. Matzler *et al* demonstrated that different frequencies (35 GHz and 5.3 GHz) could be employed to discriminate between layers of snow pack based on temperatures and wetness.

### **E. Geology and Geomorphology**

The geological and geomorphological investigations associated with the missions focused on observing sand covered features in Arabian deserts (Dabbagh *et al* and Schaber *et al*), mapping of volcanic lava fields and observations of associated deformations (Zebker *et al*, Rosen *et al*, and Murino *et al*) and mapping of alluvial flood plains (Hess *et al*). The restricted range of wavelengths of the SIR-C/X-SAR instruments (3.1 cm to 23.5 cm) limits the penetration range of the beams and thus restricts the application of the system in subsurface investigations. Dabbagh *et al* used L-band copolar (HH) data to penetrate up to four meters of sand in the Arabian Peninsula to reveal older geologic features such as drainage channels. The authors found that the X-band (VV) data could penetrate up to three meters of sand. Schaber *et al* employed the C- and L-band data in a similar manner in an Egyptian desert overlain with a shallower sand layer (two meters). The authors found that C-band cross polar (HV), the L-band copolar, and the L-band cross polar data all produced enhanced images and were able to reveal deeper rock formations and fractures, while shallow quaternary drainage channels were visible at all channels. They also concluded that L-band copolar data at small incidence angles may be able to detect shallow groundwater deposits in arid regions, a potentially valuable contribution.

The volcanology investigations focused on analysis of lava fields and geologic structure and deformation of volcanoes in southern Italy and Kilauea Volcano, Hawaii. Murino *et al* employed C- and L-band copolar (HH) and cross polar (HV) data to reveal lava fields of different ages (5000 years and 10,000 years) and to separate lava fields from undisturbed areas. In the Lattari and Picentini mountains, three sets of geologic lithologies were identified and fault lines were clearly evident on the images. The Kilauea Volcano studies

reported by Zebker *et al* and Rosen *et al* attempted to measure the deformation that occurred in the time span between the two missions, as well as short term (daily) deformation between successive passes on the same missions. A vertical deformation of up to 14 cm was observed over an area of several square kilometers around the volcano in the time between the two flights. Comparisons with GPS (global positioning system) field measurements showed that while the maximum deformation agreed to within 2 mm, estimates of the deformation did not correspond to the field measurements at any one point in the field, implying that the radar data can detect general deformation trends over large areas, but not exact geographical values. It was also found that the L-band data was superior to the C-band for vegetated areas for these analyses.

Hess *et al* employed C and L-band multi-polarization data to map areas of flooded forests in the Amazon rainforest and to discriminate between vegetation classes corresponding to water tolerance. This study was part of an ongoing investigation by Kasischke *et al* to quantify methane fluxes and production of Amazon rainforests. Vegetation classes corresponding to different rates of methane production were successfully identified.

## **F. Precipitation and Climate**

Precipitation and climate studies focused on the use of multifrequency, multipolarization radar data to estimate rainfall rates and classify precipitation types (Jameson *et al*) and to observe glacier dynamics (Rignot *et al*, Matzler *et al*, and Rott *et al*). The Shuttle missions afforded the unique opportunity to observe storm dynamics associated with Cyclone Odille (April, 1994) and Typhoon Seth (October, 1994) using a variety of radar frequency/polarization configurations. Quantification of rainfall rates was approached as an inversion problem, for instance, to estimate the radar parameters most likely to have produced the observed scattering profile. As such, the collected data provided an opportunity to develop and test inversion algorithms to be employed with the Tropical Rainfall Measuring Mission (TRMM) satellite that was launched in 1997. Rainfall profiles were obtained from the C-copolar (VV) and X copolar (VV) scatterometer data. The inversion algorithm demonstrated that rain rates could be estimated within small error bounds at higher altitudes ( $> 7$  km), but that error increased greatly at lower altitudes and was greatest at heights less than 5 km. Rainfall mechanisms could also be accurately discriminated, as convective rainfall was separated from stratiform dynamics. Another similar study approached the problem through the conventional method of development of reflectivity or rainfall rate relationships, known in the radar field as Z-R relationships. Again, good results were obtained, although the authors point out that, as in the previous case, actual field verification of the results are not possible.

The radar-based glacier studies of Rignot *et al*, Matzler *et al* and Rott *et al* are included in this section because of the relationship between glacier dynamics and long term climate change. Northern latitude glaciers in Austria were studied as well as southern glaciers in Chile. The focus of the studies was to map the extent of the glaciers, estimate ice velocities, observe glacial calving (separation), and attempt to identify areas within the glacier field of accumulation or ablation. In some cases, equivalent water content of glacial snowpack was also estimated. Glacier dynamics are studied by radar interferometry, that is, calculation of the phase difference of two images acquired at different passes at the same incidence angle. The phase differences are related to the surface displacement of the glacier. In this case, the L-band and C-band data were acquired on each pass at a spatial resolution of about thirty meters, and the interferograms were computed for each band. Image analysis can be employed to determine the direction and rate of ice flow and to identify areas where ice is accumulating or abating. Rott *et al* determined that the Moreno Glacier in the south Patagonia icefield showed a displacement of about 17 cm/d over the period of the October mission

to an accuracy of 2 cm/d, and that the glacier shows a net annual accumulation of 5540 mm of equivalent water to an accuracy of +/- 500 mm.

### **G. Surface Mapping and Topography**

The surface mapping investigations associated with the April and October 1994 Shuttle missions were focused on the development of relationships between measured backscatter from the SIR-C/X-SAR radars and surface roughness and topographic characteristics. One major research team, Weeks *et al*, focused on this effort, while others also addressed it as a secondary issue associated with hydrologic investigations (see specifically Souyris *et al* and Zribi *et al*). Zribi *et al* and Rakotoarivany *et al* sought to assess the sensitivity of radar backscatter data to soil roughness over bare soils in Orgeval, France during wet seasons. In addition, simulated backscatter data from two numerical models were compared to observed SAR data taken over surfaces with varying roughness. The authors found that differences in backscatter response were high over areas with moderate periodicity and height root mean square. It was also found that one well known backscatter model (IEM, Integral Equation Method) performed well for smooth surfaces while a different one performed better for rough surfaces.

Weeks *et al* tested the applicability of several inversion algorithms to relate SAR backscatter to surface characteristics in Death Valley, California, USA. The authors found that a foreground/background inversion scheme was able to separate surface roughness signal from background noise through filtering of the different radar frequencies. However, the signal to noise relationship was a significant function of roughness scale and frequency. Large scale features could be accurately identified as could small scale features to some degree. Intermediate scale features were more difficult to identify. The authors were able to identify four levels of surface features from the data and conclude that a stable algorithm must sacrifice roughness resolution.

### **H. Summary and Conclusions**

Due to the nature of earth science investigations, it is not to be expected that some fundamental breakthrough in understanding of the physical or biological processes under observation could be realized from one or more short term remote sensing missions. The measurements obtained during these missions represent mere snapshots of the processes under the particular set of environmental conditions that prevailed at the time of the missions. Thus, fundamental knowledge of the processes must be gained from repeated observations under the full range of conditions which can occur at the test sites, and enough sites must be tested in order to gain sufficient information to make informed inferences. This is necessarily a slow and tedious process. However, progress can be made from discrete missions such as the two SIR-C/X-SAR flights in three categories.

1. Clear demonstrations of the capability of active microwave instruments to measure some processes that have important scientific or practical value, and thus provide impetus for further mission or satellite development;
2. Development and testing of algorithms that can be employed with current satellites or other instruments to enhance their productivity or usefulness; and,
3. Advance basic algorithm development to use microwave backscatter measurements to observe and understand important physical or biological processes with scientific or practical implications.

It is clear that the SIR-C/X-SAR missions made significant contributions in all three of these areas. Clearly, the most important of these is the very significant results in the first category. In the areas of forest mapping and biomass estimation, ocean wave observations, rainfall quantification, snow cover mapping and estimation of water content, glacier observations, and crustal deformation associated with volcanoes and earthquakes the SIR-C/X-SAR results provided convincing evidence of the ability of the instruments to provide accurate measures of quantities associated with these important processes. The results of these missions contributed significantly to the utility of the Tropical Rainfall Measuring Mission (TRMM) satellite launched in 1997 to observe and quantify tropical rainfall and to the design and launch of future satellites. The operation of these satellites has the potential to make tremendous contributions to basic science and may have great practical impact on the lives of the people of the United States and elsewhere. A few of these developments are listed in Table I-10.

Attempts to develop algorithms to work with existing satellites such as ERS-1, -2 or JERS-1 generally failed to produce convincing results. The results in oceanography and forest mapping demonstrated that current satellite instruments lack either the spatial resolution or radar frequency-polarization characteristics to adequately observe the processes associated with these fields. In the cases of hydrology (vegetation correction) and wetland flooding cycles the investigators conclude that the existing ERS-1, -2 and/or Canadian Radarsat might be employed with correction algorithms to adequately observe the important processes. Of course, the anticipated launch of new satellites will complement and extend the capability of the existing satellite systems and will allow for the development of algorithms to correct the radar backscatter signal for surface roughness and vegetation effects in soil moisture estimation.

Progress was also made in the area of algorithm development. This was particularly apparent in the fields of surface roughness and topographical mapping and precipitation quantification. It appears that significant progress was made in the development and testing of inversion algorithms to determine parameters associated with the observed backscatter signal in these cases. In some cases, including surface roughness and soil moisture estimation, it was determined that significant problems occur with the use of existing algorithms. It appears that the use of active microwave instruments is still in its infancy in the field of hydrology, and considerable basic work on algorithm development needs to be done before it can become an operational reality.

**Table I-10. Earth observation impacts on science and society.**

<i>Forest mapping and biomass estimation</i>	improved ability to close the global carbon cycle should significantly enhance analyses of global warming trends and impacts. Also, improved and timely forest mapping should impact the efficiency of forest management practices and influence the market for wood products such as paper and furniture. Prices to the consumer should reflect this increased efficiency.
<i>Ocean wave observations</i>	improved ability to forecast ocean waves using an integrated numerical model updated with satellite observations will impact the lives of people living in coastal environments subject to hurricane activity. Improved storm surge estimates will guide managers in making more informed decisions with regard to construction standards and evacuation warnings and planning.
<i>Glacier observations</i>	accurate, routine and timely measurements of glacier movement, deformation, accumulation/ablation, and water content will significantly improve estimates of global warming due to the relationship between glacier dynamics and global temperatures. Melting glaciers are responsible for the majority of observed sea level rise over the past century, so again, improved estimates of these quantities will have significant impact on people living in coastal communities.
<i>Observations of crustal deformation</i>	the SIR-C/X-SAR missions showed that crustal deformations could be measured over large spatial areas to an accuracy of 2 mm. Accurate and consistent measurements of crustal deformation in the vicinity of volcanoes and fault lines will lead to better understanding of the processes of volcanic eruptions and earthquakes. This better understanding should lead to improved prediction capability for these natural disasters.
<i>Snow cover mapping and estimation of water content</i>	the success of the investigations in this area may have the most immediate benefit to the general public. Convincing evidence was provided of the ability of active microwave radars to accurately map areas of snow cover, estimate the depths of the snow layers and quantify the equivalent water content of the snow. As snow pack provides most of the water for replenishment of reservoirs in the western United States, the use of the measurements to be provided by future satellites will give water managers in this region invaluable information about future water supplies. This will make for a greatly improved efficiency of water use. This improved efficiency should be reflected in the cost of water and electricity to the consumer.
<i>Rainfall observation and quantification:</i>	the launch of the new satellites will make possible the consistent observation of precipitation processes over much of the earth. They will complement the existing TRMM mission, which was itself greatly impacted by the knowledge in radar reflectivity/rain rate relationships gained from the SIR-C/X-SAR results. Accurate radar estimates of storm dynamics and precipitation rates will greatly improve weather forecasting and flood forecasts with obvious benefits to the general public.

# SPACELAB SCIENCE RESULTS STUDY: MICROGRAVITY PHYSICAL SCIENCES

**Robert J. Naumann**

## **Introduction**

The variety of disciplines accommodated by the thirty-six Spacelab flights logically group into three distinct categories.

1. External Observations in which the Shuttle/Spacelab is used as an observing platform,
2. Microgravity Physical Sciences that make use of the microgravity environment to further the studies of Fluid Physics, Combustion Science, Materials Science, and Biotechnology, and
3. Microgravity Life Sciences that study the response and adaptability of living organisms to the microgravity environment.

Because of the bulk of the material involved and the diverse interests, the report has been divided into three sections with the previously mentioned titles. This section deals with the Microgravity Physical Sciences as defined above.

The purpose of this Spacelab Science Results Study is to document the contributions made in each of the major research areas by giving a brief synopsis and analysis of the experiments, and an extensive list of the publications produced by each investigator team. We have also endeavored to show how these results impacted the existing body of knowledge, where they have spawned new fields, and, if appropriate, where the knowledge they produced has been applied. Since a new generation of young researchers will make up the cadre of investigators that utilize the International Space Station (ISS), we feel it is important to leave a legacy of the results, some positive, some negative, of the previous experiments that have been performed. Hopefully, the new generation will build on the successes and learn from the failures of the past.

The material used in this segment of the study came from many sources including the Mission Summary Reports, Mission and/or Investigator Team websites, the International Distributed Experiments Archives (IDEA, which contains the NASA Microgravity Research Experiments (MICREX) database, the NASDA experiment archive, and the ESA Microgravity Database), the Compendex\*Web, the NASA Life Sciences Data Archive, the Science Citation Index, the NASA Office of Biological and Physical Research Task Books, various survey papers, conference proceedings, and the open literature publications of the investigators.

The bibliography is rather extensive and includes papers generated by the various investigators during the course of the development of their experiments as well as the results and the applications of their results. There is, perhaps, a lack of uniformity in the number of documents listed since some investigators left a much more extensive document trail than others. Also, several of the investigators had spent a good fraction of their careers in the development of their experiments. Even though this study was restricted to the experiments actually performed on Spacelab missions, in several cases experiments performed on suborbital rockets or on non-Spacelab Shuttle flights went in to the development of the Spacelab experiment. Therefore, the results from these flights were also included.

The number of publications generated by this aspect of the Spacelab program is quite impressive, as summarized in Table II-1.

**Table II-1. Microgravity science publications generated by Spacelab experiments.**

	<u>Total Publications</u>	<u>Journal Articles</u>
Fluids and Combustion	681	378
Materials Science	999	461
<u>Biotechnology</u>	<u>598</u>	<u>360</u>
Total	2278	1199

We regret that time and resources did not permit iteration with the investigators, as we would have liked. If a result is misinterpreted or if references were missed, we apologize. We tried to include every relevant experiment that was flown on a Spacelab mission, but invariably when dealing with this many experiments in a limited time, an important experiment or result is bound to be missed. It is our hope that with the bibliography and other reference material included, interested parties can locate any information we were unable to provide.

## **I. FLUIDS AND COMBUSTION IN MICROGRAVITY**

The study of the behavior of fluids in microgravity is fundamental to the understanding of virtually all other microgravity science since the suppression of fluid flows resulting from buoyancy effects is the primary reason for most microgravity experiments. (The exceptions being cases in materials science where the hydrostatic head may cause deformations in extremely weak solids or in the life sciences where there is evidence that the unloading of the cytoskeleton may be responsible for altered cellular behavior.) As a result, many of the fluids experiments were aimed at providing information to support the materials science experiments. One of the striking features in much of the research on the behavior of liquids in space is the importance of capillary or interfacial phenomena after buoyancy effects are essentially removed. Clearly these phenomena are present in normal gravity, but are often neglected because their effects are often masked by buoyancy-driven flows. The ability to uncouple gravity effects from non-gravitational effects, so that the latter can be studied in more detail, has been one of the primary justifications for the study of fluid phenomena in microgravity.

Gravity has a profound effect on the behavior of fluid systems undergoing second-order phase transformations as the compressibility vanishes. Consequently, the microgravity environment has been used to advantage to perform critical tests of fundamental theories dealing with the universality of material behavior near a critical phase transition.

Combustion experiments in microgravity are a special case of fluid experiments in which chemical reaction must be included. However, the motivation for performing this class of experiments in space is basically the same: the need to separate gravity-related from non-gravity related effects and to use the simplifications obtained by effectively eliminating convective transport in order to gain a better understanding of the basic principles involved. It is also important to understand combustion in the virtual absence of gravity to develop design criteria and emergency procedures for dealing with fire safety in the operation of manned laboratories in space.

### **A. Capillarity Effects on Liquid Configurations**

In dealing with partially filled containers in low gravity, it is important to be able to predict where the liquid will be. Generally this will be determined by the geometry of the container and the contact angle between the liquid and the container wall. The Young-Laplace-Gauss equation can then, in principle, be solved to give the minimum surface. One of the difficulties with the theory is that a friction is involved in moving the contact line. As a result, the contact angle depends on whether the contact line is advancing or receding, giving rise to a phenomena known as contact angle hysteresis. Several experiments were carried out to see how well such systems could be modeled.

For example, on Spacelab-1 (SL-1), Haynes recorded the spreading of a tethered drop of silicone oil when it touched another clean aluminum plate. Here, the aim was to understand the dynamics of an advancing contact line.

In another experiment on SL-1, Padday established silicone oil floating zones between two axisymmetric plates of unequal sizes. Using the Young-Laplace-Gauss equation to calculate the pressure from the

configuration of the zone, he was able to measure the disjoining pressure (the pressure that must be applied to remove the film) in the film that spread over the larger plate. Padday likened his directing the Payload Specialist to do his experiment and having to rely on his surrogate to describe what was happening to the way the pioneering Belgian physicist, Plateau, had to operate more than a hundred years ago when he did similar experiments using neutrally buoyant immiscible fluids. Plateau was blind.

Padday repeated the experiment on Spacelab D-1 to study the effects of rotation and vibration on the zone shape. Both monorotation (rotation of the cone plate only) and isorotation (rotation of both end plates) did not visibly change the zone shape contrary to theoretical calculations based on the Laplace equation. Induced axial vibration did not induce harmonic wave movement and apparently increased the stability of the zone. The rupture of the liquid zones was also analyzed during these experiments. The rupture occurred rapidly at two places in the thin column. The column became a satellite drop and the liquid at end plates relaxed to a spherical drop shape. The satellite drop rebounded between the liquid/air surfaces, but did not penetrate these surfaces.

Vreeburg investigated the behavior of silicone oil in a partially filled plastic cylinder as it was spun up and spun down on Spacelab-1. The objective was to test the ability to model the behavior of propellants in partially filled tanks in low gravity. He conducted a similar experiment on the D-1 flight using doubly distilled water in a plastic cylinder to investigate the effects of vibration and the movement of the contact line. He was able to predict the resonant frequencies with reasonable accuracy, but the behavior of the contact line presented some difficulty. At first glance, it appeared that the contact line had stuck. However, closer analysis revealed that the contact line did move a small amount and that the oscillating contact angle exhibited some hysteresis.

A tribology experiment was carried out on Spacelab-1 by Pan with Gause and Whitaker. Drops of oil were deposited on stainless steel surfaces with various surface treatments and finishes and the rate of spreading was recorded. In a second part of the experiment, the configuration of the oil film in a journal bearing was investigated. In the normal function of a journal bearing, the clearance space is only partly filled with lubricant and gravity drainage positions the lubricating film so that shear forces can move the lubricant to the region where it is needed. The investigators wanted to know if such a bearing would operate in the absence of gravity drainage with and without a load.

Concus, Finn and Weislogel came up with a design of a container that admitted a continuum of possible rotationally symmetric configurations for a given fill fraction and contact angle, but none of the configurations were stable. They presented an interesting question: how would nature select an equilibrium configuration? They found the answer using the glove box on USML-1 (United States Microgravity Laboratory-1). No one told Mother Nature that the configuration had to be rotationally symmetric, so she simply selected a nonsymmetric configuration. Again, the effect of contact line sticking and contact angle hysteresis was noted when the Payload Specialist was trying to coax the fluid into its equilibrium shape. The small residual gravity may also have played a role in determining the shape of the liquid.

It can be shown theoretically that a liquid will penetrate into a wedge if the contact angle  $\gamma < \gamma_0 = \pi/2 - \alpha$ , where  $\alpha$  is the half-angle of the wedge. Langbein fabricated test cells from quartz plates with rhombic cross sections at different half-angles. These were partially filled with an index matching fluid after the walls were coated with FC-724 to provide the desired range of contact angles. The contact angle was

changed by heating the test cells in the Bubble, Drop, and Particle Unit (BDPU) on the second International Microgravity Laboratory (IML-2). Langbein expected to see the liquid rise in the wedge-shaped corners of the test cells when the contact angle became less than the critical value  $\gamma_c$ . However, the resulting surfaces did not match the computed surfaces, and even though the contact angle became less than the critical value, wetting was not observed. He attributed this behavior to contact line friction that caused the volume change during heating and cooling to be accommodated by varying the contact angle rather than by moving the contact line.

Concus and his team carried out a variation of Langbein's experiments on USML-2. They machined a shape they called a "canonical proboscis" along diametrical opposite sides of an acrylic cylinder. The special shape has the property such that, for a given radius of curvature, the contact angle remains constant as the liquid penetrates into the cavity. The right and left shapes were chosen to accommodate different contact angles. Three such vessels were constructed: one in which the right and left contact angles were subcritical, one in which the right and left contact angles included the critical angle, and one in which both contact angles were supercritical. It was anticipated that the liquid would rise slightly higher in the side closer to the critical contact angle for the subcritical cell, that the liquid would rise in the supercritical side at the expense of the subcritical side in the intermediate cell, and the liquid would rise in both sides of the supercritical cell. This is essentially what was observed, except that the liquid did not rise spontaneously in any of the cases because of contact line friction. Only after considerable mechanical tapping and coaxing by the Payload Specialist were these results achieved. Observation of the supercritical cell after seven days indicated that the liquid had continued to creep along the walls, but at a very slow rate. A wedge-shaped container with a variable wedge angle was also used in this series of experiments. Here the liquid in the wedge rose rapidly as the wedge angle reached the critical value.

## **B. Zone shape and stability**

Microgravity offers the possibility to conduct experiments with free liquid surfaces on a scale not possible on Earth. One process of interest to materials scientists is the use of a floating zone for crystal growth. A molten zone is created in a rod of feed material and is traversed along the rod. New feed material enters the advancing zone and a single crystal can be grown at the receding interface. Of primary interest is the stability of such zones. Lord Rayleigh (see Proceedings of the Royal Society (Proc. Royal Soc.), 29 (1879) 71) showed that a cylindrical liquid column would become unstable and break if the length exceeded the circumference. But what happens if the zone is not cylindrical? Or if it is rotated, which is sometimes done to even out asymmetries in heating? Or vibrated by mechanical disturbances in the spacecraft? Many of these questions had been approached theoretically and experimentally using a Plateau tank. But they had never actually tested in an actual microgravity situation. As was discovered when an unexpected "jump rope" or C-mode instability showed up in a simple rotating liquid zone experiment on Skylab, the presence of a neutral buoyant solution in a Plateau tank is a different boundary condition, which can often change the result of an experiment.

Martinez and Meseguer compared computational predictions of the stability of extended liquid columns of silicone oil under various mechanical manipulations with observations during the SL-1, D-1, and D-2 flights. The liquid columns were suspended between two metal discs with a radius of 1.75 centimeter (cm) and a 30-degree receding sharp edge to prevent liquid spreading. Cylindrical columns with length/diameter ratios of 2.86 were established several times. This maximum length is short of the Rayleigh limit of 3.14,

but appeared to be bounded by the ambient noise (g-jitter) during the mission. A long cylindrical column was subjected to vibrational frequencies of 0.1, 0.3, 0.7, 1.1, and 1.6 Hertz (Hz). No movement of the liquid was observed for the 0.1 Hz vibration. However, standing waves with two, three, four, and five inner nodes were found for the remaining frequencies, respectively. The number of nodes for the respective frequency was successfully predicted by theory. Destabilization of the columns, caused by rotation at increasing rates, occurred near the theoretical limit. When liquid bridges were subjected to perturbations beyond the stability limits, they broke into two separate drops. The relative volumes of these drops were predicted by theory. During one of the runs, when subjected to 10 rpm of isorotation, the column broke in an amphora-shape mode, as predicted.

Langbein also investigated the resonances of vibrating liquid columns using pressure sensors mounted on the endplates. This proved to be an effective method for observing when resonance occurs. His results compared favorably with ground tests in a Plateau tank and with theory he developed. An accidental misalignment of one of the discs on one experiment caused the zone to spill, illustrating the sensitivity of the zone stability to non-axisymmetric configurations.

Microgravity offers a unique opportunity for purifying glass by zone refining and then making cylindrical preforms by a quasi-containerless process. A long zone (near the Rayleigh limit) could be formed and allowed to cool below the working temperature in the middle. This portion could then be clamped and the two molten zones extended to the length of the sample. The critical issue becomes the stability limits of a solid suspended on each end by a liquid zone while it is cooling. Using small lexan rods, Naumann and Langbein investigated the stability of this double floating zone configuration. If the two zones have equal volume and are bulging, the float will remain centered. However, if the zones are extended, the float switches to an asymmetric mode with a long, slim zone on one side and a short fat zone on the other. Theory indicates that the presence of the solid between the two liquid zones actually tends to stabilize the system and, for cylindrical zones of equal volume, it will remain stable up to and slightly beyond the limit in which the total zone length equals the circumference.

Using the glove box on USML-1, Naumann also investigated the feasibility of pulling optical fibers in low gravity using silicone oil with different viscosities and honey as model materials. It turns out that it is much easier to pull long strand of viscous liquids on Earth because gravity drainage stabilizes the strand against the Rayleigh instability. Such strands broke almost immediately in microgravity, as predicted by Rayleigh's theory. (Rayleigh had attempted to test his calculations, without much success, by observing the breakup of strands of treacle laid on waxed paper.)

The Rayleigh limit ( $\text{Length/Diameter} = \pi$ ) for a cylindrical bridge is a consequence of surface tension forces that tend to restore the bridge below the Rayleigh limit and tend to pinch-off the bridge above the Rayleigh limit. However, these forces can be modified by the presence of an electric field. Charging a liquid bridge produces a radial electric field, which makes the bridge less stable. Conversely, an axial field should stabilize the bridge. The only present electrohydrodynamic theory governing such effects is the "leaky dielectric" theory developed by G. I. Taylor (see Proc. Royal Soc. A291 (1966) 27-64) which has remained largely untested.

Burcham, Sankaran, and Saville decided to test Taylor's "leaky dielectric" theory by applying strong axial electric fields to liquid bridges, extending them beyond the Rayleigh limit, and then slowly relaxing the

field to find the point where the cylindrical shape transitioned to the amphora (vase-like) mode occurred and the point where the bridge would eventually break. Their interest lay in obtaining a reliable, well-tested theory to guide in the development of miniature fluidics systems that utilize electrodynamic forces for pumping and manipulating fluids to carry out chemical reactions on a microchip.

Two dimensionless parameters control the stability of the electrodynamic stabilized liquid bridge, the  $L/D$  ratio, and a  $\Delta$  parameter that measures the electrodynamic stabilizing force to the surface tension destabilizing force. Runs were made with a neutrally buoyant 2-phase system (castor oil in 12,500 St. silicone oil) for comparison with laboratory experiments in a Plateau tank. A single phase bridge (castor oil doped to 10 times the conductivity of neat oil) was extended to  $L/D = 4.32$  and became cylindrical with a  $\Delta = 0.95$ . An unexpected result was the transition from the cylindrical to the amphora shape occurring at different values of  $\Delta$ , depending on whether the field was increasing or decreasing. Also, according to theory, it shouldn't matter if the applied field is alternating current (AC) or direct current (DC), as long as the frequency is above the free charge relaxation time. They were not able to stabilize the bridge with an AC field. As is often the case, a good experiment asks more questions than it answers, and this experiment seems to be no exception. The investigators are now sorting out which aspects of Taylor's theory are correct and what parts need improvement.

### **C. Marangoni Convection**

The atoms or molecule at the surface of any solid or liquid cannot form as many bonds as those in the interior simply because they have fewer nearest neighbors. This gives rise to an excess surface energy (that is, the atoms or molecules on the surface have less negative energy than the more tightly bound atoms or molecules in the interior). If the surface is deformable, as in the case of a liquid, it will take a shape that minimizes the surface area in order to lower its energy. Furthermore, work is required to create new surface. This work is the product of the force that must be applied and the distance it must act, so the surface energy per area is equivalent to the force per distance or surface tension.

The surface tension is a function of temperature as well as composition. Therefore, if there is a variation of either temperature or composition along a free surface of a liquid, there will be an unbalanced force that can drive flows along the surface. These flows are usually called Marangoni flows after the Italian who studied these phenomena. (The "no-slip" boundary conditions at a solid-liquid interface suppress the surface flows. Therefore it is generally accepted that Marangoni convection only occurs in the presence of free surfaces.) Microgravity dramatically reduces buoyancy-driven convection, but microgravity experimenters must still contend with Marangoni convection. On Earth, buoyancy-driven flows compete with or add to Marangoni flows, so space provides an excellent place to study Marangoni flows without this interference.

Microgravity offers the possibility to conduct experiments with free liquid surfaces on a scale not possible on Earth. For example, floating zone crystal growth is possible in space for systems whose surface tension is not able to support the zone in a gravity field. Also the zone can be extended in space, which allows better control of the thermal gradient and the interface shape. However, temperature gradients along a molten zone can cause convective flows in the melt. This prompted a number of fluid experiments to quantify the effect of these convective flows.

From a fluids point of view, it is more convenient to study the flows in the floating zone process in a half-zone. The process is simulated by deploying the liquid column between two metal discs that are maintained at different temperatures. On SL-1, Napolitano, Monti, and Russo applied temperature differences between columns of silicone oil and measured the flows and heat transport induced by Marangoni convection for comparison against numerical computations. A second experiment on D-1 used a concave cold disc and a radial temperature distribution on the hot disc to simulate the interface shape in a floating zone crystal growth experiment. The results were similar to those obtained on SL-1. Experiments were also carried out with a two liquid zone by adding dioctyl-phthalate to the silicone oil. Upon heating, one of the liquids went into the center of the zone, forming a drop.

When growing crystals by the floating zone process, it is often desirable to have the melt in the zone well mixed. Therefore, some convection can be helpful. What needs to be avoided is unsteady or time-dependent convection that can result as the Marangoni flows get stronger. When this occurs, thermal and compositional fluctuations at the growth interface produce unwanted growth defects called striations in the growing crystal.

Chun and Siekmann investigated the transition from steady to unsteady flows in the half-zone configuration on the D-2 mission. They found a critical Marangoni number (ratio of driving force to viscous drag ( $Ma$ )) that produced the lowest oscillating mode; one in which the flow pattern becomes non-axisymmetric and rotates around the axis of the zone. At a higher Marangoni numbers, the flow becomes turbulent or chaotic with no defined structure.

On D-2 Monti with Carotenuto, Albanese, Castagnolo, and Ceglia noted that small scale half-zone experiments conducted in the laboratory went into the unsteady oscillatory mode at lower Marangoni numbers than some of the earlier flight experiments. They investigated the onset of unsteady flow as a function of aspect ratio and diameter of the zone. They concluded that for a given diameter, the critical Marangoni number increased with aspect ratio (length/diameter), and for a given aspect ratio, it also increases with diameter.

One method that has been considered for controlling Marangoni convection in floating zone crystal growth would coat the molten zone with a viscous immiscible liquid-phase encapsulant such as  $B_2O_3$  (boron III oxide). Some flow would still result but since the surface of the low viscosity melt would have to drag the viscous encapsulant with it, the flow would be damped to the point that unsteady convection would not result. Several attempts have been made to model such a multi-layer configuration and Legros and Georis developed a 2-dimensional experiment that was flown on IML-2 and on the Life and Microgravity Science (LMS) mission to test such models. They deployed a three layer fluid system that consisted of a layer of 10 cSt silicone oil sandwiched between two layers of higher viscosity Fluorinert FC-70 oil which was contained on the top and bottom by sapphire windows. A lateral thermal gradient was established and the flow was visualized using marker particles and a laser light cut. The observed flows were qualitatively similar to the expected behavior; the interfaces moved from hot to cold with the return flow through the middle of each layer. However, the measured flows turned out to be considerably larger than the computed flows. The reason for the discrepancy is still being investigated. One possible reason is that the computations assumed constant material properties, whereas the viscosities of the flows do change considerably with temperature.

There is also considerable interest in Marangoni convection along horizontal surfaces. Such flows are prevalent in combustion processes such as pool burning and may be seen around the wick of a burning candle. Strong surface tension gradients occur in the growth of silicon and other crystals by the Czochralski process in which the crystal is pulled from a large heated pot of molten silicon. Such flows are usually unsteady and may be turbulent. The resulting thermal fluctuations are the primary cause of the striations seen in Czochralski-grown silicon.

During the D-1 mission, Schwabe, Lamprecht, and Scharmann investigated Marangoni convection in a 20 x 20 x 20 millimeter (mm) cell with an open surface sandwiched between two heating blocks. To avoid the problem of having to fill the cell in space, they melted a block of tetracosane (paraffin) that served as their working fluid. With one heater set at 60°C, they raised the temperature of the other block. To their surprise, no flow was observed even after a  $\Delta T$  of 55°C was established. Finally, at a  $\Delta T$  of 60°C, a strong flow developed. They concluded that the surface of the tetracosane must have been contaminated with a substance that either lowered the surface tension or resisted the surface stress until it finally broke through at a  $\Delta T$  of 60°C.

The experiment was repeated using silicone oil on D-2 by Cramer, Metzger, Schwabe, and Scharmann. Care was taken to maintain a flat upper free fluid interface at the beginning of the experiment. Flow was measured by observing tracer particles illuminated by a vertical light cut. The temperature field was measured using holography interferometry. A lower than expected temperature in the cooling loop caused unexpected cooling at the top surface, which resulted in a more complicated three-dimensional flow pattern. The formation of “tracer rings” was observed in which the tracer particles tended to accumulate along streamlines that passed close to a free surface.

Enya was interested in Marangoni convection in Bridgman crystal growth that might occur if the melt is not in contact with the ampoule walls. He also chose paraffin as a model and saw no evidence of Marangoni flows.

The surface tension of most fluids decreases with increasing temperature, but Limbourg-Fontaine, and Petre determined that an aqueous solution of n-heptanol had a surface temperature minimum at 40°C. During the D-1 mission, they differentially heated this fluid in a 1 x 1 x 3 cm test cell so that surface tension increased more-or-less symmetrically on either side of the center of the cell. A small convective roll first developed near the hot wall, flowing from cool to hot, or from lower to higher surface tension, as would be expected. However, instead of seeing a counter-rotating flow on the cold side, the flow near the hot end expanded to fill the test cell and eventually formed a second co-rotating cell near the cold end. The reason for this unexpected behavior is still being investigated.

Ostrach, Kamotani, and Pline carried out an elaborate set of experiments on USML-1 and USML-2 aimed at determining the factors involved in the transition from steady to unsteady surface tension-driven flows. Of particular interest was the role of surface deformation in this transition. If surface deformation is unimportant, as some theories suggest, then it should be possible to predict the onset of unsteady flows with a single parameter, the critical Marangoni number. On the other hand if surface deformation does play a key role in the transition, a surface deformation parameter will be required to completely specify the conditions for the onset of unsteady flows. Thus it became necessary to explore a wide range of parameters in order to establish the transition conditions.

Silicone oil was contained in a cylindrical test cell. A sharp pinning edge confined the height of the oil in the test cylinders so that different surface shapes could be obtained by adjusting the filling. The oil could be spot heated at the center with a carbon dioxide laser, or heated by an immersed heater. This feature allowed experiments to be conducted in the constant temperature or the constant flux mode. Surface temperature was measured with an imaging infrared radiometer. Marker particles assisted flow visualization.

The test cell on USML-1 was 10 cm in diameter and 5 cm deep. The fluid was 10 cSt silicon oil. Very nice surface tension driven flows were observed, but no transition to oscillating flows was observed within the operating range of the instrument. A series of test cells with diameters 1.2, 2, and 3 cm were used for USML-2. The 10 cSt oil was replaced with 2 cSt oil and a Ronchi interferometer was added for the USML-2 experiment to measure surface deformations.

A total of fifty-five tests were made with the six different size and heating configurations. Flows in the smallest cells with the cartridge heater began oscillation at the same temperature difference as their 1-gravity (1-g) counterparts, indicating that buoyancy drive flows are not the dominating factor for this size and smaller. The time-dependent flow exhibited a small azimuthal oscillation superimposed on a slowly rotating flow about the thermal axis. The thermal image indicated first a pulsating or rotating 2-lobe or 3-lobe pattern, depending on the temperature difference and cell geometry. It was found that the Marangoni number alone is not sufficient to characterize the onset of oscillatory flows, but a critical value of a surface deformation parameter, which they defined, describes the onset of oscillation in microgravity.

The previously described Marangoni convection experiments had variations in surface tension along the fluid surface. In such experiments, convection should begin as soon as there is an unbalanced force. In other words, there should be no threshold thermal gradient required to start the flow, just as in the case of buoyancy-driven free convection when the thermal gradient has a component perpendicular to the gravity vector. However, in the famous Rayleigh-Benard problem, the gravity vector is aligned with the thermal gradient (cold over hot). Even though this is an unstable configuration, flows will not develop until a critical value of the Rayleigh number is reached. The Rayleigh number is a measure of the rate heat is being convected to the rate it is being conducted. If the Rayleigh number is small, a displaced parcel of fluid can accommodate thermally before it can rise very far, hence will settle back into place. If the Rayleigh number is large, the fluid cannot be accommodated thermally and it will continue to rise, forming circulating Benard cells. Rayleigh was able to predict the critical value of the Rayleigh number corresponding to the onset of convective flows for different boundary conditions at the top and bottom of the cell.

If the top surface is a free liquid boundary, the system is also subject to unstable Marangoni convection (actually this problem was first studied by Pearson (see J. R. A. Pearson, *Journal of Fluid Mechanics* (J. Fluid Mech.) 4 (1958) 489-500). The system can lower its energy by replacing the cooler fluid with higher interfacial energy at the top surface with warmer fluid from the interior that has lower interfacial energy. However, for this to happen the Marangoni number must exceed a critical value.

One can see immediately that the two types of convection will be in competition in a gravity field. Therefore, it is necessary to eliminate gravity if one is to get an accurate test of the surface tension effect. This experiment was first performed on Apollo missions 14 and 17 during the return from the moon (see P. G. Grodzka and T. C. Bannister, *Science* 176 (1972) 506-508, also *Science*, 187 (1975) 165-167) when a somewhat higher value than the theoretical Marangoni number was measured for the onset of convection.

It should be appreciated that this is not a trivial experiment to perform accurately. The theory requires a flat interface and that the temperature gradient in the sample be uniform. This latter condition requires a very carefully controlled heating program.

Legros, Dupont, Queeckers, Petre and Schwabe essentially duplicated the Grodzka-Bannister experiment on D-2 with better controls than were available on the Apollo spacecraft. They modified the theory to account for non-equilibrium heating and varied the heating rate to investigate the effect of non-equilibrium temperature profiles on the critical Marangoni number. For a fast heat-up (fourteen times the heating rate to approach equilibrium heating), they measured a critical Marangoni number of ninety-five against their calculated value of 101. For a slower heat up (seven times the equilibrium heating rate) they measured a critical value of seventy-seven compared with their theoretical value of 82.4. Unfortunately, due to a technical problem with the heater, they were unable to obtain an experimental value for the equilibrium case.

Lichtenbelt, Drinkenburg, and Dijkstra investigated solutally-driven unstable Marangoni convection in a mixture of acetone and water with a free surface on the D-1 mission. As the acetone evaporated from the surface, the surface tension increased. Since the system can lower its energy by replacing its higher interfacial energy surface layer with fluid richer in acetone from the interior, the system is subject to a convective instability. At a critical Marangoni number, an overturning flow will develop. This is a common situation in many industrial applications such as distillation, adsorption, and desorption and is also an important factor in the drying of paint, especially lacquers with a volatile solvent. A similar process is responsible for “wine tears”, the tendency for drops to form above the surface of a fortified wine or brandy. Lichtenbelt and the others wanted to investigate the effects of the surface tension without gravitational interference. Quite unexpectedly, no convection was seen in space as long as the fluid interface was kept flat (this was done by filling the cuvette to the anti-spread barrier). Convective rolls did appear as some fluid was drained out and the interface became more curved. It was speculated that either the surface became contaminated or that the critical Marangoni number had not been attained. A compositional gradient may have been established when the surface became curved which drove a thresholdless flow.

When a liquid contacts a solid, fluid dynamists usually assume a “no-slip” boundary condition. It is commonly believed that contact of the fluid with the wall resists any imbalance of interfacial forces, so that Marangoni convection need be considered only in experiments that have free surfaces. Consequently, experimenters using closed fluid systems, such as the Bridgman configuration, for directional solidification generally ignore the possibility of unwanted flows from Marangoni convection. There has been some speculation about a second order Marangoni effect in which these unbalanced forces can still drive very small flow in spite of the “no-slip” condition, but there has been no direct experimental confirmation of such flows. However, it is well known that Marangoni flows around bubbles in a liquid will drive bubbles toward decreasing interfacial energy (usually toward the hotter regions of the liquid). What is not generally appreciated is that these flows also stir the melt.

Using the glove box on USML-1, Naumann differentially heated a cylindrical cell containing Krytox 143AZ, a low viscosity fluoro carbon fluid. A 1 cm<sup>3</sup> void had been intentionally left when filling the chamber to simulate the head space needed for thermal expansion. Since the fluid wet the container, the void became a bubble, which migrated to the heated end of the test cell. There it lodged between the plug heater and one wall. Marker particles in the fluid revealed a strong flow around the bubble that penetrated the entire test cell. The resulting flows near the cold end, which would represent the forming solid in a directional

solidification experiment, were several orders of magnitude higher than the flows expected from spacecraft residual accelerations. Flows such as this may explain some of the unexpected mixing that was observed in the early Skylab and Apollo-Soyuz Test Program (ASTP) experiments.

A similar observation was made by Azuma on SL-J. In this case, secondary flows associated with a large bubble that had become attached to the hot wall caused smaller bubbles to be brought into its vicinity and formed a line along the thermal gradient.

#### **D. Drop and Bubble Migration**

Young, Goldstein, and Bloch (YGB) solved the Navies-Stokes equations for a spherical drop or bubble in an infinite liquid with an imposed temperature gradient. Taking into account the flows from the unbalanced interfacial forces, they showed that the droplet would be propelled in the direction of decreasing interfacial tension (see J. Fluid Mech. 6 (1959) 350). Since they did not have access to a microgravity environment, they tested their theory by balancing the surface tension forces against buoyancy forces.

Naehle, Neuhaus, Siekmann, Wozniak and Srulijes tested the YGB model in the absence of buoyancy forces on the D-1 mission by injecting bubbles of air and drops of water into Wacker AK100 silicon oil. They confirmed the fact that the bubbles remained spherical, which eliminated some speculation that the YGB model may be in error because it didn't account for possible distortion of the bubble under the combined influence of surface tension stresses and Stokes drag. They found qualitative agreement with the velocities predicted by the YGB theory for small Marangoni numbers, but the observed velocities became progressively lower than predicted for  $Ma > 1$ . The YGB model predicts that the velocity should be directly proportional to the Marangoni number, but does not take into account convective thermal transport. Therefore, it is only valid in the limit of vanishing Marangoni number and corrections are required to the model for this effect. The droplets of water did not move at all. (It is a well-known experimental fact that the Marangoni effect is virtually impossible to observe in water because of trace quantities of surface active contaminants that tend to nullify the driving force.)

Neuhaus and Feuerbacher also tested the YGB model on the D-1 mission. Bubbles were deployed in three different silicone oils (Wacker AK100, AS100, and AP100) all of which had the same viscosities and thermal properties, but differed in the number of phenol groups. A temperature gradient was established and the bubbles were monitored holographically. The velocity of the bubbles in the AK100 oil with only 6% phenol groups agreed reasonably with the YGB predictions. Bubbles in the AP100 oil with 28% phenol groups did not move at all. Bubbles in the AS100 oil with an intermediate number of phenol groups moved at 40% of the velocity predicted by the YGB theory. The investigators suggested the additional of a "surface dilatational viscosity" term to the YGB formulation to account for the resistance of the surface to deform.

Subramanian and his team at Clarkson University used the Bubble, Drop, and Particle Unit (BDPU) on IML-2 to measure the velocity of air bubbles and Fluorinert FC-75 drops in 50 centi-Stoke (cSt) silicone oil under a thermal gradient. They also found that the scaled velocity decreased with Marangoni number, as would be expected. Since the velocity of a drop or bubble depends directly on the radius, larger drops would be expected to overtake and engulf smaller drops. This effect is believed to be one of the mechanisms in the agglomeration of minority phase droplets during the solidification of monotectic alloys. However,

Subramanian's group observed an interesting effect in that a small drop leading a large drop can slow the motion of the large drop. (Naehle and his team observed that when a large drop leads a small drop, it still moves faster than the smaller drop, but the velocities of both drops are lower than they would be as individual drops.) Subramanian and his team speculated that a thermal wake behind the first drop reduces the driving force on the second drop and designed an experiment on LMS to study this effect further. Here they found that when two or three drops were injected into the chamber, the second and third drops did not always follow a straight path across the chamber, as single drops did. Instead, they followed a sinuous, helical path around their expected trajectory. Sometimes a larger trailing drop would actually move around and pass the leading drop.

Viviani investigated the motion of bubbles in n-heptanol that has a surface tension minimum at 40°C. Instead of stopping at the 40°C isotherm, as was expected, the bubbles continued toward the cold wall, but did appear to slow down as they approached the 10°C cold wall. On his LMS experiment, Viviani set the cold wall temperature to 5°C, and the bubbles came to rest in the vicinity of the 8-10°C isotherm. Why the statically measured surface tension is a minimum at 40°C, and the apparent dynamic surface tension is a minimum at a lower temperature is still not understood. (Recall that a similar anomaly was observed in Legros' Marangoni convection experiment with n-heptanol on D-1.)

Monti attempted to investigate the interaction of water droplets and air bubbles in tetracosane (paraffin) with an advancing solidification front on IML-2, but encountered technical difficulties. The experiment was completed successfully on the LMS mission. One 0.9 mm bubble was pushed by the front that was advancing at the rate of 1 micron/second. Larger bubbles and water drops were engulfed. No motion of drops or bubbles in the molten tetracosane from Marangoni effect was observed. (Recall that Schwabe's team observed no Marangoni flow in molten cosane in their Spacelab-1 experiment.)

Bewersdorff attempted to observe bubble transport by chemical waves using the HOLOP (Holographical Optical Laboratory) facility on D-1. As the chemical reaction spreads, the thermal gradients generated by the heat of reaction can transport gaseous or liquid inclusions by the Marangoni effect. The reaction of Zhabotinski was selected for wave generation and the gas inclusions were to be generated from Zn particles. Unfortunately, problems with the HOLOP prevented the detailed recordings from which the migration of the bubbles was to have been recorded.

Straub used the BDPU facility on IML-2 to study evaporation and condensation kinetics by measuring bubble growth (evaporation) and collapse (condensation) respectively in a supersaturated and supercooled liquid (Freon R11) under isothermal conditions. Varying degrees of supersaturation were obtained by varying the pressure in the container. The microgravity conditions permitted the study of the process in a stationary bubble without the buoyancy disturbing the temperature field in the vicinity of the bubble as the latent heat is absorbed or released. This allowed the kinetics of the process to be worked out and the accommodation coefficients to be determined. The results of this experiment were used to design the pool boiling experiment that was developed for the LMS flight.

### **E. Heat Transfer in Microgravity**

It is generally assumed that heat transport in boiling is largely the result of buoyancy-driven convective flows. The bubbles that nucleate on the hot surface rise, carrying their latent heat with them. Similarly,

the hot liquid near the surface, being less dense, will rise, causing overturning flows that carry heat away. The practice of cooling small electronic devices by immersing them in a pool of dielectric liquid with appropriate vapor pressure, such as Freon, was considered by many not to be feasible in space because it was assumed that vapor would form around the device resulting in inefficient heat transfer. However, Straub and co-workers proved otherwise on the LMS flight.

They immersed small heaters in the form of copper discs one to three mm in diameter in Freon 123 and measured the temperature and power in order to get the heat transfer coefficients over a range of temperatures or heat fluxes. Surprisingly, they found that heat transfer in microgravity was only slightly less efficient than it is in unit gravity. Thermocapillary jets were observed, and appear to be an effective mode of heat transfer. These results may cause the theories of boiling in normal gravity to be revisited and it may be possible to design systems that take advantage of capillarity along with buoyancy to improve the efficiency of boilers on Earth.

The Capillary Pumped Loop (CPL) was developed in the 1960's at the NASA Lewis Research Center (now the NASA Glenn Research Center) as a heat transfer device, similar to a heat pipe. The technique works quite well in normal gravity, but its operation in microgravity has been erratic. A transparent model of the device was fabricated and flown on MSL-1R (Microgravity Science Laboratory Reflight) by Halliman and Allen to gain insight into its operation without gravity with the hope of correcting the problem. It was found that in the absence of gravity drainage, liquid films form and accumulate in the vapor return lines. Eventually, Rayleigh instabilities set in and liquid bridges form which obstruct the lines. In particular, these liquid slugs tend to form in bends in the line. The result is diminished ability to transport heat.

## **F. Critical Point Phenomena**

A number of peculiar things happen in the vicinity of a second order or critical phase transition, such as takes place at the terminal point of the coexistence region between a liquid and its vapor. As the critical point is approached, the densities of the liquid and vapor become the same and the system fluctuates between the two states as though it can't make up its mind as to whether it wants to be a liquid or a vapor. These fluctuations produce a kind of opalescence when the test cell is viewed. At the critical point, the compressibility becomes infinite so that even the smallest temperature difference can cause very strong convection. Many of the other thermodynamic properties change dramatically near the critical point where, for example, the velocity of sound as well as the thermal diffusivity goes to zero, while the heat capacity becomes infinite.

Other systems, such as a magnetic system near the Curie point (the temperature at which thermal motion becomes sufficient to destroy the magnetization) or the demixing of a homogeneous liquid into two immiscible liquids at the critical consolute temperature, exhibit similar behavior. The divergence of certain parameters near the critical point in each of these systems show the same exponential behavior, thus leading to the theory of universal behavior near a critical phase transition, regardless of the system. Ken Wilson was awarded the Nobel Prize in 1982 for applying group renormalization theory to determine the exponential behavior of these diverse systems near a critical point (see K.G. Wilson, *Physical Review B* (Phys Rev B) 4 (1971) 3174).

On USMP-2 and -3 Gammon and his group at the University of Maryland used photon-correlation light-scattering spectroscopy to measure the density fluctuations as the critical point of xenon. They were able to record a number of photon correlation functions processed in real time, from which they could measure the decay rate of the fluctuations. The forward scatter intensity from the flight data showed a much sharper peak as the critical temperature was crossed than the ground control. They were able to locate the phase boundary to within  $\pm 20$  milliKelvin (mK). The limiting factor in the experiment turned out to be unexpected window heating from the seventeen microwatt laser which prevented the experimenters from obtaining correlograms closer than 2 mK from the critical point.

On IML-1, Beysens was able to show that the phase separation that occurs when a near-critical single component vapor ( $\text{SF}_6$ , sulfur hexafluoride) is quenched into the liquid-vapor coexistence region belongs to the same universal class as a two-component immiscible liquid system (methanol-cyclohexane) that is quenched from above its consolute temperature into the two-liquid phase region. Since gravity is also involved in phase separation, this could only be demonstrated in microgravity. He also observed that the growth rate for small volume fractions of the droplet phase in immiscible liquids followed either a  $1/2$  power law (diffusive growth) or a  $1/3$  power law (Ostwald ripening) (slow growth) but followed a first power growth law (fast growth) for larger volume fractions.

At temperatures below the critical point, a liquid can coexist with its vapor, whereas at and above the critical isotherm, only a gas can exist. Klein and Wanders sought to observe the homogenization of the two phases as the system is heated to its critical point. Since the compressibility diverges at the critical point, they sought to eliminate any hydrostatic head by performing the experiment on D-1 with near critical sulfur hexafluoride,  $\text{SF}_6$ . Surprisingly, they found that it was very difficult to homogenize the sample at the critical point. It was later realized that since the thermal expansion also diverges and the thermal diffusivity goes to zero at the critical point, even the slightest thermal gradient could cause large differences in density distribution and the equilibration time would be much longer than the mission duration.

The divergence of the heat capacity on either side of the critical point is one of the important tests of universality of critical behavior. A characteristic  $\lambda$ -shape of the heat capacity versus temperature with a singularity at the critical temperature is predicted theoretically. Measurements of the slope in this vicinity are used to determine the exponent governing the rate at which the heat capacity diverges. One of the difficulties encountered in such measurements is caused by the fact that the compressibility of the system also diverges. Thus there is a large density variation in any finite test cell because of the hydrostatic pressure and the actual critical condition is met at only one point in the test cell. Measurement of heat capacity of the cell then integrates over near-critical conditions, but cannot provide accurate data near the peak in the curve.

Nitsche and Straub tried to obtain a more accurate measurement of the heat capacity of sulfur hexafluoride near its critical point on the D-1 flight. Much to their surprise, the data in the vicinity of the critical point ( $C_v$ ) was smeared out even more than on Earth. Instead of the expected peak at the critical point, they measured only a broad hump. It was later found that, instead of a well-mixed system with the fluid wetting the walls of the test chamber, a phase separation occurred and persisted because of the very long diffusion time as the critical point is approached.

The test chamber was redesigned by Straub and Haupt for a repeat attempt on D-2. By cooling through the critical temperature ( $T_c$ ), the “real” behavior of  $C_v$  could be determined to within 0.9 mK from  $T_c$ , whereas

ground measurements became disturbed by gravity at 15 to 20 mK from  $T_c$ . The heat capacity exhibited the sharp peak when cooling through the critical point and the universal coefficients were within experimental error of those obtained from group renormalization theory. Considerable hysteresis was seen in the  $C_v$  behavior when heating from the two-phase region, through the critical point, into the single phase region, which is attributed to the “critical slowing down” of phase homogenization as the chemical diffusivity vanishes. The heat capacity is described by the expression  $A^{-1/\alpha} |\tau|^\alpha + B$  the measured critical exponent  $\alpha$  was found to be  $0.109 \pm 0.02$ ; theory predicts  $\alpha = 0.110 \pm 0.0045$  (see Le Guillou and Zinn-Justin, Phys Rev B (1980) 3976).

The same experiment also confirmed the phenomena of “critical speeding up” or the “piston effect” for rapid heat transport near the critical point despite the fact that thermal diffusivity vanishes in this region. This effect had been seen on the ground, but was attributed to convective mixing as the compressibility diverges. However, the D-2 experiment confirmed the heating was due to an isentropic expansion instead of convective transport. By heating the wall of a container filled with a highly compressible fluid, a thin boundary layer is heated from diffusive heat transfer. The fluid in the boundary layer expands adiabatically, compressing the bulk fluid. Since the bulk fluid becomes heated by the adiabatic compression, heat transfer is virtually instantaneous.

Beysens used the “piston effect” to quench near critical  $SF_6$  from the single phase region into the two-phase region on IML-2. A planned maneuver during one of the runs demonstrated how acceleration disturbs the piston effect thermal transport. He also observed two different growth regimes in the same system: a fast growth regime with a first power time dependence, and a slow growth regime with a  $1/3$  power time dependence, depending on the quench depth.

Ferrell used the critical point facility on IML-2 to measure electrostriction effects and the time constant for thermal diffusion near the critical point of  $SF_6$ . Electrostriction is the deformation of a fluid from an applied electric field. The effect can be quite pronounced near a critical point because of the divergence in compressibility, however, it is slow to develop because of the long thermal diffusion times. The thermal diffusion measurements agreed with ground based measurements more than 100 mK above the critical temperature, but were lower by a factor of 1.7 at 1.4 mK above  $T_c$ .

Precision measurements of the thermal field using high sensitivity (microKelvin,  $\mu K$ ) thermistors by Michels on IML-1 confirmed the theoretical model for isentropic heat transfer from the piston effect.

Klein used the piston effect to heat and cooled  $SF_6$  through the critical point and observed the effect with laser light scattering. He observed critical opalescence almost immediately after cooling through  $T_c$ , but found that hours were required for the system to come to thermal equilibrium. He also determined that the gas-liquid configuration in the two-phase region is determined by interfacial effects. Homogenization after heating into the single-phase region scales with the correlation length, which goes as  $(T - T_c)^{-0.63}$ .

Lipa sought to circumvent some of the problems associated with attempting to measure critical phenomena at the liquid-vapor critical point. Instead he chose to measure the heat capacity in liquid helium at the lambda-transition, the temperature at which normal helium (He) is transformed into superfluid He-II. This transition is known as the lambda transition because of the  $\lambda$ -shape of the heat capacity in the vicinity of the transition. Since He remains a liquid on either side of the transition, the divergence in compressibility

is avoided. However, the transition temperature is pressure dependent, so that in a gravity field, critical conditions exist at only one plane in the system. However, since the order parameter for the lambda transition is a two-component superfluid wavefunction, as opposed to the scalar density difference in the gas-liquid critical point, these two systems are not in the same universal classes, hence the critical exponents will not be the same.

Lipa and his group at Stanford had developed a thermometry system using Superconducting Quantum Interference Devices (SQUID) to detect minute magnetic changes in a paramagnetic salt, which can be directed related to temperature with nanoKelvin (nK) resolution. With this device, they were able to measure a sharp peak in the heat capacity curve to within a few 100 nK of the lambda point before the pressure variations in the finite test cell began to smear out the data. They were limited in how small they could make the test cell because of the correlation length over which the atoms act collectively. Therefore, they carried the experiment on USMP-1 to obtain measurements to within a few nK.

One unforeseen difficulty was heat pulses from cosmic rays and charged particle radiation. They were eventually able to calibrate out and work around these events. Lipa found the value for the critical exponent to be  $-0.01285 \pm 0.00038$ . This value falls between the theoretical predictions of  $-0.007 \pm 0.006$  (Le Guillou and Zinn-Justin, Phys Rev B (1980) 3976) and  $-0.016 \pm 0.006$  (Albert, Phys Rev B (1982) 4912). In a sense, the lambda point is an ultimate test of the theory because of its unique sharpness. The value of such a test can best be described by a direct quote from Lipa:

“...this is at the foundations of condensed matter physics. We need to be sure the foundations are right so we can be confident of the scientific structure which supports our technology base. There is another angle, but maybe even harder [to explain]: RG [renormalization group theory] is used extensively in the Standard Model of elementary particles. There is a well-established relationship between this and critical phenomena. So one might one day get some insight into the ‘theory of everything’ via an obscure aspect of helium. Bit of a stretch, but that’s where Nobel prizes come from!”

A follow-on experiment on USMP-4 extended the heat capacity measurements near the lambda-point in which the He is confined to a spacing of 57 microns by carefully machined silicon (Si) discs. The objective is to test scaling predictions for the transition to a lower dimension system. Normally, this transition takes place only when the dimension is on the order of Angstroms ( $\text{\AA}$ ), but in semiconductors it can be as large as 0.1 micron, a length being approached by modern electronics. Since the correlation length diverges near a critical point, the distance over which the transition occurs can be greatly magnified. Attempts are now being made to correlate the data from the flight experiment with theory and other measurements.

## **G. Drop Dynamics**

On Spacelab-1, Rodot and Bisch analyzed the deformations of a tethered drop of silicone oil as it was oscillated at various frequencies. They were able to determine the various resonance modes and compare with theory.

Wang studied the rotation and fission of freely suspended liquid drops on Spacelab 3 (SL3) and again on USML-1 and USML-2 using the 3-axis acoustic levitator. These experiments are tests of a classical

astrophysical problem dealing with the formation of double stars (see S. Chandrasekhar, Proc. Royal Soc. London A286 (1965) 1-26). Qualitative agreement with theory was found in the Spacelab 3 experiment, but the drops tended to fission before the theoretical rotation rate was reached and the drop had been flattened by the acoustic radiation pressure. On USML-1, Wang and Trinh measured the bifurcation point as a function of drop shape and were able to show that the bifurcation point agreed with theory in the limit of spherical drop shape. A comprehensive study of the effect of drop flattening on the 2-lobed bifurcation point was carried out on USML-2. The experiments were supported by a series of experiments carried out in the glove box by Trinh to test various droplet injection techniques.

Other experiments conducted with the 3-axis acoustic levitator by Wang and his team at Vanderbilt University investigated core centering in compound drops. It was shown that an induced sloshing mode produced centering forces in drops with a gas core (liquid shells) as well as drops with an immiscible liquid core. Understanding of the centering forces could be important in the manufacturing of perfectly concentric glass shells for Inertially Confined Fusion experiments (ICF).

Weinberg attempted to use the three-axis acoustic levitator on USML-1 to measure the interfacial tension between two immiscible liquid phases by oscillating a compound drop, but ran into technical difficulties when attempting to deploy the two droplets. Yamanaka and Kamimura had similar difficulties when they attempted to measure the surface tension waves on stationary and rotating drops in a tri-axis acoustical chamber on SL-J.

If the induced oscillations in a drop have large amplitudes, various non-linear effects show up. Energy can be fed from one mode of oscillation to another, an effect known as mode coupling was observed. A hysteresis effect in the amplitude response was observed as the exciting frequency was swept back and forth across the resonant frequency, with a peculiar jump in amplitude. Finally, the onset, transition, and fully developed chaotic oscillations of drops were observed. Understanding the conditions leading to chaotic oscillations are important from a practical as well as an academic point of view because droplet evaporation and combustion increase with increasing oscillation amplitude and frequency. Additional experiments involving the extraction of physical property data from large, non-linear oscillation of acoustically levitated drops were carried out using a single axis interference levitator in the glove box on MSL-1R by Leal, Trinh, Thomas, and Crouch.

Sahdal, with Trinh, Thomas, and Crouch used the same device on MSL-1R to determine if the deformation and rotation of an acoustically levitated drop could be controlled well enough to measure internal flows within the drop. In particular, they wanted to determine if Marangoni flows from spot heating the drop on one side could be measured. By reducing the power level to the minimum required to keep the droplet positioned in microgravity, the shape distortion could essentially be eliminated (at least to their limit of measurement of the ratio of the axes, which was 1%). Drop rotation in a single axis levitator results from any slight misalignment of the acoustic reflector or asymmetric reflections from the container walls and has always been difficult to control. By fine-tuning the position of the acoustic reflector, drop rotation could be reduced to 0.1 rotations per second (rps).

Apfel and his team at Yale University used the 3-axis levitator on USML-1 and USML-2 to study the behavior of surfactants by observing the frequency and amplitude of freely suspended oscillating drops. They were able to extract material properties such as dynamic surface tension and shear as well as dilata-

tional surface viscosities. The dramatic difference in diffusion and sorption times between Triton X-100 and bovine serum albumin (BSA) was illustrated. Since BSA is a slow sorber, the Marangoni stresses are significant, leading to much faster damping than for pure water.

Marston, with Trinh and Depew, used an ultrasonic resonator in the glove box on USML-1 to investigate the positioning, shaping, and agglomeration of bubbles and oil drops in water. It was possible to coat the inside of a bubble with oil and study the centering mechanism.

## **H. Miscellaneous Experiments**

### *1. Super Fluid Helium Experiment.*

Superfluid helium possesses several characteristics that make it uniquely suited for cooling space-based instruments. Such instruments include the Infrared Astronomical Satellite (IRAS) and the Space Infrared Telescope Facility (SIRTF). Liquid helium 4 (He 4) and its rare isotope, helium 3, remain liquid at absolute zero. At a temperature of 2.17 K and a vapor pressure of 5.1 kP (38.4 Torr), He 4 undergoes a transformation to a superfluid state. In this state, He 4 can transport large amounts of heat at very small temperature differences. Heat is transported by coherent wave motion rather than by diffusion. Its effective thermal conductivity is several orders of magnitude higher than any other material. The high thermal conductivity is maintained in thin films and pores so small that a normal liquid would be immobilized. The advantage of this property is that the thin films, held to walls by van der Waals forces, are superfluid. Therefore, the entire superfluid mass behaves as a single thermal mass with a temperature difference of a few milli-Kelvins.

Under certain conditions, superfluid helium has zero effective viscosity whereas the viscosity for bulk motions is not zero (about 1/100 of water). Therefore, the system may be extremely sensitive to small surface tension forces and/or vehicle accelerations since the natural damping of these motions is limited.

Another unique characteristic of superfluid helium is known as the fountain effect. In small pores or thin films, the application of a small temperature gradient along the pores sets up a pressure differential that tends to push the liquid to the warmer end. This fountain pressure is used in zero gravity to contain the liquid in the cryostat, while allowing the vapor created by heat flow into the bulk helium to evaporate to space. A porous plug is placed in the vent line. The outer end is cooled by the evaporation of liquid to gas, and the resulting temperature differential generates a pressure that keeps the liquid in the tank.

A Super Fluid Helium Experiment was flown Spacelab 2 by a team from the Jet Propulsion Lab (JPL) headed by Mason. The technological and scientific objectives were divided into three separate investigations:

1. the Quantized Surface Wave (QSW) experiment to investigate third-sound surface waves in films of superfluid helium,
2. the Bulk Fluid Dynamics (BFD) experiment to determine the response (slosh modes and decay time) of superfluid helium to known acceleration levels, and
3. the Bulk Thermal Dynamics (BTD) experiment to determine temperature fluctuations and variations (to within 10 mK) associated with slosh modes.

Surface waves are on the order of a micron in normal gravity and damp out fairly rapidly. In microgravity ( $\mu g$ ), they tend to be thicker and were observed to persist for as long as 60 seconds. The other two objectives were reported met, but details were not given.

## *2. Geophysical Fluid Flow.*

Hart developed a method of simulating the three-dimensional geophysical fluid flows under the combined influence of rotation, thermal gradients, and a gravity-like central force. The Geophysical Fluid Flow Cell (GFFC) consists of a stainless steel hemisphere surrounded by a sapphire hemisphere with a layer of silicone oil between. An alternating high voltage was applied between the inner and outer so that the induced polarization in the silicone oil interacts with the electric field to give a gravity-like body force on the fluid. By heating and cooling different regions while the system was rotated, convective flows could be produced that are analogous to large-scale flows in planetary or stellar atmospheres or interiors. There are four dimensional parameters that characterize the flows in the GFFC: the Prandtl number, fixed at 8.4; the aspect ratio (gap width to inner radius), fixed at 2.65; the Taylor number, which measures the ratio of rotational forces to viscous forces; and the Rayleigh number, which measures the buoyancy-drive thermal convection to conductive heat flow. The convective flow fields in the hemisphere were visualized via Schlieren and shadowgraph photography. An ultraviolet (UV)-sensitive dye was added to the silicone oil to aid in flow visualization.

The GFFC was flown on Spacelab 3 and again on USML-2. The primary objective of Spacelab 3 experiment was to study the interaction of rotation and convection similar to that which occurs in the atmosphere of a rotating planet like Earth or Jupiter. A variety of interesting flow structures was observed as rotation rates and equator to pole heating was varied. The observed flows were used to check 3-dimensional computational models.

Several classes of experiments were conducted on USML-2: slow rotation, simulating mantle-like flows; fast rotation, simulating solar-like flows; symmetric heating, simulating solar or Earth core; and differential heating, simulating Jupiter's or Earth's atmosphere.

Rotation with spherical heating produced banded patterns not seen before in numerical simulations and may provide an alternative view of the mechanisms responsible for the observed structure of the Jovian atmosphere.

In slow rotation experiments, climatic "states" in the form of two distinct convective patterns were found to exist with the same external conditions, differing only by the initial conditions. These patterns are persistent and are insensitive to small changes in the external conditions. Data was obtained on how these states break down under larger changes in operating conditions. The transition from anisotropic north-south "banana convection" to the more isotropic convection was studied. This information may lead to a scaling argument for classifying different planetary atmospheres.

Other experiments with latitudinal heating show evidence of baroclinic wave instabilities and successfully showed how spiral wave convection breaks down into turbulence.

### 3. Order–Disorder Transitions.

Chaikin used the glove box on USML-2 to study assembly of colloidal systems as a function of solid volume fraction. Computer simulations indicated that, for volume fractions ranging from 0.545 to 0.74, short range van der Waals-like forces between the spheres would cause them to form into close-packed crystal-like structures, very much like atoms in a metal form close-packed crystalline structures. For volume fractions less than 0.494, the particles should remain in solution, and crystals could coexist with solution in the intermediate range. A metastable, glass-like phase was also predicted to exist for volume fractions greater than 0.58.

These predictions were tested by suspending 0.5 micron PMMA (*polymethylmethacrylate*) spheres in mixtures of decalin and tetralin for index matching. After homogenization, the suspensions were allowed to relax into their equilibrium configuration. The formation of the crystal structures could be observed and analyzed from diffraction patterns created by shining laser light through the suspension, similar to the analysis of metallic structures using X-ray diffraction. Particle motion was studied using dynamic light scattering. By “pinging” the system and observing the response of the structure, the elastic properties could also be inferred.

In normal gravity the configurations were not in equilibrium because sedimentation was much stronger than Brownian motion. Crystals were formed which tended to be mixtures of face centered cubic (FCC) and random hexagonal close-packed (RHCP) structures. In microgravity, the FCC phase was not observed and the structure was entirely RHCP. (By random HCP, we mean that the probability of every third layer being different is 0.5, or in other words, the chance of seeing ABC is the same as ABA.) Also, wing-like dendrites were observed in the microgravity structures that were never seen in the ground controls. It is not clear if dendrites actually start to form and are sheared off by sedimentation, or if the conditions favorable to their formation are absent.

A glassy phase was formed on Earth with a volume fraction of 0.619 that remained in this metastable state for more than a year without crystallizing. The same system crystallized in microgravity in 3.6 days. By the end of the mission it had grown to 1 cm and filled the container. Further, it survived re-entry and remained in the lab for six months, after which it was “remelted” by stirring. It then re-grew into the disordered glassy phase.

These studies were extended on MSL-1R to study nucleation and growth from time-resolved Bragg and low angle light scattering as well as measurement of elastic modulus from dynamic light scattering.

### 4. Mixing And Demixing of Transparent Liquids.

Langbein used a floating zone configuration to study the effects of capillarity on the mixing and demixing of two immiscible liquids on D-1. A mixture of benzylbenzoate and 40 Volume% paraffin oil was deployed between two discs. The upper disc was heated above the consolute temperature. Marangoni convection stirred the mixture and the interior counter flow carried bubbles, inadvertently introduced, to the surface where they ruptured, thus demonstrating this as an effective finning technique. As heating progressed, the critical wetting condition temperature was exceeded and the benzylbenzoate spread across the heated disc, in accordance with the critical point wetting theory of Cahn (see J. W. Cahn, *Journal of Chemical Physics*

(J Chem Phys) (1977) 667). The rising inner column of benzylbenzoate thinned and eventually broke into two segments. Eventually, through diffusion and Marangoni convection, the benzylbenzoate at the heated plate exceeded the consolute temperature and homogenized with the paraffin oil. Under passive cooling, a fog developed in the upper region as the temperature fell below the consolute temperature. The droplet in the fog eventually coalesced to form the two liquid phases.

#### *5. Particle Dispersion Experiment.*

Marshall studied the aggregation of various small particles in the glove box on USML-1 and -2 to obtain a better understanding the collapse of dust and debris in astrophysical and planetary settings. The dust grains were dispersed by a puff of gas in a transparent 125 cm<sup>3</sup> chamber and the aggregation was observed with high magnification video recording.

Aggregation was observed to be very rapid in all cases. Dielectric grains of quartz and volcanic ash particles aggregated into chains or filaments that were many tens of grains in length. Larger (400 micron) particles formed single particle chains up to a centimeter in length. Conductive copper particles formed similar chain-like aggregates. The size and shape of the particles did not seem to affect the type of structure that was formed, however, the chain length did appear to be proportional to the number density of the particles.

#### *6. Passive Accelerometer.*

Until STS-50 (USML-1), the quasi-steady acceleration on the Shuttle from gravity gradient and atmospheric drag had never been measured. The conventional accelerometers, used by the NASA Glenn Research Center in their SAMS (Space Acceleration Measurement System) system, respond to the higher frequency accelerations from the normal vibrational modes of the Shuttle, but the baseline bias is such that the extraction of a quasi-steady acceleration of less than one micro-g (microgravity) from the milli-g oscillatory accelerations cannot be done accurately. Alexander prepared a simple 2 cm diameter tube filled with water that also contained a 2 mm steel ball. The ball was positioned near one end of the tube with a magnet and then was simply allowed to fall in the residual gravity field. From the observed motion of the ball, the direction and magnitude of the quasi-steady acceleration could be determined from the Stokes formula for a falling sphere (after corrections for wall effects). Accelerations measured at the middeck were typically 4 to 5 micro-g with the direction essentially along the X-axis (along the fuselage - the Shuttle was flying in the tail-down attitude). Acceleration measured near the Crystal Growth Furnace (CGF) was typically 0.5 micro-g and it was evident that the residual gravity vector was not along the furnace axis as had been planned.

### **I. Combustion Experiments**

There are two compelling reasons for the study of combustion in microgravity. One is the issue of fire safety in the design and operation procedures of orbiting laboratories; the other is take advantage of the weightless state to study certain combustion phenomena in more detail and to test various models in which convection has been ignored in order to be mathematically tractable.

Examples of the first category of experiments are the Solid Surface Combustion Experiment, the Smoldering Combustion Experiment, and Wire Insulation Flammability Experiment, which were carried out on USML-1.

Smoldering combustion can be extremely dangerous in a space station since it can remain virtually undetected for some time, but the increased temperature, due to the absence of convection to carry the heat away, can greatly increase the amount of toxic fumes generated. Stocker and Olson along with Fernando-Pello found dramatic increases in carbon monoxide and light organic compounds when a porous urethane foam smoldered in microgravity as compared to normal gravity, even though there was little difference in temperature and char patterns.

The wire flammability studies were carried out by Greenberg and Sacksteder and Kashiwagi to simulate the behavior of a possible electrical fire in space without convection and with forced convection. The wires were nichrome covered with 1.5 mm diameter polyethylene insulation. Ignition of a wire without forced convection resulted in a quiescent cloud of vapor that ignited but failed to propagate. Under forced convection, the spreading flame stabilized around a bead of molten insulation. Flame spread in concurrent flow was twice as fast as in counter current flow and soot production was greater under counter current flow. The flames quenched rapidly when the airflow was shut off.

The Solid Surface Combustion Experiment on USML-1 conducted by Altenkirch was the fourth of a series in which thin sheets of combustible materials were ignited in a controlled oxygen environment. Other Spacelab missions that carried this experiment included Spacelab Life Sciences-1 (SLS-1), IML-1, and SL-J. The objective of the series of experiment was to obtain the flame spreading and soot formation as a function of pressure and oxygen content for comparison with theoretical models. These data and the resulting models go into flammability requirements for materials usage requirements in spacecraft and space experiment design. Unfortunately, the experiment design permitted only one test per Shuttle flight.

A capability for running multiple solid surface combustion tests was introduced in a glove box experiments carried out on USMP-3 in the Forced Flow Flame Spread Test (FFFT) that is a forerunner of a facility for use on the International Space Station. Fuel in the form of a tape or cylinder is fed into a small wind tunnel at the same rate as the flame spread so that the flame front remains in the instrumented region for diagnostic measurements. These measurements are used for comparison with theory. A team from the NASA Glenn Research Center led by Sacksteder carried out fifteen experiments using sheets and cast cylinders of cellulose with concurrent airflows ranging from two to eight cm/second.

Kashiwagi and Olson also used the glove box on USMP-3 to investigate ignition and the transition to flame spread or smoldering combustion in 25 samples. Airflow was varied from 0 to 6.5 cm/second; ignition was initiated by a hot wire across the middle of thin (2-D) samples and by the focused beam of a halogen lamp for thicker (3-D) samples. In the 2-D samples, ignition occurred more readily under microgravity conditions and the flame spread was always in the upstream direction. In the 3-D sample ignition was from a spot in the middle of the sample and the char pattern was fan shaped, the internal angle of the fan increasing with airflow velocity.

Griffin and Gard compared the ability of the smoke detectors used on the Shuttle and those proposed for the International Space Station to detect fires. A near field module, installed in the USMP-3 glove box, contained the sample to be burned and the near field diagnostics that included collector grids for TEM (tunneling electron microscopy) analysis of the smoke particles. Combustion products were blown through Teflon hoses to the far field module which contained the two smoke detectors, then returned to the glove box to be removed by the glove box filters. Samples tested included a candle, paper, Teflon and kapton

coated wires, and silicone rubber. It was found that sensitivity to various combustion products in space is different than on Earth because the size distribution of the products is altered by the combustion process in microgravity.

Various experiments were conducted to take advantage of the quiescent microgravity environment to study a variety of combustion processes. One topic of significant practical interest is soot production. Soot is usually an undesirable product of combustion for several reasons. One reason is that soot is a visible pollutant; one sees soot in the black fumes emitted by diesel trucks, processing plants, and chimneys. (It should be noted that recent changes in Environmental Protection Agency (EPA) regulations call for significant reductions in amounts of such particulate materials in the atmosphere.) In addition, soot production is tied to the emission of carbon monoxide — a toxic material — and PAHs (polyaromatic hydrocarbons), many of which are carcinogenic. Another of soot's undesirable qualities is that the thermal radiation, or heat emission, of soot particles is often responsible for the spreading of fires. Soot also hampers efforts to fight fires because its presence can obscure their sources, making it more difficult to extinguish them. However, soot production is useful to the carbon black industry, which is a large industry that uses soot in such products as tires, black plastic, and dry-cell batteries. In addition, many furnace applications rely heavily on heat radiation from soot to transfer heat from flames to boiler tubes in order to produce steam from water. For all of these reasons, understanding the production of soot is a goal that is important to researchers. Once understood, the process could be manipulated to control both visible and invisible pollution from combustion technologies like diesel engines and aircraft gas turbines, to enhance fire-fighting abilities, and to produce soot with qualities that are beneficial to industry.

The geometry and behavior of a candle flame were investigated by Ross using the glove box on USML-1. This was the first evidence that diffusive transport was rapid enough to sustain a candle flame. After an initial transient in which the flame is spherical and yellow, indicating soot is being formed, a steady state is reached in which the flame is hemispherical and burns with a blue color, indicating little or no soot formation. Minor transient acceleration disturbances caused increased luminosity and soot production.

Fiber supported droplet combustion experiments were carried out on USML-2 and on MSL-1R by Williams. By tethering the droplets on a silicon fiber, they could be kept in the field of view of the video recorder so that the burning rate and other parameters could be recorded. The objective is to test theories of droplet combustion and soot formation that are of importance to improving the efficiency of internal combustion engines, gas turbine engines as well as home and industrial oil burning heating systems. Microgravity allows droplet size to be increased to as much as 5 mm so that the combustion process can be studied in detail. Once the theory is developed, its predictions can then be scaled back to the droplet sizes used in the actual combustion processes.

Williams carried out a similar experiment with free floating droplets on MSL-1R to determine if the tether he had used previously had any effect on the combustion process. The droplet is formed by injecting heptane through two injectors on opposite sides of the test platform within the chamber. The injectors are retracted after the drop is formed. The drop is then ignited by two hot-wire igniters that are brought near the droplet from opposite sides to begin combustion with minimum disturbance to the droplet. The burning droplet is then observed and recorded using video cameras and high-resolution photographs.

The “Structure of Flame Balls at Low Lewis Numbers” (SOFBALL) experiment of Paul Ronney was performed on MSL-1R. In this experiment, a container was filled with various combustible mixtures near their lean limit of combustion. A flame ball was created by an electrical spark. A stationary spherical flame front develops as fuel and oxygen diffuse into and heat and combustion products diffuse out of the flame ball. This is the simplest possible geometry in which to study the chemical reactions and the heat and mass transport of lean combustion processes. Over 50 years ago, Zeldovich found that the equations for steady heat and mass conservation had a solution corresponding to a stationary flame front, but he also showed that the solution was unstable. He did, however, consider the possibility that heat loss might be a stabilizing factor, which is apparently the case since some of the flame balls lasted the full 500 seconds until the experiment timed-out. It is expected that these experiments will provide new insight on combustion processes in the lean burning limit, which are important in improving the efficiency of engines and heating systems.

Soot formation in laminar flames was also studied on the MSL-1 and MSL-1R mission by Faeth. Soot formation in turbulent diffusion flames is of greater practical interest, but their direct study is difficult because of their time and spatial dependence. Therefore, laminar flames are studied to obtain the basic relations needed to develop a tractable theory, the justification being that there are known similarities of gas-phase processes between laminar and turbulent flames. Laminar flames are still affected by buoyancy effects that complicate the analysis, thus the need to study them in microgravity. The flames to be studied are hydrocarbon fuelled and burn in still air. Measurements include flame shape, soot volume fraction, soot temperature distribution, gas temperature distributions, and flame radiation. The flames in low gravity were much longer than in 1 g due to the absence of buoyancy-driven convection. It was also found that the simplified theoretical analysis of non-buoyant laminar flame developed in 1979 by Spalding gave excellent predictions of flame shape after making an empirical flame length parameter to account for the soot luminosity.

Enclosed laminar flames are commonly found in practical combustor systems such as gas turbine combustors, jet engine afterburners, and in power plant combustors. The enclosure is in the form of a duct with either co-flow or cross flow. The diffusion flame is located where the fuel jet and oxygen meet. Typically, the flame is anchored at the burner, but as the fuel velocity is increased, the flame front moves away from the burner jet. Eventually, the flame jumps ahead of the jet and is said to be lifted. Too high a fuel velocity will cause the flame to blow out. The stability of such flames in low gravity was investigated by Brooker, Jia, Stocker, and Chen of the NASA Glenn Research Center on USMP-4. The fuel was a 50 V% mixture of methane and nitrogen. A free-jet theory of Chung and Lee predicted that lifted flames would not be stable for Schmidt numbers (ratio of kinematic viscosity to chemical diffusivity) less than 1, which is the case for the dilute fuel mixture used in these tests. However, it was shown that the co-flow in the duct did tend to stabilize the lifted flame, both in normal gravity as well as in microgravity, although higher co-flow velocities were required to lift the flame and to cause blow-out in microgravity.

## **J. Assessment of the Science**

A number of the early microgravity fluids experiments investigated the shape and stability of liquid zones to support anticipated materials science experiments that might use extended floating zones for crystal growth. Perhaps the most important contribution from most of this work was the demonstration that the behavior of such zones could indeed be computationally modeled. However, one experiment used the

zone shape to measure the disjoining pressure of a film and another experiment stabilized an extended zone beyond the Rayleigh limit in a test of Taylor's "leaky dielectric theory". The latter has applications in the design of fluidic systems.

Many of the microgravity fluids experiments were directed to the study of Marangoni convection. Since this type of convection is independent of gravity, it clearly acts in terrestrial processes along with buoyancy-drive convection, and therefore must be considered. These space experiments clearly demonstrated the existence of such flows (which may have been debated in some quarters since they cannot be demonstrated independently in normal gravity), as well as the ability to quantify and model their effects, although it was also found that such flows can be unexpectedly quenched by contaminants. Considerable work went into determining under which conditions the steady Marangoni flows become time-dependent and new criteria for this transition have been developed. This knowledge is important for the design of floating zone crystal growth experiments in which time-dependent flows produce growth defects.

The classical theory of Young, Goldstein, and Bloch that describes the motion of droplets or bubbles in a fluid driven by the Marangoni effect was found to apply only in the limit of vanishing Marangoni number and corrections to the theory have been developed. It was also shown that multiple drops or bubbles can interact through the thermal wakes left as they move through the fluid. Finally, it was found that fluid properties such as dilatational viscosity, which are not accounted for in the Marangoni number, can significantly affect the motion. These findings are significant in the design of many materials and chemical processes used on Earth as well as in microgravity.

Several experiments involving pool boiling and heat transfer in microgravity produced some surprising results in that the ability to dissipate heat from a submerged heater was only slightly diminished. Instead of an insulating vapor film forming around the heated, as was expected, strong thermocapillary jets formed which proved to provide an efficient heat transfer mechanism. Not only is this significant for the design of systems that have to work in a microgravity environment, but it may be possible to take advantage of such jets to improve the efficiency of terrestrial boilers.

The behavior of several systems near critical phase transitions was studied. Unanticipated difficulties were encountered in approaching the critical point because of the "critical slowing down" phenomena. These difficulties were overcome and the critical exponents that govern the divergence of thermophysical properties as the critical point is approached were determined with improved accuracy. These appear to be consistent with the predictions the coefficients obtained from Wilson's group renormalization calculations.

A number of experiments were carried out on levitated drops to test and refine theories of droplet oscillation, shape and fissioning under rotation, core centering, and nonlinear effects. Techniques for extracting properties measurements from oscillating droplets were demonstrated. Some of these measurement techniques were utilized in obtaining thermophysical data from undercooled melts in the electromagnetic levitator on MSL-1R.

Other investigations included a three dimensional simulation of geophysical flows under the influence of a central gravity-like force together with rotation and differential heating, particle aggregation, order-disorder transitions in the assembly of an ensemble of hard spheres, mixing and demixing of immiscible systems, the management of superfluid helium in low gravity, and the demonstration of a simple falling sphere method for measuring the quasi-steady residual acceleration on the Shuttle.

The dozen or so combustion experiments have produced a wealth of information that is not only applicable to fire safety in space vehicles, but also fundamental to understanding the combustion process in droplets, combustion near the lean-burn limit, the formation of soot in various combustion processes.

### **K. New Technology and Technical Spin-offs**

Heat and mass transport from fluid flow is so fundamental to all of materials processing that it is difficult to single out specific applications where such research has made direct contributions. Marangoni convection, which is often ignored in terrestrial processing, can be significant, even in the presence of buoyancy convection, if there are free surfaces, bubbles, or immiscible droplets present. These space experiments have provided a much better understanding of the effects of these types of flows that are not only needed for the design of future microgravity experiments, but apply to many terrestrial processes as well. Hopefully, the publications resulting from the microgravity research will make the terrestrial process engineers aware of the importance of including the effects of such flows in their process design.

The fundamental work that was done on drop oscillations and the development of techniques for extracting materials properties from their observations can be considered enabling technology for extending the measurements of thermophysical properties into the undercooled molten state using electromagnetically suspended droplets. Such measurements are key to the development of new metallic glass systems and other metastable alloys.

The combustion research has the potential of leading to more efficient combustion processes with a reduction of unwanted combustion products such as soot and other noxious contaminants. Furthermore, the flammability testing and developments in spacecraft fire safety also have direct applications to home and industrial fire safety.

## II. MATERIALS SCIENCE EXPERIMENTS

Normally one categorizes materials as metals, ceramics, semiconductors, and polymers, reflecting the nature of their chemical bonding. Microgravity experiments have primarily focused on metals and semiconductors, although the distinction gets blurred when ceramics are added to metals to form composites. The primary emphasis in the study of metals has been to understand the evolution of their microstructure and to develop techniques for controlling it during processing. The primary emphasis in the study of semiconductors can be the growth of single crystals with controlled composition and defect formation. Key to the success of both of these endeavors is knowledge of the thermophysical properties of the constituents in the liquid phase. As it turns out there is a compelling reason for certain of these measurements to be made in a low gravity environment. Levitation techniques for certain thermophysical properties measurements permit the measurement of certain properties in the deeply undercooled, which are of value for predicting the cooling rate required for glass formation, which leads to the final section of glass formation experiments in microgravity.

### A. Metals, Alloys, and Composites

#### *1. Introduction.*

Metals tend to be ductile because their crystal structure contains slip systems that allow planes of atoms to slide over one another through the dislocation mechanism. A dislocation is a missing line of atoms in the otherwise regular spacing in a small crystalline grain of the metal. Under stress, the dislocation can move through the grain, resulting in the net displacement of a whole plane of atoms, much like moving a rug by forming a small kink and then moving the kink across the rug. Pure or elemental metals are generally too weak to be used for most structural applications because of their ductility. However, they can be strengthened dramatically by blocking the motion of the dislocations. There are several methods for accomplishing this. They may be alloyed with other metals whose atoms are larger or smaller than the host metal (solid solution hardening). The resulting irregularity in the lattice tends to block the motion of the dislocations. Since dislocations cannot propagate from one grain to another, promoting a fine grain structure will strengthen a metal. Dispersing very small particles or fibers throughout the metal is also effective means of strengthening a metal. These particles can either be precipitated from a dissolved component as the metal is cooled (precipitation hardening), or a second phase, often a refractory ceramic, can be added to form a composite.

When one attempts to solidify a multicomponent system from the melt, difficulties arise. The foreign atoms don't fit into the lattice as easily as the host atoms forming the matrix, and segregation results. The melt containing the rejected atoms will have a different density from the bulk solution resulting in solutally-driven convection which causes the final solid to have a non-uniform composition on a macroscopic scale (macrosegregation). Dispersed particles will have a different density and will tend to either sink or float. Particle behavior is also affected by the interfacial energy between their surface and the melt, which determines if they are wetted by the melt.

Much of what goes on in a multi-component melt is affected by gravity, but some of the more subtle interfacial effects are not. These interfacial effects may play important roles in many terrestrial processes,

but are poorly understood because they are masked by gravitational effects. Using microgravity as a tool to sort out the non-gravitational from the gravitational effects may add to our understanding of how these processes operate, which can lead to advanced materials with enhanced properties.

With the large computational capability that now exists, much use is being made of computer modeling of solidification processes, particularly in the case of large, expensive castings. In principle, it is now possible to compute the temperature and compositional fields as the casting solidifies and use these to predict the resulting microstructure, provided we know all of the processes taking place, and also have accurate knowledge of the thermophysical properties of the materials of interest. Unfortunately, many of the thermophysical properties, such as diffusion coefficients and thermal conductivities, are not known for the molten state and are difficult to measure because convective transport can easily influence the measurement. Therefore, there is great interest in using the microgravity environment to make this type of measurement.

Normal freezing generally produces equilibrium phases, that is, atomic configurations that are the most ordered or have the minimum free energy. Recently, there has been much interest in trapping non-equilibrium or metastable phases by various rapid solidification techniques because of their interesting properties. For example, metallic superconductors with the highest transition temperature (for metallic systems) such as  $\text{Nb}_3\text{Sn}$  (niobium III tin) and  $\text{Nb}_3\text{Ge}$  (niobium III germanium) have the so-called A15 structure, which is a nonequilibrium phase. Metallic glasses are another example that is useful because their lack of grain structure makes them more resistant to corrosion. Iron-based metallic glasses have found useful applications as high efficiency transformer cores because the absence of grain structure makes it easier for magnetic domains to move, resulting in much smaller hysteresis losses.

It is possible to magnetically levitate metallic samples in microgravity so that they can be melted and solidified without physical contact. Without a foreign surface to initiate nucleation, a melt may be cooled several hundred degrees below its normal freezing point. This provides an opportunity to measure properties of a melt in an undercooled state. Knowing the viscosity and surface tension of materials in this state may provide clues for more effective means for trapping metastable phases.

The alloy solidification experiments that have been performed on Spacelab fall into three general categories:

1. experiments designed to understand how the microstructure evolves during solidification,
2. studies of interfacial effects that control the distribution of second phase particles, and
3. measurements of thermal physical properties.

## 2. Microstructure Evolution.

The strength and other properties of an alloy depend on its microstructure, which is characterized by the size, orientation, and composition of the grains that make up the solid. One of the main tasks of a materials scientist is to design solidification processes to produce the microstructure that will give the material the desired properties. With the present computational capability, it is possible to design a complex mold so that the heat and mass flow will produce the desired microstructure throughout the final casting. However, in order to do this, the basic laws governing the development of the microstructure must be known along with the thermophysical properties of the components. Establishing the physical basis for the various laws that describe the solidification process has, over the last half-century, transformed metallurgy from an indus-

trial art based on empiricism to a more exact science. Because of the complicating effects of convection, many of the laws in use today are based on theories that assume no convective flows. We know that they don't apply exactly, but we use them anyway, assuming they are basically correct, and then try to fix them up by adding the effects of convection. But most of these theories have never been tested in the absence of convection so various subtleties may have been overlooked. The ability to experiment in microgravity provides an opportunity to test some of these theories to make sure they are basically correct.

a. Lamella spacing in eutectic systems. A binary eutectic system is characterized by the so-called eutectic reaction in which a homogeneous melt of a specific composition, at a specific temperature, solidifies into two distinct solid phases, referred to as the alpha and beta phase. There is only limited solid solubility of component A in the beta-phase or of component B in the alpha phase because the two solid phases either have a large difference in their atomic diameters, or they form different crystal structures. The composition and temperature at which this reaction occurs is called the eutectic point in the phase diagram and the eutectic temperature must be less than the melting point of either of the pure materials. Since the two solid phases must separate upon solidification, they usually form a series of very thin plates or lamella of alternating composition (some low volume fraction eutectics form a series of parallel rods instead of lamella). The spacing between the lamella is controlled by the rate at which component B, which is rejected in the region where the alpha phase is solidifying, can diffuse to the region where the beta phase is solidifying, and vice versa. In 1966, Jackson and Hunt (Transactions of the Metallurgical Society of AIME (Trans. Met. Soc. AIME) 236 (1966) 1129) developed a theory that showed that the product of the solidifying velocity and the square of the spacing between the lamella must equal a constant for a specific material that depends on the diffusion coefficient and other properties of the material involved. The Jackson Hunt theory considered only diffusive transport. Since a eutectic solidifies congruently, that is, a melt of uniform composition is transformed directly into a two-phase solid, there is little chance for convection to act, even in a gravity field and, indeed, the theory seemed to be correct.

Part of the interest in solidifying eutectics in microgravity arose from an experiment performed by Larson, then at Grumman in Bethpage, New York, during the Apollo-Soyuz flight. Larson directionally solidified the MnBi-Bi (manganese bismuth) eutectic system, which is a low volume-fraction system in which the MnBi phase forms an aligned rod-like structure instead of lamellae in the Bi matrix. The intermetallic compound, MnBi is an interesting permanent magnet material and Larson was trying to improve its strength by using microgravity to get better alignment in the MnBi rods. To his surprise, he found that the rods were finer and more closely spaced than his ground control sample. Interestingly, the samples he processed on Earth followed the Jackson-Hunt theory very nicely while his space samples departed significantly from the theory. Subsequent tests using magnetic fields on the ground to help suppress convection, gave results similar to his flight samples. This seemed very strange because the Jackson-Hunt theory considers only diffusive transport; no convection. Yet there are apparent departures from the theory when convection is suppressed. Larson attempted to repeat his experiment on the MSL-2 flight using Co-Sm (cobalt-samarium), another important magnetic system. Unfortunately, equipment problems prevented him from obtaining useful data.

Mueller and Kyr performed an experiment similar to Larson's on SL-1 and on D-1 using the InSb-NiSb (indium antimony-niobium antimony) pseudo-binary eutectic system. They also performed the experiment in higher g-levels using a centrifuge. Their results were similar to Larson's: agreement with Jackson-Hunt theory when convection is present, finer structure and spacing in the absence of convection. They found

that the volume fraction of the NiSb phase in their final solid was lower than their starting eutectic composition and suggested that thermal diffusion (Soret effect) may have caused this composition shift away from the eutectic and that this was responsible for the apparent departure from the Jackson-Hunt law. The convective stirring in the 1-g sample apparently does not affect the spacing between the phases, but does keep the bulk fluid at more or less constant composition by simply overwhelming the Soret effect.

However, Favier and de Goer directionally solidified Ag-Ge (silver germanium),  $\text{Al}_3\text{Ni-Al}$  (aluminum nickel), and  $\text{Al}_2\text{Cu-Al}$  (aluminum copper) on TEXUS suborbital rockets and on SL-1. They found no change in the lamella spacing or volume fraction for the Ag-Ge and the  $\text{Al}_2\text{Cu-Al}$  systems, but found coarser spacing and increased volume fraction of the minority phase in the microgravity sample of  $\text{Al}_3\text{Ni-Al}$ , just the opposite result of Mueller and Kyr. The change in volume fraction again argues for the possibility that Soret diffusion may have shifted the starting composition away from the eutectic composition, which could explain the change in spacing.

Wallrafen and Dupré attempted to directionally solidify  $\text{LiF-LiBaF}_3$  (lithium fluoride-lithium barium fluoride) eutectic on D-2. In 1-g experiments, the component  $\text{LiBaF}_3$  tended to accumulate in the lower regions of the melt. The accumulation of the  $\text{LiBaF}_3$  component was eliminated in the D-2 samples, indicating the separation of this component must have been gravity related rather than a result of Soret diffusion. No difference in volume fraction or lamella spacing was observed between the space and ground samples.

Tensi reported a reduction in interdendritic spacing under microgravity conditions in hypoeutectic  $\text{AlSi}_{11}$  (aluminum silicate) on D-2 and in  $\text{AlSi}_7$  on D-1 and found no change in the volume fraction of the silicon. These experiments were run with a gradient of 15K/cm at growth velocities of 0.5, 1, and 2 mm/minute. The 0.5 mm/minute produced a plane front solidification, while the others resulted in dendritic solidification. The material between the primary dendrites had eutectic composition and the spacing of the lamella in this interdendritic material was substantially less in the microgravity samples. Since there was no change in the volume fraction, Soret diffusion was apparently not effective in this system. Tensi argues that the increased spacing in the 1-g sample is a result of micro-convection that increases the transport of material between lamella, thus increasing the effective diffusion length that results in the increased spacing.

Ohno and Motegi investigated a different aspect of eutectic microstructure. Instead of directionally solidifying, they melted and cooled hypo- and hypereutectic compositions of the  $\text{Al}_2\text{Cu}$  system using the Continuous Heating Furnace on SL-J so that they could compare the resulting microstructures in the presence and absence of gravity. When the hypoeutectic  $\text{Al}_2\text{Cu}$  system is quenched in normal gravity, the first-to-freeze primary Al dendrites, being less dense than the bulk melt, will detach from the wall and float to the top. When the excess Al has been removed in this manner, columnar grains of eutectic composition grow along the direction of heat flow. In space, the primary Al dendrites simply remained on the wall and the remaining eutectic formed columnar structures around them. Grains of primary  $\text{Al}_2\text{Cu}$  are the first to freeze in the hypereutectic composition. Being denser, these primary  $\text{Al}_2\text{Cu}$  grains settle to the bottom. When the excess Cu is removed in this manner, the remaining melt solidifies as columnar eutectic grains. In space, however, the primary  $\text{Al}_2\text{Cu}$  appeared along the walls, but no free  $\text{Al}_2\text{Cu}$  crystals were observed. Small gas bubbles were also found near the walls and larger ones in the middle of the final ingot. It was speculated that these originated from adsorbed gas in the graphite crucible.

b. Interfacial stability. As solidification progresses in a binary or multi-component system, the rejected solute builds up in front of the solidification interface which has the effect of lowering the freezing temperature at the interface since some of the component with the higher freezing temperature has already been removed. However, the bulk melt away from the solidification interface has the original composition, which has a higher freezing point. Therefore, the freezing point of the melt rises from the lower value at the growth front to the higher value of the bulk melt. Unless the imposed thermal field in front of the solidification interface is everywhere higher than the local freezing point of this melt, the melt is said to be constitutionally undercooled, which leads to an interfacial instability. If a small portion of the growth interface is somehow displaced ahead and it finds the local freezing point to be higher than the local temperature, it will continue to advance. Thus the interface will break down, first into a cellular pattern if the constitutional undercooling is small, or into long finger-like projections if the undercooling is larger. The sides of these projections will also break down to form secondary arms, which in turn can break down to form tertiary arms. The resulting structure resembles a fir tree, hence the term “dendrite”.

A simple constitutional supercooling criterion (known as the CS criterion) was developed by Rutter and Chalmers in 1953 (Canadian Journal of Physics (Can. J. Phys.) 31 (1953) 15) that predicts the ratio of the gradient required to stabilize the interface to the growth velocity for a given solidification system. In 1964, Mullins and Sekerka (Journal of Applied Physics (J. Appl. Phys.) 34 (1964) 323) developed a more rigorous theory based on a stability analysis that included the liquid-solid interfacial energy that can provide a stabilizing effect on the interface. Like most theories concerning solidification phenomena, it was necessary to assume no convection in order to simplify these analyses.

Carlberg used a multi zone furnace in a Getaway Special canister (GAS can) on SL-J to solidify gallium (Ga)-doped Ge using the gradient freeze technique with Peltier pulsing for interface demarcation. In this process, the solidification rate increases as the specimen is solidified. Carlberg was able to show that the flight, as well as ground based, results were consistent with the predictions of Mullins and Sekerka so long as the experiment was configured with little convection (vertical with stabilizing thermal gradient). However, he was able to show significant departure from the M-S theory as convection was increased.

Potard, Duffar, and Dusserre devised a method for monitoring conditions at the interface based on the heat being supplied and/or extracted from the growth process. The latent heat of fusion being liberated as the crystal grows is proportional to the growth rate as well as the area. Thus, if this heat can be measured, it should be possible to determine the conditions at the growth interface. Three samples were prepared for the Gradient Heating Furnace: one with pure InSb, one with pure InSb but with a step area change, and one with doped InSb to produce an interfacial breakdown due to constitutional undercooling. The ampoules were covered with super insulation to provide an adiabatic radial boundary condition. Heat was introduced and extracted through graphite plugs at each end of the ampoule. The heat flux meters consist of adjacent fine wire thermocouples in the graphite plugs. The technique was demonstrated in a semi-qualitative manner on the D-1 flight in that seeding and growth transients could be identified and the measured heat fluxes were in reasonable agreement with the mathematical models of the process.

A unique and highly sophisticated apparatus for studying details of the solidification process was developed by Favier and coworkers at the CENG, Grenoble under a cooperative program between NASA and the French Space Agency (CNES) and the French Atomic Energy Commission (CEA). The official name is Materials for the Study of Interesting Phenomena of Solidification on Earth and in Orbit, or MEPHISTO. Three 6

mm diameter, 900 mm long samples are processed in parallel. Resistance and thermal measurements are made on one sample while Seebeck voltage measurements are made on another. Peltier pulsing is applied to the third sample to mark the solidification interface for post flight analysis. The middle 500 mm of the samples are melted using two furnaces. One solidification front is kept stationary while the other is moved back and forth to create a solidification front that can be move at different velocities. By measuring the differential Seebeck voltage between the stationary and moving interface, the kinetic undercooling can be determined as a function of growth velocity. At the freezing point, a solid will remain in equilibrium with its melt indefinitely. This kinetic undercooling is the driving force for continued solidification. The kinetic undercooling will be small for plane front solidification, but since additional interfacial energy must be provided as the plane front begins to break down, the kinetic undercooling must get larger. Thus, the transition from plane front solidification to cellular growth can be observed as a change in the Seebeck voltage and the critical growth velocity where the plane front interface begins to break down can be determined accurately. Many applications ranging from bulk growth of semiconductors to single crystalline turbine blades require plane front solidification and it is important to know how fast they can be solidified before this breakdown occurs. The MEPHISTO instrument, flown on USMP-1, 2, 3, and 4, provided the first opportunities to perform a critical test of the Mullins-Sekerka theory as well as to explore other important phenomena involved in the solidification process.

Favier used the USMP-1 opportunity to explore the interfacial breakdown in Bi-doped Sn and the USMP-3 opportunity to quantify the disturbance and recovery of growth interface as a result of thruster firings. Abbaschian used the USMP-2 and 4 flights to investigate interfacial stability on the other side of the phase diagram, Sn-doped Bi. Unlike most metals that solidify in an atomically rough interface, which allows the interface to form nearly along the local freezing line, Bi solidifies along crystalline planes, which are seen as facets. The properties of a faceted crystal depend on the direction relative to the crystal axis and are said to be anisotropic. The primary motivation for the study of the solidification of a Bi-rich alloy was to test the extension of the Mullins-Sekerka stability criterion to include the effects of anisotropy, which acts to stabilize the interface against breakdown into cellular and dendritic growth.

Where single crystals of uniform composition are required, the interface can be stabilized by applying a sufficient thermal gradient at the growth interface to prevent interfacial breakdown. However, in most alloy solidification processes, the first-to-freeze dendrites, surrounded by the last-to-freeze interdendritic fluid, determine the microstructure of the resulting solid. Therefore, it becomes important to know how dendrite growth depends on processing parameters so that one can engineer the desired microstructure.

Nguyen Thi and Li, with Billia, Camel, Drevet, and Favier investigated the transition from deep cellular to dendritic microstructure. Three aluminum-lithium alloys with the same composition were directionally solidified in the same temperature gradient but at three different velocities in the GFQ (Gradient Furnace with Quench). The microstructure of the solid-liquid interface was quenched in. The cellular or dendritic pattern is then revealed by grinding followed by chemical etching on longitudinal and/or transverse sections. Macrosegregation is determined by chemical analysis and microsegregation by SIMS (secondary ion mass spectroscopy).

A similar experiment was performed using the AGHF (Advanced Gradient Heating Furnace) on the LMS mission. The samples were Al-1.5wt%Ni. In this system, which can be stabilized both thermally and solutally on the ground, influence of strong convective flows are seen in the 1-g sample.

Billia and Jamgotchian along with Favier and Camel investigated the effect of convection on cellular growth on D-1. Samples of lead (Pb) with varying amounts of thallium (Tl) were directionally solidified above the morphological stability limit in order to cause the interface to break down into a cellular structure. The microgravity sample exhibited very regular cellular structures, whereas less regular structures are seen in the ground based control samples. The more complex structures in the 1-g samples were attributed to the effects of thermo-solutal convection. Because of thermal fluctuations in the flight furnace, the actual growth rate is not known, thus relating the cellular spacing to growth velocity was not possible.

c. Dendrite formation. Whenever solidification takes place in a medium where the surrounding temperature is lower than the local freezing temperature, the growth front can become unstable and dendrites can form. This situation can occur either by constitutional undercooling in the case of alloy solidification, or by the fact that a certain amount of undercooling is required to nucleate the solid from either the melt or the vapor. A classic example of the latter is the formation of ice dendrites (snow flakes). Their intricate shapes have fascinated scientists and philosophers alike, and the study of their formation is the confluence of pure physics from the point of view of pattern formation and material science where interest is in the evolution of microstructure in alloys.

Camel, Favier, Dupuy, and Le Maguet studied the formation of dendrites in hypo- and hypereutectic compositions of the Al-Cu systems at very low solidification velocities (1 micron/second with a gradient of 30°C/cm) on the D-1 mission. In the ground control experiment in which Al-24Wt%Cu hypoeutectic composition was directionally solidified in the vertical stabilizing configuration (stable with respect to both thermal and solutal gradients), considerable radial segregation was observed and the interdendritic spacing ranged from 350 – 450 microns. This is much less than the 1400 microns expected from scaling laws based on higher solidification rates. The flight sample showed no radial or longitudinal segregation and the dendrite spacing was very close to the expected scaled value. Apparently, in normal gravity considerable solutal convection occurs in the extended mushy zone resulting from the low solidification velocity. Multiple cross sections taken from the large dendrites in the flight sample allowed, for the first time, the reconstruction of an actual dendrite formed in an opaque system. The resulting reconstruction provided valuable information on the secondary and tertiary arm spacing and on the ripening of the dendrite arms.

The McCays and coworkers used the ammonia chloride-water system as a transparent metal analog to study the effect of convection on the dendritic structure of castings on IML-1. The mixture was cooled from the bottom, representative of a mold placed on a chill block. The growing columnar dendrites were observed holographically as heat was extracted from the system. The dendrites in the ground control experiment grew only half as fast as those in the flight experiment and the mushy zone (the region where the dendrites are growing, which consist of solid dendrites and interdendritic fluid) was much more dense in the ground control. Even though the system is thermally stable (hot over cold), the convective flows along the stalks of the dendrites greatly influence the concentration field in the growth region and must be considered in any attempt to model such a system.

When liquid metal is poured into a mold, columnar dendrites grow from the chilled surface into the melt. In most cases, it is desirable to have small equiaxed dendrites throughout the final casting to form a fine-grained structure. In practice, this is accomplished by adding inoculants to the melt in order to promote the nucleation of small grains ahead of the solidification front. These grains will grow dendritically in all directions, thus forming equiaxed dendrites. Dupouy, Camel, Botalla, Abadie, and Favier investigated the

transition from columnar to equiaxed growth by directionally solidifying Al-4Wt% Cu alloy with an Al-Ti-B (aluminum-titanium-boron) grain refiner on the LMS mission. A simple theory proposed by Hunt (Materials Science and Engineering (Mater. Sci. Engr.) 65 (1984) 75) relates the transition to the undercooling, the thermal gradient, and the number of nuclei, but ignores the effects of convection and the buildup of the solute boundary layer in front of the advancing solidification front. The purpose of the space experiment is to decouple the convection effects from the solute build up in order to develop corrections to the theory. The experiments showed a continuous transition from a purely equiaxed to an anisotropic microstructure and the transition departed significantly from the Hunt model.

Similarly, Sato used  $\text{TiB}_2$  particles as a grain refiner in a TiAl-based alloy on IML-2. The  $\text{TiB}_2$  particles all settled to the bottom of the 1-g sample when it melted and the resulting structure consisted of columnar dendrites. A uniformly distributed equiaxed grain resulted in the flight sample.

Glicksman and co workers at RPI (Rensselaer Polytechnic Institute) carried out a series of precisely controlled dendritic growth experiments on USMP-2, 3, and 4 to investigate the fundamental theories of dendrite growth. Instead of investigating dendritic growth in constitutionally undercooled systems, these experiments observed the growth of dendrites in pure transparent organic systems at undercoolings ranging from 0.05 to 2.0 K. This choice of systems, succinonitrile for the first two experiments and pivalic acid for the third experiment, allowed real time observations of the actual growth of the dendrites so that precise measurements could be made of the growth rate and tip geometry in systems that were analogs of metal solidification. Succinonitrile crystallizes in a body-centered cubic structure and pivalic acid crystallizes in a face centered cubic structure. Both systems have unusually low entropies of fusion, more typical of metals than of organics.

One of the governing factors in the growth of these thermal dendrites is the heat flow from the dendrite to the surrounding melt. An exact solution the conductive heat flow problem had been obtained by Ivantsov for a parabolic shaped dendrite which relates the product of growth rate and tip radius to the undercooling. However, there seems to be no fundamental relationship between the tip radius  $R$  and the growth velocity  $V$ . The question becomes, how does nature select a unique operating state? Experimental observations of pure systems suggest that  $V R^2$  is either a constant for a specific material, or a weakly varying function of the undercooling. A large body of terrestrial data has been taken on several systems, but convection effects, especially in the crucial region of low undercoolings where the growth rate is comparable to the convective flow velocities, has not been able to provide an adequate test of the selection rules governing this process. This was the motivation behind this set of flight experiments.

The microgravity experiments show that convection increases the growth rate by a factor of 2 for undercoolings less than 0.5 K, and is still significant for undercoolings up to 1.7 K. The measured product of tip radius and growth velocity in microgravity falls much closer to the Ivantsov solution than the terrestrial data. The slight deviations maybe attributed to the formation of side branches on the dendrites, possible wall effects from the growth chamber, and the fact the observed shape of the dendrite tip is a slightly different shape from the parabola assumed in the Ivantsov solution. Now that the heat transfer away from the growing dendrite is properly accounted for, the physics of shape selection can be approached with reliable data.

In addition to establishing the data required to understand the fundamentals of dendritic growth, the large number of highly detailed photographs of dendrites growing under carefully controlled and well documented conditions are being shared with researchers at other universities interested in studying other aspects of dendrite growth such as the side arm growth rates and spacing.

Herlach, Barth and Holland-Moritz with Flemings and Matson used the TEMPUS facility on MSL-1R to study dendrite formation in undercooled Ni and Ni-0.6At% Cu. Discrepancies between observed dendrite growth velocity and predictions using the Boettinger, Coriell, and Trivedi (BCT) model (*in Rapid Solidification Processing, Principles and Technologies IV*. Ed. Mehrabian and Parrish, Claitor's, Baton Rouge 1988) were believed to be due to convection, especially at low undercoolings where the growth velocity is on the order of the flow velocities. Surprisingly, the flight results did not show any significant difference.

d. Coarsening. Coarsening is of major importance in the evolution of microstructure of alloys, particularly dispersion hardened alloys in which the added strength provided by the dispersed phase declines rapidly if the particles grow past a critical size. Coarsening is driven by the excess interfacial energy in a finely dispersed second phase, which could be lowered if fewer larger particles were present. The melting point of a small particle is lower than a larger particle of the same composition (Gibbs-Thompson effect) so the smaller particles dissolve to feed the growth of larger particles (the rich get richer at the expense of the poor). The process was first recognized by Ostwald and is known as Ostwald ripening. The mathematical details were worked out independently by Landau and Slyozov and by Wagner, and the result is known as the LSW theory. One key result of the LSW theory is that the cube of the average particle radius varies directly with time according to

$$R(t)^3 - R(0)^3 = K_{LSW} t$$

Where  $R(0)^3$  is the initial average radius and  $K_{LSW}$  is a constant which contains the relevant material properties such as the interfacial energy and diffusion coefficient. However, the classical LSW analysis is based on a mean field theory that ignores the finite volume of the dispersed phase. Various attempts have been made to formulate a correction for finite volume, which give widely varying results. However, all of the corrections retain the  $R^3$  relationship and differ only in how the  $K(\phi) / K_{LSW}$  varies with volume fraction,  $\phi$ . Furthermore, there has not yet been a definitive test to differentiate between these various theories.

On SL-1, Kneissl and Fischmeister took a different approach to the study of monotectic systems. Instead of cooling from above the consolute temperature into the immiscible region in microgravity, they prepared samples of zinc (Zn) with small volume fractions of Pb on Earth by rapid quenching. These were heated into the two-liquid phase region in space, thus avoiding the nucleation and possibly the critical wetting that occurs when cooling through the immiscible region. The massive phase separation seen by most of the other experiments with hypermonotectic systems was avoided and they were able to study the coarsening of the dispersed particles. Kneissl and Fischmeister observed considerable coarsening of the dispersed phase. The distribution of the smaller particles resembled the classical LSW theory, but there were more of the larger particles than the theory predicted. The mechanism for producing these larger particles was not clear. A substantial increase in coarsening rate with increasing volume fraction was observed, but scatter was too large to make a definitive conclusion. A similar experiment on D-1 by Ratke, Theiringer, and Fischmeister used the Al-In system. However, technical problems prevented useful data return.

Alkemper, Snyder and Voorhees attempted such a definitive experiment on the MSL-1R flight. They dispersed 10 micron Sn particles in a Pd-Sn (palladium-tin) eutectic alloy and heated the samples at 2°C above the eutectic temperature for a predetermined period of time and then quenched to room temperature. The samples were later cut into sections and the particle size distribution measured with a digital scanning camera with a microscope objective. The lighter Sn particles all floated to the top in the ground control sample, as would be expected. The flight sample yielded K-values of 2.47, 3.3, and 6.9 micron<sup>3</sup>/second, respectively, for volume fractions of 10%, 20%, and 70%. Difficulty was encountered, however, in determining the  $K_{LSW}$  corresponding to 0 volume fraction. Voorhees used the grain-groove technique developed by Hardy at NIST (National Institute of Standards and Technology) to determine the interfacial energy between the solid and the melt and obtains  $K_{LSW} = 1.01$  microns<sup>3</sup>/second. The resulting values for  $K(\phi) / K_{LSW}$  exceed the predictions of all of the theories by a factor of 2. The measurements of the physical constants used to obtain  $K_{LSW}$  are being reviewed.

e. Liquid phase sintering. Liquid phase sintering (LPS) is a widely used process for forming composites containing refractory particles such as tungsten (W), rhenium (Re), or various carbides in a metal matrix. Sintered products include cutting tools, bearings, contact points, and other irregularly shaped parts where it is desirable to combine extreme hardness with the toughness and thermal or electrical conduction of the metal matrix. The refractory particles are combined with the metal matrix powder and isostatically pressed and heated to above the melting point of the host phase. If proper attention is paid to the wettability of the refractory particles, the molten host metal will infiltrate between the grains of the solid particles and envelop them. There are some obvious gravity effects because of the large difference in densities often encountered between particle and host phase. Consequently, this restricts the process to large volume fractions of the solid phase since the solid particles will essentially have to support themselves during the process. Even under these circumstances, there are differences in the particle size and morphology between the top and bottom of the specimen due to the gravity-imposed hydrostatic pressure.

Kohara conducted liquid phase sintering experiments on SL-J using W in 3.5 to 30 Wt% Ni. The powders were compressed into cylinders, placed in boron nitride (BN) crucibles and heated to 1500°C for 60 to 300 minutes. The samples with low volume fractions on the matrix material retained their shapes during the process, but those samples in which the matrix material could form a continuous liquid layer over the outer surface changed to a spherical shape in microgravity.

German, Upadhyaya, and Iacocca at Penn State University conducted liquid phase sintering experiments on SL-J, IML-2 and on the MSL-1R missions using W particles in a Fe-Ni (iron-nickel) matrix. On IML-2, the samples contained from 78 – 98 Wt% W in 5 Wt% increments. Liquid-solid segregation did not occur in the flight sample, but the lack of hydrostatic pressure prevented the sample from achieving 100% densification, as it would have in normal gravity. Instead, gas pores formed which were stable and became a discrete phase within the microstructure. Many of the pores had large distorted shapes as they interconnected W particles. Systems that distort in 1-g also distort in micro-g, except instead of attaining the characteristic elephant foot shape, the micro-g samples tend to reshape into spheres. This would indicate that viscous flows driven by surface tension can be significant. The major results from this series of experiments are universal models for coarsening, slumping and distortion, and grain agglomeration.

f. Thermosolutal convection. In dilute systems (systems in which the alloying component is small enough so that its presence does not significantly affect the density of the melt), it is possible to eliminate

solute redistribution on a global scale in normal gravity by directionally solidifying the sample in a vertical stabilizing configuration (hot over cold). Since heat must be applied through the walls, there will still be some convection from the horizontal thermal gradients, but these flows will primarily affect the radial distribution of solute in the solid. Non-dilute systems can be stabilized even more if the rejected component is denser than the bulk melt. However, if the rejected component is less dense, it will tend to rise and upset the stabilizing thermal gradient. Coriell showed that such a system would be unstable even if the thermal gradient were high enough to provide a monotonic decrease in density along the vertical direction. This comes about because solute diffusion is much slower than thermal diffusion so if a parcel of fluid is displaced vertically, it will equilibrate thermally with its surroundings faster than compositionally, find itself still lighter than its surroundings, and will continue to rise. This is known as the double-diffusive problem and received much attention from oceanographers because of the phenomena of salt-fingering. The ocean surface is warmed by the sun, which tends to thermally stabilize the system, but evaporation increases the salt concentration at the surface, which tends to destabilize the system and produce overturning convection.

Coriell's analysis also showed that such systems could even be unstable under microgravity conditions if the concentration of solute increased more than a few percent. Rex and Sahm tested this theory on the D-1 mission by directionally solidified an Al -3 wt%Mg (magnesium) alloy at a growth rate of approximately 4mm/minute under a thermal gradient of 13K/mm. This should place the sample well within the region of stability predicted by Coriell. Indeed, the space sample solidified with a plane front and had a longitudinal compositional profile consistent with purely diffusion-controlled transport. The experiment was repeated on D-2 by Stehle and Rex with Cu-30.1Wt%Mn. The growth rate was varied from approximately 1.2 microns/second, which corresponds to the stability limit estimated by Coriell for 10 to 4 g, to 16 microns/second. The composition of the flight samples was consistent with diffusion controlled growth throughout.

Unfortunately, the above experiments lie well within the stability regime, so they don't really test the limits of stability. Leonartz directionally solidified the transparent succinonitrile-0.45Wt% acetone and succinonitrile-0.33 Wt% ethanol systems on a rotating centrifuge (NIZEMI) facility on the IML-2 flight. In this manner, the g-level could be varied from 0.001 to 1 g by changing the rotation speed of the centrifuge. The observed thermo-solutal convective velocities were well under the solidification velocity for g-levels up to 0.01 g, thus no effect on interface shape could be observed. Coriell's predictions indicated the thermosolutal stability should occur at 0.001g for the succinonitrile-0.45Wt% acetone system for a thermal gradient of 1 K/mm and solidification velocities less than 2 microns/second. Instead, the instability was observed at 0.1g. Coriell's theory considered the least stable wavelengths in an infinite surface. If this wavelength happens to be longer than the width of the chamber, wall effects will limit the instability, which appears to be the case in this experiment.

g. Monotectic systems. As discussed previously, some metallic systems tend to be immiscible in the solid phase and form eutectic structures when they solidify. Other systems also have regions of immiscibility in the melt. Atoms of one component generally prefer to be next to like atoms, just as molecules of water in an oil and water mixture prefer to be next to water molecules and oil molecules prefer to be next to oil molecules. Such systems are said to have positive heat of mixing, meaning that the internal energy of the system is higher in the mixed state than it would be if the components were separated. If this were the complete story, such systems would always separate, just as oil and water tend to do.

The other factor is the entropy of mixing. Entropy is related to the number of possible states available to the system. If a deck of cards is cut in half, there are only a few ways the deck could be arranged so that all the black cards were in one stack and all the red cards in the other. On the contrary, there are many more ways the deck could be arranged to find the black and red cards mixed. Thus we say the mixed state is more probable, and if we were playing with a randomly shuffled deck, we would almost always expect to find some degree of mixing of the cards.

It was the genius of J. Willard Gibbs to recognize that a system reaches equilibrium, not when the configurational energy (enthalpy) is a minimum, but when enthalpy minus the product of entropy and temperature is a minimum. This combination is called the Gibbs free energy, or sometimes just the free energy, and it is this function that determines when an equilibrium phase transformation takes place. For example, atoms are more tightly bound together in a solid than in a liquid, so the solid has a lower (more negative) internal energy than the melt. However, since atoms are free to move around in a melt, the melt has higher entropy. When the temperature is raised to the point where the product of entropy and temperature overcomes the difference in internal energy between the solid and liquid, the liquid phase will have the lowest free energy and the system melts.

Similarly, in a mixture of atoms with a positive heat of mixing, there will be a temperature above which the entropy of mixing term overcomes the positive heat of mixing and a homogeneous solution will result. The lowest temperature at which this condition is met for all compositions in the immiscible region is called the critical consolute temperature. (Theoretically, there should be a temperature above which oil and water should completely mix, but this is above the boiling point of water.) If this critical consolute temperature happens to fall below the equilibrium freezing point, there will be no liquid phase immiscibility.

The critical consolute temperature corresponds to an inflection point in the free energy versus composition curve. At temperatures below the critical consolute temperature, the free energy curves will have two minima and two inflection points. The binodal or two-liquid phase region is mapped out by the locus of points where a mutual tangent exists between these two regions of the free energy curve. The inflection points in the free energy curves define a region called the spinodal. Between the binodal curve and the spinodal curve there exists a region of metastability, meaning an energy barrier must be overcome in order to form the second liquid phase, just as an energy barrier must be overcome in order to form a solid from a liquid. Just as in solidification, this energy may be overcome heterogeneously by forming a nucleus at a low energy site such as the container wall, or homogeneously by forming a nucleus from an undercooled melt. However, in the spinodal region there is no barrier to forming the second liquid phase. If the melt is undercooled into this region before nucleation occurs, it will spontaneously decompose into the two liquid phases. This process is known as spinodal decomposition.

When a region of liquid phase immiscibility exists, it does so only over a limited range of compositions. There will be composition at which the melt will remain homogeneous until it forms a solid rich in the component with the highest freezing point and a liquid rich in the component with the lower freezing point. The temperature and composition at which these three phases can coexist is an invariant point, similar to the eutectic reaction in which a melt of homogeneous composition decomposes into two solids of different composition ( $L \rightleftharpoons S_1 + S_2$ ) except, in this case,  $L_1 \rightleftharpoons S + L_2$ . This is called a monotectic reaction and systems in which this reaction occurs are called monotectics. Compositions richer than the monotectic composition in the higher melting point component are called hypomonotectics and can be solidified from

the melt in the same manner as hypoeutectics. It is also possible to solidify the monotectic composition if care is taken to prevent convective flows from sweeping the second liquid phase away from the solidification front. But any attempt to solidify a hypermonotectic composition by cooling the melt through the two-liquid phase region will result in a highly segregated solid because the two liquid phases will always have different densities and will separate by sedimentation before the solid can be formed by equilibrium solidification. (It is possible to form a fairly homogeneous solid of hypermonotectic composition by various rapid quenching processes in which solidification takes place before the two liquid phases can separate, but this would generally require that the sample be thin so that heat can be removed rapidly.)

There are a large number of binary metallic systems that exhibit monotectic behavior and attempts to form alloys of these systems was one of the first quests of the microgravity program. A mixture of krytox oil and water was shown to remain mixed for several hours in a simple demonstration experiment on Skylab, so it was known that in the absence of sedimentation such a mixture could be held in a metastable state more-or-less indefinitely. But, much to the surprise of these early experimenters, almost complete phase separation was observed in every attempt to solidify a monotectic system by cooling a melt through the two-liquid phase region, even when the process was carried out in a virtually weightless environment. Generally, one of the phases is enveloped by the other phase, much like the yolk of an egg. This was quite different from the ground based results in which the denser phase was always found at the bottom of the crucible. Clearly, some interfacial effects are operating to cause phase separation that had obscured by gravity-driven sedimentation.

As the melt is cooled into the metastable two-liquid phase region, drops of the minority phase may nucleate homogeneously within the majority or host phase. As heat is extracted from the system, these droplets will be subjected to a thermal gradient. Since the interfacial energy between the two fluids is temperature dependent, the difference in temperature across the droplet will result in an unbalanced force along its surface. The resulting Marangoni convective flows will drive the droplet toward the region of higher temperature. According to the YGB theory, the velocity of a droplet propelled by this mechanism is directly related to the droplet size. Thus, as droplets overtake one another and become larger, they move faster and are able to overtake smaller droplets and become larger still. This mechanism could certainly explain how the minority phase could coalesce in the last region to solidify.

In the meantime, Cahn developed a theory of critical wetting quite independently of the microgravity experiments on monotectic systems. According to Cahn's theory, there will be a region of temperature below and extending to the critical consolute temperature over which one of the two liquid phases will perfectly wet the container wall. When this occurs, there will be no barrier to this phase nucleating and spreading over the container wall, thereby forcing the other phase away from the wall.

A TEXUS rocket experiment by Ahlborn and Lohberg, using Al 10Wt% In in an  $\text{Al}_2\text{O}_3$  (aluminum oxide or alumina) crucible which is preferentially wet by the In-rich phase, found most of the indium-rich minority phase in contact with the crucible and surrounding the aluminum-rich majority phase. Some small amount of In-rich phase was also found near the center of the Al-rich region, presumably driven there by Marangoni convection. Potard, in a separate rocket experiment used the same components in a SiC crucible, which is wet by the Al-rich phase. He found the In-rich minority phase was completely surrounded by the Al-rich phase. Gelles and Markworth flew Al-90Wt% In in an alumina crucible on OSTA-2 and found a few

relatively large LI droplets with many smaller ones distributed through the In-rich matrix. These smaller droplets were adjacent to, but generally not touching, the crucible wall. These experiments demonstrate the critical wetting and spreading that occurs according to Cahn's theory if the minority phase wets the crucible walls in preference to the majority phase.

On Spacelab-1 and D-1, Ahlborn and Lohberg demonstrated with a variety of systems including Zn-Bi, Zn-Pb, Zn-Bi-Pb, and Al-Pb, that the minority phase was always transported to the hottest portion of the sample during the solidification process, presumably by Marangoni-induced droplet motion.

Kamio directionally solidified Cu-Pb at the monotectic composition. The resulting microstructure consisted of irregularly shaped Pb rods in a Cu matrix; however, a layer of Pb above the quenched growth front suggest that growth may not have taken place exactly at the monotectic composition. The ground control sample showed similar microstructure. A hypermonotectic Al-In sample was also flown, but a leak in the ampoule prevented any results from being obtained.

Togano and co-investigators succeeded in casting a ternary monotectic system on SL-J. Compositions of 1, 2, and 3 At% each of Pb and Bi was contained in an Al matrix. The starting material was prepared by chill casting ingots with the specified compositions. These were heated to 1580K in ten minutes, held for 34 minutes, and quenched to 873K in 70 seconds. The flight samples had a reasonably well dispersed array of (Pb, Bi) particles with 90% under 50 microns, although some voids were also present. Ground control samples had almost complete phase separation, as would be expected. The flight samples were then sheathed in Cu and drawn into wires of 0.35 mm diameter. This resulted in a type II superconductor in the form of a dispersion of (Pb, Bi) fibers in an Al matrix. The superconducting transition was 8.7K, the critical field was 1.9 T, and the critical current density was 5000A/cm<sup>2</sup>.

On the D-2 mission, Sangriorgi, Muolo, Ferrari, Passerone, and Rossitto investigated the influence of crucible wetting on the phase distribution when the Cu-Pb monotectic system solidified. Cu-rich and Pb-rich melts were solidified in graphite, sapphire (Al<sub>2</sub>O<sub>3</sub>), and boron nitride (BN) crucibles. Care was taken to reduce the gradients in the system during cooling to less than 0.4K/cm to reduce Marangoni flows. When the Pb-rich phase was the majority phase, it preferentially wet the sapphire crucible and surrounded the Cu-rich phase, which is consistent with Potard's results. However, when the Cu-rich phase was the majority phase, no preferential wetting of the graphite or the BN crucible was observed and a fairly regular structure resulted. This seems inconsistent with Cahn's prediction that one of the two phases should have become perfectly wetting and spread over the wall of the crucible. However, the temperature at which the Cu-rich composition enters the two-liquid phase region may have been sufficiently lower than the critical consolute temperature so that critical wetting may have been avoided.

An attempt was made to directionally solidify hypomonotectic Al-In by Andrews and Coriell on the LMS mission. The flight sample contained a number of large voids, apparently from gas trapped or generated during the process. Care was taken to analyze the trapped gas in the ampoule and it was determined that the gas was mostly N<sub>2</sub> with some H<sub>2</sub> (hydrogen) and CO<sub>2</sub> (carbon dioxide).

On a follow-on experiment on USMP-4, Andrews elected to work with a transparent monotectic system, succinonitrile-glycerol, to elucidate the wetting and spreading characteristics of the minority phase. Test cells consisted of a sandwich of microscope slides with a thin, 0.13 mm, Teflon gasket between them. The

cells were heated to 90°C to homogenize the melt (critical consolute temperature is 83°C). They were then placed on a back-lit table for viewing with a video-equipped stereo microscope. It was anticipated that succinonitrile-rich droplets would preferentially wet the Teflon gasket so that, if succinonitrile happens to be the minority phase, the system would be unstable against critical wetting. If succinonitrile is the majority phase, the system should be stable and a uniform dispersion of glycerol droplets in the succinonitrile host phase should occur. For compositions from 70 to 55Wt% glycerol, droplets of glycerol formed on or near the Teflon gasket, but did not spread along it. Contact angles ranged from 30° to 80°. However, at 45 to 50Wt% glycerol, a film of glycerol was observed to have formed along the Teflon gasket, indicating perfect wetting. Below 45 Wt% glycerol (succinonitrile is the majority phase), stable dispersions of glycerol droplets were seen as expected. At 15Wt% glycerol, no glycerol droplets were seen near the interface as if they had somehow been repelled by the interface.

One of the applications of the research on monotectic systems is a strip casting technique developed by Metallgesellschaft in Frankfurt that balances the sedimentation of the droplets with Marangoni convection. This process can produce endless strips of finely dispersed Pb or Bi in an Al or Al +5Wt%Si alloy. Aluminum alloys with uniformly dispersed phases of Pb or Bi are presently being investigated as candidates for advanced bearing for automobile engines. The present strip casting process can provide a dispersed phase up to 7 Wt% Bi, but a higher percentage would be desirable. The process has been extensively modeled, but more information is needed on the Marangoni flows and on the resulting coalescence of the droplets. Ratke, Prinz, and Ahlborn designed an experiment for the D-2 mission to obtain the data needed to improve the model. A molten zone is passed through a strip-cast sample freeing the Bi droplets when the monotectic temperature is reached. The droplets are propelled toward the higher temperature region by thermal Marangoni convection where they begin to dissolve, creating a solutal gradient, which also influences the Marangoni convection. As the droplets move forward, a backstreaming flow is produced in the host material, which also changes the local composition. As the temperature is reduced at the cold end of the zone, the droplets the Marangoni-induced flow is reversed and the droplets tend to coalesce before they are incorporated into the dendritically solidifying Al-Si host material.

This highly complex process has been modeled computationally, but present computational capability can only track some 5000 droplets, whereas millions of droplets are involved in the actual process. Measurement of the droplet distribution in the final solid enables the extraction of important physical parameters such as the interfacial energy as a function of composition, and provides information on the importance of droplet coalescence from the Marangoni-induced droplet motion.

One problem with the solidification experiment had always been the fact that the experimenters could only see the final result and had to theorize what sequence of events must have occurred to reach the final state. For example, they had no way of knowing if the melt decomposed spontaneously, or if droplets formed and then coalesced, or if coalescence occurred during the solidification by particle pushing by the solidification front.

Otto tried to resolve this problem using the MAUS (Messenschaftliche Autonome Experiment Unter Schwerelosigkeit) facility on the orbital platform SPAS-01 (Shuttle Pallet Satellite) on the OSTA-2 mission (STS-7). Using a small X-ray source, he took shadowgraphs of the decomposition of a Ga-Hg (gallium-mercury) mixture as it was cooled into the two-liquid phase region at different cooling rates. He was able to observe individual droplets after they grew to 0.2 mm in diameter. The droplets did not appear to

be homogeneously distributed, but may have nucleated heterogeneously on low energy sites. No particle motion was observed, either from Marangoni convection, or from the residual acceleration. This is a fairly good indication that the droplets either nucleated on or stuck to the Teflon container walls.

On D-1, Ecker attempted to observe the directional solidification of the transparent succinonitrile-ethanol system using holography. Unfortunately, the film transport on the Hasselblad camera failed and the data was lost.

Similarly Braun, Ikier, Klein, Schmitz, Wanders and Woermann investigated phase separation in immiscible liquid systems using transparent analogs to metallic systems on the D-2 mission. A mixture of butoxy-ethanol and water has a region of immiscibility that is a function of pressure. The sample is stabilized at 18 bars at a temperature just below the two-liquid phase region and then the pressure is released to 1 bar. Thus the region of immiscibility is entered isothermally with no mechanical mixing. The decomposition and droplet growth was monitored holographically. Initially the droplets grew to an equilibrium diameter of approximately three microns by diffusion. They remained at this diameter for one hour with a slight increase in diameter due to Ostwald ripening, and then showed a rapid increase in diameter due to Marangoni convection when the thermostat was turned off and thermal gradients developed.

h. Particle/solidification front interactions. Small ceramic particles are sometimes added to metals to block the motion of dislocations (dispersion hardening) or for flux pinning in type II superconductors. In the preparation of composite materials, it is important to know how such particles interact with the solidification front. If the particle is not wetted by the melt, intermolecular forces will tend to repel the particle. These forces are pitted against inertia and a drag force, which tend to engulf the particle. There have been a number of theoretical attempts to model this process and it is generally accepted that, for a particular system, there is a critical velocity below which the particle will be pushed ahead of the solidification front, and above which it will be engulfed by the advancing solid. Buoyancy and convective flows complicate the picture in normal gravity and it is important to be able to separate these effects from the more fundamental interactions that take place at the solidification front.

Klein attempted to measure pushing of 40 micron Pb spheres and air bubble in a transparent CsCl (cesium chloride) melt during the OSTA-2 mission. A gradient of 65 k/cm was established in special furnace with sapphire windows that allowed the advancing solidification front to be photographed. Initially the Pb drops were pushed by a solidification front moving at 4 microns/second. Interestingly, the bubbles did not move in the direction of the thermal gradient, as would be expected from Marangoni convection, but were overtaken by the solidification front (they may have been stuck on the walls). When the bubbles were overtaken by the solidification front, they were not engulfed, but instead formed channels into the solid. Eventually, the front was disturbed by the bubbles to the point that meaningful data could no longer be extracted.

Potard and Morgand attempted to use a vapor-emulsion technique on SL-1 to obtain a uniform dispersion of bubbles in a directionally solidified Al-Zn (aluminum-zinc) ingot. The concentration of Zn ranged from 1 to 5At%. It was expected that the high vapor pressure of Zn would form a uniform distribution of gas bubbles in the final solid. For reasons that are not clear, the Al failed to wet the SiC crucible and the expected results were not achieved.

Langbein and Roth investigated the interaction of solid particles with an advancing solidification interface on D-1. A copper sample containing 1 volume% molybdenum (Mo) particles (2 to 4 microns in diameter)

was placed in an alumina container. The sample was directionally solidified with a decreasing rate. Bubbles also formed as the sample was directionally solidified. In the lower region (highest solidification speed) the Mo particles were aligned along boundaries of cellular growth. Some of the Mo particles were captured and transported by the bubbles. In some cases, Mo crystals as large as 20 microns had grown inside the bubbles. Other bubbles had filled with Cu, while others had remained as voids. Some of these voids remained spherical, while others were pear-shaped with their tails pointing toward the hot end.

Poetschke and Rogge conducted a similar experiment on D-1. They used 1 to 20 micron alumina particles as well as 1 to 4 micron Cu particles in a Cu matrix. The alumina particles formed aggregates as they were pushed by the planar solidification front. The Mo particles were strung along cellular boundaries as was the case reported by Langbein and Roth.

On the LMS mission, Stefanescu and co-workers at the University of Alabama sought to examine particle engulfment and pushing in the case of a planar solidification front intersecting spherical, non-wetting particles. He chose pure Al for the host metal and zirconia particles, which were found to be non-wetting at the melting point of Al. The starting material was prepared by casting ingots of Al with a small volume fraction of 500 micron zirconia particles. He used the AGHF to directionally solidify these ingots at different rates. Preliminary results indicated that the pushing-to-engulfment transition occurs between 1.9 and 2.4 microns/second in the ground based experiments and between 0.5 to 1.0 microns/second for the flight samples. Analysis is still in progress to ascertain whether wetting actually occurred in these samples. Stefanescu attributes the difference between the ground and flight results to convective flows near the solidification interface, which can impart a roll to the particles giving them a slight lift. This effect was seen in a transparent analog experiment using succinonitrile as a metal model.

Stefanescu repeated his experiment on USMP-4 using transparent systems so that the actual pushing and engulfment process could be observed. The choice of host materials was succinonitrile, a non-faceting material, and biphenyl, a faceting material. Polystyrene beads of varying diameters were used with the succinonitrile and glass beads were used with the biphenyl. The polystyrene beads had much lower thermal conductivity than the succinonitrile host, whereas the glass beads had much higher conductivity than their host. Several unexpected phenomena were observed. The glass beads tended to move along the surface of the biphenyl in the flight experiment, which was thought to be a result of the anisotropy of the faceted interface. Also the interface began to show signs of a cellular structure toward the end of the experiment and beads that had previously been pushed were engulfed. It was not clear if this was the result of a build-up of solute (even though extreme care had been taken to purify the material beforehand) or if the thermal gradient was somewhat lower at the end of the cuvette. As a result, only the data taken in the first 5 mm were considered.

Again the critical velocity was found to be higher on the ground than in space. This was attributed to the Saffman force resulting from convective flows that tends to lift the particle away from the interface. A theory developed by Shangguan, Ahuja, and Stefanescu predicts the critical velocity to be given by

$$v_{cr} = \left( \frac{\Delta\gamma a^2}{3\eta KR} \right)^{1/2}$$

where  $\Delta\gamma$  is the difference between the particle-liquid and the particle-solid interfacial energies,  $a$  is the atomic spacing,  $\eta$  is the kinematic viscosity,  $K$  is the ratio of particle to liquid thermal conductivity, and

R is the particle radius. This model was validated for the case of zirconia particles being pushed by Al in the LMS experiment and is within the experimental error of the lower bound for the succinonitrile-poly-styrene particles on USMP-4. However, the model predictions are much lower than the experimental data for the biphenyl-glass system. The anisotropy of the interface as well as the motion of the particles along the interface may contribute to this discrepancy.

On the LMS mission, Hecht and Rex investigated the pushing and entrapment of 13 micron  $\text{Al}_2\text{O}_3$  particles on a commercial 2014 Al alloy. They observed pushing during the plane front transient that was consistent with the model predictions of Potschke and Rogge. However, at the higher solidification velocity when the front became dendritic, they found particles trapped in the interdendritic fluid between the secondary dendrite arms and acknowledged the difficulty of extending theories based on idealized conditions to “real-world” problems.

Froyen and Deruyttere formed a number of metal matrix composites on the SL-1 mission. Micron sized SiC (silicon carbide) and  $\text{Al}_2\text{O}_3$  particles were mechanically mixed with Al powder and hot extruded into bars. The samples were then coated with an  $\text{Al}_2\text{O}_3$  skin and melted and solidified in the isothermal furnace. A more uniform distribution of particles was obtained in the flight samples and the microhardness was more uniform, a result the investigators attribute to the reduced convection and sedimentation. Additional experiments were conducted on D-1 using a Cu matrix in a graphite crucible. Again the  $\text{Al}_2\text{O}_3$  particles were uniformly dispersed and the flight sample had improved hardness. The SiC particles decomposed, the Si forming a solid solution with the Cu while the graphite was expelled. The W and Mo particles oxidized near the presence of gas bubbles and were not uniformly distributed.

Muramatsu and Dan reported that they obtained uniform dispersions of TiC (titanium carbide) in Ni by heating specimens prepared by powder techniques in the Large Isothermal Furnace (LIF) during the SL-J mission. No further details were given.

Also on SL-J, Suzuki with Miura and Mishima coated short carbon fibers with Al-1 At% In and heated the aggregate to 700°C for ten minutes to form an ultra-low density (10% that of Al) composite material with high stiffness, suitable for on-orbit fabrication of structural components. They did find some unexpected local coagulations of Al in regions where the coatings on the fibers were drawn away. This led to a somewhat lower compression strength of the composite than had been expected.

One of the more important “real world” problems has to do with attempts to dispersion harden superalloy single crystal gas turbine blades by incorporating very small (submicron) oxide particles during the growth process in order to increase their creep resistance. A uniform dispersion can be achieved by powder metallurgical techniques, which can then be made denser by hot isostatic pressing (HIP). But when the blade is melted so that it can be directionally solidified into a single crystal, the particles tend to agglomerate and are not uniformly incorporated into the superalloy matrix. The solidification velocities required to achieve plane front solidification are generally below the critical velocity for engulfment of such small particles. At higher solidification, the particles tend to be pushed laterally by the dendrites and wind up being clumped together, trapped in the last-to-freeze interdendritic fluid. This problem prompted several flight experiments by industrial firms trying to sort out gravitational effects from non-gravitational effects that remain as barriers to developing this process.

One group of experiments focused on the use of a thin oxide skin to replace the ceramic moulds used to form the turbine blades. It was hoped that in the absence of hydrostatic pressure, a thin skin could retain the shape of the blade during the directional solidification process. Eliminating the heat transfer through the mould would allow a much sharper thermal gradient to be applied during the directional process, which helps stabilize the growth front at higher solidification velocities. One of the major difficulties had to do with keeping the skin intact during the volume changes involved during the melting and solidification process.

The use of “skin technology” was first demonstrated on Spacelab-1 by Luyendijk, Nieswaag, and Alsem who directionally solidified a gray cast iron ingot with a 50 micron  $\text{Al}_2\text{O}_3$  skin. Gray cast iron actually shrinks on melting so the alumina skin did not have to withstand a volume expansion from melting. In fact the melt separated into two parts during the process. The skin remained intact during the process, although some micro-cracks were observed. Small iron droplets were found along the outer surface of the skin. It was speculated that they formed by condensation from the vapor. A similar experiment was flown on D-1 by Nieswaag and Sprenger with the objective of determining the diffusion of sulfur in the cast iron. Again the skin kept its shape with only a few drops that squeezed through the pores, but it was not clear if free surface existed near the thermocouple grooves. Unfortunately, problems with the translation mechanism prevented an accurate assessment of the diffusion of the sulfur.

On the D-2 mission Amende solidified a cast iron rod in which portions were alloyed with different compositions of Cr (chromium) and Si. The rod was coated with a thin skin of MgO-stabilized zirconia. The thermal expansion of the alloys was twice that of the zirconia skin. The objectives were to see if the ceramic skin could accommodate the alloys during melting and resolidification, and to see if any of the alloys reacted with the skin. The skin did successfully contain the melt, although the portion containing the Cr alloy detached from the remainder of the rod. It was speculated that the skin was preferentially wetted by the Cr alloy, and that the interfacial tension was responsible for the separation of this portion.

Barbieri and Patnelli with Gondi and Montanari investigated a variety of composites, some using powder Ag-Cu as the eutectic composition and others using powder Al as the matrix, some with  $\text{Al}_2\text{O}_3$  film coating, some with Ni coating, and others with no coating. Some samples contained micron-sized  $\text{Al}_2\text{O}_3$  particles, while others were compacted to 85% fractional density so that bubbles would serve as the dispersed phase. Generally, the  $\text{Al}_2\text{O}_3$  coatings retained their shape during solidification, although some leakage was observed. The lamella spacing in the micro-g eutectic samples were twice as large as the 1-g counterparts, which was attributed to a slower cooling rate resulting from less thermal contact in the low-g case. For the most part, the bubbles were swept by the solidification front to phase and grain boundaries. The oxide particles tended to aggregate in both space and ground control samples, although the aggregates appeared to be more uniformly distributed in the space samples.

Confinement of the melt and shape retention in a superalloy was successfully demonstrated on the D-1 mission by Sprenger, using a gamma/gamma prime-alpha, Ni/Ni<sub>3</sub>Al-Mo alloy coated with an 80 micron thick yttria (Y) -stabilized zirconia skins that had been applied by plasma spraying. (A similar experiment was attempted on SL-1, but could not be run because of technical difficulties.) Volume expansion was successfully compensated for by a small hole drilled into the end of the sample. Shape was maintained through the cylindrical sample and into the flattened region near the end. There were no holes or pores in the sample and no evidence of Marangoni convection, which indicated that the melt had remained in contact

with the skin. Directional solidification of this alloy produces a regular arrangement of Mo fibers contained within a Ni/Ni<sub>3</sub>Al (gamma/gamma prime) matrix. The flight sample exhibited a carbide phase not seen in earth-processed samples. It was suggested that convective flows may transport the carbon away from the solidification front, thus preventing this phase from forming during processing in normal gravity.

On D-2, Amende and Holl attempted to melt and resolidify actual gas turbine blades that had been formed by powder techniques and coated with a 150 micron yttria-stabilized zirconia skin. The blade material was the Ni-base CMSX6 superalloy with 0.5Wt% 50nm Al<sub>2</sub>O<sub>3</sub> particles. The coating remained intact, but the evolution of the gas trapped in the pores of the pressed powder sample caused swelling of the oxide skin and the loss of shape.

Busse along with Deuerler and Poetschke investigated the gravitational influence on the aggregation of submicron Al<sub>2</sub>O<sub>3</sub> powders on the D-2 mission. It had originally been speculated that such powders tend to agglomerate because they were not wet by their metallic host. If the metal melt did not penetrate the region between two touching particles, London-van der Waals forces would cause the particles to clump together. However, preflight ground based tests revealed that the particles tended to clump whether or not they were wet by the molten. Further, it was found that the particles tended to clump into micron-sized spherical clusters by Brownian motion as soon as the CMSX-6 superalloy matrix melted. These clusters they tended to form chains on the order of 10 microns long during the solidification process. The chains of clustered particles became trapped in the interdendritic fluid where they tended to be aligned by the dendrites. The only significant difference between the flight and ground samples was a slight increase in the size of the clusters and length of the chains in the ground control experiments, indicating that gravity had little influence on the agglomeration process.

## **B. Crystal Growth Experiments**

### *1. Introduction.*

Semiconductors as a class of materials can include semi-metals, ceramics, and polymers. They are characterized by the fact that they have a small energy gap (less than a few electron volts) between their valence band and their conduction band. Because of this small energy gap, they can be easily manipulated to either conduct or not conduct electricity, a property that provides the means for modern electronics. Unlike most metals, in which the current is carried by electrons, conduction in semiconductors takes place through the action of both electrons in the conduction band and holes left by the electrons in the valence band. These materials can also absorb photons to promote electrons from the valence band to the conduction band to act as detectors of radiation or solar energy converters. Finally, certain of these materials can be configured so that current flowing through them reunites electrons in the conduction band with holes in the valence band to produce photons, giving rise to light emitting diodes and solid state lasers.

The ability to grow large, extremely pure, single crystals of silicon was key to the vast electronics industry that has been developed over the last several decades and silicon will continue to dominate this industry for the foreseeable future. It is plentiful, cheap to produce, and has all of the desired properties needed for most applications. It does have a few drawbacks, however. The charge carrier mobility is relatively low, so it is not suitable for very high frequency applications or high speed switching applications. Also, it is not a direct band gap material, meaning that electrons cannot directly go from the conduction band to the

valence band, emitting light in the process. Therefore, it is not suitable for making the solid-state lasers that are finding wide use in the optical communications industry.

For these reasons, there has been considerable attention paid to compound semiconductors such as gallium arsenide (GaAs) because of the high charge carrier mobility that allows much higher switching speeds than Si. Unlike silicon, GaAs is a direct bandgap material, meaning that an electron can fall directly from the conduction band to the valence band and emit a photon of light with an energy equal to the bandgap energy. Thus such a material can be used to fabricate light emitting diodes (LED) or solid-state lasers. Thus it can be used as both a transmitter and a receiver on the same chip in fiber optical systems. Its unique band structure allows it to be used as a Gunn-effect oscillator for low cost radar devices. Its higher bandgap allows it to operate at higher temperatures and makes it less susceptible to radiation effects. This feature makes it a more desirable material for use in extreme environments such as in geocentric or deep space missions.

It is also possible to combine elemental or compound semiconductor systems to form solid solution alloys with a band gap somewhere between the band gap of the initial components. Thus it becomes possible to engineer materials to obtain a particular band gap for a specific application. For example, cadmium atoms may be substituted for 20% of the mercury atoms in mercury telluride (HgTe) to form  $\text{Hg}_{0.8}\text{Cd}_{0.2}\text{Te}$  that has a band gap equivalent to 10.6 microns, the wavelength of a  $\text{CO}_2$  laser. This class of materials has found extensive use as infrared detectors and thermal imaging devices.

Most electronic or opto-electronic applications require compositionally homogeneous, high quality single crystals. However, materials of interest are not necessarily restricted to the more traditional semiconducting materials (those found in groups II through VI in the periodic table). Many organics and even some polymers have interesting optical and opto-electronic properties. Studies of single crystals are important to other fields as well; for example, the study of zeolite crystals as catalysts. To include this broader spectrum of activities involving crystal growth, this section will cover all of the microgravity experiments where crystal growth is the primary emphasis (except for protein or other biological macromolecules – here the number of experiments is so large that they require a separate section).

## *2. Melt Growth of Electronic and Photonic Materials.*

The conductivity of semiconducting materials is extremely sensitive to the presence of trace quantities of certain impurities called dopants, which are often added to bulk semiconductors in order to tailor their electrical properties for a specific task. It is important that the concentration of these dopants be uniform throughout the material so that the electrical properties will be the same. Generally, these impurity atoms are not incorporated into the lattice as readily as the host atoms, which leads to a phenomenon known as segregation. When solidifying from the melt, the rate at which the impurity or dopant atoms are incorporated into the growing crystal is directly proportional to their concentration at the growth interface. Ideally, the concentration of rejected atoms will build up in front of the growth interface as growth proceeds to form a diffusion layer. Eventually, an equilibrium is reached wherein the rate at which dopant atoms from the feed are entering the diffusion layer equals the rate at which the dopant atoms enter the growing crystal. Growth under these conditions is said to be diffusion controlled and once this equilibrium condition is reached, the remainder of the material will have uniform composition.

Convective flows can cause the dopants to be distributed non-uniformly, both on a microscopic scale (microns) as well as macroscopically. Global flows in the melt will tend to stir the diffusion layer containing rejected component back into the bulk liquid, thus preventing the diffusion controlled equilibrium to be reached. The result is a continuously varying composition as growth proceeds. Microscopic non-uniformities, usually in the form of striations, were believed to be a result of growth rate fluctuations caused by unsteady or turbulent convective flows in the melt. If the unsteady flows caused the temperature at the growth interface to fluctuate, even slightly, the interface will jump ahead and fall back as growth proceeds. More dopant atoms are incorporated when the growth front is accelerated, thus forming what are known as type I growth rate striations. The early Skylab experiments demonstrated that growth striations in dilute systems such as doped elemental or simple compound semiconductors, could be eliminated in microgravity and that diffusion controlled growth conditions could be established. This prompted a number of attempts to grow bulk multi-component alloy-type systems with the objective of obtaining better compositional homogeneity necessary to achieve uniform electronic and optical properties.

a. Bridgman growth. In the Bridgman growth technique, developed by Percy Bridgman at Harvard University, the entire sample is melted (except for the seed if a seed crystal is used) and then the sample is slowly lowered from the furnace to allow the material to solidify so that the successive rows of atoms build up in an ordered fashion to form a single crystal. Stockbarger later added a second heater at the cold end of the furnace to provide better control of the growth interface and to reduce the sample cooling rate in order to reduce thermal stresses in the newly formed crystal. Technically, this should be called the Bridgman-Stockbarger technique, although Bridgman growth is a more-or-less generic term for any directional growth method.

By placing the hotter melt above the cooler growth region, the system is thermally stable and convection can be minimized. However, it is necessary to add heat to the melt through the sides of the growth ampoule and extract it through the growing crystal. This produces small radial thermal gradients in the melt causing the warmer fluid near the walls to rise while the cooler melt near the center falls. This circulation distorts the buildup of the diffusion layer at the growth interface resulting in radial segregation. This effect was first quantified by Brown (1985) using computational fluid dynamical computations.

Macrosegregation becomes a major problem in Bridgman growth of non-dilute or alloy-type systems when the rejected component is less dense than the bulk melt. When the diffusion layer builds up to a critical point, characterized by a dimensionless parameter called the Rayleigh number, its lighter fluid will rise and remix with the bulk fluid. If the growth system is turned upside down to prevent this from happening, the system becomes thermally unstable. Thus it becomes impossible to stabilize such a system against overturning convective flows in the presence of gravity. In fact, Coriell (1980) has shown that such double-diffusive systems may be unstable even in microgravity if the lower density component is more than a few percent of the total composition.

Rodot grew three Ag-doped PdTe crystals that were 17 mm in diameter by the Bridgman method on SL-1. She reported better homogeneity and somewhat lower dislocation densities on the flight samples as compared to the ground control that exhibited growth striations.

Crouch and Fripp from the NASA Langley Research Center attempted to grow homogeneous lead-tin-telluride ( $\text{Pb}_{0.8}\text{Sn}_{0.2}\text{Te}$ ) in the General Purpose Rocket Furnace (GPRF, a relic left over from the SPAR (Space

Applications Rocket) suborbital program) on the D-1 mission and observed almost complete mixing. This material is similar to mercury-cadmium-telluride (MCT) and is of interest for infrared detector and laser applications. The rejected component in this system (SnTe) is less dense than the host material and therefore is subject to the double diffusive instability predicted by Coriell. Whether or not this experiment met Coriell's stability criterion was not established, nor were there any accelerometers on the mission that could record the direction and magnitude of the quasi-steady residual acceleration.

The experiment was repeated on USMP-3 using the Advanced Automated Directional Solidification Furnace (AADSf). Computational analysis indicated the minimal mixing should occur if the g-vector was nearly along the furnace axis with hot over cold. Three identical ampoules were loaded into a single cartridge for sequential processing. The first ampoule was to be processed with the g-vector was nearly along the furnace axis with hot over cold, the second with the g-vector was nearly along the furnace axis with cold over hot, and the third with the g-vector nearly perpendicular to the furnace axis. The plan was to compare the solute redistribution with the orientation during growth. For reasons that are not clear, large voids appeared in each of the samples and they were essentially completely mixed. This experiment was repeated on USMP-4. Unfortunately, a growth ampoule ruptured during the growth process and no results were obtained.

Yamada and Kinoshita also grew PbSnTe by the Bridgman method using the Gradient Heating Furnace on SL-J. Their ampoule contained a plunger to keep the melt in contact with the ampoule walls. Even so, they found voids in the flight sample. However, the fraction of Sn remained about 0.16 after the initial transient, indicating little or no convective mixing. The etch pit density ranged from  $1 \times 10^5$  to  $9 \times 10^5 \text{ cm}^{-2}$ , or about 1/10 the typical value for Earth grown crystals. The intrinsic carrier density is also lower in the space grown crystal and the mobilities are  $1580 \text{ cm}^2/\text{Vs}$  at 77K and  $2620 \text{ cm}^2/\text{Vs}$  at 4.2K, about three times higher than typical Earth grown values. A small amount of melt leaked past the plunger and formed small spherical crystals. The etch pit density in these crystals that formed without wall contact was  $O(10^4 \text{ cm}^{-2})$ .

Tatsumi, Shirakawa, Murai, Araki, and Fujiwara grew the ternary  $\text{In}_{0.97}\text{Ga}_{0.03}\text{As}$  by the Bridgman method on SL-J with the purpose of determining the solute redistribution in the grown ingot. A plunger was used to eliminate free surfaces in the melt. They report an effective distribution coefficient of 2.6 versus a value of 3.2 for their ground control, indicating that considerable convective mixing had taken place.

Matthiesen grew two Se (selenium)-doped GaAs crystals in the Crystal Growth Furnace on USML-1. The objective was to obtain a uniform dopant distribution, both axially as well as radially. A second objective was to examine the effects of transients on dopant distribution. Two translation periods were executed, the first at 2.5 microns/second and after a specified time, which was different between the two experiments, the translation rate was doubled to 5.0 microns/second. The translation was then stopped and the remaining sample melt was solidified using a gradient freeze technique in the first sample and rapid solidification in the second sample. Post-flight using quantitative infrared transmission imaging, indicated that the first sample initially achieved diffusion controlled growth as desired. However, after about 1 cm of growth, the segregation behavior was driven from a diffusion controlled growth regime to a complete mixing regime. Measurements in the second flight sample indicated that the growth was always in a complete mixing regime. In both experiments, voids in the center line of the crystal, indicative of bubble entrapment, were found to correlate with the position in the crystal when the translation rates were doubled.

The experiment was repeated on USML-2 using a new method for preparing the sample that eliminated the voids seen in the USML-1 flight sample. The first sample went polycrystalline at the meltback interface. The furnace temperature was adjusted to move the predicted growth interface for the second sample toward the hotter part of the furnace. It grew as a single crystal for 5 mm before the onset of polycrystalline growth. Both samples had an initial growth rate of 0.5 microns/second. The interface shapes through the growth have been marked by Peltier pulsing. The dopant distribution has not yet been published.

On D-2, Duffar and Abadie grew crystals of Te doped GaSb and  $\text{Ga}_{0.9}\text{In}_{0.1}\text{Sb}$  using ampoules whose sides were covered with super insulation to provide an axial heat flow through the sample. Heat was conducted into and out of the ampoule through graphite plugs at either end. The objective was to measure solute redistribution during the Bridgman growth process and to investigate the dewetting effect that had been observed in many previous microgravity directional solidification experiments. For this purpose, the silica ampoules were roughened to reduce the wetting by the melt. One of the seeds for the growth of  $\text{Ga}_{0.9}\text{In}_{0.1}\text{Sb}$  contained only 2% In in order to eliminate the growth transient. Two of the ampoules broke, but the liquid was trapped and did not escape. The liquid did not appear to have wet the roughened ampoules, but the roughness apparently caused parasitic nucleation. The dilute sample had an axial solute distribution indicative of diffusion-controlled transport, but the non-dilute samples showed extensive mixing. No information was reported on the radial segregation.

Duffar also investigated the effects of interface curvature in a non-dilute pseudo-binary system,  $\text{In}_{0.20}\text{Ga}_{0.80}\text{Sb}$  using the AGHF on the LMS flight. It was also hoped to obtain more information on the ampoule dewetting phenomenon seen in many microgravity directional solidification experiments. The rejected InSb is denser than GaSb, so the system can be both thermally and solutally stable. However, since the freezing point is compositionally dependent, the interface will generally not be an isotherm. Two different crucibles were used: a quartz crucible, which has a low conductivity and should minimize the interfacial curvature, and a BN crucible, which is a better conductor and should produce a more curved interface. Since the macrosegregation was the object of interest in the experiment, no attempt was made to grow a single crystal. The flight samples exhibited the classic profile for complete mixing as described by the Scheil equation. This surprising result is still not understood.

Alloy systems that are stable against double-diffusive convection (rejected component more dense than the bulk melt) are subject to another source of radial segregation. This comes about because the thermal conductivity of many semiconductor systems is greater in the melt than in the solid. The heat flow from the melt into the solid is complicated by the presence of the wall of the growth ampoule, which often has a thermal conductivity between that of the solid and the melt of the sample material. This causes some heat to flow from the melt into the wall at the growth interface causing the interface to become concave. If the rejected component is more dense than the bulk melt, it will tend to flow toward the lowest point on the solidification interface and, since the rejected component will generally lower the freezing point, the interface will become even more distorted. Radial segregation produced by this mechanism prompted attempts to grow alloy systems such as HgZnTe and HgCdTe in microgravity.

Before the USML-1 flight, it was recognized that for good macroscopic homogeneity to be obtained in the more demanding Bridgman growth systems, it would be necessary to minimize transverse accelerations by keeping the Crystal Growth Furnace (CGF) axis more-or-less aligned with the quasi-steady residual acceleration. A major portion of this mission was flown with the orbiter's attitude calculated to do just

that. Lehoczky from the NASA Marshall Space Flight Center prepared a  $\text{Hg}_{0.84}\text{Zn}_{0.16}\text{Te}$  experiment, which was considered to have the most stringent requirement for this condition. However, unanticipated venting forces imparted a very slight, approximately 0.5 micro-g, transverse acceleration throughout most of the flight. Lehoczky's experiment was terminated prematurely which prevented a detailed analysis of his sample, but dopant inhomogeneities consistent with this unanticipated acceleration could clearly be seen in the portion that could be analyzed.

For technical reasons, USML-2 could not meet Lehoczky's stringent attitude requirements, but he was able to fly  $\text{Hg}_{0.8}\text{Cd}_{0.2}\text{Te}$  sample in the Advanced Automated Directional Solidification Furnace (AADSf) on USMP-2. During the USMP-2 mission, the orbiter was maneuvered into several different attitudes so that the residual g-vector made varying angles relative to the growth direction. Lehoczky reports.

“Significant differences were observed during three long, but uninterrupted, periods at constant attitude. Compositional variations along the crystal circumference indicate residual fluid flows for the least favorable vector orientations. Identifiable regions exist in which a transverse vector has pushed the material against the ampoule wall and allowed it to readily contract away from the opposite wall. Such surfaces showed etch pits produced by preferential evaporation at defect sites. X-Ray scattering showed that the regions pulled away from the wall tended to be less strained or of higher quality material than the opposite surface, and considerably better than the Earth-grown material. Composition determination on the surface of the material demonstrated significant difference dependent on the direction of the residual acceleration vector. These are clear indications of three-dimensional fluid flow. A significant portion of the boule was grown with a component of the vector aligned in a direction from liquid to solid. Synchrotron X-ray studies of this material showed it to be single crystal and of much lower defect density.”

An attempt to re-fly Lehoczky's experiment on USMP-4 was thwarted when a ruptured ampoule from another experiment shut down the furnace before his sample could be processed.

Since Lehoczky's requirements could not be met on USML-2, a substitute experiment was flown to explore the important question of the effect of furnace orientation relative to the residual g-vector on solute redistribution during directional solidification experiments. Lichtensteiger prepared a Ga-doped Ge sample. This model system was chosen because its characteristics are well-understood. Two analytical techniques were used to characterize the material, Peltier pulsing to mark the interface periodically, and high resolution spreading resistance measurements to map out the dopant distribution. The first crystal growth was started with the Shuttle in the most favorable attitude for crystal growth. Later, the attitude was changed to a gravity gradient attitude. The average dopant profile appears to be purely diffusive throughout the entire growth. No change was seen as a result of the maneuver. However, there is a consistent difference in dopant concentration across the sample that is indicative of flows that would produce radial segregation. (Unfortunately, acceleration data at the furnace is not given.) A second crystal was grown during a period when the Shuttle was in the solar inertial attitude. Since this attitude is unstable with respect to the gravity gradient, frequent thruster firings are required. Significant disturbances were seen in the dopant profile for the growth that took place during this attitude.

These results clearly demonstrate the extreme sensitivity of this type of growth system to very small accelerations and verify the predictions based on computational fluid dynamical modeling. They also provide additional evidence that wall effects play a significant role in defect formation.

In many of the earlier American and Russian Bridgman growth experiments in reduced gravity, the solidified ingot was found to be smaller than the growth ampoule and the melt appears to have pulled away from the ampoules during the solidification process. The effect was noticed on the first directional solidification experiments flown on Skylab and several of the investigators reported fewer growth defects in the portions of the sample that apparently solidified without wall contact. Several theories have been suggested to explain why the growing crystal might avoid wall contact in microgravity, but the exact mechanisms have not yet been tested or verified. Clearly, partial wall contact would affect the heat transfer, something that is not considered in setting up the experiment, which could place the growth front in a non-optimum position in the furnace. The existence of free surfaces also opens the possibility for Marangoni convection that can produce unwanted mixing of the diffusion layer with the bulk melt.

Single crystalline CdTe is widely used as a substrate for focal plane arrays as well as for nuclear detector applications. Because of its high bandgap, it is transparent to infrared radiation, so it can serve as a window for the HgCdTe detectors, which can be grown epitaxially directly onto the CdTe window. However, it is difficult to grow CdTe with low dislocation densities and it has a tendency to form twins. Often small quantities of Zn are added to strengthen the lattice. Larson wanted to investigate how gravity might influence the formation of these defects in  $\text{Cd}_{0.95}\text{Zn}_{0.05}\text{Te}$ . Because of the small mole fraction of Zn and because its distribution coefficient is close to 1, macrosegregation is not a serious problem when growing this material in normal gravity. Since the melt in Larson's experiment had some void space in the growth ampoule to allow for thermal expansion, the unanticipated 0.5 micro-g lateral acceleration from the venting on USML-1 had the fortuitous effect of nudging the melt against one wall of the growth ampoule and leaving the opposite side of the melt free of wall contact. For his flight results, Larson reported.

“Macrosegregation was predicted, using scaling analysis, to be low even in one-g crystals and this was confirmed experimentally, with nearly diffusion controlled growth achieved even in the partial mixing regime on the ground. Radial segregation was monitored in the flight samples and was found to vary with fraction solidified, but was disturbed due to the asymmetric gravitational and thermal fields experienced by the flight samples. The flight samples, however, were found to be much higher in structural perfection than the ground samples produced in the same furnace under identical growth conditions except for the gravitational level. Rocking curve widths were found to be substantially reduced, from 20/35 arc seconds (in one-g) to 9/20 arc seconds (in  $\mu\text{-g}$  [microgravity]) for the best regions of the crystals. The FWHM of 9 arc seconds is as good as the best reported terrestrially for this material. The ground samples were found to have a fully developed mosaic structure consisting of subgrains, whereas the flight sample dislocations were discrete and no mosaic substructure was evident. The defect density was reduced from 50,000-100,000 (in one-g) to 500-2500 EPD (in  $\mu\text{-g}$ ). These results were confirmed using rocking curve analysis, synchrotron topography, and etch pit analysis. The low dislocation density is thought to have resulted from the near-absence of hydrostatic pressure which allowed the melt to solidify with minimum or no wall contact, resulting in very low stress being exerted on the crystal during growth or during post-solidification cooling.”

Larson repeated this experiment on USML-2 using a novel ampoule design that would minimize wall contact with the sample. He was able to grow 20 mm of sample without any wall contact and 21 mm with only partial wall contact. A second sample had a spring-plunger system that forced the sample to fill the ampoule, thereby assuring wall contact. Preliminary analysis showed that twin formation was virtually zero in the region grown without wall contact, whereas the sample in the spring-loaded ampoule was highly strained at the exterior and heavily twinned.

These results clearly demonstrate that wall effects are a major source of defect formation on the ground as well as in space grown crystals.

b. Traveling heater method. A variation of the Bridgman growth technique is the traveling heater method (THM). Instead of melting the entire charge, only a small portion of the charge is melted and the molten zone is moved through the sample by the traveling heater. Usually the dopant atoms of interest have a small distribution coefficient meaning that only a small fraction of the dopants in the melt will be incorporated into the solid. Thus a specific quantity of dopant can be added to the initial zone to be melted and this quantity will remain almost the same as the zone is moved through the sample. This process, known as “zone leveling”, produces a reasonably uniform distribution of dopant on a macroscopic scale. However, turbulent flows in the molten zone can still result in microscopic inhomogeneities or striations.

For compound systems, such as gallium arsenide (GaAs) or cadmium telluride (CdTe), the material is often grown by the traveling solvent zone, a variation of the traveling heater method in which the melt contains an excess of the metal. The excess metal lowers the melting point of the solution, which allows the growth to take place at lower temperatures and also lowers the vapor pressure of the volatile component. The lower growth temperature reduces the number of inherent point defects that will always be present in crystals, and also reduced the thermal stress on the lattice, which generally reduces the dislocation density.

Schoenholtz, Dian, and Nitsche grew Cl-doped CdTe crystals by the traveling heater method using a Te solvent zone on SL-1 and on D-1. The SL-1 experiment was terminated prematurely which caused the crystal to crack, but the experiment was repeated on D-1. There were some problems with the heating lamp in the Mirror Heating Facility (MFT) and the rotation mechanism failed. As a result, the traveling zone was asymmetric and the desired temperature was not reached. The etch pit density (a measure of dislocations) was 5 to 10 times lower than the seed on the hot side of the grown material, but was many times higher on the cooler side.

Benz and Danilewsky at the Institute of Physics, University of Stuttgart, together with Nagel, Wacker-Chemtronics, also carried out a series of growth experiments with doped compound semiconductor using the traveling heater method (THM). The mono-ellipsoid ELLI furnace (Elliptical Mirror Furnace) was used to process a 15 mm diameter S-doped InP and a 10mm diameter Te-doped GaSb during the SL-1 and D-1 missions. Benz reported reduced striations in the InP sample and the “space-grown Te doped GaSb crystal was found to be nearly striation free with only residual dopant inhomogeneities, while ground-processed crystals showed pronounced structures of rotational and non-rotational periodic striations over the whole cross section of the crystal” (the sample is rotated to smooth out axial thermal inhomogeneities which causes the rotational inhomogeneities). On the D-2 mission, a 20 mm diameter GaAs crystal was grown from a traveling Ga solvent zone. The heater lamp was dimmed periodically to mark the growth interface. The results were very much like those obtained on the D1 flight in that the type I striations due to convection driven growth rate fluctuations were eliminated.

Harr, Dornhaus, and Brotz grew the solid solution ternary, lead-tin-telluride ( $\text{Pb}_{0.8}\text{Sn}_{0.2}\text{Te}$ ) from a Pb-Sn rich solution during the D-1 mission. As mentioned previously, this material is subject to double-diffusive convection and is impossible to stabilize using the Bridgman growth technique in normal gravity. The traveling solvent zone technique has the advantage that complete convective mixing in the solvent zone is not undesirable because the source material is continually feeding new nutrient into the traveling solvent zone, thus keeping the composition more-or-less constant. However, it is essential to control the solvent zone temperature very precisely in order to obtain the desired composition of the growing solid. Harr found improved compositional homogeneity in the flight sample whereas “a tin content segregation was found in THM part of the earth-grown sample, but not in the microgravity sample. Additional oscillations of tin content were found along the entire ground sample.” It was noted that the diameter of the flight crystal was slightly smaller than the ampoule and that growth facets and etch pits could be seen on the surface. In the absence of hydrostatic pressure, the melt did not press against the wall, allowing the solid to form without direct wall contact. Selective evaporation from the free surface apparently formed the etch pits. The material was p-type and the hole mobility was found to be  $5500 \text{ cm}^2/\text{Vs}$  in the microgravity sample, compared to  $1900 \text{ cm}^2/\text{Vs}$  found in the ground-based reference sample. Harr attributes this improvement to a reduction of scattering centers induced by a reduction of stresses produced by contact with ampoule wall.

Iwai and Segawa grew single crystal  $\text{PbSnTe}$  by the travelling zone method using the mirror furnace on SL-J. The starting material was a 10 mm diameter Bridgman-grown rod of  $\text{PbSnTe}$ . A zone was melted and translated at 2 mm/hr for 4 hours. Te bubbles were observed on the surface of the molten zone. On the ground control, these bubbles rose, creating a void, which eventually caused the zone to become unstable and break. The bubbles in the flight sample remained distributed in the molten zone, but no void was found in the grown crystal. The Sn content in the grown crystal increased with distance from the seed but eventually leveled off as equilibrium in the zone was reached. Again it was found that intrinsic carrier concentration was lower and mobility was higher in the micro-g sample.

c. Floating zone growth. In the traveling heater method described above, the samples were enclosed in quartz ampoules. However, short molten zones can be supported by their surface tension even in normal gravity and much larger zones can be deployed in microgravity. Removing contact with the ampoule wall offers many potential advantages such as elimination of contamination from the wall material (a serious problem at high temperatures), elimination of wall-induced stress which cause dislocations, and elimination of heat transfer through the wall in the vicinity of the growth interface which warps the isotherms in this critical region causing growth defects. However, thermal gradients along the freely suspended melt can drive strong and even turbulent convective flows (Marangoni convection). Steady flows in the molten zone may even be desirable since they tend to homogenize the composition of the melt, but turbulent flows can produce unwanted growth rate striations. Because of this, Marangoni convection has been the subject of intense study, both from the fluid dynamists as well as from the crystal growers.

Eyer and Nitsche from the Kristallographisches Institut Universitat, Freiburg, grew P (phosphorus)-doped Si using the Mirror Heating Facility on the SL-1 mission. They found that the striations in the flight sample were similar to those seen in the ground control sample and concluded that turbulent Marangoni convection, rather than buoyancy-driven convection, was indeed responsible for the striations. Croell and Nitsche repeated this experiment on D-1 in which the Si rods were coated with a 5micron thick, coherent, amorphous silica film. Two sources of boron were also deposited on the surface to serve as the dopant.

Despite some technical difficulties with sample overheating, they were able to show that the thin Si coating was effective in suppressing Marangoni flows.

Koelker used a pedestal melt technique to solidify a Si sample with free surfaces (similar to the method used by Walter to solidify an InSb drop on Skylab). The end of a Czochralsky-grown Si rod was melted in the mirror furnace to form a spherical drop approximately 1 cm<sup>3</sup>. On SL-1 the sample was rotated at 10 rpm (rotations per minute) as it was pulled out of the furnace at 1 mm/minute. The initial molten silicon drop was spherical, but the growing crystal very strongly deviated from the spherical shape and assumed more or less the shape of a rocket nose (conical) once solidified. Post-flight examination of the sample revealed that a thin, dark surface layer had formed on the surface of the specimen, probably due to a carbon-based impurity of unknown origin. Initially, only widely spaced striations were observed which appeared to be associated with the rotation and translation of the sample (due to the heating asymmetry of the double ellipsoid furnace). Toward the end of growth, more closely spaced striations were seen and attributed to non-steady Marangoni flows. On D-1, the sample was not rotated and remained uncontaminated. In this case, a dense pattern of randomly fluctuating striations were seen which are clearly due to non-steady Marangoni flows.

Nishinaga, Sugano, Saitoh, and Katoda (University of Tokyo) wanted to see if Koelker's result may have been due to thermal non-uniformities in the image heating furnace, so they used a more stable resistance heated furnace on their SL-J experiments. In one of their experiments, they heated a single crystalline Si rod to form a spherical drop, similar to that of Koelker, except for the use of a resistance-heated furnace. Unfortunately, instead of the drop remaining at the tip of the rod, it moved to the side where it contacted the quartz ampoule and broke into pieces as it cooled. In the second experiment, they heated a single crystal of Si in the form of a sphere that was contained in a quartz crucible. The plan was to melt the outer layers of the sphere and allow it to recrystallize using the unmelted center as the seed. However, the molten Si got through the quartz ampoule and touched the Ta (tantalum) cartridge, which resulted in a eutectic reaction causing a loss of Si. Consequently, the regrown region was a hemisphere with several facets on the outer surface. This portion, when cut and polished, revealed no striations.

Carlberg, Camel, and Tison grew two 10 mm diameter gallium-doped germanium crystals using the float zone process during the D-2 mission. The evacuated growth ampoules had getters to remove any traces of oxygen and other impurities that might contaminate the melt surface. Seebeck voltage measurements were made to detect growth rate fluctuations that might occur from unsteady Marangoni convection. No fluctuations were observed, although an asymmetrical dopant distribution in the sample was attributed to steady Marangoni convection.

Building on the findings from SL-1 and D-1, several investigators attempted to grow gallium arsenide on D-2. As mentioned previously, gallium arsenide (GaAs) is a material of great technological importance. Being a compound rather than an elemental system, the growth problems with GaAs are multiplied. Not only is it necessary to be able to control dopant homogeneity and structural defects, but stoichiometry must also be controlled, which means an overpressure of arsenic vapor must be maintained to prevent loss of this volatile component. Unlike silicon, which has a strong covalent bond and can be grown dislocation-free in large diameters by the float zone process on Earth, the surface tension to density ratio of GaAs limits the diameter that can be grown by the float zone technique on Earth to about 7 to 8 mm in diameter, too small for device applications. The mixed ionic-covalent bonds in GaAs are weaker and dislocations and

other defects form more readily. As a result, dislocation densities tend to be fairly high, typically on the order of  $10^5/\text{cm}^2$ .

Hermann and Muller from the Institut fuer Werkstoffwissenschaften, Universitat Erlangen, grew four single crystals of silicon doped-gallium arsenide by the float zone process that were 20 mm in diameter, more than twice the diameter than can be grown by float zone in normal gravity. A special heater controls an arsenic source to provide the necessary arsenic overpressure. As a result, stoichiometry was maintained with no evidence of either gallium or arsenic precipitates. They were able to control the shape of the growth interface by controlling the height of the molten zone. When the interface was nearly flat, the dislocation density dropped to  $5 \times 10^3 \text{ cm}^{-2}$ . Rocking curve width, which measures the internal order of the crystal, was as low as 11.6 seconds of arc, comparable to the best quality crystals grown on Earth. Dopant striations were observed, which were attributed to unsteady Marangoni convection. A cobalt-samarium (Co-Sm) magnet was inserted near the end of several samples to help suppress the Marangoni convection, but the field was too weak to prevent unsteady Marangoni flows. Similar results were obtained by Croell, Tegetmeier, Nagel, and Benz with Te-doped gallium arsenide.

Nakatani, Takahashi, Ozawa, and Nishida grew a single crystal of InSb by the float zone process using the mirror furnace on SL-J. The seed was a 20 mm diameter rod of single crystal and the feed was polycrystalline InSb. A zone 45 mm long was melted and propagated at the rate of 0.33 mm/minute, resulting in a single crystal 20 to 30 mm in diameter and 100 mm long. An oxide skin formed on the crystal that apparently prevented Marangoni convection since the grown crystal was free of striations, as determined by X-ray topography. Dislocation densities were also low and the electrical resistivity doubled over the length of the zone.

Samarskite is a naturally occurring mineral that is composed of five phases containing Ca, Fe (iron), Y (yttrium), U (uranium), Th (thorium), Nb, Ta, and O. Alpha particles from the decay of U and Th have destroyed its native structure, so it is difficult to determine how this mineral was formed. Takekawa, Shindo and Sugitani set out to crystallize this material using the traveling solvent floating zone in the image furnace on SL-J. Several peritectic reactions are apparently involved in which solid 1 plus a liquid reacts to form solid 2. This means that solid 1 must diffuse through the liquid to reach the forming solid 2. Because of the various density differences, this scenario is difficult to arrange in normal gravity. The material was successfully melted, but large bubbles in the melt interfered with the growth process and the results are inconclusive.

d. Liquid phase epitaxial growth. As discussed previously, there are advantages to growing systems with high melting temperatures from a solution in which one of the metal components acts as a solvent. Suzuki, Kodama, and Ueda developed a unique method for growing GaAs from Ga that they demonstrated on SL-J. The Ga doped with Sn was enclosed in a cube whose sides were single crystal wafers of intrinsic GaAs with different orientations. When the system was heated, some of the GaAs dissolved in the molten Ga and then redeposited as Sn-doped GaAs when the system was cooled back to ambient. Since there were no free surfaces, Marangoni convection was eliminated and the liquid phase epitaxial growth could be studied in the absence of convective flows.

The growth on the top wafers was thicker than on the bottom wafers in 1-g and was uniform and thicker in microgravity. The surface morphology of the upper wafers was much rougher than the bottom wafers in the ground control while the flight samples were generally smoother, an effect that must be due solely to

convective flows. In general, growth on (111) surfaces was somewhat thicker than on (100) faces. There was no difference in the normalized depth distribution of the dopant atoms. Type II striations, which arise from macrostep propagation, are seen in both flight and ground control samples, but are distinctly different. In the flight samples, the striations are thin and run parallel to the growth surface, whereas in the ground samples the striations pass through the growth layer.

## 2. *Crystal Growth from the Vapor.*

For materials that lend themselves to physical or chemical vapor transport, growth from the vapor offers some attractive alternatives to growth from the melt. Growth can take place at temperatures considerably lower than the melting point, thus avoiding some of the higher temperature problems associated with melt growth. Gravity-driven convection will definitely influence the growth process, perhaps in ways that are not yet completely understood or appreciated. For example, Rosenberger has shown that compositional gradients arising from the interaction of multicomponent systems with any vertical wall will always result in horizontal density gradients that produce buoyancy-driven convective flows. Convective transport is governed by the product of the Grashof number and the Schmidt number. The Grashof number is directly proportional to gravity and measures the convective flow. The Schmidt number, which is the ratio of kinematic viscosity to chemical diffusivity, can be as high as several thousand for melt growth systems, but is approximately 1 for a typical vapor growth process. Therefore, diffusion limited growth conditions can be obtained under far less stringent acceleration conditions than those required for melt growth.

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Several vapor crystal growth experiments on the Shuttle have produced provocative results that are not at all understood. For example, on OSTA-2, Wiedemeier grew unseeded GeSe crystals by closed tube physical vapor transport using the GPRF. The two growth ampoules contained different pressures of Xe (xenon) that served as a buffer in the transport since the primary purpose of the experiment was to understand the vapor transport process without the effects of gravity. In the ground control experiment, many small crystallites formed a crust inside the growth ampoule at the cold end. The flight experiment produced dramatically different results; the crystals apparently nucleated away from the walls and grew as thin platelets that eventually became entwined with one another, forming a web that was loosely contained by the ampoule. Even more striking was the appearance of the surfaces of the space-grown crystals. These were mirror-like and almost featureless, exhibiting only a few widely spaced growth terraces. By contrast, the crystallites in the ground control experiments conducted under identical thermal conditions had many pits and irregular, closely spaced growth terraces. The experiment was repeated during the D-1 mission using two additional pressures of Xe in order to add additional points to the transport versus pressure curve. The unusual morphology of the space grown crystal was also seen on this flight.

Additional vapor growth experiments were carried out by Wiedemeier on USML-1 and on USML-2 in which  $\text{Hg}_{0.4}\text{Cd}_{0.6}\text{Te}$  was grown epitaxially on (100) CdTe substrates by closed-tube chemical vapor deposition using  $\text{HgI}_2$  (mercuric iodide) as the transport agent. Considerable improvements in the USML-1 flight samples were observed in terms of surface morphology, chemical microhomogeneity, and crystalline perfection. The surfaces of the ground control samples had a wavy step-terrace structure, whereas the flight samples were mirror smooth such that growth steps could not be resolved at 500x. Compositional differences were 2 to 3 times smaller in the flight sample. Rocking curve widths of the space-grown epitaxial layers were 90 to 120 arc seconds, less than half the ground control and equal or less than the best epitaxial layers grown on the ground by the MOCVD (Metal Organic Chemical Vapor Deposition) technique. These improvements were attributed to the sensitivity of the  $\text{Hg}_{1-x}\text{Cd}_x\text{Te-HgI}_2$  vapor transport system to minute fluid dynamic disturbances that are unavoidable in normal gravity.

The primary objective of the USML-2 experiment was to measure the effect of microgravity on the initial epitaxial growth process, effects that had been annealed out during the growth in the USML-1 experiment. Consequently, the growth times were much shorter on USML-2 so that the transition from the initial growth islands to epitaxial layers could be observed along with the propagation of birth defects from the interface to the epitaxial layer. Inspection of the growth islands on the flight sample revealed well-developed faces and facets indicating a higher degree of order than the ground control which was confirmed by their measured etch pit densities that were 50 times lower.

Mercuric iodide forms a layered structure, similar to graphite, in which the A-B planes are bonded by van der Waals forces. Consequently, the crystalline structure is very weak, especially at the growth temperature, and it was thought that the performance of the material as a room temperature nuclear spectrometer might be limited by defects caused by self-deformation during the growth process. Schneppe and van den Berg grew mercuric iodide crystals by physical vapor transport on Spacelab 3. Their growth technique was similar to the method used by EG&G Corporation to grow this material commercially. A seed was placed on a temperature-controlled pedestal and was surrounded by a container whose walls had been coated with the source material. A small temperature difference was maintained between the walls and the seed to drive the growth process.

It was possible to increase the growth rate on Spacelab 3 to more than twice the rate on the ground without spurious nucleation. The space-grown crystal was 1.2 x 1.2 x 0.8 cm and weighed 7.2 grams. It exhibited sharp, well-formed facets indicating good internal order. This was confirmed by  $\gamma$ -ray rocking curves that showed a single peak and were approximately one third the width of the multi-peaked curves from the ground control crystals; however there was still evidence of lattice strain in the flight sample. Measurements just after the flight showed that both electron and hole mobility were significantly enhanced in the flight crystal, although, for reasons that are not clear, these values decreased after some time. It was speculated that this degradation might be a result of handling this extremely soft material.

The experiment was repeated on IML-1 with similar results. This time the rocking curves on the flight crystal were sharper and more symmetric, although, in one area, a second peak was observed which indicated two domains misoriented by 0.1 degree. Again the electron mobility and  $\mu\tau$  product (product of mobility and carrier lifetime) showed slight improvement over the ground, while a dramatic improvement was seen for the hole mobility and hole  $\mu\tau$  product. It is still not understood whether the improved qual-

ity of the flight crystals was due to the elimination of the weight of the crystal during its growth, or to the diffusion-controlled transport conditions that produced a more uniform growth environment.

Cadoret also grew  $\text{HgI}_2$  on SL-1 and on IML-1. On SL-1, he used an unseeded closed tube physical vapor transport technique. Three growth ampoules were prepared, one under high vacuum, one containing 0.1 Torr Ar as a buffer gas, and the third containing styrene to poison one of the growth faces in order to promote the growth of flat platelets. Larger single crystals were obtained in space as opposed to smaller polycrystals in the ground control. A seeded technique was used on the IML-1 experiment with highly purified material supplied by EG&G. The space-grown crystal exhibited flat, well-defined faces and produced a rocking curve with a FWHM of  $0.04^\circ$  (Full-Width at Half-Maximum, used to describe a measurement of the width of an object in a picture when that object does not have sharp edges, and to compare the quality of images obtained under different observing conditions). The ground control crystal was quite irregular in shape and was of such poor quality that a rocking curve could not be obtained.

On the D-1 mission, Bruder, Dian, and Nitsche grew a CdTe crystal from the vapor phase by closed tube sublimation/condensation by placing the source material in the focus of the monoellipsoidal mirror furnace and heated it to about 880 degrees Celsius. The heat flow in the ampoule was modified by a tight fitting Ni net on the outside to give a slightly convex shape to the growth interface to prevent parasitic nucleation. Unfortunately, the seed quality in the flight sample turned out to be much poorer than the ground control so that a meaningful comparison could not be made. The large etch pit density in the material near the seed did diminish somewhat as the growth of the flight sample progressed, but did not reach the lower value of the ground control.

Using the three-zone Gradient Heating Facility on D-1, Launay grew Ge by closed tube chemical vapor transport with  $\text{GeI}_4$  (germanium IV iodide) as the transport agent. Polycrystalline Ge was located at the hot and cold zones and a single crystal substrate was attached to a wall at an intermediate temperature. Ampoules with different transport gas pressures were processed simultaneously to obtain the mass flux as a function of transport gas. These results were in good agreement with a one-dimensional model assuming purely diffusive transport. The quality of the epitaxial layers grown in space is much higher than those made on earth. On earth the layers exhibit a multitude of little holes on the surface, whereas the flight layers were smooth.

Kimura, Nishimura, and Ono with Takayami grew InP during the D-2 mission using a closed tube chemical vapor transport using  $\text{InCl}_3$  as the transport agent. The grown layer is doped with S (sulphur) while the substrate is doped with Fe so that the layers will be distinguishable. Rocking curves for the both the space and ground control epi-layers showed single peaks, signifying that they were single crystalline, although the FWHM of the space sample was slightly wider than the ground control, which was also slightly wider than the substrate. This would indicate slightly more lattice strain in the layer grown in microgravity. The transport rate increased linearly with pressure of the transport gas in the ground control experiments, but started to fall off to a constant value for the flight experiments, which would be expected for diffusion controlled transport. The thickness of the epilayers varied considerably in the ground control samples that were much thicker in the center and thinned rapidly near the periphery of the substrate. The flight samples, on the other hand, were uniformly coated.

### 3. *Crystal Growth from Aqueous Solution.*

a. Co-deposition growth. Galster and Nielson used a three chamber method to grow calcium tartrate ( $\text{CaC}_4\text{H}_4\text{O}_6$ ) and calcium carbonate ( $\text{CaCO}_3$ ) crystals from solution on SL-1. Solutions in the outer chambers are allowed to diffuse through a buffer in the middle chamber where they react to form the crystal as a co-precipitate. An attempt was also made to grow TTF-TCNQ (tetrathiafulvalene-tetracyanoquinodimethane), an organic conductor, but the growth solution deteriorated before the experiment was activated. No information on the quality of the crystals was available.

Authier, Lefauchaux, and Robert grew brushite ( $\text{CaHPO}_4 \cdot 2\text{H}_2\text{O}$ ) and lead monite ( $\text{PbHPO}_4$ ) crystals on SL-1 using a similar method. The space grown crystals were analyzed by X-ray topography and were found to be of comparable quality to those grown on the ground using gels to control convection.

On IML-1, Kanbayashi and Anzai grew an organic charge transfer complex by diffusing donor and acceptor starting materials into a central chamber containing a suitable solvent, similar to the method used in the above experiments. One growth apparatus was mounted to a passive vibration damper to see if g-jitter affected the growth of the system. By shortening the distance over which diffusion must occur and using more concentrated solutions, they reported that they were able to grow a crystal in space in one week that would take three months on the ground. Their space and ground control crystals were comparable, although the space crystal grown with the vibration damper was somewhat fatter. Electron spin resonance showed that the space and ground crystal had the same electronic structure in which free electrons existed in a narrow conduction band. Both space and ground crystals had a superconductivity transition at 1.2K under 7 kilobars applied pressure.

Anzi also attempted to grow TTF-TCNQ by the same technique on SL-J, but no crystals formed because of technical difficulties.

b. Controlled nucleation. Controlling nucleation in microgravity experiments presents several difficulties. Cooling a solution into saturation usually results in nucleation at the walls. Inserting a seed generally caused the propagation of defects into the growing crystal (ghost of the seed). Using the glove box on USML-1, Kroes, Lehoczky, and Reiss demonstrated a novel method for initiating and controlling nucleation in solution crystal growth. A hot concentrated solution of L-arginine phosphate monohydrate ( $\text{C}_6\text{H}_{14}\text{N}_4\text{O}_2\text{H}_3\text{PO}_4 \cdot \text{H}_2\text{O}$ ) or LAP was injected into a cooler lightly saturated solution of the same. Copious nucleation resulted as the warmer solution cooled. Most of the crystals drifted to the walls under the influence of residual gravity. A few of the crystals remained suspended and grew as large as 3 x 5 x 0.5 mm.

c. Cooled sting growth. Triglycene sulfate (TGS) is a long wavelength pyroelectric infrared detector material. Lal grew TGS crystals on Spacelab 3 and on IML-1 using a novel cooled-sting approach. The seed crystal is mounted on a small pedestal through which a heat pipe can extract heat from the crystal using a thermoelectric device. Thus the bulk growth solution can be held at near saturation while the fluid at the growth interface is driven to supersaturation required for growth by extracting heat through the crystal. This technique eliminated the spurious nucleation within the growth cell that had plagued many of the earlier attempts to grow crystals from aqueous solution in microgravity. By growing under diffusion controlled transport conditions, it was hoped to avoid liquid/vapor inclusions. These are the most common types of defects in crystals grown from solution and are believed to be caused by the nonuniform growth conditions resulting from convective flows.

On SL-3, an oriented seed was cut from an Earth-grown TGS crystal. Irregular growth occurred primarily around the perimeter of the seed, which made it difficult to analyze. An improved seeding technique was used on IML-1 which produced a much more uniform region of new growth. In normal gravity, good crystal can be grown on the (100) face, but growth on the (010) face tends to be non-uniform and multi-faceted. However, uniform growth was achieved on the (010) seed used in the IML-1 flight. In order to grow sufficient material to analyze during the mission, an undercooling of 4°C was used to promote faster growth (approximately 1.6 mm/day). Despite this accelerated growth, the quality of the crystal was exceptionally good. There was a smooth transition from seed to new growth without the veil of dislocations surrounding the seed crystal (called the ghost of the seed), which is normally seen when crystals are seeded on the ground. The TGS crystal grown on the IML-1 mission was examined with high resolution monochromatic synchrotron X-radiation diffraction imaging using the National Synchrotron Light source at Brookhaven National Laboratory. The X-ray topographic images indicate an extraordinary crystal quality. The only inclusions are due to the incorporation of polystyrene particles intentionally inserted in the growth solution to study the fluid motion in low-g. The detectivity ( $D^*$ ) of the space grown crystal was found to be significantly higher than the seed crystal and the loss tangent was reduced from 0.12-0.18 for the seed to 0.007 for the space grown material.

The growth of these crystals was monitored by periodically taking shadowgrams, Schlieren photographs, and holograms of the growing crystal and its surrounding medium. The concentration profiles could be visualized from the shadowgraphs and Schlieren images, and determined quantitatively from the reconstructed holograms. These graphic images confirmed that the concentration field was purely diffusion-limited and inspired some of the protein crystallographers to try growing their protein systems in space. Small polystyrene marker particles were added to the growth solution on the IML-1 flight to visualize whatever flows might exist as a result of residual accelerations.

d. Growth of zeolites. Zeolites are a class of crystalline aluminosilicate materials that form the backbone of the chemical process industry worldwide. They are used primarily as adsorbents and catalysts. One of their most important roles is that of a “cracking” catalyst in the petroleum industry. New applications for zeolites include selective membranes, chemical sensors, polymer-zeolite composites, and molecular electronics. For these reasons, there is an intensive interest in obtaining a better understanding of how they nucleate and grow with the aim of being able to tailor their structure for specific applications.

Various forms of zeolite crystals, including zeolite-A, X, Beta, and Silicalite were grown by Sacco on USML-1 and -2 with the aim of getting larger and more uniform crystals. In general, the crystals grown in space with nucleation control grew 10 to 25% larger in linear dimension than their ground controls. The zeolite-X crystals grown on USML-2 were 25 to 50% larger than their ground controls and twice as large as grown on USML-1. For the most part, the flight samples had higher Si/Al ratios than did their control samples and one of the A crystals exhibited the theoretical Si /Al ratio of 1.00, which not been seen before. Space-grown Beta crystals were free of line defects that are common in those grown on the ground. X-ray diffraction studies indicated slightly smaller unit cell volumes, which indicates fewer defects. A comparison of the catalytic activity of the space and ground-grown crystals has not yet been published in the open literature.

## C. Thermophysical Properties Measurements

Anyone attempting to model solidification processes will soon find that reliable thermophysical property data, especially data on transport properties such as diffusion coefficients and thermal diffusivity for molten systems, are difficult to come by. Generally such measurements are made in thin capillary tubes to minimize the effects of convective transport, but any attempt to measure such transport properties on Earth will always be contaminated to some degree by buoyancy driven convective flows. Furthermore, a simple demonstration experiment by the crew on Skylab, in which they layered strong tea and clear water into a plastic toothbrush holder, showed a bullet-like diffusion region between the tea and water instead of the expected planar diffusion front. This observation suggested that wall effects may influence to diffusion of one component into another and raised the specter that much of the diffusion data that had been taken in capillary tubes may also be in error.

### *1. Measurement of Diffusion Coefficients.*

On Spacelab-1, Frohberg, Kraatz, and Wever measured the interdiffusion coefficient of  $\text{Sn}^{112}$  and  $\text{Sn}^{124}$  over a temperature range of  $240^{\circ}\text{C}$  to  $1250^{\circ}\text{C}$ . The diffusion coefficients measured on the ground were 30 to 50% higher than those measured in space, which they attribute to convective transport. Results in a 3 mm diameter cell were indistinguishable from those in a 1 mm diameter cell, indicating that wall effects were not significant. The precision with which the interdiffusion coefficient could be determined from the space data was 50 times better than the ground-based data. With this higher precision, the isotope effect could easily be measured. An unexpected result was the fact that the space data seemed to follow a  $T^2$  law rather than an Arrhenius law, typical of diffusion in solids. This departure from the classical vacancy diffusion law for solids may shed new light on the structure of liquid metals. They followed this experiment with measurement of interdiffusion of  $\text{In}^{113}$  and Sn at different temperatures on D-1. Again they found that the diffusion coefficient followed a  $T^2$  dependence.

The finding that the diffusion coefficient seems to follow a  $T^2$  law in the liquid metallic systems investigated on Spacelab-1 and D-1 raised a number of interesting issues. Does this law apply to all liquid metals? What happens in the undercooled or glassy state? Where does transition to the solid Arrhenius-like behavior occur? Does the  $T^2$  law also apply to diffusion in aqueous solutions? A group of diffusion experiments were planned for the D-2 mission to address these questions.

Frohberg and co-investigators looked for possible deviations from the  $T^2$  law in systems that had low coordination numbers or those that tended to form associates. The argument was that if the glass forming metals followed an Arrhenius behavior in the glassy state, there might be some deviation from the  $T^2$  law at the lower temperatures. Consequently, they choose to measure self-diffusion in Pb, Sb, and In and for impurity diffusion for In in Sn and for Sn in In. They found no significant deviation from the  $T^2$  law for any of these systems.

Richter and Merckens developed a flowing junction cell for the measurement of diffusion coefficients using a Savart Interferometer that they had tested on TEXUS 8. They attempted to use this cell on the D-1 mission to measure the interdiffusion of  $\text{NaNO}_3$ - $\text{AgNO}_3$  (sodium nitrate-silver nitrate), but technical difficulties prevented them from being able to locate the phase boundary of the molten system.

Merkens, Richter, Golbach, Jurek, Klessascheck next attempted to measure the ionic diffusion in the molten  $\text{KNO}_3\text{-AgNO}_3$  (potassium nitrate-silver nitrate) eutectic salt system at five different temperatures ranging from  $150^\circ\text{C}$  to  $330^\circ\text{C}$  using real time holography. The molten salts were injected into a flow cell for each run. Unfortunately, a bubble in the melt made it difficult to extract the holographic data and, consequently, diffusion coefficients at only two temperatures were obtained. These values were substantially lower than ground based measurements, again demonstrating the necessity of making this type of measurement in space, but it was not possible to test the  $T^2$  law for salt systems with only two data points.

Robert, Lefauchaux, and Bernard measured the diffusion coefficients of aqueous solutions of glycine, valine, and lead nitrate at three different concentrations on the D-2 mission using real time optical holography. The experiment was activated by pulling out a thin metal sheet that separated the portion of the cell containing the solute from the pure solvent portion. In all cases the diffusion coefficients became smaller with increasing concentration. For valine and glycine the diffusion coefficients measured in flight were slightly higher than the ground control, but for lead nitrate the space value was twice as high as the ground control. This later effect was unexpected and is still being investigated. It is possible that the fluid motion imparted by removing the sheet separating the two chambers produced unwanted mixing in the flight sample. Such mixing would have been suppressed in the ground control experiment because of the large stabilizing density difference between the two liquids.

Urbanek and Hehenkamp investigated the diffusion of Ni in molten Cu, Cu-Al and Cu-Au. A single crystal of Ni was diffusion bonded to the Cu alloys and the melt was held at  $1150^\circ\text{C}$  so that the Ni remained solid. This was done to assure a plane diffusion front at the Ni source. The Ni that dissolved into the Cu alloy melt was allowed to diffuse through the sample until it was quenched. The distribution of Ni was determined by electron microprobe tracing. The measured diffusion coefficients again were significantly lower than those measured on the ground. However, the isoconcentration profiles show more Ni in the middle of the Cu and Cu-Ag alloys and the interface between the Ni single crystal and the melt shows a bulge in the middle. This suggests that convective flows must have occurred along the outer surface of the melt toward the Ni interface with a return flow through the core of the sample. This type of behavior would be expected of Marangoni flows, except that, in this case, the sample had been coated with a 200 micron thick layer of alumina skin that had remained intact. The possibility of second order Marangoni flows that can occur without a free surface has been speculated, but no such flows have ever been observed directly.

A follow-on experiment to measure self-diffusion in molten Sn at five temperatures up to 1622K was carried out on MSL-1 by Itami and co-investigators in which  $\text{Sn}^{124}$  was used as a tracer and its distribution was determined by SIMS. They found that the diffusion coefficient varied as  $T^{1.81}$  for their data and  $T^{2.04}$  for all microgravity data.

Using a combination of rocket experiments along with an experiment on MSL-1, Uchida's team measured the diffusion of  $\text{Pb}_{0.8}\text{Sn}_{0.2}\text{Te}$ -  $\text{Pb}_{0.7}\text{Sn}_{0.3}\text{Te}$  over a temperature range of 1223K (melting) to 1573K. This composition is of interest as an infrared detector material, but it is difficult to grow by directional solidification because it is subject to double diffusive instabilities. Consequently, the diffusion coefficient had not previously been determined. Their combined set of experiments determined an expression  $D = 6.7 \times 10^{-9} (T / T_{\text{melt}})^{2.6} \text{ m}^2/\text{s}$ .

Yoda, Masaki, and Oda measured the diffusion coefficient of Sn as a function of temperature on SL-J and on MSL-1R. Their results fall right on the same curve as Froberg's data.

However, on SL-J, Yamamura, Yoda, Ohida, and Masaki doped LiCl-KCl eutectic with a trace quantity of AgCl and measured the diffusion of Ag<sup>+</sup> using an electropotential method over a temperature range of 640K to 860K. Their data seemed to follow an Arrhenius curve.

Dan and Muramatsu attempted to measure the interdiffusion of Ag and Au on SL-J. However, the sample appeared to have been convectively mixed by Marangoni convection.

On SL-1, Braedt, Braetsch, and Frischat measured the interdiffusion between Na<sub>2</sub>O-3SiO<sub>2</sub> and Rb<sub>2</sub>O-3SiO<sub>2</sub> (rubidium oxide-silicon oxide) glass melts. The sample consisted of stacked cylinders of glasses having different compositions that were heated to 1180°C with an effective processing time of 1370 seconds. The concentration profiles were obtained using an electron microprobe. The microgravity samples exhibited concentration profiles parallel to the original interface, while the ground control samples had wavy profiles indicative of convective flows. The interdiffusion coefficient at 1180°C fits the Arrhenius plot with the results of TEXUS missions and ground based results at lower temperatures.

The removal of a bubble from a viscous glass is difficult enough on Earth, but becomes a major problem in micro-gravity without the assistance of buoyancy forces. For this reason, it is necessary to measure diffusion coefficients of gases in glass melts. During the D-2 mission Jeschke and Frischat measured the diffusion of He in a model glass system by observing the shrinkage of a preformed He bubble in a cylindrical glass sample as it was heated to 1100°C.

Thermodiffusion, sometimes called the Soret effect or the Ludwig effect, results from the migration of atoms of different species in a thermal gradient. One of the techniques used for isotope separation is based on this principle. It can also be important in the solidification of multicomponent alloys by shifting the composition at the interface as the solidification proceeds, although in most Earth-based processes, the effect of thermal migration is completely overwhelmed by convection and it is generally ignored. However, the effect may have been responsible for shifting the composition away from the eutectic point in several microgravity eutectic solidification experiments.

Malmejac and Praizey demonstrated the effectiveness of microgravity for measuring thermodiffusion (Soret effect) on Spacelab-1. They loaded Sn with 0.04 Wt% Co into zirconia shear cells and subjected them to a 200K/cm thermal gradient for six hours. A graphite piston kept the melt in contact with the walls to prevent unwanted Marangoni convection. The cells were then sheared into six segments that were analyzed for Co concentration by neutron activation. Similar cells were processed in a thermally stable configuration (hot over cold) on the ground. The flight samples had two times as much Co in the hot end as in the cold end, whereas the ground control samples showed a constant Co concentration throughout. From the flight samples, the investigators were able to determine the heats of transport and the Soret coefficients for both the Co in Sn and for the different isotopes of Sn. A follow-on experiment on D-1 confirmed the isotopic heat of transport for Sn and obtained the heat of transport for Ag<sup>109</sup> and for Bi<sup>209</sup> in Sn.

Bert and Dupuy-Philon investigated the thermomigration of the Ag<sup>+</sup> and K<sup>-</sup> ions in the molten salt system, AgI<sub>x</sub>-KI<sub>1-x</sub> near the eutectic composition on D-1 and D-2 by potential difference between electrodes at the

hot and cold ends of the sample. This measurement is then related to the Soret coefficient. The Soret was much smaller than anticipated so that the D-1 experiment could only determine that the Soret coefficient is positive (the heavier AgI migrated to the cold side of the cell). The longer duration of the D-2 experiment permitted the first accurate measurements of the Soret coefficient for this system.

## *2. Undercooling Experiments.*

The equilibrium melting (freezing) point is the temperature at which there is no difference between the free energy of the melt and solid, thus a solid can remain in equilibrium with its melt at this temperature indefinitely. A solid will begin to melt as its temperature is raised to the equilibrium melting point, but a melt will not begin to freeze at this temperature. The interfacial energy between the embryonic solid and the liquid must somehow be found. This required energy is proportional to the interfacial area, or the square of the radius of the solid, assuming it is a sphere. However, the tighter binding energy of the solid, which is proportional to the cube of its radius, can lower the free energy. According to this elementary model of nucleation, the free energy of a potential nucleus initially increases with size because of the extra interfacial energy, but eventually decreases with size due to the increased solid bond formation. Therefore, there is a critical size for a viable nucleus and a free energy barrier that must be overcome to form a viable nucleus. Near the equilibrium melting point, atoms or molecules in the liquid start to form clusters, which are broken up by thermal agitation. As the temperature is lowered below the freezing point these clusters can grow larger before they are broken up by thermal agitation. The probability that a sufficient number of particles will come together to form a viable cluster before it is broken up by thermal agitation increases with decreasing temperature. If there are solid surfaces present, especially if they are crystalline in nature, they offer a low energy nucleation site and the solid can form by heterogeneous nucleation at temperatures close to equilibrium melting temperature, or with very little undercooling. If there are no low energy nucleation sites, the melt will continue to undercool until it nucleates homogeneously. Thus, if low energy nucleation sites can be avoided, it is possible to undercool a melt by as much as 20 to 25% of its absolute melting temperature. When nucleation in an undercooled melt occurs, the heat of fusion is quickly given off heating the melt back to its equilibrium melting point, a phenomenon known as recalescence. However, if the melt is undercooled to the point that the heat of fusion is not sufficient to raise the temperature back to the melting point, the melt is said to be hypercooled.

In recent years, a great deal of attention has been given to rapid solidification processing. If the heat can be removed rapidly enough so that the atoms in the melt simply do not have time to arrange themselves into orderly crystalline form, they more-or-less become frozen in place. Such processing has led to amorphous or glassy metals, quasi-crystals with 5-fold symmetry, and a variety of non-equilibrium phases, some with interesting properties such as the niobium based A-15 superconductors. The ability to form metastable phases is greatly enhanced by starting with a deeply undercooled melt. Therefore, there is a great need to understand the properties of melts in the undercooled state.

There are essentially two ways to eliminate the low energy nucleation sites: eliminate physical contact with the melt, or encase the melt in an amorphous, non-reacting flux. The latter has been demonstrated by Whittmann, Gillessen, Otto, and Roestel on D-2. By suspending melts in  $B_2O_3$ , they were able to undercool eutectic Ag-Ge by 100K below its melting point of 924K and Fe -22Wt% Ni was undercooled by 392K, into the hypercooling regime. When this system is undercooled, the  $\delta$ -ferrite phase is nucleated first. However, during recalescence, the released heat of fusion brings the undercooled melt back to the melting temperature and the  $\gamma$ -austenitic phases forms. However, when hypercooled, as was the case here, some of the original  $\delta$ -phase is retained.

Free falling droplets in drop tubes have been deeply undercooled, but it is difficult to measure the thermophysical properties of a falling drop. An orbiting spacecraft provides an opportunity to study a free falling drop, but because the drop and the spacecraft do not fall at exactly the same rates, a small non-contacting body force is required to keep the droplet in position. Non-contacting positioning forces can be electrostatic, electromagnetic (EM), acoustic, or aerodynamic.

Electromagnetic position is particularly suited for the study of undercooled metallic melts in space. While it is possible to levitate metallic melts in normal gravity, the sample becomes distorted to the point that it is not possible to obtain surface tension and viscosity data from drop oscillation and measuring volume changes with temperature becomes difficult. Also, the heat input from the induced currents required for levitation interfere with the undercooling of the sample. These difficulties are avoided in a microgravity environment.

An early attempt to use electromagnetic levitation to study undercooling on orbit was made on MSL-2 using a modified version of the EM levitator developed for use on the SPAR suborbital rocket program, prior to the time the Shuttle became operational. Flemings provided six samples but a coolant-loop problem prevented useful data from being attained.

The TEMPUS facility was developed by the Institute for Space Simulation in Cologne, Germany. It uses a quadrupole coil for positioning and a dipole coil for heating. Since very small positioning forces are required in a microgravity environment, electromagnetic-driven flows for positioning can be minimized. The sample chamber can be evacuated, or backfilled with an inert gas to suppress evaporation of samples with high vapor pressure. The system was first flown on the IML-2 mission. Unfortunately, most of the samples had gotten contaminated during their preflight storage and could not yield the desired thermophysical data. Also, some positioning instabilities were discovered. As a result, the facility was reworked and was reflown on the MSL-1 and MSL-1R flights.

Egry, Lohoefer, Seyhan, and Feuerbacher measured the viscosity and surface tension of two alloys,  $\text{Co}_{80}\text{Pd}_{20}$  and  $\text{Pd}_{78}\text{Cu}_6\text{Si}_{16}$ . The first was chosen because it has a low viscosity and deeply undercools, while the second is a good glass former and consequently has a high viscosity. Surface tension is obtained by pulsing the positioning coils to cause the drop to oscillate. The frequency of oscillation is related to the mass and surface tension by Rayleigh's formula and the viscosity can be obtained by the rate of decay of the oscillations. (Since Rayleigh's formula only applies to spherical drops, this method cannot be used with the distorted melts levitated in normal gravity.) Egry was able to run thirty heating and cooling cycles on the  $\text{Co}_{80}\text{Pd}_{20}$  alloy, undercoolings as much as 350K were obtained, well into the hypercooling regime. The surface tension was found to decrease linearly with temperature while the viscosity follows an Arrhenius behavior.

The eutectic point of the  $\text{Pd}_{78}\text{Cu}_6\text{Si}_{16}$  alloy was used to calibrate the pyrometer. The addition of Cu supposedly improves the glass forming ability of this system, but lowers the amount of undercooling that can be achieved to about 70 K, probably to the formation of CuO on the surface. This also may be responsible for the increased scatter in the surface tension and viscosity data. The surface tension again is seen to decline linearly with increasing temperature, but the scatter in the viscosity is such that no distinction can be made between Arrhenius, Vogel-Fulcher, or power law behavior.

The changing resistivity of the sample with temperature changes the inductance of the TEMPUS heating coil, thus by measuring the voltage, current, and phase of the heating current, resistivity could be inferred. Calibration to obtain the coil constants was done with samples of known resistivity. The resistivity of the  $\text{Co}_{80}\text{Pd}_{20}$  alloy was found to increase linearly with temperature in both the solid and liquid state, but with a higher value and slightly higher slope in the case of the liquid.

Solid  $\text{Co}_{80}\text{Pd}_{20}$  is a good ferromagnet with a Curie temperature of 1250 K. The measured inductance in both solid and undercooled melt exhibited a dramatic change when cooled below 1360 K with a sharp increase at 1250K. This increase was interpreted as magnetic ordering. There had been speculation as to whether a ferromagnet could exist in the liquid state. There appears to be no fundamental reason to believe that it could not; it's just that the Curie temperature of every known magnetic material happens to lie below its melting point. This is the first evidence suggesting that ferromagnetism does indeed exist in the liquid state.

In order to estimate the nucleation probability, and thus the cooling rate required to form a metallic glass, it is necessary to know the difference in the Gibbs free energy between the solid and the liquid state as well as the viscosity and the interfacial energy. The Gibbs free energy is the sum of the enthalpy of the liquid plus the product of the entropy of fusion and temperature. The enthalpy of the liquid can be obtained by integrating over the heat capacity of the liquid.

Fecht and Johnson developed a non-contact method for measuring the heat capacity, thermal conductivity, and total hemisphere emissivity of a small spherical sample using AC calorimetry. The heating field is modulated at frequencies ranging from 0.05 Hz to 0.2 Hz. The heat capacity is related to a correlation function of modulation frequency, the internal (heat up) relaxation time, and the external (heat loss) relaxation time. Also, thermal expansion and volume change on melting can be determined by direct observation of the suspended drop.

This technique was applied by Fecht and Wunderlich to two glass-forming alloys,  $\text{Zr}_{65}\text{Al}_{7.5}\text{Cu}_{17.5}\text{Ni}_{10}$  and  $\text{Zr}_{60}\text{Al}_{10}\text{Cu}_{18}\text{Ni}_9\text{Co}_3$ . The  $\text{Zr}_{65}\text{Al}_{7.5}\text{Cu}_{17.5}\text{Ni}_{10}$  system exhibited a large increase in heat capacity near the glass transition temperature, which was not seen in the other system. This anomalous behavior is thought to be associated with some liquid structure and is still being investigated. Also, the ratio of thermal conductivity to electrical conductivity in the crystalline  $\text{Zr}_{65}\text{Al}_{7.5}\text{Cu}_{17.5}\text{Ni}_{10}$  system follows the Wiedemann-Franz law, but the measured thermal conductivity in the undercooled state was significantly higher. This departure could be a result of flows from electromagnetic stirring, although the viscosity in this temperature range is so high that it cannot be measured by the drop oscillation method.

Johnson, Lee, and Glade carried out similar investigations on  $\text{Zr}_{57}\text{Nb}_5\text{Ni}_{12.6}\text{Al}_{10}\text{Cu}_{15.4}$  and  $\text{Ti}_{34}\text{Zr}_{11}\text{Al}_{7.5}\text{Cu}_{47}\text{Ni}_8$ . They also find a strong increase in heat capacity with undercooling. The  $\text{Ti}_{34}\text{Zr}_{11}\text{Al}_{7.5}\text{Cu}_{47}\text{Ni}_8$  sample exhibited a large anomaly in heat capacity just above the liquidus temperature. This was thought to be the result of a possible phase separation in the melt.

Frohberg, Roesner-Kuhn, and Kuppermann developed a real time method for analyzing surface oscillations of liquid levitated drops based on a FFT (Fast Fourier Transform) analysis of the temperature-time signal and applied this technique to the measurement of the surface tension of pure zirconium, several stainless steel alloys, and glass forming alloys  $\text{Zr}_{11}\text{Ti}_{34}\text{Cu}_{47}\text{Ni}_8$  and  $\text{Zr}_{57}\text{Cu}_{12.6}\text{Ni}_{15.4}\text{Nd}_5\text{Al}_{10}$ . In these glass forming alloys, the viscosity increases so rapidly with decreasing temperature that surface oscillations cannot be detected,

thus making surface tension measurements in the undercooled state impossible. However, measurements at higher temperatures can be used to infer surface tension in this region. Unlike other systems in which surface tension increases and temperature is lowered, the  $\text{Zr}_{57}\text{Cu}_{12.6}\text{Ni}_{15.4}\text{Nd}_5\text{Al}_{10}$  system exhibits a strong decrease in surface tension with decreasing temperature. It is speculated that this anomalous behavior may be due to a change in the surface composition as temperature is lowered. Al has a surface tension near the lowest measured value and if it segregated to the surface, it would be the active surface component.

Volume change with temperature is a basic measurement in glass formation. In most materials (except for those that have open diamond-like structures), specific volume decreases as the melt temperature is lowered and a sharp drop in volume is seen as the crystalline solid is formed. As the temperature of the solid is lowered further, the volume continues to decrease, but at a slower rate-reflecting the volumetric coefficient of expansion for the solid. For glass formation, the nucleation of the crystalline phase must be avoided and the melt continues to shrink in volume at the liquid rate past the normal freezing temperature. When the glass transition temperature is reached (the point at which the atoms or molecules no longer have sufficient thermal energy to freely move about each other) the material becomes a glassy solid rather than an undercooled liquid. This transition is identified, not by an abrupt change in volume, but by a change in the slope of volume versus temperature to reflect a volumetric coefficient of expansion more typical of a crystalline solid.

Samwer and Damaschke developed a special camera for measuring volume changes in samples being processed in the TEMPUS. On the MSL-1R mission they measured the volume versus temperature of the glass forming alloy  $\text{Zr}_{11}\text{Ti}_{34}\text{Cu}_{47}\text{Ni}_8$ . They found two distinct slopes in the liquid phase: a smaller slope well above the normal melting point, and a steeper slope beginning approximately 40°C above melting point that continued past the melting point. The data did not extend to the glass transition temperature because of poor contrast between the sample and the background.

Bayuzick, Hofmeister, Morton and Robinson used the TEMPUS, an electromagnetic containerless processing facility, on MSL-1R to investigate the effect of convective flows on nucleation. The possibility of “dynamic” nucleation, perhaps the result of subcritical embryonic clusters somehow being brought together by shearing flows to form a viable nucleus, has been speculated, but no definitive experimental confirmation of whether or not this is a significant factor in nucleation has been obtained. The electrostatic levitator allows them to conduct repeated undercooling experiment on the same sample, thus eliminating this source of variability. Their choice of materials was pure zirconium because it has a high solubility for contaminants found in the bulk and in the high vacuum environment and oxides, nitrides, and carbides do not form in the melt or on the surface.

They measured the distribution of undercoolings where nucleation occurred with the positioning coils set at the minimum power, and at the highest power. Numerical modeling indicates that the flows are laminar at the lowest power setting with characteristic velocities of 4 cm/s, corresponding to a Reynolds number of approximately 200. At the higher power setting the flows approach the transition regime. They found no significant difference in the undercooling statistics. However, in experiments in which the heater power had been above 220 V, they found the samples would not undercool. Based on a computation model of Flemings and Trapaga, it is believed that the flows associated with the higher heater setting caused cavitation and that the collapse of these cavitation bubbles cause nucleation to occur.

Flemings and Matson investigated the phase selection process by which undercooled Fe-Cr-Ni steels solidify. Initially the  $\delta$ -ferritic phase nucleates with the characteristic recalescence signature and starts to grow; shortly thereafter, a second recalescence is seen as the metastable  $\delta$  phase transforms into the stable  $\gamma$  or austenitic phase. However, it was observed that in microgravity the second recalescence was delayed by a considerable amount compared to samples levitated electromagnetically on the ground. The decreased convection in microgravity is believed to be responsible for this delay. This investigation has led to a new growth competition model to account for the role of convection in the phase selection in the final solid.

Herlach, Holland-Moritz, Kelton, Bach, and Feuerbacher attempted to determine the maximum undercooling as well as the thermophysical properties of alloys that form polytetrahedral quasicrystals with short range order. Since this order is similar to what is believed to exist in the melt, there should be a low interfacial energy between the melt and the solid, hence the degree of undercooling should be limited. Samples of  $\text{Al}_{60}\text{Cu}_{34}\text{Fe}_6$  and  $\text{Al}_{65}\text{Cu}_{25}\text{Co}_{10}$  were processed in the TEMPUS facility. Unfortunately, the samples had become contaminated and no significant undercooling was achieved.

#### **D. Optical Glass Formation**

Single crystals have good optical transmission, but are impractical for many applications. Multiple reflections from grain boundaries of polycrystalline materials make them totally unsuitable for optical applications. Therefore glasses, which do not have grain boundaries, are used for the vast majority of optical systems. Grain boundaries also represent regions where there are unsatisfied bonds and which are therefore more vulnerable to chemical attack. Thus glasses also find many applications as corrosion resistant coatings or containers.

The crystalline state has the lowest configurational energy for most materials, hence is the equilibrium state. The amorphous or glassy state is metastable, but can exist more or less indefinitely if the viscosity of the material is high enough to prevent the atoms from moving into their equilibrium crystalline configuration. Good glass formers are systems that have high viscosities near the melting point so that, if crystallites are nucleated, they cannot grow significantly while the material is being cooled to ambient. Glass formation can always be enhanced by rapid cooling, but there is a limit to the rate at which heat can be removed from a system, especially from larger systems. Also rapid cooling produces large strains in the system that can produce optical distortion and possibly cracks or other defects.

An alternative method for enhancing glass formation is to lower the probability of nucleation. In order for a more ordered phase to form, an ordered cluster of atoms must first form to serve as a substrate for the ordered phase to grow on. This can occur either spontaneously in the melt (homogeneous nucleation) or the ordered phase can heterogeneously nucleate on a foreign solid particle or on the crucible wall. The probability of homogeneous is extremely small near the melting point, and does not become appreciable until the material is cooled to some 20 to 25% below its absolute melting temperature. Since viscosity increases exponentially with decreasing temperature, eliminating heterogeneous nucleation sites can greatly decrease the cooling rate required for glass formation, and thus increase the ability to form glasses in systems that do not generally form glasses. There are a number of such systems that are of potential interest because of their extended infrared transmissivity, their electro-optical properties, or their potential as hosts for lasers.

Braetsch and Frischat investigated the nucleation and crystallization of glasses on the D-1 mission. Lithia-silica and  $\text{Na}_2\text{O-B}_2\text{O}_3\text{-SiO}_2$  glasses were formed in glassy carbon crucibles at different cooling rates. The glasses formed in space exhibited greater homogeneity than the ground control based on variations in refraction analysis and microprobe analysis. The difference was ascribed to the fact that nuclei that formed at the wall were not transported to the remainder of the melt in microgravity. The crystalline phase  $\text{Li}_2\text{O-2SiO}_2$  in the lithia-silica system showed a spherulitic growth under normal gravity, whereas a dendritic growth was observed under microgravity. In the  $\text{Na}_2\text{O-B}_2\text{O}_3\text{-SiO}_2$  system both micro-g and 1 g samples displayed microstructure which could have been formed by a spinodal type phase separation process, however, the micro-g sample was more fine-grained.

Soga heated a glass specimen contain Au particles in the Image Furnace during the SL-J mission with the objective of obtaining the temperature-volume relation and to analyze the flows as it melted. A large unexpected volume increase was encountered near the glass transition temperature, bubbles formed in the specimen, and devitrification occurred at the surface. (No further details were available.)

The ability to position and melt a sample without physical contact offers some unique opportunities to extend the range of glass formation from ceramic systems by eliminating potential nucleation sites that might exist on container walls. Also, many glass forming systems are extremely corrosive in the melt and will easily become contaminated by the crucible. Generally, such systems are not conductive enough in the melt to be levitated and heated electromagnetically. Since they also generally require an atmosphere to prevent loss of volatile components, acoustical levitation is an attractive choice. However, difficulties have been encountered in attempts to use a resonance chamber, such as the 3-axis levitator developed by JPL for the study of drop physics, when it is necessary to operate over a wide temperature range. The single axis levitator technique, which uses a reflector to set up a series of interference nodes, is more tolerant of temperature changes. Its principal disadvantage is the weak radial positioning forces which are provided by the Bernoulli effect, which contributes to frequent sample loss.

The Single Axis Acoustic Levitator (SAAL), originally developed as a suborbital facility, was flown on OSTA-2 and on D-1 with samples prepared by Ray and Day. Technical difficulties were encountered on the OSTA-2 flight and no useful results were obtained. On the D-1 mission, two samples of pressed gallia-calcia powder were successfully melted, cooled into the glassy state, and retrieved. This low viscosity glass was formed at a much slower cooling rate (two to three times slower) in space than is possible in a crucible, which reflects the absence of low energy nucleating sites on the levitated sample. A sample of soda-lime glass containing a large void was also deployed with the objective of producing a concentric shell suitable for use as an inertially confined fusion target. The sample was successfully melted and recovered, but the bubble escaped during the process.

A more sophisticated acoustical levitator furnace was flown on SL-J. Hayakawa and Makiyara successfully processed a  $\text{CaO-PbO-B}_2\text{O}_3$  sample and two gallia-calcia-germania samples, although they reported that some bubbles remained in the samples.

## **E. Miscellaneous Experiments**

Fukuzawa and Furuyama set out to analyze the mechanisms by which Al, Si, and Mn act as deoxidizing agents for steel. An iron alloy containing about 1% of each of these elements was rolled into a 0.1 mm sheet that was sandwiched between 5 mm diameter iron rods containing different levels of oxygen content. These samples were then placed in alumina crucibles and sealed under 100 Torr Ar (argon) in a Ta cartridge. The cartridges were heated in the Large Isothermal Furnace on SL-J at 1600°C for 54 minutes and then quenched. The results appear to be inconclusive.

Wada and Dohi investigated the production of nano-particles in microgravity on SL-J. Four glass bulbs were prepared in which 50 mg of Ag was attached to the W filament. The bulbs were then filled with different pressures of Ar or Xe. The filaments were heated to approximately 1150°C and the brightness and smoke evolution was recorded on video. Particles ranging from 20 to 50 nm were deposited on the walls of the bulbs containing Ar. The bulbs containing Xe produced a burst of smoke that, according to the investigators, "...indicates a local accumulation of vapor atoms with pressure higher than the surrounding gas, which cannot be interpreted in terms of a conventional diffusion model of a Langmuir sheath".

## **F. Assessment of the Science**

### *1. Metals, Alloys and Composites.*

Many of the earlier flight experiments in this field were exploratory in nature and yielded results that were difficult to interpret. As a result, their findings were reported in conferences and often were never published in the mainstream literature where they were likely to be read by scientists not involved in the space program. As the investigators became more sophisticated and knew what lines of investigation were more likely to pay off, the program became more productive scientifically.

The primary advantages of studying solidification of metallic systems in microgravity is the ability to isolate gravitational from non-gravitational effects, to make properties measurements that are difficult to make accurately in the presence of gravity, and to test fundamental theories that have help transform metallurgy from an art to a science over the past forty years.

Most of the theories that guide our laboratory experiments and that we use to design industrial processes contain simplifying assumptions, such as ignoring convection. Such assumptions are necessary in order to be able to establish general laws that extend over a wide range of conditions, whereas the addition of factors like convection would generally be applicable only to a specific situation. Of course, since convective flows are a fact of life in most processes carried out on Earth, the theories do not always apply directly unless the effects of convection are modeled into the process for a specific task (which is becoming more common given the computational capabilities now available). Still many of the theories we use have never been rigorously tested because, before flight opportunities became available, we had no way to impose the conditions assumed by the theory. Observed discrepancies were generally explained away by convective effects that we were not able to control. But this leaves a nagging question: are there subtle errors in the theory because something important was left out, or were the simplifying assumptions that were made too unrealistic? These are important issues that need to be settled.

The importance of microgravity experiments such as Glicksman's work on dendrite growth is to assure that the basic theories used for modeling microstructures in castings are on firm foundations, or at least to understand where their weaknesses lie. Obviously, these theories will have to be modified to account for convection if they are to be used in terrestrial applications, but it is essential to be able to start from a theory that is at least fundamentally correct.

The ability to isolate gravitational from non-gravitational effects has unmasked many subtle but important effects and provided much new insight into modeling and controlling processes. For example, it was generally not suspected that Soret diffusion could be instrumental in changing the composition of the system during a directional solidification process. The effect did not become apparent until the convective flows were essentially eliminated, but it operates just the same and should be considered in a process model if high accuracy is required. Similarly, the profound influence of interfacial effects that produce phase separation in immiscible systems were not appreciated until the effects of gravity were removed.

## *2. Crystal Growth.*

The quasi-steady acceleration requirements for diffusion-controlled solutal transport have proven to be very stringent, especially for Bridgman growth of materials with high Schmidt numbers (the ratio of viscosity to chemical diffusivity) that are characteristic of many semiconductor systems of interest. The Shuttle is not a practical platform for this class of experiments since they require close alignment of the net residual acceleration vector with the furnace axis over a period of days. This was attempted on USML-1, only to be thwarted by an unsuspected acceleration of less than a half micro-g from the venting of the flash evaporators. Hopefully, the environment on the ISS will be more suited to this important crystal growth technique.

Melt growth experiments that used the traveling zone or float zone technique are more tolerant of the residual acceleration because of the much smaller melt region and because some gentle convective mixing in the molten region can actually be beneficial so long as it does become unsteady. The Japanese as well as the Europeans have had outstanding successes in growing various semiconductor systems up to 20 mm in diameter using the float zone process in the mirror furnace. For reasons that are not clear, American investigators have not pursued this process in microgravity. Perhaps the most important contribution from the melt growth experiments in microgravity was the clear demonstration of the role of wall effects in the formation of twins and other growth defects. Even in enclosed growth systems the dislocation densities seemed to be generally lower and the mobility seemed to be higher than in the ground controls. Whether this effect was a result of less convection at the growth interface, partial wall contact, or of lack of hydrostatic pressure is not clear, but the reason begs for an answer.

Similarly, crystals grown by both closed tube physical and chemical vapor transport continue to exhibit better uniformity and lower defects when grown in microgravity for reasons that are not well-understood. Also crystals grown from aqueous solution under diffusion limiting conditions were of outstanding quality, virtually free of dislocations, inclusions, and other visible defects. All of these results indicate that convective flows in the vicinity of the growth interface are somehow responsible for the generation of growth defects even though the exact mechanism is not understood. This would appear to be a fruitful topic for the theoreticians to consider while waiting for the next experimental results to come from the ISS (International Space Station).

Crystals grown from aqueous solution under diffusion controlled conditions were also of outstanding quality, especially when the supersaturation could be controlled using the cooled sting technique. The zeolite crystals also showed some encouraging results.

### *3. Measurement of Thermophysical Constants.*

Anyone involved in process modeling will applaud the possibility of obtaining accurate thermophysical data, especially data on the properties of high temperature melts. The most disturbing aspect of the results from diffusion measurements in microgravity is the realization of how inaccurate our present data base on properties of molten systems really must be. The fact that diffusion coefficients of melts measured in space turn out to be typically 30 to 50% lower indicates that virtually all of diffusion measurements for molten materials are in error and would imply similar errors for thermal conductivities and other transport-related properties. Since it would hardly be practical to try to remeasure all of our liquid phase thermophysical properties in space, we should carefully re-evaluate our laboratory measurement techniques with the aim of either eliminating or accounting for convective transport.

Of equal importance is the new microgravity data on the temperature dependence of the diffusion coefficient. For the first time, these data are sufficiently accurate to establish that liquid phase diffusion, at least in some molten systems, does not follow an Arrhenius type behavior, indicating a substantially different mechanism from solid state diffusion. Establishing the temperature behavior of various transport coefficients of a variety of melts will give new insight into the theory of liquids as well as provide benchmarks for such theories to predict.

Finally, the amount of thermophysical data that could be extracted from a levitated melt without contact is truly impressive as well as the insight such data gives to the behavior of materials in the undercooled state.

### *4. Optical Glass Formation.*

Despite the potential for being able to undercool corrosive melts without physical contact in microgravity in order to form glasses of unique composition, such experiments have been hampered by the lack of a reliable levitator. Several attempts at levitating such melts using acoustic pressure have produced only limited success because of instabilities that occur as the temperature is changed over a wide range. Consequently, this important class of experiments has received little attention in the recent microgravity program.

## **G. New Technology and Technical Spin-offs**

Unless the cost of going to space can be dramatically reduced, most of the technological payoff from the microgravity materials science program will have to come from applying the knowledge gained in space to Earth-based processes. Knowing that the basic principles upon which most of our processing technology is based, together with the prospect of obtaining more accurate thermophysical data, will improve process modeling and result in higher quality, lower cost products. The Europeans are making extensive use of process modeling to substitute lower cost precision casting for machining in automotive frames, engine parts, and in fittings used in the A330 Airbus. They have also used data obtained from microgravity experiments to develop a continuous casting process in which Marangoni convection is used to balance

sedimentation in order to get a uniform dispersion of bismuth particles in an aluminum-silicon alloy for use in self-lubricating bearings.

Crystal growers are learning about the effects of convection from the microgravity community and are now making more use of static and rotating magnetic fields in order to control unsteady flows. They, too, are now making extensive use of computational modeling to design their processes to achieve computational control. Given the deleterious effects of wall contact, new techniques may evolve that use a “soft” wall or other method for avoiding this problem in terrestrial growth processes.

Traditional methods for measuring transport properties of molten systems certainly need to be reexamined and calibrated against measurements made in microgravity.

### III. BIOTECHNOLOGY

The Biotechnology investigations carried out on the Spacelab missions include biomolecular crystal growth, electrokinetic separations, electrofusion, and the applications-oriented biotechnological research being carried out by the NASA-sponsored Centers for Space Commercialization (CSC). The vast majority of the experiments have been devoted to the growth of biomolecular crystals such as proteins, nucleic acids, and viruses. The more fundamental experiments dealing with living organisms, such as those carried out in the Biorack, will be covered under Section 3: Life Science.

#### A. Biomolecular Crystal Growth

##### *1. Background.*

The biological activity of a protein (or other biological macromolecule) depends on its three-dimensional conformation or structure. Knowing this structure not only provides important clues to understanding of the function of living organisms at the molecular level, but also offers the means of directly altering or blocking the action of certain unwanted proteins or viral particles associated with a disease state. This intervention requires finding its active site and then finding or designing a molecule that fits into this site to render it inactive, much like fitting a key into a lock. In fact, many pharmaceutical agents operate in this manner. Until recently, effective drugs had to be sought out by intuition and much trial and error testing. Now it is becoming possible to design a drug for a specific task by knowing the structure of the target molecule. It is much easier to design a key to fit a lock if one knows the structure of the lock. X-ray crystallography remains the most powerful (and, for large macromolecules, the only) method for determining the three-dimensional structure of such molecules.

When a crystal is illuminated by an X-ray beam, the beam is reflected by the various planes of atoms in a particular direction according to Bragg's law, which relates angle between the incident beam and the reflection to the lattice spacing of the planes producing the reflection. The array of Bragg reflections forms a diffraction pattern that can be recorded, either on film or electronically. Mathematically, this diffraction pattern is equivalent to a complex Fourier transform of the three-dimensional electron density map of the atoms in the unit cell of the crystal, which happens to be the protein molecule of interest. In principle, the Fourier transform can be inverted to obtain the electron density map of the protein molecule from which, with a lot of skill and patience, the three dimensional structure of the molecule can be inferred.

Unfortunately, present technology, particularly the lack of a coherent X-ray source such as an X-ray laser, allows us to record only the intensity of the Bragg reflections that corresponds to the real part of the complex Fourier transform; the imaginary part containing the phase information is lost. One method for recovering the lost phase information, requires the growth of additional crystals in which a heavy metal, such as mercury, is incorporated into the molecule of interest. Because of the large number of electrons associated with the heavy metal atom, it acts as a reference point of zero phase and, by comparing the diffraction patterns with and without the heavy metal atom, the phase information can be recovered. Pioneers in this field, such as Nobel Laureates Max Perutz and John Kendrew, spent many years developing this technique and were able to solve the structure of some of the simpler biological-macromolecules (hemoglobin and myoglobin), which earned them the 1962 Nobel Prize in Chemistry. Since then, at least twenty-seven Nobel prizes have been awarded for work in this field.

It should be appreciated that before NASA got involved in this field, the structures of only a few hundred unique proteins had been solved. With the advent of powerful new computers, ultra bright synchrotron X-ray sources, and sophisticated data collection methods, the number of unique protein structures that have been determined has risen dramatically. However, the ability to obtain crystals of sufficient size and internal order has now become the limiting barrier in this field of research.

## *2. Microgravity's Contribution to Protein Crystallography.*

The protein crystal growth experiment developed by Walter Littke that was carried out during the first Spacelab mission may prove to be the single most significant experiment in the Spacelab program. Littke reported that his space-grown crystals of beta-galactosidase grew twenty-seven times (by volume) larger than his ground control crystals, and that his lysozyme crystals grew 1000 times larger. Although the crystals of beta-galactosidase were still too small to provide meaningful X-ray diffraction data, this was the first real indication that microgravity could significantly improve an Earth-based process.

When Charlie Bugg, then the Associate Director of the Comprehensive Cancer Center at the University of Alabama in Birmingham, learned of Littke's result, he immediately began preparations for a flight experiment involving proteins of interest to his Center. He also recruited several major pharmaceutical companies to join in a collaborative effort to explore the use of microgravity to obtain better crystals of proteins they were attempting to structure, which resulted in the formation of the Center for Macromolecular Crystallography, supported by the NASA Commercialization program.

A few simple try-and-see protein crystallization experiments were carried out during Shuttle flights prior to the Challenger accident. By the time the Shuttle flights resumed, MSFC, with Teledyne-Brown Engineering, had developed a semi-automated Vapor Diffusion Apparatus (VDA) that deployed twenty individual hanging drop protein crystallization experiments. Several of these trays can be inserted into the middeck locker Refrigerator/Incubator Modules (R/IMs) developed by McDonnell Douglas to support their earlier electrophoresis experiments. The individual cells in the VDA are equipped with a double barreled syringe so that the protein could be stored in one barrel and the precipitating agent in the other to prevent premature nucleation and crystallization before the experiment was in orbit. The solutions were mixed by a crew-member repeatedly extruding and withdrawing the two fluids. After mixing, a small drop of the mixture is left hanging in a small chamber surrounded on three sides by a porous medium containing a higher concentration of precipitating agent. The water in the hanging drop diffuses through the vapor space to equilibrate against the higher concentrated precipitating agent in the porous medium, thus providing the driving force for crystallization. Before de-orbit, the crew member manually retracts the drops containing the crystals back into the syringe and a plunger seals the end of the syringe for the trip back home.

The first Shuttle flight after the Challenger accident (STS-26) yielded crystals of four different proteins that were shown to have better diffraction resolution than the best crystals of these proteins that had ever been grown on Earth. This feat is even more remarkable considering that the crystals produced in only a handful of space experiments are compared with the best crystals of these particular proteins that have been grown in thousands of experiments by the world's most qualified researchers whose professional success depends heavily on obtaining the molecular structure from the X-ray diffraction data from these crystals. These results formed the impetus for the present major effort in protein crystallography sponsored by NASA and ESA (the European Space Agency). (See DeLucas, et al, Science, 246: (1989) 651 - 654.)

It should be understood that one does not solve a protein structure with one or two crystals. Because of the very complex structure of large biological macromolecules, many thousands of data points must be taken in order to obtain the inverse complex Fourier transform of the diffraction pattern. Crystals also tend to degrade in the X-ray beam, so a number of crystals may be required to obtain a complete data set. The process may then have to be repeated with a heavy metal additive to recover the lost phase information. Hydrogen atoms do not have enough electrons to show up in the diffraction pattern, so critical hydrogen bonds must be inferred from complementary structure. Often the available data is not sufficient to accurately describe the critical shape and bond structure in the active area, so there is a constant search for higher resolution data in order to refine the structure. Finally, if a drug is to be designed to block the active site of a particular protein or other biological macromolecule, additional crystals must then be grown in which the candidate drug molecule, called the substrate, is incorporated into the active site of the target protein in order to check the fit. Therefore, it can be appreciated that a more-or-less steady supply of high quality crystals may be required to obtain the structure of a protein molecule.

If space is to play a significant role in obtaining the structure of biological macromolecules, a permanent facility in space, such as the Internal Space Station, will be required. Many of the proteins that did not crystallize, or did not grow large enough crystals to analyze during the times available to the various Shuttle missions, should produce results on the Space Station. Since protein crystals have a limited storage time, they may degrade before they can be taken back to Earth during the planned crew exchanges. Also, bringing them through re-entry g-loading may also degrade them (this is still an open issue). Therefore, serious concern is being given to an on-orbit X-ray analysis facility on the Space Station.

In order to appreciate the advantages offered by space-grown crystals, something needs to be said about the requirements needed to obtain good diffraction data from crystals. The ability of a crystal to diffract X-rays depends on the size and shape of the crystal, on the periodicity or regularity of the lattice points which locate the unit cells (long range order), and how well the individual molecules in each unit cell are positioned and oriented. The intensity of a Bragg reflection is proportional to the square of the number of unit cells illuminated by the X-ray beam. Generally, a crystal must be somewhere around 0.3 to 0.5 millimeters on a side to produce the required number of higher order reflections needed to obtain high resolution data. However, with the very bright X-ray sources now available from synchrotrons, it is becoming possible to work with smaller crystals.

However, larger crystals don't necessarily mean higher resolution or diffraction efficiency. Defects such as dislocations, small angle grain boundaries, twins, or inclusions eliminate large numbers of molecules from producing coherent reflections as well as contribute to the incoherent noise background, thus reducing the signal to noise ratio even at small diffraction angles. Diffraction efficiency is defined as the total number of Bragg reflections at some level (usually five standard deviations) above the background noise. Resolution is defined as the spacing of the highest index planes that produce detectable Bragg reflections. Since Bragg's law requires that the sine of half the angle between the incident beam and the reflected beam be inversely proportional to the lattice spacing producing the reflection, the largest angle at which reflections can be seen is a measure of the resolution. Even if the lattice has good long range order, molecules that are mis-oriented or slightly out of place at each lattice site will degrade the large angle diffraction data needed to obtain the molecular structure to high resolution.

The space-grown crystals tend to show improvements both in terms of long range order as well as better molecular orientation within the unit cells. Interestingly, a number of space-grown crystals seem to last longer in the X-ray beam before degrading. This increased radiation resistance could also be an indication of higher internal order in which more molecular bonds are available to hold the structure together. It should be emphasized that, even apparently incremental improvements of a fraction of an Angstrom in resolution, can be crucial in locating the binding sites in the active region. The increased resolution from the space-grown crystals has allowed the refinement of several important molecular structures and, in some cases, the determination of structure for the first time.

### *3. Results from the Protein Crystal Growth Program in the United States (US).*

Since the resources for protein crystal growth on orbit are small and since the acceleration requirements needed to improve the growth of protein crystals does not seem to be as stringent as for other fields of microgravity research, NASA-sponsored protein growth experiments have been able to utilize the available space on a number of Shuttle flights that were not dedicated to microgravity research, thus giving them many more flight opportunities than ESA or NASDA (the National Space Development Agency of Japan) experiments. Since many individual growth experiments can be carried on each mission, the forty Shuttle flights, including eight Spacelab flights and six MIR deployments, as of August, 1997 (the last of the dedicated Microgravity Physical Sciences Spacelab missions was MSL-1R in July, 1997), have produced many hundreds of individual experiments. Some 183 different biomolecular systems had been investigated (some only once, others repeatedly). Many of these individual experiments produced no crystals or crystals that were too small for X-ray diffraction analysis (usually due the limited flight time available on the Space Shuttle). A few experiments yielded crystals that were inferior to those grown terrestrially, but 72 of these experiments produced crystals that definitely had superior qualities. Of these 72 experiments, thirty-four produced larger crystals of that particular system than had previously been grown on the ground, fourteen experiments produced crystals with a new morphology, forty experiments produced crystals that had 10% or better diffraction efficiency (better signal to noise ratio indicating better long range order), nine experiments had less thermal motion (indicating better order in the unit cell), twenty-seven experiments had increased resolution of up to 0.3 Å, four had increased resolution of from 0.3 to 0.5 Å, and fourteen had increased the resolution by better than 0.5 Å. A complete summary of these experiments can be found at the Marshall Space Flight Center Protein Crystal Data website (see Appendix D for a list of addresses).

The VDA mounted in a temperature-controlled enclosure (such as the R/IM, the CR/IM (Commercial Refrigerator/Incubator Module), the Thermal Enclosure System (TES), or the Single locker Thermal Enclosure System (STES)) was the workhorse in the early days of protein crystal research in the United States' through USML-2, when it was replaced with more efficient hardware. Since the University of Alabama in Birmingham's (UAB) Center for Macromolecular Crystallization (CMC) had become the original focal point in the United States for crystallizing macromolecules in space, they offered guest investigator flight opportunities to both domestic and foreign collaborators from industries and other universities. They not only maintained the VDA hardware, but were also able to assist other investigators in preparing their samples for flight and in analyzing the post flight results. Significant results from the various Spacelab missions using the VDA are summarized below (Table II-2).

**Table II-2. Protein crystal growth experiments in VDA by mission.**

IML-1 (STS-42)	Guest Investigator: H. Einspahr (Bristol-Myers Squibb)	reported larger crystals of 2 Domain CD4. No increase in resolution was noted.
	Guest Investigator: K. Ward (NRL)	reported larger crystals of bacterial luciferase. No increase in resolution was noted.
	Co-Investigator: A. McPherson (U. California)	reported canavalin crystals that were comparable in size to 1g, with uniform high visual quality. Increased reflections over resolution range (higher diffraction efficiency), but no increase in resolution. Canavalin is the major storage protein of leguminous plants and a major source of dietary protein for humans and domestic animals. It is studied in efforts to enhance nutritional value of proteins through protein engineering. It is isolated from jack bean because of its potential as a nutritional substance.
	Guest Investigator: S. Aibara (Kyoto U.)	reported a new monoclinic form of lysozyme crystals with different lattice parameters.
	Co-Investigator: D. Carter (NASA/MSFC, now New Century Pharmaceuticals)	reported a dramatic improvement in diffraction efficiency over all Bragg angles for human serum albumin. Crystals diffracted to highest resolution ever obtained, including growth in gels. Human serum albumin is the most abundant blood serum protein; it regulates blood pressure and transports ions, metabolites, and therapeutic drugs. It also has multifunctional binding properties that range from various metals, to fatty acids, hormones, and a wide spectrum of therapeutic drugs.
	Co-Investigator: A. McPherson (U. California)	found a new hexagonal crystalline form for satellite mosaic tobacco virus (SMTV) and collected the first X-ray diffraction data on this form. The satellite tobacco mosaic virus is the spherical T=1 icosahedral satellite virus of the classical rod virus TMV, and is a plant pathogen. Its importance lies in the study of virus structure, ribonucleic acid (RNA) structure and virus assembly.
	Guest Investigator: L. Delbaere (U. Saskatchewan)	obtained two diffraction quality crystals of anti-HPr Fab fragment crystals. Unfortunately, the crystals began to deteriorate while waiting to get time on the synchrotron. Even so, the data collected was comparable to the crystals grown on STS-31, which had narrower mosaic spread and diffracted to the same resolution as Earth-grown crystals with 10 times the volume.
	Guest Investigator: G. Birnbaum (NRC, Canada)	grew Fab YST9-1 crystals that exhibited slightly higher resolution with much higher diffraction efficiency (higher signal to noise) throughout the resolution range. Fab YST9-1 represents a class of antibodies that have specificity to

**Table II-2. Protein crystal growth experiments in VDA by mission.**

IML-1 (STS-42)	Guest Investigator: G. Birnbaum (NRC, Canada) cont'd	polysaccharide antigens, those that occur on cell surfaces. Thus, it can be used to recognize a certain type of cell.
Spacelab-J (STS-47)	Guest Investigator: C. Betzel (European Molecular Biology Lab, Hamburg)	obtained the highest resolution ever obtained from a crystal of the receptor of epidermal growth hormone that allowed, for the first time, the evaluation of the real space group by partial data collection. The space crystal diffracted to 6 Å, which is an improvement of 2 to 4 Å over the best Earth-grown crystals. The receptor for the epidermal growth factor is increasing in its importance as a prognostic factor for a series of human malignancies since many such malignancies are characterized by its over-expression. Knowledge of the three-dimensional structure of this receptor would open the possibility of tailoring appropriate drugs for the treatment of numerous types of tumors. At the present time, however, the crystal structure of only one hormone receptor (growth hormone) and none of the growth factor receptors have been solved.
	Guest Investigator: S. Aibara (Kyoto U.)	repeated his IML-1 experiment with lysozyme and again found the monoclinic form with different unit cell parameters.
USML-1 (STS-50)	Co-Investigator : A. McPherson (U. California)	obtained several large crystals of recombinant canavalin. The crystals apparently degraded somewhat before they could be analyzed, but even so, a slight improvement in resolution was seen.
	Guest Investigator: E. Arnold (Rutgers U.)	obtained several large crystals of HIV reverse transcriptase complexed with antibody (Fab) against gp4. Relative Wilson plots showed the space crystals to be better ordered (less thermal noise) as the limiting resolution was approached.
	Guest Investigator: M. Navia (The Althexis Co.)	grew human proline isomerase crystals that were considerably larger than the ground control, large enough that neutron diffraction analysis would be possible. No twinning or clustering was observed in the space-grown crystals (both are often problems with these crystals when grown in normal gravity). The space-grown crystals were optically clearer and had sharper facets than the Earth-grown crystals. Unfortunately, they began to degrade (edges began rounding) before X-ray analysis could be performed. Even so, they exhibited significantly higher diffraction efficiency, but no significant increase in resolution.
USMP-2 (STS-62)	Guest Investigator: L. Delbaere (U. Saskatchewan)	repeated his growth experiment with anti-HPr fab fragment crystals. Again he was able to grow larger crystals with a significant increase in diffraction efficiency, but with no significant increase in resolution. The detailed structure of the anti-HPr Fab fragment protein would provide a picture

**Table II-2. Protein crystal growth experiments in VDA by mission.**

USMP-2 (STS-62)	Guest Investigator: L. Delbaere (U. Saskatchewan) cont'd	of an antibody binding site that recognizes a bacterial “foreign” protein antigen. By learning what antibody binding sites look like we may better understand how antibodies function in the immune system.
ATLAS-3 (STS-66)	Co-Investigator: D. Carter (NASA/MSFC, now New Century Pharmaceuticals) Co-Investigator: E-K. Ossama (UAB)	repeated his human serum albumin growth experiment. Again he got larger crystals with higher diffraction efficiency, but no significant increase in resolution. obtained crystals of aldehyde reductase that exhibited higher diffraction efficiency, but no significant increase in resolution.
ASTRO-2 (STS-67)	Guest Investigator: D. Eggleston (Smith- Kline Beecham) Guest Investigator: L. Delbaere (U. Saskatchewan)	grew crystals of bovine parathyroid hormone that had higher diffraction efficiency, but no significant increase in resolution. obtained larger crystals of PEP carboxykinase that showed higher diffraction efficiency, but no significant increase in resolution.
USML-2 (STS-73)		no significant results were obtained from the VDA hardware on this mission because the proteins degraded during multiple launch delays.

One of the most significant experiments in the program sponsored by the United States was the set of crystallization experiments performed in the glove box in which Larry DeLucas, the Payload Specialist on USML-1, was able to mix proteins and set up experiments on orbit, very much as he does in his own terrestrial laboratory. He had developed a special set of hardware that would allow him to monitor the nucleation and early growth and make necessary adjustment when necessary. When the crystal appeared to be growing properly, this glove box hardware could be transferred to the CR/IM to provide thermal control during the rest of the growth process. This apparatus was flown in USML-1 and USML-2.

Much was learned from the opportunity for a trained crystallographer to fly as a Payload Specialist on the USML-1 mission. Four proteins that were crystallized with the glove box hardware had failed to crystallize in previous Shuttle missions using the VDA hardware. It was suspected that the mixing of the protein with the precipitant been inadequate in the VDA, especially when the more viscous precipitants such as polyethylene glycol (PEG) were used. With the glove box hardware, the Payload Specialist could mix the protein and precipitant solutions thoroughly by stirring or by withdrawing and re-extruding the solution from a Hamilton syringe. It was noted that many of the growth systems seemed to take longer to nucleate and grow than they did on the ground and that many experiments had crystals that were growing nicely, but were still too small for diffraction experiments when the mission was over.

For some experiments, a micro-manipulator was used to withdraw small seed crystals grown on previous days with the glove box hardware and inject them into a more concentrated growth medium. This procedure proved to be straightforward in microgravity. It was shown that a similar technique could be used in microgravity to withdraw grown crystals and mount them in x-ray capillaries for analysis. Since the crystals are typically suspended within the middle of the protein drop, the most difficult aspect of this procedure (withdrawing the crystal into the capillary) was easily accomplished in microgravity.

It also became clear that high magnification microscopy with video transmission will be extremely useful on future missions. This capability will allow crewmembers to display results to scientists stationed on the ground so that they can aid in the decision making process, thereby optimizing the chance of producing high quality crystals. Hopefully, this demonstration will serve as a model for how such experiments will be performed on the International Space Station in which the growth process can take full advantage of the extended low gravity time. Significant results using the glove box hardware are noted in Table II-3.

Engineers at the UAB-CMC developed an improved second generation VDA-2, which was flown on MSL-1 and MSL-1R. The primary difference between this new device and the old VDA is the addition of a third barrel to aid in mixing the sample. After the protein and precipitating agent are deployed as before, the drop is repeatedly sucked into and extruded out of this third barrel. The VDA-2 carries eighty individual crystal growth experiments in a CR/IM that provided temperature control.

It was known the crystals grown in the VDA-2 on the shortened MSL-1 flight did not have sufficient time to grow large enough to produce useful data, so the experiments were reactivated after the Shuttle landed in hopes of salvaging the valuable proteins. None of the resulting crystals produced diffraction data that was superior to their ground control. Consequently, the same set of proteins was flown on MSL-1R with spectacular results. Eight of the ten growth systems produced diffraction quality crystals, and five of them produced the best X-ray quality crystals ever obtained. Some of the results from investigators using the VDA-2 are summarized in Table II-4.

The UAB-CMC also developed hardware for batch crystallization that was termed the Protein Crystallization Facility (PCF) to produce large numbers of crystals to meet a commercial requirement. Crystallization was driven by withdrawing heat from one end of a cylinder. The PCF first flew on STS-37 where it was used to produce batch quantities of insulin crystals. Most of these crystals remained suspended in the growth medium, but some were stuck to the walls. It was found that the free-floating crystals were much better ordered than those that grew on the walls, thus confirming one of the hypotheses as to why crystals seem to grow better (at least some of the time) in microgravity. Further, the increased X-ray resolution of these crystals provided the clearest picture yet of the structure of this important molecule. Results from Spacelab flights of the PCF are summarized in Table II-5.

Eventually, some of the UAB-CMC collaborators developed new hardware more suited to their purposes, and formed additional collaborative teams of investigators interested in using their new hardware. For example, Carter, while he was at the NASA Marshall Space Flight Center, was selected as a flight principle investigator by NASA. He developed the protein crystallization apparatus for microgravity (PCAM) module that was first flown on USMP-2 and the diffusion-controlled crystallization apparatus (DCAM) that was flown together with the PCAM on USML-2.

The PCAM is a simplified vapor diffusion apparatus that utilizes a sitting rather than a hanging drop. A stack of nine units can be activated and deactivated by turning a single knob. A single locker temperature enclosure system (STES) that fits in a middeck locker can accommodate 378 units, six times the capacity of the older VDA. Furthermore, an inexpensive disposable user interface is provided that permits rapid *in situ* evaluation of results and allows users to carry the grown crystals back to their laboratories without having to remove the crystals from the apparatus. The PCAM can also be cryogenically stored.

**Table II-3. Microgravity glovebox protein crystal growth experiments by mission.**

USML-1 (STS-50)	Principal Investigator: L. DeLucas	grew the longest crystal of monoclinic Factor D ever grown, a form that is difficult to grow reproducibly on Earth. Although, the space-grown crystal was only 1/3 as thick as the best Earth-grown crystal, the diffraction intensity was comparable to the best Earth-grown crystal, and it diffracted to 0.1 Å greater resolution. Also, the relative Wilson plot indicated a significant improvement in internal order at the higher resolution range. Using the X-ray data from the space crystal together with previous Earth-grown crystals, the three-dimensional structure of Factor D was worked out. This represents the first structure of a complement protein ever determined at atomic resolution. (See Narayana, Structure of Human Factor D: A Complement System Protein at 2.0 Å Resolution, Journal of Molecular Biology, 235 (1994) 695). Factor D is an enzyme necessary for activation of the complement system that plays an important role in host defense against pathogens.
	Guest Investigator: H. Einspahr (Bristol-Myers Squibb)	malic enzyme is an NAD-dependent enzyme isolated from a parasitic nematode. It is being studied to exploit the differences in the structure from the human form to aid in the development of an antiparasitic drug. Einspahr obtained crystals of malic enzyme that were much smaller than typical Earth-grown crystals. However, these space-grown crystals proved to be of exceptional quality. A space-grown crystal only 1/5 the volume of an Earth-grown crystal produced 25% more Bragg reflections and diffracted to 2.6 Å resolution, an improvement of 0.6 Å. The relative Wilson plots also show a dramatic improvement in internal order as the resolution limit is approached. The enhanced stability of the space-grown crystals in the x-ray beam was documented with these crystals, providing further evidence of better internal order (more bonds satisfied).
USML-2 (STS-73)	Guest Investigator: S. Aibara (Kyoto U.)	obtained lysozyme crystals that showed slightly higher improved diffraction efficiency and resolution as compared to his ground control, but were inferior to the best lysozyme crystals grown on Earth.
	Co-Investigator: L. Howell (Hospital for Sick Children, Toronto)	duck delta II crystallin is a protein that is similar to the key enzyme that causes the disease argininosuccinic aciduria. The three-dimensional structure of this protein will lead to a better understanding of the metabolic processes involved in this disease. The protein supplied by Howell produced square pyramidal crystals rather than the usual flat plates seen on the ground. However, the crystals appeared to be striated and diffracted poorly. It is believed the protein was degraded by the launch delays associated with STS-73.

**Table II-4. Protein crystal growth experiments flown on the VDA-2 on MSL-1R.**

M. Jedrzejewski (UAB-CMC)	The hyaluronidase crystals grown by M. Jedrzejewski diffracted 0.2 Å better than the best data ever collected on earth-grown crystals and these data are being used to refine the structure for a vaccine against bacterial infections.
G. Oliva (U. of Sao Paulo)	Glyceraldehyde 3-phosphate dehydrogenase (GAPDH), a target for drugs to combat Chagas' disease provided by G. Oliva, produced crystals of a different space group that diffracted to 2.0 Å, an improvement of 0.8 Å over the best ground-based data. From these results, ground-based growth procedures were modified to produce the new space group, which diffracted to 2.2 Å resolution.
V. Erdmann (Freie Universität Berlin)	Experiments with 5S rRNA by V. Erdmann produced the best crystals ever grown of this ribosomal RNA. The space-grown crystals diffracted to 7.5 Å and yielded the first complete data set for this macromolecule from which the space group could be determined. The best ground grown crystals diffracted only to 9.0 Å. 5S rRNA is an essential component of ribosomes. Structural data will aid in understanding the process of protein biosynthesis.
Y. Devedjiev (UAB-CMC)	NAD synthetase is also a target molecule for anti-bacterial drugs. Crystals of a complex of NAD synthetase with an inhibitor drug provided by Y. Devedjiev yielded diffraction data 0.3 Å better than had ever been obtained before. The data are being used to study how well the proposed drug block the active site for this target molecule.
C. Betzel (DESY, Hamburg)	Crystals of Proteinase K and Proteinase K with a substrate complex provided by C. Betzel showed a 0.3 Å improvement over the best crystals ever produced before. Proteinase K is one of the most aggressive proteases known and can even degrade keratin. It is used in several industrial applications such as soap powder. This investigation is aimed at understanding the binding between the target molecule and the substrate.

**Table II-5. Protein crystal growth experiments flown on the PCF by mission.**

USMP-1 (STS-52)	M. Long (UAB - CMC)	Alpha-interferon crystals grown by M. Long grew somewhat larger than their ground controls but were still too small for X-ray diffraction analysis.
USML-2 (STS-73)	G.D.Smith (Hauptman-Woodward Medical Research Institute) and Eli Lilly	The objective of this experiment conducted by G.D. Smith and Eli Lilly was to produce large quantities of a new form of recombinant human insulin. Unlike the earlier flights in which both bovine and human insulin produced well-formed free-floating crystals, all of these crystals grew on the container walls. It is not clear whether the slightly different molecular of this form of insulin caused the crystals to nucleate on the walls, or if the optimal crystallization conditions were different for this system.

The DCAM is a liquid diffusion dialysis method for growing crystals designed primarily as a totally passive device to be used on MIR. Since there is limited crew time available, the DCAM was designed to be totally passive, that is it requires no crew interaction. The protein solution and precipitating agent are stored in adjacent chambers connected by a small diameter tube filled with a gel. This gel-filled plug acts as a fuse that controls the activation rate of the experiment. A total of twenty-seven DCAM units can be fitted into a STES.

Both the PCAM and DCAM have attracted a variety of guest investigators who want to use his hardware. Carter later left NASA and founded New Century Pharmaceuticals, Inc., but remains a NASA-sponsored principle investigator. In this role he continues to offer guest investigator flight opportunities to both domestic and foreign collaborators from other industries and universities whose requirements are suited to his hardware.

Many of the protein and life science experiments were degraded by the delays in the launch of STS-73. Nevertheless, there were some successes with the PCAM hardware as summarized in Table II-6.

**Table II-6. Protein crystal growth experiments flown on the PCAM on USML-2.**

Guest investigators: C.H. Chang and P.J. Ala (Dupont Merck Pharmaceutical Co.)	obtained the largest crystal and highest quality data yet obtained for a particular HIV (human immunodeficiency virus) protease/inhibitor complex. The increased resolution allowed a refinement of the data so that a better understanding of the binding of the inhibitor molecule can be obtained.
Guest investigators: J.P. Wery and D. Clawson (Eli Lilly)	obtained the largest crystal ever grown of onogene product, raf kinase, a drug target for cancer therapy. Unfortunately, the crystals were still too small for structural determination.
Guest Investigator: M. Wardell (Cambridge U., UK, now Washington U, St. Louis)	human antithrombin III is important on the control of blood coagulation by forming complexes with thrombin and other coagulation proteases, a process that is accelerated by heparin. On a previous Shuttle flight, Wardell had obtained crystals of this molecule which allowed the refinement of the structure so that the region of the heparin binding site to be seen for the first time. Unfortunately, the protein deteriorated during the delay in launching STS-73.
Guest investigators: J. Rose and B.C. Wang (U. Georgia)	obtained the largest crystal of neurophysin/vasopressin complex grown to date. The crystal exhibited a high degree of optical perfection. X-ray analysis is in progress.
Guest Investigator: J-P Declercq (Universite Catholique de Louvain, Belgium)	obtained the largest crystals of L-alanine dehydrogenase ever grown. Unfortunately, the resolution is still not sufficient to obtain structural information.

G.K. Bunick used Carter's DCAM to crystallize nucleosome core particles which have a total molecular weight of 102 kD. Because of the launch delay of STS-73, most of the nucleosome core particles crystallized on the ground. However, a few of the DCAM units were set for longer times and the produced large crystals with a new morphology that diffracted to a higher resolution than any crystals grown previously. Table II-7 describes the experiments flown on the DCAM on STS-83 and STS-94.

**Table II-7. Protein crystal growth experiments flown on the DCAM by mission.**

MSL-1 (STS-83)	Guest investigator: C. Chang (Dupont Pharmaceuticals)	despite the early termination of MSL-1, several protein systems grew crystals large enough for X-ray analysis. However, The primary value of this flight was the optimization of the growth conditions for the next flight. Chang grew diffraction size crystals of HIV protease complex with a proprietary inhibitor, but the crystals were twinned. There was not sufficient protein to support the STS-94 flight, but the system was reflown on STS-85 under more optimal conditions. The crystals from this mission were the largest ever grown and provided data to 1.8 Å. With this resolution, a detailed image of the inhibitor bound to the active site was obtained.
MLS-1R (STS-94)	Guest Investigator: J-P Declercq (Uni- versite Catholique de Louvain, Belgium)  Investigators: B. Thomas and P. Vekilov (UAH, Center for Micro- gravity and Materials Science)	Declercq grew the largest and highest quality crystal of pike parvalbumin ever grown. This protein is of interest to fundamental biochemistry. Previous diffraction limit for pike parvalbumin is 1.7 Å and for all parvalbumin structures in the Brookhaven Data Bank the highest resolution is 1.5 Å. Declercq's crystal diffracted to the limit of measure of the Hamburg synchrotron, which is 0.9 Å. Based on the number of reflections at this angle, it is estimated that the actual resolution is closer to 0.6 Å. The crystals were also subject to neutron diffraction studies at Grenoble.  crystals of lysozyme and ferritin grew under special conditions to support fundamental research by Thomas and Vekilov into why some crystals grow better in microgravity. Hopefully, this line of research will lead to improvements in terrestrial growth processes.

McPherson was also selected as a flight principle investigator by NASA and he developed a simple crystallization module designed to take advantage of the long duration microgravity environment on the Mir station to grow crystals by liquid-liquid diffusion. The protein and precipitant solutions are flash frozen separately and the frozen solids are placed next to each other in a small container. These individual experiments are formed into three bundles that are stacked in a sealed aluminum cylinder. The cylinder is then placed inside an aluminum vacuum jacket, a dewar or container specially designed for holding cold gases or air, lined with a calcium silicate absorbent. The absorbent was filled with liquid nitrogen to delay crystal growth until thawing occurs aboard Mir. After the Shuttle docks with Mir, the crew secures the dewar in a quiet area of the Mir station to minimize vibration. The liquid nitrogen continued to boil off into Mir's oxygen/nitrogen atmosphere. In orbit, the samples thaw after the nitrogen evaporated allowing the liquids to slowly interdiffuse. The gradual increase in concentration of the precipitant within the protein solution causes the proteins to crystallize. This occurs very slowly, allowing formation of large crystals with highly uniform internal order. Growth by liquid-liquid diffusion is not practical on Earth because the differences in solution densities will cause rapid mixing by gravity-driven convection. Furthermore, the greater density of the crystals will cause them to settle to the bottom of the container.

The GN<sub>2</sub> dewar (used for gaseous nitrogen) was flown on six MIR docking missions; one of these, SL-M (STS-71), was a Spacelab mission. On this mission, 167 individual experiments involving eighteen different growth systems were carried in a single dewar.

A number of proteins have been successfully crystallized by this method resulting in larger crystals with considerable improvement in resolution. Examples include leg hemoglobin, catalase, canavalin, STMV, cellulase, concanavalin B, and thaumatin.

McPherson also developed a hand-held diffusion test cell (HHDTC) that was flown on USML-2, MSL-1 and MSL-1R. The unit consists of a group of eight cells that use the liquid-liquid diffusion method for crystallization. The cells are backlit for observation of the growth process. The cell design is a forerunner of a more sophisticated system to be used on the ISS with more diagnostic measurements.

#### *4. Results from the Protein Crystal Growth Program in Europe.*

Littke carried out his landmark experiment using a liquid-liquid diffusion apparatus in the Cryostat facility on Spacelab-1. Unfortunately, his attempt to obtain diffraction quality  $\beta$ -galactosidase crystals on D-1 failed because of equipment problems. A third attempt on IML-1 yielded crystals that were too small for X-ray analysis.

The Cryostat on IML-1 provided McPherson the opportunity to compare crystals of canavalin and STMV grown by liquid-liquid diffusion with identical systems grown in the VDA on the same mission. Differences were noted in the kinetics of crystallization by the two methods. A crystal of SMTV was grown in the cryostat that was an order of magnitude larger in volume than had ever been grown on Earth. The diffraction resolution was improved from 6 Å to 4Å. This represents the best resolution ever obtained from a virus crystal. The best canavalin crystals were grown in the VDA. They were of superior optical quality and exhibited increased diffraction efficiency, but showed no significant increase in resolution. (See previous section, US Program Results)

The development of the Advanced Protein Crystallization Facility (APCF) on IML-2 made it possible to accommodate a larger number of samples (up to 48) and allows its users to choose their method of crystallization between

1. liquid/liquid diffusion or free interface diffusion (FID), in which the protein and a salt solution are separated by a buffer and are allowed to flow together when activated (the method used in the Cryostat);
2. Dialysis (DIA), in which protein and salt solutions are separated by a membrane through which the salt will diffuse slowly into the protein; and
3. Vapor diffusion or hanging drop (HD), where crystals will form inside a drop of protein solution as solvent evaporates from the drop to a reservoir (similar to the VDA).

It also provided a capability for real-time video recording of the growth process and was enhanced for the LMS mission by the addition of a Mach-Zehnder-Interferometer that could measure changes in the concentration field as the crystals grew, thus providing better insight into the crystal-growth process in microgravity.

The IML-2, USML-2, and LMS missions offered multiple flight opportunities to a number of investigators, a requirement for success in this area of research where it is often necessary to adjust or refine an experiment multiple times, since growth conditions optimized for normal gravity may not be optimum in microgravity. As with many of the US investigators, the time on orbit was not long enough in a number of cases to grow large enough crystals for diffraction studies. Also, some of the proteins loaded into the experiments on USML-2 degraded during the 23-day delay in the launch that caused by weather and technical problems. However, there were some noteworthy successes.

G. Wagner crystallized bacteriorhodopsin on IML-1, IML-2, and USML-2. Bacteriorhodopsin converts light energy to voltages in the membrane of photoenergetic microorganisms that are chemically and genetically distinct from bacteria and higher living organisms. Resolution of the three-dimensional structure of this protein will help scientists understand the mechanisms used to convert light energy to energy for growth. Crystals from their IML-1 experiment improved the resolution from 8 Å (from previous ground-based work) to 6 Å. Using the APCF on IML-2, two different growth techniques were explored and larger cubic crystals were obtained. In a new experiment protocol, first used under microgravity conditions during the USML-2 mission, both the compact alignment of the crystalline filaments of bacteriorhodopsin and the crystal size were greatly improved which resulted in an increase in diffraction power to 3.8 Å.

Ribosomes are responsible for the translation of the genetic code to proteins. While they are the only organelles in living cells to have been crystallized, most of the Earth-grown crystals are very thin and crack upon handling, causing severe difficulties in data collection. Yonath and H. Hansen grew crystals of a ribosome particle on D-2, IML-2, and USML-2. In all cases, the space-grown crystals tended to be somewhat more rounded and bulkier than their Earth-grown counterparts, which seems to make them less fragile and easier to handle. However, none of the crystals were large enough for X-ray diffraction analysis.

On D-2, IML-2, USML-1, and LMS, V. Erdmann and S. Lorenz crystallized the nucleic acid 5S rRNA from *Thermus flavus*, an essential component of the ribosome that is needed for biosynthesis. The crystals on IML-2 were fewer in number and larger than the ground-controls, but diffracted only to the same resolution (15 to 20 Å). It was noted, however, that seven weeks had lapsed before the space crystals could be analyzed, which may have caused some degradation. Similar results were obtained on USML-2, although, in this case, the material is known to have deteriorated during the launch delay. Engineered 5S rRNA (modified to reduce internal motions) grew larger in space than in ground controls, but did not diffract to as high a resolution as the best ground grown crystals. (Erdmann later was able to get crystals that diffracted to 7.4 Å using the VDA-2 on MSL-1R. See the prior section on the US program.)

N. Chayen and co-workers crystallized the protein apocrustacyanin C on IML-2, USML-2, and on LMS. Apocrustacyanin C is a member of the lipocalin family of proteins, which binds to certain pigments that are widely distributed in plants and animals. Knowledge of the structure of the lipocalins will enable scientists to engineer these proteins to produce carriers that will bind more strongly to the pigment crocetin, which has anticancer properties. On IML-2, she found no significant increase in resolution in her flight samples, but did report seeing “halos” around the growing crystals which would correspond to the region of depleted blue-colored protein near the growth interface, indicative of growth under diffusion-limited transport conditions. She also reported motion of the crystals, which she attributed to Marangoni convection driven by concentration gradients along the surface of the hanging droplet and suggested that crystals growing from a surface, as in a dialysis chamber, might have better order (contrary to the findings of M.

Long in the PCF). Mosaicity (rocking curve) measurements on the crystals grown on USML-2 showed a spread in data with no significant difference between space and ground based growth. The space grown crystals on LMS diffracted to a much higher resolution than the ground controls, but were 12 times larger (by volume). Mosaicity measurements and X-ray topographic measurements were unavailable.

W. de Grip was interested in the structure of visual pigments, such as rhodopsin, which are the primary photoreceptor proteins for a variety of light-regulated processes. Knowledge of the structure of such proteins may help understand signal transduction on the molecular level. Crystals grown on IML-2 were somewhat larger than the ground controls, but were not large enough for X-ray diffraction studies. Unfortunately, no useful crystals were obtained from the USML-2 flight because of problems with the reactor.

Broutin, M. Ries-Kautt, and A. Ducruix crystallized collagenase and photoreaction center (PRC) proteins on USML-2. The PRC crystals diffracted poorly because they degraded while being stored at 20°C prior to launch. However, the space-grown collagenase showed a dramatic increase in diffraction efficiency, although there was no significant increase in resolution.

Broutin, M. Ries-Kautt, and A. Ducruix extended their study of the effects of microgravity on the growth of hen egg white lysozyme (HEWL) on USML-2. Using the APCF on Spacehab-1, they grew examples of the tetragonal form that diffracted to 1.3 Å. This was better than any previous published data, but there was no significant difference between the ground and space-grown crystals. On USML-2, they grew the monoclinic and triclinic form of HEWL. The ground and space-grown crystals of both forms diffracted to 1.45 Å, better than any previously published, although there are unpublished reports of 0.99 Å resolution for the triclinic form grown on the ground. The original plan was to also crystallize the protein Grb2, an adapter protein involved in the transfer of signals from one cell to another. However, this protein was found to be unstable before the final loading for the USML-2 flight.

The bacteriophage lambda lysozyme is a small protein of 158 amino acids involved in the dissolution of the cell walls of bacteria. J-P Declercq and C. Evard grew crystals of this protein on USML-2 hoping to learn more about the method of destruction employed by this organism from the structure of its lysozyme. However, they obtained only small needle-like crystals and concluded that optimum crystallization conditions must be different in microgravity than on Earth.

J. Helliwell grew crystals of HEWL on IML-2. This type of lysozyme is easy to grow and it was one of the first proteins whose structure was determined. Therefore, it has been widely used as a model protein for studying the growth of proteins. In this experiment, rocking curves (a measure of crystal long range order) from space-grown crystals were found to be reduced from 0.0067 degrees for earth grown controls to 0.0017 degrees. It was noted that the decrease in rocking width is proportional to the increase in peak height of reflections with, after corrections for volume in the beam, the microgravity crystals displaying peak intensity levels three to four times that of the earth grown counterparts. It was readily possible to find reflections for the microgravity- grown case at 1.2 Å.

The experiment was repeated on LMS in a chamber with a Mach-Zehnder interferometer and video imaging capability. Stability problems with the laser caused some difficulty in interpreting the interferograms, but depletion regions around the crystals were evident. Growth rate and crystal motion were monitored using the CCD video camera. All crystals seemed to follow a general drift at the rate of approximately 40

Å/second, although occasionally there were spurts where they moved approximately 0.2 mm over a two hour period which corresponds to a rate of 300 Å/second. Unlike Chayen's experiment, which used the hanging drop method, these experiments used the dialysis method, hence there was no free liquid surface that could support Marangoni convection. (The observed drift was most likely due to the quasi-steady residual accelerations (atmospheric drag plus gravity gradient) and the sudden spurts could be the results of changes in attitude of the Shuttle.) Periods of increased growth rate were also noted that could be correlated with crew exercise periods.

J. Martial and L. Wyns synthesized a series of *de nova* proteins, named octarellins, that are designed on the basis of an alpha/beta barrel structure in order to understand the molecular forces that stabilize their structures. Attempts to crystallize several of these systems on IML-2 and on USML-2 produced only needle-like crystals, too small for X-ray analysis. However, some crystals produced in the ground control units were able to provide low resolution diffraction data.

L. Sjölin crystallized ribonuclease S using the vapor diffusion method in the APCF on IML-2. The crystals grown in space were similar in size and number to those grown terrestrially, although the space-grown crystals tended to have flatter faces, generally a sign of greater perfection. Also, some of the control samples had cracks that were not found in any of the flight crystals. Ten data sets were then collected from both earth-grown and space-grown crystals. The results from the statistical analyses of the ribonuclease S crystal data indicate that, when crystal growth conditions are optimized, the space-grown crystals of ribonuclease S show a smaller mosaic spread than crystals under comparable conditions on earth. Analysis of the three-dimensional X-ray data from all ten crystals of ribonuclease from both space and earth clearly shows that the variance between the different data sets is less for the space grown crystals. A similar experiment was attempted on USML-2 using glutathione S transferase. Unfortunately, technical problems prevented the return of useful crystals.

J. Ng, B. Lorber, A. Théobald-Dietrich, D. Kern, and R. Giegé grew thermophilic aspartyl-tRNA synthetase on IML-2, USML-2, and LMS. Aminoacyl-tRNA synthetases are the enzymes that attach specifically the amino acids to transfer RNA, and thus are responsible for the correct expression of the genetic code. On IML-2 it was found that the crystallization conditions used on the ground were not proper for microgravity. Only small crystals were observed which appeared to be growing by Ostwald ripening. These results were used to set the crystallization conditions for the USML-2 experiment. Unfortunately the protein denatured during the launch delay and no usable crystals were produced on this flight. On the LMS flight, only one dialysis reactor contained crystals. However, this reactor contained three unusually large, high quality crystals, the largest being over 3 mm in length and free of any visual imperfections. These crystals produced almost twice the number of Bragg reflections than the Earth-grown crystals (93% increase in diffraction efficiency) but did not extend the resolution significantly. The mosaicity spread (rocking curve width) was reduced by a factor of 8 in the space-grown crystals, implying a dramatic increase in internal order.

Giege and his co-workers added thaumatin, a plant sweetening protein, to their experiment on USML-2 and found fewer, but substantially larger crystals in the space reactors. The space crystals, especially those that grew suspended in the fluid, were perfectly formed and free of any visual imperfections. They reported an improvement in resolution from 1.7Å to 1.5Å with improved diffraction properties as judged by relative Wilson plots. The rocking curve width was reduced from 0.055° to 0.023° for the crystals grown in space. Similar results were obtained from the LMS flight. In this case the rocking curve width (FWHM) was reduced from 0.047° to 0.018°.

McPherson used the liquid-liquid diffusion capability of the APCF on IML-2 to crystallize canavalin, STMV, satellite panicum mosaic virus (SPMV), and turnip yellow mosaic virus (TYMV). Both rhombohedral and hexagonal forms of canavalin grew in the same flight chambers, a highly unusual situation on the ground that was not seen in the control experiments. The crystals were quite large ( $>1$  mm) and exhibited high optical quality, free of any imperfections. Previous flight had produced canavalin crystals of similar optical quality, but showed little or no increase in X-ray diffraction resolution. Relative Wilson plots of these crystals showed marked improvement over the best canavalin crystals ever grown on Earth. These crystals also diffracted to higher resolution and provided data to refine the structure of canavalin. Very large ( $>1.5$  mm) cubic crystals of STMV grew in the flight reactor, as much as 30 times the volume of the largest cubic STMV ever grown on Earth. Again these crystals diffracted to  $2 \text{ \AA}$  better than the best cubic STMV grown on Earth. The TYMV crystals exhibited a different morphology attributed to diffusion controlled versus convective transport. They did not show any improvement in X-ray diffraction resolution, however. No useful crystals of SPMV were returned. This system uses PEG (polyethylene glycol) as the precipitating agent, and, as was discovered by DeLucas, the slow diffusion time for this liquid does not provide adequate mixing in microgravity in the time frame of these experiments.

McPherson added thaumatin, catalase, concanavalin B, and tomato aspermy virus to the materials to be crystallized on USML-2. The thaumatin in this experiment was grown by liquid-liquid diffusion to compare with the result of the Strasbourg team who used the dialysis growth method (see Giege above). Only thaumatin grew high-quality crystals with sizes as large or larger than those grown on Earth. It was suspected that the other materials deteriorated during the launch delay of USML-2.

The thaumatin experiment was repeated on LMS. In both flights, the quality of the thaumatin crystals was excellent in all cases, except those where the crystals grew with faces against walls. These showed extensive striations. The thaumatin crystals increased in size with increasing protein concentrations. This interesting observation points out another advantage of growth in microgravity. On Earth, convection would continuously expose the growth interface to the high concentration, causing very rapid growth leading to many growth imperfections. In microgravity, the diffusion field limits the transport and keeps the growth rate slow even at high protein concentrations. The flight crystals diffracted strongly to the maximum resolution that the data collection system could achieve, approximately  $1.5 \text{ \AA}$ , an improvement of  $0.2 \text{ \AA}$  from the best Earth-grown crystals. An improvement of 30% in diffraction efficiency was also noted. The mosaicity of the flight crystals was measured at  $0.020^\circ$  FWHM versus  $0.048^\circ$  for the best terrestrially grown thaumatin crystal. (Note: ground control experiments cannot use liquid-liquid diffusion because of the very rapid gravity-driven convective mixing of the two fluids.)

W. Weber and Ch. Betzel continued their work on the various forms of receptors of Epidermal Growth Hormone (also known as Epidermal Growth Factor or EGF) that they began using the VDA on SL-J. However, now they used the European APCF that was flown on the USML-2, and LMS missions. Diffraction data from three crystals grown on USML-2 again showed a maximum resolution of  $6 \text{ \AA}$  with a remarkably high quality of Bragg reflections, confirming the SL-J results. The best Earth-grown crystals of this particular receptor had yielded comparable results but required larger sizes and much more time to grow. The crystals grown on LMS did not produce usable diffraction data.

P. Fromme and W. Saenger crystallized the protein complex Photosystem I, which is responsible for the primary conversion of visible light into chemical energy in water-oxidizing photosynthesis. The objective

of this experiment was to determine the complete arrangement of chlorophyll molecules that perform this conversion process. On Earth, the largest of the hexagonal rod-like crystals grew on the dialysis membrane and was 2 mm long and 0.5 mm Ø (volume of 0.4 mm<sup>3</sup>). The USML-2 flight produced crystals that were 4 mm long and 1.5 mm Ø (volume of 7 mm<sup>3</sup>) even though, for technical reasons, the flight crystals could not grown be at their optimum growth temperature. In spite of this, the crystals still diffracted to 3.8 Å, and the mosaic spread reduced slightly to approximately 0.7°. The experiment was repeated on LMS and, for reasons unknown, the flight reactors failed to nucleate crystals even though all the ground control reactors produced diffraction quality crystals.

L. Wyns, M.H.D. Thi, and D. Maes investigated the growth of CcdB crystals, a protein involved in the control of cell death that may lead to the design of new antibiotics and anti-tumoral drugs. The quality of terrestrially grown crystals of this protein was not sufficient to obtain high-resolution diffraction data and twinning was a serious problem. In addition, they wanted to crystallize two specific serine-to-cysteine mutants (Ser74Cys and Ser94Cys), proteins that had not produced crystals large enough for data collection. Small needle shaped crystals of CcdB were obtained in the hanging drop reactors on both USML-2 and on LMS, but they diffracted no better than Earth-grown counterparts and twinning is still a problem. No useful crystals of the mutants were obtained on either mission.

Zagari and coworkers crystallized *Sulfolobus solfataricus* alcohol dehydrogenase on the USML-2 and LMS missions. Alcohol dehydrogenase (ADH) is an enzyme that occurs in large amounts in the livers of mammals, where it plays an important role in several physiological functions, including the breakdown of alcohol. Mammalian ADH is unstable at high temperatures or in the presence of organic solvents, properties that limit its biotechnological application to the synthesis of organic compounds. ADH from *Sulfolobus solfataricus*, a bacterium that thrives at high temperatures, has greater thermal stability, however, and is scarcely affected by the presence of organic solvents. Given these properties, the enzyme is a good candidate for industrial applications. Crystals of useful size can be grown on Earth, but are badly twinned, thus preventing the collection of diffraction data. Some success had been obtained with growth in gels, which also reduce convective effects, prompting the experiments in microgravity.

Since the protein is known to be very stable, it was not reloaded during the 23-day delay in launching USML-2. However, both flight and ground control experiments, activated at the same time, produced only small crystals that diffracted poorly, suggesting that degradation of the protein did occur. The experiment was repeated on LMS with much better results. The space-grown crystals diffracted to significantly higher resolution and exhibited increased stability in the X-ray beam. Unfortunately, analysis of the X-ray data revealed that the space-grown crystals were still twinned.

T. Richmond and A. Mader crystallized nucleosome core particles. The nucleosome shapes the DNA molecule by twisting and bending it, and forms higher order structures on the scale of genes. The laboratory crystals have an anisotropic mosaicity spread, which they hope to reduce by growing crystals of these particles in microgravity. Unfortunately, the growth conditions they had to use in the APCF were not optimal for this material and, consequently, the space-grown crystals showed no significant improvement over the ground control growth experiments. Neither produced as good a result as the optimized laboratory growth methods.

J. Garcia-Ruiz, F. Otalara, D. Rondon, and M. Novella used the APCF on LMS to test the Mach Zehnder interferometer, measure growth rate and crystal motion, investigate the use of high protein concentration in

liquid-liquid diffusion growth, and to explore the concept of growing protein crystals in X-ray capillary tubes. The protein chosen was HEW lysozyme, which is one of the standard proteins, used for investigating the growth of protein crystals. They were able to record interferograms, but ran into difficulty in interpreting them because of instabilities in the laser. Their observations of particle motion were similar to those described by Helliwell. Growth rates were observed to increase initially and then decline with time, as would be expected from growth under diffusion-limited transport condition as the diffusion field spreads out.

Since crystals ultimately have to be mounted in X-ray capillary tubes for analysis, this operation raises the possibility of damage to the fragile crystal. The confined growth environment may offer an advantage, however. One of the arguments for why protein crystals grow better in microgravity is that diffusion limited growth slows the rate at which nutrient is transported to the growing crystal so that growth becomes transport limited rather than kinetics limited. This gives surface kinetics a chance to go to equilibrium, assuring that each ad-molecule has a chance to find its lowest energy configuration, which would produce greater order in the lattice. An analogy would be the filling of an arena for a rock concert or a soccer match. If the doors were opened wide, the crowd rushes in, there is great confusion in finding the proper seats, and many fans do not wind up in their assigned seats. Here, the filling of the seats is limited by the rate at which people can find any old seat, which would correspond to crystal growth under kinetics limited conditions. On the other hand, if only a few people were allowed in at any one time, the filling of the arena would be transport limited and the people would have a much better chance of being in the right seat, which would correspond to ad-molecules finding their right position and orientation in the lattice.

When a crystal grows on Earth, the nutrient next to the growth interface is depleted and the lighter solvent rises, bringing more solute to the growth site. Since growth kinetics are slow for most proteins, the convective flows always bring nutrient to the crystal faster than it can be incorporated into the lattice. Thus the growth in normal gravity is generally kinetics limited. In space, solute must diffuse in from the surrounding region, which slows the transport to the growing crystal. However, the laws of diffusion are such that this depleted region (so called diffusion length) is approximately the radius of the growing crystal and the diffusion limited transport may not be slow enough to be the limiting factor in the growth rate of the crystal. In fact, Vekilov recently showed that growth instabilities may arise when transport and kinetics are in competition, and that this situation could explain why some proteins produce inferior crystals when they are grown in space. (See Vekilov, et al, *Physical Review* 54/6 (1966) 6650-6660). Growing crystals in X-ray capillary tubes in space may have the added benefit of extending the diffusion length and assuring that growth actually becomes transport limited.

Garcia-Ruiz and his colleagues grew HEW lysozyme, which has come to be a standard protein for studying growth phenomena in microgravity. The space grown crystals typically diffracted to 1.25 Å (one crystal diffracted to 1.15 Å), which is comparable to the best lysozyme crystals grown on Earth with highly purified material. The longer diffusion length provided by the X-ray capillary may have acted as an effective filter for the higher molecular weight impurities usually found in lysozyme. The Garcia-Ruiz team found a spread of mosaicities (rocking curve width) ranging from 5 arc seconds ( $0.0014^\circ$ ) to 20 arc seconds ( $0.005^\circ$ ), depending on the part of the crystal they examined. These roughly correspond to the flight and ground-based values obtained by Helliwell. Since the first growth incorporates the nearby impurities before the diffusion field has a chance to develop and act as a filter or to limit the growth rate, this could explain why different parts of the crystal exhibited different mosaicities. Similar results have been seen in ground-based work by Garcia-Ruiz using the gel-acupuncture method for growth.

## B. Other Biotechnology Experiments

### 1. Electrophoresis.

Electrophoresis, and its related electrokinetic separation processes such as isoelectrofocussing, is widely used for separation of proteins on an analytical scale. The protein molecules take on a particular surface charge (zeta potential) in a buffer solution. When an electric field is applied, the molecules will move under the influence of the applied field. Usually, the proteins migrate through a gel. The combination of the attraction by the applied field and the drag through the pores of the gel give each protein a specific mobility so that they will become separated spatially as the process is continued. Because this process is limited to microgram quantities, it is used primarily as an analytical tool.

Attempts to scale electrophoresis to a preparative scale by replacing the gel with a continuous flowing sheet of sample plus buffer solution has enjoyed only limited success on the ground, primarily because buoyancy driven convection places severe restrictions on the sample concentration and the thickness of the flowing buffer sheet. These factors limit the throughput of continuous flow electrophoresis (CFE), causing it to largely lose favor with researchers in preference to other methods, such as column chromatography, as a preparative separation method. There are certain potential advantages to CFE, however. It is a universal method, as opposed to column chromatography, where the columns have to be designed to separate specific proteins. Also, it can be applied to cell separation without having to tag the cells as is required by various cell sorting techniques.

The potential advantages of CFE prompted the McDonnell Douglas Corporation to develop a space continuous flow electrophoresis device (CFES) with the hopes of carrying out preparative electrophoresis on a commercial scale by widening the flow chamber and using a highly concentrated sample stream. The CFES flew seven times on the early Shuttle flights and worked reasonably well, but the separation was never as clean as was hoped for. Eventually, their commercial partner found a ground-based alternative to separate their product, and the project was dropped.

The unexplained broadening of the concentrated sample stream prompted Snyder and Rhodes at NASA/MSFC together with Saville at Princeton University to carefully examine the electrohydrodynamics involved in the distortion of a concentrated sample stream because of the mismatch in conductivity and dielectric constant between the sample and the surrounding buffer. Such effects had gone unnoticed in the development of CFE machines for terrestrial use because they were usually masked by convective effects. None-the-less, these electrohydrodynamic effects had to be operating, even though on a scale of lesser importance, but they could ultimately become a significant factor as other limitations are overcome by clever designs.

Interest in re-evaluating the potential of CFE in space on the part of the Japanese and the French led to the inclusion of two CFE systems on IML-2. The Japanese Free Flow Electrophoresis Unit (FFEU) was designed primarily as a separation device and was first flown on the Spacelab-J mission during which Kuroda and his team from Osaka University Medical School attempted to separate a group of standard proteins (horse cytochrome C, chicken conalbumin, and bovine serum albumin) in order to test the resolution as a function of concentration, flow rate, and operating voltage. Their results were inconclusive due to technical difficulties. On the same mission, Akiba attempted to separate three strains of *Salmonella typhimurium* LT2 cells, each of which has a different surface charge corresponding to its sensitivity to antibiotics. A

clean separation was obtained for one of the cell types, but the peak of the third cell line unexpectedly overlapped with the second, thus preventing their separation.

On IML-2, Kobayashi successfully separated two types of nematode DNA from a DNA mixture using the FFEU with a special buffer to operate in the isoelectric focussing mode. The sample detector indicated sharp, well-defined sample streams. However, a bubble in the separation chamber caused some irregularity in the collection.

Okusawa also used the FFEU on IML-2 to extract IgG from a culture medium of STK1 cells. He reports that the cells cultured in space produced twice as much IgG as their ground control. The sample detector indicated the separation was much more stable in space than on the ground, although bubbles in the chamber caused difficulty in the sample collection.

Hymer used the Japanese Free Flow Electrophoresis Unit (FFEU) on IML-2 to separate rat anterior pituitary organelles with the aim of separating out those vesicles that contained growth hormone (GH). The vesicles were obtained from the lysate of pituitary cells cultured in space. Due the absence of sedimentation, he was able to use a higher concentration of the lysate in space, and hence was able to increase the throughput by a factor of 5.6. He did notice a wider band spread of the GH-producing particles that were separated in space. The plan to separate the GH-producing cells from other cells using the FFEU could not be carried out due to equipment problems, but was performed on the ground at KSC eight hours after landing. Pituitary cells that were fed in space, for unknown reasons, produced five times as much GH as the ground control. Further, it was found that their electrophoretic mobility had increased by a factor of two as compared to cells that had been cultured on Earth.

The other electrophoretic device flown on USML-2 was the French Recherche Applique sur la Methodes de Separation Electrophorese Spatiale or RAMSES. This instrument was designed as a research tool as well as a separation device. It could be operated with AC fields to examine the electrohydrodynamic sample stream distortion without the complicating cross flows involved in the actual separation process.

Sanchez and Clifton characterized the separation ability of the RAMSES system by separating various standard proteins, hemoglobin, and dyed BSA. A much broader range of operating conditions are available in microgravity and the flows were stable under all conditions studied, confirming that gravitational effects limit the operating range on Earth. Dilute samples differing in mobility by only  $3 \times 10^{-9}$  m<sup>2</sup>/Volt/second could be separated. However, the more concentrated samples spread so that their peaks overlapped. This electrohydrodynamic phenomenon is due to the difference between the conductivity and dielectric constant of the sample and the buffer. The investigators were, however, able to increase the throughput of a biologically active sample by a factor of five by concentration and still get as good a separation as on Earth. All of these results were supported by extensive computer modeling.

Snyder and Rhodes had also planned to investigate the effect of high sample concentration and electrohydrodynamic instabilities in the absence of shear flow. Unfortunately, their experiment could not be run due to an electrical failure in the RAMSES equipment.

## 2. *Electrofusion.*

Electrofusion has emerged as an important new hybridization technique on the cellular level for the formation of hybridomas for making monoclonal antibodies as well as for somatic hybridization in sexually incompatible plants. In the later application, hybridization and exchange or recombination of organelles can be achieved by fusion of protoplasts by the reversible electric breakdown of their plasma membranes. With this method, protoplasts are first brought into close membrane contact by a weak alternating electrical field and then subjected to a high voltage pulse of short duration to induce local membrane reorganization at the contact area. However, for this process to be successful it is necessary for the two electrically aligned cells to remain in the same relative positions for a certain time after the application of the high voltage pulse. Gravity tends to interfere with this process, especially when the protoplasts have different densities. This consideration prompted a number of microgravity experiments using the TEXUS suborbital rocket program, which led to the electrofusion experiments on the D-2 Spacelab mission.

During the D-2 mission, Hampp and his team at Univertat Tübingen performed electrofusion experiments on three different systems:

1. tobacco as a model system,
2. *Helianthus* (sunflower) as an important crop, and
3. *Digitalis* (foxglove) as a plant of pharmacological interest.

The resulting fusion products were cultivated (along with parental cells) for 10 days under microgravity, and subsequently regenerated on the ground for biochemical analysis.

The alignment times were shortened for all three systems, however, for some reason the tobacco did not respond to the first pulse and increased voltage had to be applied. Consequently, the heterofusion yield for the tobacco was only 0.3 to 1.5% in both flight and ground control experiments. However, the yield for *Helianthus* was increased by four-fold in microgravity and the yield for *Digitalis* was increased by a factor of ten.

## 3. *ASTROCULTURE*<sup>TM</sup>.

ASTROCULTURE<sup>TM</sup> is a state-of-the-art plant growth chamber for space as well as terrestrial research that was developed by the Wisconsin Center for Space Automation and Robotics (WCSAR), a NASA-sponsored Commercial Space Center (CSC) located in the College of Engineering at the University of Wisconsin-Madison. This chamber uses many of the technologies developed by WCSAR and its industrial partners which includes the ASTROPORE® humidity control system, high intensity LED light sources, a porous tube water-nutrient delivery system, a unit for removing ethylene which does not require consumable materials, and proprietary software to coordinate and monitor operation of these subsystems. This chamber represents an integration of agriculture and automation, two of WCSAR's core technical strengths. The traditional method of studying plants has been in their natural environment. Over the past few decades that approach has changed to one of research in a controlled environment such as the ASTROCULTURE<sup>TM</sup> where scientists are able to control each variable.

The primary missions of the WCSAR are to support:

1. industry in the identification and development of new products and new technologies for the commercial marketplace,
2. NASA in the development of technologies that will contribute to the human exploration and development of space, and
3. dissemination of WCSAR program experience for educational purposes.

The ASTROCULTURE™ facility first flew on USML-1 and subsequently has flown on a number of Shuttle flights including the USML-2 Spacelab mission. The earlier flights were primarily tests of the various subsystems in microgravity, which culminated in an actual demonstration of the growth of potato tubers on USML-2 that could be used as a source of food on later extended duration missions. The potato tubers developed normally, despite the lack of gravity, and the starches they produced were very much the same as the starches produced by potatoes grown on Earth except for the reduced activity of the enzyme, ADP-glucose pyrophosphorylase. This later finding is not understood and requires further study.

Later flights investigated the growth of other plants as possible food sources for extended manned missions including the growth of dwarf wheat plants from seed-to-seed on the MIR station. It was also demonstrated during the STS-95 mission that the microgravity of space provides a particularly suitable environment for transgenic plant alterations. A scaled-up version of the ASTROCULTURE™ facility is being developed for the International Space Station to provide food to the crew.

A number of the technologies that went into the development of the ASTROCULTURE™ flight hardware have found their way into the commercial market. For example, owners of large commercial nurseries nationwide are now using the module's water and nutrient delivery tubes. The project also developed a system of air humidification/dehumidification that does not need a gas or liquid separator as other systems do. The LED (light emitting diode) arrays used for lighting in the facility produce an average continuous output of four to six watts at a wavelength of 660 nm. This output is equivalent to the terrestrially sensed output of the sun at this wavelength at high noon. These LED chips are arrayed on an alumina tile substrate that may be formed to provide optical power focused on a specified target area that can be used as energy efficient lighting systems for large-scale commercial nurseries. These arrays also offer a low cost alternative to laser light sources in a wide range of medical applications such as measuring blood sugar levels or use in photodynamic cancer therapy.

#### *4. BioServe.*

BioServe Space Technologies is a NASA Center for Space Commercialization located jointly at the University of Colorado in Boulder, Colorado, and Kansas State University in Manhattan, Kansas. The primary mission of BioServe is to facilitate commercial use of the unique environment of space. BioServe focuses on research in biomedical, pharmaceutical, bioprocessing, bioproducts, agricultural, and environmental areas. Areas of investigation can be categorized to include studies on whole organisms, mammalian cells, viruses, plants, microorganisms, biocrystal growth, biomaterials, bones/skeletal materials, and other related topics. In general, reduced gravity has been shown to alter one or more aspects associated with each of the above categories. Ongoing research is directed towards identifying the underlying causes of the altered outcomes and exploring the potential of related commercial applications.

A Generic Bioprocessing Apparatus (GBA) payload was flown for the first time on USML-1 (STS-50). The GBA module replaces a middeck locker and provides confinement and environmental control for up to seventy-two Fluid Processing Apparatus (FPAs). Each FPA can be thought of as an automated test tube in which up to three different fluids can be mixed at different times in order to perform an individual experiment. (For example, an activator can be added to a culture medium at the beginning of the experiment and a fixative added at the termination.) On USML-1, the crew activated the FPAs individually. On later flights, the FPAs were packaged in groups of eight so that the entire group could be activated manually or automatically (this setup is called a Group Activation Pack or GAP). Individual FPAs can be placed into an optical density measurement device inside the GBA to collect turbidity data, providing real-time experimental reaction rates. Variations of the standard FPA configuration include a Gas-Exchange FPA (GE-FPA), a Plant-FPA (P-FPA) and an Insect FPA (I-FPA). Inserts are also used to facilitate protein crystal growth experiments. The different designs address specific experimental requirements such as providing larger habitats (insects) or allowing gas exchange within the GAP atmosphere to increase the available amount of oxygen/carbon dioxide. The T-GAP (toroid) contains a single volume insert (no activation or termination) that replaces the eight FPAs to provide a larger experimental volume for specific applications. Other modifications can be considered on an “as needed” basis.

The Commercial GBA can either be flown as an isothermal containment module (GBA-ICM) with a set temperature ranging from 4°C to 37°C, or as an incubator (GBA-INC). A Fluid GBA was designed to dispense carbonated beverages on STS-77 and a Plant GBA designed to support plant growth was flown on STS-77 and on MSL-1 and 1R. All told, GBAs have been flown on eighteen Shuttle flights, including two extended stays on MIR. More than 100 plant experiments have been conducted and more than 2500 space experiments have been performed in FPAs, and another 120 experiments have been performed in Bioprocessing Modules (BPMs, a JSC-developed device whose function is similar to the FPA).

These flights have been used to investigate a wide variety of microgravity effects, many of which were totally unexpected and could not have been predicted from simple fluid mechanical arguments. A few examples are given in Table II-8.

**Table II-8. Experiments using BioServe hardware.**

Accelerated growth of microorganisms.	Many experiments have demonstrated that bacteria, paramecia, and other microorganisms grow faster in microgravity. One argument that has been suggested is that since the organism does not have to swim against gravity, more resources can be devoted to growth. The BioServe experiment, which demonstrated enhanced growth of a nonmetal strain of <i>E. coil</i> (ATCC 4157), shows that other factors are responsible. Growth in suspension cultures as well as on agar substrates was enhanced in microgravity.
Enhanced cellular production.	The production of the antibiotic monorden by the fungus <i>Humicola fuscoatra</i> was increased by 190% in microgravity, which is consistent with reports of increased production of cell products from other cell lines in a weightless environment.
Altered development of organisms.	In one set of experiments, the development of brine shrimp was significantly increased in microgravity. However, in another set of experiments, the differentiation of bone marrow macrophages was retarded, although their growth was enhanced.
Enhanced enzymatic activity.	Enzymes such as plasmin, collagenase, and cellulase were shown to degrade fibrin, collagen, and cellulose respectively 30 to 50% faster in microgravity than in normal gravity. A smaller enhancement was also observed in clinostat experiments.
Enhanced expression of auxin-regulated genes.	Plant growth and development is highly sensitive to auxin and altered sensitivity can have dramatic effects on such things as root growth and the production of metabolites of pharmaceutical interest.
Plant growth and development in absence of gravitational cue.	The role of the statocytes (specialized cells though to be the gravity sensors) in gravitropism (an organism's response to gravity) is reasonably understood, but not the mechanism by which the gravity force is turned into a biochemical signal. BioServe is interested in how plants, in the absence of gravitational cues, signal for ethylene production, cell wall thickness, lignin production, and the partitioning of carbohydrate between lipid and starch production. This knowledge might allow them to manipulate plants to optimize plant products, both in space as well as on Earth.
Magnetic combing of collagen.	Collagen can be grown in vitro on Earth, but it is disordered at the fiber level, which makes it undesirable for implants. BioServe demonstrated that it could be "combed" in microgravity by drawing fixed magnetic bacteria through it with a strong magnetic field as it is being polymerized.
Growth of biocrystals.	BioServe has demonstrated that different growth techniques, for example osmotic dewatering, dialysis diffusion, and microdialysis, can also produce higher quality biocrystals in microgravity (as evaluated by X-ray diffraction resolution, mosaicity, and stability in an X-ray beam).

## C. Science Assessment

### 1. *Biomolecular Crystal Growth.*

The growth of protein and other macromolecular biomaterials has been and still is more of an art than a science. There are many variables that can affect the growth process, many of which are not well understood, and are not always controlled. Furthermore, nucleation is a stochastic event so that there is always a certain amount of randomness involved, even if all other variables are controlled. As a result, it is not unusual for apparently identical experiments to yield quite different results. Traditionally, structural molecular biologists have set up large arrays of growth experiments not just to screen for optimum growth conditions, but also to improve their chances of obtaining at least one growth chamber with usable crystals. Since their primary job was to obtain molecular structure, not to investigate growth processes, these workers seldom had the opportunity or the background to investigate the fundamentals of the growth process.

There is no question that some growth systems have produced crystals of outstanding quality in microgravity and, in a number of cases, the space-grown crystals were superior to the best crystals of those particular systems that had ever been grown on Earth. These findings have attracted the attention of some of the theoreticians who study the formation of crystal structure in small molecule systems. Exactly how does gravity affect the growth process? Why do some protein systems seem to benefit from microgravity while others do not? Can we apply this knowledge to improve the growth of protein crystals on Earth? NASA is now vigorously supporting this avenue of research. Consequently, this growth problem is being attacked by a multi-disciplinary approach, which includes protein chemists, solid-state physicists, surface scientists, fluid dynamists and computational process modelers. International meetings sponsored by several crystal growth societies are now being held on an annual basis and are attracting an increasing number of participants.

There are a number of theories and conjectures that have been set forth as possible explanations for this phenomenon; several of these have already been discussed in the preceding sections. One of the more paradoxical findings has been the fact that the space-grown crystals in many cases have been both larger and better organized. Generally better internal order requires slower growth rates, which would be the case if diffusion controlled transport became the rate limiting step in the growth process. Therefore, the growth rate in space should always be equal or less than the growth rate on Earth where convection provides additional transport. How then can the space-grown crystals grow larger in the same length of time as their ground control counterparts?

One possible answer is that the space crystals continue to grow while the growth of their Earth counterparts slows and eventually ceases. This well-known, but poorly documented, phenomenon of growth cessation had been one of the factors that limited the size of many protein systems and it has been demonstrated that the problem is exacerbated by forced convection (see Pusey et al, *Journal of Crystal Growth* 90 (1988) 105-111). It was speculated that the convective flows bring contaminants to the vicinity of the growing crystal where they may poison the growth interface. For this theory to hold, the contaminants must be incorporated into the crystalline lattice in preference to the protein monomers; otherwise, convective flows would have the beneficial effect of sweeping the build-up of the partially rejected impurities away from the growth front. It is known that protein growth solutions are frequently contaminated by higher order oligomers of the native protein that form spontaneously. Whether these oligomers are preferentially incorporated and, if so, how their presence might poison the growth interface is still not clear. However, the results obtained

by Garcia-Ruiz from growth in X-ray capillaries lend credence to the hypothesis that the diffusion fields actually do make an effective filter for higher molecular weight contaminants and that their reduction does in fact improve the growth and quality of the crystal. Subsequently, it has been found that by paying more attention to the purity of the starting material, dramatic improvements can also be made in terrestrially grown crystals. Progress such as this may ultimately prove to be the most valuable contribution the space experiments can make to the field of macromolecular crystal growth and structure-based drug design.

Another issue that must be addressed is why so many space experiments have failed to produce high quality crystals. One to two weeks is marginal for the growth of many systems and a number of flights have returned crystals that were simply too small for X-ray diffraction analysis. Longer duration flights, which will be possible on the ISS, should help this situation immensely, as evidenced by the successes McPherson has had with his GN2 dewar experiments on the Mir station. In addition, there seems to be some evidence that growth conditions that have been optimized for normal gravity may not be optimal under purely diffusion-limited conditions, and some tinkering with the growth conditions in space may be required. The problem of maintaining control over the many possible variables, such as the presence of trace contaminants, plagues space experiments as it does terrestrial experiments, making it difficult to get reproducible results. Finally, according to Vekilov's theory, growth of some systems in microgravity may actually move the growth mechanism from a region of stability to an unstable one. Unfortunately, the physical properties of only a few protein systems are known well enough to be able to apply this theory, and a rigorous test of the theory has not yet been performed.

Even though the success rate of obtaining superior crystals by growing them in space is only 20 to 25% for a given protein (that is, one or more of all the space experiments with that particular protein produced better crystals than had previously been produced on Earth), the scientific and industrial interest has been very high. Guest investigators from a number of research foundations, medical schools, and pharmaceutical industries have committed their own resources to participate in the program. It should be understood that although these Guest investigators do not pay NASA to fly their experiments, neither does NASA pay them for their efforts. They commit their own time and travel expenses as well as provide the highly valuable purified proteins to support the experiment. The scientific output has also been impressive.

## *2. Electrokinetic Separation.*

Even though the flight experiments were hampered by equipment problems, it is fairly clear that enhanced throughput from a continuous flow electrophoresis device can be achieved in a microgravity environment by the use of more concentrated samples and wider spacing between the walls of the flow channel. However, increasing the sample concentration exacerbates the electrohydrodynamic effects caused by the mismatch in conductivity and dielectric constant between the sample stream and the buffer curtain, which tends to degrade the resolution. Understanding these effects may lead to the development of more efficient continuous flow electrophoresis machines for terrestrial use, but it appears unlikely that the gain in efficiency would be sufficient to justify carrying out such separations in space unless they were done in conjunction with materials that were already in space (for example, products from some cell culture or fermentation process).

### *3. Electrofusion.*

Although there have been only a limited number of space experiments (mostly rocket flights) to investigate the advantages of using microgravity in the creation of hybridomas and hybrid plants by electrofusion, the results look encouraging. The role of gravity in the process is clearly not understood, but given that the process seems to benefit from space, more research to understand the process is certainly merited.

### *4. Commercial Biotechnology.*

The WCSAR ASTROCULTURE™ effort is more of a technology development than a scientific endeavor. However, it has produced some very useful spinoff products, such as the closed plant growth system that allows complete control of the growth environment, the proprietary water and nutrient delivery tubes, as well as the air humidification /dehumidification systems for use in plant nurseries, and the efficient LED light source for plant growth and medical applications. The work on the use of microgravity for transgenic plant alterations is intriguing since the role of gravity is not understood in the process, but as in the case of electrofusion, it apparently is important and needs to be understood.

The BioServe effort is extremely broad based scientifically and is carrying out an extensive research program to catalog how various organisms respond to the microgravity environment with the goal of exploiting those characteristics which they find useful for commercial purposes. Many of their findings, such as the accelerated growth of certain organisms, enhanced production of cell products, and enhanced enzymatic activity in microgravity are surprising, and are not easily understood from simple fluid modeling of gravity effects in living organisms.

## **D. Economic and Societal Impacts**

Of all the NASA-sponsored microgravity endeavors, the Biotechnology effort offers by far the greatest promise of economic and societal benefit. Structure-based drug design, which requires improved methods for crystallizing biomolecular materials, has the potential to produce pharmaceutical compounds with fewer side effects. In today's highly competitive, cost-sensitive drug market, macromolecular crystallography can help pharmaceutical manufacturers bring exclusive, proprietary drugs to market faster and with significantly lower development costs. Therefore, any improvement in obtaining the crystals of interest that NASA can make, either in space or on the ground, translates into significant potential cost and health benefits. Crystals grown in space have already contributed to the direct solution of several protein and viral structures and to the refinement of many others. Some of the more promising drugs under development, in which space played a significant role, are summarized in Table II-9.

The NASA-sponsored Center for Macromolecular Crystallography now employs more than 100 scientists and engineers working on crystal growth, structure determination, and the next generation of flight experiments. They collaborate with thirty-seven universities and have twenty-one industry partners that contribute over \$2 million per year in direct funding. There are now four spin-off companies (BioCryst Pharmaceuticals, Inc., Ibbex Pharmaceuticals, Inc. and Diversified Scientific, Inc., in Birmingham, Alabama, and New Horizons Pharmaceuticals in Huntsville, Alabama) that have been created as a result of the NASA-sponsored work in this area.

**Table II-9. Biotechnology products developed at least in part from space research.**

Insulin	Pharmaceutical companies had been searching for way to control the release of human insulin so that diabetics could take fewer injections and have a more constant supply. One promising binding agent turned out to be toxic to humans. Space grown crystals provided the clue as to what was going was going on and led to a solution of the problem.
Protein blockers	Factor D is a protein that often stimulates the immune system to overreact from the trauma following open-heart surgery. A particularly large crystal of this protein grown on USML-1, when merged with other data, provided the structural information. Drugs to block this protein are in Phase II clinical trials and may be available by 2001.
Disease enzymes	Space grown crystals of glyceraldehyde 3-phosphate dehydrogenase (GAPDH), an essential enzyme in the parasite that is responsible for Chagas' disease, were instrumental in refining this protein. Drugs based on the structure of this molecule are in pre-clinical trials.
Antibiotics	NAD-synthetase is a target for a wide spectrum antibiotic under development that pre-clinical trails have shown to be effective against anthrax, pseudomonas, and flesh eating bacteria. Space grown crystals played a role in obtaining its structure. A crystal grown on STS-95 improved the resolution from 1.6 Å to 0.9Å. These data should prove useful to help improve knowledge of the active site if it becomes necessary to adjust the design of the drug that is presently being tested.

BioCryst uses data from the space experiments to help design new structure-based drugs. Presently, they are developing drugs to treat cutaneous T-cell lymphoma (in phase I/II human clinical trials), psoriasis (in phase I/II human clinical trials), stroke and certain complications of open heart surgery (preclinical trials), viral influenza (preclinical trials), and AIDS (preclinical trials).

Ibbex has used the protein structures developed initially by the Center for Macromolecular Crystallography to develop drug for cystic fibrosis, bacterial vaginosis, and Chagas' disease, all of which are in preclinical trials. Chagas' disease is a devastating parasite disease that affects more than 18 million people in South America and 150,000 in the US. The high-resolution data from the malic enzyme crystal obtained in the glove box experiment on USML-1 played a major role in obtaining the structure of this protein.

Diversified Scientific is commercializing the improved crystallization techniques based on the knowledge gain from the space experiment. This equipment will allow other pharmaceutical companies to improve the crystals they grow in the laboratory in order to further stimulate the use of structure-base drug design.

Some of the technological benefits that have come from the other NASA-sponsored Commercial Space Centers that work in biotechnology, BioServe and WCSAR, have already been discussed. Their work on utilizing microgravity to improve the process of transgenic plant alterations could have significant societal and economic benefits by producing food crops that mature faster. BioServe's work on controlling the production of lignin in wooded plants could also have a major impact on the building as well as the pulp paper industry.

# **SPACELAB SCIENCE RESULTS STUDY: MICROGRAVITY LIFE SCIENCES**

**Marian L. Lewis, Editor**  
**Karen L. Murphy, Compiler**

## **A. Introduction**

The variety of disciplines accommodated by the thirty-six Spacelab flights logically group into three distinct categories.

1. External Observations in which the Shuttle/Spacelab is used as an observing platform,
2. Microgravity Physical Sciences that make use of the microgravity environment to further the studies of Fluid Physics, Combustion Science, Materials Science, and Biotechnology, and
3. Microgravity Life Sciences that study the response and adaptability of living organisms to the microgravity environment.

Because of the bulk of the material involved and the diverse interests, the report has been divided into three sections with the previously mentioned titles. This section deals with the Microgravity Life Sciences as defined above.

The purpose of this Spacelab Science Results Study is to document the contributions made in each of the major research areas by giving a brief synopsis and analysis of the experiments, and an extensive list of the publications produced by each investigator team. We have also endeavored to show how these results impacted the existing body of knowledge, where they have spawned new fields, and, if appropriate, where the knowledge they produced has been applied. Since a new generation of young researchers will make up the cadre of investigators that utilize the International Space Station (ISS), we feel it is important to leave a legacy of the results, some positive, some negative, of the previous experiments that have been performed. Hopefully, the new generation will build on the successes and learn from the failures of the past.

The material used in study came from many sources including the Mission Summary Reports, Mission and/or Investigator Team websites, the International Distributed Experiments Archives (IDEA, which contains the NASA Microgravity Research Experiments (MICREX) database, the NASDA experiment archive, and the ESA Microgravity Database), the National Library of Medicine's Medline database, the NASA Life Sciences Data Archive, the Science Citation Index, the NASA Office of Biological and Physical Research Task Books, various survey papers, conference proceedings, and the open literature publications of the investigators.

We also wish to acknowledge the work of our student assistants, Ann Pierce, Gayla Pounders, and Olga Kostrova, who spent many hours searching various databases for reference material.

## **B. Overview**

Life sciences experiments were flown on seventeen of the thirty-six Spacelab missions between 1981 and 1998. More than three hundred and seventy-five separate experiments were designed, developed, and conducted by more than one hundred and thirty-eight principal investigators and five hundred and thirty-six co-investigators. Over a thousand publications and reports were published and results from more recent Spacelab missions, including Neurolab, are still appearing journals. This document describes the objec-

tives, results and significance of these experiments, including the impact of the research on subsequent science and technology, the facilities used, a narrative summary of the most significant scientific findings, and a bibliography of publications resulting from Spacelab missions research. Information in this document was obtained from available sources, predominantly NASA and ESA websites. The addresses for website source material are included in Appendix D.

Table III-1 lists the missions on which microgravity life sciences experiments were flown. This table also includes mission duration, which increased from a little over two days on STS-2 (OSTA-1) to almost seventeen days on STS-78 (LMS). The complexity of microgravity life sciences payloads evolved in parallel with increased time on orbit.

**Table III-1. Spacelab missions which included microgravity life sciences experiments.**

Mission	Launch	Landing	Mission Duration			Payload Designation
			Days	Hours	Minutes	
1. STS- 2	11/12/81	11/14/81	2	6	13	OSTA-1
2. STS- 3	03/22/82	03/30/82	8	0	4	OSS-1
3. STS-9	11/29/83	12/08/83	10	7	47	Spacelab 1
4. 51-B	04/29/85	05/06/85	7	0	8	Spacelab 3
5. 51-F	07/29/85	08/06/85	7	22	45	Spacelab 2
6. 61-A	10/30/85	11/06/85	7	0	44	Spacelab D-1
7. STS-40	06/05/91	06/14/91	9	2	14	Spacelab SLS-1
8. STS-42	01/22/92	01/30/92	8	1	14	IML-1
9. STS-47	09/12/92	09/20/92	7	22	30	Spacelab J
10. STS-55	04/26/93	05/06/93	9	23	39	Spacelab D-2
11. STS-58	10/18/93	11/01/93	14	0	12	Spacelab SLS-2
12. STS-65	07/08/94	07/23/94	14	17	55	IML-2
13. STS-71	06/27/95	07/07/95	9	19	22	Spacelab Mir
14. STS-73	10/20/95	11/05/95	15	21	53	USML 2
15. STS-78	06/20/96	07/07/96	16	21	48	LMS
16. STS-90	04/17/98	05/03/98	15	21	50	Neurolab

Life sciences experiments fall into three major discipline areas:

- 1) Advanced Human Support Technology,
- 2) Biomedical Research and Countermeasures, and
- 3) Gravitational Biology and Ecology.

Table III-2 shows the major disciplines and the several sub-disciplines under each of these categories.

For each of the Spacelab missions, the disciplines were further subdivided to describe the individual experiments. Table III-3 lists experiment specific categories. The majority of this section is a narrative summary of the most significant scientific findings from the Spacelab microgravity life sciences missions.

These experiments utilized a number of different facilities designed and adapted to provide maximum capability for the various experiments. Some of the major microgravity life sciences supporting facilities flown on the Spacelab missions are further described in Appendix C.

**Table III-2. Life sciences discipline categories.**

<b>Advanced Human Support Technology</b>	<b>Gravitational Biology and Ecology</b>
Advanced Environmental Monitoring	Cell Biology
Advanced Life Support	Developmental Biology
Space Human Factors Engineering	Evolutionary Biology
	Molecular Biology
<b>Biomedical Research and Countermeasures</b>	Global Monitoring and Disease Prediction
Clinical Research	Gravitational Ecology
Countermeasures	Organismal and Comparative Biology
Environmental Health	Molecular Structures, Physical Interactions
Physiology, Behavior and Performance	Plant Biology
Radiation Health	

**Table III-3. Experiment specific categories.**

Animal Physiology	Metabolism and nutrition
Biorhythms	Muscle physiology
Bone Physiology	Musculoskeletal
Cardiovascular/Cardiopulmonary	Neuromuscular and Sensory-motor
Cell Proliferation and Differentiation	Neurophysiology
Clinical Medicine	Neuroscience
Developmental Biology	Neurovestibular
Electrolyte physiology	Pharmacology
Endocrinology	Plant Physiology
Genetics	Pulmonary Physiology
Gravity Sensing	Radiation Biology
Hematology	Rat Bone Physiology
Human Physiology	Rat Hematology
Immunology	Regulatory Physiology
Interdisciplinary physiology	Renal Physiology
Membrane Behavior	

The number of publications resulting from Spacelab research is shown in Table III-4. Since data are still under analysis for the Spacelab mission experiments flown in the late 1990's, additional publications will continue to be available over the next few years.

In the text of this section, references to principal investigators and mission indicate data presented in the tables and not published papers. In a few cases, reference is made to a paper and the full citation is given in the text. Papers published from the research of the Spacelab missions are included in the bibliography presented in Appendix B. These publications can be located from the names of investigators shown in the tables in the text.

**Table III-4: Number of Life Sciences Publications Resulting from Spacelab Experiments.**

<b>Mission</b>	<b>Year</b>	<b>Journals</b>	<b>Other</b>	<b>Total</b>
STS-2/OSTA-1	1981	1	0	1
STS-3/OSS-1	1982	5	1	6
STS-9/Spacelab 1	1983	59	18	77
STS-51F/Spacelab 2	1985	4	3	7
STS-51B/Spacelab 3	1985	74	78	152
STS-61A/Spacelab D-1	1985	36	52	88
STS-40/Spacelab Life Sciences 1	1991	44	35	79
STS-42/International Microgravity Laboratory 1	1992	38	40	78
STS-47/Spacelab J*	1992	79	489	568
STS-58/Spacelab Life Sciences 2	1993	36	25	61
STS-55/Spacelab D-2	1993	21	34	55
STS-65/International Microgravity Laboratory 2	1994	37	38	75
STS-71/Spacelab Mir	1995	112	168	280
STS-73/United States Microgravity Laboratory 2	1995	20	6	26
STS-78/Life and Microgravity Spacelab	1996	70	44	114
STS-90/Neurolab	1998	198	146	344
Totals		833	1177	2010

\* Total number of publications shown includes information from NASDA's report (presented by Dr. Shunji Nagaoka) at the "Spacelab Accomplishments Forum", Washington, D.C. March 10-11, 1999. NASA/CP 2000-210332.

## I. GRAVITATIONAL BIOLOGY AND ECOLOGY

### A. Cell And Molecular Biology

Cell and molecular biology investigations were conducted on eight of the nineteen Spacelab missions which included Microgravity Life Sciences experiments. They were flown under the Life Sciences discipline category "Gravitational Biology and Ecology". The experiment specific categories included cell growth and metabolism, organelles and structures, immunology, hematology, bacteria and viruses, yeast, circadian rhythm, and protoplasmic streaming. Experiment descriptions and publications resulting from the individual experiments in each category are given in Appendices A and B, respectively. The following summaries of the significant findings for each experiment category are a compilation extracted from available Internet information and publications abstracts, and are presented as an overview of experimental results.

In the interpretation of all cell biology experiments flown in space, it is important to understand that differences in growth, metabolism and function can reflect differences in hardware used as well as the particular characteristics of launch, payload location on the Shuttle, and other mission and experiment specific parameters including temperature changes during an experiment, length of the mission, starting and stopping of the 1g in-flight reference centrifuge during sampling, and storage of samples. Significant differences in response to space flight are also cell type and culture dependent. Not all cell types respond in the same way to conditions of space flight. For instance, human lymphocytes are shown to be 90% blunted in growth response in microgravity (Cogoli, A. *et al*, Cell sensitivity to gravity. *Science* 225: 228-230 (1984)) yet other cell types, some of which are described below, appear to be unaffected by space flight and microgravity.

#### 1. Cell proliferation and differentiation.

Investigations with single cells in culture flown on various microgravity-accessing launch vehicles have consistently shown that biological mechanisms such as proliferation, metabolism, and differentiation are altered as a result of space flight (Cogoli, A, *et al*, Gravity effects on single cells: Techniques, findings and theory. In: *Adv. in Space Biol. and Med.*, JAI Press Inc. 1, 183-248 (1991)). The Spacelab missions on which cell proliferation, differentiation and metabolism experiments were conducted are shown in the table (III-5) below.

Experimental results from the hybridoma cells flown on Spacelab D-1 showed no clear effect of microgravity on cell proliferation, but the number of cells in the flown cultures was slightly lower than corresponding one-gravity (1g) controls. Viability of the cells was 15% reduced compared to ground controls, although non-fixed flown cells resumed a normal growth rate when cultured under normal conditions in the laboratory post-flight. Based on amino acid analysis, there was no significant difference in the metabolism of the flown cells, although the biosynthesis of glycine and beta-alanine were increased by a factor of 1.4 in microgravity compared to the 1g controls. Though not large, these differences are important because they provide more evidence that cells alter their metabolic processes during space flight.

Somewhat different results were found in the hybridoma cell experiment flown on IML-1. The IML-1 experiment used hybridoma cells of a sub-clone of the cell line 7E3-N, which produces antibodies against lipopolysaccharide binding protein. These cells showed a significant increase in cell proliferation between the second and fourth day, though a growth lag was evident and cells appeared to begin growing only after

**Table III-5. Experiments involving single cells in culture.**

<b>Spacelab Designation</b>	<b>STS Mission</b>	<b>Launch Year</b>	<b>Duration (days)</b>	<b>Cell Type</b>	<b>Principal Investigator</b>
Spacelab D-1	61-A	1985	7+	Hybridoma cells	Bouteille, M.
IML-1	STS-42	1992	8+	Hybridoma cells	Cogoli, A.
				Virus transformed cells	Cogoli, A.
				Hamster kidney cells/beads	Cogoli, A.
				Mouse cells	Veldhuijzen, J.P.
Spacelab -J	STS-47	1992	7+	Monkey kidney (JTC-12)	Sato, A.
				Bone cells	Partridge, N.
Spacelab D-2	STS-55	1993	9+	Human dermal fibroblasts	Mueller, P.K.
IML-2	STS-65	1994	14+	Osteoblasts	Kumei, Y.
				Mouse cells	Heinlein, U.A.O.
				Mouse cells	DeLaat, S.W.
USML-2	STS-73	1995	15+	SF9 Insect cells	Johnson, T.

day two in microgravity. Analysis of metabolic data revealed that the production of monoclonal antibodies, glucose and glutamine consumption, and secretion of lactate and ammonia on a per cell basis were lower in microgravity than in 1g. These data show that microgravity has a significant effect on the metabolism of cells. Production of monoclonal antibodies commercially in space does not seem to be advantageous based on this experiment.

Murine Friend Leukemia virus transformed cells were flown on IML-1 to investigate proliferation and differentiation in microgravity. These cells are used as a model for murine erythropoiesis since they differentiate in the presence of dimethylsulfoxide toward erythroid lines. Results for all parameters tested showed no significant differences in microgravity and the 1g in-flight control and ground responses. There was a slight but not significant increase in cell growth in flown cells after 140 hours of incubation. The amount of hemoglobin produced was the same in flight and ground controls. Cell morphology and mitotic index showed no significant changes between flight and ground controls. Thus Friend cells do not appear to change their behavior in microgravity. These results are extremely significant because they illustrate clearly by the parameters measured (growth, metabolism and differentiation) that not all single cell types are affected by space flight and microgravity.

Hamster kidney cells (American Type Cell Culture Collection (ATCC) CCI 15) grown on Cytodex 3 micro-carrier beads were flown on IML-1 to evaluate a dynamic cell culture system (DCCS) and to investigate the behavior of anchorage-dependent hamster kidney cells on the beads with respect to proliferation, production of tissue plasminogen activator (t-PA, a blood-clot dissolving agent), and cell metabolism in microgravity. Results showed that microgravity had no effect on cell growth and metabolism of the hamster kidney cells. Data on pH, glucose and lactate concentration showed that the DCCS functioned adequately and the cells consumed almost all of the available glucose. Production of t-PA was similar in all cultures and no significant differences among cultures was seen for ammonia and glutamine, confirming that metabolic processes did not appear to be affected in these cells in microgravity.

On SL-J, a very significant experiment using monkey kidney derived cultured cells (JTC-12) was flown to evaluate the rearrangement of the cytoskeleton to gain understanding of the direct effects of microgravity

on the cytoskeleton and cell structure and proliferation. Results showed no differences between flight and ground control cells in early culture in microgravity. Proliferation, glucose use and urokinase (also a t-PA) secretion were similar in cells returned alive and cultured postflight. The cells from flight had decreased numbers in the S phase and increased numbers in the G2M phase of the cell cycle indicating a possible space flight- or microgravity-related cell cycle block, but not in G1 as is usual for aging cultures. This is usually indicative of some perturbation or stress. Perhaps the most significant finding was that electron microscopy of cells fixed in microgravity showed little bundle rearrangements of microfilaments at the cell margin. Morphologically, this was significantly different from ground controls and provides additional evidence of cytoskeletal/membrane interface perturbation induced by space flight.

Human dermal fibroblasts were flown on the Spacelab D-2 mission to evaluate biosynthesis of collagen to gain understanding of bone mass loss during space flight. These cells were chosen because they are easily isolated and maintained in culture, and the collagen biosynthetic profile is similar to that of bone forming cells. The most significant results showed that the cells remained attached to coverslips and were thus alive, and that all cultures synthesized collagen I, III and V. Quantitative analysis showed a 40% increase in collagen synthesis in microgravity compared to 1g controls. Another very significant finding was that hypergravity, at 1.44g, 6.6g, and 10g, decreased collagen synthesis. At 10g, collagen synthesis was reduced 85% compared to 1g. Relative proportion of collagen from total protein synthesized, the secretion of collagen from the cells, proline hydroxylation of individual collagen alpha-chains, and the relative proportion of collagens I, III, and V synthesized were not adversely affected by space flight. These data show that the collagen biosynthetic process is not affected (in these cells) by microgravity and imply that some factor other than collagen synthesis is responsible for bone mass loss in space.

Control of proliferation arrest and release is extremely important to space flight research since the cells in the flight hardware must be turned over for installation into the orbiter approximately twenty-four hours prior to liftoff. Johnson *et al* have developed a factor, CeReS-18, that causes cell cycle arrest in cultured insect cells. Dilution by the addition of culture medium releases cells from arrest. The usefulness of this factor in microgravity research was demonstrated on USML-2. This significant finding has potential for stabilizing cultures for future microgravity missions.

## 2. Immunology.

Cell mediated immunological response in the body is achieved by the T lymphocytes (T cells) of the immune system. T cells are activated and increase in number in response to stimulation by antigen presenting cells as a defense against infection by organisms such as bacteria, fungi, and viruses. In the laboratory, T cell activation response can be elicited by use of concanavalin A (Con-A), a mitogen derived from plants that acts as an antigen to stimulate growth and function of T lymphocytes. T cells in blood drawn from astronauts and cosmonauts during the early space flight missions showed a significantly blunted response to mitogenic challenge that persisted for up to seven days after the flight. Eleven cell immunology-related experiments were flown on five of the Spacelab missions as shown in the table (III-6) below.

A landmark experiment was conducted by Cogoli *et al* on the Spacelab 1 mission flown on STS-9 in 1983. This experiment has led to increasingly sophisticated research by a number of investigators over the years since, yet without discovery of the causative mechanism(s) for reduced lymphocyte growth in microgravity. The experiment on Spacelab 1 was the first to show a dramatic, quantitative response to space flight

**Table III-6. Experiments involving immunology.**

Spacelab Designation	STS Mission	Year	Duration (days)	Cell Type	Principal Investigator
Spacelab 1	STS-9	1983	10+	Human lymphocytes	Cogoli, A.
Spacelab D-1	STS-61-A	1985	7+	Lymphocyte activation (ex-vivo)	Cogoli, A.
				Lymphocyte activation (in-vitro)	Cogoli, A.
SLS-1	STS-40	1991	9+	Lymphocyte proliferation (beads)	Cogoli, A.
				Lymphocyte proliferation (IL-1,2)	Cogoli, A.
SL-J	STS-47	1992	7+	Antibody production	Suganuma, T.
Spacelab D-2	STS-55	1993	9+	Growth of lymphocytes	Reske, K.
				Activation of lymphocytes	Reske, K.
IML-2	STS-65	1994	14+	Lymphocyte movement	Cogoli, A.
				Lymphocyte proliferation	Cogoli, A.
				Lymphocyte activation	Cogoli, A.
				Cytokines	Schmitt, D. A.

at the single cell level. The objective of the experiment was to establish whether functional changes occurred in cells of the immune system and to investigate whether single cells are sensitive to gravitational changes. Normal peripheral human T lymphocytes were growth stimulated in flight by addition of Con-A. In microgravity, activation of the cells was 90% less than that of the ground controls (Cogoli, A. *et al*, Cell sensitivity to gravity. Science 225: 228-230 (1984)). The experiment was repeated on D-1 and an in-flight 1g centrifuge was included as a control, in addition to the ground controls. Again activation response was reduced by 90% in microgravity compared to ground. However, the response of cells in the 1g centrifuge was intermediate between microgravity and the ground control, indicating a gravity-sensitive mechanism in lymphocyte response. Cosmic radiation was ruled out as a factor since cells in the 1g in-flight centrifuge, which may shield radiation, appeared normal. The most significant result of the D-1 mission was the confirmation of the SL-1 results that showed 90% blunted growth response of T lymphocytes in microgravity.

A second experiment flown by Cogoli *et al* on D-1 used whole blood drawn from astronauts to study the role of space flight stress on the immune system. Whole blood, drawn before, during, and after the mission, was cultured in the presence of Con-A. The most significant finding was the confirmation of earlier results showing blunted T cell response to mitogenic challenge during flight and for up to seven days post-flight, suggesting that physical and psychological stress during space flight depresses the human immune system. Additionally, the experiment again confirmed Cogoli's SL-1 results.

To gain further information on the mechanisms causing reduced lymphocyte response during space flight, Cogoli *et al* flew two experiments on SLS-1. The mechanisms involved in T cell activation are very complex and require sequential expression of a number of genes coding for specific factors in the signal transduction cascade. Cell to cell interaction is necessary and antigen-presenting cells (macrophages) must come into contact with the resting T cells in order to stimulate the T cell activation cascade. In the experiments flown on SLS-1, Cogoli mixed microcarrier beads with the cells as a way to increase cell contact interactions. The results were surprising. Although lymphocytes do not normally attach to substrata, the cells attached to the microcarriers and activation in microgravity, in response to Con-A, was double that of ground controls. The cells without microcarrier beads again failed to respond to Con-A, thus confirming the SL-1 and D-1 results. In addition, in the presence of microcarriers the secreted signaling factors, IL-1 (interleukin-1),

IL-2 (interleukin-2) and interferon-gamma (IFN- $\gamma$ ), were significantly increased in microgravity compared to cultures with no beads. After forty-six hours in microgravity, IL-2 increased by more than 400% in bead cultures compared to cultures without beads. Cogoli's conclusions from these results suggested that depression of *in vitro* activation of suspended lymphocytes during space flight may be due to failure of monocytes acting as accessory cells since secretion of IL-1 was significantly inhibited in microgravity. Based on the two experiments flown on SLS-1 Cogoli concluded that in microgravity:

- 1) IL-2 is produced independently of IL-1,
- 2) IL-1 production is triggered only when monocytes adhere to microcarriers,
- 3) the expression of IL-2 receptors depends on IL-1 and
- 4) if sufficient IL-1 is present, activation is enhanced in microgravity.

These conclusions were challenged by later experiments on IML-2.

On IML-2 Cogoli *et al* again tested the response of peripheral lymphocytes to the Con-A challenge. This time the relative concentrations of the mixed populations of lymphocytes were evaluated pre-flight. The population contained 82.5% lymphocytes and 6.5% monocytes with granulocytes comprising 11%. Again mitogenic activation was significantly reduced (80%) in microgravity compared to ground. In the 1g in-flight centrifuge control, activation was reduced by 50% of ground. (It should be noted that the 1g was not maintained completely because of an early but corrected centrifuge malfunction and start/stops of the centrifuge to remove samples at appointed times). Addition of exogenous IL-1 and IL-2 alone or in combination did not increase the activation in microgravity but did slightly increase secretion of interferon-gamma. In this experiment the secretion of IL-1 by monocytes was not inhibited and therefore the failure of lymphocytes to grow in microgravity is not due to faulty secretion of IL-1 by the monocytes, but to some other factor, perhaps involving the IL-2 receptor.

In a second experiment on IML-2, Cogoli *et al* used the NIZEMI microscope system and the same lymphocyte preparation as described above to visualize the motion and interactions of human lymphocytes in suspension in the presence of Con-A in microgravity. This experiment was designed to answer the question of whether inadequate cell-to-cell interaction is a reason for blunted lymphocyte activation in microgravity. Cell to cell interactions were visualized from videotapes made at selected times after addition of Con-A to the cells. The tapes clearly showed that the cells are capable of autonomous motion in random directions. In fact, the mean velocity of cells in microgravity was significantly higher than at 1g. In addition, they formed aggregates that grew in size with time in microgravity. This effectively disproved the formerly held theory that lack of cell-to-cell interaction is the reason for blunted lymphocyte response in microgravity. Both in flight and ground cultures, the aggregates changed size and shape throughout the observation periods. Individual cells also changed their shape, from round to elongated and vice-versa. Movements consisted of rocking and twisting and single cells changed location and migrated in and out of aggregates. These observations are extremely significant and prove that cell to cell interactions, necessary for lymphocyte activation, absolutely do occur in microgravity and that lack of activation is not because of a failure of cells to interact. So, the nil activation of human lymphocytes in microgravity remains a mystery. A clue from these extremely important Spacelab investigations is that lymphocytes are not progressing through the cell cycle, resulting in the dramatically decreased activation and growth.

Using Balb/c cells, a mouse strain, cultured in the presence of an antigen, and lymph node cultures of mixed T and B cells, Cogoli *et al* showed on IML-2 that antigen recognition and subsequent proliferation

in microgravity is 3% to 24 % that of ground controls depending on cell type. The first step in T-cell recognition of antigen appears to be significantly compromised in microgravity.

Two experiments were conducted by Reske *et al* on the Spacelab D-2 mission that further clarified potential mechanisms causing blunted activation and secretory function of lymphocytes. In the normal activation of T cells, antigen-presenting cells must contact resting T cells. This requires close contact between accessor and responder T cells. In Reske's approach, two cell types, ovalbumin (Ova)-specific T-responder cells (3DO-54.8) and accessor cells (A20.2J in the investigators nomenclature), were mixed. The objective of the experiment was to investigate accessor cell and responder T helper cell interactions. The most significant results were that the cells in this mixed culture grew as well in microgravity as in the 1g in-flight and ground controls. The objective of Reske's second experiment on D-2 was to measure cytokine secretion in the mixed cell cultures. Several important findings were that very small amounts of IL-1 and no IL-3 were secreted by the T-responder cells in microgravity, whereas cells in the ground controls and the in-flight 1g centrifuge control secreted comparable amounts of IL-2 and IL-3. The most significant finding, discovered by evaluation of the RNA extracted from the co-cultures, showed that the level of lymphokine transcripts did increase in microgravity, but the cells did not secrete these cytokines. Although the cells may be competent to synthesize these cytokines, some mechanism prevents secretion into the culture medium. The microcarrier beads appeared to facilitate secretion of IL-1 by the monocytes in Cogoli's experiments, which then led to the observed two-fold increase in activation of the lymphocytes. The reason for increased secretion of cytokines in the presence of microcarrier beads in microgravity has not been clarified.

Schmitt *et al* conducted an experiment on IML-2 aimed at determining how microgravity affects the amount and subcellular distribution of protein kinase C (PKC), an important factor in the early events of the T cell signal transduction cascade. In this case, Jurkat cells, a T lymphoblastoid cell line, and U 937, a monocyte-like cell line, were flown. Both of these are human leukemic origin, continuous cell lines. Results showed that distribution of PKC in these cells was significantly different from ground controls indicating a gravity-related effect on distribution of this critical intracellular signaling enzyme. In contrast to Reske's findings with co-cultured cells, IL-1 $\beta$  in cellular fractions was reduced by 30% in microgravity-exposed cells compared to the 1g on board controls. This confirms that a microgravity- and cell type-related response is involved in IL-1 metabolism.

In summary, these Spacelab experiments have demonstrated that cell to cell contacts, necessary for T cell activation, do occur in microgravity and IL-1 secretion and synthesis may be involved, though IL-1 release is not impaired in the presence of microcarrier beads or accessor/responder cell co-cultures. Addition of microcarrier beads promotes activation two-fold higher than ground controls, yet without beads, lymphocyte activation in microgravity is almost totally abolished. The reasons for this are not clear. Signal transduction involving PKC appears to be altered in microgravity. Mechanisms remain an enigma yet very significant progress has been made as a result of the Spacelab missions. The impact to crew health on long term missions because of impaired cell mediated immunity is not known and remains a significant biomedical area to be investigated. Ongoing research is needed to investigate regulatory gene expression and signal transduction pathways as well as the role of apoptosis and cell cycle progression in order understand why lymphocytes do not grow in microgravity.

### 3. Bacteria, yeasts and other organisms.

Previous studies on United States (U.S.) biosatellites and Soviet Salyut missions showed an increase in bacterial growth rate (Kordium, V.A. *et al*, Nankove Dunka Publishers, Kiev. pp. 64-68, 1978 and R.H., *et al*. NASA SP-104: 304-324, 1971). The experiments conducted on Spacelab D-1, D-2, IML-1, IML-2 and USML-2 confirmed that the growth rate in bacteria as well as in some other organisms is increased. In addition, antibiotic sensitivity is reduced and genetic transfer between bacterial cells is different in microgravity compared to ground controls. The table (Table III-7) below shows the Spacelab missions on which these investigations were conducted.

**Table III-7. Bacteria, yeast, and other organisms.**

Spacelab Designation	STS Mission	Launch Year	Duration (days)	Investigation	Principal Investigator
Spacelab 1	STS-9	1983	10+	Circadian rhythm (fungus)	Sulzman, F.
Spacelab D-1	61-A	1985	7+	Growth and differentiation	Mennigmann, H.
				Antibacterial activity	Tixador, L.
				Genetic recombination	Ciferri, O.
				Circadian rhythm (algae)	Mergenhagen, D.
				Protoplasmic streaming	Sobick, V.
				<i>Paramecium tetaurelia</i>	Planel, H.
IML-1	STS-42	1992	8+	Antibiotic activity	Tixador, L.
				Growth and sporulation	Mennigmann, H.
				Yeast chromosomes	Bruschi, C.V.
				Protoplasmic streaming	Block, I.
Spacelab D-2	STS-55	1993	9+	Growth and sporulation	Mennigmann, H.
				Yeast metabolism	Donhauser, D.
IML-2	STS-65	1994	14+	Microenvironment	Bouloc, P.
				Yeast growth (bioreactor)	Cogoli, A.
				Protoplasmic streaming	Block, I.
				Gravitaxis ( <i>Loxodes</i> )	Hemmersbach, R.
				Growth ( <i>Dictyostelium</i> )	Ohnishi, T.
USML-2	STS-73	1995	15+	Growth and development	Klaus, D.

In addition to increased growth rate, *Bacillus subtilis* flown on D-1 showed reduced sporulation in microgravity. Mennigmann et al postulated that this was due to the rapid growth and high population density causing depletion of nutrients and cell death before sporulation could occur. Later on IML-1, sporulation occurred in microgravity at high frequency, thus demonstrating that under proper conditions bacteria are able to form spores in space. Using shielded hardware on these Spacelab missions, these experiments showed that effects were due to microgravity and not cosmic radiation. On USML-2, Klaus further investigated the mechanism of increased bacterial growth in microgravity. He found that the kinetics of the growth curve in *Escherichia coli* (*E. coli*) is changed. The lag phase time is decreased, growth phase is increased and there are more cells at the end of logarithmic growth going into the stationary phase.

Physical properties including reduced convection and altered surface tension in microgravity may affect the microenvironment of cells. This in turn could influence the interaction of the cell membrane with this environment and alter the position of receptors on the membrane surface. On IML-2 Bouloc conducted an

experiment to evaluate the influence of the microenvironment on growth and membrane signal transduction in motile and non-motile strains of *E. coli*. The motile strain showed no significant differences in growth between flight and ground cultures. Conversely, the lag phase of the non-motile strain was shorter than ground controls. This is in agreement with the reduced lag phase in growth curve kinetics on USML-2 reported by Klaus. Interestingly, the lag phase in Bouloc's experiment was also shorter in non-motile bacteria maintained in the 1g centrifuge in flight which suggests that some factor other than gravity may influence bacterial growth during space flight. Cosmic radiation may be ruled out since the cells were shielded in the 1g in-flight centrifuge in IML-2. Signal transduction in *E. coli*, measured by analysis of expression of an osmotic shock response gene, showed that the system transducing osmotic information from external medium to the cytoplasm is functional in microgravity.

Transfer of genetic material from one bacterium to another can occur by three means: conjugation, transduction, and transformation. In conjugation an ordered transfer of a portion of a chromosome occurs through a conjugation bridge formed between the donor and recipient cells. On D-1 Ciferri *et al* found that conjugation in *E. coli* was enhanced by 40% in microgravity compared to ground controls. The number of conjugation pairs was the same in space and ground, thus the increase in transfer is hypothesized to be the result of the low-shear environment of space allowing stability of bridges and uninterrupted transfer of the chromosome. A second gene transfer mechanism, transduction, achieves genetic transfer between bacteria via bacteriophages and the third genetic transfer mechanism is transformation or transfer of genes from one bacterium to another by plasmids. There was no difference in genetic material transfer between flight and ground by these two mechanisms.

Altered sensitivity of bacteria to antibiotics in microgravity was shown on D-1 and IML-1 by Tixador *et al*. The minimum inhibitory concentration of antibiotics was increased two to four fold in microgravity compared to ground controls. Three possible explanations may account for this. One is that bacteria proliferate more rapidly, achieving a higher biomass, and thus a higher concentration of antibiotic is needed. A second explanation is that transport of antibiotics into the cells may be altered in microgravity due to modification of membrane permeability. The third hypothesis is that both of the above may operate together. The experiment of Tixador *et al* on IML-1 showed shorter doubling times and earlier entry into the stationary phase for bacterial populations in flight compared to ground. No differences were shown by electron microscopy in the ultrastructures between flight and ground cells and the cellular envelopes had the same thickness. In the presence of antibiotic, the lag phase was increased and the growth rate was decreased. The doubling time in flight was shorter than ground, even in the presence of the antibiotic. These results suggest that the increased growth rate, not permeability of the cells, is the primary reason for reduced response of bacterial populations to antibiotics during space flight.

An objective of an experiment of Donhauser with strains of yeast (*Saccharomyces cerevisiae*) flown on the D-2 mission was to investigate modification of brewing yeasts for improvement of growth, efficiency of fermentation, fermentation by-products, and beer quality. Fermentation experiments were carried out with total populations and also with selected clones. Results showed that in some cultures faster fermentation, higher ester content or better beer quality was achieved in microgravity compared to ground controls. However, insufficient head retention and reduced fermentation rates were also observed, indicating a need for careful control of these processes if genetic engineering of better beer is to be achieved from microgravity processes. In addition to the fermentation data, this experiment also yielded information on the genetics of the yeasts. The karyotypes of the total yeast populations remained stable during the mission. Data from

the cloned cultures grown in microgravity displayed four different karyotypes yet no mutations were found in ground controls. Two experiments to evaluate chromosome behavior in yeast were also conducted on IML-1 (Bruschi *et al*). The objectives were to evaluate cell yield, survival, and ability to undergo meiosis, and to monitor mitotic chromosome segregation and recombination in space-flown yeasts. There were no changes in total cell yield or survival in either experiment, and yeast populations can be cultured in microgravity. The most significant finding was the recovery of intergenic mitotic recombinants in flown cell populations. The data show that mitotic recombinations were significantly more frequent than meiotic chromosome segregation.

In an experiment flown as part of IML-2, Cogoli *et al* evaluated the performance of a miniaturized bioreactor designed to study the effects of prolonged space flight on continuous cultures of single cells. They were successful in qualifying the bioreactor and additionally the experiment provided significant information on growth and cell cycle of yeast (*S. cerevisiae*). No remarkable differences were found in cell cycle, proliferation, cell volume, ethanol production or glucose consumption, and no morphological anomalies were found. Both flight and ground cultures in the bioreactors showed the presence of budding scars although bud scar frequency was significantly higher in flight samples (17%) than in ground controls (5%).

*Paramecium tetaurelia* has been shown in experiments previous to Spacelab D-1 to increase growth rate and cell volume significantly and decrease cell dry weight and protein content (Planel H. *et al*, Space flight effects on *Paramecium tetaurelia* flown aboard Salyut 6 in the Cytos I and Cytos M experiments. (Advances in Space Research 1: 95-100 (1981)). Whether these effects were due to microgravity or cosmic radiation could not be determined on the early flights. The experiment flown on Spacelab D-1 was designed to use the in-flight 1g-reference centrifuge which can shield the organism from cosmic radiation allowing separation of microgravity and radiation effects. In agreement with previous results, the experiment on Spacelab D-1 showed significantly higher growth rate in microgravity. A comparison of data from microgravity and the 1g in-flight centrifuge demonstrated that effects on *Paramecium* growth and volume in space are due to the effect of microgravity and not to cosmic radiation.

Two species of ciliates, *Paramecium* and *Loxodes*, were flown on IML-2 to evaluate gravitaxis, or swimming against gravity. These ciliates both use gravity as a cue for spatial orientation (gravitaxis) and to control their swimming velocity. *Paramecium* exhibits fast responses and has a swimming sensory cell, and *Loxodes* senses accelerations via statocyst-like organelles. The objective of this experiment was to determine the gravity threshold for gravitaxis in microgravity by adding back gravitational (g) forces through the slow rotating centrifuge-microscope, NIZEMI. Evaluation of response was measured using computer controlled image analysis of swimming tracks of the two ciliates. Results showed that the threshold for gravitaxis of *Paramecium* is below 0.3g and above 0.16g. For *Loxodes* the experiment did not yield threshold data, however, prolonged cultivation in space did not change size and content of the barium sulfate granules (statoliths) in the statocyst-like organelles of *Loxodes*.

Another experiment on IML-2 evaluated gravitaxis of the slime mold *Physarum polycephalum* (a multinucleated [plasmodial], acellular slime mold, class Myxomycete) using the NIZEMI centrifuge microscope and video recorder. *Physarum* changes the rhythm of its periodic contractions and dilatations when subjected to accelerational variations. Reaction to gravitational stimuli in this organism was shown on D-1 and IML-1. On IML-2 the threshold for gravitaxis, or acceleration sensitivity, was shown to be 0.1g. Results suggested that very small acceleration above this threshold induced a complete response process. These

experiments showed the ability of the slime mold cells to respond to acceleration changes, and prove that gravity response in *Physarum* is based on the direct effect of gravity. Direct effect is due to density differences within the cell and relayed via primary gravity receptors. The very low acceleration sensitivity indicates that the gravity receptors should be rather large and dense cell organelles, denser than the rest of the cell. Though the specific gravity receptor has not yet been identified in *Physarum*, candidates are the numerous nuclei and/or very numerous mitochondria. Both of these organelles acting in concert could serve as an effective gravity sensing system.

Two experiments were conducted to evaluate the streaming potential of slime mold (*Physarum polycephalum*), one on Spacelab D-1 and the other on IML-1. One of the biophysical questions posed by scientists is whether the streaming potential of protoplasm could be changed in the absence of gravity. The giant cell of *Physarum polycephalum* has millions of nuclei, is thus a plasmodium, and the plasmodium has numerous protoplasmic tubes containing fluid protoplasm. A system of contractile proteins generates rhythmic contractions and relaxations of the tubes that can easily be measured. Results from the D-1 experiment showed highly regulated contraction-relaxation cycles in microgravity. This was considered to be an adaptive reaction of the organism to weightlessness. A very significant finding was the general gravisensitivity in a cellular organism that has no specialized structure to perceive gravity. To better understand whether a cell without a specialized structure for gravity perception can perceive and process gravistimuli, *Physarum* was flown again on IML-1. Results confirmed those of the D-1 experiment by implying the existence of a gravireceptor but without unequivocal identification of a definitive structure or organelle in the cell.

Two different strains of the unicellular green algae *Chlamydomonas reinhardtii* were used on D-1 to evaluate circadian rhythm. Photoaccumulation served as a measure of responsiveness of circadian rhythm. Many organisms have a periodicity of 24 hours but on Earth it is not possible to discriminate between an internal biological clock and a circadian rhythm based on normal terrestrial rotation. Although there were some differences in amplitude, the results of this study showed that in microgravity the circadian rhythms of *Chlamydomonas* did not differ significantly from ground control experiments thus this organism appears to have an endogenous biological clock. Cell proliferation and survival rates in microgravity were higher and no mutations were found in flown samples.

## B. Developmental Biology

Developmental biology experiments were flown on eleven Spacelab missions. A total of forty-one experiments were conducted and sixteen different species were studied including several species of insects, brine shrimp, jellyfish, amphibians (frogs and newts), fish, mouse, and quail. Table III-8 below shows the missions on which these experiments were flown.

Several experiments were flown to evaluate the effects of the microgravity environment on the development of insects. Effects of space flight on the development of *Drosophila melanogaster* were successfully evaluated on Spacelab D-1, IML-1 and IML-2. The significant findings from the D-1 experiment showed that embryos develop in space but with some variations in timing of the developmental process. IML-1 experiments essentially repeated the D-1 experiment and results showing early embryonic development under conditions of microgravity and the in-flight 1g centrifuge and ground controls are summarized as follows:

- 1) Oocyte (egg) production was significantly increased in microgravity compared to the 1g in-flight centrifuge and ground controls.
- 2) Embryos continuously exposed to microgravity were larger than controls.
- 3) Larvae showed thoracic and/or head abnormalities in the microgravity samples.
- 4) The lifespan of adult males continuously exposed to microgravity was shortened (75% that of controls), while the life span of females was unaffected.

On IML-2, the influence of microgravity on different developmental stages of *Drosophila* were further investigated to confirm previous conclusions and to evaluate whether mitochondrial metabolism may be involved in aging. Again the IML-2 experiment confirmed that *Drosophila* can develop in microgravity through all developmental stages. Additionally, delayed hatching and slower development in microgravity were again shown. Post-flight, all embryos, larvae, pupae and imagoes (mature insects) recovered and had normal morphology and function, although males showed an accelerated aging response in terms of vitality assays (mating and negative geotaxis) as well as life span and survival differences. In fact, flown males died significantly earlier than non-flown males. In-flight video of the behavior of the flies showed that young males exhibited markedly increased locomotor activity in microgravity compared to ground, and most of the males in flight were continuously moving. In contrast to male life span data, the females did not age more rapidly than ground controls yet females also showed increased locomotor activity in microgravity. Flies maintained on the 1g in-flight centrifuge had life-spans similar to those maintained in the centrifuge on the ground suggesting that microgravity may increase aging rate in *Drosophila*. Evaluation of mitochondrial 16S ribosomal RNA showed that microgravity-exposed flies had decreased 16S RNA compared to ground controls. This provides evidence that mitochondrial metabolism may be different in microgravity and could play a role in early aging. In general, a significant overall conclusion from these experiments is that in the absence of gravity, the developmental parameters most dependent on gravity were identified. These experiments with *Drosophila* have significantly advanced our understanding of the influence of gravity on morphogenetic development in embryos.

Progressing from insects to higher animals, the effects of microgravity on development of ephyrae (the swimming larval stage) from polyps of *Aurelia aurita* (jellyfish) and the development of the graviceptors of the ephyrae, formation or demineralization of statoliths and swimming/pulsing behavior were evaluated on IML-2 and SLS-1. The most significant findings from these two experiments showed that the number of ephyrae formed per polyp were slightly higher in flown groups at eight hours after launch compared to

**Table III-8. Developmental biology experiments.**

<b>Spacelab Designation</b>	<b>STS Mission</b>	<b>Launch Year</b>	<b>Duration (days)</b>	<b>Species Studied</b>	<b>Principal Investigator</b>
Spacelab D-1	61-A	1985	7+	<i>Carausius morosus</i> <i>Drosophila</i> <i>Xenopus</i> <i>Xenopus</i>	Buecker, H. Marco, M. Neubert, J. Ubbels, G.
SLS-1	STS-40	1991	9+	<i>Aurelia</i> differentiation	Spangenberg, D.
IML-1	STS-42	1992	8+	Brine shrimp <i>Drosophila</i> <i>Xenopus</i> Mouse long bone <i>Carausius morosus</i>	Paulsen, A. Marco, R. Ubbels, G. Veldhuijzen, J. Buecker, H.
SL-J	STS-47	1992	7+	<i>Xenopus</i> Chick	Souza, K. Suda, T.
USML-1	STS-50	1992	13+	Brine shrimp and wasps	Spooner, B.
Spacelab D-2	STS-55	1993	9+	<i>Xenopus</i> and fish <i>Xenopus</i> and fish <i>Xenopus</i> and fish	Neubert, J. Horn, E. Rahmann, H.
IML-2	STS-65	1994	14+	<i>Aurelia</i> development Japanese red-bellied newt <i>Drosophila</i> Sea Urchin <i>Xenopus</i> <i>Medaka</i> (fish) development Japanese red-bellied newt Mouse long bone	Spangenberg, D. Wiederhold, M. Marco, R. Marthy, H.J. Ubbels, G.A. Ijiri, K. Yamashita, M. Veldhuijzen, J.
USML-2	STS-73	1995	15+	Pre-metatarsals (mouse)	Klement, B.
Spacelab Mir	STS-71	1995	9+	Avian blood vessel (quail) Afferent innervation (quail) Vestibular development (quail) Life cycle (quail) Contractile protein (quail) Eye development (quail) Skeletal develop. (quail) Visuo-vestibular (quail) Fecundity (quail)	Lelkes, P. I. Fermin, C.D. Fritzsche, B. Hester, P.Y. Anderson, P. Conrad, G.W. Doty, S. Shimizu, T. Wentworth, B.
LMS	STS-78	1996	16+	<i>Medaka</i> (fish) development	Wolgemuth, D.J.
Neurolab	STS-90	1998	15+	Insect gravity sensor Vestibular organs Motor development Neuronal development CNS development Aortic baroreflex	Horn, E.R. Wiederhold, M. Walton, K. Kosik, K. Nowakowski, R. Shimizu, T.

pre-launch values. Perhaps the most significant finding was the ability of the jellyfish in microgravity to synthesize jellyfish-thyroxine (Jf-T4), which is required for ephyra production. There was no difference in morphology between space and ground developed ephyrae but abnormalities were found in pulsing behavior. This suggests an abnormal development of graviceptors or the neuromuscular system or a defect in the integration of impulses between the systems.

Sea urchin larvae (*Sphaerechinus granularis*) were flown on IML-2 to determine whether mineralization and formation of skeletal structure occur properly and if larvae with skeletons already developed on the ground would lose mineral in microgravity. Sea urchin larvae in two developmental stages were flown. To determine if already formed skeletons de-mineralize in microgravity, larvae in the pluteus stage with internal skeleton already formed were chosen. This stage is characterized by a transient calcareous structure composed of calcium carbonate crystallized as calcite and a small amount of magnesium and organic matrix. To test whether larvae could mineralize a skeleton in microgravity, embryos in the blastula stage in which the skeleton is not yet formed were also used. Significant results were that larvae developed skeletons in flight and no pronounced loss of mineral from already formed skeletons occurred. However, the skeletons that were formed showed some unusual architecture, indicating that the process of association and positioning of the cells which determine the size and shape of the skeleton are particularly sensitive to environmental perturbations. Evaluation of calcium and magnesium did not show significant differences between flight and ground samples.

Five of the Spacelab missions, D-1, D-2, IML-1, IML-2 and SL-J, included investigations into the role of gravity and weightlessness on developing amphibian eggs. These experiments used eggs of *Xenopus laevis* (African three-clawed frog) to determine if fertilization occurs in microgravity and if embryo development is initiated. The most significant results, discovered on IML-1, showed for the first time that fertilization of a vertebrate egg can occur in microgravity and that embryos develop bilateral symmetry after sperm penetration. This implies that gravity is not required for establishment of a normal dorso-ventral axis in *Xenopus*. The experiment flown on SL-J further characterized amphibian development by showing that embryos in microgravity progressed through gastrulae and neurula stages and formed normal tadpoles. Finally, the experiment conducted on IML-2 confirmed previous findings and added further information on development. Results from these Spacelab missions may be summarized as follows: *Xenopus* eggs, fertilized and developed in microgravity, form normal axis and neural plates and the tadpoles develop normally. Cortical rotation and cytoplasmic rearrangements that occur in normal development are not gravity dependent. Formation of the blastocoel is altered in microgravity. These anomalies do not interfere with mesoderm induction and development however, and from about the 9th stage forward the embryos recover and develop normally into normal tadpoles.

A series of experiments with *Xenopus*, cichlid fish, and the Japanese red-bellied newt were designed to evaluate development of gravity receptors in microgravity. In the newt, the gravity receptor organ contains sensory hair cells covered by a layer of dense stones or otoconia. The inner ear of juvenile developing newts flown on IML-2 showed significantly larger saccular otoliths and some differences in assembly of components of the otoconia. This implies that gravity influences normal development of gravity receptors. An experiment flown on Spacelab D-1 by Neubert *et al* to test whether the arrangement of statolith organs are affected by weightlessness revealed no effects on flown larvae. An unknown otolith-like structure was found, although whether this developed because of weightlessness *per se* is not clear. *Xenopus* larvae, returned alive, swam in closed circles at first but returned to normal swimming patterns after one to two days.

Three experiments were flown on D-2 to further evaluate the effect of weightlessness on development of gravity sensing organs. Rahmann *et al* compared swimming behavior in larval toad (*Xenopus laevis*) and cichlid fish (*Oreochromis mossambicus*) and demonstrated the strong influence of altered gravity on behavior. Alterations in the gravity environment induced somewhat pronounced, long-lasting behavioral reactions followed by long-term adaptation to the gravity changes. Changes in brain biochemistry were found in fish and tadpoles subjected to hypergravity (3g) and electron microscopy data showed that after exposure to microgravity, the energy metabolism was reduced in neurons in the gravity integration center of the brainstem. There were also changes in the gravity-sensitive epithelial cells in the inner ear of fish larvae. The experiment of Horn *et al* on D-2 further described specific effects of gravity deprivation on vestibular-ocular reflexes. Eye movements are influenced by two components of the gravity sensing system. One is the otolith organ, which is sensitive to linear accelerations and especially to gravity, and the second is the semicircular canal organ that is stimulated by angular accelerations. These components interrelate behavioral response and eye movements. The fish youngsters and *Xenopus* tadpoles exposed to microgravity showed some differences in eye movement response. In *Xenopus*, there was a significant effect of weightlessness on the static vestibular-ocular reflex but this was not shown in the fish youngsters. Conclusions are that gravity deprivation acts on developmental process of the vestibular system, if its onset is before the first appearance of the gravity induced response. Animals with reflex experience develop normal vestibular reflex behavior even in the absence of gravitational stimulus. Gravity-associated behavioral changes on D-2 were described by Neubert *et al*. Just hatched tadpoles in the ground controls fixed themselves to the chamber walls in the direction of the gravity vector with heads up. In microgravity they fixed themselves to the walls of the culture chamber with heads to the left and tails to the right at a 90-degree angle compared to the ground controls. In agreement with other experiments, swimming behavior was changed. The tadpoles swam in narrow somersaults, in circles or floated motionless in random positions. Some of the fish swam in large circles, darted around randomly or floated motionless. After return to earth, the fish re-adapted and swam normally after about sixteen hours, but the tadpoles continued to swim in circles, loops or in screw-like patterns for at least six days. The body morphology of flown tadpoles was sickle-shaped instead of straight, probably reflecting the preferred loop-swimming mode.

Avian development was evaluated on chicken eggs fertilized before launch on SL-J and quail eggs on a series of Spacelab Mir missions. For chick embryos, all tissues including cartilage and bone formed in seven and ten day old chick embryos during space flight. After flight, these chicks continued to develop and hatched normally.

For the quail experiments flown on the Spacelab Mir Missions, a general description was prepared by Dr. Timothy Jones, NASA Ames Research Center.

“Experiments studying the effects of space flight on embryo development in Japanese quail (conducted in 1990 and 1992 on Mir) revealed that embryonic development and hatching is possible under space flight conditions. However, abnormalities were detected during various phases of this development. The presence of the abnormalities, and the decreased number of hatches in comparison to a control group on Earth, provide some information of space flight effects on embryo development. The exact nature of these effects is still unclear, and it is uncertain whether they may be direct or indirect. The purpose of this investigation, then, is to determine the nature of these effects and the mechanisms by which they occur. Of special interest is the role that gravity plays in the development of the dorsal and ventral sides of the body.

The (Shuttle Mir) experiment began when a set of quail eggs that had been fertilized before launch were sent to Mir on the Space Shuttle. These eggs were incubated (kept at a constant warm temperature) in space on the Mir in a specially designed incubator, and development of the quail embryos was allowed to proceed. Then, during various stages of growth and development, incubation was stopped, and a portion of the eggs were put in a fixative solution so that they could be returned to Earth for later analysis. On Earth, researchers performed postflight analyses on the fixed embryos to determine how microgravity affected the development of the quail eggs, specifically the effects on position and location of embryo organs, formation of a body axis, formation of a visual system (eyes), and development of musculoskeletal systems (deposition of bone and mobilization of minerals, and development of muscles).” (Refer to the list of principle investigators in Table III-8 as a source to search for more detailed results as they become available.)

The response of skeletal tissue cells to microgravity was evaluated on IML-1 using fetal mouse long bones (metatarsal) from 16-day-old (non-mineralized) and 17-day-old (mineralized) fetal mice. Significant results showed no effect of microgravity on growth or lengthening of long bones during the four-day culture period but a significant reduction in the extension of the mineralized zone in the 16-day-old bones. Decreased mineralization in microgravity was shown also by a 37% reduction in calcium uptake in space compared to the in-flight 1g control and ground control. There was no significant difference between the 1g in-flight control and ground control indicating that mineralization was being impaired in microgravity. Resorption of mineralized matrix was determined by measuring release of calcium 45 from pre-labeled 17-day-old bones. In microgravity, calcium release increased by 37% indicating that osteoclast resorption in bone is stimulated in microgravity.

Results from the developmental biology experiments flown on the Neurolab (STS-90) mission are included in the following table (Table III-9).

### **C. Plant Biology**

Plant biology experiments were flown on thirteen of the nineteen Life Sciences Spacelab missions. More than thirty individual experiments, most with multiple objectives evaluating multiple plant types, were conducted addressing the general areas of plant growth and development, gravity sensing and response, metabolism, lignification and support hardware development. Because of the amount of information produced by the Spacelab plant biology experiments, the most significant scientific findings are shown in the plant biology discipline category tables (Tables III-9, III-10, III-11, and III-12) following this summary.

A summary of the results on plant growth and development from experiments performed on a number of plant types (oat, mung bean, aniseed, rapeseed protoplasts, wild carrot, *Arabidopsis* and its mutants, *Hemerocallis* (daylily), and *Neurospora* (fungus)) showed that responses are generally plant type and species specific. Root orientation is strongly dependent on gravity but amyloplasts resting on the endoplasmic reticulum or cytoskeletal elements does not account totally for all gravity-sensing mechanisms in plants and the mechanisms are still unclear. Evaluation of columella cells of growing roots fixed in microgravity showed that the amyloplasts are randomly distributed and not located at the side of the cell toward the gravity vector as on Earth. In general, seed germination and plant growth progressed well in microgravity. Root and shoot development was evaluated, and gravity direction sensing and magnitude of the g-force, or threshold, was determined for a number of plant types. The thresholds, which are the minimum g-force for each species required to elicit a response, were surprising low. Without the access to microgravity, it would have been impossible to determine

**Table III-9. Developmental experiments flown on Neurolab (STS-90).**

Principal Investigator	Species	Objectives and Results
Wiederhold	<i>Biomphalaria glabrata</i>	Observe statocysts produced in mollusks reared in microgravity 50% increase in statocyst number in microgravity, statocyst size remained comparable. Most animals showed no, or minimal, crawling on landing day and gradually obtained a gravitactic directional preference by day 4 after landing.
	<i>Xiphophorus helleri</i>	Observe formation of otoliths in fish reared in microgravity. Embryonic fish had larger otoliths than ground controls. Juvenile fish showed no difference.
Walton	<i>Rattus norvegicus</i>	Examine the adaptability of the motor system to gravitational changes. Motor coordination and vestibular reflex development were impaired by early exposure to microgravity, and a critical period was determined for the development of normal motor function.
Horn	<i>Acheta domesticus</i>	Examine the specific influence of gravity on the functional development of the gravity sensing organs and central nervous system. Gravity related compensatory head movement was not influenced by microgravity while a central neuron which is probably involved in the transmission of information flow between the gravity sense organ and the neck muscles was affected.
Kosik	<i>Rattus norvegicus</i>	Examine the effect of gravity on the spatial learning neural center. Some differences in exploration patterns and learning strategies were noted in the flight subjects, but normalized in short order. No long-term effects were noted.
Nowakowski	<i>Mus musculus</i>	Examine neural cell proliferation, and neuronal migration and differentiation. Flight animals showed significant modification to the proliferating cell population.
Shimizu	<i>Rattus norvegicus</i> , <i>Mus musculus</i>	Determine the effect of gravity on the aortic baroreflex response.

the threshold value since g-acceleration can be added back in microgravity but gravity cannot be removed (except for seconds in the KC-135 or drop towers and up to twelve minutes in sounding rockets, not long enough to investigate growth responses) here on Earth. Use of the NIZEMI centrifuge-microscope allowed visualization of the bending responses of seedling roots. This provided extremely significant information on the influence of gravity related to developing plants on Earth as well as the effects of microgravity. Lignification was significantly reduced in microgravity. Without the requirement to grow strong stems to hold plants upright as in 1g, the plants adapted to microgravity by reducing lignin synthesis.

A potentially commercial process showing advantage in the microgravity environment was electrofusion. Two types of protoplasts from tobacco leaf tissue were successfully electrofused at a higher efficiency in microgravity because the protoplasts remained in suspension rather than sedimenting, thus permitting more contacts between the cells and higher fusion efficiency. Leguminous plants formed nodules in the presence of *Rhizobium* bacteria. This showed that gravity is not necessary for normal co-development of nitrogen-fixing

bacteria and leguminous plants, important information for future cultivation of legumes on space stations, long-duration missions, or Lunar outposts. A commercially developed and available plant growth facility, Astroculture™, allowed the cultivation of potatoes (1.5 cm diameter in approximately sixteen days) in microgravity. Technology developed as a part of this facility is being used for ground-based purposes ranging from treatment of cancer patients to horticulture. Still in the area of plant growth facilities development, the Greenhouse experiment conducted in the Russian/Bulgarian-developed plant growth facility called the “Svet” was launched on SL-Mir and continued producing for over 700 days, until the termination of the Mir program. Probably one of the most complex plant experiments ever attempted in space, the facility grew plants such as lettuce, radishes, and wheat on Mir to allow seed-to-seed growth, proving that food crops can be grown in microgravity, and is being used as a model for similar facilities planned for the International Space Station.

Tables III-10, -11, -12, -13 present a summary of the results from the Spacelab plant biology experiments.

**Table III-10. Plant growth and development.**

Mission	PI	Species	Results and Comments
OSTA-1	Brown	<i>Helianthus annuus</i>	98% germination rate in microgravity.
OSS-1	Slocum	Oat	Seedlings normal, normal ultrastructure features. Cortex cell mitochondria morphology appeared swollen. More vacuoles in peripheral root cap cells
		Mung bean	Normal tissue organization. Root cap cells in flight samples collapsed and degraded. Ultrastructure showed 1) loss of organelle integrity, 2) highly condensed cytoplasm. This experiments germinated seeds just hours before launch Conclusions: Loss of putative gravity-sensing cells may be very significant for long-term plant orientation in space.  Demonstrated differing tissue sensitivity in the two species grown in space.
	Krikorian	Oats	Root lengths 6% less than controls. Number of roots growing upward 74% compared to 0% for ground. Much chromosome fragmentation and breakage Root tips seemed more adversely affected than shoot growing regions. Metaphase chromosomes generally more contracted and poorer spread
		Mung Bean	Number of cell divisions about half normal ground grown seedlings. No gross morphological changes. Metaphase chromosomes generally more contracted and poorer spread. This experiment germinated seeds just hours before launch
SL-1	Brown	<i>Helianthus annuus</i>	Seedling nutation (spiral growth) found in test plants.
D-1	Theimer	Anis callus cults	90% of cell clones showed polarity - primordia of leaves and/or roots. Electron microscopy of roots showed well-developed statocytes with amyloplasts Growth into normal anise plants after landing

**Table III-10. Plant growth and development cont'd.**

Mission	PI	Species	Results and Comments
IML-1	Rasmussen	Rapeseed protoplasts and embryonic cell line of carrot ( <i>Dacus carota</i> )	Protoplasts in microgravity delayed synthesis of new cell wall. Single cells were enlarged, formed few aggregates versus ground controls were small, 8-12 aggregates. Calli from protoplasts exposed to microgravity had highly reduced growth. Growth into normal plants after landing (12 and 16 weeks after landing). 3-day old protoplasts mainly contained large cells with big vacu-oles and 2-4 cells per aggregate compared to ground with smaller cells and 8-19 cells/aggregate. Most significant results: retarded regeneration process possibly due to initial effect on cytoskeleton or stress of space flight On the ground, cells concentrate in a layer perpendicular to gravity vector, while in microgravity protoplasts were randomly distributed causing absence of cell-cell interaction
	Briarty	<i>Arabidopsis thaliana</i> and its aux-1 mutant	Objectives were to determine root and shoot growth rates, to observe hypocotyl hook. Root, shoot and total length in space-grown plants not different from ground. In microgravity there was no obvious orientation of root and shoot. Angle of hypocotyl hook was different in microgravity compared to ground. No differences seen in cotyledons Significant difference in cytoplasmic volume, more occupied by lipids in space samples
SL-J	Miyoshi	<i>Neurospora crassa</i>	Objectives were to understand development of circadian rhythm in microgravity in the mold, <i>Neurospora</i> . Results: Both flight and ground showed five definite conidium band patterns of circadian rhythm. Growth of <i>Neurospora crassa</i> was increased in microgravity compared to ground
	Krikorian	<i>Hemerocallis</i>	Successful somatic embryogenesis but more slowly in space. Increased occurrence of binucleate cell Chromosomal aberrations and reduced cell division rate not due to re-entry effects (cells fixed in microgravity).
	Sato	Tobacco	Shoot regeneration occurred under space flight conditions, but not multiple shoot formation. Growth, especially of stems, was heterogeneous compared to ground samples, and fresh weight was lower. Microtubule formation, chloroplast development, and meristem growth were all reduced in microgravity.
USML-1	Luttges	Alfalfa, Clover	No difference in mass or length in flight versus ground. Flight seedlings had significantly greater mass and length in the root than the shoot compared to ground.
IML-2	Krikorian	<i>Hemerocallis</i>	Flight samples had chromosomal damage while ground controls did not. Epidermal development of flight samples was poorer than ground controls. Perturbation is real and not an artifact of reentry or postflight adaptation.

**Table III-10. Plant growth and development cont'd.**

Mission	PI	Species	Results and Comments
SL-Mir	Salisbury	<i>Triticum aestivum</i> (Wheat)	Plants grew for 90 days but did not produce flowers or seeds, where ground controls produced heads with no seeds. Ethylene in the cabin atmosphere was determined to have caused the sterility.
USML-2	Tibbitts	Potato ( <i>Solanum tuberosum</i> cv Norland)	Plants grew in the chamber in microgravity with effective starch accumulation similar to ground controls. Activity of the starch synthetic enzyme, ADP-glucose pyrophosphorylase, was reduced.
D-1	Perbal	Lentil	No significant difference in length of lentil roots. Roots showed variable orientation in microgravity, 1g roots grew toward the g-vector. Roots grown in microgravity and placed on the 1g in-flight centrifuge showed strong gravitropic curvature proving that the statocysts which had never sensed gravity were capable of responding to centrifugal acceleration. The amyloplasts in statocytes grown in microgravity gathered in the center of the cell at a certain distance from the endoplasmic reticulum, while those developed in the 1 g centrifuge showed normal polarity with the nucleus near the proximal wall, endoplasmic reticulum near the distal wall. The significant findings from this experiment was that it demonstrated that the statolith could not exert pressure on the endoplasmic reticulum because of distance in location of the two organelles in the cells in microgravity. Thus, statolith contact or pressure on the ER is not the mechanism for gravisensing. This association of statoliths and the ER in gravisensing could not have been clearly separated under normal ground conditions.

**Table III-11. Plant gravity sensing.**

Mission	PI	Species	Results and Comments
D-1	Volkman	Cress roots ( <i>Lepidium sativum</i> )	Germination rate in microgravity is the same as 1g. Growth curves are similar for all three conditions, similar growth kinetics. In ground controls, roots grew mostly parallel to the gravity vector while in space, roots grew at angles up to 60 deg with reference to the seed plate. Statolith structure was the same as ground samples thus structural polarity was maintained thus, structural polarity is genetically determined. Statocysts had less parallel ER. Amyloplasts were more rounded and starch grains had clear areas in their centers and the amount of starch was lower than 1g cells. Seeds were germinated in space. The most significant result: structural polarity that persists in space-grown plants is genetically determined.
IML-1	Perbal	Lentil roots ( <i>Lens culinaris</i> )	Objective: to measure bending response times to determine effect of microgravity and threshold of gravity force needed to elicit the response. Results: Roots bend in response to changes in orientation of gravitational field. The bending was quantitatively estimated by measuring the minimum duration and the total duration of the stimulation required to produce a bend response. Seeds were germinated in space. Data and calculations showed consistency with the hypothesis that amyloplasts exert pressure on the cytogel lining of the longitudinal wall of statocytes. Alternatively, the amyloplasts may exert tension on the actin filament network as a gravity detecting mechanism.
	Heathcote	Wheat ( <i>Triticum aestivum</i> )	Objective: to evaluate seedling curvature exposed to phototropic stimulation. Results: Curvature response in microgravity was not significantly different from ground. Relationship between stimulus and curvature response was shown. The dose (light exposure duration) curve was not significantly different in space vs. ground and seedling curvature did reverse curvature (autotropism) in microgravity. Circumnutation (oscillation) was seen in 50% of flight seedlings. Three-day old coleoptiles were used.
	Brown	Oat ( <i>Avena sativa</i> )	Objective: to determine threshold time and g-force intensity for gravity response in seedlings. Results: Curvature response in microgravity not greatly different from ground. The shortest gravity stimulation to cause a response in 1g was 2.0 min., the threshold extrapolated at less than 1 min. In flight the least g-value applied was 0.1 g and this caused a significant bending response thus if there is an absolute threshold for gravitropic response, it must be below 0.1g. Seeds germinated in space in the dark and gravity was added back incrementally by use of a variable speed centrifuge

**Table III-11. Plant gravity sensing cont'd.**

Mission	PI	Species	Results and Comments
D-2	Hock	Bassidiomycetes ( <i>Flammulina velutipes</i> )	<p>Fruiting bodies exhibited random orientation in microgravity. Ground fruiting bodies point exactly opposite direction of acceleration force. Results: Fruiting bodies in microgravity grew away from the substrate</p> <p>No impairment of cap morphogenesis and growth intensity. Flat stipes indicated that acceleration force is required for regular development of stipes. Ultrastructure of the graviperceptive growth region of the stipe did not show sedimentable cell components that could act as statoliths. Significant conclusions: This experiment revealed two totally different growth reactions: the gravity independent avoidance reaction shown by growth opposite the substrate and the gravity-dependent orientation shown by random orientation in space-flown samples compared to orientation opposite the direction of the gravity vector in controls. In addition, this experiment showed that gravity is required for proper development of the stipes in fungi and also, this experiment showed that fungi do not have statoliths for sensing gravity. Gravitropic bending involves growth inhibition at the upper side of a horizontally oriented transition zone. Accumulation of vesicles at the lower part of this region was the first ultrastructurally observable response to altered acceleration. These vesicles cause expansion of the central vacuole and subsequent differential enlargement of the lower side of the stipe leading to directional bending based on gravitational force direction.</p>
	Volkmann	Cress	<p>Objective: investigate graviperception on plants by determining the threshold values for minimum gravitational force inducing a bending effect in roots.</p> <p>Results: In microgravity roots exhibit larger bending angles and root curvature begins early after adding g-force stimulus compared to ground.</p> <p>Gravity-grown roots can sum two stimuli of intensity. Amyloplasts in microgravity roots were distributed at random. Seeds were germinated in space.</p>
IML-2	Volkmann	Cress	<p>Objective: to determine whether for gravity controlled processes the reciprocity law is operable (i.e. equal gravity doses (gravity x time) would give equal results without regard of individual values chosen for acceleration (above threshold)).</p> <p>Results: In general, roots grown in microgravity respond to g-stimulus in shorter times after stimulation than roots grown in the 1g centrifuge and the degree of curvature was larger for microgravity roots. Results showed that the gravitropic curvatures produced by gravity doses were not the same and do not confirm the reciprocity law. Seedlings were germinated in microgravity and curvature of roots was observed with the NIZEMI variable rate centrifuge and microscope.</p>

**Table III-11. Plant gravity sensing cont'd.**

Mission	PI	Species	Results and Comments
IML-2	Perbal	Lentil	<p>Objective: to determine whether settling of statoliths onto the endoplasmic reticulum regulates growth response in root growth. Root orientation is strongly gravity dependent.</p> <p>Results: In microgravity there were strong oscillations of the root tip. Curving to right and left were similar indicating there was no memory the direction imposed by 1g. Root length, growth rate and cell elongation length in microgravity were not significantly different from 1g. The transfer from 1g to microgravity did not modify cell elongation in the roots. The root cap has at least one inhibitor that regulates root growth. The results showed that symmetrical release of this inhibitor is not gravity dependent. Seeds were germinated in microgravity.</p> <p>A significant finding is that in statocytes, the sedimentation of amyloplasts onto the endoplasmic reticulum should not induce any signal of cell elongation. Yet, there is a definite effect of gravity on root orientation and growth and the mechanism has yet to be found.</p>
	Sievers	<i>Chara Thalli</i>	<p>Objective: to test a safe fixing device and procedure to investigate ultra-structure of organelles and cytoskeletal elements.</p> <p>Results: The device and procedure were validated. In <i>Chara</i>, vacuoles containing barium sulfate particles are located about 10-30 microns from the outermost apical cell wall and function as statoliths. Statoliths do not fall on the apical cell wall in 1g because they are suspended by an actin network. In microgravity, statoliths translocated towards the base of the cells. Rhizoids grew 18 hours in darkness at 1g before launch and 30 hours in microgravity.</p>
	Iversen	<i>Brassica napus</i> L Wild type and agra- vitropic transgenic <i>B. napus</i> L	<p>Objective: to evaluate growth, morphology, and gravitropic sensitivity.</p> <p>Results: Both wild type and the agravitropic Brassicas showed expected root elongation.</p> <p>Ground studies showed significant difference in root growth rate between wild type and transgenic, while in microgravity no difference between root growth rate occurred in wild type. Subjectively, total growth in both types was higher for ground control than transgenic space grown roots. On the ground, the wild type showed normal curvature, agravitropic roots showed no response to gravity vector direction. In microgravity, both root types were agravitropic.</p> <p>After flight, unfixed samples were cultured for 24 months. Flown plants still showed agravitropic behavior. Ground controls were capable of regeneration into intact plants, however, no plants could be regenerated from flown samples.</p> <p>The most significant conclusion was that difference in growth in the ground control between wild type and the agravitropic root type appeared to be eliminated in microgravity.</p>

**Table III-11. Plant gravity sensing cont'd.**

Mission	PI	Species	Results and Comments
IML-2	Johnsson	Cress roots	<p>Objective: to test whether characterizations for “Random Walk” are valid for growth of cress roots in microgravity. Random walk is characterized by mean value of deviation angles of root tip at a given time being zero and the variance of the mean square value of deviation angles increasing linearly with time.</p> <p>Results: In microgravity the observed growth patterns and linearity of deviation patterns with time followed the predictions of random walk hypothesis. Observed that length of cress roots in microgravity was shorter than ground. Curvature of root at a particular point changed with time in microgravity but not in the 1g centrifuge. Initiation of the experiment in microgravity began by transfer of containers from 5 deg. C to 23 deg C.</p>
	Haeder	<i>Euglena gracilis</i>	<p>Objective: to investigate whether Euglena has an active gravireceptor and to determine the threshold for graviperception. Euglena are unicellular photosynthetic freshwater flagellates that normally exhibit negative gravitaxis.</p> <p>Results: Threshold response to acceleration was between 0.08 and 0.16 g indicating a very low g- level orientation response for Euglena. The dose-response curve (more g-force applied) was sigmoidal indicating of an active physiological gravireceptor rather than passive mechanical reorientation due to asymmetry of the baricenter of the cell. Swimming behavior under applied accelerations showed that the cells swim at a speed that is a vectorial addition of their propulsion velocity and the sedimentation velocity. In microgravity cells swim at about 160 microns per second and the value for 1g is 130 microns per second, when the swimming is against acceleration. This corresponds well to a sedimentation rate of 30 microns per second for immotile cells at 1g.</p>
USML-2	Hilaire	Starchless <i>Arabidopsis</i> mutant	<p>Objective: to compare location of starchless plastids in columella cells mutant. Arabidopsis seedlings in microgravity, centrifuged, and clinorotated.</p> <p>Results: In stationary seedlings starchless plastids were equally located in the mid- and distal third of the columella cells. After centrifugation of these seedlings at 20g for 5 minutes, starchless plastids were sedimented to the distal third of the cells.</p> <p>Plastids from flight were distributed in the proximal third. Clinorotated seedlings had plastids mostly in the middle third of the columella cells.</p> <p>Significant conclusions were that the density of the plastids without starch does not prevent redistribution based on gravity treatment. Also, on a cellular level, clinorotation is a poor simulation of microgravity with this organism and under the conditions of the test.</p>
	Smith	Clover ( <i>Trifolium repens</i> )	<p>Objective: to compare the gravity response of clover seedlings grown in space, on Earth, and in a slow-rotating clinostat for physiological variance.</p> <p>Results: No significant difference in root bending response between flight and ground controls after landing, clinorotated seedlings responded poorly after rotation was ended. Flight seedlings had intact root caps, necessary to plant gravity response. Seeds were germinated in microgravity and had a 5-hour delay between landing and initiation of gravity testing.</p>

**Table III-12. Plant metabolism.**

Mission	PI	Species	Results and Comments
D-1	Jung-Heiliger	Horse Chestnut ( <i>Aesculus hippocastanum</i> L)	Objective: to study calcium uptake inhibitor on production of secondary metabolites of a pharmaceutically relevant cell culture. Results: No changes in secondary metabolism were detected in microgravity samples. Nifedipine (calcium uptake inhibitor) reduced the formation of hydroxybenzoic and hydroxycinnamic acid derivatives. Additional findings: viability was 70% in microgravity compared to 80% for ground at comparable sampling times. Nifedipine reduced viability to about 25 % for both flight and ground samples. No differences in ultrastructure were seen between flight and ground samples. Cosmic radiation and other conditions of space flight did not affect ploidy level. Plantlets from suspension cell cultures plated on solid nutrient medium could be grown.
D-2	Hampp	Protoplasts of leaf tissue of <i>Nicotiana tabacum</i> and <i>N. rustica</i>	Objectives: to achieve electrofusion of the two protoplasts types in microgravity and to investigate metabolic response in the protoplasts generated. Results: Electrofusion was successful (20% were identified as hybrids) and the protoplasts generated showed good viability in flight and ground. Development was in the normal range for all cultures. Protein content was stable, specific cytoskeletal polypeptides (actin and tubulin) were not influenced by microgravity. Metabolites including ATP, ADP, NADH, NADPH, NAD and NADP showed kinetics typical for regenerating protoplasts and 1g in flight and ground controls were virtually identical. In microgravity, relative increase in ATP, NAD(H), and NADP(H) were reduced. Ratio of reduced and oxidized pyridine nucleotides (NADH/NAD) and ATP/ADP was lower. Fructose-2,6-biphosphate content in microgravity was decreased. This suggests relative increase of gluconeogenesis over glycolytic activity. Significant conclusions: The combination of growth and metabolite parameters toward down-regulation of energy metabolism in microgravity yet growth and cell division were still about the same as for 1g.
	von Keller	Sunflower ( <i>Helianthus</i> ) mesophyll and hypocotly protoplasts	Objective: to achieve electrofusion of the two species of sunflower protoplasts. Results: The fusion rate in microgravity was 25.5% whereas ground fusion was 25.2% in one set and 26% in microgravity compared to 15% for ground in a second set of electro-fusions. The final yield of hybrids in microgravity was 13 % compared to 1g with less than 4.5%. Significant conclusions: Electro-fusion in microgravity is more efficient because on the ground the cells sediment before forming heterospecific fusion partners.
	Eisenbeiss	Foxglove ( <i>Digitalis lanata</i> EHRH and <i>Digitalis purpurea</i> L.)	Objective: to achieve electrofusion of the two species of foxglove protoplasts. Results: The fusion rate in microgravity was 6.7% whereas ground fusion was 0.7%. Observed changes in the metabolic properties of fused cells were found in both flight and ground, indicating that the changes were not related to growth and fusion in microgravity.

**Table III-12. Plant metabolism cont'd.**

Mission	PI	Species	Results and Comments
USML-2	Gallegos	<i>Arabidopsis thaliana</i> wild type and 3 starch altered mutants	Objectives: To evaluate ethylene production in three starch altered mutants and wild type <i>Arabidopsis thaliana</i> in microgravity, and ground static and rotated plants. Results: Ethylene production was very high in all three mutants for all gravity conditions. The wild type produced significantly more ethylene in static plants. Horizontal clinorotation resulted in higher ethylene production than static and vertical rotation in the wild type plants. Static and vertical rotation plants produced the same amount of ethylene
	Wong	Clover plants and <i>Rhizobium</i>	Objective: to investigate whether nodulation process can occur in microgravity and whether gravity is important in the recognition of legume by <i>Rhizobium</i> . Results: All plants developed 2 to 3 nodules. All nodules were induced by <i>Rhizobium</i> strain TA1 suggesting that the early steps for nodulation in legumes can occur in microgravity.
	Guikema	Clover plants	Objective: to examine the results of ethylene biosynthesis inhibitors on the space induced increase in ethylene synthesis in sweet clover. Results: Inhibitors such as AOA inhibited ethylene synthesis in both space flight and ground controls.
	Li	Seedlings	Objective: to confirm effect of microgravity on gene expression of auxin regulated genes in higher plants. Results: Expression of auxin related genes is enhanced in higher plants in microgravity.
MSL-1/1R	Li	Tomato ( <i>Lycopersicon esculentum</i> )	Objective: to study the use of genetic markers in auxin studies. Results: GH3 was specifically active in flight plants but not in the ground controls. It was activated in the vascular tissue of shoots, potentially reflecting the microgravity mediated changes in the growth and development patterns of shoot material.
	Stodieck	Wheat and <i>Rhizobium</i>	Objective: to evaluate the influence of microgravity on the interaction of <i>Rhizobium</i> and plants. Results: Reaction of the organisms was enhanced and nodule-like structures formed on wheat roots during the flight. The pseudonodules were slightly larger than those on ground controls and showed higher levels (four times greater) of acetylene reduction activity, and indirect measure of nitrogen fixing activity.
		Vinca ( <i>Catharanthus roseus</i> )	Objective: to establish a profile of the vinca alkaloids in <i>C. roseus</i> . Results: Metabolite concentration in pathways leading to the production of Vindoline, Catharanthine, and Ajmalicine were low with no distinct difference between flight and ground. Vincamine concentrations were slightly higher in flight, but there was not enough sample material to determine if the level was statistically significant.
		Vinca ( <i>Catharanthus roseus</i> )	Objective: to implement a safe and effective protocol for the use of radio-nucleotides in space flight research. Results: Uptake distribution profiles of calcium-45 and iron-59 by both flight and ground samples were similar, indicating a uniformity of growth conditions and consistency of uptake and transport mechanisms for calcium and iron.

**Table III-13. Plant lignification.**

Mission	PI	Species	Results and Comments
OSS-1	Cowles	Mung bean Pine seedlings Oat seedlings	Objectives: to evaluate root/shoot orientation and lignification in seedlings germinated in space. Results: Flight seedlings were shorter than controls in all three species. 25 to 40% of the bean and oat roots grew upward and mung bean roots were disoriented. Flight mung beans had a significant reduction in lignin content compared to controls. In flown pine seedlings, phenylalanine ammonia-lyase and peroxidase activities were reduced. The most significant finding was that the lignin synthesis is reduced in microgravity.
		Mung bean Pine seedlings Oat seedlings	Objectives: to evaluate lignification in microgravity Results: Overall reduction of lignin in pine seedlings was 4 to 5 % while the flight mung beans produced significantly less lignin than ground controls. Seedlings grew towards the light and almost half of the roots grew toward light as well and 25-40% of mung bean and oat roots grew towards the light. Flight seedlings were shorter than ground. Results supported the hypothesis that lignin synthesis is reduced in microgravity.
SL-2	Cowles	Mung bean Pine seedlings Oat seedlings	Objectives: to evaluate root/shoot orientation and lignification in seedlings germinated in space. Results: Lignin content of flight seedlings was significantly reduced in all three plant types compared to the 1g controls. In young pine seedlings, lignin content in flight seedlings was 13% less than ground controls. Mung bean and oat seedlings averaged 23 to 24% less lignin than controls. These data confirm the results of the earlier experiment on OSS-1 that gravity is an important factor in lignification.
LMS	Lewis	Loblolly pine Douglas fir	Objective: to evaluate compression wood formation in seedlings Results: Compression wood formation occurred in both flight and ground controls, indicating that the stress response is more mechanical than gravitactic.
MSL-1/1R	Stodieck	Loblolly pine ( <i>Pinus taeda</i> )	Objectives: to establish an experimental approach to evaluate the process of lignification for space flight and establish a baseline of data for future experiments. Results: Growth and health of plants in flight and ground was good over the duration of the flight. Reaction wood development was induced in both flight and ground samples.

## D. Radiation Biology

Experiments to evaluate radiation levels and effects on living systems, and to obtain information on levels of radiation within the spacecraft and Spacelab, were flown on seven of the nineteen Spacelab missions that included life sciences payloads. Seventeen radiation experiments were flown, ten of which evaluated effects on life forms including insects, bacteria, mammalian cells, nematodes, yeast, and plants. Six experiments provided information on the levels of radiation in different locations on the Shuttle and in some of the experiment specific hardware including Biorack, the access tunnel, the pallet, and the Shuttle middeck. One experiment reported dosimetric information on the crew. Radiation has been a topic of biomedical concern since the beginning of human space flight and must be taken into consideration, either as to its effect on individual experiments or in experiment specific hardware shielding, when any biological experiments are conducted in space.

The primary type of radiation evaluated, HZE (high Z element), is cosmic radiation produced by heavy, high energy and charge particles (ions) from neutrons released by interactions of primary galactic radiation with the Earth's atmosphere. This densely ionizing component of cosmic radiation is the most damaging to cells and tissues. Hits by HZE cause damage to cells from the nuclear disintegration stars produced by protons and neutrons in the irradiated tissue. Another type of radiation that should be considered comes from ionizing components of the radiation field. These include photons, electrons, muons, pions and protons. Tables III-14 and III-15 give mission information related to radiation experiments.

**Table III-14. Radiation levels on the Shuttle, Spacelab and experiment-specific hardware.**

<b>Spacelab Designation</b>	<b>STS Mission</b>	<b>Launch Year</b>	<b>Duration (days)</b>	<b>Location Evaluated</b>	<b>Radiation Type</b>	<b>Principal Investigator</b>
SL-1	STS-9	1983	10+	Spacelab Access tunnel Pallet	Overall dose and HZE	Shopper, E.
Spacelab D-1	61-A	1985	7+	Biorack	HZE and Ionizing	Buecker, H.
IML-1	STS-42	1992	8+	Biorack	HZE	Reitz, G.
Spacelab D-2	STS-55	1993	9+	Spacelab Access tunnel Pallet	Overall dose and HZE	Shopper, E.
IML-2	STS-65	1994	14+	Biorack Shuttle middeck Spacelab	Ionizing and HZE	Reitz, G.
Spacelab Mir	STS-71	1995	9+	Spacelab and Mir	Overall dose	Badhwar, G.

Information from SL-1 showed that overall dose measurement in millirads (mrad) and observed HZE particles vary as a function of spacecraft location and inclination and it is important to consider that the South Atlantic Anomaly is directional (protons are primary contributors) while galactic heavy ion flux is omnidirectional. The South Atlantic Anomaly is an area of enhanced radiation caused by the offset and tilt of the geomagnetic axis with respect to the earth's rotation axis, which brings part of the radiation belt well into the Earth's atmosphere, below 500 km in altitude. On SL-1, inside the Spacelab module, the overall absorbed dose varied from 102 to 143 mrad and 190 mrad on the pallet. The HZE particles on SL-1 varied from 42 to 167 tracks per square centimeter.

**Table III-15. Effects of radiation on living organisms.**

<b>Spacelab Designation</b>	<b>STS Mission</b>	<b>Launch Year</b>	<b>Duration (days)</b>	<b>Species Studied</b>	<b>Principal Investigator</b>
SL-1	STS-9	1983	10+	<i>Bacillus subtilis</i>	Horneck, G.
				Mixed species	Reitz, H. D.
				<i>Arabidopsis thaliana</i>	Kranz, A. R.
D-1	61-A	1985	7+	<i>Carausius morosus</i>	Buecker, H. J.
IML-1	STS-42	1992	8+	<i>Carausius morosus</i>	Buecker, H. J.
				X-rayed yeast	
				Yeast mutants	Ross, H.D.
				Nematode	Nelson, G. A.
SL-J	STS-47	1992	7+	Corn seeds	Nagaoka, S.
				Soybean seeds	
				<i>Artemia salina</i> eggs	
				<i>B. subtilis</i> and plasmids	
				<i>Drosophila melanogaster</i>	Ikenaga, M.
D-2	STS-55	1993	9+	<i>Bacillus subtilis</i>	Horneck, G.
				<i>Deinococcus</i> strains	
				<i>E. coli</i> plasmid pBR 322	
IML-2	STS-65	1994	14+	<i>E. coli</i> strains	Horneck, G.
				Skin fibroblasts (primary)	
SL-Mir	STS-71	1995	9+	Humans	Yang, T.

Components of the Biorack facility were evaluated for radiation on IML-1. Eight track-detector stacks placed inside Biorack Type I containers were used for measurements. Two of the stacks were placed in the 37°C incubator, four in the 36°C incubator and two on the 1g centrifuge. Plastic track detectors gave a measure of the flux of heavy charged particles. Nuclear disintegration stars were determined in nuclear emulsions. Results showed that thermal neutron flux was at least 0.7 neutrons per square centimeter per second. The conclusion from the IML-1 experiment was that the radiation exposure on astronauts during the mission was higher than the mean annual public exposure, but well below the limits defined for space flight. The mean annual public exposure is noted by the National Council on Radiation Protection for someone in North America as 360 mrem (a rem is the amount of ionizing radiation required to produce the same biological effect as one rad of high-penetration x-rays). Similar tests were done on IML-2 to evaluate locations inside Biorack, the Shuttle middeck and Spacelab. IML-2 had an inclination of 28.5 degrees and an altitude of 296 km, where IML-1 had an inclination of 57 degrees and flew at 302 km altitude. Measured radiation was mainly due to protons of the South Atlantic Anomaly of the radiation belt. Thermal neutron flux accounted for some radiation. A dose rate of about 3.4 micro Gy/day in tissue was calculated as an estimate (1 Gy is the equivalent of 100 rad). Heavy ion flux in different positions within Biorack varied between 0.5/cm and 0.2/cm. Comparison of results from IML-1 and IML-2 showed a higher heavy ion flux variation for the different locations in IML-2 (a factor of more than six compared to a factor of two in IML-1). Thus the conclusion was that the only way to obtain confident information about radiation intensity and type is to measure radiation on each mission in the vicinity of the experiment of interest. Assumptions made that the Biorack facility components shield biological experiments may not be totally valid.

A similar measurement of the same general areas of Biorack on D-1 provided additional information that experimental conditions for biological experiments in space must consider that dosimetric data may not be sufficient for proper assessment of test data. At the cellular level, hits are not evenly distributed and thus averaging of radiation doses in the general area may not provide accurate information for the experiment. Information from D-2 indicated that the highest measurements were obtained in the Spacelab tunnel, the Spacelab end cone, and an experiment rack near the end cone.

### *1. Effects of radiation on living organisms.*

Results from a large variety of test organisms in different developmental stages placed in different locations on the Shuttle have provided a database on radiation effects. On Spacelab-1 a sandwich-like combination of thin foils made up of different types of tissue-equivalent nuclear track detectors of varying sensitivity were used to detect radiation due to HZE particles. The foils were interspersed with layers of biological test organisms to allow analysis of tracks of the HZE particles and relate this to the effect on individual organisms in the foils. Results from SL-1 agreed with previous results from the Apollo and Apollo-Soyuz missions. Even single HZE particles can induce dramatic effects in individual cells. From these experiments, it became evident that modeling radiation damage markedly underestimated the real effects and actual damage to cells and organisms.

On SL-1 and D-2, experiments were conducted to evaluate the effects of vacuum and solar ultraviolet radiation, separately and in combination, on prokaryotes. While sunlight provides the energy that is the basis for life on Earth, ultraviolet (UV) radiation has adverse effects on living organisms. Part of the UV is completely absorbed by the Earth's atmosphere but some of the UV (280 to 315 nm) reaches the surface. The amount of this damaging UV that reaches Earth's surface depends on many factors, the most important of which is the stratospheric ozone layer. An objective of the experiments on SL-1 and D-2 was to study the effects of full spectrum of extraterrestrial UV radiation, alone or in combination with space vacuum, on a prokaryote. Spores of *Bacillus subtilis* strains were exposed to the full ultraviolet spectrum (>170 nm) including selected ranges of wavelengths of 220, 240, 260, and 280 nm. For vacuum exposure, the organisms were placed either in hermetically sealed or unsealed containers vented to the outside. Containers were placed on the pallet of SL-1. Results from SL-1 showed that vacuum exposure for ten days reduced viability to about 50 % of the samples at 1 atmosphere (atm). In the ground-based test, vacuum only slightly reduced viability of the spores. Additionally, in space a ten-fold higher frequency of histidine prototropic mutations occurred. For spores subjected to radiation and vacuum, there was a nine times higher sensitivity than that which resulted in spores radiated but maintained at 1 atm. Repair-deficient strains of *B. subtilis* showed higher UV sensitivity than the wild type strain and the sensitivities of flown strains were greater than those of ground strains.

On D-2, three hundred and eight biological samples were exposed to UV, vacuum, or a combination of both. As shown on SL-1, reduced survival of *B. subtilis* was more evident in samples exposed to both vacuum and UV-radiation. Survival was affected by the repair capacity of the strains investigated and injury of the spore DNA (deoxyribonucleic acid) in the form of DNA strand breaks was assumed to be the mechanism of damage. Simulated ground-based data on ozone depletion showed a strong increase in biological effect with decreasing ozone concentration.

Seeds of *Arabidopsis thaliana* were flown on SL-1 to evaluate the outcome of heavy ion particle radiation (HZE) on germination, growth and development. Seed embryos were evaluated in which HZE-tracks were found running through or near the root or shoot meristem, the growth tissue at the tip of the roots and shoots. Sixty-three percent of the embryos hit or grazed by one cosmic HZE-particle inside the root meristem showed lethal damage and 18.1% had abnormal root growth. Embryos in which shoot meristem was hit or grazed by a single HZE showed 90% lethality and abnormal growth occurred in 10% of the survivors. This experiment provided very significant confirmation that a lesion caused by only one cosmic heavy ion is capable of affecting the initial process of gravitropic response in plant roots.

Eggs of the stick insect, *Carausius morosus*, have different sensitivities when exposed to cosmic radiation at different developmental stages. Experiments flown on Spacelab D-1 and IML-1 show that effects of HZE particles combined with microgravity are synergistic. The early stages of development were highly sensitive to single hits of cosmic ray particles as well as to microgravity. The rate of anomalies was about 10% for all groups of flown samples, compared to less than 1.2% for ground controls. There was a significant decrease in hatching rate for eggs and a very high proportion of malformations in the group of eggs hit by an HZE particle in microgravity. Deformations were found in abdominal segments, antennae and the extremities. A delay in growth was attributed to cosmic radiation from hits by HZE particles.

The nematode *Caenorhabditis elegans*, evaluated by Nelson on IML-1, showed normal gross anatomy, symmetry and gametogenesis in microgravity. No defective karyotypes or cell distributions were seen and pairing, disjoining, and recombination of chromosomes were comparable to ground. There were, however, a variety of mutants isolated in the *unc-22* gene and in essential genes balanced by the *eT1* translocation. These mutants, when isolated from regions where HZE particles were identified, were more severe than those from random screening. Large chromosome deletions were found among the *unc-22* mutants. The rate of mutagenesis in flown worms was significantly higher than in ground controls.

Nagaoka *et al* in an experiment on SL-J evaluated the effect of cosmic HZE radiation that can easily penetrate the outer wall of the Shuttle to reach the inside, and secondary radiation generated from effects of HZE interacting with the Shuttle and payloads. Species evaluated included corn and soybean seeds, bacteria and brine shrimp. The soybean seeds were more sensitive than the corn seeds. *Artemia salina* (brine shrimp) eggs exposed to radiation showed that pyknosis, a contraction of the nucleus indicating cell death, was significantly higher in the cells of juveniles in microgravity than in ground controls, and *B. subtilis* plasmid measurements showed damages to plasmid DNA or to host genes with about a 20% difference between flight and ground. *Drosophila melanogaster* flown on SL-J were evaluated for HZE damage. Results showed that the X chromosomes in flown flies had twice the frequency of lethal genes compared to ground controls. In the radiation sensitive strain, the mutation frequency was significantly higher than ground controls while the wild type strain showed no significant differences between flight and ground groups.

## 2. DNA repair in microgravity.

Organisms in these experiments were subjected to radiation pre-flight to test repair abilities in microgravity. An experiment on IML-2 used *Escherichia coli*, a human primary fibroblast line, and PQ37 cells (a strain of *E. coli*) to test the hypothesis that increased radiation sensitivity of biological systems in microgravity is caused by the effect of microgravity on cellular repair processes. Results showed that this is not the case. Indeed, no significant differences were found between flight and ground in the rejoining kinetics of radiation

induced double-strand break of DNA in *E. coli*, and in microgravity the intact DNA increased with increased time in space. In human skin fibroblasts, the rejoining kinetics were almost identical in microgravity, the 1g in-flight centrifuge control, and in the ground controls. The *E. coli* strain PQ37 also repaired its DNA under all gravity conditions. The conclusions were that prokaryotes and human fibroblast cells are able to repair DNA lesions in microgravity as efficiently as on the ground and gravity is not required in the repair process. These results were corroborated by another experiment on IML-2 using *Bacillus subtilis*. The objective was to test the influence of microgravity on the cellular repair process by evaluating the survival of spores of *B. subtilis* in microgravity after UV radiation pre-flight on the ground. The irradiated spores were germinated in static microgravity and in the 1g in-flight centrifuge as well as in ground controls. Results again proved that DNA repair can be initiated and function normally in microgravity.

While the results of experiments with various bacteria showed that the DNA repair process is as efficient in microgravity as in 1g, an experiment with yeast flown on IML-1 provides some evidence that repair in this organism may be delayed under mission conditions. Yeast cells irradiated with X-rays before launch were capable of repairing some of the damage, but the repair rate was reduced in microgravity. Whether conditions of space flight or microgravity *per se* influenced the repair of double strand breaks in yeast flown on this mission is not clear from this experiment.

## II. BIOMEDICAL RESEARCH AND COUNTERMEASURES

### A. Animal Physiology

Animal physiology studies flew on eight of the Spacelab missions. Animal physiology experiment specific areas included bone, muscle, cardiovascular, neurophysiology, renal physiology and endocrinology, immunology, metabolism and nutrition, and chronobiology. The rat was the most studied species, but physiology experiments involving mouse, fish and avian species are also included in this section. There were more than one hundred individual animal physiology experiments flown. Descriptions are given below for each of the experiment specific categories.

#### 1. Bone.

Fourteen experiments to investigate effect of microgravity on bone and cartilage formation, mineralization, endocrinology, and metabolism were flown on five of the Spacelab missions. The primary animal species used for these investigations was *Rattus norvegicus* (rat). Table III-16 gives an overview of the missions and experiments on bone in animal models.

**Table III-16. Animal Physiology - Bone.**

Spacelab Designation	STS Mission	Launch Year	Duration (days)	Investigation	Principal Investigator
Spacelab 3	STS-51B	1985	7+	Mineralization of matrix	Duke, P. J.
				Kidney function, calcium excretion	Mangelsdorf, D.
				Bone loss	Doty, S. B.
				Histomorphometric changes	Wronski, T.
				Bone metabolism	Patterson-Buckendahl, P.
				Bone maturation	Russell, J.
				Bone cell turnover	Roberts, W.
SLS-1	STS-40	1991	9+	Bone minerals	Rosenberg, G.
				Calcium metabolism	Kaplansky, A. S.
				Bone regeneration	Oganov, V. S.
IML-1	STS-42	1992	8+	Biomechanics	Bakulin, A. V.
				Chondrogenesis	Duke, P. J.
SLS-2	STS-58	1993	14+	Histomorphometric changes	Alexander, C.
				Bone minerals	Oganov, V. S.
				Metabolism	Shigematsu, T.
				Bone, calcium & space flight	Morey-Holton E.
				Bone cell turnover and recovery	Zerath, E.
LMS	STS-78	1996	16+	Histomorphometric study	Durnova, G. N.
				Corticosteroids in bone loss	Wronski, T. J.

Skeletal loss in the long bones, primarily weight-bearing bones, is well documented, yet the mechanisms are not clear. Earlier experiments on the Cosmos unmanned orbiting spacecraft showed that production and mineralization of bone matrix was retarded, with fewer collagen fibers, and collagen was less mature in flown versus ground controls. The effect of microgravity on cartilage development and bone formation can result in marked skeletal changes including decrease in bone volume and altered biochemical properties. Loss of bone mass remains one of the most important biomedical concerns to long-duration human habitation of microgravity environments.

An experiment on SL-3 by Duke showed that even during a short space flight, less matrix is formed and there is less mineralization in rat bones. The primary defect was at the level of initial matrix production. Compared to ground controls, flown animals had very low sodium (Na) and potassium (K) values, magnesium (Mg) levels were unaffected, and sulfur (S) levels were less than half of control values. Calcium (Ca) values were less in both mineralized and non-mineralized areas of the bone samples. As a follow up to investigate the production of collagen by bone, primary mouse bone cells in culture were flown on IML-1. This experiment addressed chondrogenesis in skeletal development. Endochondrial ossification involves collagen synthesis as well as other factors. Using cells from hind and forelimbs of mouse embryos, Duke found no significant differences in cellular nodule appearance between flight and ground samples. Flight cultures formed aggregates of cells with abnormally smooth surfaces and these showed unusual ruffled structures. Indications of chondrogenesis were evident in flight cells yet mineralized matrix did not form. Conclusions were that although chondrocytes could function, proliferation of rough endoplasmic reticulum and production of matrix did not occur in flown cells.

To investigate the activity of bone forming cells, Doty evaluated osteoblasts from the tibias of adult rats flown on SL-3. He found no significant differences in alkaline and acid phosphatase, Golgi activity, secretory granule size, and lysosomal activity between flight and ground controls. However flown samples had smaller cytoplasmic volume, indicating possible differences in the processing of protein, possibly including procollagen, in microgravity. This could result in reduced formation of new bone. Leading to understanding of osteoporosis in space, Oganov *et al* on SLS-1 showed that bone regenerative potentials decreased, thus stimulating the process of osteoporosis. Based on results of previous flight experiments that showed a reduction in trabecular bone caused by the inhibition of new bone formation and increased resorption, Durnova *et al* investigated the effect of microgravity on spongy bone on SLS-2 (trabecular bone is the small needle-like, flat projections of bone or scaffolding between the red and yellow bone marrow that constitute the inner part of bones). In the proximal metaphysis of the tibia of rats, no changes were found in the growth plate of spongiosa in flown rats compared to ground controls. However, evaluations of rats sacrificed five hours after landing show significant decrease in spongiosa due to reduction in trabeculae. Flight rats sacrificed fifteen days post-flight had primary spongiosa volumes 23% higher and secondary spongiosa volumes 22% lower than control rats. Increased space between trabeculae resulted from decreased trabeculae. Visual examination of the tibia from animals sacrificed in flight and at five hours after landing showed larger numbers of osteoclasts and thus high resorptive capability. In agreement with other reports, the conclusion was that space flight causes changes that are characteristic of the early stages of osteopenia.

Evaluations by weighing humeral bone from rats flown on SLS-2 by Zerath *et al* indicated that normal growth was unaffected by space flight. However, flown animals exhibited inhibition of bone formation in humeral proximal metaphysis and thoracic vertebrae, and a decrease in bone volume in humeral metaphy-

sis. Samples at fourteen days after flight showed that osteoblastic and osteoid surfaces had returned to normal and bone volume in the humeri was normal. The static bone formation was not restored in thoracic vertebrae. The caudal vertebrae did not show differences in osteoblast cell growth for cells isolated and cultured in vitro. Thus humeri, thoracic, and caudal vertebrae showed different patterns of response and recovery. This is an important finding and confirms the fact that gravitational loading (or unloading) of bones leads to differences in bone turnover rate in different bones.

A comprehensive experiment flown by Morey-Holton *et al* on SLS-1 evaluated growth, metabolism, gut and renal involvement in calcium loss during space flight, and recovery of bone-related parameters post-flight. The rats remained in good condition during the mission as evidenced by normal weight gain. Post-flight changes compared to ground controls included:

- 1) decrease in food consumption for about three days,
- 2) increase in urine volume,
- 3) no change in urinary matrix/mineral parameters,
- 4) no change in ionic calcium or blood pH on landing day or fourteen days after landing,
- 5) no difference in bone length, density, mineral/matrix or biomechanics and
- 6) bones grew normally throughout the experiment.

No gross change in endosteal osteoblast histochemistry was found. The control showed increased alkaline phosphatase and a decrease in tartrate-resistant acid phosphatase (bone differentiation enzymes) activity at fourteen days, while these enzymes in flown rats did not change. The mineralization of bone at the periosteal surface of the tibia-fibula junction decreased about 15% in flown rats during flight and did not return to normal until fourteen days after landing. The humerus was not affected by space flight. Conclusions from this research were that re-adaptation of rapidly growing rats in 1g after flight requires at least a week. Space flight changes in bone mineralization are related to bone site and age of the animal. Young rats appear to be extremely sensitive to gravitational loading while age-related bone loss may be influenced by a decreased sensitivity to gravitational loading.

Metabolic studies of Kaplansky on SLS-1 evaluated bones, blood plasma, and endocrine factors that participate in bone metabolism regulation. Limb bones and lumbar vertebrae were evaluated. Results showed a decrease in secondary spongiosa and increase in bone resorption surface in proximal metaphyses of tibiae. These are signs of developing osteoporosis. These changes correlated with biochemical data showing decreased alkaline phosphatase activity and increased activity of tartrate-resistant acid phosphatase (a bone resorption enzyme). There were decreases in bone calcium, phosphorus, sodium and chloride, and depressed function of thyroid C-cells producing calcitonin, necessary for normal mineralization of bone matrix. Mineral metabolism changes confirmed previous findings that calcium is higher and phosphorus is lower in blood of flown animals. Somatotrophic activity was depressed in the pituitary, leading to decreased synthesis and secretion of growth hormone.

Another experiment evaluating mechanisms of bone loss during space flight was flown on SL-3 by Mangelsdorf *et al*. The kidneys function in regulating calcium retention by a mechanism that involves 1,25-dihydroxyvitamin D3 ( $1,25-(OH)_2D_3$ ). Kidneys from five flight and five ground controls were evaluated post-flight and evaluated for 1,25-dihydroxyvitamin D3 receptors. There was no demonstrable difference in qualitative or quantitative evaluation between  $1,25-(OH)_2D_3$  receptors in the kidneys of flown and ground control rats. These data suggest that these receptors do not play a vital role in regulating renal calcium excretion during space flight. Instead, kidneys appear to be functioning normally by excreting calcium in

response to the artificially induced state of hypercalciuria (higher than normal calcium in the blood). The hypercalciuria occurs because of demineralization of bone, and thus regulation of calcium loss is related to bone processes, not kidney function.

## 2. Muscle.

Fourteen experiments investigating muscle physiology in rats were flown on three Spacelab missions. Topics of these experiments are presented in the table (Table III-17) below. The soleus, a primary weight-bearing muscle sometimes referred to as the antigravity muscle, was the subject of several investigations. As was predicted, the soleus showed the most dramatic changes in response to microgravity. Flexor muscles, such as the tibialis anterior, and extensor muscles (extensor digitorum longus) were not significantly affected by gravitational unloading in microgravity.

**Table III-17. Animal Physiology - Muscle.**

<b>Spacelab Designation</b>	<b>STS Mission</b>	<b>Launch Year</b>	<b>Duration (days)</b>	<b>Investigation</b>	<b>Principal Investigator</b>
Spacelab 3	STS-51B	1985	7+	Rat soleus	Edgerton, V.R.
				Muscle protein and glucogen	Henriksen, E.J.
				Biochemistry and morphology	Riley, D.
				Biochemical properties	Tischler, M.
SLS-1	STS-40	1991	9+	Biochemical properties	Steffen, J.
				Contractile properties	Oganov, V. S.
				Protease activity	Riley, D. A.
				Myosin Isoenzymes	Hoh, J. F.Y.
				Biochemical and metabolic props.	Baldwin, K. M.
SLS-2	STS-58	1993	14+	Biochemical and metabolic props.	Baldwin, K. M
				Morphology	Ilyina-Kakeuva, E.
				Muscle fiber proteins	Kato, K
				Morphology of muscle fibers	Marini, J. F.
				Muscle fiber function	Mounier, Y.
				Beta-adrenoceptors in muscle	Ohira, Y.
				Microscopy and protease activity	Riley, D.A
				Histochemical & biochemical	Yoshioka, T.
				Muscle metabolism	Stein, T.

General significant findings included:

1. Muscle atrophy occurs in microgravity but interstitial edema and sarcomere lesions appear to be related to postflight activity (Riley, SLS-2).
2. Space flight induced significant fiber shrinkage, or atrophy, and increased expression of fast muscle characteristics (fast myosin) in slow fibers. In addition, muscle damage, resulting from muscle atrophy in microgravity, that occurred postflight included thrombosis of microcirculation, interstitial and cellular edema, muscle fiber fragmentation, sarcomere disruptions, activation of phagocytic cells, and elevated ubiquitin conjugation suggesting protein breakdown. Accelerated aging-like involution of neuromuscular junctions was found in caged rats, and thus was not just a characteristic of space flight. The abductor longus muscle appeared more susceptible to damage, probably due to resumption of activity after flight. (Riley, SLS-1).
3. To define the size and metabolic responses to space flight and to determine the specificity of these responses to muscle and energy-related enzyme activity of ATPase, rat muscles were evaluated for a number of characteristics after the Spacelab-3 mission. Results showed wet weight of flight muscles significantly reduced (36% loss in soleus and 15% loss in extensor digitorum longus). The greatest relative fiber atrophy occurred in muscles with highest proportion of light ATPase fibers. An increase in the proportion of fast oxidative glycolytic fibers in some muscles at the probable expense of slow oxidative fibers was also seen. (Edgerton, V. R., SL-3)
4. The slow-twitch fibers of skeletal muscle work against gravity and it was postulated that slow-twitch antigravity muscles would be reduced after space flight. Microgravity affects muscle fiber type and muscle isomyosin composition. Soleus muscles in flown rats showed marked increase in the proportion of fibers expressing fast type II isomyosin. In microgravity, muscle fibers changed from slow to fast but the change was not as dramatic as the tail-suspension model in 1g. Slow fibers atrophied faster than fast fibers. The hypothesis that some slow fibers convert to fast was shown by this experiment. (Hoh, J.F.Y., SLS-1).
5. Since microgravity has been shown to cause changes in the slow-twitch fibers of the soleus muscle, and the density of beta-adrenoceptors (beta-AR) in the rat soleus decrease in flown rats, metabolic adaptation was tested in the rat plantar is muscle. Results showed that beta-AR was significantly reduced, due to a change in the number of receptors, after flight and did not return to normal levels at nine days post-flight. Succinct dehydrogenase activity was reduced by 24%. This returned to normal nine days after landing. The significant conclusion was that the changes in metabolic enzymes were associated with decrease in inner membrane enzymes in the mitochondria (Ohira, Y., SLS-2).
6. Investigation of contractile properties of skeletal muscles in rats after a nine-day flight showed that the greatest changes occurred in weight-bearing soleus muscles. The changes included a decrease in the diameter of fibers, in isometric tension, and in contraction velocity. These results confirm that muscle function in flight is reduced, resulting in the greatest change in the weight-bearing muscles after return to earth. (Oganov, V. S., SLS-1).
7. Even short duration space flight causes significant changes in contractile properties of the antigravity (slow-twitch) skeletal muscles. Myosin heavy chain phenotype and muscle mass mediate these changes. (Baldwin, K.M., SLS-2)
8. Tail-suspension rats showed higher glucogen concentration in the soleus as did flown rats (see Table III-16). Recovery from tail suspension was accompanied by decreased tyrosine whereas flown rats showed a higher level of tyrosine, indicating negative protein balance and less recovery (Henriksen, E.J., SL-3).

Significant information on responses of specific muscle types and muscle metabolism and atrophy in rats returned after flight compared to hind limb suspension models and ground controls was gained from experiments flown on SL-3. The muscles of the leg, including the soleus, vastus intermedius, and plantaris, are weight-supporting muscles. These showed significant changes under conditions of gravitational unloading, whereas the muscles that primarily have a flexor activity, such as the tibialis anterior, showed fewer effects. Changes that were detected in flown rats after the seven day Spacelab 3 mission included muscle weight loss, changes in contraction speed, flight-related atrophy, reduced growth, and a dramatic increase in glycogen indicating significant alteration in energy metabolism. This information as well as relevant information from SLS-2 is summarized for the individual muscle types and shown in Table III-18 below.

**Table III-18. Some effects of space flight on specific muscles.**

Muscle Studied		Effect of Space flight	PI (Mission)
SO	Soleus	36% wet weight loss	Edgerton (SL-3)
		Significant decrease in mass	Baldwin (SLS-2)
		Speed-related contraction 25% faster	Baldwin (SLS-2)
		Flight-related atrophy	Henriksen (SL-3)
		Dramatic increase in glycogen	Henriksen (SL-3)
		Tyrosine levels greater than control	Henriksen (SL-3)
PL	Plantaris	Significant decrease in mass	Baldwin (SLS-2)
		Reduced growth	Henriksen (SL-3)
GN	Gastrocnemius	Reduced growth	Henriksen (SL-3)
EDL	Extensor digitorum longus	15% wet weight loss	Edgerton (SL-3)
		Reduced growth	Henriksen (SL-3)
TA	Tibialis anterior (flexor)	No decrease in mass	Baldwin (SLS-2)
		No reduced growth	Henriksen (SL-3)
VI	Vastus intermedius	Significant decrease in mass	Baldwin (SLS-2)

### 3. Cardiovascular physiology and hematology.

The following table (Table III-19) shows the mission information for cardiovascular and hematology experiments conducted on the Spacelab missions.

Human adaptation to microgravity results in loss of red blood cell (RBC) mass, reduction in plasma volume and decrease in total blood volume. Induced-induced anemia is the subject of a number of investigations to discover the potential mechanisms. Use of rats as a model to investigate space adaptation responses on the Spacelab missions proved an excellent means to investigate space anemia. The first of four experiments to investigate erythropoiesis and space anemia was flown on SL-3 by Lange *et al.* This experiment demonstrated a significant increase in hematocrits (ratio of packed cells to whole blood volume), RBC counts, hemoglobins and neutrophils (the increased cell counts could be due to artificially increased concentrations because the plasma volume was reduced in space flight as a result of fluids shifts and loss in microgravity). On SL-3, Lange also found a significant reduction in the percentage of lymphocytes, confirming earlier reports that lymphocytes are affected by space flight. Bone marrow, spleen and erythropoietin (EPO), the hormone that stimulates RBC precursors in the bone marrow to development into mature RBCs, showed no significant

**Table III-19. Animal Physiology - Cardiovascular physiology and hematology.**

<b>Spacelab Designation</b>	<b>STS Mission</b>	<b>Launch Year</b>	<b>Duration (days)</b>	<b>Investigation</b>	<b>Principal Investigator</b>
Spacelab 3	STS-51B	1985	7+	Space flight anemia	Lange, R. D.
				Cardiac structure & AMP metabolism	Philpott, D. E.
SLS-1	STS-40	1991	9+	Erythropoiesis (2 parts)	Lange, R. D.
SLS-2	STS-58	1993	14+	Erythropoiesis	Ichiki, A. T.
				Hematology/renal physiology	Alfrey, C. P.
				Heart muscle adaptation	Mironneau, C.
				Immunohistochemistry	Gabrimon, J.
				Cardiac deconditioning	Farhi, L.

differences between flown and ground animals. Bone marrow cells of flown rats could be induced by EPO to produce erythroid colonies, thus the changes in RBC numbers was apparently not due to faulty cell response to EPO stimulation. Alfrey *et al* also found on SLS-1 that erythropoiesis appeared to be stimulated normally in microgravity. On SLS-2, Ichiki *et al* found serum EPO levels to be the same in rats bled in flight and in ground controls, but after landing the EPO levels were significantly higher for flown rats.

Lange *et al* on SLS-1 and colleagues Ichiki *et al* on SLS-2 further investigated space flight anemia and effects of microgravity on hematopoietic cells. On SLS-1 the experiment was designed to study regulatory parameters that modulate RBC survival. Results showed a significant decrease in the number of EPO-responsive erythroid progenitor cells. This would seem to be in contrast to the SL-3 and SLS-1 results. It should be considered that differences in age of animals tested or the types of cells tested (peripheral blood versus bone marrow precursor cells) may give different results. A consistent finding in all experiments was the reduction in lymphocytes in peripheral blood. There was also a decrease in monocytes and eosinophils and an increase in the number of neutrophils.

An experiment conducted on SLS-2 investigated the cardiovascular system's adaptation to microgravity. In humans, characteristic adaptation to upper body fluid shifts in space include increased heart rate, blood pressure and total peripheral vascular resistance, and decreased venous pressure. Upon return to Earth, re-adaptation causes a severe increase in heart rate, and low blood pressure. Results of the study with heart tissue removed from rats after flight on SLS-2 showed that the contractile strength of the heart muscle was decreased. There was also a reduction in specific affinity to alpha 1 adrenoreceptors, indicating that reduction in contractile strength is due to a decrease in sensitivity rather than a decrease in number of the adrenoreceptors. An interesting conclusion, in light of the involvement of protein kinase C in lymphocyte activation signal transduction, was the implication that desensitization of adrenoreceptors due to microgravity may be dependent on increased protein kinase C activity, a potentially interesting area for future research and mechanism studies. On SL-3, Philpott *et al* investigated cardiac deconditioning at the level of ultrastructure and cyclic AMP. He found changes in ultrastructure and biochemistry in heart tissue of flown rats. Changes included accumulation of lipid droplets, changes in glycogen deposits and changes in microtubules. Biochemically, changes in adenylate cyclase and low KM phosphodiesterase did not differ from ground controls, however; a decrease in high KM phosphodiesterase was found in flown heart tissue. Protein kinase activity decreased, adrenergic responses were affected, and intracellular signal processing of the receptor interactions was modified. Metabolic processes were also altered in microgravity.

#### 4. Endocrinology.

Experiments to determine the effects of microgravity on hormone and regulatory peptide synthesis and release have shown that space flight has significant effects on animal physiology. Most (twelve) of the animal physiology experiments in this area were flown on the Spacelab-3 mission. One flew on SLS-1 and five endocrinology-related experiments were flown on SLS-2 for a total of eighteen endocrinology-related experiments on the three Spacelab missions. Table II-20 provides information on Spacelab missions with endocrinology-related experiments.

**Table III-20. Animal Physiology - Endocrinology.**

<b>Spacelab Designation</b>	<b>STS Mission</b>	<b>Launch Year</b>	<b>Duration (days)</b>	<b>Investigation</b>	<b>Principal Investigator</b>
Spacelab 3	STS-51B	1985	7+	Atriopeptin (AP-3) in plasma	Inge, W.H.
				Renin secretion	Hartle, D.K.
				Pituitary function	Hymer, W. C.
				Liver enzymes	Merrill, A.H.
SLS-1	STS-40	1991	9+	Salivary gland biochemistry	Mednieks, M.I.
				Growth hormone releasing factor	Grindeland, R.E.
				ANF regulation	Gerzer, R.
				ANF-sensitive guanylyl cyclase	Gharib, C.
SLS-2	STS-58	1993	14+	ANP binding sites	Gharib, C.
				Calcium loss/fluids balance	Natochin, Y.V.
				Hypothalamus/GABA activity	Krasnov, I.B.
				Catecholamines	Gabrion, J.
				Brain/natriuretic peptide	Gabrion, J.
				Stress hormones	Kaplansky, A.S.
				Pro-ANP and ANP	Gabrion, J.
				Thyroid function	Loginov, V.I.
				Pituitary somatotrophs	Alekseyev, E.I.

Fluid shifts to the upper body during space flight, an effect that is related to changes in fluid regulating hormones. Atrial natriuretic factor (ANF) is one of the hormones that regulates fluids shifts. ANF is secreted in response to increased pressure in the cardiac atria from increased shift of fluids to the upper body. ANF activates membrane-bound guanylyl cyclase coupled receptors (GC-A receptors). A second type of guanylyl cyclase coupled receptor is an apparent target for a natriuretic peptide in the brain. A third receptor appears to be coupled to adenylyl cyclase. In addition to ANF, other hormones, including vasopressin and catecholamines, regulate response to fluids shifts, and renin influences blood pressure. Atriopeptin (AP-3) is released when right atrial stretch receptors are stimulated (possibly by fluid shifts in microgravity). The atriopeptins cause natriuresis and diuresis by direct action on the kidney as well as inhibition of aldosterone

and vasopressin secretion and dilation of large vessels, resulting in further central pooling of blood.

The following table (Table III-21) provides some of the significant findings on effects of hormone synthesis and function in animals during space flight on Spacelab missions.

**Table III-21. Animal Physiology - Endocrinology experiment results.**

Mission	Principal Investigator	Species/tissue	Results - microgravity versus ground
SL-3	Inge	Rat/heart	<p><i>Objective:</i> to evaluate atriopeptin (AP-3) location in plasma of spaceflown rats.</p> <p><i>Results:</i> Demonstrated profound effect of use of halothane anesthesia. This caused 400% increase in level of AP-3 in plasma. The right and left atria had higher levels of AP-3 than control rats but the difference was not statistically different. These rats were subjected to landing stresses and this experiment demonstrated the need for obtaining samples in-flight.</p>
	Mednieks	Rat/salivary gland	<p><i>Objective:</i> to evaluate effect of space flight on biochemical changes in salivary gland. Salivary gland biochemistry and morphology can provide information on hormonal and environmental response, specific reactions of the oral cavity, and exocrine gland function. Catecholamines cause altered cell morphology and changes in cyclic AMP-dependent protein kinase (cA-PK) activity and cell location.</p> <p><i>Results:</i> Enogenous protein phosphorylation increased in parotid and sublingual glands. cA-PK activity showed no significant difference in flown animals however, there was an increase in labeling of regulatory subunits in the parotid cell particulate fractions from flown animals. Cyclic AMP appears to be involved as a mediator of cA-PK association and subcellular subunit distribution.</p>
	Hartle	Rat/ plasma	<p><i>Objective:</i> to detect alteration in renin secretion in space-flown rats. Renin secretion is regulated by cardiovascular, hormonal and neural mechanisms. Renin-angiotensin-aldosterone system affects blood pressure by promoting positive sodium balance and enhancing vasoconstrictor tone. Atriopeptin III augments shifts and promotes diuresis and natriuresis.</p> <p><i>Results:</i> No significant differences were found in plasma renin concentration between flight and control animals. Halothane anesthesia did not cause a significant increase in plasma renin.</p>
	Hymers	Rat/pituitary glands	<p><i>Objective:</i> to evaluate release of growth hormone (GH) from pituitary glands in spaceflown rats. Preliminary results from earlier flight indicated that release of GH from cells may be impaired in microgravity.</p> <p><i>Results:</i> Pituitary glands of flown rats contained two to three times more intracellular hormone than controls but released significantly less. Conclusions were that since balance between somatostatin and GH releasing hormone regulate hormone secretion, microgravity may alter this relationship to lower release rates. Previous results that release of GH will be confirmed.</p>
	Loginov	Rat/thyroid glands	<p><i>Objective:</i> to evaluate thyroid changes in microgravity.</p> <p><i>Results:</i> Histological examination showed decrease in the size and number of type 3C-cells. There was evidence for reduced biosynthesis and secretory activity in microgravity.</p>

**Table III-21. Animal Physiology - Endocrinology experiment results cont'd.**

Mission	Principal Investigator	Species/tissue	Results - microgravity versus ground
SL-3	Merrill	Rat/liver	<p><i>Objective:</i> to investigate activities of liver enzymes. Lipid metabolism is a major function of the liver and previous results of space flight showed changes in enzymes of lipid metabolism.</p> <p><i>Results:</i> Serine palmitoyltransferase (SPT) activity was significantly lower in flown rats. Glycerol 3-phosphate acyltransferase (GPAT) activity was not significantly different. Microsomal protein of flight rats was 33% lower than controls and there was no difference in sphingomyelin (SM) content. Conclusions were that this may reflect major effects due to long-chain based synthesis in glycolipids or SM changes. The changes in hepatic SM metabolism in flight suggests changes in cellular membranes in microgravity.</p>
SLS-1	Gerzer	Rat/liver	<p><i>Objective:</i> to study effect of weightlessness on response of ANF-sensitive guanylyl cyclase system.</p> <p><i>Results:</i> the activity of ANF-sensitive guanylyl cyclase was unaltered in tissues from animals exposed to microgravity. Conclusions, it is probable that the cellular response to circulating ANF is unaltered during space flight.</p>
		Rat/liver	<p><i>Objective:</i> to determine possible alteration of ANF regulation in weightlessness.</p> <p><i>Results:</i> ANF-sensitive guanylyl cyclase activity was unaltered indicating no apparent altered receptor subtype distribution during exposure to weightlessness.</p>
	Gharib	Rat/brain	<p><i>Objective:</i> to evaluate effect of space flight on neurological basis of endocrine regulating cells factors.</p> <p><i>Results:</i> Brain stem nonadrenergic cells were tested. Vasopressin was decreased in the hypothalamus and increased in the posterior pituitary. Norepinephrine changes indicated stress reaction associated with landing (again pointing out the need to obtain tissues in-flight). Results suggested that ANF may be involved in fluid electrolyte imbalances in the brain in-flight.</p>
		Rat/brain	<p><i>Objectives:</i> to determine the affinity and number of atrial natriuretic peptide (ANP) binding sites in choroid plexus and meninges of rats flown on SLS-1.</p> <p><i>Results:</i> The number of ANP binding sites was significantly increased without significant changes in binding affinity in the third and lateral ventricles. At different sites in brain and in meninges ANP binding sites were unchanged. Binding affinity was significantly reduced in the meninges but not in choroid plexus. General conclusions, ANP is presumed to reduce cerebrospinal fluid (CSF), the number of binding sites in cerebral ventricles would lead to reduction in CSF production in microgravity while lowered affinity of ANP binding sites in meninges could relate to outflow of CSF into subarachnoid spaces in the brain. Vasopressin was significantly increased in the posterior pituitary and decreased in the hypothalamus due to stress on landing.</p>

**Table III-21. Animal Physiology - Endocrinology experiment results cont'd.**

Mission	Principal Investigator	Species/tissue	Results - microgravity versus ground
SLS-1	Natochin	Rat/multiple	<p><i>Objective:</i> to accumulate new data on calcium loss occurs during space flight.</p> <p><i>Results:</i> Water and sodium content of skin and a decrease in water, sodium, and potassium content in the heart were observed. There were no changes in these parameters in other tissues. The changes probably represent adaptation to microgravity. Fluid-electrolyte homeostasis in animal tissues returned to normal after return to 1g.</p>
	Krasnov	Rat/brain	<p><i>Objective:</i> to assess space flight effects on gamma-aminobutyric acid (GABA) and other enzymes in the hypothalamus.</p> <p><i>Results:</i> Post-flight, glutaminase activity was decreased by 22.7% in the arcuate nucleus and 30.4% in the medial eminence of the hypothalamus. This suggests possible role of glutamate in regulation of growth hormone secretion.</p>
SLS-2	Alekseyev	Rat/pituitary	<p><i>Objective:</i> to study histological and cytokaryometric changes in somatotroph cells in glands flown rats. Previous flights showed progressive minimization of endocrine regulatory function and inhibition of growth hormone (GH) production and secretion.</p> <p><i>Results:</i> Pituitary glands in rats sacrificed after 5 hours in flight had greater GH concentration than controls. Conclusions were that space flight diminishes functional activity of somatotroph cells. Back in 1g, rats recovered and this activity returned to normal.</p>

#### 5. Metabolism and nutrition.

Nine experiments were flown on three Spacelab missions, SL-3, SLS-1 and SLS-2, to investigate the digestive and metabolic changes that occur during and after space flight. Previous experiments with animals have shown that space flight significantly affects metabolism. Table III-22 provides information on the experiments involving the metabolism and nutrition of rats flown on the Spacelab missions.

**Table III-22. Animal Physiology - Metabolism and nutrition.**

Spacelab Designation	STS Mission	Launch Year	Duration (days)	Investigation	Principal Investigator
Spacelab 3	STS-51B	1985	7+	Hepatic enzyme adaptation	Hargrove, J.L.L.
SLS-1	STS-40	1991	9+	Exocrine function, pancreas	Smirnov, K.V.
				Gastric hypersecretory syndrome	Smirnov, K.V.
				Digestive transport function	Smirnov, K.V.
				Microbial/epithelial tissue	Szylit, O
				Metabolic potential/microflora	Szylit, O.
SLS-2	STS-58	1993	14+	Lipid peroxidation	Popova, I.A
				Digestive physiology	Szylit, O
				Energy and structure/liver	Ivanova, S.M.

The Spacelab mission experiments advanced understanding of the qualitative and quantitative changes in lipid metabolism, the interactions between the function of endogenous intestinal microflora and digestive function, and digestive enzyme activity and function during and after space flight. Metabolic breakdown of nutrients, medications, and many hormones occurs in the liver and numerous hepatic enzymes regulate catabolic function. Adaptation to space flight includes biochemical changes in the liver to accommodate energy requirements, including glycolysis and lipid peroxidation. Hargrove and Jones (SLS-3) found a 20-fold higher glycogen content in flown rats post-flight compared to ground controls. In addition, glucose levels and enzymes of the citric acid cycle were decreased, and glycolysis and ATP synthesis were increased (Ivanova *et al*, SLS-2). Experiments of Popover *et al* on SLS-1 showed that space flight did not significantly affect the antioxidant protection component in liver and other tissues, but after return to 1g, readaptation caused in changes in antioxidant protection. Endemic intestinal microflora provide enzymes that interact synergistically with the host to facilitate digestion in the small intestine. A very important finding was that lipid metabolism was greatly altered by space flight. Lipase activity was significantly decreased (Smirnov *et al*, SLS-1) and short chain fatty acid concentration was significantly increased (Szyliet *et al*, SLS-1 and SLS-2) indicating a different energy-providing metabolism in microgravity. Popova *et al* (SLS-2) concluded that changes in basic metabolism in erythrocytes and lymphocytes were due to structure and function of their membranes because lipid and phospholipid composition of the membranes was changed. This can be extremely significant to the understanding of mechanisms responsible for blunted lymphocyte response to antigen stimulation during space flight. The following table (Table III-23) further describes each of the metabolism and nutrition experiments and lists most significant results for each.

**Table III-23. Animal Physiology - Metabolism and nutrition experiment results.**

Mission	Principal Investigator	Species/tissue	Results microgravity versus ground
SL-3	Hargrove	Rat/liver	<i>Objective:</i> to determine whether hepatic enzyme concentrations change during space flight. <i>Results:</i> Twenty-fold higher glycogen content in liver of animals post-flight than ground controls. Microsomal protein, cytochrome P-450 was reduced in flown animal tissue.. Glutathione S-transferase, tyrosine aminotransferase, and cytochrome b5 were not statistically different from ground values.
SLS-1	Smirnov	Rat/pancreas	<i>Objective:</i> to investigate biochemistry of exocrine compartments of the pancreas. <i>Results:</i> Complex changes in digestive enzymes occurred. At 9 days post-flight, amylolytic activity of the pancreas was still elevated and lipase activity was significantly decreased. Pancreatic insufficiency during space flight requires further study.
		Rat/stomach	<i>Objective:</i> to investigate mucous membrane of stomach of rats after space flight. <i>Results:</i> Increased peptic potential , more marked on day 9 post flight. Hypersecretory gastric syndrome was evident in flown animals. This is characterized by high activity of gastric pepsinogen-production cells and increased gastric level of hydrochloric acid. In flown animals this was correlated with increased level of gastrin, the principal physiologic activator of gastric epithelial cells.

**Table III-23. Animal Physiology - Metabolism and nutrition experiment results cont'd.**

Mission	Principal Investigator	Species/tissue	Results - microgravity versus ground.
SLS-1	Smirnov	Rat/duodenum jejunum, and ileum sections of small intestine	<i>Objective:</i> to investigate morphological and biochemical changes in mucous membrane of small intestine after space flight. <i>Results:</i> Complex changes in enzyme activities. In protein membrane hydrolysis there was a shift of proximodistal gradient dipeptidase activity indicating a compensatory activity. Lipid digestion had a number of alterations in digestive pattern and showed a significant decrease of non-glyceridelipase activity and an increase in alkaline phosphatase activity in small intestine. No significant changes were found in carbohydrate enzymatic. The membranes and activities of the small intestine seem to be very adaptive in space and in return to 1g post-flight.
	Szylit	Rat/ intestinal microflora	<i>Objective:</i> to assess bacterial and endogenous metabolic potentials of intestine. <i>Results:</i> Slight decrease in pH and significantly enhanced total short chain fatty acid concentration. All of this was normal by 9 days post-flight. Microbial glycolytic activities were not modified by space flight. Mucous containing cells were increased for some mucin types. Microsomal glutathione-S-transferase was three-fold enhances in flight rats.
		Rat/intestinal microflora	<i>Objective:</i> to investigate fermentation and bacterial glycolytic activities in cecal compartment of rats. <i>Results:</i> Space flight resulted in a significant increase of total short chain fatty acid concentration. Histochemical evaluations showed an increase in the mucin -containing cells. Xenobiotic metabolizing enzymes showed some changes, all were normal by 9 days post-flight. Conclusions were that space flight alters digestive physiology and the detoxification processes and thus affect general metabolism.
	Popova	Rat/lipid peroxidation	<i>Objectives:</i> to study effect of microgravity and space flight on lipid metabolism. <i>Results:</i> Space flight factors did not significantly affect antioxidant protection and intensity of lipid peroxidation.
SLS-2	Szylit	Rat/intestinal microflora	<i>Objectives:</i> to investigate intestinal microflora interactions and intestinal function. <i>Results:</i> Slight decrease in pH, significant enhancement of total short chain fatty acids. The microbial glycolytic activities of Beta-glucosidase Beta-galactosidase, and acetylgalactosaminidase were not altered. There was an increase in number of mucin containing cells and the specific activity of glutathione-S-transferase in flown cells was 3 times higher than ground controls.

**Table III-23. Animal Physiology - Metabolism and nutrition experiment results cont'd.**

Mission	Principal Investigator	Species/tissue	Results microgravity versus ground
SLS-2	Ivanova	Rat/liver	<p><i>Objective:</i> to measure enzyme activities in plasma and subcellular fractions in liver.</p> <p><i>Results:</i> Glucose and isocitric dehydrogenase levels were decreased, glycolysis and ATP synthesis were increased. Immediately after recovery, hypoglycemia disappeared and hyperglycemia was noted. Other changes in metabolic enzymes were found but all returned to normal values by two weeks after landing. Changes in basic metabolic parameters in Erythrocytes and lymphocytes were presumably caused by changes in the structure (lipid and phospholipid composition) and function of their membranes. This is a very significant finding and provides insight into membrane mechanisms causing nil growth of T lymphocytes in microgravity.</p>

## 6. Immunology

Five experiments were flown on three Spacelab missions, SL-3, SLS-1 and SLS-2, to investigate immune response of rats exposed to spaceflight as shown in the table (Table III-24) below.

**Table III-24. Animal Physiology - Immunology.**

Spacelab Designation	STS Mission	Launch Year	Duration (days)	Investigation	Principal Investigator
Spacelab 3	STS-51B	1985	7+	Interferon-gamma production	Gould, C.L.
				Cytokine production	Gould, C.L.
				Otoconial morphology	Konstantinova, I.
SLS-1	STS-40	1991	9+	Activity of immune cells	Konstantinova, I.
SLS-2	STS-58	1993	14+	Immunity mediators	Konstantinova, I.
				Immune function	Konstantinova, I.
				Antiviral immunity	Konstantinova, I.

Results of previous experiments have demonstrated that immune system alterations occur in animals and humans as a result of spaceflight. These are detected immediately after flight, and after time appear to normalize to pre-flight function. The immune changes predominantly manifest as decreases in proliferation and function of T lymphocytes reflected as changes in the cytotoxic activity of natural killer cells and the production of cytokines.

The objective of an experiment flown on SL-3 by Gould *et al* was to determine if weightlessness alters interferon-gamma (IFN-gamma) production by spleen cells of flown rats. Spleens were removed post-flight and cells were suspended in growth medium in the presence of concanavalin A to induce proliferation and interferon-gamma production. The spleens of flown rats were substantially reduced in weight compared to controls and, possibly because of this, the production of IFN-gamma was reduced. Seven of the ten ground controls produced IFN-gamma while only one of the ten flown rat's cells produced detectable IFN-gamma.

Gould suggests that a reduction in T lymphocyte number or function, or stress *per se*, could have caused the lack of IFN-gamma production by the spleen cells of flown rats.

In experiments flown on SLS-1 and SLS-2 to evaluate the production of cytokines in flown rats, Konstantinova *et al* found that T lymphocyte activity in rats during spaceflight was significantly decreased compared to ground controls. The cells from rats dissected immediately after landing did not grow, in contrast to the increased growth of cells from rats dissected fourteen days post-flight. Activity of spleen natural killer cells was reduced during and after flight and returned to normal after fourteen days at 1g. No significant changes in bone marrow natural killer cell activity were found between flight and controls. Production of interleukin 1 and 2 and tumor necrosis factors alpha and beta in spleen cell cultures of flown rats was reduced. At landing, IFN-alpha and gamma were diminished. In summary, cell-mediated immunity in rats was significantly suppressed during spaceflight. Konstantinova concluded that the time course of recovery of immune function after flight suggests that the changes may truly indicate a response of the immune system to spaceflight that could increase over time.

## 7. Neurophysiology.

Twenty-seven experiments were flown on six Spacelab missions, SL-3, SLS-1, SL-J, SLS-2, IML-2, and Neurolab, to investigate the effects of spaceflight on the brain and nervous system, and the general neurophysiology of animals. Table III-25 provides information on experiment types and mission.

Physiological systems are generally regulated by the nervous system and many of these systems have been shown to be affected by spaceflight. Temperature regulation, fluid volume and water intake, calcium metabolism and neuromuscular control of movement are all altered in the microgravity environment. Viewed as adaptations to microgravity, these functions are mediated by changes in brain neurotransmitter interactions. Spacelab experiments were designed to evaluate enzymes involved in neurotransmitter and energy metabolism, neuron morphology, brain ultrastructure, and mammalian gravity receptors. The vestibular gravity receptors (maculas) in mammals are functionally specialized structures in the inner ear. There are two components in the sensory system that report the position of the head with respect to gravity and also sense linear acceleration but not rotational movement. Type I macular sensory hair cells are part of a highly channeled, direct circuit, and type II macular hair cells sense, as well as distribute and modify, the information coming in from the sensory system. The following table (Table III-26) presents significant information gained from the Spacelab experiments on neurophysiology and adaptation of the rat neurotransmitter system in response to time in microgravity.

**Table III-25. Animal Physiology - Neurophysiology.**

<b>Spacelab Designation</b>	<b>STS Mission</b>	<b>Launch Year</b>	<b>Duration (days)</b>	<b>Investigation</b>	<b>Principal Investigator</b>
Spacelab 3	STS-51B	1985	7+	Neurotransmitter receptors CNS, functional metabolism Otoconial morphology	Miller, J.D. Murakami, D. M. Ross, M.
SLS-1	STS-40	1991	9+	Cytochemistry of neurons Brain morph.& histochemistry Spinal cord & dorsal root ganglion Ultrastructure, brain cortex Neuron morphology Neuron morphology Mammalian gravity receptors	Gershtein, L.M. Krasnov, I.B. Krasnov, I.B. Dyachkova, L.N. Leontovich, T.A. Leontovich, T.A. Ross, M.D.
SL-J	STS-47	1992	7+	Visuo-vestibular adaptation (fish)	Mori, S.
SLS-2	STS-58	1993	14+	Nonadrenergic response Brain morphology Brain Ultrastructure Proprioceptive cerebellum Mammalian gravity receptors	Gharib, C. Krasnov, B. Krasnov, B. Krasnov, B. Ross, M.D.
IML-2	STS-65	1994	14+	Vestibular adaptation	Takabayashi, A.
Neurolab	STS-90	1998	15+	Otolith Neurology Neuro-muscular interaction Vestibulo-Ocular Reflex Development of Vestibular Circuits Neuromuscular Development Central nervous system Vestibular Adaptation Neural Coding Gene Expression in the Brain Neural Plasticity	Highstein, S.M. Baldwin, K.M. Cohen, B. Raymond, J. Riley, D.A. Fuller, C.A. Holstein, G.R. McNaughton, B.L. Pompeiano, O. Ross, M.D.

**Table III-26. Animal Physiology - Neurophysiology experiment results.**

Mission	PI	Species/tissue	Results and Comments
SL-3	Miller	Rat/brain	Objectives: to study neurotransmitter receptors in brains of space-flown rats. Results: Only a few receptor changes occurred in microgravity. An increase in a hippocampus receptor may reflect neuromodulation in the specific area via serotonergic neurons.
	Murakami	Rat/hypothalamus	Objective: to examine changes in the pattern of metabolic activity in the brain. Results: The drinking activity of the rats affected the cytochrome oxidase activity and soma size in the paraventricular nucleus (PVN). Rats with normal drinking patterns, showed decreased neuronal metabolism within the PVN relative to controls. Mild dehydration increased neuronal metabolism. Examination of other hypothalamic and motor system nuclei did not show obvious changes in metabolic activity.
	Ross	Rat/maculas	Objectives: to determine whether gravity receptors show degeneration during short and long term exposure to microgravity. Results: Otoconia of both flight and ground samples showed normal configurations with no signs of degeneration in any of the flight samples. Flight samples did show growth of new otoconia at the surface of existing otoconia, and saccular otoconia were more rounded than in ground controls.
SLS-1	Gershtein	Rat/left hemisphere	Objective: To assess spaceflight effects on neurotransmitter enzymes and energy metabolism in neurons Results: There was a decrease in monoamine oxidase activity in fibrillar structures of the 5th layer of the somatosensory cortex and the head of the caudate nucleus and acetyl cholinesterase in bodies of neurons of the caudate nucleus. Thus, significant adaptational changes in brain chemistry occurred in microgravity.

**Table III-26. Animal Physiology - Neurophysiology experiment results cont'd.**

Mission	PI	Species/tissue	Results and Comments
SLS-1	Krasnov	Rat/spinal cord	Objectives: to evaluate spaceflight on the spinal cord and dorsal root ganglia. Results: No changes were found at landing, or nine days after, in the enzyme activity of the anterior horns of the spinal cord. A lowered cytochromoxidase activity was observed in the motor neurons of the anterior horns of the spinal cord. Motor neuron hypofunction appears to be a result of spaceflight.
	Lowry	Rat/visual cortex, olfactory cortex	Objectives: to assess spaceflight effects on ultrastructure in the brain cortex. Results: Changes in neuronal and glial cells suggested active restructuring post-flight. Changes in visual and olfactory cortexes were found.
	Leontovich	Rat/visual cortex	Objectives: to assess spaceflight effects on dendrite geometry and orientation. Results: Significant increase of body size of pyramidal neurons in flight animals was found. There was an increase in the length of apical dendrites in the upper layers of the visual cortex. The apical system was well developed and associative connections between various cortical compartments was possible. There was indication of restructuring of the dendrite system of the visual cortex neurons in microgravity.
	Leontovich	Rat/medulla oblongata	Objectives: to assess spaceflight effects on orientation of dendrites. Results: There was no significant difference between flight and ground control animals with respect of dendrite geometry of the giant multipolar neurons of regions of the medulla oblongata. There was a significant difference in amount of branching of dendrites between landing and day 9 post-flight. This suggested structural rearrangement of the dendrite tree of neurons that developed during and after flight. This is reflective of adaptation to microgravity.
	Ross	Rat/maculas	Objectives: to determine effects of spaceflight on the otoconia and neuroepithelium in vestibular organs. Results: There were increased numbers of hair cells immediately after landing. Spaceflight appears to return vestibular gravity sensors so that they can function in microgravity. In addition the release of transmitter substance making the hairs more sensitive was suggested.
SL-J	Mori	Fish (carp) cerebellar activity	Objectives: to evaluate mechanisms of sensory conflict theory by use of fish with one otolith removed compared to normal fish. Results: The dorsal light response was used to measure fish response. Fish turn away from the light. Behavior of the normal carp supported the sensory conflict hypothesis for genesis of space motion sickness. This fish showed confused behavior peaking at day 2 and adapting to microgravity by day 4. The recovery indicates that the cerebellum may participate in recovery in microgravity. The otolith-less carp, conditioned for two months before launch to adapt to the loss of an otolith, behaved like the normal carp indicating that sensory compensation other than the vestibule may be confused by weightlessness.

**Table III-26. Animal Physiology - Neurophysiology experiment results cont'd.**

Mission	PI	Species/tissue	Results and Comments
SLS-2	Krasnov	Rat/brain	Objective: to examine somatosensory and visual cortex of spaceflown rats. Results: Electron microscopic examination of somatosensory cortex showed ultrastructural changes in the II through IV layers which suggested that a lower number of signals entered the cortex in microgravity. Microgravity induced changes were reversible but not completely at 14 days after flight.
	Krasnov	Rat/cerebellar vermis	Objectives: to study the anterior vermis, a structure that regulates anti-gravitational muscles, to gain understanding of adaptation of antigravity muscles in microgravity. Results: Higher cytochrome oxidase activity was found. This indicated dorsal central lobe function during flight.
	Gharib	Rat/brainstem	Objectives: to measure norepinephrine (NE) content in brainstem sympathetic cells to gain information on blood pressure regulation. Results: No significant changes in NE content were found in brainstem or kidney and heart in spaceflown animals compared to ground.
	Ross	Rat/maculas	Objectives: to investigate structural changes within the inner ear in response to microgravity, determine the effects of microgravity on vestibular organs, and determine vestibular response to 1g readaptation. Results: Preliminary results confirm early flight test results of the maintenance of neural plasticity of mammalian gravity receptors during flight.
IML-2	Takabayashi	Goldfish ( <i>Carassius auratus</i> )	Objectives: Investigate the adaptation of fish to microgravity and readaptation to 1 g. Results: Unusual swimming behavior and posture was seen in flight fish, and the visual system did not provide cues to stabilize posture. Fish with different vestibular functions on the ground behaved differently in microgravity.
Neurolab	Highstein	Toadfish ( <i>Opsanus tau</i> )	Objectives: to record responses of primary afferents of the otolithic origins and document efferent action on them in normal and microgravity. Results: Within the first day postflight, the magnitude of response to an applied translation was on average three times greater than for controls. The reduced gravitational acceleration in orbit apparently resulted in an up regulation of the sensitivity of utricular afferents. By 30 h postflight, responses were statistically similar to control. The time course of return to normal afferent sensitivity parallels the reported decrease in vestibular disorientation in astronauts following return from space.

**Table III-26. Animal Physiology - Neurophysiology experiment results cont'd.**

Mission	PI	Species/tissue	Results and Comments
Neurolab	Baldwin	Rat/muscle	<p>Objectives: to determine the interactive role of gravity, innervation, and thyroid hormone in myosin development.</p> <p>Results: Body weights, and muscle weights, in flight animals were significantly lower than ground, a result not due to lack of nutrition. Flight samples showed blunted MHC gene expression in the developing soleus muscle, creating a profile seen normally in fast muscles; this effect was completely countered in thyroid deficient animals. In contrast, the thyroid deficient animals had their plantaris muscle maintained in an undifferentiated state in both flight and ground.</p> <p>Important finding: Both somatic and muscle specific factors linking the thyroid growth hormone-insulin like growth factor-1 (IGF-1) is pivotal to the normal development of skeletal muscle. The interaction of gravity and thyroid hormone in particular determines the contractile phenotype in developing muscle.</p>
	Raymond	Rat and mouse/brain tissue	<p>Objectives: to determine if microgravity causes structural, biochemical or molecular changes to neurovestibular tissues.</p> <p>Results: The maturation of the vestibular efferent system was similar in microgravity and on the ground. Thus, maturation of the efferent system between the study times was not sensitive to a change in gravitational environment. These results suggest that periods of microgravity at earlier stages are required to identify critical periods in peripheral vestibular system development.</p>
	Riley	Rat/muscle neurons	<p>Objectives: to define the effects of microgravity on the development of the neuromuscular system and to determine if these effects persist after reexposure to gravity.</p> <p>Results: Spaceflight resulted in microgravity-unloading and reduced neonate-dam and neonate-neonate interactions. Inflight weight loss was recovered within one month postflight. Soleus fiber growth was stunted, with a suggestion of a persistent deficit in soleus myoblast function. Differentiation of muscle fibers was retarded, while enhanced towards fast type. Spaceflight temporarily increased soleus susceptibility to reloading damage. Elimination of multiple innervation was completed during spaceflight. The pattern of terminal branching of motor nerve endings was less complex, implying delayed maturation. Spaceflight retarded the growth of spinal motor neurons.</p>
	Holstein	Rat/brain tissue	<p>Objectives: to assess differences in cerebellar morphology and amino acid neurotransmission between flight and ground.</p> <p>Results: The morphology of flight rats showed neuronal and synaptic plasticity in the nodulus not seen in ground controls. The differences included structural alterations such as the formation of lamellar bodies and the presence of degeneration, suggesting that excitotoxicity may play some part in short term neural response to spaceflight. Comparison of the changes to non-vestibular tissue indicates that the findings may be specific to otolith-recipient cerebellar zones.</p>

**Table III-26. Animal Physiology - Neurophysiology experiment results cont'd.**

Mission	PI	Species/tissue	Results and Comments
Neurolab	McNaughton	Rat	<p>Objectives: to study how the neural orientation system performs and adapts to low gravity.</p> <p>Results: Information caused a rejection of the working hypothesis about the effects of 3-dimensional navigation in microgravity on the spatial selectivity of hippocampal place cells. Nonetheless, the cells were dramatically affected by these conditions in a fashion that was more complicated than predicted. In addition, some of the changes seen demonstrate clearly the ability of the cognitive mapping system to adapt to new conditions and create stable representations of the environment over time.</p>
	Pompeiano	Rat/ brain	<p>Objectives: to visualize brain changes in the expression of the immediate early genes (IEGs).</p> <p>Results: With respect to control rats, the number of labeled cells increased in flight animals in the medial and spinal vestibular nuclei (but not in the lateral vestibular nucleus) at FD2 (launch g force from 1 to 3 g, then reaching 0 g), decreased at FD14 (adaptation to 0g), greatly increased at R + 1 (landing g force at 1.5-1.8 g then 1 g), and returned to baseline levels at R + 13 (readaptation to 1 g). Similar changes in IEG expression were also observed in the nucleus of the solitary tract, the area postrema and the central nucleus of the amygdala. In particular, in these vegetative areas the number of Fos-positive cells decreased in flight rats with respect to controls at FD14, but significantly increased at R + 1. Thus, altered gravitational fields produced molecular changes in vestibular nuclei controlling somatic functions, as well as in related medullary and basal forebrain structures regulating vegetative functions.</p>
	Ross	Rat/ macula	<p>Objectives: to determine if otoconial mass increases during long-term flight, determine the molecular substrate of synaptic plasticity, and whether the period of macular readaptation to 1 g is affected by the length of exposure to microgravity.</p> <p>Results: The most important finding of this research is that the results with synapses indicate that great changes in mean number are already evident in both kinds of hair cells by day 2 of flight. The ~75% increment in ribbons in type I cells on day 2 fell by day 14 in flight, so that the difference between FD14 in flight and the basal control was insignificant. In the case of type II hair cells, the ~98% increment by day 2 in flight had fallen to an ~44% increment by day 14, which was insignificant compared to the basal control. (The change was on the verge of significance at <math>p &lt; 0.0534</math>). The findings in both type I and type II cells indicate that a further adjustment in synaptic mean took place as the gravity sensors (and the rats) became fully adapted to the space environment.</p> <p>The findings thus far suggest different functions in gravity sensing for the two maculae, even though both are sensors of gravitoinertial forces. The utricular macula exhibits the greater synaptic plasticity in a weightless environment. The Neurolab findings suggest that there are different combinations of type I and type II hair cells comprising receptive fields in the two macular sensors.</p>

## 8. Miscellaneous.

This section includes experiments that did not fit other categories but provided significant information relevant to animal physiology changes in responses to spaceflight. The following table (Table III-27) provides information on experiment type and mission.

**Table III-27. Animal Physiology - Miscellaneous.**

Spacelab Designation	STS Mission	Launch Year	Duration (days)	Investigation	Principal Investigator
Spacelab 3	STS-51B	1985	7+	Biological rhythms	Fuller, C.A.
				Spermatogonia	Philpott, D.E.
				Microbial flora	Kraft, L.M.
				Squirrel monkey, response	Fuller, C.A.
				Qualification of animal facility	Callahan, P.X.
				Capabilities of the animal facility	Fast, T. N.
SLS-1	STS-40	1991	9+	Lung tissue	West, J.B.
SLS-2	STS-58	1993	14+	Kidney homeostasis	Serova, L.V.
IML-2	STS-65	1994	14+	Fish mating behavior	Ijiri, K.

An experiment flown on SL-3 by Fuller *et al* dealt with circadian timing in rats and showed that normal expression of the circadian timing system is significantly modified in microgravity. Temperature fluctuation became delayed in flight. Normal phase period pre-flight was  $23.9 \pm 0.2$  hours. In-flight the temperature rhythm was  $24.4 \pm 0.3$  hours. Heart rate phase rhythm was stable in flight and ground tests with a mean period of  $23.9 \pm 0.2$  hours. The heart rate *per se* was depressed in microgravity probably due to reduced load on the cardiovascular system.

In another experiment on SL-3, Philpott *et al* studied the effects of spaceflight on spermatogonia. Twelve hours after landing, testes were removed from rats flown on SL-3. The average weight loss of testes in flown rats was 7.1% compared to controls. A count of spermatogonial cells showed a significant decrease of 7.5% in cell population number. Radiation was not considered to be sufficient to cause the reduction in cell count. Possible explanations for reduced cell number are stress from adapting to weightlessness, transportation, or other conditions of spaceflight.

The behavior of non-human primates can be useful in verifying or predicting human responses. Squirrel monkeys flown on SL-3 (Fuller) were evaluated for possible symptoms of space adaptation syndrome (SAS). Criteria for response were feeding behavior and general behavior. A reduction in feeding behavior was noted in both of the monkeys with return to normal feeding by day four. One flight monkey showed a series of behaviors similar to flight crewmembers affected by space adaptation syndrome. This included lethargy and reticence to move around in the cage. The monkey maintained sleep posture and showed little resistance to being moved. Whether this behavior mimics SAS in humans is difficult to say. It is clear, however, that monkeys undergo an adaptation to microgravity similar to other animals and humans.

## B. Human Physiology

The Spacelab missions contributed significantly to the understanding of human physiological adaptation to the space environment and re-adaptation to 1g post-flight. Experiments addressed the areas of bone, muscle, cardiovascular and pulmonary physiology, hematology, kidney function, endocrinology, immunology, neuro-physiology, and circadian rhythm. A total of more than one hundred and twenty human physiology experiments were conducted on fourteen of the Spacelab missions. Significant findings in each of the experiment specific categories are presented in this section.

### 1. Bone.

Human bone physiology experiments were conducted on seven of the Spacelab missions. The experiments addressed bone metabolism, calcium flux and mineral loss, and the hormones related to the maintenance of bone. Objectives were to advance understanding and provide information on causes of bone loss and possible countermeasures to prevent this loss during spaceflight. Spacelab missions including bone-related experiments are shown in the table (Table III-28) below.

**Table III-28. Human Physiology - Bone.**

<b>Spacelab Designation</b>	<b>STS Mission</b>	<b>Launch Year</b>	<b>Duration (days)</b>	<b>Investigation</b>	<b>Principal Investigator</b>
SL-2	STS-51F	1985	7+	Bone metabolism	Schnoes, H.K.
Spacelab D-1	STS-61A	1985	7+	Plasma osteocalcin	Vermeer, C.
SLS-1	STS-40	1991	9+	Mineral loss	Arnaud, C.D.
SL-J	STS-47	1992	7+	Bone metabolism	LeBlanc, A.
SLS-2	STS-58	1993	14+	Mineral loss	Arnaud, C.D.
SL-M	STS-71	1995	9+	Calcium metabolism	Lane, H.
LMS	STS-78	1996	16+	Bone response	Cann, C.E.
				Bone metabolism	LeBlanc, A.

Bone is a dynamic tissue that is continuously undergoing remodeling by the interactions of osteoblasts to build, and osteoclasts to destroy, bony tissue. Not only does bone function in support, protection, and movement and as a reservoir for the stem cells that differentiate into cells of the immune system and blood, but bone is also a storage tissue for fat and minerals. Calcium is involved in a large number of normal cellular processes and maintenance of nervous system homeostasis, and when the level of calcium is low in the bloodstream it is recruited from bone. Deposit and release of bone calcium and minerals goes on almost continuously. Rapid loss of bone mass occurs under microgravity conditions because of the exit of calcium and other minerals. Loss of bone is one of the most important human health-related concerns and could limit future exploration of space. Due to reduction of the gravity and impact stress of normal walking in Earth gravity environments, bone mass and the levels of hormones that regulate calcium in the body decrease significantly causing calcium resorption from bone into the bloodstream. The disruption of calcium metabolism and balance, while adaptive in microgravity, causes serious imbalances in the body. Bone resorption appears to begin immediately upon reaching microgravity and the increased calcium levels in the bloodstream cause higher excretion of calcium

in urine and decreased absorption by the intestines. Countermeasures are not simple since increased calcium intake in microgravity could cause still more urinary excretion of calcium and increase risk of kidney stones.

Osteocalcin, a non-collagenous protein in bone, is synthesized by osteoblasts and its plasma level can be used as a marker for osteoblast activity and bone metabolism. High levels of osteocalcin in the plasma usually indicate fast growing bone. An experiment on Spacelab D-1 (Vermeer) designed to evaluate osteocalcin in plasma from blood drawn before launch, in-flight and after landing did not show significant differences in osteocalcin levels that could be attributed to flight.

On SLS-1, Arnaud *et al* found that serum ionized calcium increased dramatically on flight day two, to levels 40% above control in all crewmembers tested. This level is considered to be severe hypercalcemia. At day eight, serum ionized calcium levels remained high, 35% above normal, indicating that clinically significant hypercalcemia was maintained throughout the flight. Parathyroid hormone (PTH), released when blood levels of ionized calcium decline, decreased to about 50% of control throughout the flight (PTH causes calcium release from the bone matrix by stimulating osteoclast activity and bone resorption). The finding that PTH was decreased biologically validated the increase in serum-ionized calcium and negated the possibility the PTH caused the hypercalcemia. Serum calcium values were close to that of control values one day after landing and were no different from the control at six days post-flight. Levels of 1,25-dihydroxyvitamin D did not differ from controls on flight day two but declined by 40% by flight day eight.

## 2. Muscle.

Humans were the subjects for a number of Spacelab mission investigations on muscle physiology and adaptation to microgravity. Experiments were flown on eight of the missions as described in Table III-29.

**Table III-29. Human Physiology - Muscle.**

<b>Spacelab Designation</b>	<b>STS Mission</b>	<b>Launch Year</b>	<b>Duration (days)</b>	<b>Investigation</b>	<b>Principal Investigator</b>
SLS-1	STS-40	1991	9+	Protein metabolism	Stein, T. P.
IML-1	STS-42	1992	8+	Musculoskeletal function	Wing, P.C.
SL-J	STS-47	1992	7+	Muscle atrophy	LeBlanc, A.
D-2	STS-55	1993	9+	Nitrogen & protein	Fern. E.B.
SLS-2	STS-58	1993	14+	Protein metabolism	Stein, T.P.
IML-2	STS-65	1994	14+	Musculoskeletal function	Ledsome, J.R.
SL-M	STS-71	1995	9+	Skeletal muscle	Feedback, D.
				Muscle performance	Siconolfi, S.
LMS	STS-78	1996	16+	Contractile properties (2)	Cerretelli, P.
				Musculoskeletal function	Tesch, P.
				Single muscle fibers	Fitts, R.H.
				Muscle atrophy	Edgerton, V.R.
				Skeletal muscle	DiPrampo, P.
				Muscle atrophy	LeBlanc, A.
				Protein metabolism	Stein, T.P.

The muscular system and neural control components of the neuromuscular system are significantly affected by spaceflight. Just after launch, very rapid adaptation to hypergravity, and then to microgravity, of motor control must occur. Humans in space must determine their orientation without normal cues. The degradation in skeletal muscle function after time in space may be, in part, an outcome of altered motor functions or how humans move in microgravity. In addition, impaired musculoskeletal function has been noted in astronauts after spaceflight. Both muscle atrophy and neuromuscular control and contractile force of individual muscle fibers may contribute to a decrease in muscle strength. Data from animals flown on Spacelab-3 and Cosmos 1887 indicated that skeletal muscle atrophy predominantly affects the slow-twitch fibers in muscles of animals. In humans, the responses may be different. Experiments on Shuttle missions have shown a greater atrophy of fast-twitch fibers. Information from the Spacelab mission experiments provides very significant insights into muscle function adaptation during spaceflight and re-adaptation upon return to 1g.

Two experiments investigated muscle protein metabolism as a way to gain understanding of the loss of lean body mass due to muscle wasting of astronauts. Results of Fern *et al*, on D-2, showed a significant increase in the rate of protein oxidation in-flight and at four days postflight, and a significant decrease in the rate of protein synthesis, breakdown or retention in-flight. These parameters had not returned to preflight values at 60 days postflight. On SLS-1, Stein investigated protein metabolism and found that nitrogen balance was decreased during spaceflight. This was greatest on day one when food intake was reduced and again at the end of the mission. On flight day eight, all six subjects showed a protein synthesis rate approximately 30% higher than preflight baselines. These results were considered to be related to stress response during spaceflight.

A number of experiments dealing with muscle function were flown on the Life and Microgravity Spacelab flight. They are listed in Table III-30.

### 3. Cardiovascular function.

Cardiovascular adaptation in microgravity occurs rapidly and is characterized by a shift of as much as 2000 ml of fluid toward the upper body. The experiments on human subjects to evaluate cardiovascular response in microgravity were generally involved with fluids shifts, heart function and orthostatic intolerance upon return to 1g. Investigations were conducted on ten Spacelab missions and involved more than twenty-six experiments with multiple sub-investigations. The missions involved are shown in the table below (Table III-31).

Given that individual differences exist, in general the description of cardiac adaptation for humans in space is similar to that described by Saekiguchi for the Japanese payload specialist on SL-J. Blood pressure and heart rate increased on day one and returned to normal by the third day. Astronauts generally experience decreased performance, facial edema, over-swelling of the veins, and stiffness in movement early in the mission. While cardiovascular adaptation in microgravity is rapid and effective, the orthostatic intolerance that occurs after spaceflight is associated with significant dysfunction and clinically apparent orthostatic intolerance. Characteristically, some astronauts feel faint and exhibit varying degrees of disability in standing. On D-2, Arbeille and Blomqvist found that maximal cardiac pump performance was maintained in space. In the upright position after flight, stroke volume was reduced by about 25% and heart rate increased 35% with a parallel increase in peripheral resistance. This confirmed SLS-1 data which showed standing heart rate after flight increased from 82 beats per minute preflight to 98 postflight, and the stroke volume was decreased from 52 ml preflight to 42 ml postflight. They concluded that orthostatic intolerance may occur by diverse mechanisms. Results were corroborated

**Table III-30. Life and Microgravity Spacelab muscle experiments.**

PI	Tissue	Results and Comments
Cerretelli	Triceps surae	Objectives: to evaluate the changes induced by space flight in muscle function. Results: No significant impairment to contractive parameters during flight, but significant impairment was seen during the recovery period after landing.
Tesch	Quad- riceps	Objectives: to investigate the potential mechanisms that govern a decrease in muscle function in response to spaceflight. Results: After 12 days of bed rest, maximal voluntary contraction (MVC) decreased by 8% and maximal surface electromyogram (EMG) was reduced by 21%, but MVC and EMG normalized by 12 days ambulation.
Fitts	Calf muscle	Objectives: to study the effects of microgravity on skeletal muscle function and to establish the cellular causes of the reduced functional capacity of skeletal muscle. Results: Spaceflight decreased force and increased shortening velocity of single $\text{Ca}^{2+}$ -activated muscle cells expressing type I MHC. This greatly reduced the impact that impaired force production had on absolute peak power. Thick filament density and spacing in the soleus were unchanged. Preflight thin filament density decreased significantly ( $P < 0.01$ ) as a result of a 17% filament loss and a 9% increase in short filaments. Results also demonstrated that 1) slow and fast gastrocnemius fibers showed little atrophy and loss of P(o) but increased V(o) after a typical 17-day spaceflight, 2) there is, however, considerable intersubject variation in these responses, possibly due to intersubject differences in in-flight physical activity, and 3) in these four astronauts, fiber atrophy and reductions in P(o) were less for slow and fast fibers obtained from the phasic fast-twitch gastrocnemius muscle compared with slow and fast fibers obtained from the slow antigravity soleus
Edgerton	Calf and upper right arm	Objectives: to examine the controls of movement under varying conditions, a human's ability to adapt movement skills to perform successfully under rapidly changing gravitational conditions, the physiological adjustments occurring in these different conditions that may be responsible for alterations in movement precision and limitations in physical performance during postflight and recovery, and the physiological mechanisms that trigger neuromuscular adaptations to spaceflight. Results: Compared with pre- and post-flight values, there was a marked increase in the total EMG activity of the tibialis anterior and the musculus soleus and no change in the medial gastrocnemius (MG) EMG activity in-flight. These data indicate that space flight, as occurs on shuttle missions, is a model of elevated activation of both flexor and extensor muscles, probably reflecting the effects of programmed work schedules in flight rather than a direct effect of microgravity.
LeBlanc	Calf, thigh, and back	Objectives: to measure the volumes of the calf, thigh, and back muscles and whole body lean mass, and to determine the changes in the muscle volumes and soft tissue distribution between landing and landing plus two days, and to determine the calf muscle transverse relaxation time before and after flight. Results: There were no significant changes in the volume of the psoas, anterior calf and gastrocnemius measured immediately after return to Earth (R+0). Significant decreases of 3 to 10% were measured in the volume of soleus, quadriceps, hamstrings and intrinsic back muscles. Fluid distribution findings suggest that reambulation after flight causes swelling of muscles that lasts several weeks and is probably associated with muscle damage and/or repair. There were no significant changes in lean tissue after flight, but there appeared to be loss in total body fat (2.8kg), which paralleled changes in total body weight.

by Baisch *et al* in experiments on D-2 in which stand tests postflight showed increased heart rates, lower stroke volumes and cardiac deconditioning. Conclusions were that lower body fluid pooling appears to be a minor contributor to postflight orthostatic intolerance and that changes in central integration mechanisms brought about by microgravity may play a larger role in orthostatic intolerance.

**Table III-31. Human Physiology - Cardiovascular function.**

<b>Spacelab Designation</b>	<b>STS Mission</b>	<b>Launch Year</b>	<b>Duration (days)</b>	<b>Investigation</b>	<b>Principal Investigator</b>
SL-1	STS-9	1983	10+	Venous pressure	Kirsch, K.L.
				Cardiovascular function	Scano, A.
D-1	STS-61A	1985	7+	Venous pressure	Kirsch, K. L.
				Fluid shift/cardiac performance	Baisch, F.
SLS-1	STS-40	1991	9+	Autonomic cardiovascular control	Eckberg, D.L.
				Cardiovascular deconditioning	Farhi, L.E.
				Cardiovascular adaptation	Blomqvist, C.G.
IML-1	STS-42	1992	8+	Venous pressure	Thirsk, R.B.
SL-J	STS-47	1992	7+	Health monitoring Japanese PS	Saekiguchi, C.
				LBNP countermeasure	Charles, J.B.
D-2	STS-55	1993	9+	Cardiovascular regulation	Arbeille, P.
				Leg fluid distribution	Baisch, F.J.
				Segmental fluid content & perfusion	Baisch, F.J.
				Left ventricular configuration	Beck, L.E.J.
				Tonometry - intraocular pressure	Draeger, J.
				Carotid baroreceptor -cardiac reflex	Eckberg, D.L.
				Gas exchange, ventilation, heart rate	Stegemann, J.
				Tissue thickness (fluid shifts)	Kirsch, K.A.
				Central venous pressure	Foldager, N.
SLS-2	STS-58	1993	14+	Cardiovascular adaptation	Blomqvist, C.G.
				Cardiovascular deconditioning	Farhi, L.E.
IML-2	STS-65	1994	14+	LBNP countermeasure	Charles, J.B.
SL-M	STS-71	1995	9+	Physiological response, descent	Charles, J.
				Orthostatic tolerance, LBNP	Charles, J.
				Aerobic capacity	Mikhaylov, V.
				Metabolic response to exercise	Lane, H.
				Thermoregulation	Fortney, S.
Neurolab	STS-90	1998	15+	Cardiovascular regulation	Blomqvist, C.G.

To understand where fluids pool in the upper body, Kirsch *et al*, in experiments flown on D-2 to evaluate fluid shifts within superficial tissues of the upper and lower parts of the body, found that tissue thickness decreased about 16% around the tibia and increased by 7% in the forehead. They calculated that about 410 ml of fluid leaves lower limbs and about 40 ml accumulates in the superficial tissues of the head. After landing this is reversed. Swelling of the head decreases within three to five days in space but does not disappear until after landing. Draeger *et al* on D-2 measured intraocular pressure to investigate fluids shifts. The intraocular pressure preflight measured about 10 mm Hg whereas immediately after entering microgravity this pressure increased by about 100%. After four to five days on orbit, pressure declined

to preflight values. Twenty minutes after landing, intraocular pressure decreased to about 30% less than preflight values.

Experiments on SL-Mir by Charles *et al* showed that long duration spaceflight effects are similar to short-term exposure. Most autonomic cardiovascular adaptations occur within the first days of spaceflight. On Mir, these changes persisted for at least four months in flight. Conclusions from the SL-Mir experiments were that long-duration spaceflight did not cause higher incidence of orthostatic problems compared to shorter duration Shuttle flights. This should be confirmed with a larger test subject pool in future long duration flight experiences. Heart rate and blood pressure during re-entry showed a, lower than expected, small increase over values seen during normal preflight and intravehicular activities.

#### 4. Hematology and immunology.

Hematology and immunology experiments were flown on four of the Spacelab missions as shown in the following table (Table III-32).

**Table III-32. Human Physiology - Hematology and immunology.**

<b>Spacelab Designation</b>	<b>STS Mission</b>	<b>Launch Year</b>	<b>Duration (days)</b>	<b>Investigation</b>	<b>Principal Investigator</b>
SL-1	STS-9	1983	10+	Erythrokinetics	Leach, C.S.
				Humoral immune response	Voss, E.
SLS-1	STS-40	1991	9+	Erythrokinetics	Alfrey, C.P.
				Blood volume	Alfrey, C.P.
SLS-2	STS-58	1993	14+	Erythrokinetics	Alfrey, C.P.
SL-M	STS-71	1995	9+	Metabolism of RBCs	Lane, H.
				Peripheral mononuclear cells	Sams, C
				Humoral immune function	Konstantinova, I.

Hematology experiments were flown on SL-1, SLS-1, SLS-2 and SL-Mir. A consistent finding after spaceflight has been a significant reduction of red blood cell (RBC) mass. On Spacelab-1, erythropoietin, the hormone that stimulates differentiation of bone marrow stem cells to form into mature RBCs, was decreased on day eight in-flight and at landing. To evaluate erythrokinetics, Alfrey *et al* tested astronauts preflight, in-flight and postflight on SLS-1. Three subjects were studied during flight and each had a significant decrease in RBC mass and plasma volume. Plasma volume decrease occurred on day one of flight. Erythropoietin levels decreased in the first 24 hours and remained low throughout the mission. Clearing of RBCs from circulation was similar before and during flight. The rate of dilution of pre-labeled cells by new RBCs in-flight was significantly decreased compared to preflight values. The rate of production of new RBCs within bone marrow was similar after one day of flight to the rate three months preflight and also the postflight values, but during spaceflight there was a reduction in the number of newly formed red blood cells in circulation indicating a mechanism between development in the bone marrow and release into circulation.

Experiments on SL-Mir again showed a rapid decrease in total blood volume (12%) within twenty-four hours. This decrease in plasma volume caused an apparent increase in hematocrits compared to preflight values. Erythropoietin levels in the serum were also reduced. The release of newly produced RBCs, which

is under the control of erythropoietin, was terminated immediately after entering microgravity. Lane *et al* concluded that down-regulation of RBC production during spaceflight is due to ineffective erythropoiesis resulting from decreased erythropoietin release into the serum. Additional studies on Mir 18 over longer time will be very useful. The adaptation process to microgravity with regard to RBC mass and survival represents a state of anemia which can be used to gain understanding of the mechanisms of erythropoiesis during spaceflight.

Two experiments to evaluate response of the human immune system were conducted on SL-Mir (Sams and Lesnyak, Sams and Konstantinova). Changes in immune response have been consistently found in astronauts and cosmonauts yet the mechanisms are not clearly understood and the impact to health and productivity of flying long-duration missions has not been determined. The immune system involves both cell-mediated response of T-lymphocytes and the production of antibodies (humoral or blood-borne) by B-cells. B-cells are specialized white blood cells that release antibodies into the bloodstream when stimulated by infectious organisms. The T-cells rid the body of cells infected with bacteria, viruses, fungi and parasites. Maintenance of immunity in the body occurs by a very complex cascade of molecular and cellular events involving differentiation of cells and secretion of cytokines (cellular messenger molecules) and production of immunoglobulins. One experiment on SL-Mir was designed to investigate whether antibodies are produced in response to antigen introduced by vaccination and to determine the time course of the response. This experiment is long-term beginning with STS-71 in 1995 and continuing on Shuttle-Mir missions for several years. Initial results for this experiment include:

- Only minor shifts in the levels of isotype specific antibodies between the preflight and in-flight pre-immunization period.
- Limited response by immunized crewmembers as indicated by the increase of antigen-specific antibody titers.
- General immunoglobulin levels did not change significantly during or after flight in any of the crewmembers.

The second experiment series was designed to determine the phenotypic alterations in circulating immune cell subpopulations during spaceflight compared to populations observed immediately after flight and to assess functional changes in the peripheral immune cells. The roles of specific cytokines, including interleukin-1, interleukin-1 receptor antagonist, and interleukins-2, -6, and -10, tumor necrosis factor alpha, granulocyte/macrophage colony stimulating factor, and immunoregulatory factors such as prostaglandin E2, were evaluated to assess spaceflight-induced immune suppression. Results from this experiment include:

- Absolute levels of peripheral granulocytes were significantly elevated following space flight, but the levels of circulating lymphocytes and monocytes were unchanged.
- Analysis demonstrated a decreased percentage of T cells, with percentages of B cells and natural killer (NK) cells unchanged after flight, a significant decrease in the percentage of the CD14+ CD16+ monocytes, and an increased CD4/CD8 T cell ratio.
- Production of interleukin-2 (IL-2) by CD3+, CD4+, and CD8+ T cells was significantly decreased.
- Production of interferon gamma (IFN gamma) by CD8+ T cells was not altered by space flight, but CD4+ T cells decrease IFN-gamma production.
- Serum and urine stress hormone analysis indicated significant physiologic stresses in astronauts following space flight.
- Altered peripheral leukocyte subsets, altered serum and urine stress hormone levels, and altered T cell cytokine secretion profiles were all observed postflight.

- There appeared to be differential susceptibility to space flight regarding cytokine secretion by T cell subsets. These alterations may be the result of either microgravity exposure or the physiologic stresses of landing and readaptation to unit gravity.

### 5. Pulmonary function.

The human lung is very sensitive to gravity; and on Earth there are large differences in gas flow, blood flow and gas exchange between upper and lower portions of the lung. Pulmonary blood flow (perfusion) is greater near the bottom of the lung and becomes smaller toward the top. Gas flow (ventilation) is distributed throughout the lung, though there are still large differences. Generally it is believed that these differences are primarily due to the pull of gravity. Comprehensive studies of pulmonary function on the SLS-1, SLS-2 and D-2 missions showed, however, that much of the imbalance in lung ventilation and perfusion is maintained in microgravity. The following table (Table III-33) shows the Spacelab missions on which pulmonary function experiments were flown.

**Table III-33. Human Physiology - Pulmonary function.**

Spacelab Designation	STS Mission	Launch Year	Duration (days)	Investigation	Principal Investigator
SLS-1	STS-40	1991	9+	Ventilation inhomogeneity Pulmonary function	Paiva, M. West, J.B.
D-2	STS-55	1993	9+	Pulmonary perfusion(2) Ventilation distribution Pulmonary function	Linnarsson, L. Paiva, M Henriksen, O.
SLS-2	STS-58	1993	14+	Pulmonary function Single-breath tests Pulmonary deconditioning	West, J.B. Paiva, M. Farhi, L.
LMS	STS-78	1996	16+	Pulmonary function	West, J.B.
Neurolab	STS-90	1998	15+	Pulmonary function	West, J.B

The respiratory system is highly sensitive to gravity, which causes top to bottom differences in intrapleural pressure, alveolar size, ventilation and perfusion, gas exchange, and determines chest wall configuration. Significant findings from experiments evaluating pulmonary function in microgravity are shown in Table III-34.

**Table III-34. Human Physiology - Pulmonary function experiment results.**

Mission	PI	Objectives and Results
SLS-1	Paiva, M.	<i>Objective:</i> to assess pulmonary ventilation. <i>Results:</i> This was the first study to report inhomogeneity of pulmonary ventilation determined by multiple-breath nitrogen washouts during sustained microgravity. Primary determinants of ventilatory inhomogeneity during tidal breathing in the upright posture are not gravitational in origin.

**Table III-34. Human Physiology - Pulmonary function experiment results cont'd.**

Mission	PI	Objectives and Results
SLS-1	West, J.	<p><i>Objective:</i> to determine how various aspects of pulmonary function are affected by weightlessness.</p> <p><i>Results:</i> Pulmonary capillary blood volume and membrane diffusing capacity both rose significantly in microgravity and suggest that the lung is much more uniformly perfused with blood in microgravity. Lung volume changes showed functional residual capacity reduction but no decrease in vital capacity except early in the flight. Surprising reduction in residual volume probably due to reduction in gravitational deformation of the lung in microgravity. Decrease in resting tidal volume suggests changes in neurological control of breathing.</p>
D-2	Paiva	<p><i>Objective:</i> to analyze chest wall mechanics and continue studies on lung ventilation.</p> <p><i>Results:</i> Confirmed finding of SLS-1 that most of the ventilation inhomogeneity in the lungs does not depend on gravity related factors.</p>
D-2	Linnarsson	<p><i>Objective:</i> to investigate pulmonary perfusion homogeneous distribution in space.</p> <p><i>Results:</i> Data suggest the microgravity does not altogether abolish perfusion inequalities in the lung. Conclusions, factors unrelated to gravity play an important role in determining distribution of pulmonary perfusion.</p>
SLS-2	West, J.B.	<p><i>Objective:</i> to study pulmonary function in microgravity.</p> <p><i>Results:</i> Although total ventilation fell, alveolar ventilation was unchanged in microgravity compared with standing in normal gravity (1 G). There were no significant changes in O<sub>2</sub> uptake, CO<sub>2</sub> output, or end-tidal PO<sub>2</sub> in microgravity compared with standing in 1 G. Residual ventilation-perfusion ratio (VA/Q) inequality was the same in microgravity as in preflight standing, suggesting that during this portion of a prolonged exhalation the inequality in 1 G was not predominantly on a gravitationally induced topographic basis.</p>
	Paiva, M.	<p><i>Objective:</i> to study anomalous behaviors of helium (He) and sulfur hexafluoride (SF<sub>6</sub>) during single breath tests in microgravity</p> <p><i>Results:</i> Ground tests showed a steeper slope for SF<sub>6</sub> than for He, while inflight tests showed SF<sub>6</sub> with a similar or flatter slope than He. This suggests that microgravity causes conformational changes in the acini or changes in the cardiogenic mixing in the lung periphery, altering the position and/or extent of the quasi-stationary concentration front.</p>
	Farhi, L.	<p><i>Objective:</i> to study cardiovascular and pulmonary deconditioning during spaceflight.</p> <p><i>Results:</i> Resting mean arterial blood pressure and diastolic pressure were lower in flight than erect. The increase in cardiac output with oxygen consumption in flight was less than that at 1 G. Resting stroke volume (heart) in flight fell with increasing oxygen consumption, whereas stroke volume erect rose and stroke volume supine remained constant. The blood pressure response to exercise was not different in flight from erect or supine. We conclude that true microgravity causes a cardiovascular response different from that seen during any of its putative simulations.</p>
LMS	West, J.B.	<p><i>Objectives:</i> to study lung function after the stress of heavy exercise in microgravity; to study the effects of microgravity on the musculoskeletal aspects of breathing during rest, heavy exercise, and deep breathing; to measure the body's response to inhaled carbon dioxide; and to study how gas is distributed within the lung.</p> <p><i>Results:</i> Lung volume and pulmonary tissue volume pre and post exercise showed no difference. Microgravity markedly reduces the ventilatory response to hypoxia, but leaves the response to inhaled carbon dioxide unaltered. Cardiac output and stroke volume initially increased on entry into microgravity, then decreased, then increased again after day 12. Moderate exercise appears to have no deleterious effects on the lung in microgravity.</p>

## 6. Kidney function.

Table III-35 shows the Spacelab missions on which kidney function experiments were flown.

**Table III-35. Human Physiology - Kidney function.**

Spacelab Designation	STS Mission	Launch Year	Duration (days)	Investigation	Principal Investigator
SL-3	STS-51B	1985	7+	Fluid regulation	Schneider, H.
SLS-1	STS-40	1991	9+	Fluid-electrolyte regulation	Leach-Huntoon, C.
IML-1	STS-42	1992	8+	Energy expenditure	Parsons, H.G.
SL-J	STS-47	1992	7+	Endocrine changes	Seo, H.
D-2	STS-55	1993	9+	Fluid balance and kidney function	Norsk, P.
				Fluid regulation	Gerzer, R.
				Glucose tolerance	Maass, H.P.
				Endocrine function	Riondino, G.
				Fluid regulation	Roecker, L.
SLS-2	STS-58	1993	14+	Fluid-electrolyte regulation	Leach-Huntoon, C.
SL-Mir	STS-71	1995	9+**	Fluid and electrolyte homeostasis	Lane, H.
				Renal stone risk assessment	Whitson, P.A.
				Pharmacokinetic changes	Putcha, L.

\*\* Launched on STS-71 but continuing on Mir long-term.

Information from humans in space indicates that an increase in central blood volume leads to increased renal output of sodium and fluid and a consequent decrease in extracellular fluid volume. Early in the flights, astronauts loose two to four kg of body mass, mostly due to extracellular fluid volume loss. The objective of experiments flown on SLS-1 and SLS-2 by Leach-Huntoon *et al* was to gain further understanding of adaptive changes that alter fluid, electrolyte, renal and circulatory status of humans in microgravity. Preliminary results indicate that glomerular filtration rate was elevated in-flight especially on flight day eight. Plasma volume was 22% lower than preflight and extracellular fluid volume was 15% below preflight value and was still low at day eight. Fluid intake and urine volume decreased sharply and mean intake remained at least 20% below preflight values throughout the mission. Plasma levels of aldosterone were reduced 60% on day one and 28% on day eight and atrial natriuretic peptide (ANP) was reduced 22% and 60% on days one and eight respectively. Cortisol levels increased during flight. The difference between potassium intake and urinary excretion of potassium was 191% more negative on day one and only 39% more negative on day two compared to preflight. Serum potassium remained at least 20% elevated. Norepinephrine in plasma and urine was reduced by 17% at all sampling times. Urinary epinephrine decreased 80% between days one and two. Most of the changes occurred early in the mission but some were prolonged including hematocrits, serum osmolality and sodium, epinephrine, angiotensin I, and cortisol.

The objective of an experiment flown on D-2 by Norst *et al* was to investigate the endocrine and renal mechanisms of fluid volume control and how humans adapt to microgravity by challenging the system with an intravenous isotonic saline infusion. In ground-based tests, the test parameters were measured on subjects in two body positions, supine and seated. The hormones that affect fluid balance and kidney function include vasopressin, norepinephrine, epinephrine, atrial natriuretic peptide, adrenocorticotrophin, cortisol, aldosterone, and active renin. Results from D-2 showed that renal sodium excretion was doubled

two to three hours after test initiation in microgravity. This compared with the values for seated subjects on the ground but was blunted during the first hour compared with supine positioned test subjects on the ground. Norepinephrine levels were highest at three hours. Levels of aldosterone and renin were similar to those of seated ground subjects. These data indicate that microgravity-adapted renal responses to infusion reflected a condition between ground based seated and supine subjects. The elevated norepinephrine, renin, and aldosterone levels in-flight were not related to renal sodium excretion and urinary output rate.

Although short-term effects of microgravity on fluid and electrolyte homeostasis are known from the experiences of humans flying on the Shuttle, the long-term effects are not yet defined. SL-Mir provides an excellent means to investigate homeostasis regulating factors long-term in microgravity. Lane and Grigoriev investigated the role of the kidneys in regulation of fluid and electrolyte excretion and retention on SL-Mir. Data showed the expected plasma volume decrease averaging 5% during Mir 18. Extracellular fluid was reduced from 19.5 to 15.6 liters. These values are similar to those from a fourteen-day Shuttle mission. Conclusions are that changes in fluid volume that occur early in a flight remain throughout long-term missions. Levels of two hormones important for fluid and electrolyte homeostasis (antidiuretic hormone and ANP) were reduced after 110 days of spaceflight.

Factors predisposing humans to increased risk of renal stones include excretion and negative calcium balance as a result of bone mineral loss, decreased urinary output after the first few days in microgravity, urinary pH changes, magnesium and citrate concentrations and increased urinary phosphate. These changes all can increase urinary supersaturation of stone-forming salts. Seventy percent of the renal stones in humans on Earth are composed of calcium oxalate and the remaining 30% are uric acid, struvite and cystine stones. Studies from Shuttle missions of four to fourteen days on a total of 150 astronauts showed that immediately after flight the urine of most crewmembers is saturated with stone-forming salts, placing them at risk of developing calcium oxalate and uric acid stones. There was also a difference in stone-forming salt concentrations between the short- and long-duration missions. Studies on SL-Mir (Whitson) and continuing long-term on Mir are designed to further investigate the effect of long-term habitation in microgravity on the risk of the development of kidney stones.

## 7. Neurophysiology.

Space motion sickness affects approximately 50% to 75% of Shuttle crewmembers in gradations of severity and presents a problem early in short-duration missions, especially when the workload is heavy. It is important to understand the threshold for the perception of vestibular inputs in order to improve methods for prevention, prediction and treatment of space motion sickness. This section addresses the areas of perception of gravity stimulus, posture, movement and locomotion, vestibular response, and circadian patterns. Neurophysiology experiments were flown on nine Spacelab missions (Table III-36) and more than thirty individual experiments have been conducted.

a. Vestibular responses and space adaptation syndrome. To explore the full range of neuro-vestibular adaptation, a series of experiments were conducted on SLS-1 by Young *et al.* Evaluations were conducted for:

- 1) visually induced roll/visual-vestibular interaction (visually-induced feelings of self-motion are normally inhibited if vestibular signals fail to confirm self motion);

**Table III-36. Human Physiology - Neurophysiology.**

<b>Spacelab Designation</b>	<b>STS Mission</b>	<b>Launch Year</b>	<b>Duration (days)</b>	<b>Investigation</b>	<b>Principal Investigator</b>
SL-1	STS-9	1983	10+	Vestibular reactions and sensations Mass discrimination (short-term) Mass discrimination (prolonged) Eye movements during sleep Vestibular adaptation Reflex mechanisms	von Baumgarten, R. Ross, H.E. Ross, H.E. Quadens, O. Young, L.R. Reschke, M.
SL-3	STS-51B	1985	7+	Autogenic feedback effectiveness	Cowings, P.S.
D-1	STS-61A	1985	7+	European vestibular experiments Vestibular adaptation Inversion illusions & space sickness Mass discrimination Spatial description Arm positioning Tonometry	von Baumgarten, R. Young, L.R. Mittelstaedt, H. Ross, H.E. Friederici, A. Veringa, F. Draeger, J.
SLS-1	STS-40	1991	9+	Vestibular experiments on Spacelab	Young, R.
IML-1	STS-42	1992	8+	Vestibular investigations Space adaptation syndrome	Reschke, M.F. Watt, D.
SL-J	STS-47	1992		Autogenic feedback effectiveness Vestibular investigations	Cowings, P.S. Koga, K.
SL-Mir	STS-71	1995	9+**	Motor control Postural equilibrium Anticipatory postural activity Biomechanics of movement Coordination Autonomic function Gaze control	Tada, A. Paloski, W. Layne, C. Bloomberg, J. Bloomberg, J. Harm, D. Reschke, M.F.
LMS	STS-78	1996	16+	Canal and otolith integration Torso rotation Circadian Rhythms	Reschke, M.F. Douglas, G.D. Monk, T.
Neurolab	STS-90	1998	15+	Neural Cardiovascular Regulation Neural Cardiovascular Control Autonomic Neuroplasticity Autonomic Neurophysiology Sleep and Respiration Spatial Orientation Melatonin as Hypnotic Visuo-Motor Coordination Vestibular investigation Visual-Otolithic Interactions	Baisch, F. Blomqvist, C. Eckberg, D. Robertson, D. West, J.B. Oman, C. Czeisler, C. Bock, O. Berthoz, A. Clement, G.

\*\* Launched on STS-71 but continuing on Mir long-term.

- 2) vestibulo-ocular reflex (the angular vestibulo-ocular reflex was tested using a rotating chair; this reflex is affected by otolith input; in microgravity, the otolith is not stimulated);
- 3) awareness of position (knowledge of limb and body position may be altered in microgravity);
- 4) responses to linear acceleration (the sled was used to test the response of linear acceleration sensors);
- 5) postflight postural instability and muscle fatigue;
- 6) space motion sickness recording.

Crewmembers were trained to log motion sickness symptoms according to a well-being scale. Motion sickness susceptibility was measured using a head movement comparison test.

Results were as follows.

- Use of visual cues was variable and depended on the individual.
- After flight all subjects showed an increase in postural instability and a strong tendency to sway when the visual field rotated.
- No consistent vestibulo-ocular reflex changes were noted on orbit.
- In awareness-of-position tests in-flight, pointing accuracy was very poor. The bias was toward pointing low. Performance was always better with eyes closed only while pointing. In this case results were similar to ground. Recovery to preflight accuracy returned by 7 days postflight. This shows that primary adaptation in microgravity is loss of the external spatial map and complete recovery requires several days after flight.
- Muscle fatigue showed that isometric muscle strength was reduced by 10% to 50% postflight in ankle plantarflexion and unchanged in dorsiflexion. The fatigability did not return to baseline by day 7 postflight.

Data from two experiments flown on D-1 provided significant information on vestibular reactions in microgravity. The experiments of von Baumgarten on D-1 showed the following.

- Non-thermoconvective nystagmus (eye movements) was confirmed.
- The threshold for perception of direction of linear acceleration was not significantly changed.
- A marked decrease in ocular counterrolling gain occurred immediately after reentry but recovered.
- Susceptibility to space motion sickness (SMS) was not predictable based on ground tests.
- After day three, SMS dropped and remained low thereafter.

An experiment flown on D-1 by Mittelstaedt and Glasauer investigated inversion illusions (perceiving oneself and the room to upside down despite being upright relative to a familiar room). This phenomenon is not well understood. In ground-based studies, sixty control individual and five astronauts participated and motion sickness symptoms were noted as levels of discomfort. In-flight results showed the following.

- Postural bias was negatively correlated with discomfort. (Crewmembers became sick without regard to position of the body in the spacecraft).
- Sensations of trunk tilt and respective concomitant reflexes are missing in microgravity when the head is tilted with respect to the trunk.
- Perception of vertical polarity persists in absence of or in contradiction to vertical position indicating existence of force-independent components in determination of vertical position.
- The overall conclusion is that saccular bias toward the Z-axis may be the main determinant in the cue-free inversion illusion process.

One experiment, flown on SL-3 by Cowings *et al* and investigating the effect of autogenic feedback (motion tolerance, autonomic control) as a countermeasure for space motion sickness, found that autogenic feedback was effective for controlling space motion sickness in some but not all crewmembers. Individual autonomic response to spaceflight was different from ground simulation tests.

b. Gravity perception. In microgravity, gravitational cues are effectively absent except for inertial cues which could be perceived by mass. Ross *et al* devised an experiment on SL-1 to investigate mass discrimination by use of weighted balls and cards. Results showed that thresholds for mass discrimination in microgravity were higher, by a factor of about 1.8, than preflight. Discrimination was impaired still at nine days in-flight. These results suggest that humans are less sensitive to inertial mass than to weight and that adaptation can only partially compensate for loss of gravity. Ross also found in mass discrimination tests that weight perception in-flight was almost half that of ground perception. Discrimination remained impaired during the flight and for two or three days after landing. These findings were confirmed and expanded on D-1 to show that normally, on the ground, arm movement is slow during weight judgments while fast movements may interfere with static weight perception. In-flight results were opposite and error percentages were greater.

Friederici studied the relevance of gravity to spatial coordinate assignment and mental representation of space and spatial relations on D-1. In preflight tests errors were less than 10% and mean reaction time was normal. In-flight, both subjects found naming spatial relationships more demanding but spatial relations are adequately described in microgravity and adaptation facilitates this.

c. Locomotion. U.S. and Russian space travelers experience locomotor and postural equilibrium disturbances often after spaceflight. Preliminary findings of Bloomberg's evaluations of astronaut locomotion on SL-Mir showed significant alteration in head-trunk coordination after long-duration flight. Astronauts appeared to have adopted a head-on-trunk locking movement by turning head and upper body at once. This head-trunk coordination disrupts gaze stabilization during locomotion. Also, coordination patterns of muscle activation for lower limb muscles were altered postflight. Evaluations by Layne *et al* of SL-Mir crewmembers indicated that reaction time of muscles and the sway (while standing) increased in some individuals shortly after return to Earth. Addition of foot pressure in microgravity as a countermeasure may retard muscle atrophy and maintain function of neuromuscular reflexes.

d. Neurolab. The final Spacelab flight, STS-90, focused on neurophysiology and flew ten human neurophysiology experiments, results of which are included in the table (Table III-37) below.

**Table III-37. Neurolab human neurophysiology experiment results.**

PI	Objectives and Results
Baisch	<p><i>Objective:</i> to study the mechanisms underlying orthostatic intolerance and cardiovascular dysregulation.</p> <p><i>Results:</i> Heart rate, blood pressure, and total peripheral resistance increased significantly during LBNP experiments in-flight. The decrease in stroke volume, the increased pooling of blood, and the increased filtration of plasma into the lower limbs during LBNP indicated that a plasma volume reduction and a deficit of the interstitial volume of lower limbs rather than a change in cardiovascular control was responsible for the in-flight response. Post-flight LBNP showed no signs of cardiovascular deterioration. The still more pronounced haemodynamic changes during LBNP reflected the expected behavior of cardiovascular control faced with less intravascular volume. Conclusion: the cardiovascular changes in-flight are a consequence of a fluid deficit rather than a consequence of changes in autonomic signal processing.</p>
Berthoz	<p><i>Objective:</i> to study how the central nervous system integrates sensory data to coordinate movement.</p> <p><i>Results:</i> EMG data indicated that the bulk of muscle activity is concentrated around the time of impact, both on the ground and during flight. Anticipatory muscle activity appears to be less well synchronized in flight and is initiated earlier with respect to ball impact when compared to pre- and postflight data. These observations suggest that subjects apply a constant acceleration model when predicting the time to contact, but that visual information corrects for gross differences between predicted and observed trajectories up until a short time (approximately 300 milliseconds) prior to impact. EMG activity appears to be graded according to the ball's velocity, both during flight and on the ground, indicating that the subjects can predict the kinetic energy stored in the falling ball. Oscillations of the hand immediately after flight indicate, however, that subjects misjudge the momentum and/or mass of the ball during a short (1-2 day) transition period between 0-G and 1-G.</p>
Blomqvist	<p><i>Objective:</i> to study the integration of the autonomic nervous and circulatory systems.</p> <p><i>Results:</i> Stroke volume was lower and heart rate higher during post-flight than pre-flight upright tilt. Total peripheral resistance was higher in some but not in all astronauts. Postflight sympathetic nerve activity, as measured directly by microneurography, was appropriately higher in all astronauts at rest and during upright tilt. Exposure to microgravity also augments sympathetic responses. The combined data provides strong evidence against microgravity-induced degradation of major cardiovascular control mechanisms.</p>
Bock	<p><i>Objective:</i> to study visuo-motor performance in microgravity.</p> <p><i>Results:</i> Pointing responses were slowed distinctly in microgravity, but the speed of tracking movements was not affected. The secondary task had comparable effects on tracking performance in space and on Earth. Conclusions: Response slowing in space is not due to an increased dependence on visual feedback, since it persists without hand vision. Differential effects of microgravity on pointing and tracking could be due to subjects' strategic decisions.</p>
Clement	<p><i>Objective:</i> to study visuo-otolithic interactions in microgravity.</p> <p><i>Results:</i> (1) Ocular counter-rolling (OCR) is generated predominantly in response to interaural linear acceleration; (2) the increased OCR during centrifugation on Earth is a response to the head dorsoventral 1 g linear acceleration component, which was absent in microgravity. The dorsoventral linear acceleration could have activated either the otoliths or body-tilt receptors that responded to the larger gravito-inertial acceleration (GIA) magnitude (1.4 g), to generate the increased OCR during centrifugation on Earth. A striking finding was that magnitude of OCR was maintained throughout and after flight.</p>

**Table III-37. Neurolab human neurophysiology experiment results cont'd.**

PI	Objectives and Results
Cohen	<p><i>Objective:</i> to determine the relationship between orientation vectors associated with pre-and post-rotatory nystagmus and with ocular counterrolling (OCR), and to determine how OCR and otolith-ocular orienting response to gravity is affected by spaceflight.</p> <p><i>Results:</i> The vestibular system appeared to be functioning in a relatively normal fashion in space, except at insertion and landing. Their perception of the gravito-inertial acceleration (GIA) as gravity was unaltered, and they did not perceive tilts of the GIA as translation in flight. Otolith-ocular tilt reflexes, such as OCR, as well as spatial orientation of the aVOR and of OKN toward the GIA were maintained in flight.</p>
Czeisler	<p><i>Objective:</i> to study the use of melatonin as a sleep aid in microgravity.</p> <p><i>Results:</i> Total sleep time is reduced and sleep is disrupted in space. For this mission reduced total sleep time was at least partially due to the truncated sleep opportunities resulting from delayed bed-times. The analyses suggest that melatonin did not significantly improve sleep for these subjects due to the melatonin capsules being taken after, not 30 minutes before, scheduled bedtime. In addition, the subjects were apparently able to entrain to the average 23.66-hour day. These two factors suggest that melatonin was given after the onset of endogenous melatonin production, a time that has consistently failed to demonstrate hypnotic effects. Flight alterations of sleep duration were followed by marked increase in REM sleep after return to Earth.</p>
Eckberg	<p><i>Objective:</i> to study baroreceptors and the changes in the cardiac-nervous system relationship in microgravity.</p> <p><i>Results:</i> Baseline muscle sympathetic activity is increased in space. Resting blood pressure is the same as on Earth. Arterial pressure changes, triggering and reflecting autonomic responses, were substantially greater in space than on Earth. Sympathetic baroreflex gain was the same in space and on earth, while vagal baroreflex gain was insignificantly diminished in space.</p>
Oman	<p><i>Objective:</i> to study the shift of the balance between visual and vestibular cues in microgravity.</p> <p><i>Results:</i> Most astronauts become more dependent on dynamic visual and proprioceptive cues, and some also respond to static visual orientation cues. The direction of the subjective vertical is labile and can influence figure recognition and shading interpretation.</p>
Robertson	<p><i>Objective:</i> to study how microgravity affects the overall function of the autonomic nervous system.</p> <p><i>Results:</i> The orthostatic intolerance (OI) of microgravity is in the hyperadrenergic category, and these studies have led to the discovery of genetic etiologies of OI such as norepinephrine transporter deficiency. Both basal muscle sympathetic nerve traffic (MSNA) and stimulated by lower body negative pressure is heightened rather than suppressed during spaceflight. In addition systemic norepinephrine spillover and clearance under the same conditions revealed that previous in-flight catecholamine measures likely underestimated systemic norepinephrine release given that in both systemic clearance and spillover were increased during flight and for one or two days after return to Earth.</p>

### III. ADVANCED HUMAN SUPPORT TECHNOLOGY

#### Human Factors

Human factors include all of the factors across the disciplines that impinge on the health, performance, safety, and well being of humans in orbiting spacecraft, planetary bases and space stations. Experiments flown on Spacelab missions in the areas of air and water quality and cognitive performance are shown in the table (Table III-38) below.

**Table III-38. Human Factors.**

Spacelab Designation	STS Mission	Launch Year	Duration (days)	Investigation	Principal Investigator
IML-1	STS-42	1992	8+	Mental workload	Alexander, H.L.
IML-2	STS-65	1994	14+	Microbial air sampler	Pierson, D.
				Cognitive performance	Schiflett, S.
SL-M	STS-71	1995	9+	Trace chemical (air quality)	James, J.
				Trace chemical (water quality)	Sauer, R.
				Microbial investigation	Pierson, D.
				Viral reactivation	Pierson, D.
LMS	STS-78	1996	16+	Cognitive performance	Schiflett, S.

#### 1. Environmental contaminants.

Microbial evaluation of the crew, air, surfaces and water on the Mir Station is critical to understanding the ecology of microbial organisms that inhabit crew living areas. Based on findings over the past twenty-five years it is evident that microbial ecology on spacecraft undergoes quantitative and qualitative changes. Investigations by Pierson *et al* on microbial biota from SL-Mir provide information on incidence and mechanisms of microbial transmission between crewmembers and work station/crew transmissions. Isolations of organisms from air, water and surfaces were shown to be within the International Space Station acceptability limits.

The environment of a spacecraft contains chemical contaminants that can be potential threats to crew health and safety, especially on long-duration missions. These airborne pollutants must be identified and controlled and air must be scrubbed and rendered compliant with safety levels. Evaluations of air quality are a significant part of the human factors considerations. Studies by Pierson, James, and others addressed air quality on the Mir station.

On Mir, approximately 50% of the potable water supplied to crewmembers was produced by direct recycling of water from humidity condensate. The other primary source was from potable water delivered by re-supply spacecraft from the ground or from fuel cell water that was transferred from the Shuttle. Experiments to assess the reliability of the water supply system were done to support future water requirements for International Space Station needs based on information from Mir. Water samples collected on the Mir 18 mission and on the STS-71 SL-Mir mission were analyzed and considered to be of general potable water quality although it exceeded water quality standards for total organic carbon (TOC). Ground supplied

water was considered of general potable water quality although it exceeded standards for TOC, turbidity and chloroform.

## *2. Microgravity environment effects on cognitive performance of humans.*

Space travelers are subjected to a number of stresses during spaceflight. These include physical isolation, confinement, lack of privacy, fatigue and changing work/rest cycles. Studies on Earth have shown that changing work/rest cycles can degrade cognitive performance and productivity. Based on the hypothesis of some scientists that performance will be less optimal in space, Schiflett *et al* designed experiments to determine the effect of microgravity on cognitive skills critical to the success of operational tasks in space. The tests include a number of cognitive, mood, fatigue, memory and performance tests.

## APPENDIX A - INVESTIGATORS AND EXPERIMENTS

Mission	Experiment Title	Investigators	Discipline
STS-2/ OSTA-1	Shuttle Imaging Radar (SIR-A)	Charles Elachi, Walter E. Brown Jr., Gerald G. Schaber, Louis F. Dellwig, Anthony W. England, R. Stephen Saunders, M. Guy, Harold C. MacDonald	Earth Observations
	Shuttle Multispectral Infrared Radiometer (SMIRR)	Alexander F.H.Goetz, Lawrence C. Rowan	Earth Observations
	Feature Identification and Location Experiment (FILE)	R.T. Schappell, John C. Tietz, W. E. Sivertson Jr., R. Gale Wilson	Earth Observations
	Measurement of Air Pollution from Satellites (MAPS)	Henry G. Reichle Jr., H. Andrew Wallio, Wilfred Donald Hesketh, William L. Chameides, L. K. Peters, Wolfgang Seiler, J. W. Swinnerton, Reginald E. Newell, Klaus B. Ludwig	Earth Observations
	Ocean Color Experiment (OCE)	Hongsuk H. Kim, Robert S. Fraser, Lamdin R. Blaine, H. Van der Pieper, Norden E. Huang	Earth Observations
	Night/Day Optical Survey of Lightning (NOSL)	Bernard Vonnegut, Marx Brook, Otha H. Vaughn Jr.	Earth Observations
	HEFLEX Bioengineering Test (HBT)	Allan H. Brown, D.K. Chapman	Life Science: Plant
STS-3/ OSS-1	Characteristics of Shuttle Induced Atmosphere	Jerry L. Weinberg, Frank J. Giovane, D.W. Schuerman, J.A.M. McDonnell	Astronomy
	Solar Flare X-ray Polarimeter Experiment	Robert Novick, Gary A. Chanan	Solar Physics
	Solar Ultraviolet Spectral Irradiance Monitor	Guenter E. Brueckner, John-David F. Bartoe, Dianne K. Prinz, Michael E. Van Hoosier	Solar Physics
	Vehicle Charging and Potential Experiment	Peter M. Banks, Charles R. Chappell, W. John Raitt, P. Roger Williamson, Nobuki Kawashima, H.B. Liemohn, Richard M. Goldstein, Uri Samir, James L. Burch, Lewis M. Linson	Space Plasma Physics
	Microabrasion Foils	J.A.M. McDonnell, W.C. Carey, D.G. Dixon	Space Plasma Physics
	Contamination Monitor	Jack J. Triolo, Carl R. Maag, Roy McIntosh Jr., Paul Porzio	Space Plasma Physics
	Plasma Diagnostic Package (PDP)	Donald A. Gurnett, Henry C. Brinton, David L. Reasoner, Louis A. Frank, Nobie H. Stone, Nicola d'Angelo	Space Plasma Physics
	Cytological and Ultrastructural Studies on Root Tissues	R. D. Slocum, A. W. Galston, J. J. Gaynor, Abraham D. Krikorian	Life Science: Plant
	Karyological Observations in Developing Root Seedlings	Abraham D. Krikorian, J.R. Cowles, S.A. O'Connor, H.W.Scheld	Life Science: Plant
	Influence of Weightlessness in Lignification of Plant Seedlings	Joseph R.Cowles, R. Lemay, C.Peterson, H.W.Scheld	Life Science: Plant
	Thermal Canister Experiment	Stanford Ollendorf	Technology

Mission	Experiment Title	Investigators	Discipline
STS-7/ OSTA-2	Vapor Growth of Alloy-Type Semiconductor Crystals	Herbert Wiedemeier, E. A. Irene, C. C. Wang	Physical Science: Materials
	Liquid Phase Miscibility Gap Materials	Stanley H. Gelles, A.J. Markworth	Physical Science: Materials
	Containerless Processing of Glass Forming Melts	Delbert E. Day	Physical Science: Materials
	Stability of Metallic Dispersions	Guenther H. Otto	Physical Science: Materials
	Solidification Front	Hermann Klein, J. Poetsche, H.U. Walter, A. Bewersdorff	Physical Science: Materials
STS-9/ SL-1	Far UV Astronomy using the FAUST Telescope	C. Stuart Bowyer, George C. Courtes, Roger F. Malina, J. M. Deharveng, Jean-Claude Berges	Astronomy
	Very Wide Field Galactic Camera	George C. Courtes, Rudolf Decher, M. Viton, J.P. Sivan, Gilmer A. Gary	Astronomy
	Spectroscopy in X-ray Astronomy	R.D. Andresen, Livio Scarsi, G. Boella, S.J. Kellock	Astronomy
	Isotope Stack	Rudolf Beaujean, Georg Siegmom, Siegmom Enge	Astrophysics
	Active Cavity Radiometer Solar Irradiance Monitor	Richard C. Willson, Reinhard Beer, James M. Kendall Sr.	Solar Physics
	Measurement of the Solar Spectrum from 170 to 3200 nm	Gerard O. Thuillier, H. Neckel, R. Pastiels, Paul C. Simon, Jacques E. Blamont, D. Labs	Solar Physics
	Absolute Measurement of the Solar Constant	D. Crommelynck, Vincente Domingo	Solar Physics
	An Imaging Spectrometric Observatory	Marsha R. Torr, George R. Carignan, Thomas M. Donahue, James C.G. Walker, Sushil K. Atreya, Douglas G. Torr	Space Plasma Physics
	Space Experiments with Particle Accelerators (SEPAC)	Tatsuzo Obayashi, William T. Roberts, Peter M. Banks, James L. Burch, Charles R. Chappell, William W. L. Taylor	Space Plasma Physics
	Radiation Environment Mapping	Eugene V. Benton, Allen L. Frank, David D. Peterson, Ronald M. Cassou	Space Plasma Physics
	Investigation on Atmospheric H and D through the Measurement of Lyman Alpha	Jean-Louis C. Bertaux, Florence Goutail, G. Kockarts	Space Plasma Physics
	DC and Low Frequency Vector Magnetometer	R. Schmidt	Space Plasma Physics
	Study of Low-Energy Electron Flux and its Reaction to Active Experimentation	Klaus Wilhelm, R. Schmidt, Wolfgang Studemann	Space Plasma Physics
	Phenomena Induced by Charged Particle Beams	Christian Beghin, Jean-Jacques Berthelier, H. H. Arends, D. Klinge, Trevor R. Sanderson, Jean-Yves Delahaye, B. Narheim, Bernt N. Maehlum, J. Lavergnat, Jan Troim, T. Moe, D. Henry	Space Plasma Physics
	Grille Spectrometer	Marcel Ackerman, Marie P. Lemaitre, Christian Muller, A. Girard, Jacques Vercheval, J. Laurent, M. Besson, Carlos H. Lippens	Atmospheric Science

Mission	Experiment Title	Investigators	Discipline
STS-9/ SL-1	Waves in the OH Emissive Layer	Michel Herse, Satya Prakash, Guy Moreels	Atmospheric Science
	Atmospheric Emission Photometric Imaging	Steven B. Mende, Robert J. Naumann, Kenneth S. Clifton, Gary R. Swenson, David L. Reasoner, Bill J. Duncan, Robert H. Eather	Atmospheric Science
	Microwave Remote Sensing Experiment	G. Dieterle, Paul de Loor	Atmospheric Science
	Melting and Solidification of Metallic Composites	L. Froyen, A. Deruyttere	Physical Science: Materials
	Directional Solidification of Eutectic Alloys	J.J. Favier, J. DeGoer	Physical Science: Materials
	Adhesion of Metals	F. Rossitto, G. Ghersini	Physical Science: Fluids
	Influences Affecting Separation in Monotectic Alloys Under Microgravity	H. Ahlborn, K. Lohberg	Physical Science: Materials
	Lead-Telluride Crystal Growth under Microgravity Conditions	M. Rodot, O. Tottereau	Physical Science: Materials
	Oscillation of Semi-Free Liquid Spheres in Space	H. Rodot, C. Bisch	Physical Science: Fluids
	Solidification of Near Monotectic Zn Pb Alloys	H. Fischmeister, A. Kneissl	Physical Science: Materials
	Crystal Growth from Solution	G. Galster, K.F. Nielsen	Physical Science: Materials
	Vacuum Brazing under Microgravity	K. Frieler, R. Stickler, E. Siegfried	Physical Science: Materials
	Directional Solidification of Aluminum Zinc Vapour Emulsion	C. Potard, P. Morgand	Physical Science: Materials
	GaSb Semiconductor Crystals under Microgravity	K.W. Benz, G. Nagel	Physical Science: Materials
	Self-diffusion of Sn112 and Sn124 in Liquid Tin	G. Froberg, K.H. Kraatz, H. Wever	Physical Science: Fluids
	Unidirectional Solidification of Cast Iron	T. Luyendijk, H. Nieswaag, W. Alsem	Physical Science: Materials
	Unidirectional Solidification of Eutectics (InSb-NiSb)	G. Muller, P. Kyr	Physical Science: Materials
	Bubble Reinforced Materials	P. Gondi, R. Montanari, F. Barbieri, C. Patuelli	Physical Science: Materials
	Growth and Characterization of Brushite and Lead Monetite	M. C. Robert, F. Lefeaucheaux, A. Authier	Physical Science: Materials
	Solution Growth of Cadmium Telluride	R. Schnholz, R. Nitsche, R. Dian	Physical Science: Materials
	Float Zone Crystallization of Silicon	A. Eyer, H. Leiste, R. Nitsche	Physical Science: Materials
	Protein Crystal Growth	W. Littke, C. John	Physical Science: Biotech
	Axisymmetric free Surface Behaviour of Moving Liquid in a Cylinder in Microgravity	J.P.B. Vreeburg	Physical Science: Fluids
	Crystallization of Silicon	H. Koelker	Physical Science: Materials
	Free Convection in Low gravity	L.G. Napolitano, R. Monti	Physical Science: Fluids
	Interdiffusion in the Glass Melt System (Na <sub>2</sub> O+Rb <sub>2</sub> O)3SiO <sub>2</sub>	M. Braedt, V. Braetsch, G.H. Frischat	Physical Science: Fluids
	Thermomigration of Cobalt in Liquid Tin	Y. Malméjac, J.P. Praizey	Physical Science: Fluids

Mission	Experiment Title	Investigators	Discipline
STS-9/ SL-1	Crystal Growth of Mercury Iodide by Physical Vapor Transport	R.Cadoret, P. Brisson	Physical Science: Materials
	Kinetics of Spreading of Liquids in Microgravity	J.M.Haynes	Physical Science: Fluids
	Floating Zone Stability in Zero Gravity	I. Martinez, I. DaRiva, J. Meseguer, A. Sanz	Physical Science: Fluids
	Capillary Forces in a Low Gravity Environment	J.F.Padday	Physical Science: Fluids
	Tribology Experiments in Zero Gravity: Bearing Lubricant Wetting, Spreading and Operating Characteristics in Zero-G	Coda T. Pan; R. L. Gause; Ann F. Whitaker	Physical Science: Fluids
	Effects of radiation and microgravity on plant systems	A.R.Kranz, H. Buecker	Life Science: Radia- tion
	Radiation Measurement aboard Spacelab 1	E. Schopper	Life Science: Radia- tion
	Advanced Biostack Experiment	Horst Buecker, G.Reitz	Life Science: Radia- tion
	Eye Movements During Sleep	O. Quadens	Life Science: Human Physiology
	Effects of Rectilinear Acceleration, Optokinetic and Caloric Stimuli in Space	Rudolf J. von Baumgarten	Life Science: Human Physiology
	Mass Discrimination during Prolonged Weightlessness	Helen E. Ross, E. Brodie, A. Benson	Life Science: Human Physiology
	Measurement of Central Venous Pressure by Puncturing an Arm Vein	K. Kirsch	Life Science: Human Physiology
	Ballistocardiographic Research In Weightlessness	A. Scano, E. Rispoli, F. Strollo, G. Cama, L. Guidetti, G.Brazzoduro	Life Science: Human Physiology
	Micro-organisms and Biomolecules in the Space Environment	Gerda H. Horneck	Life Science: Cell and Molecular/Radiation
	Lymphocyte Proliferation in Weightlessness	Augusto Cogoli	Life Science: Cell and Molecular
	Collection Blood Samples for Determining A.D.H., Aldosterone, and other Hormones	K. Kirsch	Life Science: Human Physiology
	Influence of Space Flight on Erythrokinetics in Man	Carolyn S. Leach	Life Science: Human Physiology
	Effects of Prolonged Weightlessness on the Humoral Im- mune Response of Humans	Edward W.Voss, Jr.	Life Science: Human Physiology
	Vestibular Experiments	Laurence R. Young	Life Science: Human Physiology
	Vestibulo-Spinal Reflex Mechanisms	Millard F. Reschke	Life Science: Human Physiology
	Preliminary Characterization of Persisting Circadian Rhythms During Spaceflight: Neurospora as a Model System	Frank M. Sulzman	Life Science: Cell and Molecular
	Personal Electrophysiological Tape Recorder	H. L. Green	Life Science: Human Physiology
	Nutation of <i>Helianthus annuus</i> in a Microgravity Envi- ronment	Allan H. Brown, D.K. Chap- man, Anthony O. Dahl	Life Science: Plant
	Metric Camera Experiment	Michael L. Reynolds, Gottfried L. Konecny	Technology
STS-41D/ OAST-1	OAST-1 Solar Array	M.L.Brumfield, R.S. Pappa, J.B. Miller, R.R. Adams	Technology
STS-41G/ OSTA-3	Measurement of Air Pollution from Satellites (MAPS)	Henry G. Reichle Jr.	Atmospheric Science
	Shuttle Imaging Radar-B (SIR-B)	Charles Elachi	Earth Observations
	Large Format Camera (LFC)	Bernard H. Mollberg	Earth Observations
	Feature Identification and Location Experiment (FILE)	W.E. Sivertson Jr., R. Gale Wilson	Earth Observations

Mission	Experiment Title	Investigators	Discipline
STS-51B/ SL-3	Studies of the Ionization of Solar and Galactic Cosmic Ray Heavy Nuclei	Sukumar Biswas, Ramanath Cowsik, J. N. Goswami, P. J. Kajarekar, Shyam Lal, Nemani Durgaprasard, J. S. Yadav, M. N. Vahia	Astrophysics
	Auroral Imaging Experiment	Thomas J. Hallinan, Don L. Lind	Space Plasma Physics
	Atmospheric Trace Molecules Spectroscopy (ATMOS)	Crofton B. Farmer, John H. Shaw, Moustafa T. Chahine, Fredric W. Taylor, James M. Russell III, J. E. Harries, Reinhard Beer, Rudolphe J. Zander, Joel Susskind, Odell Raper, James B. Breckinridge, Steven C. Wofsy, Rudolph A. Schindler, Robert H. Norton Jr., Robert A. Toth	Atmospheric Science
	Very Wide Field Camera	Georges Courtes, J.P. Sivan, Rudolf Decher, Gilmer A. Gary, M. Viton	Atmospheric Science
	Dynamics of Rotating and Oscillating Free Drops	Taylor G. Wang, Eugene H. Trinh, Daniel D. Elleman	Physical Science: Fluids
	Geophysical Fluid Flow Cell Experiment	John E. Hart, George H. Fichtl, Juri Toomre, William W. Fowles, Peter A. Gilman, Fred W. Leslie	Physical Science: Fluids
	Solution Growth of Crystals in Zero-Gravity	Ravindra B. Lal, Roger L. Kroes	Physical Science: Materials
	Mercuric Iodide Growth	Wayne F. Schnepple, M.M. Schieber, Lodewijk van den Berg	Physical Science: Materials
	Crystal Growth of Mercury Iodide by Physical Vapour Transport	Robert Cadoret, P. Brisson	Physical Science: Materials
	Rat Maintenance in the Research Animal Holding Facility During the Flight of Spacelab 3	Tom N. Fast, Oliver Chee, Bonnie P. Dalton, Richard E. Grindeland, Lanny C. Keil, Lisbeth M. Kraft, P.R. Lundgren, Patricia Patterson-Buckendahl, Tom Reilly, M. Ruder, S. Scibetta, John W. Tremor, Marilyn Vasques	Life Science: Animal Physiology
	Autogenic Feedback Training (AFT)	Patricia S. Cowings, Joe Kamiya, Neal E. Miller, William B. Toscano, Joseph C. Sharp	Life Science: Human Physiology
	Urine Monitoring Investigation (UMI)	Carolyn Leach-Huntoon, Howard J. Schneider	Life Science: Human Physiology
	1, 25-Dihydroxyvitamin D3 Receptors in Space Flown vs. Grounded Control Rat Kidneys	David J. Mangelsdorf, Mark R. Haussler, Samuel L. Marion, J. Wesley Pike	Life Science: Animal Physiology
	Atriopeptin in Atria and Plasma of Rats Orbited aboard NASA Spacelab 3 for Seven Days	Walter H. Inge, Diane K. Hartle	Life Science: Animal Physiology
	Biochemical and Morphological Evaluation of the Effects of Space Flight on Rat Salivary Glands	Maija I. Mednieks, Arthur R. Hand	Life Science: Animal Physiology
	Bone Maturation in Rats Flown on the Spacelab 3 Mission	Jean E. Russell, David J.J. Simmons	Life Science: Animal Physiology
	Census of Osteoblast Precursor Cells in Periodontal Ligament (PDL) of Spacelab 3 Rats	W. Eugene Roberts, P.J. Fielder, M.R.R. Gonsalves, A.C. Maese, L.M.L. Rosenner	Life Science: Animal Physiology

Mission	Experiment Title	Investigators	Discipline
STS-51B/ SL-3	Changes in Functional Metabolism in the Rat Central Nervous System Following Spaceflight	D.M.Murakami, Charles A. Fuller, J.D. Miller	Life Science: Animal Physiology
	Early Adaptation to Altered Gravitational Environments in the Squirrel Monkey	Charles A. Fuller	Life Science: Animal Physiology
	Effect of Flight in Mission SL-3 on Cytokine Production by Rats	Cheryl L.Gould, Mark Lyte, G. Sonnenfeld, Jo Ann Williams	Life Science: Animal Physiology
	Effect of Flight in Mission SL-3 on Interferon-gamma Production by Rats	Cheryl L. Gould, Adrian D. Mandel, Gerald Sonnenfeld, Jo Ann Williams	Life Science: Animal Physiology
	Effect of Seven Days of Spaceflight on Hindlimb Muscle Protein, RNA and DNA in Adult Rats	Joseph M. Steffen, X. J. Musacchia	Life Science: Animal Physiology
	Effects of Weightlessness on Neurotransmitter Receptors in Selected Brain Areas	J.D. Miller, C. A. Fuller, Mona McConnaughey, B.A. McMillen, D.M. Murakami, H.L. Williams	Life Science: Animal Physiology
	Electron Microprobe Analyses of Calcium, Sulfate, Magnesium, and Phosphorous Distribution in Incisors of Spacelab-3 Rats	Gary D.D. Rosenberg, David J.J.Simmons	Life Science: Animal Physiology
	Hematologic Parameters of Astrorats Flown on Spacelab-3	Robert D. Lange, Richard B. Andrews, Christopher D.R. Dunn, L.A. Gibson, J.B.Jones, Paul Wright	Life Science: Animal Physiology
	Hepatic Enzyme Adaptation in Rats after Spaceflight	James L.L.Hargrove, Dean P. Jones	Life Science: Animal Physiology
	Hepatic Enzymes of Sphingolipid and Glycerolipid Biosynthesis in Rats from Spacelab 3	Alfred H. Merrill, James L. L. Hargrove, Elaine Wange	Life Science: Animal Physiology
	Homeostasis and Biological Rhythms in the Rat during Spaceflight	Charles A. Fuller	Life Science: Animal Physiology
	Microgravity Associated Changes in Pituitary Growth Hormone (GH) Cells Prepared from Rats Flown on Spacelab 3	Wesley C. Hymer, M. Far- rington, Tom N. Fast, Richard E. Grindeland, C. Hayes, K. Motter, L. Patil	Life Science: Animal Physiology
	Microgravity Changes in Heart Structure and Cyclic-AMP Metabolism	Delbert E. Philpott, L. Cheng, R. Egnor, A.Fine, Katharine H. Kato, Maija I. Mednieks	Life Science: Animal Physiology
	Microprobe Analyses of Epiphyseal Plates from Spacelab 3 Rats	Pauline Jackie Duke, Marion Campbell, Liliana Janer, D. Montufar-Solis, Jennifer Morrow	Life Science: Animal Physiology
	Morphologic and Histochemical Studies of Bone Cells from SL-3 Rats	Stephen B. Doty	Life Science: Animal Physiology
	Morphological and Biochemical Changes in Soleus and Extensor Digitorum Longus Muscles of Rats Orbited in Spacelab 3	D. A. Riley, J. L. W. Bain, S. Ellis, T. Satyanarayana, F.R. Sedlak, G.R.Slocum	Life Science: Animal Physiology
	Muscle Protein and Glycogen Responses to Recovery from Hypogravity and Unloading by Tail-Cast Suspension	Erik J. Henriksen, Paul H. Cook, Stephen Jacob, Marc E. Tischler	Life Science: Animal Physiology
	Osteocalcin as an Indicator of Bone Metabolism during Spaceflight	Patricia Patterson-Buckendahl, Sara B. Arnaud, Christopher E. Cann, Richard E. Grindeland, R. B. Martin	Life Science: Animal Physiology
	Otoconial Morphology in Space-Flown Rats	Muriel D. Ross, Oliver Chee, Kathleen Donovan	Life Science: Animal Physiology
	Plasma Renin Concentrations of Rats Orbited for Seven Days aboard NASA Spacelab 3	Diane K. Hartle, Walter H. Inge	Life Science: Animal Physiology

Mission	Experiment Title	Investigators	Discipline
STS-51B/ SL-3	Reduction of the Spermatogonial Population in Rat Testes Flown on Spacelab 3	D. E. Philpott, S. Black, R. L. Corbett, W. Sapp, J.H. Stevenson, C.S. Williams	Life Science: Animal Physiology
	Response of Amino Acids in Hindlimb Muscles to Recovery from Hypogravity and Unloading by Tail-Cast Suspension	Marc E. Tischler, Paul H. Cook, Erik J. Henriksen, Stephen Jacob	Life Science: Animal Physiology
	Results of examination of the Respiratory System in Spacelab-3 Flight Rats	Lisbeth M. Kraft	
	Spacelab 3: Histomorphometric Analysis of the Rat Skeleton	Thomas J.J. Wronski, A.C. Maese, Emily R. Morey-Holton, C. Walsh	Life Science: Animal Physiology
	The Influence of Spaceflight on the Rat Soleus	V.R. Edgerton, R.E. Grindeland, T. P. Martin	Life Science: Animal Physiology
	Ames Research Center Life Sciences Payload (ARCLSP)	P. X. Callahan, C.L. Schatte, W. E. Berry, T. N. Fast, G. A. Funk, R. E. Grindeland, W.A. Lencki	Life Science: Animal Physiology Technology, Life Science: Animal Physiology
STS-51F /SL-2	Small, Helium-Cooled Infrared Telescope (IRT)	G.G. Fazio, W. Hoffman, F. Low, G. Rieke, E. Urban, G.J. Melnick, D.G. Koch, E.T. Young, T. Gautier	Astronomy
	Hard X-Ray Imaging of Galactic Clusters and Other Extended X-Ray Sources (XRT)	A. Peter Willmore, Gerry K. Skinner, Chris J. Eyles	Astronomy
	Elemental Composition and Energy Spectra of Cosmic Ray Nuclei (CNRE)	Dietrich Muller, Peter Meyer, Jacques J. L. Heures, James E. Lamport, Simon Swordy	Astrophysics
	Solar Magnetic and Velocity Field Measurement System/ Solar Optical Universal Polarimeter (SOUP)	Alan M. Title	Solar Physics
	Solar Coronal Helium Abundance (CHASE)	J. Leonard Culhane, Alan H. Gabriel, Keith Norman, Bruce E. Patchett, P. Borrill, Jim Lang, John H. Parkinson, Kenneth J. H. Phillips	Solar Physics
	High Resolution Telescope and Spectrograph (HRTS)	Guenter E. Brueckner	Solar Physics
	Ejectable Plasma Diagnostics Package	Louis A. Frank	Space Plasma Physics
	Plasma Depletion Experiments for Ionospheric+Radio Astronomical Studies	Michael J. Mendillo, Paul A. Bernhardt	Space Plasma Physics
	Vehicle Charging and Potential (VCAP)	Peter M. Banks, W. John Raitt, P. Roger Williamson, Nobuki Kawashima, Tatsuzo Obayashi, Kay D. Baker	Space Plasma Physics
	Solar UV Spectral Irradiance Monitor (SUSIM)	Guenter E. Brueckner, John-David F. Bartoe, Michael E. Van Hoosier, O. Kjeldseth Moe, Carole Jordan, K. R. Nicholas	Atmospheric Science
	Properties of Superfluid Helium in Zero-G	Peter V. Mason, G. Wang, D.J. Collins, S. Chazanoff, P.J. Cowgill, D. Petrac, J.R. Gatewood, T. D. Elleman	Physical Science: Fluids
	Vitamin D Metabolites and Bone Demineralization	Heinrich K. Schnoes	Life Science: Human Physiology
	Interaction of Oxygen and Gravity Influenced Lignification	Joseph R. Cowles, Gary C. Jahns, R. Lemay	Life Science: Plant

Mission	Experiment Title	Investigators	Discipline
STS-61A /SL-D1	Floating Zone Hydrodynamics	I.Martinez,I. DaRiva, J.Meseguer, A.Sanz	Physical Science: Fluids
	Capillary: Adhesion Forces in Liquid Films	J.F.Padday	Physical Science: Fluids
	Liquid Motions in Partially Filled Containers	J.P.B.Vreeburg	Physical Science: Fluids
	Bubble Motions Induced by Temperature Gradient	R. Naehle; D. Neuhaus; J. Siekmann; G. Wozniak	Physical Science: Fluids
	Marangoni Convection in an Open Boat	D. Schwabe, R. Lamprecht, A. Scharmann	Physical Science: Fluids
	Marangoni Flows	L.Napolitano, R. Monti, G. Russo	Physical Science: Fluids
	Marangoni Convection in Relation to Mass Transfer from the Liquid to the Gas Phase: MACO A and MACO B	A.A.H.Drinkenburg, J.H. Lichtenbelt, H.A.Dijkstra	Physical Science: Fluids
	Surface Tension Induced Convection around a Surface Tension Minimum	J.C.Legros, M.C.Limbourg-Fontaine, G.Petre	Physical Science: Fluids
	Geophysical Fluid Flow Cell Experiment	Robert B. Pond	Physical Science: Fluids
	Bubble Transport by Chemical Waves	A.Bewersdorff	Physical Science: Materials
	Atomic Diffusion and Transport in Liquid Metals	H.Weaver, G.Frohberg, K.H. Kraatz	Physical Science: Fluids
	Measurement of the Thermally Induced Ludwig-Soret Effects	J.Dupuy, J. Bert, I Moussa, D. Henry	Physical Science: Fluids
	Inter-diffusion of Molten Salts	J.Richter, W. Merkens	Physical Science: Fluids
	Homogeneity of Glasses	G.H. Frischat, V. Braetsch	Physical Science: Materials
	Thermodiffusion in Liquid Metallic Alloys	J.P. Praizey	Physical Science: Fluids
	Heat Capacity Near Critical Point	J.Straub, K. Nitsche	Physical Science: Fluids
	Density Distribution and Phase Separation in Fluids at the Critical Point	H.Klein, K.Wanders	Physical Science: Fluids
	GETS – Boundary Layers in Solidifying Transparent Melts: Holographic Observation of Solidification Processes	A.Ecker, P.R.Sahm	Physical Science: Materials
	Aluminum/Copper Solid-Liquid Interface Diffusion	H.M.Tensi, J.J.Schmidt	Physical Science: Materials
	Planar Front Solidification of Aluminium Magnesium Alloys	S.Rex, P.R.Sahm	Physical Science: Materials
	Dendritic Solidification of Aluminum-Copper Alloys	J.J.Favier, D.Camel	Physical Science: Materials
	Cellular Morphology in Lead Thallium Alloys	B.Billia, J.J.Favier, H.Jamogotchian, D.Camel	Physical Science: Materials
	Directional Solidification of Indium Antimonide-Nickel Antimonide Eutectic: Determination of Gravity Induced Convection on Fiber Spacing	G. Mueller, P.Kyr	Physical Science: Materials
	The Behaviour of Aluminum Oxide Particles at the Solidification Front of Copper	J.Poetschke, V.Rogge	Physical Science: Materials
	Particles at Melting and Solidification Fronts	D. Langbein, U.Roth	Physical Science: Materials
	Skin Technology: Eutectic Solidification	H. Sprenger	Physical Science: Materials
	Skin Casting on Grey Cast Iron	H. Sprenger, H. Nieswaag, M. Malinowski	Physical Science: Materials

Mission	Experiment Title	Investigators	Discipline
STS-61A /SL-D1	Melting and Solidification of Metallic Composites	A. Deruyttere, L.Froyen	Physical Science: Materials
	Floating Zone Crystallization of Silicon	R. Nitsche, W. Mueller, A. Croell	Physical Science: Materials
	Crystallization of a Silicon Sphere	H. Koelker	Physical Science: Materials
	Growth Rate Measurement of Doped Indium Antimonide Crystal by a Calorimetric Method under Microgravity	C. Potard, T. Duffar, P.Dusserre	Physical Science: Materials
	Containerless Processing of Glass Forming Melts-Determination of Critical Cooling Rates and Melt Homogenization	Day, Delbert E.; Ray, C.S.	Physical Science: Materials
	Growth of Single Crystals of Binary III-V Semiconductors by the Travelling Heater Method (Tellurium doped Gallium Antimonide (GaSb))	K.W. Benz, G. Nagel, A. Danilewsky, B. Notheisen	Physical Science: Materials
	Growth of CdTe by the Travelling Heater Method from Tellurium Solution	R. Nitsche, R. Schoenholtz, R. Dian	Physical Science: Materials
	Growth of Single Crystals of Binary III-V Semiconductors by the Travelling Heater Method (Sulphur doped Indium Phosphide (InP))	K.W. Benz, G. Nagel, A. Danilewsky, B. Notheisen	Physical Science: Materials
	Growth of PbSnTe by the Travelling Heater Method	M. Harr, R. Dornhaus, G. Brotz	Physical Science: Materials
	Liquid Phase Miscibility Gap Materials	S.H.Gelles; Alan J. Markworth	Physical Science: Materials
	Semiconductor Materials-Suppression of Body Force Gravity-Driven Convection in Directionally Solidified PbTe-SnTe	Roger K. Crouch; Archibald L. Fripp; W.J. Debnam	Physical Science: Materials
	Vapour Zone Crystallization of Cadmium Telluride	R. Nitsche, R. Dian, M.Bruder	Physical Science: Materials
	Solutal and Thermal Convection in Ge-I2 Vapour Phase	J.C. Launay	Physical Science: Materials
	Vapour Growth of Alloy-Type Crystal	H. Wiedemeier	Physical Science: Materials
	Protein Single Crystal Growth under Zero Gravity	W. Littke	Physical Science: Biotech
	Separation of Immiscible Melts	H. Ahlborn, K. Loehberg	Physical Science: Materials
	Mixing and Demixing of Transparent Liquids	D. Langbein	Physical Science: Fluids
	Separation of Fluid Phases and Thermocapillary Bubble and Drop Motion in a Temperature Gradient	R. Naehle, D.Neuhaus, J. Siekman, G.Wozniak	Physical Science: Fluids
	Effects of microgravity on Lymphocyte Activation ( <i>ex-vivo</i> )	A. Cogoli, B. Bechler, O. Mueller, E. Hunzinger	Life Science: Cell and Molecular
	Effects of microgravity on Lymphocyte Activation ( <i>in-vitro</i> )	A. Cogoli, B. Bechler, O. Mueller, E. Hunzinger	Life Science: Cell and Molecular
	The <i>Paramecium</i> experiment	H. Planel, G. Richoilley, R. Tixador, J. Templier, J.C. Bes, G. Gasset	Life Science: Cell and Molecular
	Effect of Microgravity on Hybridoma Mammalian Cell Behaviour and Structure	M. Bouteille	Life Science: Cell and Molecular
	Circadian clock of <i>Chlamydomonas reinhardtii</i> in space	D. Mergenhagen, E. Mergenhagen	Life Science: Cell and Molecular
	Antibacterial activity of antibiotics in space conditions	R. Tixador, L. Lapchine, N. Moatti, G. Richoilley, J. Templier, G. Gasset	Life Science: Cell and Molecular

Mission	Experiment Title	Investigators	Discipline
STS-61A /SL-D1	Growth and Differentiation of <i>Bacillus subtilis</i> under microgravity conditions.	H.D. Mennigmann, M. Lange	Life Science: Cell and Molecular
	Effect of $\mu$ g on genetic recombination in <i>Escherichia coli</i>	O. Ciferri, O. Tiboni, G. Di-Pasquale, A.M. Orlandoni, M.L. Marchesi	Life Science: Cell and Molecular
	Contraction Behaviour and Protoplasmic Streaming in the Slime Mould	V. Sobick, I. Block, W. Brieglab, K.E. Wohlfart-Botterman	Life Science: Cell and Molecular
	Embryogenesis and organogenesis of <i>Carasius morosus</i> under spaceflight conditions	H. Buecker, R. Facius, G. Horneck, G. Reitz, E.H. Graul, H. Berger, H. Hoeffken, W. Ruether, W. Heinrich, R. Beaujean, W. Enge	Life Science: Developmental/ Radiation
	Dosimetric Mapping inside Biorack	H. Buecker, R. Facius, G. Reitz, W. Heinrich, R. Beaujean, W. Enge, T. Ohrndorf, E. Schopper	Life Science: Radiation
	Structure and function of the gravireceptor	J. Neubert, W. Briegleb, A. Schartz, I. Hertwig, B. Kruse	Life Science: Developmental
	The role of gravity in the establishment of the dorso-ventral axis in the amphibian embryo.	G.A. Ubbels	Life Science: Developmental
	Gravi-reception of cress roots ( <i>Lepidium sativum</i> L.)	D. Volkmann, H.M. Behrens, A. Sievers	Life Science: Plants
	Differentiation and Emryogenesis in Aniseed Cultures in Microgravity	Roland R. Theimer, R.A. Kudielka, I. Rosch, H. Koch	Life Science: Plants
	Statocyte Polarity and Geotrophic Response	G. Perbal, D. Driss-Ecole, G. Salle, J. Raffin	Life Science: Plants
	European experiments on the vestibular system	R. von Baumgarten	Life Science: Human Physiology
	Vestibular Adaptation	Laurence R. Young	Life Science: Human Physiology
	The effect of microgravity on plasma-osteocalcin	C. Vermeer, M.M.W. Ulrich	Life Science: Human Physiology
	Venous Pressure in Space	K.L. Kirsch, L. Roecker, F. Haenel	Life Science: Human Physiology
	Tonometry	J. Draeger, R. Wirt, R. Schwartz	Life Science: Human Physiology
	Early Adaptation to body fluid and cardiac performance	F. Baisch, L. Beck, M.D. Samel, A. Samel, L.D. Montgomery	Life Science: Human Physiology
	Mass discrimination and adaptation to weightlessness	H.E. Ross, E. Schwartz, P. Emmerston	Life Science: Human Physiology
	Spatial Description: aspects of cognitive adaptation	A.D. Friederici, W.J.M. Levelt	Life Science: Human Physiology
	Causation of inversion illusions and space sickness	H. Mittelstaedt, S. Glasauer	Life Science: Human Physiology
	Arm Positioning	F. Veringa	Life Science: Human Physiology
	Embryogenesis <i>Drosophila melanogaster</i>	M. Marco, J. Jurardo-Gonzales, I. Vernos, M. Calleja, M. Carratala	Life Science: Developmental
STS-61B/ EASE- ACCESS	Experimental Assembly of Structures in Extravehicular Activity (EASE)	David Akin	Technology
	Assembly Concept for Construction of Erectable Space Structures (ACCESS)	Walter L. Heard	Technology

Mission	Experiment Title	Investigators	Discipline
STS-61C /MSL-2	Undercooled Solidification in Quiescent Levitated Drops	Merton C. Flemings	Physical Science: Materials
	Orbital Processing of Aligned Magnetic Composite	David J. Larson, Jr.	Physical Science: Materials
	Physical Phenomena in Containerless Glass Processing- Model Fluids	R.S. Subramanian	Physical Science: Fluids
	Dynamics of Compound Drops	Taylor G. Wang	Physical Science: Fluids
STS-35/ ASTRO-1	Wisconsin Ultraviolet Photopolarimetry Experiment (WUPPE)	Arthur D. Code, Ken Nordsieck, Chris Anderson	Astronomy
	Hopkins Ultraviolet Telescope (HUT)	Arthur F. Davidsen, William G. Fastie, Paul D. Feldman, R.C. Henry, H.W. Moos	Astronomy
	Ultraviolet Imaging Telescope (UIT)	Theodore P. Stecher, Andrew M. Smith, Morton S. Roberts, Ralph C. Bohlin, Derck L. Massa	Astronomy
	Broad Band X-ray Telescope (BBXRT)	Peter J. Serlemitsos, Elihu A. Boldt, Stephen S. Holt, Richard F. Mushotzky, Jean H. Swank, Francis E. Marshall, Richard L. Kelley, Robert Petre, Andrew E. Szymkowiak	Astronomy
STS-40/ SLS-1	Solid Surface Combustion Experiment	Robert A. Altenkirch	Physical Science: Fluids
	Influence of Weightlessness Upon Human Autonomic Cardiovascular Controls	Dwain L. Eckberg, Janice M. Fritsch-Yelle	Life Science: Human Physiology
	Inflight Study of Cardiovascular Deconditioning	Leon E. Farhi, Robert A. Klocke, Albert J. Olszowka, David R. Pendergast, Mary Ann Rokitka, Barbara E. Shykoff	Life Science: Human Physiology
	Vestibular Experiments in Spacelab	Laurence R. Young, Carlo DeLuca, Byron K. Lichtenberg, Daniel Merfeld, Kenneth E. Money, Charles M. Oman, Serge H. Roy, Douglas G.D. Watt	Life Science: Human Physiology
	Protein Metabolism During Space Flight	T. Peter Stein, R. Gregg Settle	Life Science: Human Physiology
	Fluid-Electrolyte Regulation During Spaceflight	Carolyn S. Leach-Huntoon, Clar- ence P. Alfrey, Joel I. Leonard, Paul C. Rambaut, Wadi N. Suki	Life Science: Human Physiology
	Pulmonary Function During Weightlessness	John West, Ann Elliott, Harold Guy, G. Kim Prisk, Peter Wagner	Life Science: Human Physiology
	Lymphocyte Proliferation in Weightlessness	Augusto Cogoli, Birgitt Bechler, Marianne Cogoli, Sue B. Criswell, Helen Joller, Peter Joller, Otfried Muller	Life Science: Human Physiology
	Influence of Space Flight on Erythrokinetics in Man	Clarence P. Alfrey, Carolyn S. Leach-Huntoon, Mark M. Udden	Life Science: Human Physiology
	Cardiovascular Adaptation to Microgravity	C. Gunnar Blomqvist, Jay C. Buckey, Francis Andrew Gaff- ney, Lynda D. Lane, Benjamin D. Levine, Robert M. Peshock, Donald E. Watenpugh, Sheryl J. Wright	Life Science: Human Physiology

Mission	Experiment Title	Investigators	Discipline
STS-40/ SLS-1	Pathophysiology of Mineral Loss During Space Flight	Claude D. Arnaud, Christopher E. Cann	Life Science: Human Physiology
	Regulation of Erythropoiesis During Space Flight (Part 2)	Albert T. Ichiki, Zuhair Al-Lebban, Linda A. Gibson	Life Science: Animal Physiology
	Regulation of Erythropoiesis During Space Flight (Part 1)	Robert D. Lange, Albert T. Ichiki, J.B.Jones	Life Science: Animal Physiology
	Regulation of Blood Volume During Space Flight	Clarence P. Alfrey, Theda B. Driscoll, Ronald G. Nachtman, Mark M. Udden	Life Science: Human Physiology
	Bone, Calcium and Space Flight	Emily R. Morey-Holton, Christopher E. Cann, Stephen B. Doty, W. Eugene Roberts, Arthur C. Vailas	Life Science: Human Physiology
	A Study of the Effects of Space Travel on Mammalian Gravity Receptors	Muriel D. Ross	Life Science: Animal Physiology
	Effects of Microgravity-Induced Weightlessness on <i>Aurelia</i> Ephyra Differentiation and Statolith Synthesis	Dorothy B. Spangenberg	Life Science: Developmental
	Skeletal Myosin Isoenzymes in Rats Exposed to Microgravity	Joseph Foon Yoong Hoh	Life Science: Animal Physiology
	Effects of Microgravity on Biochemical and Metabolic Properties of Skeletal Muscle in Rats	Kenneth M. Baldwin, Vince J. Ciazozzo	Life Science: Animal Physiology
	The Effects of Microgravity on the Electron Microscopy, Histochemistry and Protease Activities of Rat Hindlimb Muscles	Daniel A. Riley, Stanley Ellis, A.L.Haas	Life Science: Animal Physiology
	Bone Biomechanics	Philip C. Johnson, A.V. Bakulin, Emily R. Morey-Holton	Life Science: Animal Physiology
	Ultrastructure of the Brain Cortex	V.P.Popovic, Ludmilla N. Dyachkova, Oliver H. Lowry	Life Science: Animal Physiology
	Catecholamines, Vasopressing, Atrial Natriuretic Factor (ANF) and ANF Receptors in the Rat Brain	Claude C. Gharib, Jacqueline Gabrion, Jean-Marc Pequignot, Gerald Sonnefeld	Life Science: Animal Physiology
	Atrial natriuretic peptide and Guanylate Cyclase	Rupert Gerzer	Life Science: Animal Physiology
	ANP binding sites are increased in choroid plexus of SLS-1 rats after 9 days of space flight	C. Gharib, R.V. Ballard, J. Davet, J. Gabrion, S. Herbute, J. Olivier, M. Viso	Life Science: Animal Physiology
	Effects of Spaceflight on Anterior Pituitary Receptors	Richard E. Grindeland	Life Science: Animal Physiology
	Metabolic and Structural Changes in Bone and Systems Regulating Bone Growth Metabolism	Alexander S. Kaplansky, E.I. Alekseyev, T.E. Burkovskaya, G.N. Durnova, N.Y.Fedotova, M.V.Frontasyeva, S.F. Gundorina, E.I. Ilyina-Kakueva, V.I. Loginov, Emily R. Morey-Holton, V.M. Nazarov, Irena A. Popova	Life Science: Animal Physiology
	Effect of Spaceflight Factors on the Functional Activity of Immune Cells	Irina V. Konstantinova, Robert D. Lange, Henry A. Leon, A.T. Lesnyak, A.A. Markin, D.O. Meshkov, T.G. Orlova, M.P. Rykova	Life Science: Animal Physiology
	Cytochemistry of Neurons	L.M. Gershtein, Fernando E. D'Amelio, Nancy G. Daunton, William R. Mehler, A.V. Sergutina	Life Science: Animal Physiology
	Neuronal Morphology	T.A. Leontovich, P.V. Belichenko, A.A. Fedorov, Oliver H. Lowry, M.A. Makhanov	Life Science: Animal Physiology

Mission	Experiment Title	Investigators	Discipline
STS-40/ SLS-1	Perceptive Structure of the Brain: Morphology and Histochemistry	Igor B. Krasnov, Nancy G. Daunton	Life Science: Animal Physiology
	Spinal Cord and Dorsal Root Ganglion Morphology and Histochemistry	Igor B. Krasnov, V.I. Drobyshev, V. Reginald Edgerton, Oliver H. Lowry, I.V. Polyakov	Life Science: Animal Physiology
	Histochemistry of the Hypothalamus	Igor B. Krasnov, Richard E. Grindeland, Paul E. Sawchenko, Wylie Vale	Life Science: Animal Physiology
	Morphology of Neurons of the Brain Cortex	T.A. Leontovich, P.V. Belichenko, A.A. Fedorov, Oliver H. Lowry, M.A. Makhanov	Life Science: Animal Physiology
	Tissue Fluid-Electrolyte Composition	Yuri V. Natochin, S.Y. Ivanova, Lanny C. Keil, E.A. Lavrova, Luva V. Serova, E.I. Shakhmatova, E.V. Snetkova	Life Science: Animal Physiology
	Osteogenesis: Tissue Factors of Regulation	Victor S. Oganov, Olga R. Kabitskaya, Emily R. Morey-Holton, D.D. Sumarokov	Life Science: Animal Physiology
	Contractile Properties of Skeletal Muscles	Victor S. Oganov, V. Reginald Edgerton, Olga E. Kabitskaya, L.M. Murasko, Daniel A. Riley	Life Science: Animal Physiology
	Lipid Peroxidation and Antioxidant Defense System	Irena A. Popova, A.A. Markin, Alfred H. Merrill, O.A. Zhuraleva	Life Science: Animal Physiology
	Mechanism of Formation of the Gastric Hypersecretory Syndrome of the Stomach	K.V. Smirnov, N.P. Goncharova, R.A. Pechyonkina, Robert W. Phillips	Life Science: Animal Physiology
	Exocrine Functions of the Pancreas: Mechanisms of Changes	K.V. Smirnov, N.P. Goncharova, Paul Lacy, R.A. Pechyonkina	Life Science: Animal Physiology
	Study of the Digestive Transportation Function of the Small Intestine	K.V. Smirnov, N.P. Goncharova, Robert W. Phillips, R.A. Pechyonkina	Life Science: Animal Physiology
	Histologic examination of lung tissue	John B. West, Ann Elliott, O. Mathieu-Costello	Life Science: Animal Physiology
	Ventilatory inhomogeneity determined from multiple-breath washouts during sustained microgravity on Spacelab SLS-1	M. Paiva, A.R. Elliott, H.J.B. Guy, G.K. Prisk, J.B. West	Life Science: Human Physiology
	Influence of microgravity on different metabolic potentials of intestinal microflora (Effect of Microgravity on the Relations Between Microbiological and Epithelial Tissue and Functions of the Gastrointestinal Tract)	Odette Szylit, C. Andrieux, J.C. Meslin, L. Nugon-Baudon, S. Rabot, M. Viso, R. Ravisce	Life Science: Animal Physiology
STS-42/ IML-1	Protein Crystal Growth (PCG)	Charles E. Bugg, Daniel Carter, Howard Einspahr, Louis Delbaere, Patrica Weber, Keith Ward, Don Voet, Ada Yonath, George Birnbaum, Edward Arnold, Shigeo Aibara, Manuel Navia, Arthur Frankel	Physical Science: Biotech
	Single Crystal Growth of Beta-Galactosidase and Beta-Galactosidase/Inhibitor Complex	W. Littke	Physical Science: Biotech
	Crystal Growth of the Electrogenic Membrane Protein Bacteriorhodopsin	G. Wagner	Physical Science: Biotech
	Crystallization of Proteins and Viruses in Microgravity by Liquid-Liquid Diffusion	Alexander McPherson, Charles E. Bugg	Physical Science: Biotech
	Study of Solution Crystal Growth in Low-Gravity (TGS)	Ravindra B. Lal; J. Trolinger; A. Batra; William R. Wilcox	Physical Science: Materials

Mission	Experiment Title	Investigators	Discipline
STS-42/ IML-1	An Optical Study of Grain Formation: Casting and Solidification Technology (CAST)	Mary H. McCay; L. Smith; T. McCay; S. Lowry; J. Hopkins; M. Vesko; R. Porter	Physical Science: Materials
	Vapor Crystal Growth Studies of Single Mercury Iodide Crystals	Lodewijk van den Berg; C. Bac-cash; L. Frank	Physical Science: Materials
	Mercury Iodide Nucleations and Crystal Growth in Vapor Phase (MICG)	Robert Cadoret; L. van den Berg; F. Le Lay	Physical Science: Materials
	Organic Crystal Growth Facility (OCGF)	Akio Kanbayashi, Hiroyuki An-zai, Keizo Murata, Masaaki Ohm-asa, Kenji Hagiya, Aiko Yamazaki, Seiichiro Yamamoto, Nobumori Kinoshita, Madoka Tokumoto, Akira Negishi, Eiji Nagaki, Yo-shito Arai, Yoshiaki Anno	Physical Science: Materials
	Study of Density Distribution in a Near-Critical Simple Fluid	Antonius C. Michels	Physical Science: Fluids
	Heat and Mass Transport in a Pure Fluid in the Vicinity of a Critical Point (BEM2)	Daniel Beysens	Physical Science: Fluids
	Phase Separation of an Off-Critical Binary Mixture (BEM1)	Daniel Beysens	Physical Science: Fluids
	Critical Fluid Thermal Equilibration Experiment	R. Allen Wilkinson	Physical Science: Fluids
	Phase Partitioning Experiment (PPE)	Donald E. Brooks, J. Van Alstine, J. Harris, J. Boyce	Physical Science: Biotech
	Proliferation and Performance of Hybridoma Cells in Microgravity (HYBRID)	Augusto Cogoli, B. Bechler, M. Cogoli	Life Science: Cell and Molecular
	Cultivation of Hamster Kidney Cells in a Dynamic Cell Culture System (CULTURE)	Augusto Cogoli, F.K. Gmuen-der, G. Lorenzi, C.G. Nordau	Life Science: Cell and Molecular
	Chondrogenesis in Micromass Cultures of Mouse Limb Mesenchyme Exposed to Microgravity (CELLS)	Pauline Jackie Duke, T. Hewitt	Life Science: Animal Physiology
	Effects of Microgravity and Mechanical Stimulation on the In- Vitro Mineralization and Resorption of Fetal Mouse Bones (BONES)	Jacobos-Paul Veldhuijzen, J.J.W.A. van Loon, E. Burger, G. Kampen	Life Science: Devel- opmental
	Why Microgravity Might Interfere With Amphibian Egg Fertilization and the Role of Gravity in Determination of the Dorsal/Ventral Axis in Developing Amphibian Embryos (EGGS)	Geertje A. Ubbels, M. Reijnen, J. Meijerink, J. Narraway	Life Science: Devel- opmental
	Leukemia Virus Transformed Cells to Microgravity in the Presence of DMSO (FRIEND)	A. Cogoli, B. Bechler, E. Hunz-inger, O. Meuller, M. Cogoli	Life Science: Cell and Molecular
	Genetic and Molecular Dosimetry of HZE Radiation (RADIAT)	Gregory A. Nelson, Philip S. Harman, Wayne W. Schubert, E. Benton	Life Science: Radia- tion
	Dosimetric Mapping Inside Biorack (DOSIMTR)	Guenther Reitz, R. Facius, R. Beaujean, C. Heilmann, M. Schaefer, W. Enge, W. Heinrick	Life Science: Radia- tion
	Embryogenesis and Organogenesis of Carausius Morosus (MOROSUS)	Horst Buecker, R. Facius, G. Reitz, R. Beaujean, W. Enge, W. Heinrids, E. Graul, W. Rucher	Life Science: Devel- opmental/ Radiation
	Effects of Space Environment on the Development of Drosophila Melanogaster (FLY)	Roberto Marco, J. Gonzalo-Jurado, M. Calleja, M. Man-zanares, M. Maroto, E. deJuan, J. Miquel	Life Science: Devel- opmental
	Microgravitational Effects on Chromosome Behavior (YEAST)	Carlo V. Bruschi, Michael S. Esposito, J. Colasanti	Life Science: Cell and Molecular

Mission	Experiment Title	Investigators	Discipline
STS-42/ IML-1	Growth and Sporulation in Bacillus Subtilis Under Microgravity (SPORES)	Horst-Dieter Menningmann, M. Heise, M. Lange, B. Ernst	Life Science: Cell and Molecular
	Studies on Penetration of Antibiotics in Bacterial Cells in Space Conditions (ANTIBIO)	Rene Tixador, G. Tap, N. Moatti, L. Lapchine, C. Woldringh, B. Eche, P. Toorop, F. Delmotte, J.P. Moatti, G. Gasset, G. Richoilley, J. Bes, J. Templier, G. Farre	Life Science: Cell and Molecular
	Gravity Related Behavior of the Acellular Slime Mold Physarum Polycephalum (SLIME)	Ingrid Block, A. Wolke, W. Briegleb, K. Wohlfarth-Bottermann	Life Science: Cell and Molecular
	Genotype Control of Gravidresponse, Cell Polarity and Morphological Development of Arabidopsis Thaliana in Microgravity (SHOOTS)	Edmund P. Maher, L. Greg Briarty, T.H. Iversen	Life Science: Plant
	Effects of Microgravity Environment on Cell Wall Regeneration, Cell Divisions, Growth and Differentiation of Plants From Protoplasts (PROTO)	Ole Rasmussen, C. Baggerud, T.H. Iversen, R. Wyndale, J. Christiansen	Life Science: Plant
	Gravitropic Responses of Plants in the Absence of a Complicating G-Force (Gravity Threshold (GTHRES))	Allan H. Brown, Anders Johnson, David G. Heathcote	Life Science: Plant
	Response to Light Stimulation: Phototropic Transients - A spaceflight experiment to investigate the effects of a range of unilateral blue light stimulations on the movements of wheat coleoptiles (FOTRAN)	David G. Heathcote, Allan H. Brown, David K. Chapman	Life Science: Plant
	Transmission of the Gravity Stimulus in Statocyte of the Lentil Root (ROOTS)	Gerald Perbal, D. Driss-Ecole, J. Raffin, G. Salle, K. Waldon	Life Science: Plant
	Energy Expenditure in Spaceflight (EES)	Howard G. Parsons, M. Preshaw, H. Krouse, J. Thirsk	Life Science: Human Physiology
	Position and Spontaneous Nystagmus (PSN)	Joseph A. McClure	Life Science: Human Physiology
	Measurement of Venous Compliance & Evaluation of an Experimental Anti-Gravity Suit (MVC)	Robert B. Thirsk, L. Goodman, M. Pecaric, K. Ackles, J. Bennett, J. Charles, R. Aaslid, M. Kassam, P. Dunphy, D. Leiski, P. Sullivan, R. Bondar	Life Science: Human Physiology
	Assessment of Back Pain in Astronauts (BPA)	Peter C. Wing, R. Gagnon, L. Susak, F. Gagnon, I. Tsang	Life Science: Human Physiology
	Space Adaptation Syndrome Experiments (SASE)	D.G. D. Watt, G. Melville-Jones, J. Lackner, J. Landolt, M. Reschke, L. Young, A. Bensen, F. Guedry, R. Jell, D. Parker	Life Science: Human Physiology
	Biostack (BSK)	Horst Buecker, E. Benton, A. Kranz, U. Bork, R. Facius, J. Schott, W. Ruether, O. Gaul, J. Keifer, A. Tallentire, S. Takasaki, F. Masami, I. Ken-Ichic, T. Hiroshi, W. Enge, Guenther Reitz, R. Beaujean, M. Schaefer, W. Heinrich	Life Science: Radiation
	Radiation Monitoring Container Device (RMCD)	Shunji Nagaoka, Tadayoshi Doke, Koichi Ogura, Hiroaki Yamada, Tan Takahashi, Fumio Yatagai, Masanobu Ishikawa, Fumio Takahashi, Osamu Yazu	Life Science: Radiation

Mission	Experiment Title	Investigators	Discipline
STS-42/ IML-1	Microgravity Vestibular Investigations (MVI)	Millard F. Reshke, D. Anderson, A. Berthoz, O. Black, G. Clement, B. Cohen, F. Guedry, J. Homick, C. Oman, M. Igarashi, P. Dizio, R. Lackner, D. Parker, J. Vanderploeg, S. Wood, W. Poloski, A. Benson, R. Jell, D. Watt, T. Raphan, O. Garriott	Life Science: Human Physiology
	Mental Workload and Performance Experiment (MWPE)	Harold L. Alexander, B. Lichtenberg	Life Science: Human Factors
	Repair of radiation induced genetic damage under micro-gravity	H.D.Pross	Life Science: Radiation
STS-45/ ATLAS-1	Imaging Spectrometric Observatory (ISO)	Marsha R. Torr, Douglas Torr	Atmospheric Science
	Atmospheric Trace Molecule Spectroscopy (ATMOS)	Michael R. Gunson, Reinhard Beer, Linda R. Brown, Odell F. Raper, Geoffrey C. Toon, Robert A. Toth, Crofton B. Farmer, Curtis P. Rinsland, Rodolphe Zander	Atmospheric Science
	Grille Spectrometer (Grille)	Marcel Ackerman, Jean Bes-son, Claude Camy-Peyret, Dirk Frimout, Andre Girard, Nicole Papineau, Martine de Maz-iere, Carlos Lippens, Christian Muller, Jacques Vercheval, Jean-Paul Meyer	Atmospheric Science
	Atmospheric Lyman-Alpha Emissions (ALAE)	Jean-Louis C. Bertaux, Florence Goutail, Rosine Lallement, H. Le Texier, Gaston Kockarts	Atmospheric Science
	Millimeter-Wave Atmospheric Sounder (MAS)	Gerd Hartmann, Niklaus Kempfer, Klaus F. Konzi, Phillip R. Schwartz, Christoph Aellig, Richard M. Bevilacqua, Thomas Pauls, Charles L. Croskey, John J. Olivero, Enrique Puliafito, Werner Degenhardt, J. Langen	Atmospheric Science
	Shuttle Solar Backscatter Ultraviolet (SSBUV)	Ernest Hilsenrath, Richard P. Cebula, Donald F. Heath, John E. Frederick, Bruce W. Guenther, James E. Mentall, Richard D. McPeters, Alvin J. Miller, Walter G. Planet	Atmospheric Science
	Solar Spectrum Measurement (SOLSPEC)	Gerard O. Thuillier, Michel Herse, Dietrich Labs, William Peetermans, Paul Simon	Solar Science
	Active Cavity Radiometer (ACR)	Richard C. Willson	Solar Science
	Measurement of Solar Constant (SOLCON)	D. Crommelynck, Bruce R. Barkstrom, Vicente Domingo	Solar Science
	Solar Ultraviolet Spectral Irradiance Monitor (SUSIM)	Guenter E. Brueckner, Judith Lean, Dianne Prinz, Michael VanHoosier	Solar Science
	Atmospheric Emissions Photometric Imaging (AEPI)	Steven B. Mende, Stuart K. Clifton, David L. Reasoner, Gary Swenson	Space Plasma Physics

Mission	Experiment Title	Investigators	Discipline
STS-45/ ATLAS-1	Space Experiments with Particle Accelerators (SEPAC)	James L. Burch, Peter M. Banks, Nobuki Kawashima, William T. Roberts, C. Richard Chappell, David L. Reasoner, William W.L. Taylor	Space Plasma Physics
	Energetic Neutral Atom Precipitation (ENAP)	Brain A. Tinsley, R.P. Rohrbaugh, W.B. Hanson	Space Plasma Physics
	Far Ultraviolet Space Telescope (FAUST)	C. Stuart Bowyer, George Courtes, Jean-Michel Deharveng, Michael Lampton, Roger Malina	Astronomy
STS-47/ SL-J	Space acceleration measurement system (SAMS)	Richard DeLombard	Physical Science: Materials
	Inflight Demonstration of the Space Station Freedom Health Maintenance Facility Fluid Therapy System	Charles Lloyd	Physical Science: Materials
	Preparation of Ni-base Dispersion Strengthened Alloys	Yuji Muramatsu, Takehiro Dan	Physical Science: Materials
	Growth experiment of narrow band-gap semiconductor PbSnTe single crystal in space	Tomoaki Yamada, Kyoichi Kinoshita	Physical Science: Materials
	Growth of PbSnTe Single Crystal by Traveling Zone Method	Souhachi Iwai, Yuzaburo Segawa	Physical Science: Materials
	Growth of Semiconductor Compound Single Crystal with a Floating Zone Technique	Isao Nakatani, Satoshi Takahashi, Kiyoshi Ozawa, Isao Nishida	Physical Science: Materials
	Casting of superconducting filamentary composite materials	Kazumasa Togano, Hiroki Fujii, Hiroaki Kumakura, Hitoshi Kitaguchi, Hitoshi Wada	Physical Science: Materials
	Formation Mechanism of Deoxidation Products in Iron Ingots Deoxidized with Two or Three Elements	Akira Fukuzawa, Sadao Furuyama, Fumiaki Matsumoto, Satoshi Iwasaki	Physical Science: Materials
	Diffusion in liquid state and solidification of binary system	Takehiro Dan, Takashi Kimura, Yuji Muramatsu, Toshihiro Yamagata, Ken-ichi Hosimoto	Physical Science: Materials
	Behavior of Glass at High Temperatures	Naohiro Soga, Kazuyuki Hirao, Katsuhisa Tanaka, Kazuki Nakanishi, Teiichi Hanada	Physical Science: Materials
	Growth of Spherical Silicon Crystals and Surface Oxidation	Tatau Nishinaga, Kunihiro Asada, Takuo Sugano, Osami Saito, Takashi Katoda, Masato Kishi	Physical Science: Materials
	Study on solidification of immiscible alloy	Akihiko Kamio, Hiroyasu Tezuka, Shinji Kumai, Tsuneo Takahashi	Physical Science: Materials
	Fabrication of Ultra-low Density/High-stiffness Carbon Fiber and Aluminum Composite	Tomoo Suzuki, Yoshinao Mishima, Seiji Miura	Physical Science: Materials
	Study on Liquid Phase Sintering	Shiro Kohara	Physical Science: Fluids
	Fabrication of Si-As-Te:Ni ternary amorphous semiconductor in microgravity environment	Yoshihiro Hamakawa, Hiroaki Okamoto, Kiminori Hattori, Toshinaga Sada	Physical Science: Materials
	Gas Evaporation in Low Gravity Field: Congelation Mechanism of Metal Vapors	Nobuhiko Wada, Manabu Kato, Shinya Sawai, Masaya Sengoku, Toshikazu Sato, Toshiaki Goto, Toshiaki Noda, Masaaki Tani, Minoru Dohi	Physical Science: Materials

Mission	Experiment Title	Investigators	Discipline
STS-47/ SL-J	Drop dynamics in an acoustic resonant chamber and interference with the acoustic field	Tatsuo Yamanaka, Heihachiro Kamimura	Physical Science: Fluids
	Bubble Behavior in a Thermal Gradient and Stationary Acoustic Wave	Hisao Azuma, Mitsuru Onishi, Shoichi Yoshihara, Sachio Ogiwara	Physical Science: Fluids
	Preparation of Optical Materials For Use in Non-visible Region	Junji Hayakawa, Masaki Maki-hara, Kohei Fukumi	Physical Science: Materials
	Marangoni Effect-induced Convection in Material Processing Under Microgravity	Keiichi Kuwahara; Enya, Shintaro; Uchida, Hiroyuki; Ochiai, Junichi; Akiyoshi, Ryou; Ohara, Akiko	Physical Science: Fluids
	Solid Surface Combustion Experiment (SSCE)	Robert A. Altenkirch	Physical Science: Fluids
	Solidification of Eutectic System Alloys in Space	Atsumi Ohno, Tetsuichi Motegi	Physical Science: Materials
	Growth of Samarskite Crystals under Microgravity Conditions	Shunji Takekawa, Isamu Shindo, Yoshinori Sugitani	Physical Science: Materials
	Crystal-growth experiment of organic metals in low gravity	Hiroyuki Anzai, Shinichi Nakatsuji, Eiji Nagaki, Yoshito Arai, Yoshiaki Anno, Akio Kanbayashi	Physical Science: Materials
	Crystal Growth of Compound Semiconductors (InGaAs) in a Low-gravity Environment	Masami Tatsumi, Shigeo Murai, Suguru Shirakawa, Takashi Araki, Shinsuke Fujiwara	Physical Science: Materials
	Experimental Study of Morphological Stability During Different Convection Conditions	T. Carlberg	Physical Science: Materials
	Protein Crystal Growth	Charles E. Bugg.; E. L. Amma; A. Arnone; J. K. Baird; B. Broom; D. O. Frazier; H. Blair; L. W. Graeme; P. Lu; E. J. Meehan; Daniel Carter; Roger L. Kroes; Lawrence J. DeLucas; Alexander McPherson	Physical Science: Biotech
	Separation of Bacterial Cells by Free-flow Electrophoresis	Takio Yamaguchi, Shunji Nagaoka, Teruhiko Akiba, Muneo Takaoki, Atsuko Nishi, Hiroyuki Matsumiya, Fusao Tomita	Physical Science: Biotech
	Separation of Biogenic Materials by Electrophoresis Under Zero Gravity	Masao Kuroda, Tatsuya Tanaka, Mitsuo Uozumi, Hiroshi Wada, Kunio Tagawa	Physical Science: Biotech
	Crystal Growth of Enzymes Under Microgravity	Yuhei Morita, Shigeo Aibara, Fumizo Mikami	Physical Science: Biotech
	Magnetic Resonance Imaging after Exposure to Microgravity	Adrian LeBlanc	Life Science: Human Physiology
	Plant Culture Research (Gravity, Chromosomes, and Organized Development in Aseptically Cultured Plant Cells)	Abraham Krikorian	Life Science: Plant
	Lower Body Negative Pressure: Countermeasure for Reducing Post-Flight Orthostatic Intolerance	John B. Charles	Life Science: Human Physiology
	Affects of Weightlessness in the Development of Amphibian Eggs Fertilized in Space	Kenneth Souza, Steven Black, Muriel D. Ross, Richard Wassersug	Life Science: Developmental
	Bone Cell Growth and Mineralization in Microgravity	Nicole Partridge	Life Science: Cell and Molecular
	Autogenic Feedback Training (AFT)	Patricia S.Cowings, Joe Kamiya, Neal E. Miller, William B. Toscano, Joseph C. Sharp	Life Science: Human Physiology

Mission	Experiment Title	Investigators	Discipline
STS-47/ SL-J	Health Monitoring of Japanese Payload Specialist-Autonomic Nervous and Cardiovascular Responses under Reduced Gravity	Chiharu Sekiguchi, Tadashi Murai, Masanori Ishii, Kazuyoshi Yajima, Kiyoshi Nakayama	Life Science: Human Physiology
	Endocrine and Metabolic Changes of Payload Specialist during Spacelab-J	Hisao Seo, Nobuo Matsui, Yoshiharu Murata, Norihiro Miyamoto, Fukuji Kanbe, Yoshitaka Hayashi, Yoshihiro Tamura	Life Science: Human Physiology
	Neurophysiological study on visuo-vestibular control of posture and movement in fish during adaptation to prolonged weightlessness	Shigeo Mori, Genyo Mitarai, Akira Tkabayashi, Sadaharu Takagi, Shiro Usui, Manabu Sakakibara, Makoto Nagatomo, R.J. von Baumgarten	Life Science: Animal Physiology
	Comparative Measurement of Visual Stability in Earth and Cosmic Space	Kazuo Koga, Tadaaki Mano, Mitsuro Kida, Yoshihiro Ohta, Keiichiro Tstji, Takuo Goto, Ryoji Osaka	Life Science: Human Physiology
	Studies on the Effects of Microgravity on the Ultrastructure and Function of Cultured Mammalian Cells	Atsushige Sato, Yasuhiro Kumei, Toshio Hongo, Kazuko Sato, Tatsuo Hamasaki, Ichiro Masuda, Toru Nakajima, Takeo Omura, Masayoshi Kaiho, Tetsuji Sato, Kenjiro Wake	Life Science: Cell and Molecular
	Study of the effects of microgravity on cell growth of human antibody producing cells and their secretions	Toshio Suganuma, Hisayoshi Ooka, Tamotsu Fukuda	Life Science: Cell and Molecular
	Organ differentiation in cultured plant cells under microgravity	Fumihiko Sato, Atsushige Sato, Yasuyuki Yamada, Hisashi Matsushima, Satomi Takeda	Life Science: Plant
	The Effect of Microgravity on Calcium Metabolism and Bone Formation in Chick Embryo	Tatsuo Suda, Hiroshi Horikawa, Yutaka Nagai, Katsuhiko Arai, Fujio Suzuki, Hiroyoshi Endo, Kosaku Maruyama, Shushichi Takahashi, Teru Ishibashi, Emiko Watanabe, Sumihare Noji, Isamu Kashima, Sadao Yasugi, Mitsuru Naito, G.M. Cohen, G.W. Conrad, R.S. Tuan	Life Science: Developmental
	Genetic effects of HZE and cosmic radiation	Mituo Ikenaga, Isao Yoshikawa, Moto Kojyo, Yumiko Kato, Toshikazu Ayaki, Haruko Ryo, Kanji Ishizaki, Tomohisa Kato, Hanako Yamamoto, Ryujiro Hara	Life Science: Radiation
	Manual Control in Space - Research on perceptual motor functions under microgravity condition	Akira Tada, Masanori Okabe	Life Science: Human Physiology
	Consideration of Biological Effects of Cosmic Radiation and Development of Measures to Protect Astronauts from Radiation	Shunji Nagaoka, Tadayoshi Doke, Kazuki Harada, Takayoshi Hayashi, Takeo Ohnishi, Koichi Ogura, Hiroaki Yamada, Tan Takahashi, Fumio Yatagai, Masanobu Ishikawa, Fumio Takahashi, Hiroshi Tanooka	Life Science: Radiation
	Circadian Rhythm of Conidiation in Neurospora Crassa	Yasuhiro Miyoshi, Yuji Mori-yasu, Mineo Iseki	Life Science: Plant
	Israeli Space Agency Investigation About Hornets (ISA-IAH)	Jacob S. Ishay	Life Science: Developmental

Mission	Experiment Title	Investigators	Discipline
STS-50/ USML-1	Orbital Processing of High-Quality CdTe Compound Semiconductors	David J. Larson; J. I. D. Alexander; G. Bostrup; F. M. Carlson; Donald C. Gillies; D. F. Jankowski; G. P. Neitzel; B. Steiner; R. R. Neugaonkar; William R. Wilcox	Physical Science: Materials
	Crystal Growth of Selected II-VI Semiconducting Alloys by Directional Solidification	Sandor L. Lehoczky; Frank Szofran; Donald C. Gillies; Sharon D. Cobb; Ching-Hua Su, Y.-G. Sha; R. N. Andrews; L. N. Bubulac	Physical Science: Materials
	The Study of Dopant Segregation Behavior During the Growth of GaAs in Zero Gravity	David H. Matthiesen; J.A. Majewski; J. Kafalas; S. Motakef	Physical Science: Materials
	Vapor Transport Crystal Growth of Mercury Cadmium Telluride	Wiedemeier, Heribert	Physical Science: Materials
	Surface Tension Driven Convection Experiment (STDCE)	Simon Ostrach; Alexander D. Pline; Yasuhiro Kamotani	Physical Science: Fluids
	Drop Dynamics Experiment: Core-Centering of Compound Drops in Capillary Oscillations	Taylor G. Wang; C.P. Lee; M. Barmatz; A. V. Anilkumar; K.C. Lin; E. H. Trinh	Physical Science: Fluids
	Science and Technology of Surface Controlled Phenomena	Robert E. Apfel; Yuren Tian; Tao Shi; Xiaoyu Zheng; D. Elleman; R. Glynn Holt	Physical Science: Fluids
	Measurement of Liquid-Liquid Interfacial Tension and Phase Separation Kinetics of Fluid Glass Melts	Michael C. Weinberg; G.F. Neilson; Eugene H. Trinh; Carl Baertlein; R. Shankar Subramanian	Physical Science: Fluids
	Zeolite Crystal Growth (ZCG)	Albert Sacco; N. Bac; E.N. Coker; A. G. Dixon; J. Warzywoda; R. W. Thompson	Physical Science: Materials
	CGBA: Formation of 3-Dimensional Bacteriorhodopsin Gels in Microgravity	R. Birge; D. Govender; M. W. Luttges; S. Simske; L. Stodieck	Physical Science: Biotech
	Glovebox Protein Crystal Growth (GPCG)	Lawrence J. DeLucas, K. M. Moore; M. van der Woerd; T. L. Bray; C. Smith; M. Carson; S. V. L. Narayana; W. M. Rosenblum; A. D. Clark; R. G. Nanni; J. Ding; A. Jacobo-Molina; G. Kamer; S. H. Hughes; L. L. Clancy; G. S. J. Rao; P. F. Cook; B. G. Harris; S. H. Munson; B. C. Finzel; P. C. Weber; F. A. Lewandowski; K. P. Wilson; J. A. Thomson; C. J. Meade; S. P. Bishop; B. J. Dunbar; E. Trinh; J. Prahl; Albert Sacco; Charles E. Bugg; Drake Eggleston; James Knox; Keith Ward; Alexander McPherson; Daniel Carter; Edwards Arnold; Manuel A. Navia; Bud Suddath; T. L. Nagabhushan; Ponzy Lu; Howard Einspahr; Ed Meehan	Physical Science: Biotech
	CGBA: Viral Protein Assembly in Microgravity	Richard Consigli; D. Chan; A. Paulsen; S. Rottinghaus; T. Johnson; S. Simske; Marvin Luttges; Louis Stodieck	Physical Science: Biotech

Mission	Experiment Title	Investigators	Discipline
STS-50/ USML-1	CGBA: Protein Crystal Growth Habit	P. Todd; M. Sportiello; M.W. Luttges; S. Simske; L. Stodieck	Physical Science: Biotech
	CGBA: Lysozyme Crystallization by Osmotic Dewatering	P. Todd; M. Sportiello; M.W. Luttges; S. Simske; L. Stodieck	Physical Science: Biotech
	CGBA: Mass Crystallization of Lysozyme	P. Todd; M. Sportiello; M.W. Luttges; S. Simske; L. Stodieck	Physical Science: Biotech
	Commercial Generic Bioprocessing Apparatus (CGBA)	L. Stodieck, M. Robinson, M. Luttges	Technology
	Directed Orientation of Polymerizing Collagen Fibers	L. Stodieck; Marvin Luttges; T. Bergren; M.C. Robinson	Physical Science: Biotech
	Solid Surface Combustion Experiment	Robert A. Altenkirch.; Kurt Sacksteder; Subrata Bhattacharjee; Prashant A. Ramachandra; Lin Tang; M. Katherine Wolverton	Physical Science: Fluids
	Space Acceleration Measurement System	Charles Baugher	Physical Sciences: Materials
	Passive Accelerometer System	J. Iwan D. Alexander; Melissa J.B. Rogers; Charles Baugher; Robert Naumann	Physical Science: Materials
	Interface Configuration Experiment	Paul Concus; Robert Finn; Mark M. Weislogel	Physical Science: Fluids
	Stability of a Double Float Zone	Robert J. Naumann; Dieter Langbein; Narayanan Ramachandran	Physical Science: Fluids
	Solid Surface Wetting Experiment	Eugene H. Trinh, J. Depew	Physical Science: Fluids
	Marangoni Convection in Closed Containers	Robert J. Naumann	Physical Science: Fluids
	Smoldering Combustion in Microgravity	A. Carlos Fernandez-Pello; Sandra L. Olson; Dennis P. Stocker; Jose L. Torero	Physical Science: Fluids
	Wire Insulation Flammability Experiment	Paul S. Greenberg; Kurt R. Sacksteder; Kashiwagi, Takashi	Physical Science: Fluids
	Candle Flames in Microgravity	Howard Ross; D. L. Dietrich; J. S. T'ien	Physical Science: Fluids
	Fiber Pulling in Microgravity	Robert J. Naumann; B. J. Dunbar; D. Nover	Physical Science: Materials
	Nucleation of Crystals From Solutions In A Low-g Environment	Roger L. Kroes; Sandor L. Lehoczy; Donald A. Reiss	Physical Science: Materials
	Oscillatory Dynamics of Single Bubbles & Agglomeration in an Ultrasonic Field	Philip L. Marston; Eugene H. Trinh; Jon Depew; Thomas J. Asaki	Physical Science: Fluids
	Stability of a Double Float Zone	Robert J. Naumann; Narayanan Ramachandran	Physical Science: Fluids
	Oscillatory Thermocapillary Flow Experiment	Simon Ostrach; Alexander D. Pline; Yasuhiro Kamotani	Physical Science: Fluids
	Particle Dispersion Experiment	John R. Marshall	Physical Science: Fluids
	Zeolite Glovebox Experiment	Albert Sacco	Physical Science: Biotechnology
	Extended Duration Orbiter Medical Project	J. Travis Brown	Life Science: Human Physiology
	CGBA: Fibrin Assembly in Microgravity and Magnetic Fields	Konrad Pollmann; S. Simske; Marvin Luttges; Louis Stodieck	Physical Science: Biotechnology

Mission	Experiment Title	Investigators	Discipline
STS-50/ USML-1	Astroculture™	Theodore W. Tibbitts; R. J. Bula; R.C. Morrow; W.R. Dinauer, N. Duffie	Technology
	CGBA: Effect of space flight on tumor necrosis factor alpha induced cell lysis	Keith Chapes	Life Science: Cell and Molecular
	CGBA: Lymphocyte Activation in Microgravity	Marian L. Lewis	Life Sciences: Cell and Molecular
	CGBA: Development of Brine Shrimp in Microgravity	Brian S. Spooner	Life Sciences: Developmental
	CGBA: Development of Miniature Wasps in Microgravity	Marvin Luttges	Life Sciences: Developmental
	CGBA: Rhizobia Development in Microgravity	P.P. Wong	Life Sciences: Plant
	CGBA: Seed Germination and Early Plant Morphology in Microgravity	A. Hoehn, J. Guikema	Life Sciences: Plant
	CGBA: Effects of Gravity on the Growth and Development of <i>E. Coli</i>	D. Klaus; S. Simske; Marvin Luttges; Louis Stodieck	Life Sciences: Cell and Molecular
	CGBA: Effects of Microgravity on <i>E. coli</i> and MS-2 Bacteriophage Disinfection by Iodinated Resins.	G.L. Marchin, Joann Silverstein and Gail M. Brion	Life Sciences: Cell and Molecular
	CGBA: Microgravity Effects on Rhizobia	James Urban	Life Sciences: Plant
	CGBA: Cell-surface inhibitor activity in microgravity	T.C. Johnson	Life Sciences: Cell and Molecular
	CGBA: Spleen cells	Joseph Murray	Life Sciences: Cell and Molecular
	CGBA: Proteo-Lipid Membrane Formation and Encapsulation Efficiency During Spaceflight	D. Claassen; Brian Spooner; J. van Twest; S. Simske; Marvin Luttges; Louis Stodieck	Physical Science: Biotechnology
	CGBA: Liposome-reconstituted cardiac gap junction channeling activity	D.E.Claassen, B.S.Spooner	Physical Science: Biotechnology
	Investigations into Polymer Membrane Processing	Vince McGinniss; Lisa McCauley	Physical Science: Biotechnology
	Protein Crystal Growth (PCG/RIM/VDA)	Charles E. Bugg; Lawrence J. DeLucas; Howard Einspahr, T.L. Nagabhushan, Daniel Carter, Drake Eggleston, Alexander McPherson, M.Sundaralingam, Keith Ward, Edward Arnold, Manuel Navia, Patricia Weber, D. Voet, Robert Naumann, Alexander McPherson, Arthur Frankel, E. Meehan	Physical Science: Biotechnology
STS-52/ USMP-1	Lambda-Point Experiment (LPE)	John A. Lipa; Talso C.P.Chui	Physical Science: Fluids
	Materials for the Study of Interesting Phenomena of Solidification on Earth and in Orbit (MEPHISTO)	Jean Jacques Favier; J.P. Garandet; Andre Rouzaud; Jean Comera	Physical Science: Materials
	Space Acceleration Measurement System (SAMS)	Charles Baugher	Physical Science: Materials
STS-56/ ATLAS-2	Atmospheric Trace Molecule Spectroscopy (ATMOS)	Michael R. Gunson, Reinhard Beer, Linda R. Brown, Odell F. Raper, Geoffrey C. Toon, Robert A. Toth, Crofton B. Farmer, Curtis Rinsland, Rodolphe Zander	Atmospheric Science

Mission	Experiment Title	Investigators	Discipline
STS-56/ ATLAS-2	Millimeter-Wave Atmospheric Sounder (MAS)	Gerd Hartmann, Nicklaus Kampf, Klaus F. Kunzi, Phillip R. Schwartz, Christoph Aellig, Richard M. Bevilacqua, Thomas Pauls, Charles L. Crosskey, John J. Olivero, Enrique Puliafito, Werner Degenhardt, Paul Hartogh, Alfred Loidl, Michael Richards, Jorg Langen	Atmospheric Science
	Shuttle Solar Backscatter Ultraviolet (SSBUV)	Ernest Hilsenrath, Richard P. Cebula, John Frederick, Bruce Guenther, Donald Heath, Richard D. McPeters, James E. Mentall, Alvin Miller, Walter Planet	Atmospheric Science
	Solar Spectrum Measurement (SOLSPEC)	Bruce Cebula, John Frederick, Bruce Guenther, Donald Heath, Richard D. McPeters, James E. Mentall, Alvin Miller, Walter Planet	Solar Science
	Active Cavity Radiometer (ACR) Irradiance Monitor	Gerard O. Thuillier, Michael Herse, Dietrich Labs, William Peetermans, Paul Simon	Solar Science
	Measurement of Solar Constant (SOLCON)	Richard C. Willson, Roger S. Helizon	Solar Science
	Solar Ultraviolet Spectral Irradiance Monitor (SUSIM)	Dominique A. Crommelynck, Bruce R. Barkstrom, Vincente Domingo, Guenter E. Brueckner, Michael E. VanHoosier, Dianne K. Prinz, A. Colaprete, R. W. Shepperd, K. A. Wahl, and D. R. Rodier	Solar Science
STS-55/ SL-D2	Galactic Ultrawide-Angle Schmidt System Camera (GAUSS)	T. Miski, K.-H. Weber, L. Schmidtbreick, W. Schlosser, P. Kocz, S. Wiemann, M. Juetten	Astronomy
	Modular Optoelectronic Multispectral Stereo Scanner (MOMS-02)	J. Bodechtel, S. Jutz, F. Lanzl, P. Seige, F. Ackermann, J. Zilger, D. Meissner, H. Winkenbach	Earth Observations
	Atomic Oxygen Exposure Tray (AOET)	German Space Agency (DARA)	Atmospheric Science
	Floating-Zone-Growth Of GaAs	A. Croll, A. Tegetmeier, G. Nagel, K.W. Benz	Physical Science: Materials
	A Highly Precise Measurement of the Molecular Transport of Heat Energy for Different Concentrations of a Binary Liquid Mixture of Low Viscosity under Microgravity	A. Delgado; R. Greger; H. J. Rath	Physical Science: Materials
	Single Crystal Growth of GaAs by the Floating Zone Method on D2	F.M. Herrmann, G. Mueller	Physical Science: Materials
	Floating Zone Crystal Growth Of Gallium-Doped Germanium	T. Carlberg, D. Camel, P. Tison	Physical Science: Materials
	Hysteresis Of The Specific Heat CV During Heating And Cooling Through The Critical Point	J. Straub, A. Haupt	Physical Science: Fluids
	Diffusion Of Nickel In Liquid Copper-Aluminum And Copper-Gold Alloys	J. Urbanek, Th. Hehenkamp	Physical Science: Materials
	Cellular-Dendritic Solidification With Quenching Of aluminium-Lithium Alloys	H. Nguyen Thi, Q.Li, B.Billia, D.Camel, B. Drevet, Jean-Jacques Favier	Physical Science: Materials
	Directional Solidification Of A Cu-Mn Alloy (COMET)	M. Stehle, S. Rex	Physical Science: Materials

Mission	Experiment Title	Investigators	Discipline
STS-55/ SL-D2	Growth Of GaAs From Gallium Solutions	K.W. Benz, G. Nagel , A.N. Danilewsky	Physical Science: Materials
	Inter-Diffusion	G. Frohberg, K.H. Kraatz, H. Wever	Physical Science: Materials
	Self-Diffusion	G. Frohberg, K.H. Kraatz, H. Wever	Physical Science: Materials
	Directional Solidification Of The LiF - LiBaF3 - Eutectic	Franz Wallrafen, K. Dupre	Physical Science: Materials
	Separation Behavior Of Monotectic Alloys	H. Ahlborn, B. Prinz, L. Ratke	Physical Science: Materials
	Liquid Columns' Resonances (LICOR)	D.Langbein, F. Falk, W. Heide, R. Grossbach, H. Bauer, J. Meseguer, J.M. Perales, A.Sanz	Physical Science: Fluids
	Stability Of Long Liquid Columns	I. Martinez, J.M. Perales, J. Meseguer	Physical Science: Fluids
	Higher Modes And Their Instabilities Of Oscillating Marangoni Convection In A Large Cylindrical Liquid Column	Ch.-H.Chun, J. Siekmann	Physical Science: Fluids
	Marangoni-Benard Instability	J.C. Legros, O. Dupont, P. Queeckers, D. Schwabe	Physical Science: Fluids
	Onset Of Oscillatory Marangoni Flows	Rodolfo Monti, L. Carotenuto	Physical Science: Fluids
	Stationary Interdiffusion In A Non-Isothermal Molten Salt Mixture	J. Dupuy-Philon, J. Bert	Physical Science: Materials
	Nucleation And Phase Selection During Solidification of Undercooled Alloys	K.Wittmann, G. Otto, F. Gillessen	Physical Science: Materials
	Heating And Remelting Of An Allotropic Fe-C-Si Alloy In A Ceramic Skin And The Effect Of The Volume Change On The Mold's Stability	W. Amende	Physical Science: Materials
	Immiscible Liquid Metal Systems	R. Sangiorgi, M.L. Muolo, F. Rossitto, A.Passerone, F. Crenna	Physical Science: Materials
	Vapor Growth of InP Crystal with Halogen Transport in a Closed Ampoule	T. Kimura; H. Ono, T. Nishimura; T. Murotani; K. Mizuguchi	Physical Science: Materials
	Convective Effects On The Growth Of GaInSb Crystals	T.Duffar, J.P. Garandet	Physical Science: Materials
	Solution Growth Of GaAs Crystals Under Microgravity	Y. Suzuki, S. Kodama	Physical Science: Materials
	Crystallization Of Nucleic Acids And Nucleic Acid-Protein Complexes	Volker A. Erdmann	Physical Science: Biotech
	Crystallization Of Ribosomal Particles	Hardy A.S. Hansen, Ada Yonath	Physical Science: Biotech
	Soret Effect Measurement in a Molten Salt Mixutre in Space	J. Bert, J. Dupuy-Philon	Physical Science: Fluids
	Eutectic Crystallization	H.-M. Tensi, T. Mack	Physical Science: Materials
	Influences on the Stability of Metal/Ceramic Dispersions with nm-Particles during Directional Solidification	P. Busse, F. Deuerler, J. Poetschke	Physical Science: Materials
	Interferometric Determination Of The Differential Interdiffusion Coefficient Of Binary Molten Salts	J. Richter, M. Gollbach, E. Jurek, T. Kessascheck, W. Merkens	Physical Science: Fluids
	IDILE: Measurements Of Diffusion Coefficients in Aqueous Solution	M.C. Robert, F. Lefaucheaux, Y. Bernard	Physical Science: Materials
	NUGRO: Phase Separation In Liquid Mixtures With Miscibility Gap	B. Braun, Ch. Ikier, H. Klein, G. Schmitz, K. Wanders, D.Woermann; B. Feuerbacher	Physical Science: Materials

Mission	Experiment Title	Investigators	Discipline
STS-55/ SL-D2	Impurity Transport and Diffusion in InSb Melt Under Microgravity Environment	M. Watanabe; Y. Nakata; T. Fujii; H. Yoshida; T. Yasunaga, U. Zimmerman, G. Klock, R. Schnettler, G.A. Neil, N.R. Klinman, D.W. Sammons	Physical Science: Fluids
	Enhanced Hybridoma Production Under Microgravity		Physical Science: Biotech
	Influence of Microgravity upon the Carotid Baroreceptor-Cardiac Reflex Response	D.L. Eckberg, T.E. Brown, V.J. Convertino, D.F. Doerr	Life Science: Human Physiology
	Leg Fluid Distribution At Rest And Under LBNP	Friedhelm J. Baisch, L.E.J. Beck, C.G. Blomqvist, J.M. Karemaker	Life Science: Human Physiology
	Determination Of Segmental Fluid Content And Perfusion	F. J. Baisch, L.E.J. Beck, J.M. Karemaker, L. Pourcelot, D. Linnarsson, B. Tedner	Life Science: Human Physiology
	Left Ventricular Function At Rest And Under Stimulation	Luis E.J. Beck, F.J. Baisch, J.M. Karemaker, Ph. Arbeille, L. Pourcelot	Life Science: Human Physiology
	Peripheral and Central Hemodynamic Adaptation To Microgravity During Rest Exercise And Lower Body Negative Pressure In Humans	O. Henriksen, P. Norsk, J. Boisen, N. Foldager, F. Jessen, J. Karemaker, S. Sadamoto, P. Sejrsen	Life Science: Human Physiology
	Tonometry - Intraocular Pressure In Microgravity	Joerg Draeger, R. Schwartz, C. Stern, S. Groenhoff, B. Hechler	Life Science: Human Physiology
	The Central Venous Pressure During Microgravity	N. Foldager, T.A.E. Andersen, F.B. Jessen, P. Ellegaard, C. Stadeager, R. Videbaek, P. Norsk	Life Science: Human Physiology
	Tissue Thickness And Tissue Compliance Along Body Axis Under Micro-G Conditions	Karl A. Kirsch, F.J. Baartz, H.-Chr. Gunga, L. Roecker	Life Science: Human Physiology
	Changes In The Rate Of Whole-Body Nitrogen Turnover, Protein Synthesis And Protein Breakdown Under Conditions Of Microgravity	E.B. Fern, O. Ballevre, C. Piguet-Welsh, H. Schierbeek, K.J. Acheson	Life Science: Human Physiology
	Regulation Of Volume Homeostasis In Reduced Gravity Possible Involvement Of Atrial Natriuretic Factor Urodilatin And Cyclic GMP	Rupert Gerzer, C. Drummer, R. Lang, J. Well, H. Stromeyer	Life Science: Human Physiology
	Effects Of Microgravity On Glucose Tolerance	Hartmut P. Maass	Life Science: Human Physiology
	The Influence Of Microgravity On Endocrine And Renal Elements Of Volume Homeostasis	P. Norsk, P. Bie, N.J. Christensen, J. Warberg, C. Stadeager	Life Science: Human Physiology
	Effects Of Spaceflight On Pituitary-Gonad-Adrenal Function In The Human	G. Riondino, A. Scano, F. Strollo, G. Strollo	Life Science: Human Physiology
	Role of Volume Regulating Hormones and Plasma Proteins in Man for the Adaptation To Micro-G And Readaptation To Terrestrial Conditions	Lothar Roecker, K.A. Kirsch, H.C. Gunga	Life Science: Human Physiology
	Pulmonary Perfusion And Ventilation In Microgravity at Rest And Exercise	D. Linnarsson, H. Larsson	Life Science: Human Physiology
	Ventilation Distribution In Microgravity	M. Paiva	Life Science: Human Physiology
	Effects Of Microgravity On The Dynamics Of Gas Exchange, Ventilation And Heart Rate In Submaximal Dynamic Exercise	Juergen Stegemann	Life Science: Human Physiology
	Cardiovascular Regulation In Microgravity	Ph. Arbeille, C. Gunnar Blomqvist	Life Science: Human Physiology
	Development Of Vestibulocular Reflexes In Amphibia And Fishes With Microgravity Experience	Eberhard Horn	Life Science: Developmental
	Comparative Investigations Of Microgravity Effects On Structural Development And Function Of The Gravity Perceiving Organ Of Two Water Living Vertebrates	Juergen Neubert	Life Science: Developmental

Mission	Experiment Title	Investigators	Discipline
STS-55/ SL-D2	Structure- And Function-Related Neuronal Plasticity Of The CNS Of Aquatic Vertebrates During Early Ontogenetic Development Under Microgravity-Conditions	Hinrich Rahmann	Life Science: Developmental
	Gravisensitivity Of Cress Roots	Dieter Volkmann	Life Science: Plant
	Influence Of Gravity On Fruiting Body Development Of Fungi	Berthold Hock	Life Science: Plant
	Significance Of Gravity And Calcium-Ions On The Production Of Secondary Metabolites In Cell Suspensions of <i>Aesculus hippocastanum</i> L.	Hildegard Jung-Heiliger	Life Science: Plant
	Influence Of Conditions In Low Earth Orbit On Expression And Stability Of Genetic Information In Bacteria	Horst Dieter Mennigmann	Life Science: Cell and Molecular
	Fluctuation Test On Bacterial Cultures	Horst Dieter Mennigmann	Life Science: Cell and Molecular
	Connective Tissue Biosynthesis In Space: Gravity Effects On Collagen Synthesis And Cell Proliferation Of Cultured Mesenchymal Cells	Peter K. Mueller	Life Science: Cell and Molecular
	Antigen-Specific Activation Of Regulatory t-Lymphocytes To Lymphokine Production	Konrad Reske	Life Science: Cell and Molecular
	Growth Of Lymphocytes Under Micro-G Conditions	Konrad Reske	Life Science: Cell and Molecular
	Culture And Electrofusion Of Plant Cell Protoplasts from <i>Digitalis lanata</i> DHRH and <i>Digitalis purpurea</i> L. suspension cultures under Microgravity: Morphological/Biochemical Characterization	M. Eisenbeiss	Life Science: Plant
	Electrofusion Of Plant Cell Protoplasts: Synthesis and Morphological/Biochemical Characterization of hetero-specific hybrids	Ruediger Hampp, B. Naton, E. Hoffmann, W. Merhrle, E. Reinhard, H. Schnabl	Life Science: Plant; Physical Science: Biotech
	Yeast Experiment Hb-L29/Yeast: Investigations On Metabolism	Siegfried Donhauser	Life Science: Cell and Molecular
	Electrofusion and regeneration of sunflower protoplasts under microgravity considering the ultrastructure	A. vonKeller	Life Science: Plant
	Personal Dosimetry: Measurement Of The Astronaut's Ionizing Radiation Exposure	Horst Buecker, Guenter Reitz	Life Science: Radiation
	Measurement Of The Radiation Environment Inside Spacelab At Locations Which Differ In Shielding Against Cosmic Radiation	Guenter Reitz	Life Science: Radiation
	Chromosome Aberration	Guenter Obe	Life Science: Radiation
	Biological Response To Extraterrestrial Solar UV Radiation And Space Vacuum	Gerda Horneck	Life Science: Radiation
STS-58/ SLS-2	Cardiovascular Adaptation to Microgravity	C. Gunnar Blomqvist	Life Science: Human Physiology
	A Study of the Effects of Space Travel on Mammalian Gravity Receptors (2 experiments)	Muriel D. Ross	Life Science: Animal Physiology
	The Effects of Microgravity on the Electron Microscopy, Histochemistry and Protease Activities of Rat Hindlimb Muscles (2 parts)	Daniel A. Riley, Stanley Ellis, A.L. Haas	Life Science: Animal Physiology
	Regulation of Blood Volume During Space Flight (2 parts)	C.P. Alfrey, T. B. Driscoll, R.G. Nachtman, M.M. Udden	Life Science: Animal Physiology
	Regulation of Erythropoiesis During Space Flight (Part 2)	Albert T. Ichiki, Zuhair Al-Lebban, Linda A. Gibson	Life Science: Animal Physiology
	Effects of Microgravity on Biochemical and Metabolic Properties of Skeletal Muscle in Rats (3 parts)	Kenneth M. Baldwin, Vince J. Ciazozzo	Life Science: Animal Physiology
	Regulation of Erythropoiesis During Space Flight (Part 1)	Robert D. Lange, Albert T. Ichiki, J.B.Jones	Life Science: Animal Physiology

Mission	Experiment Title	Investigators	Discipline
STS-58/ SLS-2	Pathophysiology of Mineral Loss During Space Flight	Claude D. Arnaud	Life Science: Animal Physiology
	Cardiovascular Deconditioning	Leon E. Farhi	Life Science: Animal Physiology
	Protein Metabolism during Space Flight	T.Peter Stein	Life Science: Animal Physiology
	Bone, Calcium and Spaceflight	E.R. Morey-Holton, C. E. Cann, S.B.Doty, W.E.Roberts, A.C.Vailas	Life Science: Animal Physiology
	Erythrokinetics in Man	Clarence P. Alfrey	Life science: Human Physiology
	Fluid-Electrolyte Regulation during Spaceflight	Carolyn S. Leach	Life Science: Human Physiology
	Vestibular Experiments in Space	Laurence R. Young	Life Science: Human Physiology
	Pulmonary Function during Weightlessness	John B. West	Life Science: Human Physiology
	DSO 612, "EnergyUtilization" (inflight)	Helen W. Lane	Life Science: Human Physiology
	DSO 623, "Lower Body Negative Pressure (LBNP) Countermeasures" (inflight)	John B. Charles	Life Science: Human Physiology
	DSO620, Physiological Evaluation of Astronaut Seat EgressAbility at Wheel Stop" (Pre- and post-flight)	Jacob J. Bloomberg	Life Science: Human Physiology
	DSO624, "Cardiorespiratory Responses to SubmaximalExercise" (Pre- and post-flight)	Alan D. Moore	Life Science: Human Physiology
	BSP: ANP, Pro-ANP, and mRNA Distribution in Rat Heart during a Spaceflight	J. Gabrion, B. Bayard, C. Bouille, S. Fagette, J. Fareh, G. Gauquelin, C. C. Gharib, Serge Herbute, Jacques Oliver	Life Science: Animal Physiology
	BSP: Biochemistry of Muscle Fiber Specific Proteins under Microgravity	Kanefusa Kato, Yataka Naguma	Life Science: Animal Physiology
	BSP: Bone Cell activity during Spaceflight and Recovery	Erik Zerath, Pierre J. Marie	Life Science: Animal Physiology
	BSP: Bone Metabolism under the Condition without Gravity	Tashi Shigematsu, Hogara Yamauchi	Life Science: Animal Physiology
	BSP: Bone Minerals and Morphological and Functional Changes	Victor S. Oganov, Olga E. Kabitskaya, N.V.Rodionova	Life Science: Animal Physiology
	BSP: Cellular Homeostasis in Microgravity: Energy and Structure	S.M.Ivanova, Irena A. Popova	Life Science: Animal Physiology
	BSP: Central (brainstem) and Peripheral (heart and kidney) Sympathetic Activity during a Spaceflight	Jacqueline Gabrion, J.M. Cottet-Emard, S. Fagette, J. Fareh, Guillemette Gauquelin, Claude C. Gharib, Jean-Marie Pequignot	Life Science: Animal Physiology
	BSP:Effect of SLS2 Spaceflight on Immunological Parameters of Rats (3 parts: Antiviral Immunity, Bone and Immunity, Immunity Mediators)	Irina V. Konstantinova, A.T. Lesnyak	Life Science: Animal Physiology
	BSP: Effects of Spaceflight on beta-Adrenoceptors in Rat Hindlimb Muscles	Yoshinob Ohira, Kazuto Saito	Life Science: Animal Physiology
	BSP: Effects of Spaceflight on Enzyme Activities and Ultrastructure of Fast-Type Skeletal Muscles of Rats	Toshitada Yoshioka, M. Tomoyukiunishima, Katsumas Yamashita	Life Science: Animal Physiology
	BSP: Functional State of Thyroid and Calcitonin Producing System of the Rat Thyroid Gland in Microgravity	V.I.Loginov	Life Science: Animal Physiology
	BSP: Histomorphometric Analysis of Bone Tissue after Weightlessness Exposure and Recovery	Christian Alexander, S. Bourrin, Laurence Vico	Life Science: Animal Physiology

Mission	Experiment Title	Investigators	Discipline
STS-58/ SLS-2	BSP: Histomorphometric Study of SLS-2 Rat Tibia	G.N.Durnova, Alexander S. Kaplansky	Life Science: Animal Physiology
	BSP: Influence of microgravity on Rat Digestive Physiology and Xenobiotic Metabolizing System – Interactions with Intestinal Microflora Alterations	Odette Szytli, C. Amdrieux, L. Nugon-Baudon	Life Science: Animal Physiology
	BSP: Kidneys and Fluid-Electrolyte Homeostasis	Luba V. Seronva, Yuri V. Natochin	Life Science: Animal Physiology
	BSP: Molecular Pharmacology of alpha-1 adrenoreceptors and calcium channels in rat vascular myocytes	Chantal Mironneau, J. Mironneau, G.Neuilly, L. Rakotoari-soa, L. Sayet-Colombet	Life Science: Animal Physiology
	BSP:Morphological analysis of pituitary somatotrophs of SLS-1 and SLS-2 rats	E.I. Alekseyev	Life Science: Animal Physiology
	BSP:Morphological and Functional adaptations of muscle fibers and muscle-tendon and nerve-muscle junctions to spaceflights	Jean Francois Marini, Jean J. Leger, Alfredo J. Zamora	Life Science: Animal Physiology
	BSP:Morphological Investigations of Skeletal Muscles of SLS-2	E.I. Ilyina-Kakueva, O.M. Pozdnyakov	Life Science: Animal Physiology
	BSP:Morphology and Histochemistry of Proprioceptive Cerebellum	Igor B. Krasnov, Richard E. Grindeland, Paul E. Sawchenko, Wylie Vale	Life Science: Animal Physiology
	BSP:Morphology of End and Intermediate Brain	Igor B. Krasnov, Ludmilla N. Dyachkova	Life Science: Animal Physiology
	BSP:Single Fiber Muscle Function	Yvonne Mounier, Corinne Cordonnier, Laurence Stevens	Life Science: Animal Physiology
	BSP: The Stressogenic effect of Microgravity: Biochemical Studies	Alexander S. Kaplansky, G.N. Durnova, Irena A. Popova	Life Science: Animal Physiology
	BSP: Ultrastructural Changes in Choroid Plexus of Rats Maintained in Microgravity during a Spaceflight	Jacqueline Gabrion, Bernard Bayard, Christian Bouille, Claude C. Gharib, Serge Herbute, Jacques Oliver, Brigitte Nguyen Than Dao	Life Science: Animal Physiology
	BSP:Ultrastructure and Histochemistry of Vestibular Structures and Vegetative Nuclei of the Brain	Igor B. Krasnov, RichardE. Grindeland, Paul E. Sawchenko, Wylie Vale	Life Science: Animal Physiology
	Central and Peripheral noradrenergic responses to 14 days of spaceflight or hindlimb suspension in rats	C.Gharib	Life Science: Animal Physiology
	Anomalous behavior or helium and sulfur hexafluoride during single breath tests in sustained microgravity	M.Paiva	Life Science: Human Physiology
STS-59/ SRL-1	Measurement of Air Pollution from Satellites (MAPS)	Henry G. Reichle, V. Conners, W. Hesketh, P. Kasibhatla, V. Kirchoff, J. Logan, R. Newell, R. Nicholls, L. Peters, W.Seiler, H. Wallio	Earth Observations
	Shuttle Imaging Radar (SIR-C)	Charles Elachi	Earth Observations
	X-Band Synthetic Aperture Radar (X-SAR)	Herwig Ottl	Earth Observations
	Comparison of SIR-C Simulated and Measured SIR-C SAR Image Spectra with Ocean Wave Spectra Derived from Buoys and Wave Production Models in the North Sea	Werner Alpers, H. Masuko, Paolo Trivero	Earth Observations
	Wave Dynamics in the Southern Ocean	Robert C. Beal, Thomas W. Gerling, Frank M. Monaldo	Earth Observations
	Multi-Incidence Angle/Multi-Frequency Effect in Satellite SAR Imagery Pertaining to Vegetation Characterization and Hydrology	R. J. Brown, H. Gwyn, T. Pultz, K.P.B. Thomson	Earth Observations

Mission	Experiment Title	Investigators	Discipline
STS-59/ SRL-1	Contribution of SAR for Estimating Soil Erosion	Paolo Canuti, H. Bork, S. Palos- cia, A. S. Ramoorthi	Earth Observations
	A Study of the Potential of Multi-component SAR Imag- ery for Agricultural and Forestry Studies	R. Cordey, G.E. Keyte, J.R. Baker, S. Quegan, G.M. Foody, N.J. Veck, A. Wielogorska	Earth Observations
	Geologic and Hydrologic Studies of Saudi Arabia under the Shuttle Imaging Radar (SIR-C) Science Plan	Abdallah Essa Dabbagh, K. Al- Hinai, H. S. Edgell, M. Khan	Earth Observations
	Biomass Modeling of the Ponderosa Pine Forests of Western North America with SIR-C/X-SAR for Input to Ecosystems Models	Frank Davis, John Melack, Jack F. Paris	Earth Observations
	SIR-C Investigations of Snow Properties in Alpine Ter- rain	Jeff Dozier, A.T.C. Chang, Walter Good, Klaus I. Itten, Christian Matzler, Shi Yafeng, Wan Zheng-ming	Earth Observations
	Applications of SIR-C Synthetic Aperture Radar to Hydrology	Edwin T. Engman, Thomas J. Jackson, William Kustas, Peg- gy O'Neill, Thomas Schmugge, Eric F. Wood	Earth Observations
	Climate Change and Neotectonic History of Northwest- ern China	Tom G. Farr, William Bull, Oliver Chadwick, Diane Evans, Alan Gillespie, Gilles Peltzer, Paul Tapponnier	Earth Observations
	Reconstruction of the Mesoscale Velocity Shear Seaward of Coastal Upwelling Regions from the Refraction of the Surface Wave Field	Pierre Flament, Hans C. Graber, D. Halpern, B. Holt	Earth Observations
	Multi-Frequency, Multi-Polarization External Calibra- tion of the SIR-C/X-SAR Radars	A. Freeman, M. Craig Dobson, P. Hoogeboom, Y. Shen, F.T. Ulaby, C.L. Werner	Earth Observations
	Like- and Cross-Polarization Calibration, Topographic Mapping and Rice Field Experiments by SIR-C/ X-SAR	Masaharu Fujita, Jun Awaka, Toshio Iguchi, Toshio Ihara, Hideyuki Inomata, Toshiaki Kozu, Takashi Kurosu, Takeshi Manabe, Harunobu Masuko, Yuji Miyagawa, Kenji Naka- mura, Takeyuki Ojima, Ken'ichi Okamoto, Toshiyuki Okuyama, Makoto Satake, Takeshi Suitz, Toshihiko Umehara, Seiho Uratsuka	Earth Observations
	Alluvial Fan Evolution in the Western Great Basin	Alan R. Gillespie, John B. Ad- ams, Milton O. Smith	Earth Observations
	Differential Radar Interferometry	R. M. Goldstein, A. K. Gabriel, Fuk K. Li, C. L. Werner, How- ard A. Zebker	Earth Observations
	Development of a Technique to Relate Eolian Roughness to Radar Backscatter Using Multi-Parameter SIR-C Data	Ronald Greeley, Dan Blumberg, A. Dobrovolskis, James Iverson, Nicholas Lancaster, Bruce White, Keld Rasmussen, Haim Tsoar, Stephen Saunders, Eilene Theilig, Stephen Wall, Howard Zebker	Earth Observations
	Evaluation of SIR-C/X-SAR Imagery for Geologic Stud- ies in China	Huadong Guo, Li Xiaowen, Wan Zhengming	Earth Observations
	X-SAR/SIR-C Radiometric Calibration Experiment	Franz Heel, H. Kietzmann, D. Wessling	Earth Observations

Mission	Experiment Title	Investigators	Discipline
STS-59/ SRL-1	SIR-C Analysis of Topography and Climate in the Central Andes	Bryan Isacks, Arthur L. Bloom	Earth Observations
	SIR-C and X-SAR Measurements in Precipitation	Arthur R. Jameson	Earth Observations
	Estimation of Total Aboveground Biomass in Southern United States Old-Field Pine Stand Using SIR-C/X-SAR Data	Eric S. Kasischke, Norman Christensen	Earth Observations
	An Investigation of the Imaging of Ocean Waves and Internal Waves with SIR-C/X-SAR	Gordon Keyte, J.P. Matthews, G. J. Wensink, R. Cordey	Earth Observations
	SIR-C Polarimetric Radar Image Simulation and Interpretation Based on Random Medium Model	Jin A. Kong	Earth Observations
	Comparative Lithological Mapping Using Multipolarization, Multifrequency Imaging Radar and Multispectral Optical Remote Sensing	Fred A. Kruse, Alexander Goetz, Franz Leberl	Earth Observations
	Relating Radar Backscatter Responses to Woody and Foliar Biomass of Pine Forests	Thuy Le Toan, P. Hoozeboom, A. Fiumara	Earth Observations
	Remote Sensing of Precipitation by Spaceborne Synthetic Aperture Radar	Fuk K. Li, David Atlas, Peter H. Hildebrand, K. Eastwood Im, Richard K. Moore	Earth Observations
	Analysis of Optical and Microwave Data to Assess Dynamics of Mexican Tropical Rain Forest	Fabian Lozano-Garcia, Antonio Lot, Daniel Pineiro	Earth Observations
	The Exploration and Reconstruction of the Middle to Late Cenozoic Drainages of the Sahara by Means of the SIR-C Mapping	John F. McCauley, Carol S. Breed, Hugues Faure, Bahay Issawi, Ted A. Maxwell	Earth Observations
	Determining the Extent of Inundation on Subtropical and Tropical River Floodplains Beneath Vegetation of Varying Types and Densities	John N. Melack, Frank Davis, Judith Meyer	Earth Observations
	Optimization of SAR Parameters for Ocean Wave Spectra	Frank M. Monaldo, David Tilly, David Lyzenga	Earth Observations
	U. S. Navy Investigations	Donald R. Montgomery, Charles Luther, O. H. Shemdin, D. Sheres, G. Valenzuela, S. Mango	Earth Observations
	Inflight Antenna Pattern Measurement for SIR-C	Richard K. Moore, Julian C. Holtzman	Earth Observations
	The Eruptive Styles of Basaltic Shield Volcanoes from Shuttle Imaging Radar-C (SIR-C) and X-SAR Data	Peter J. Mouginis-Mark, V. H. Kaupp, H. C. MacDonald, W. P. Waite	Earth Observations
	Geology of the Campanian Test Site	Pasquale Murino, J. Nithack, K. Krishnanunni, F. Jaskolla	Earth Observations
	Global Biodiversity: Assessment of Habitat Change and Species Extinctions with Multiparameter Synthetic Aperture Radar (SAR) Data	Jack F. Paris, Walter E. Westman	Earth Observations
	Turbulent Exchange at Vegetated Surfaces and Evaluation of Estimates of Canopy Structure Using SIR-C Data	Kyaw Tha Paw U, Roger Shaw, Susan Ustin	Earth Observations
	Radar Investigations of Wetland Hydrology in the Seasonal Tropics	Kevin O. Pope, Lorrain Giddings, Jack F. Paris, Byron L. Wood	Earth Observations
	Synthetic Aperture Radar Ocean Imaging Physics	Keith Raney, C. S. Nilsson	Earth Observations
	Imaging Radar Data Analysis for Forest Ecosystem Modeling	K. Jon Ranson, Guoqing Sun, Herman H. Shugart, James A. Smith	Earth Observations
	Combined Altimetry and SAR Imagery of a Desert Test Site	Chris G. Rapley, Wyn Cudlip, M. Guzkowska, Ian Mason, Jeff Ridley	Earth Observations
	High Alpine SAR Experiment	Helmut Rott, M. Buchroithner, C. Matzler, O. Reinwarth	Earth Observations

Mission	Experiment Title	Investigators	Discipline
STS-59/ SRL-1	SIR-C Surface and Subsurface Responses from Documented Test Site Localities in the Sahara, Namib, and Kalahari Deserts, Africa and the Jornada del Muerto, New Mexico	G. G. Schaber, C. Breed, P. Davis, H. A. Hamroush, B. Issawi, N. Lancaster, J. McCauley, M. N. Machette, J. T. Teller, J. M. Wilkinson	Earth Observations
	Microwave Remote Sensing Data from a Spaceborne Platform as a Tool to Monitor the Hydrological Cycle of a Floodplain Area ("VARZEA") at Northeast Brazil.	Joao Viane Soares, H. J. H. Kux	Earth Observations
	SIR-C Studies of the Precambrian Hamisana and Nakasib Structures, NE Sudan, in Arid Regions of Low Relief and in the Subsurface	Robert J. Stern, Timothy H. Dixon, Kent C. Nielson, Mohammed Sultan	Earth Observations
	The Evaluation of SIR-C Imagery for Surficial Sediment Mapping and Groundwater Management in Australia	Geoffrey R. Taylor, E. H. Fooks, J. Leach, A. K. Milne, J. Acworth, J. Odins	Earth Observations
	Polarimetric Radar Observations of Forest State for Determination of Ecosystem Process	Fawwaz T. Ulaby, M. Craig Dobson, T. Sharik, J. A. Weber	Earth Observations
	Passive and Active Calibrators for Multifrequency and Multiangle X-SAR/SIR-C Image Radiometric and Geometric Corrections	Sergio Vetrella, D. Solimini	Earth Observations
	Test of Roughness and Moisture Algorithms Using Multiparameter Space Borne SAR and Application to Surface Hydrology	Daniel Vidal-Madjar, Michel Normand, Didier Massonet	Earth Observations
	SIR-C Measurements of Soil Moisture, Vegetation and Surface Roughness, and their Hydrological Application	James R. Wang, Edwin T. Engmann, Manfred Owe, James C. Shiue	Earth Observations
	Information Extraction from Shuttle Radar Images for Forest Applications	Rudolf Winter, W. Kuehbauch, S. Mohan	Earth Observations
	SIR-C Radar Investigations of Volcanism and Tectonism in the Northern Andes	Charles A Wood, Anthony England, Minard Hall Escuela, Stanley Williams	Earth Observations
	Multifrequency Imaging Radar Polarimetry: Geophysical Factors from Penetration Phenomena	Howard A. Zebker, Charles Elachi, Philip Hartl, Jakob van Zyl	Earth Observations
STS-62/ USMP-2	Advanced Automated Directional Solidification Furnace (AADSf)	Sandor L. Lehoczky, Frank R. Szofran, Donald C. Gillies	Physical Science: Materials
	Critical Fluid Light Scattering Experiment (CFLSE-Zeno)	Robert W. Gammon, J.N. Shaumeyer, Matthew E. Briggs, Hacene Boukari, David A. Gent, R.Allen Wilkinson	Physical Science: Fluids
	Isothermal Dendritic Growth Experiment (IDGE)	Martin E. Glicksman, E.A. Winsa, Matthew B. Koss	Physical Science: Materials
	Materials for the Study of Interesting Phenomena of Solidification on Earth and in Orbit (MEPHISTO)	Reza Abbaschian, Jean-Jacques Favier, Atul B. Gokhale, Sam R. Coriell	Physical Science: Materials
	Space Acceleration Measurement System (SAMS)	Richard DeLombard, Melissa J.B. Rogers	Technology
STS-65/ IML-2	Gravitational Role in Liquid Phase Sintering	Randall M. German, R.G. Iacocca	Physical Science: Materials
	Mixing of a Melt of Multicomponent Compound Semiconductor	Akira Hirata, Nobuyuki Imaishi, Masashi Kumagawa, Yasuhiro Hayakawa, Yasunori Okano, Toshiaki Osaka, Masato Tachibana, Shin-ichi Nighizawa	Physical Science: Materials
	Effect of Weightlessness on Microstructure and Strength of Ordered TiAl Intermetallic Alloys	Masao Takeyama, Akira Sato	Physical Science: Materials

Mission	Experiment Title	Investigators	Discipline
STS-65/ IML-2	Effects of Nucleation by Containerless Processing in Low Gravity	Robert J. Bayuzick	Physical Science: Materials
	Non-Equilibrium Solidification of Largely Undercooled Melts	Dieter M. Herlach, M. Barth, K.Eckler, B. Feuerbacher, F. Gillessen, A.L. Greer	Physical Science: Materials
	Alloy Undercooling Experiments	Merton C. Flemings	Physical Science: Materials
	Structure and Solidification of Largely Undercooled Melts of Quasicrystal-Forming Alloys	Knut Urban, Dieter M. Herlach, D. Holland-Moritz	Physical Science: Materials
	Thermodynamics and Glass Formation in Undercooled Liquid Alloys	Hans J. Fecht, R.K. Wunderlich	Physical Science: Materials
	Metallic Glass Research in Space: Thermophysical Properties of Metallic Glasses and Undercooled Alloys	William L. Johnson	Physical Science: Materials
	Viscosity and Surface Tension of Undercooled Melts	Ivan Egry, G. Lohoefer, P.Neuhaus, B.Feuerbacher	Physical Science: Fluids
	Measurement of the Viscosity and Surface Tension of Undercooled Melts under Microgravity Conditions and Supporting Magnetohydrodynamic Calculations	Julian Szekely	Physical Science: Fluids
	Gravitational Role in Electrophoretic Separations of Pituitary Cells and Granules (part 1)	Wes Hymer, R. Cenci, T.Salada, K. Krishinan, G.Seaman, Shunji Nagaoka	Physical Science: Biotechnology
	Feeding Frequency Affects Cultured Rat Pituitary Cells in Low Gravity (part 2)	Wes Hymer, R. Cenci, T.Salada, K. Krishinan, G.Seaman, Shunji Nagaoka	Physical Science: Biotechnology
	Separation of Chromosome DNA of a Nematode, <i>C. elegans</i> , by Electrophoresis	Hidesaburo Kobayashi, Naoaki Ishii, Shunji Nagaoka	Physical Science: Biotechnology
	Experiments Separating the Culture Solution of Animal Cells in High Concentration under Microgravity	Tsutomu Okusawa, Kuniyoshi Tsubouchi, Kenji Baba, Ryoichi Hagi, Nobuo Hamano, Koichi Ishikawa	Physical Science: Biotechnology
	Mechanism of Vestibular Adaptation of Fish under Microgravity	Akira Takabayashi, Ken Ohara, Terue Omura, Satoru Watanabe, Shigeo Mori, Masafumi Tanaka, Soichi Sakuragi, R. von Baumgarten	Life Science: Animal Physiology
	Otoconia: Early Development of A Gravity-Receptor Organ in Microgravity	Michael L. Wiederhold, Masamichi Yamashita, Makoto Asashima, Hajime Koike	Life Science: Developmental
	Fertilization and Embryonic Development of Japanese Newts in Space	Masamichi Yamashita, Akemi Kurotani-Izumi, Yoshihiro Mogami, Makoto Asashima, Hajime Koike, Mari Imamizo, Makoto Okuno, Carl J. Pfeiffer, Shinji Komasaki, Fumie Sasaki, Yohinobu Ohira, Isamu Kashi-ma, Sakae Kikuyama, Takeo Ohnishi, Satoshi Komada	Life Science: Developmental
	Mating Behavior of the Fish (Medaka) and Development of Their Eggs in Space	Kenichi Ijiri, Hoshio Eguchi, Rie Mizuno, Tetsuo Fujii, Yasuko Taguchi, Masamichi Yamashita, Akemi Kurotani	Life Science: Animal Physiology, Developmental
	Optimization of Protein Separation: Purification of Biological Molecules by CFFE in a Microgravity Environment	Victor Sanchez, Paul Sabatier	Physical Science: Biotechnology

Mission	Experiment Title	Investigators	Discipline
STS-65/ IML-2	Electrohydrodynamic Sample Distortion during Electrophoresis	Robert S. Snyder	Physical Science: Biotechnology
	The crystallization of apocrustacyanin C1	Naomi E. Chayen, P.F. Zagalsky, E.J. Gordon	Physical Science: Biotechnology
	Crystallization of Collagenase from <i>Hypoderma lineatum</i> during the IML-2 mission	Arnaud Ducruix, Madeleine Ries-Kautt, Isabelle Broutin	Physical Science: Biotechnology
	Crystallization of the membrane protein Photoreaction Center from <i>Rhodobacter sphaeroides</i>	Arnaud Ducruix, Madeleine Ries-Kautt, Francoise Reiss-Husson	Physical Science: Biotechnology
	Crystallization of RNA molecules.	Volker Erdmann, S. Lorenz	Physical Science: Biotechnology
	Crystal Growth of a Thermophilic Aspartyl-tRNA Synthetase	R.Giege, A.Theobald-Dietrich, J.D. Ng, B.Lorber, D.Kern	Physical Science: Biotechnology
	Crystallization of Visual Pigment Rhodopsin	W. deGrip, J. Van Oostrum	Physical Science: Biotechnology
	Studies of lysozyme protein crystal perfection from microgravity crystallization	J.R. Helliwell, E.H. Snell	Physical Science: Biotechnology
	Crystallization of octarellins.	J.A. Martial, L. Wyns, K. Goraj, L. Lisgarten	Physical Science: Biotechnology
	Microgravity Effects on Macromolecule and Virus Crystallization	Alexander McPherson, S. Koszelak	Physical Science: Biotechnology
	Crystal Growth of Ribonuclease A	L.Sjölin, T. Gallagher, M. Tordova, A.J.Howard, J. Ladner, V. Langer, A. Wlodawer, G. Lilliland	Physical Science: Biotechnology
	Crystallization of Bacteriorhodopsin	G. Wagner, T.Rothaermel	Physical Science: Biotechnology
	Crystallization of ribosomal particles in space	Ada Yonath, Hardy A.S. Hansen	Physical Science: Biotechnology
	Bubble Migration, Coalescence and Interaction with Melting and Solidification Fronts	Rodolfo Monti, Raimondo Fortezza	Physical Science: Fluids
	Thermocapillary Migration and Interactions of Bubbles and Drops	R. Shankar Subramanian	Physical Science: Fluids
	Bubble Behavior Under Low Gravity	Antonio Viviani	Physical Science: Fluids
	Thermocapillary Instability in a Three-Layer System	Jean-Claude Legros, Ph. Georis	Physical Science: Fluids
	Nucleation, Bubble Growth, Interfacial Micro-Layer, Evaporation and Condensation Kinetics	Johannes Straub	Physical Science: Fluids
	Boiling on a Miniature Heater under Microgravity: a Simulation for Cooling of Electronic Devices	Johannes Straub	Physical Science: Fluids
	Static and Dynamic Behavior of Liquid in Corners, Edges and Containers	Dieter Langbein, M. Weislogel, P.Concus, R.Finn	Physical Science: Fluids
	Interfacial Phenomena In Multilayered Fluid Systems	J.N. Koster, S. Biringen	Physical Science: Fluids
	Critical Phenomena in SF4 Observed under Reduced Gravity: The Piston Effect	Daniel Beysens	Physical Science: Fluids
	Thermal Equilibration in a One-Component Fluid	Richard A. Ferrell	Physical Science: Fluids
	Density Equilibration Time Scale	Hermann Klein, C.Ikier, D.Woermann	Physical Science: Fluids
	Heat Transport and Density Fluctuations in a Critical Fluid	Antonius Michels	Physical Science: Fluids

Mission	Experiment Title	Investigators	Discipline
STS-65/ IML-2	Influence of G-Jitter on Natural Convection and Diffusive Transport	Hisao Azuma, Mitsuru Onishi, Shoichi Yoshihara, Takao Doi, Toshihiko Ohida, Masamichi Ishikawa, Shin-ichi Kamei	Physical Science: Fluids
	Space Acceleration Measurement System (SAMS)	Charles Baugher, R. deLombard	Physical Science: Materials
	Quasi-Steady Acceleration Measurement (QSAM)	Hans Hamacher	Physical Science: Materials
	Biostack (BSK)	Guenther Reitz	Life Science: Radiation
	Lower Body Negative Pressure (LBNP)	John B. Charles	Life Science: Human Physiology
	Gravisensitivity and Geo(Gravi)taxis of the Slime Mold <i>Physarum polycephalum</i> (Slime Mold)	Ingrid Block, W. Briegleb, A. Wolke	Life Science: Cell and Molecular
	Graviorientation in <i>Euglena gracilis</i> (Euglena)	Donat P. Haeder	Life Science: Plant
	Influence of Accelerations on the Spatial Orientation of the Protozoan <i>Loxodes striatus</i> (Loxodes)	Ruth Hemmersbach-Krause	Life Science: Cell and Molecular
	Effects of Microgravity on <i>Aurelia</i> Ephyra Behavior and Development (Jellyfish)	Dorothy B. Spangenberg	Life Science: Developmental
	Gravireaction in <i>Chara</i> Rhizoids in Microgravity (Chara)	Andreas Sievers, B. Buchen	Life Science: Plant
	Gravisensitivity of Cress Roots (Cress)	Dieter Volkmann	Life Science: Plant
	Lymphocyte Movements and Interactions (Motion)	Augusto Cogoli, Marianne Cogoli-Greuter, M.A. Meloni, A.Pippia, L.Sciola, A.Spano	Life Science: Cell and Molecular
	Convection Stability of a Planar Solidification Front (Moni)	Klaus Leonartz, S. Rex, G. Zimmermann, Sam R. Coriell	Physical Science: Materials
	Antigen Presentation and T-Cell Proliferation in Micro-G (Antigen)	Augusto Cogoli, Marianne Cogoli-Greuter, Dennis R. Morrison	Life Science: Cell and Molecular
	Lymphocyte Activation, Differentiation, and Adhesion Dependence on Activation (Adhesion)	Augusto Cogoli, Marianne Cogoli-Greuter, M.A. Meloni, A.Pippia, L.Sciola, A. Spano	Life Science: Cell and Molecular
	Effect of Microgravity on Cellular Activation: Protein Kinase C Signal Transduction (Phorbol)	Didier A. Schmitt, Jason P. Hatton	Life Science: Cell and Molecular
	Effect of Microgravity on Cellular Activation: Cytokine Synthesis (Cytokine)	Didier A. Schmitt, Jason P. Hatton	Life Science: Cell and Molecular
	Cell Microenvironment and Membrane Signal Transduction in Microgravity (Signal)	Philippe Bouloc	Life Science: Cell and Molecular
	Effect of Stirring and Mixing in a Bioreactor Experiment in Microgravity (Bioreactor)	Augusto Cogoli, B.Bechler, I. Walther	Life Science: Cell and Molecular
	Molecular Biological Investigations of Animal Multi-Cell Aggregates Reconstituted under Microgravity (Aggregate)	Uwe A.O.Heinlein	Life Science: Cell and Molecular
	Regulation of Cell Growth and Differentiation by Microgravity: Retinoic Acid-Induced Cell Differentiation (Mouse)	Siegfried W. de Laat	Life Science: Cell and Molecular
	Sea Urchin Larva, a Potential Model for Studying Biomineralization and Demineralization Processes in Space (Urchin)	Hans-Jurg Marthy	Life Science: Developmental
	Effects of Microgravity and Mechanical Stimulation on the In- Vitro Mineralization and Resorption of Fetal Mouse Bones (BONES)	Jacobos-Paul Veldhuijzen	Life Science: Developmental

Mission	Experiment Title	Investigators	Discipline
STS-65/ IML-2	Investigation of the Mechanisms Involved in the Effects of Space Microgravity on <i>Drosophila</i> Development, Behavior and Aging ( <i>Drosophila</i> )	Roberto Marco	Life Science: Developmental
	The Role of Gravity in the Establishment of Embryonic Axes in Amphibian Embryo (Eggs)	Geertje A. Ubbels	Life Science: Developmental
	Effect of Microgravity on Lentil Morphogenesis (Lentil)	Gerald Perbal, D.Driss-Ecole	Life Science: Plant
	Root Orientation, Growth Regulation, Adaptation, and Agravitropic Behavior of Genetically Transformed Roots (Transform)	Tor-Henning Iversen	Life Science: Plant
	Plant Growth and Random Walk (Random)	Anders Johnsson	Life Science: Plant
	Efficiency of Radiation Repair in Prokaryotes (Repair)	Gerda Horneck, P.Rettberg	Life Science: Radiation
	Radiation Repair Kinetics in Eukaryotes (Kinetics)	G.Horneck, C. Baumstark-Khan, S.Kozubek, H.Rink, M.Schaefer, C. Schmitz	Life Science: Radiation
	Real-Time Radiation Monitoring Device (RRMD)	Tadayoshi Doke, Jun Kikuchi, Takayoshi Hayashi, Nobuyuki Hasebe, Gautam D. Badhwar, Shunji Nagaoka, Mitsuyasu Kato	Life Science: Radiation
	Dosimetry Measurement and Biological Effects of Heavy Ion Beams in Space Shuttle (RADIATION) Effect of Microgravity on DNA repair capability of <i>Deinococcus radiodurans</i>	Hiroshi Watanabe, Yasuhiki Kobayashi, Masahiro Kikuchi, Kazuki Harada, Shunji Nagano	Life Science: Radiation
	Dosimetry Measurement and Biological Effects of Heavy Ion Beams in Space Shuttle (RADIATION) Effect of Microgravity on <i>Escherichia coli</i> cells and Plasmid DNA	Shunji Nagaoka, Hiroshi Watanabe, Yasuhiki Kobayashi, Tatsuo Nakano, Kazuki Harada, Yurino Obiya, Takeo Ohnishi	Life Science: Radiation
	Real-time Radiation Dosimetry and Biological Experiments for Heavy Charged Particles in Spacecraft. Investigation of Radiation Levels for Space Weather Forecast.	Fumihiko Tomita	Life Science: Radiation
	Microgravity Effects on Standardized Cognitive Performance Measures	Samuel G. Schiflett	Life Science: Human Physiology
	Spinal Changes in Microgravity	John R. Ledsome	Life Science: Human Physiology
	Gravity and the Stability of the Differentiated State of Plant Embryos	Abraham Krikorian	Life Science: Plant
	Effects of Microgravity on the Growth and Differentiation of Cultured Bone-Derived Cells	Yasuhiro Kumei, Hitoyata Simokawa, Eiji Hara, Hideo Akiyama, Ryuichi Fujisawa, Chiaki Mukai, Peggy Whitson	Life Science: Cell and Molecular
	Differentiation of <i>Dictyostelium discoideum</i> in Space	Takeo Ohnishi, Kumio Okaichi, Hideki Mastsumoto	Life Science: Cell and Molecular
	Protein Separation by continuous-flow electrophoresis	Victor Sanchez, M. Clifton, B.Schoot	Physical Science: Biotechnology
	Crystallization of copper oxalate	Lode Wyns, John Lisgarten	Physical Science: Biotechnology
	Thermally Driven Flow Experiments	Masao Furukawa, Ryosuke Futamata, Toshihiko, Yoshiro Miyazaki, Tsutomu Yamazaki	Physical Science: Fluids
	Crystal Growth of Pectate lyase	Alexander McPherson; F. Jurnak	Physical Science: Biotech
	Crystal Growth of OmpF porin	Alexander McPherson; M. Garavito	Physical Science: Biotech
	Crystal Growth of Aequorin, Phospholipase A1, Green fluorescent protein	K. Ward	Physical Science: Biotech

Mission	Experiment Title	Investigators	Discipline
STS-65/ IML-2	Crystal Growth of cytochrome c (tuna)	Alexander McPherson; H. Einspahr	Physical Science: Biotech
	Crystal Growth of alpha-thrombin (human)	P. Weber	Physical Science: Biotech
	Microbial Air Sampler	Duane Pierson	Life Sciences: Human Factors
STS-64/ LITE	Lidar In-Space Technology Experiment	M.Patrick McCormick, J. A. Coakly, D. A. Randall, R. T. Menzies, J. A. Reagan, C. S. Gardner, R. M. Hoff, C.M.R. Platt, S. H. Melfi, E.V. Browell, D.M. Winker, G.S. Kent	Atmospheric Science
STS-66/ ATLAS-3	Cryogenic Infrared Spectrometers and Telescopes for the Atmosphere (CRISTA)	Dirk Offermann, Klaus-Ulrich Großman	Atmospheric Science
	Middle Atmosphere Hight Resolution Spectrograph Investigation (MAHRSI)	Robert Conway, Michael H. Stevens, Charles M. Brown	Atmospheric Science
	Atmospheric Trace Molecule Spectroscopy (ATMOS)	Michael R. Gunson, Reinhard Beer, Linda R. Brown, Odell F. Raper, Geoffery C. Toon, Robert A. Toth, Crofton B. Farmer, Curtis P. Rinsland, Rodolphe Zander	Atmospheric Science
	Millimeter-Wave Atmospheric Sounder (MAS)	Gerd K. Hartmann, Nicklaus Kampfer, Klaus F. Kunzi, Phillip R. Schwartz, Christoph Aellig, Richard M. Bevilacqua, Thomas Pauls, Charles L. Crossekey, John J. Olivero, Enrique Puliafito, Paul Hartogh, Werner Degenhardt, Alfred Loidl, Michael Richards, Jorg Langen	Atmospheric Science
	Shuttle Solar Backscatter Ultraviolet (SSBUV)	Ernest Hilsenrath, Richard P. Cebula, John Frederick, Bruce Guenther, Donald Heath, Richard D. McPeters, James E. Mentall, Alvin Miller, Walter Planet	Atmospheric Science
	Solar Spectrum Measurement (SOLSPEC)	Gerard O. Thuillier, Michel Herse, Dietrich Labs, William Peetermans, Paul Simon	Solar Science
	Active Cavity Radiometer (ACR) Irradiance Monitor	Richard C. Willson, Roger S. Helizon	Solar Science
	Measurement of Solar Constant (SOLCON)	Dominique A. Crommelynck, Bruce R. Barkstrom, Vincente Domingo	Solar Science
	Solar Ultraviolet Spectral Irradiance Monitor (SUSIM)	Guenter E. Brueckner, Michael E. Van Hoosier, Dianne K. Prinz	Solar Science
STS-68/ SRL-2	Measurement of Air Pollution from Satellites (MAPS)	Henry G. Reichle, V. Conners, W. Hesketh, P. Kasibhatla, V. Kirchoff, J. Logan, R. Newell, R. Nicholls, L. Peters, W. Seiler, H. Wallio	Earth Observations
	Shuttle Imaging Radar (SIR-C)	Charles Elachi	Earth Observations
	X-Band Synthtic Aperture Radar (X-SAR)	Herwig Ottl, Diane Evans, Mario Calamia	Earth Observations

Mission	Experiment Title	Investigators	Discipline
STS-67/ ASTRO-2	Wisconsin Ultraviolet Photopolarimetry Experiment (WUPPE)	Arthur D.Code, Chris Anderson, Karen Bjorkman, Joni Johnson, Geoff Fox	Astronomy
	Hopkins Ultraviolet Telescope (HUT)	Arthur F.Davidsen, Samuel T. Durrance, Paul D. Feldman, Gerard A. Kriss, Knox S. Long, William P. Blair, William G. Fastie, Richard C. Henry, Jeffrey W. Kruk, H. Warren Moos	Astronomy
	Ultraviolet Imaging Telescope (UIT)	Theodore P.Stecher, Steve Maran, John Horack, Barry Madore, Susan Neff, Barbara Pfarr, Andrew M. Smith, Chan Na	Astronomy
	The Near UV Properties of Galaxies Which have Low Optical Surface Brightness (UIT)	Gregory D. Bothun	Astronomy
	Ultraviolet Extinction and Plarization of Interstellar Dust in the Large Magellanic Cloud (HUT, WUPPE)	Geoffry C. Clayton	Astronomy
	O-VI Emission and Broad-Band UV Spectra of Symbiotic Systems (HUT, WUPPE)	Brian R. Espey	Astronomy
	Investigations of Lyman Line Profiles in Hot DA White Dwarfs (HUT)	David S. Finley	Astronomy
	An Ultraviolet Survey/Atlas of Spiral Galaxies (UIT)	Wendy L. Freedman	Astronomy
	Astro-2 Observations of the Moon (UIT)	George Randy Gladstone	Astronomy
	HUT Observations of the Lyman Continuum in Starburst Galaxies (HUT)	Claus H. Leitherer	Astronomy
	Far UV Observations of Interstellar Shocks (HUT)	John C. Raymond	Astronomy
	The Extended Atmospheres of Wolf-Rayet Stars (HUT, WUPPE)	Regina E. Schulte-Ladbeck	Astronomy
	A Reconnaissance of O3 Spectra in the 900-1200 Angstrom Region (HUT)	Nolan R. Walborn	Astronomy
STS-71/ SL-M	Protein Crystal Growth Experiment	Alexander McPherson	Physical Science: Biotechnology
	Aerobic Capacity Using Graded Bicycle Ergonometry	Veleri Mikhaylov, Steven Siconolfi	Life Science: Human Physiology
	Alterations in Postural Equilibrium Control Associated with Long Duration Space Flight	W. Paloski, Jacob Bloomberg, M. Borisov, D. Harm, I. Kozlovskaya, M. Reschke, I. Tcherkirda, A. Voronov	Life Science: Human Physiology
	Anticipatory Postural Activity	Charles S. Layne, Jacob J. Bloomberg	Life Science: Human Physiology
	Assessment of Humoral Immune Function During Long Duration Space Flight	Clarence Sams, Irina Konstantinova	Life Science: Human Physiology
	Morphological, Histochemical, and Ultrastructural Characteristics of Skeletal Muscle	Daniel L. Feedback, Boris S. Shenkman	Life Science: Human Physiology
	Evaluation of Thermoregulation During Long Duration Spaceflight	Suzanne M. Fortney, Steven Siconolfi, Valeriy Mikhaylov, Yevgheny Kobzev, John Greenleaf, Richard Gonzalez, Stuart M.C. Lee, Jon Williams	Life Science: Human Physiology
	Assessment of Autonomic and Gastric Function during Spaceflight, Entry and Landing	Deborah L. Harm, Inessa Kozlovskaya	Life Science: Human Physiology
	Red Blood Cell Mass and Survival	Helen W. Lane, Svetlana Ivanova	Life Science: Human Physiology
	Physiologic Pharmacokinetic Changes during Spaceflight	Lakshmi Putcha, I. Goncharov, L. Kovachevick	Life Science: Human Physiology

Mission	Experiment Title	Investigators	Discipline
STS-71/ SL-M	The Effects of Long Duration Space Flight on Gaze Control	Millard F. Reschke, William P. Huebner, William H. Paloski, Deborah L. Harm, Jacob J. Bloomberg, I. B. Kozlovskaya	Life Science: Human Physiology
	Greenhouse	Frank B. Salisbury, Margarita Levinskikh, Boris Yendler, David Bubenheim, William Campbell, John Carman, Gail Bingham	Life Science: Plants
	Evaluation of Skeletal Muscle Performance and Characteristics	Steven F. Siconolfi, Inessa B. Kozlovskaya, Yuri Koriak, Viktor J. Stepanstov, Daniel Feedback, Charles S. Layne	Life Science: Human Physiology
	Renal Stone Risk Assessment	Peggy A. Whitson, Germain Arzamzov, Charles Y. Pak, Robert A. Pietrzyk	Life Science: Human Physiology
	Measurement of Cytogenetic Effects of Space Radiation	Tracy C. Yang, B. Fedorenko, S. Johnson, H. Wu	Life Science: Human Factors
	Avian Blood Vessel Formation in Space	Peter I. Lelkes	Life Science: Developmental
	Biomechanics of Movement During Locomotion	Jacob Bloomberg, M. Borisov, D. Harm, I. Kozlovskaya, W. Paloski, M. Reschke, I. Tcherkirda, A. Voronov	Life Science: Human Physiology
	Dynamics of Calcium Metabolism and Bone Tissue	Helen Lane, Victor Ogonov, Irina Popova	Life Science: Human Physiology
	Effect of Microgravity on Afferent Innervation	Cesar D. Fermin	Life Science: Developmental
	Effects of Weightlessness on Quail Eye Development	Gary W. Conrad	Life Science: Developmental
	Effects of Weightlessness on the Avian Visuo-Vestibular System: Immunohistochemical Analysis	Toru Shimizu	Life Science: Developmental
	Effects of Weightlessness on Vestibular Development of Quail	Bernd Fritzsche	Life Science: Developmental
	Expression of Contractile Protein Isoforms in Microgravity	Page A. W. Anderson	Life Science: Developmental
	Fecundity of Quail in Spacelab Microgravity	Bernard C. Wentworth	Life Science: Developmental
	Fluid and Electrolyte Homeostasis	Helen W. Lane	Life Science: Human Physiology
	Hypogravity's Effect of the Life Cycle of Japanese Quail	Patricia Y. Hester	Life Science: Developmental
	Inflight Radiation Measurements	Gautam Badhwar	Life Science: Radiation
	Phenotypic and Functional Analysis of Peripheral Mononuclear Cells During Long Duration Space Flight	Clarence Sams	Life Science: Human Physiology
	Physiological Responses During Descent on the Space Shuttle	John B. Charles, Valeriy Mikhailov	Life Science: Human Physiology
	Skeletal Development in Long Duration Spaceflight	Stephen B. Doty	Life Science: Developmental
	Studies of Mechanisms Underlying Orthostatic Intolerance using Ambulatory Monitoring, Baroreflex Testing, and the Valsalva Maneuver	Valeriy Mikhaylov, Janice Yelle	Life Science: Human Physiology
	Studies of Orthostatic Intolerance with the Use of LBNP	John B. Charles, Janice M. Fritsch-Yelle, Valeriy Mikhaylov	Life Science: Human Physiology

Mission	Experiment Title	Investigators	Discipline
STS-71/ SL-M	The Effects of Long Duration Space Flight on Eye, Head, and Trunk Coordination During Locomotion	Jacob Bloomberg, M. Borisov, D. Harm, I. Kozlovskaya, W. Paloski, M. Reschke, I. Tcherkirda, A. Voronov	Life Science: Human Physiology
	Trace Chemical Contamination: Water Quality	Richard L. Sauer, Yuri Sinyak	Life Science: Human Factors
	Trace Chemical Contamination: Air Quality	John T. James	Life Science: Human Factors
	Microbial air sampler	Duane Pierson	Life Science: Human Factors
	Viral Reactivation	Duane Pierson	Life Science: Human Factors
STS-73/ USML-2	Surface Tension Driven Convection Experiment	Simon Ostrach, Yasuhiro Kamotani, A. Pline	Physical Science: Fluids
	Drop Dynamics Experiment	Taylor Wang, C.P. Lee, A. Anilkumar, Eugene Trinh	Physical Science: Fluids
	Science and Technology of Surface-Controlled Phenomena	Robert Apfel, G. Holt	Physical Science: Fluids
	Geophysical Fluid Flow Cell Experiment	John Hart, J. Toomre, F. Leslie, T. Miller, D. Hathaway, G. Glatzmaier, D. Ohlsen	Physical Science: Fluids
	Orbital Processing of High Quality Cadmium Zinc Telluride Compound Semiconductors	David J. Larson, Donald C. Gillies, J.I. Alexander, F. Carlson, J. Moosbrugger, M. Dudley	Physical Science: Materials
	The Study of Dopant Segregation Behavior During the Crystal Growth of Gallium Arsenide (GaAs) in Microgravity	David H. Matthiesen, D. Carlson, J. Kafalas, M. Kaforey, S. Motakef	Physical Science: Materials
	Crystal Growth of Selected II-VI Semiconducting Alloys by Directional Solidification	Sandor L. Lehoczky, Frank R. Szofer, R.N. Andrews, Ching-Hua Su, L. Bubulac	Physical Science: Materials
	Vapor Transport Crystal Growth of Mercury Cadmium Telluride in Microgravity	Heribert Wiedemeier	Physical Science: Materials
	Zeolite Crystal Growth Furnace	Albert Sacco	Physical Science: Materials
	Glovebox Facility	Donald A. Reiss	Technology
	Interface Configuration Experiment (ICE)	Paul Concus, Robert Finn, Mark M. Weislogel	Physical Science: Fluids
	Oscillatory Thermocapillary Flow Experiment	Yasuhiro Kamotani, Simon Ostrach, A. Pline	Physical Science: Fluids
	Fiber Supported Droplet Combustion	Forman A. Williams, D. Dietrich, F. Dryer, J. Haggard, V. Nayagam, B. Shaw	Physical Science: Fluids
	Protein Crystal Growth Glovebox	Lawrence DeLucas, E. Arnold	Physical Science: Biotechnology
	Zeolite Crystal Growth Glovebox	Albert Sacco, A. Dixon, R. Thomspon	Physical Science: Materials
	Colloidal Disorder-Order Transitions	Paul Chaikin, William B. Russel	Physical Science: Fluids
	Particle Dispersion Experiment	John Marshall	Physical Science: Fluids
	Single-Locker Protein Crystal Growth - Two Methods	Daniel Carter	Physical Science: Biotechnology
	Crystal Growth by Liquid-Liquid Diffusion	Alexander McPherson, Jr.	Physical Science: Materials

Mission	Experiment Title	Investigators	Discipline
STS-73/ USML-2	Commercial Protein Crystal Growth	Larry DeLucas, E. Arnold, D. Carter, C. Chang, B.Dijkstra, D. Eggleston, H. Einsphar, A.Frankel, J.Knox, C.Kundrot, P. Lu, E.Meehan, T.L. Nagabhushan, R. Naumann, M.Navia, W. Stallings, F.L. Suddath, M. Sundaralingam, D. Voet, K. Ward, M. Wardell, P.Weber, J.-P. Wery, D. Yang	Physical Science: Biotechnology
	Advanced Protein Crystallization Facility	Gottfried Wagner	Technology
	Crystallization of Apocrustacyanin C1	Naomi E. Chayen, P.F. Zagalsky, J.R. Helliwell, T.J.Boggon	Physical Science: Biotechnology
	Crystal Structure Analysis of the Bacteriophage Lambda Lysozyme	Jean-Paul Declercq, C. Evard	Physical Science: Biotechnology
	Crystallization of RNA Molecules Under Microgravity Conditions	Volker Erdmann	Physical Science: Biotechnology
	Crystallization of the Protein Grb2 and Triclinic Lysozyme	Arnaud Ducruix, I. Broutin, M. Ries-Kautt	Physical Science: Biotechnology
	Microgravity Crystallization of Thermophilic Aspartyl-tRNA Synthetase and Thaumatin	Richard Giege, J.D.Ng, B.Lorber, A.Theobald-Dietrich	Physical Science: Biotechnology
	Crystallization in Space of Octarellins, de novo Designed (alpha/beta)-Barrell Proteins, and of a Mutated Human TIM Forming a Monomeric (alpha/beta)-Barrell Structure	Joseph Martial, K. Goraj, V. Mainfroid, Lode Wyns, M.H. Dao Thi, J.-M. Francois, I. Zegers	Physical Science: Biotechnology
	Crystallization in a Microgravity Environment of CcdB, a Protein Involved in the Control of Cell Death	Lode Wyns, M.H.Dao Thi, D.Maes	Physical Science: Biotechnology
	A Multivariate Analysis of X-ray Diffraction Data Obtained from Glutathione S Transferase	Lennart Sjölin, G. Gilliland, A. Wlodawer	Physical Science: Biotechnology
	Protein Crystal Growth: Light-driven Charge Translocation Through Bacteriorhodopsin	Gottfried Wagner, Torsten Rothaermel	Physical Science: Biotechnology
	Crystallization of Ribosomes	Ada Yonath	Physical Science: Biotechnology
	Crystallization of Sulfolobus Solfataricus Alcohol Dehydrogenase	Adriana Zagari, F. Sica, G. Sorrentino, L. Mazzarella, L. Carotenuto, C.A.Raia, M.Rossi	Physical Science: Biotechnology
	Crystallization of Turnip Yellow Mosaic Virus, Tomato Aspermy Virus, Satellite Panicum Mosaic Virus, Canavalin, Beef Liver Catalase, Concanavalin B	Alexander McPherson	Physical Science: Biotechnology
	Crystallization of the Epidermal Growth Factor (EGF) Receptor	Wolfgang Weber, C.Betzel	Physical Science: Biotechnology
	Structure of the Membrane-Embedded Protein Complex Photosystem I	Wolfram Saenger, P. Fromme	Physical Science: Biotechnology
	Crystallization of Visual Pigment Rhodopsin	Willem de Grip, J.Van Oostrum	Physical Science: Biotechnology
	CGBA: Examination of plasmin enzyme efficacy in microgravity	Ted Bateman	Physical Science: Biotechnology
	CGBA: Magnetic combing of collagen	John F. Doyle, Paul Todd, Howard Wachtel	Physical Science: Biotechnology
	CGBA: Crystallization of proteins in microgravity for high resolution structural basis for drug design	G. Shoham	Physical Science: Biotechnology
	CGBA: Protein and nucleic acid crystallization	Paul Todd, Michael Sportiello	Physical Science: Biotechnology
	CGBA: Enzymatic degradation of cellulose	Michael J. Pecaut	Physical Science: Biotechnology

Mission	Experiment Title	Investigators	Discipline
STS-73/ USML-2	CGBA: Brine Shrimp Development	Brian S. Spooner, A. Paulsen	Life Science: Developmental
	CGBA: Growth of embryonic chick calavariae osteoblasts attached to type I collagen	M.Kacena	Life Science: Cell and Molecular
	CGBA: The reversibility of cell stabilization induced by a novel cell growth regulator	Terry C. Johnson, Heideh K. Fattaey	Life Science: Cell and Molecular
	CGBA: Development, growth and activation of bone marrow macrophages- Phase II	Stephen Keith Chapes, A.D. Forsman, A.A. Beharka	Life Science: Cell and Molecular
	CGBA: Viral infection of mammalian cells	R. Consigli, E.T.Gillock, L. Grenz, S.A.Smiley, T.C.Johnson	Life Science: Cell and Molecular
	CGBA: Biochemical reaction kinetics	S.K. Chapes, R.A. Gerren	Life Science: Cell and Molecular
	CGBA: Monoclonal antibody production	R. Consigli, E.T.Gillock, L. Grenz, S.A.Smiley, T.C.Johnson	Life Science: Cell and Molecular
	CGBA: Growth of Embryonic Chick Calavariae Osteoblasts Attached to Type-I Collagen	M.A.Kacena	Life Science: Cell and Molecular
	CGBA: Plastid distribution in columella cells of a starchless arabidopsis mutant grown in microgravity	E. M. Hilaire, J. Guikema	Life Science: Plant
	CGBA: Effects of stress ethylene inhibitors on sweet clover	G.L.Gallegos, J.A. Guikema	Life Science: Plant
	CGBA: Effects of microgravity on gene expression in higher plants	Yi Li	Life Science: Plant
	CGBA: Clover (Trifolium repens) gravi-response after space flight or clinorotation	J. D. Smith	Life Science: Plant
	CGBA: Pre-metatarsal development and mineralization	Brenda Klement, Brian S. Spooner	Life Science: Cell and Molecular
	CGBA: A summary of research on bacterial growth in suspensio cultures on semisolid agar and biofilm development	David Klaus, M. Kacena, and B. Manfredi	Life Science: Cell and Molecular
	CGBA: Ethylene production in a starchless arabidopsis mutant grown in microgravity	G.L.Gallegos, J.Guikema	Life Science: Plant
	CGBA: Clover and rhizobium development during spaceflight.	P.P.Wong, J. Guikema	Life Science: Plant
	Astroculture Facility and Experiment	Raymond J. Bula, R. Morrow, T.Tibbets	Technology
	Lower Body Negative Pressure Device (LBNP)	John Charles, J.T. Brown	Technology
	Space Acceleration Measurement System	Ron Sicker	Technology
	Three Dimensional Microgravity Accelerometer	Jan Bijvoet	Technology
	Orbital Acceleration Research Experiment	Jose L. Christian, Jr.	Technology
	Suppression of Transient Accelerations By Levitation Evaluation	Gerald Nurre	Technology
STS-75/ USMP-3	The Effect of Microgravity Direction on the Growth of PbSnTe	Archibald L. Fripp, William J. Debnam, Ivan Clark, W. R. Rosch, R. Narayanan	Physical Science: Materials
	Critical Fluid Light Scattering Experiment (Zeno)	Robert W. Gammon, J.N. Shaumeyer, Matthew E. Briggs, Hacene Boukari, David Gent, R. Allen Wilkinson	Physical Science: Fluids
	Isothermal Dendritic Growth Experiment (IDGE)	Martin E. Glicksman, Matthew B. Koss, D.C. Malarik	Physical Science: Materials
	Materials for the Study of Interesting Phenomena of Solidification on Earth and in Orbit (MEPHISTO)	Jean-Jacques Favier, J. Iwan D. Alexander, J.P. Garandet	Physical Science: Materials
	Space Acceleration Measurement Systems (SAMS)	Richard DeLombard, Melissa J.B. Rogers, Kenneth Hrovat, Milton E. Moskowitz, Timothy Reckart, Kevin M. McPherson	Technology

Mission	Experiment Title	Investigators	Discipline
STS-75/ USMP-3	Orbital Acceleration Research Experiment (OARE)	Richard DeLombard, Melissa J.B. Rogers, Kenneth Hrovat, Milton E. Moskowitz, Timothy Reckart, Kevin M. McPherson	Technology
	Forced-Flow Flamespreading Test (FFFT)	Kurt R. Sacksteder, James S. Tien, Paul S. Greenberg, Paul V. Ferkul, Richard D. Pettegrew, Hsin-Yi Shih	Physical Science: Fluids
	Radiative Ignition and Transition to Spread Investigation (RITSI)	Takashi Kashiwagi, Sandra Olson	Physical Science: Fluids
	Comparative Soot Diagnostics (CSD)	David L. Urban, DeVon W. Griffin, Melissa Y. Gard, Michael Hoy	Physical Science: Fluids
STS-78/ LMS	Bubbles and Drops Interaction with Solidification Fronts	Rodolfo Monti, Raimondo Fortezza	Physical Science: Fluids
	Evaporation and Condensation Kinetics at a Liquid Vapor Interface; and Efficient Cooling of High Powered Small Electronic Devices by Boiling under Microgravity	Johannes Straub, Herman Merte	Physical Science: Fluids
	The Electrohydrodynamics of Liquid Bridges	Dudley Saville	Physical Science: Fluids
	Nonlinear Surface Tension Driven Bubble Migration	Antonio Viviani	Physical Science: Fluids
	Oscillatory Marangoni Instability	Jean-Claude Legros, Philippe Géoris, Bernard Roux, Manuel Velarde	Physical Science: Fluids
	Thermocapillary Migration and Interactions of Bubbles and Drops	R. Shankar Subramanian, R. Balasubramanian, Gunter Wozniak	Physical Science: Fluids
	Comparative Study of Cells and Dendrites During Directional Solidification of a Binary Aluminum Alloy at 1-g and under Microgravity	Henri Nguyen Thi, Bernard Billia, Denis Camel, Béatrice Drevet, Jean-Jacques Favier	Physical Science: Materials
	Coupled Growth in Hypermonotectics	Barry Andrews, Sam R. Coriell	Physical Science: Materials
	Effects of Convection on Interface Curvature during Growth of Concentrated Ternary Compounds	Thierry Duffar, Ernesto Diegueuz, Jean Paul Garandet	Physical Science: Materials
	Equiaxed Solidification of Aluminum Alloy	Denis Camel, Marie-Danièle Dupouy, Jean-Jacques Favier	Physical Science: Materials
	Interactive Response of Advancing Phase Boundaries to Particles	Ulrike Hecht, Jochen Laakmann, Stephan Rex	Physical Science: Materials
	Particle Engulfment and Pushing by Solidifying Interfaces	Doru Stefanescu, Subayu Sen, Peter Curreri, Brij Drindaw, Frank Juretzko	Physical Science: Materials
	Advanced Protein Crystallization Facility on the Life and Microgravity Sciences Mission	Alexander McPherson	Physical Science: Biotechnology
	Crystallization of EGFR-EGF	Christian Betzel	Physical Science: Biotechnology
	Crystallization of Crustacyanin Subunits	Naomi E. Chayen	Physical Science: Biotechnology
	Crystallization of Engineered 5S rRNA Molecules	Volker Erdmann	Physical Science: Biotechnology
	Crystallization of Thermus Thermophilus AspRS: Comparative analysis of aspartyl-tRNA synthetase and thaumatin crystals grown on earth and in microgravity	Richard Giege, B. Lorber, J.D. Ng	Physical Science: Biotechnology

Mission	Experiment Title	Investigators	Discipline
STS-78/ LMS	Monitoring of Lysozyme Protein Crystal Growth in Microgravity via a Mach-Zehnder Interferometer and Comparison with Earth Control Data	John Helliwell	Physical Science: Biotechnology
	Crystallization of the Nucleosome Core Particle in Space	Timothy Richmond	Physical Science: Biotechnology
	Enhanced Resolution Through Improved Crystal Quality in the Crystal Structure Analysis of Photosystem I	P.Fromme, W. Saenger, Wolf Schubert, N. Krautz	Physical Science: Biotechnology
	Mechanism of Membrane Protein Crystal Growth: Bacteriorhodopsin -- Mixed Micelle Packing at the Consolution Boundary, Stabilized in Microgravity	Gottfried Wagner	Physical Science: Biotechnology
	Crystallization of Sulfolobus Solfataricus Alcohol Dehydrogenase	Adriana Zagari, L. Esposito, F. Sica, G. Sorrentino, R. Berisio, L. Carotenuto, A. Giordano, C.A.Raia, M. Rossi, V.Lamzin, K.S. Wilson	Physical Science: Biotechnology
	Growth of Lysozyme Crystals at Low Nucleation Density	Juan Garcia-Ruiz, F. Otalora, D.Rondon, M.-L. Novella	Physical Science: Biotechnology
	Crystallization in a Microgravity Environment of CcdB, a Protein Involved in the Control of Cell Death	Lode Wyns	Physical Science: Biotech
	Effects of Weightlessness on Human Single Muscle Fiber Function	Robert Fitts, David L. Costill	Life Science: Human Physiology
	Relationship of Long-term Electromyographic Activity and Hormonal Function to Muscle Atrophy and Performance	V. Reginald Edgerton, Malcolm Cohen, Michael Greenisen, Richard E. Grindeland, John Hodgson, Roland Roy	Life Science: Human Physiology
	Effects of Microgravity on Skeletal Muscle Contractile Properties	Paolo Cerretelli, Marco V. Narici, Berndt Kayser	Life Science: Human Physiology
	Effects of Microgravity on the Biomechanical and Bioenergetic Characteristics of Human Skeletal Muscle	Pietro di Prampero, Carlo Capelli, Jachen Denoth, Jean Francois Marini, Stefania Milesi, Edgar Stuessi	Life Science: Human Physiology
	Magnetic Resonance Imaging After Exposure to Microgravity (Ground Study)	Adrian LeBlanc, Harlan Evans, Thomas Hedrick, C.Y. Lin, Linda Shackelford, M. Stewart West	Life Science: Human Physiology
	An Approach to Counteract Impairment of Musculoskeletal Function in Space (Ground Study)	Per A. Tesch, Hans E. Berg	Life Science: Human Physiology
	Direct Measurement of the Initial Bone Response to Space Flight	Christopher Cann, Claude D. Arnaud	Life Science: Human Physiology
	Measurement of Energy Expenditure During Space Flight with the Doubly Labeled Water Method	Peter T. Stein, Randall Gretebeck, Reed W. Hoyt, Helen Lane	Life Science: Human Physiology
	Extended Studies of Pulmonary Function in Weightlessness	John West, Ann Elliott, Manuel Paiva, G.Kim Prisk	Life Science: Human Physiology
	Human Sleep, Circadian Rhythms and Performance in Space	Timothy H. Monk, B.Billy, Daniel J. Buysse, Claude C. Gharib, Guillemette Gauquelin, Alexander Gundel	Life Science: Human Physiology
	Microgravity Effects on Standardized Cognitive Performance Measures using the Performance Assessment Workstation	Samuel Schiflett, Douglas Eddy, Jonathan French, Robert Chlegel	Life Science: Human Factors
	Torso Rotation Experiment	Douglas Watt, Charles M. Oman	Life Science: Human Physiology
	Canal and Otolith Interaction Studies	Millard Reschke, Alain F. Berthoz, Gilles R. Clement, Bernard Cohen, Makoto Igarashi, William H. Paloski, Donald E. Parker	Life Science: Human Physiology

Mission	Experiment Title	Investigators	Discipline
STS-78/ LMS	Lignin Formation and the Effects of Microgravity: A New Approach	Norman Lewis, Laurence B. Davin, Mi Chang, Pieter Van Heerden	Life Science: Plant
	Development of the Fish Medaka in Microgravity	Debra J. Wolgemuth, Carey R. Phillips	Life Science: Developmental
	Role of Corticosteroids in Bone Loss During Space Flight	Thomas Wronski, Bernard P. Halloran, Scott C. Miller	Life Science: Animal Physiology
	Space Acceleration Measurement System (SAMS)	Ron Sicker	Technology
	Orbital Acceleration Research Experiment (OARE)	Bill Wagar	Technology
	Microgravity Measurement Assembly (MMA)	Maurizio Nati	Technology
STS-83/ MSL-1	Laminar Soot Processes	Gerard Faeth	Physical Science: Fluids
	Structure of Flame Balls at Low Lewis-number (SOF-BALL)	Paul Ronney	Physical Science: Fluids
	Droplet Combustion Experiment	Forman Williams, Frederick Dryer	Physical Science: Fluids
	Fiber-Supported Droplet Combustion	Forman A. Williams, Renato Colantonio, Frederick Dryer, John Haggard, Vedha Nayagam, Benjamin Shaw	Physical Science: Fluids
	Protein Crystallization Apparatus for Microgravity (PCAM)	Daniel Carter, Don Abraham, Gerard J. Bunick, Chong-Hwan Chany, Jean-Paul Declercq, Louis Delbaere, B.W. Dijkstra, Drake Egglestow, John Helliwell, Craig Kundrot, John Rosenberg, William Stallings, B.C. Wang, Mark Wardell, Jean-Pierre Wery, Daniel Yang	Physical Science: Biotechnology
	Second-Generation Vapor Diffusion Apparatus	Larry Delucas	Physical Science: Biotechnology
	Handheld Diffusion Test Cells	Alexander McPherson	Physical Science: Biotechnology
	Physics of Hard Spheres Experiment	Paul Chaikin, William B. Russel, JiXiang Zhu	Physical Science: Materials
	Measurement of Diffusion Coefficient by Shear Cell Method	Shinichi Yoda, Hirohisa Oda, Toshihiko Ohida, Tadahiko Masaki, Minoru Kaneko, Kazayuki Touno	Physical Science: Fluids
	Diffusion of Liquid Metals	Toshio Itami, Hirokatsu Aoki, Minoru Kaneko, Misako Uchida, Akira Shisa, Shinichi Amano, Osamu Odawara, Tadahiko Masaki, Hirohisa Oda, Toshihiko Ohida, Shinichi Yoda	Physical Science: Fluids
	Diffusion in Liquid Lead-Tin-Telluride	Misako Uchida, Minoru Kaneko, Toshio Itami, Akira Shisa, Shinichi Amano, Toshihiko Ooida, Tadahiko Masaki, Shinichi Yoda	Physical Science: Fluids
	Impurity Diffusion in Ionic Metals	Tsutomu Yamamura, Yuzuru Sato, Hongmin Zhu, Mishia-ki Yamasaki, Toshihiko Ohida, Tadahiko Masaki, Shinichi Yoda	Physical Science: Fluids

Mission	Experiment Title	Investigators	Discipline
STS-83/ MSL-1	Liquid Phase Sintering II	Randall German, John Johnson, Shawn Liu	Physical Science: Fluids
	Diffusion Processes in Molten Semiconductors	David H. Matthiesen, William Arnold, Arnon Chait, David Stroud	Physical Science: Fluids
	Thermophysical Properties of Undercooled Metallic Melts	Ivan Egry, Georg Lohoefer, Berndt Feuerbacher	Physical Science: Materials
	Thermophysical Properties of Advanced Materials in the Undercooled Liquid State	Hans F. Fecht, Rainer Wunderlich	Physical Science: Materials
	Measurements of the Surface Tension of Liquid and Undercooled Metallic Melts by Oscillating Drop Technique	Martin G. Froberg, Michael Roesner-Kuhn	Physical Science: Fluids
	Study of the Morphological Stability of Growing Dendrites by Comparative Dendrite Velocity Measurements on Pure Ni and a Dilute Ni-C Alloy in the Earth and Space Laboratory	D. M. Herlach, M. Barth, B. Feuerbacher	Physical Science: Materials
	Undercooled Melts of Alloys with Polytetrahedral Short-Range Order	D.M. Herlach, Dirk Holland-Moritz, Heinrich Bach, Hans Fecht, Kenneth Kelton, Berndt Feuerbacher	Physical Science: Materials
	Thermal Expansion of Glass Forming Metallic Alloys in the Undercooled State	K. Samwer, B. Damaschke, Ivan Egry	Physical Science: Materials
	Experiments on Nucleation in Different Flow Regimes	Robert Bayuzick, William H. Hofmeister, Michael B. Robinson	Physical Science: Fluids
	Alloy Undercooling Experiments	Merton Flemings, Douglas Matson, Wolfgang Loser	Physical Science: Fluids
	Measurement of Surface Tension and Viscosity of Undercooled Liquid Metals	Julian Szekely, Merton Flemings, Gerardo Trapaga, Robert Hyers	Physical Science: Fluids
	AC Calorimetry and Thermophysical Properties of Bulk Glass-Forming Metallic Liquids	W.L. Johnson, David Lee	Physical Science: Fluids
	Coarsening in Solid-Liquid Mixtures	D. Peter Voorhees	Physical Science: Materials
	Bubble and Drop Nonlinear Dynamics	L.G. Leal, E.H.Trinh	Physical Science: Fluids
	A Study of Fundamental Operation of a Capillary-driven Heat Transfer (CHT) Device in Microgravity	Kevin P. Hallinan, Jeffrey S. Allen	Physical Science: Fluids
	Internal Flows in a Free Drop	S.S. Sadhal, E.H.Trinh	Physical Science: Fluids
	Astro/Plant Generic Bioprocessing Apparatus (AstroPGBA): The use of genetic markers in auxin studies in tomato, Lycopersicon esculentum	Yi Li	Life Science: Plants
	AstroPGBA: Lignin metabolism in loblolly pin, Pinus taeda	Louis Stodieck	Life Science: Plants
	AstroPGBA: Vinca alkaloid metabolism in catharanthus roseus	Louis Stodieck, Mark Kliss, Gerard Heyenga, Andrew Staehlin, Peter Wong, Yi Li, Paul Todd	Life Science: Plants
	Quasi-Steady Acceleration Measurement (QSAM)	Hans Hamacher	Technology
	Orbital Acceleration Research Experiment (OARE)	Peter Tschen	Technology
	Microgravity Measurement Assembly (MMA)	Hans Hamacher	Technology
	Space Acceleration Measurement System (SAMS)	Peter Tschen	Technology
STS-87/ USMP-4	Effects of Microgravity Direction on the Growth of PbSnTe: Compound Semiconductor Growth in a Low-G Environment	Archibald L. Fripp, William J. Debnam, William R. Rosch, N.R. Baker, Ranga Narayanan	Physical Science: Materials
	Solution Growth of GaAs Crystals under Microgravity	Sandor L. Lehoczky, Donald C. Gillies, Frank R. Szofran, Dale A. Watring	Physical Science: Materials

Mission	Experiment Title	Investigators	Discipline
STS-87/ USMP-4	Confined Helium Experiment (CHeX)	John A. Lipa, D.R. Swanson, J.A. Nissen, P.R. Williamson, K. Geng, D. A. Stricker, T.C.P.Chui, U.E. Israelsson, M. Larson	Physical Science: Fluids
	Isothermal Dendritic Growth Experiment (IDGE)	Martin E. Glicksman, D. C. Malarik, Matthew B. Koss, J.C. LaCombe, A.O. Lupulescu	Physical Science: Materials
	Materials for the Study of Interesting Phenomena of Solidification on Earth and in Orbit (MEPHISTO)	Reza Abbaschian, Sam R. Coriell, F. Chen, J.R. Mileham, H. DeGroh, V. Timchenko, E. Leonardi, G. deVahl Davis, G. Cambon	Physical Science: Materials
	Enclosed Laminar Flames (ELF)	Lea-Der Chen, Dennis Stocker, John E. Brooker, Kezhong Jia	Physical Science: Fluids
	Wetting Characteristics of Immiscibles (WCI)	J. Barry Andrews, L.J. Little	Physical Science: Fluids
	Particle Engulfment and Pushing by a Solid/Liquid Interface (PEP)	Doru Stefanescu, Subayu Sen, Brij Dhindaw	Physical Science: Materials
	Space Acceleration Measurement System (SAMS)	Melissa J. B.Rogers, K. Hrovat, K. McPherson, R. DeLombard, T. Reckart	Technology
	Orbital Acceleration Research Experiment (OARE)	Melissa J. B.Rogers, K. Hrovat, K. McPherson, R. DeLombard, T. Reckart	Technology
STS-94/ MSL-1R	Laminar Soot Processes	Gerard Faeth	Physical Science: Fluids
	Structure of Flame Balls at Low Lewis-number (SOF- BALL)	Paul Ronney	Physical Science: Fluids
	Droplet Combustion Experiment	Forman Williams, Frederick Dryer	Physical Science: Fluids
	Fiber-Supported Droplet Combustion	Forman A. Williams, Renato Colantonio, Frederick Dryer, John Haggard, Vedha Nayagam, Benjamin Shaw	Physical Science: Fluids
	Protein Crystallization Apparatus for Microgravity (PCAM)	Daniel Carter, Don Abraham, Gerard J. Bunick, Chong-Hwan Chany, Jean-Paul Declercq, Louis Delbaere, B.W. Dijk- stra, Drake Egglestow, John Helliwell, Craig Kundrot, John Rosenberg, William Stallings, B.C.Wang, Mark Wardell, Jean- Pierre Wery, Daniel Yang	Physical Science: Biotechnology
	Second-Generation Vapor Diffusion Apparatus	Larry Delucas	Physical Science: Biotechnology
	Handheld Diffusion Test Cells	Alexander McPherson	Physical Science: Biotechnology
	Physics of Hard Spheres Experiment	Paul Chaikin, William B. Rus- sel, JiXiang Zhu	Physical Science: Materials
	Measurement of Diffusion Coefficient by Shear Cell Method	Shinichi Yoda, Hirohisa Oda, Toshihiko Ohida, Tadahiko Ma- saki, Minoru Kaneko, Kazayuki Touno	Physical Science: Fluids

Mission	Experiment Title	Investigators	Discipline
STS-94/ MSL-1R	Diffusion of Liquid Metals	Toshio Itami, Hirokatsu Aoki, Minoru Kaneko, Misako Uchida, Akira Shisa, Shinichi Amano, Osamu Odawara, Tadahiko Masaki, Hirohisa Oda, Toshihiko Ohida, Shinichi Yoda	Physical Science: Fluids
	Diffusion in Liquid Lead-Tin-Telluride	Misako Uchida, Minoru Kaneko, Toshio Itami, Akira Shisa, Shinichi Amano, Toshi- hiko Ooida, Tadahiko Masaki, Shinichi Yoda	Physical Science: Fluids
	Impurity Diffusion in Ionic Metals	Tsutomu Yamamura, Yuzuru Sato, Hongmin Zhu, Mishia- ki Yamasaki, Toshihiko Ohida, Tadahiko Masaki, Shinichi Yoda	Physical Science: Fluids
	Liquid Phase Sintering II	Randall German, John Johnson, Shawn Liu	Physical Science: Fluids
	Diffusion Processes in Molten Semiconductors	David H. Matthiesen, William Ar- nold, Arnon Chait, David Stroud	Physical Science: Fluids
	Thermophysical Properties of Undercooled Metallic Melts	Ivan Egry, Georg Lohoefer, Berndt Feuerbacher	Physical Science: Materials
	Thermophysical Properties of Advanced Materials in the Undercooled Liquid State	Hans F. Fecht, Rainer Wun- derlich	Physical Science: Materials
	Measurements of the Surface Tension of Liquid and Un- dercooled Metallic Melts by Oscillating Drop Technique	Martin G. Froberg, Michael Roesner-Kuhn	Physical Science: Fluids
	Study of the Morphological Stability of Growing Dendrites by Comparative Dendrite Velocity Measurements on Pure Ni and a Dilute Ni-C Alloy in the Earth and Space Laboratory	D. M. Herlach, M. Barth, B. Feuerbacher	Physical Science: Materials
	Undercooled Melts of Alloys with Polytetrahedral Short- Range Order	D.M. Herlach, Dirk Holland- Moritz, Heinrich Bach, Hans Fecht, Kenneth Kelton, Berndt Feuerbacher	Physical Science: Materials
	Thermal Expansion of Glass Forming Metallic Alloys in the Undercooled State	K. Samwer, B. Damaschke, Ivan Egry	Physical Science: Materials
	Experiments on Nucleation in Different Flow Regimes	Robert Bayuzick, William H. Hofmeister, Michael B. Rob- inson	Physical Science: Fluids
	Alloy Undercooling Experiments	Merton Flemings, Douglas Matson, Wolfgang Loser	Physical Science: Fluids
	Measurement of Surface Tension and Viscosity of Un- dercooled Liquid Metals	Julian Szekeley, Merton Flem- ings, Gerardo Trapaga, Robert Hyers	Physical Science: Fluids
	AC Calorimetry and Thermophysical Properties of Bulk Glass-Forming Metallic Liquids	W.L. Johnson, David Lee	Physical Science: Fluids
	Coarsening in Solid-Liquid Mixtures	D. Peter Voorhees	Physical Science: Materials
	Bubble and Drop Nonlinear Dynamics	L.G. Leal, E.H. Trinh	Physical Science: Fluids
	A Study of Fundamental Operation of a Capillary-driven Heat Transfer (CHT) Device in Microgravity	Kevin P. Hallinan, Jeffrey S. Allen	Physical Science: Fluids
	Internal Flows in a Free Drop	S.S. Sadhal, E.H. Trinh	Physical Science: Fluids
	Astro/Plant Generic Bioprocessing Apparatus (AstroP- GBA): The use of genetic markers in auxin studies in tomato, <i>Lycopersicon esculentum</i>	Yi Li	Life Science: Plants

Mission	Experiment Title	Investigators	Discipline
STS-94/ MSL-1R	AstroPGBA: Lignin metabolism in loblolly pin, Pinus taeda	Louis Stodieck	Life Science: Plants
	AstroPGBA: Vinca alkaloid metabolism in catharanthus roseus	Louis Stodieck, Mark Kliss, Gerard Heyenga, Andrew Staehlin, Peter Wong, Yi Li, Paul Todd	Life Science: Plants
	Quasi-Steady Acceleration Measurement (QSAM)	Hans Hamacher	Technology
	Orbital Acceleration Research Experiment (OARE)	Peter Tschen	Technology
	Microgravity Measurement Assembly (MMA)	Hans Hamacher	Technology
	Space Acceleration Measurement System (SAMS)	Peter Tschen	Technology
STS-90/ Neurolab	Development of Vestibular Organs in Microgravity	Michael L. Wiederhold, V. Bluem, W. Becker	Life Science: Developmental
	Effects of Gravity on Postnatal Motor Development	Kerry D. Walton, R. Uinas, R. Kalb, J. DeFelipe, L. Garcia-Segura, D. Hilman	Life Science: Developmental
	Development of an Insect Gravity Sensory System in Space	Eberhart Rudolf Horn, Gunter A. Kamper, Jurgen Neubert	Life Science: Developmental
	Neuronal Development Under Conditions of Space Flight	Kenneth S. Kosik, O. Steward	Life Science: Developmental
	Reduced Gravity: Effects in the Developing Nervous System	Richard S. Nowakowski, N. L. Hayes	Life Science: Developmental
	Development of the Aortic Baroreflex Under Conditions of Microgravity	Tsuyoshi Shimizu, M. Yamasaki, M. Kaneko, H. Waki, S. Matsumoto, S. Katsuta, H. Wago, T. Nagayama, K. Katahira, H. Oishi, Y. Miyamoto, M. Miyake, T. Ohkohchi	Life Science: Developmental
	Chronic Recording of Otolith Nerves in Microgravity	Stephan M. Highstein, K. Yoshida, S. Usui, A. F. Mensinger, R. D. Boyle	Life Science: Animal Physiology
	Neural-Thyroid Interaction on Skeletal Isomyosin Expression in 0g	Kenneth M. Baldwin, Shin'ichi Takeda, V. J. Caiozzo, F. Haddad	Life Science: Animal Physiology
	Ensemble Neural Coding of Place and Direction in Zero-G	Bruce L. McNaughton, J. J. Kneirim, Gina Poe	Life Science: Animal Physiology
	Effects of Microgravity on Gene Expression in the Brain	Ottavio Pompeiano, C. Cirelli, M. Pompeiano, G. Tononi, P. D'Ascanio, P. Arrighi	Life Science: Animal Physiology
	Multidisciplinary Studies of Neural Plasticity in Space	Muriel D. Ross, Stephan M. Highstein, D. J. Anderson, E. R. Lewis, T. C. Chimento, B. R. Parnas, R. S. Zukin	Life Science: Animal Physiology
	Microgravity and Development of Vestibular Circuits	Jacqueline Raymond, C. J. Dechesne, D. Dememes, G. Desmadryl, E. Scarone, N. Sans	Life Science: Animal Physiology
	The Effects of Microgravity on Neuromuscular Development	Daniel A. Riley, M. T. Wong-Riley	Life Science: Animal Physiology
	CNS Control of Rhythms and Homeostasis During Space Flight	Charles A. Fuller, D. M. Murkami, T. M. Hoban-Higgans	Life Science: Animal Physiology
	Anatomical Studies of Central Vestibular Adaptation	Gay Robbins Holstein, G. D. Martinelli	Life Science: Animal Physiology
	Spatial Orientation of the Vestibulo-Ocular Reflex	Bernard Cohen, T. Raphan, Ian Curthoys, Martin Gizzi, Takeshi Kubo, Minjia Dai, Izumi Koi-zuka, Steven T. Moore	Life Science: Human Physiology

Mission	Experiment Title	Investigators	Discipline
STS-90/ Neurolab	Artificial Neural Networks and Cardiovascular Regulation	Friedhelm J.Baisch, Luis E.J.Beck, Rupert Gerzer, Knut Moller, Karel H.Wesseling, Christian Drummer, Martina Heer, John M. Karemaker	Life Science: Human Physiology
	Integration of Neural Cardiovascular Control in Space	C.Gunnar Blomqvist, Benjamin D.Levine, James Anthony Pawelczyk, Lynda D. Lane, Cole A.Giller, Francis Andrew Gaffney	Life Science: Human Physiology
	Autonomic Neuroplasticity in Weightlessness	Dwain L. Eckberg, Taadaki Mano, Timothy D. Hartwig, Friedhelm J. Baisch, William H. Cooke	Life Science: Human Physiology
	Autonomic Neurophysiology in Microgravity	David Robertson, RoseMarie Robertson, Andrew C.Ertl, Italo Biaggioni	Life Science: Human Physiology
	Sleep and Respiration in Microgravity	John B. West, G.Kim Prisk, Ann R.Elliott, Manuel Paiva	Life Science: Human Physiology
	Role of Visual Cues in Spatial Orientation	Charles M.Oman, Ian P. Howard, Theodore R. Carpenter-Smith	Life Science: Human Physiology
	Clinical Trial of Melatonin as Hypnotic for Neurolab Crew	Charles A.Czeisler, David F. Neri, Richard E. Kronauer, Derk-Jan Dijk, Teresa L. Shahan, Steven Shea	Life Science: Human Physiology
	Visuo-Motor Coordination During Space Flight	Otmar L.Bock, Barry Fowler	Life Science: Human Physiology
	Frames of Reference and Internal Models	Alain F. Berthoz, Francesco Lacquanti, Joseph McIntyre, Nunzio A. Borghese, Mauro Carrozzo	Life Science: Human Physiology
	Visual-Otolithic Interactions in microgravity	Gilles R. Clement, Alain F. Berthoz	Life Science: Human Physiology



## APPENDIX B - REFERENCES

These references were compiled using researcher-supplied information and reflect both the work done specifically for or from a mission, and the ongoing research of the investigators. Spacelab-related research is ongoing, and so is publication of information resulting from Spacelab data.

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## Space Plasma Physics

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## APPENDIX C - MISSION HARDWARE

*STS-2/OSTA-1*

Feature Identification and Location Experiment (FILE)  
Night/Day Optical Survey of Lightning (NOSL)  
Plant Growth Unit (PGU)  
Shuttle Multispectral Infrared Radiometer (SMIRR)

Measurement of Air Pollution from Satellite (MAPS)  
Ocean Color Experiment (OCE)  
Shuttle Imaging Radar (SIR-A)

*STS-3/OSS-1*

Contamination Monitor Package  
Plant Growth Unit (PGU)  
Shuttle/Spacelab Induced Atmosphere (SSIA)  
Solar Ultraviolet Spectral Irradiance Monitor (SUSIM)  
Vehicle Charging and Potential (VCAP)

Microabrasion Foils Package  
Plasma Diagnostic Package (PDP)  
Solar Flare X-ray Polarimeter (SFXP)  
Thermal Canister

*STS-7/OSTA-2*

Materials Experiment Assembly (MEA)

Material Science Autonomous Payload (MAUS)

*STS-9/Spacelab 1*

Absolute Measurement of the Solar Constant  
Atmospheric Emission Photometric Imaging (AEPI)  
Ballistocardiography Package  
Biomolecules in the Space Environment  
Charged Particle Beam Phenomena  
Exposure Tray  
Fungal Growth Box  
Imaging Spectrometric Observatory (ISO)  
Isotope Stack  
Mass Discrimination Test Box  
Measurements of Solar Spectrum Package  
Metric Camera Experiment Package  
Optical Filtering System  
Radiation Environment Mapping  
Space Experiments with Particle Accelerators (SEPAC)  
Venous Pressure Measurement Package  
Vestibular Helmet  
Waves in the OH Emmissive Layer Package

Active Cavity Radiometer Irradiance Monitor (ACRIM)  
Atmospheric Lyman- $\alpha$  Emissions Package  
Bearing Lubricant Experiment  
Biostack  
DC and Low Frequency Magnetometer  
Far Ultraviolet Space Telescope (FAUST)  
Grille Spectrometer (GRILLE)  
Inflight Blood Collection System (IBCS)  
Low-Energy Electron Flux Study  
Materials Science Facility (Werkstofflabor)  
Mercury Iodide Crystal Growth  
Microwave Remote Sensing Experiment  
Plant Nutation Experiment Package  
Rotating Dome  
Tissue Culture Incubator  
Very Wide Field Galactic Camera  
Vestibulo-Spinal Reflex Package  
X-ray Astronomy Spectroscopy

*STS-41D/OAST-1*

Dynamic Augmentation Experiment (DAE)  
Solar Array Experiment (SAE)

IMAX Cargo Bay Camera (ICBC)  
Solar Cell Calibration Facility (SCCF)

*STS-41G/OSTA-3*

Feature Identification and Location Experiment (FILE)  
Large Format Camera (LFC)  
Shuttle Imaging Radar (SIR-B)

IMAX Cargo Bay Camera (ICBC)  
Measurement of Air Pollution from Satellite (MAPS)

*STS-51B/Spacelab 3*

Ames Research Center (ARC) Life Sciences Payload  
Auroral Imaging Experiment  
Fluid Experiment System (FES)  
Ionization States of Cosmic Ray Heavy Nuclei (IONS)  
Vapor Crystal Growth System (VCGS)

Atmospheric Trace Molecule Spectroscopy (ATMOS)  
Drop Dynamics Module (DDM)  
Geophysical Fluid Flow Cell (GFFC)  
Mercuric Iodide Crystal Growth (MICG)  
Very Wide Field Galactic Camera (VWFGC)

*STS-51F/Spacelab 2*

Coronal Helium Abundance Spacelab Experiment (CHASE)	Cosmic Ray Nuclei Experiment (CRNE)
High-Resolution Telescope and Spectrograph (HRTS)	Inflight Blood Collection System (IBCS)
Infrared Telescope (IRT)	Plant Growth Unit (PGU)
Plasma Diagnostics Package (PDP)	Solar Optical Universal Polarimeter (SOUP)
Solar Ultraviolet Spectral Irradiance Monitor (SUSIM)	Superfluid Helium Zero-g (SFHe)
Vehicle Charging and Potential (VCAP)	X-ray Telescope (XRT)

*STS-61A/Spacelab D-1*

Biorack (BR)	Biowissenschaften (BW)
Material Science Experiment Double Rack (MEDEA)	Materials Experiment Assembly (MEA)
Navigation Experiment (NAVEX)	Prozesskammer (PK)
Vestibular Sled (VS)	Werkstofflabor (WL; Materials Science Facility)

*STS-61B/EASE-ACCESS*

Assembly Concept for Construction of Erectable Space Structures (ACCESS)  
Experiment Assembly of Structures in Extravehicular activity (EASE)  
IMAX Cargo Bay Camera (ICBC)

*STS-61C/Microgravity Science Laboratory-2*

Automated Directional Solidification Furnace (ADSF)	Electromagnetic Levitator (EML)
Three Axis Acoustic Levitator (3AAL)	

*STS-35/ASTRO-1*

Broad Band X-Ray Telescope (BBXRT)	Hopkins Ultraviolet Telescope (HUT)
Ultraviolet Imaging Telescope (UIT)	Wisconsin Ultraviolet Photopolarimeter Experiment (WUPPE)

*STS-40/Spacelab Life Sciences 1*

Accelerometer Recording Unit (ARU)	Acetylene Rebreathing Cardiac Output System
Ambient Temperature Recorder (ATR)	Animal Enclosure Module (AEM)
Ankle Torque Device	Awareness of Position Setup
Bag-In-Box (BIB) Assembly	Baroreflex Measurement System
Bicycle Ergometer	Biomedical Instrumentation Port (BIP)
Blood Holding Kit (Freezer/Refrigerator)	Blood Pressure Monitor (Continuous/Intermittent)
Body Mass Measurement Device (BMMD)	Body Restraint System (BRS)
Cardiopulmonary Control Unit (CCU)	Cardiopulmonary Rebreathing Unit (CRU)
Echocardiograph	Electromyograph (EMG)
Electronics Control Assembly (ECA)	EMG Amplifier - Posture
General Purpose Transfer Unit (GPTU)	General Purpose Work Station (GPWS)
Inflight Blood Collection System (IBCS)	Jellyfish Kit
Life Sciences Laboratory Equipment (LSLE)	Lower Body Negative Pressure Device (LBNP)
Low Gravity Centrifuge	Orbital Acceleration Research Experiment (OARE)
Orbiter Refrigerator /Freezer (OR/F)	Otolith Spinal Reflex / Drop Station
Particulate Containment Demonstration Test (PCDT)	Peripheral Venous Pressure Device
Physiological Monitoring System (PMS)	Rebreathing Assembly (RBA)
Refrigerator/Incubator Module (R/IM)	Research Animal Holding Facility (RAHF)
Rotating Dome	Saliva Collection Kit
Small Mass Measuring Instrument (SMMI)	Space Acceleration Measurement System (SAMS)
Strip Chart Recorders	System for Measurement of Central Venous Pressure (SMCVP)
System for Venous Occlusion Plethysmography (SVOP)	Tissue Culture Incubator
Tracer Kit	Urine Monitoring System (UMS)
US Lab Sled	Vacuum Interface Assembly (VIA)

*STS-42/International Microgravity Laboratory 1*

Biorack  
Critical Point Facility (CPF)  
Dynamic Cell Culture System  
Gravitational Plant Physiology Facility (GPPF)  
Mental Workload and Performance Evaluation  
Microgravity Vestibular Investigation Package  
Organic Crystal Growth Facility (OCGF)  
Protein Crystal Growth (PCG)  
Space Acceleration Measurement System (SAMS)  
Vapor Crystal Growth System (VCGS)

*STS-45/ATLAS-1*

Active Cavity Radiometer Irradiance Monitor (ACRIM)  
Atmospheric Trace Molecule Spectroscopy (ATMOS)  
Far Ultraviolet Space Telescope (FAUST)  
Imaging Spectrometric Observatory (ISO)  
Solar Backscatter Ultraviolet (SSBUV)  
Solar Spectrum Measurement (SOLSPEC)  
Space Experiments with Particle Accelerators (SEPAC)

*STS-47/Spacelab J*

Acoustic Levitation Furnace  
Aquatic Animal Experiment Unit (AAEU)  
Bubble Behavior Experiment Unit  
Continuous Heating Furnace  
Dissecting Microscope  
Electrooculograph  
Fluid Therapy System  
Frog Embryology Unit (FEU)  
Gas Evaporation Experiment Facility  
General Purpose Work Station (GPWS)  
Gradient Heating Furnace  
Israel Space Agency Investigation About Hornets (ISAI AH)  
Large Isothermal Furnace (LIF)  
Liquid Drop Experiment Facility  
Magnetic Resonance Imaging (MRI) Device  
Orbiter Refrigerator /Freezer (OR/F)  
Protein Crystal Growth (PCG)  
Refrigerator/Incubator Module(R/IM)  
Vestibular Function Experiment Unit (VFEU/NDAS)

*STS-50/United States Microgravity Laboratory 1*

Astroculture™  
Commercial Generic Bioprocessing Apparatus (CGBA)  
Crystal Growth Furnace  
Extended Duration Orbiter Medical Payload (EDOMP)  
Orbital Acceleration Research Experiment (OARE)  
Protein Crystal Growth (PCG)  
Solid Surface Combustion Module  
Surface Tension Driven Convection Experiment (STDCE)

Biostack  
Cryostat  
Fluids Experiment System (FES)  
Life Sciences Laboratory Equipment (LSLE)  
Mercury Iodide Crystal Growth (MICG) System  
Optokinetic Stimulus Goggles (OKS)  
Phase Partitioning Container  
Radiation Monitoring Container and Dosimeter (RMCD)  
Space Physiology Experiment Package

Atmospheric Emission Photometric Imaging (AEPI)  
Atmospheric Lyman- $\alpha$  Emissions (ALAE)  
Grille Spectrometer (GRILLE)  
Millimeter-Wave Atmospheric Sounder (MAS) Shuttle  
Solar Constant Measurement Experiment (SOLCON)  
Solar Ultraviolet Spectral Irradiance Monitor (SUSIM)

Ambient Temperature Recorder (ATR)  
Autogenic Feedback Training Experiment (AFTE)  
Cell Culture Chamber  
Crystal Growth Experiment Facility  
Electromyograph  
Fluid Physics Facility  
Free Flow Electrophoresis Unit (FFEU)  
Fungal Growth Chamber  
General Purpose Transfer Unit (GPTU)  
Geophysical Fluid Flow Cell (GFFC)  
Image Furnace  
Joystick and light target  
Life Sciences Laboratory Equipment (LSLE)  
Lower Body Negative Pressure Device (LBNP)  
Marangoni Convection Experiment Unit  
Organic Crystal Growth Facility  
Radiation Monitoring Device (RMD)  
Space Acceleration Measurement System (SAMS)

Candle Flames in Microgravity Package  
Commercial Refrigerator/Incubator Module (CRIM)  
Drop Physics Module  
Glovebox Facility  
Passive Acceleration System (PAS)  
Refrigerator/Incubator Module (R/IM)  
Space Acceleration Measurement System (SAMS)  
Zeolite Crystal Growth (ZCG)

*STS-52/United States Microgravity Payload 1*

Lambda-Point Experiment (LPE)	Space Acceleration Measurement System (SAMS)
Materials for the Study of Interesting Phenomena of Solidification on Earth and in Orbit (MEPHISTO)	

*STS-56/ATLAS-2*

Active Cavity Radiometer Irradiance Monitor (ACRIM)	Atmospheric Trace Molecule Spectroscopy (ATMOS)
Millimeter-Wave Atmospheric Sounder (MAS)	Shuttle Solar Backscatter Ultraviolet (SSBUV)
Solar Constant Measurement Experiment (SOLCON)	Solar Spectrum Measurement (SOLSPEC)
Solar Ultraviolet Spectral Irradiance Monitor (SUSIM)	

*STS-55/Spacelab D-2*

Anthrorack	Atomic Oxygen Exposure Tray (AOET)
Baroreflex Measurement System	Biolabor
Biorack	Cosmic Radiation Experiment Package
Galactic Ultrawide Angle Schmidt System Camera (GAUSS)	Holographic Optics Laboratory (HOLOP)
Magnetic Resonance Imaging (MRI) Device	Material Science Autonomous Payload (MAUS)
Material Sciences Experiment Double Rack for Experiment Modules and Apparatus (MEDEA)	
Microgravity Measurement Assembly (MMA)	Orbiter Refrigerator/Freezer
Radiation Detector	Robotics Experiment (ROTEX)
Werkstofflabor (WL; Materials Science Facility)	Modular Opto-Electronic Multispectral Stereo Scanner (MOMS)

*STS-58/Spacelab Life Sciences 2*

Animal Enclosure Module (AEM)	Bag-in-Box (BIB) Assembly
Bicycle Ergometer	Body Restraint System (BRS)
Electromyograph (EMG)	Electronics Control Assembly (ECA)
General Purpose Transfer Unit (GPTU)	General Purpose Work Station (GPWS)
Inflight Blood Collection System (IBCS)	Life Sciences Laboratory Equipment (LSLE)
Orbital Acceleration Research Experiment (OARE)	Orbiter Refrigerator /Freezer (OR/F)
Rebreathing Assembly (RBA)	Refrigerator/Incubator Module (R/IM)
Research Animal Holding Facility (RAHF)	Rotating Dome
Small Mass Measuring Instrument (SMMI)	Space Acceleration Measurement System (SAMS)
Vacuum Interface Assembly (VIA)	

*STS-59/SRL-1*

Measurement of Air Pollution from Satellites (MAPS)	Shuttle Imaging Radar (SIR-C)
X-Band Synthetic Aperture Radar (X-SAR)	

*STS-62/United States Microgravity Payload 2*

Advanced Automated Directional Solidification Furnace (AADSf)	
Critical Fluid Light Scattering Experiment (CFLSE-Zeno)	Isothermal Dendritic Growth Experiment (IDGE)
Materials for the Study of Interesting Phenomena of Solidification on Earth and in Orbit (MEPHISTO)	
Space Acceleration Measurement System (SAMS)	

*STS-65/International Microgravity Laboratory 2*

Advanced Protein Crystallization Facility (APCF)	Aquatic Animal Experiment Unit (AAEU)
Biorack	Biostack
Bubble, Drop and Particle Unit (BDPU)	Cell Culture Chamber Kit (CCK)
Critical Point Facility	Extended Duration Orbiter Medical Project (EDOMP)
Free Flow Electrophoresis Unit (FFEU)	Large Isothermal Furnace (LIF)
Niedergeschwindigkeits Zentrifugen-Mikroskop (NIZEMI)	Performance Assessment Workstation (PAWS)
Quasi-Steady Acceleration Measurement System (QSAM)	Real-Time Radiation Monitoring Device (RRMD)
Recherche Appliquee sur les Methodes de Separation en Electrophorese Spatiale (RAMSES)	

*STS-65/International Microgravity Laboratory 2 continued...*

Space Acceleration Measurement System (SAMS)      Spinal Changes in Microgravity (SCM)  
Thermoelectric Incubator (TEI)  
Tiegelfreies Elektromagnetisches Prozessieren Unter Schwerelosigkeit (TEMPUS)  
Vibration Isolation Box Experiment System (VIBES)

*STS-64/LITE*

Light Intensification Direction and Ranging (LIDAR) In-Space Technology Experiment (LITE)

*STS-66/ATLAS-3*

Active Cavity Radiometer Irradiance Monitor (ACRIM)      Atmospheric Trace Molecule Spectroscopy (ATMOS)  
Cryogenic Infrared Spectrometers and Telescopes for the Atmosphere-Shuttle Pallet Satellite (CRISTA/SPAS)  
Experiment of the Sun for Complementing the Atlas Payload and for Education-II (ESCAPE II)  
Middle Atmosphere High Resolution Spectrograph Investigation (MAHRSI)  
Millimeter-Wave Atmospheric Sounder (MAS)      Shuttle Solar Backscatter Ultraviolet (SSBUV) Solar  
Constant Measurement Experiment (SOLCON)      Solar Spectrum Measurement (SOLSPEC)  
Solar Ultraviolet Spectral Irradiance Monitor (SUSIM)

*STS-68/SRL-2*

Measurement of Air Pollution from Satellites (MAPS)      Shuttle Imaging Radar (SIR-C)  
X-Band Synthetic Aperture Radar (X-SAR)

*STS-67/ASTRO-2*

Hopkins Ultraviolet Telescope (HUT)      Ultraviolet Imaging Telescope (UIT)  
Wisconsin Ultraviolet Photopolarimeter Experiment (WUPPE)

*STS-71/Spacelab MIR*

Bicycle Ergometer	Data Acquisition System
Dosimeters	Dual Energy X-ray Absorptiometry (DEXA)
Dynamic Posturography System	Electromyograph
Extended Data Tape Recorder (EDTR/TEAC)	GN <sub>2</sub> Dewar
Grab Air Sampler	Inflight Blood Collection System (IBCS)
Life Sciences Laboratory Equipment (LSLE)	Lower Body Negative Pressure (LBNP) device
Orbiter Refrigerator /Freezer (OR/F)	Postural Kit
Pressure Shoe Assembly	Saliva Collection Kit
Solid Sorbent Air Sampler (SSAS)	Space Acceleration Measurement System (SAMS)
SVET Greenhouse	Tracer Kit
Transcranial Doppler (TCD)	Water Microbiology Kit
Valsalva Assembly	

*STS-73/United States Microgravity Laboratory-2*

Advanced Protein Crystallization Facility (APCF)	Astroculture™
Commercial Generic Bioprocessing Apparatus	Crystal Growth Furnace
Drop Physics Module	Geophysical Fluid Flow Cell (GFFC)
Glovebox Facility	HI-PAC Digital Television
Lower Body Negative Pressure (LBNP) Device	Microgravity Analysis Workstation (MAWS)
Orbital Acceleration Research Experiment(OARE)	Protein Crystal Growth (PCG)
Space Acceleration Measurement System (SAMS)	
Suppression of Transient Accelerations By Levitation Evaluation (STABLE)	
Surface Tension Driven Convection Experiment (STDCE)	Three Dimensional Microgravity Accelerometer (3DMA)
Zeolite Crystal Growth (ZCG) Furnace	

*STS-75/United States Microgravity Payload 3*

Advanced Automated Directional Solidification Furnace (AADSf)	
Critical Fluid Light Scattering Experiment(Zeno)	Glovebox Facility
Isothermal Dendritic Growth Experiment (IDGE)	
Materials for the Study of Interesting Phenomena of Solidification on Earth and in Orbit (MEPHISTO)	
Microgravity Analysis Workstation (MAWS)	Orbital Acceleration Research Experiment (OARE)
Space Acceleration Measurement System (SAMS)	

*STS-78/Life and Microgravity Spacelab*

Actillum	Advanced Gradient Heating Facility (AGHF)
Advanced Protein Crystallization Facility (APCF)	Ambient Temperature Recorder (ATR)
Animal Enclosure Module (AEM)	Bag-in-Box (BIB) Assembly
Bicycle Ergometer	Blood Collection Belt (BCB)
Blood Holding Kit (Freezer/Refrigerator)	Bubble, Drop, and Particle Unit (BDPU)
Dual Energy X-ray Absorptiometry (DEXA)	Electrode Impedance Meter (EIM)
Electromyograph (EMG)	Electronic Light Occlusion Goggles (ELOG)
Electronics Control Assembly (ECA)	Exercise Breathing Assembly (EBA)
Gas Analyzer System for Metabolic Analysis Physiology (GASMAP)	
Hand Grip Dynamometer (HGD)	Inflight Blood Collection System (IBCS)
Ingestible Temperature Monitoring System (ITMS)	Instrumented Vest Assembly (IVA)
Life Sciences Laboratory Equipment (LSLE)	Magnetic Resonance Imaging (MRI) Device
Medilog™ Sleep Research Recorder (MSRR)	Microgravity Analysis Workstation (MAWS)
Microgravity Measurement Assembly (MMA)	Orbital Acceleration Research Experiment (OARE)
Percutaneous Electrical Muscle Stimulator (PEMS)	Performance Assessment Workstation (PAWS)
Physiological Signal Conditioner (PSC)	Plant Growth Unit (PGU)
Pulmonary Function Facility (PFF)	Respiratory Inductive Plethysmograph (RIP) Suit
Saliva Collection Kit	Space Acceleration Measurement System (SAMS)
Thermoelectric Freezer Module	Torque Velocity Dynamometer (TVD)
Torso Rotation Experiment (TRE)	Tracer Kit
Urine Collection System (UCS)	Urine Monitoring System (UMS)
Vacuum Interface Assembly (VIA)	

*STS-83/MSL-1*

Combustion Module-1 (CM-1)	Commercial Refrigerator Incubator Module (CRIM)
EXpedite the PROcessing of Experiments to Space Station (EXPRESS) Rack	
Glovebox Facility	Hi-Pac Digital Television
Large Isothermal Furnace (LIF)	Microgravity Measurement Assembly (MMA)
Orbital Acceleration Research Experiment (OARE)	Protein Crystal Growth (PCG)
Quasi-Steady Acceleration Measurement (QSAM)	Space Acceleration Measurement System (SAMS)
Tiegefreies Elektromagnetisches Prozessieren Unter Schwerelosigkeit (TEMPUS)	

*STS-87/United States Microgravity Payload 4*

Advanced Automated Directional Solidification Furnace (AADSf)	
Confined Helium Experiment (CHeX)	Glovebox Facility
Isothermal Dendritic Growth Experiment (IDGE)	
Materials for the Study of Interesting Phenomena of Solidification on Earth and in Orbit(MEPHISTO)	
Microgravity Analysis Workstation (MAWS)	Orbital Acceleration Research Experiment (OARE)
Space Acceleration Measurement System (SAMS)	

*STS-94/MSL-1R*

Combustion Module-1 (CM-1)	Commercial Refrigerator Incubator Module (CRIM)
EXpedite the PROcessing of Experiments to Space Station (EXPRESS) Rack	

*STS-94/MSL-1R continued...*

Glovebox Facility	Hi-Pac Digital Television
Large Isothermal Furnace (LIF)	Microgravity Measurement Assembly (MMA)
Orbital Acceleration Research Experiment (OARE)	Protein Crystal Growth (PCG)
Quasi-Steady Acceleration Measurement (QSAM)	Space Acceleration Measurement System (SAMS)
Tiefelfreies Elektromagnetisches Prozessieren Unter Schwerelosigkeit (TEMPUS)	

*STS-90/Neurolab*

Actillum	Applied Potential Tomographer (APT)
Bag-in-Box (BIB) Assembly	Ball Launcher
Body Impedance Measurement (BIM) Device	Body Restraint System (BRS)
Camera Illuminator Equipment (CAMILLE)	Cold Pressor Glove Assembly
Electrode Impedance Meter (EIM)	Electromyograph (EMG)
Electronics Control Assembly (ECA)	Experiment Control Subsystem (ECS)
Gas Analyzer System for Metabolic Analysis Physiology (GASMAP)	Inflight Blood Collection System (IBCS)
Hand Grip Dynamometer (HGD)	Kinelite Processing Module (PM)
Ingestible Temperature Monitoring System (ITMS)	Lower Body Negative Pressure (LBNP) Device
Life Sciences Laboratory Equipment (LSLE)	Modular Support Structure (MOSO)
Microneurography System	Norepinephrine (NE) Spillover System
Mount Sinai Human Tilt Chair	Personal SleepKit
Optokinetic Stimulus Goggles (OKS)	Rebreathing Assembly (RBA)
Personal Melatonin / Placebo Kit	Saliva Collection Kit
Respiratory Inductive Plethysmograph (RIP) Suit	Subject Restraint System (SRS)
Static Tilt Chair	Transcranial Doppler (TCD)
Thermoelectric Freezer Module (TEFM)	Urine Monitoring System (UMS)
Urine Collection System (UCS)	Valsalva Assembly
Vacuum Interface Assembly (VIA)	Vestibular Support Kit
Vestibular Function Experiment Unit (VFEU)	Virtual Environment Generator (VEG)
Visual and Vestibular Investigation System (VVIS)	
Visuo-Motor Coordination Facility (VCF)	

## HARDWARE DESCRIPTIONS

The hardware descriptions make use of the format given below. NASA Centers have not been listed individually, and some hardware attributed to NASA may have been designed in collaboration with other organizations. All hardware described here was either designed or modified specifically for spaceflight research; off-the-shelf hardware, if known as such, was not listed.

**Title of spaceflight hardware or experiment specific hardware**

(Spacelab STS-Mission Designation) Organization that designed the hardware

Hardware or experiment description.

### **Absolute Measurement of the Solar Constant**

(STS-9) NASA

The equipment consisted of an absolute radiometer with a built in stability check. This radiometer had two channels which enabled any degradation of the black surfaces to be detected and compensated. The radiation measurements were made by using a heat balance system driven automatically by a feedback system.

### **Accelerometer Recording Unit (ARU)**

(STS-40) NASA

The Accelerometer Recording Unit (ARU) is a system used to detect head movements and measure skin pallor and temperature of the subject during several functional objectives in the E072 experiment. Components of the ARU include the head unit which houses three linear and three angular accelerometers as well as other electronics, a face-mounted temperature and pallor sensor, and a belt-mounted powerpack/signal conditioning unit. The head unit is worn in the back of the crewmember's head in a special cap. The information is passed through the battery pack and signal conditioner to the CDTR for data storage. The Photoplethysmograph (PPG) is used to measure pallor and temperature. The sensor leads are enclosed in a dielectric covering, and that covering is isolated from the human interface with dielectric tape. This information is recorded by the CDTR. Power for the ARU system is supplied by six lithium bromide "C" cell batteries. Redundant cutoff circuitry in the ARU protects against release of harmful products under cell reversal conditions. If one or two of the cells fail and prematurely discharge to zero volts, then the circuit is rendered inoperable. In the event this circuit fails, a redundant circuit will cut off operation.

### **Acetylene Rebreathing Cardiac Output System**

(STS-40) NASA

This item is used to determine cardiac output indirectly by measuring the rate of disappearance of acetylene. With this item, the subject rebreathes a gas mixture containing 0.6% medical grade acetylene. The equipment arrangement consists of an anesthesia bag connected to a Hans Rudolph Model 8530 Pneumatic valve and Alpha technologies Model VMM1 turbine flow meter. The gas concentrations are measured using a Perkin-Elmer MGA 1100 Medical Gas Analyzer. The computations are done with a Digital Equipment PDP 11/23 using specialized software. The gas mixture used is a special medical grade mixture of .6% acetylene, 9% Helium, 45% Oxygen, balance Nitrogen.

### **Actillume**

(STS-78, 90) Ambulatory Monitoring, Inc.

The Actillume is a wrist-worn activity/light storage center (32K bytes). It quantifies simultaneous motor activity and light exposure in a high-precision manner. It measures linear acceleration in the range of 0.1-g to 5-g, is resistant to spontaneous drops and contains a precision photo diode photometer which measures light exposure in the range of 0.01 to 10,000 lux. The sampling rates for the accelerometer and the light sensor are 20 samples per second and 1 sample per second, respectively. It is powered by two "1/2 AA" lithium batteries offering 350 to 500 hours of continuous operation. Dimensions are 7 x 3.8 x 2.2 cm and mass is 0.10 kg. A Nomex wrist strap with a removable gauze liner allows the crewmember to wear the Actillume on either the left or right wrist.

### **Active Cavity Radiometer Solar Irradiance Monitor (ACRIM)**

(STS-9, 45, 56, 66) NASA

The solar irradiance from far ultraviolet through far infrared wavelengths was measured by three type-V, active-cavity radiometer detectors. These detectors were electrically self-calibrated, cavity pyr heliometers each capable of defining the absolute radiation scale with an uncertainty of plus or minus 0.1%. The three

detectors were independently shuttered, and their cycles of operation were different. The three detectors were used in various combinations to provide periodic cross references on the system's performance.

### **Advanced Automated Directional Solidification Furnace (AADSf)**

(STS-62, 75, 87) NASA

The AADSf can accommodate a wide variety of metallic and semiconductor materials investigations that require directional solidification or vapor crystal growth. The AADSf science requirements specify a Bridgman-Stockbarger type furnace assembly with a "hot" zone (up to 1150oC) and a "cold" zone (200-850oC) separated by a thermal gradient zone. Directional solidification is effected by translating the sample from the hot zone into the cold zone. AADSf can process sample ampoules up to 1.2 cm in diameter and up to 25 cm in length, which are contained in a cartridge or Muffle Tube Assembly. The Muffle Tube Assembly also accommodates up to six thermocouples for sample temperature measurements and Peltier pulser leads for the solidus-liquidus interface demarcation, as required. The AADSf with a Sample Exchange Mechanism (AADSf-SEM) will accommodate up to three Muffle Tube Assemblies. To minimize the effects of gravity, AADSf is located as close as practical to the Space Shuttle Orbiter's center of gravity (c.g.) in the Orbiter's Payload Bay; therefore, all AADSf operations are designed to be fully automated with minimal crew interaction. The ground-based science investigators have the capability to monitor the science and housekeeping measurements in real-time and to command modifications to the preprogrammed operating parameters. The primary science data is the processed sample material that is returned to the Principal Investigator (PI) for analysis after each mission. During USMP-2, the AADSf was used to study the growth of mercury cadmium telluride crystals in microgravity by directional solidification, a process commonly used on earth to process metals and grow crystals. The furnace is tubular and has three independently controlled temperature zone. The sample travels from the hot zone of the furnace (1600 degrees F) where the material solidifies as it cools. The solidification region, known as the solid/liquid interface, moves from one end of the sample to the other at a controlled rate, thus the term directional solidification.

*Experiment Hardware Description:* The AADSf system, is mounted on a Multi-Purpose Experiment Support Structure (MPSS) carrier in the Shuttle's Payload Bay. A Signal Conditioning and Control System (SCCS), a Data Acquisition System (DAS) and associated cabling are required for operation of the AADSf. The SCCS provides power control to the AADSf and transmits information from the furnace to the DAS. The DAS processes the signals from the SCCS and transmits them through the MPSS carrier and Orbiter communication systems to the experimenters on Earth.

*AADSf Assembly:* The AADSf assembly consists of a Furnace Module, a Muffle Tube Assembly, and a Translation Mechanism which are all enclosed in an Experiment Apparatus Container (EAC). The AADSf-SEM features a Sample Exchange Mechanism (SEM) for processing up to three Muffle Tube Assemblies per mission. The approximate physical features of the AADSf assembly are 43 cm in diameter, 132 cm in height and a weight of 125 kg; the AADSf-SEM will have an increased weight of 165 kg and will be 168 cm tall. The furnace module is a six-zone (five heater zones and one gradient zone) Bridgman-Stockbarger design with a temperature operating range of 200 to 1150oC. Thermal control is maintained by using the MPSS freon pump package to circulate Freon 114 from the Orbiter through the AADSf system. The EAC is a cylindrical structure that contains the AADSf and mounts it to the an adapter plate on top of the MPSS carrier. It is typically sealed with 17 psia of Argon and has a maximum operating pressure of 28 psia with redundant safety valves. The Muffle Tube Assembly, made from a high-temperature alloy, fits inside the AADSf furnace chamber and encases the experiment sample that is enclosed in a fused silica ampoule. Electrical leads for Peltier pulsing and for up to six sample thermocouples are also accommodated by the Muffle Tube Assembly. The AADSf and the AADSf-SEM will be capable of processing identical Muffle Tube Assembly designs. The Translation Mechanism moves the sample through the furnace at pre-programmed rates of 0.5 to 50.0 millimeters per hour. A 28-Vdc direct drive motor powers the translation

mechanism. The SEM will use an off-the-shelf Geneva mechanism and a direct drive motor to rotate the samples in and out of the processing position. The SEM will also feature an electronics module that will perform analog-to-digital (A/D) conversion and amplification of the sample thermocouple signals before transmitting them to the SCCS. The AADSF-SEM will require new motor controller and thermocouple cards in the SCCS; no changes to the DAS are required for the SEM modification.

*Electronic Subassemblies:* The AADSF's system's two electronic subassemblies, the SCCS and the DAS, share a common adapter plate that is mounted on the side rails of the MPRESS carrier. The SCCS links the DAS and the furnace and contains the power and controllers for the AADSF. The SCCS stores program profiles for the five heater zone temperatures and the translation rates and which may be updated from the ground through the DAS. The SCCS also receives analog sensor outputs from the AADSF, such as temperatures, sample position, rate of translation and coolant flow rate. The SCCS amplifies and filters the data signals before sending them to the DAS, where they are digitized for processing by the MPRESS carrier. The DAS is a 16-bit microprocessor that controls the command and data interfaces. It provides discrete inputs, analog inputs, serial digital input/output ports, and relay drivers. The DAS receives up-linked commands, processes them (D/A conversion) and transmits them to the SCCS for furnace control. Conversely, the SCCS transmits data from the furnace to the DAS, which digitizes and transmits the data through the MPRESS System Control Unit (SCU) for downlink.

*Miscellaneous Hardware:* Miscellaneous flight hardware includes the following items:

- Fifteen cable assemblies;
- Two coldplate adapter plates (EAC and DAS/SCCS);
- Multilayer insulation (MLI) blankets (EAC and DAS/SCCS);
- Four software disks for contingency use by the crew's Payload and General Support Computer (PGSC).

### **Advanced Gradient Heating Facility (AGHF)**

(STS-78) NASA

The AGHF supports the production of advanced semiconductor materials and alloys using the directional solidification process, which depends on establishing a hot side and a cold side in the sample (a temperature gradient). It provides an extremely stable temperature environment of up to 1,400 °C, high-temperature gradients of up to 100 °C/cm in the solidification zone, slow movement of the gradient across a sample to provide slow growth rates, efficient cooling through the use of a liquid metal cooling ring attached to the sample container, and Peltier pulse marking capability. The AGHF consists of three modules mounted in one side of a Spacelab double rack: the Core Facility Module contains the processing chamber with the furnace inside; the Electronics Module contains the controls and equipment necessary to operate the furnace; and the Gas Storage Module contains argon for chamber repressurization and sample cooling. Growth rate is an important parameter in the production of many materials, yet the solidification rate often is different from the rate of movement of the sample cartridge in the furnace. To help determine the actual growth rate, the AGHF includes a Peltier pulse marking capability that sends a pulse of electrical current through the sample at specific times to mark the internal structure in the solid/liquid interface along the electric field. Demarcation occurs as a result of heating caused by the resistance encountered by the current as it moves across the interface between the liquid and solid states. By examining cross-sections of the crystal, scientists can locate these marks and determine the precise growth rate for each portion of the experiment as well as the three-dimensional shape of the solid/liquid interface at the time of the pulse. A precise understanding of these factors will improve the general knowledge of the physical phenomena involved in the solidification process, improving materials processing on Earth and future semiconductor and materials processing research in space.

### **Advanced Protein Crystallization Facility (APCF)**

(STS-65, 73, 78) ESA

The APCF is the first facility to use three methods of protein crystal growth: liquid/liquid diffusion (B), or free interface diffusion, in which a protein solution and a salt solution are separated by a buffer and are allowed to flow together slowly once the Shuttle is in orbit; dialysis (C), with protein and salt solutions separated by a membrane; and vapor diffusion (A), or the hanging drop method, where crystals form inside a drop of protein solution as solvent from the drop diffuses to a reservoir. For all three methods, crystallization will occur at a constant temperature of 20 °C. Upon reaching orbit, the crew activates the unit, monitors the facility as it operates, and deactivates the equipment shortly before re-entry. Video images will be made of crystals as they form. The APCF has 2 units, each of which has 48 crystallization reactors. The Center for Biophysical Sciences and Engineering (CBSE) produced a Protein Crystallization Facility as well, flown as part of the STS-73 Protein Crystal Growth Spacelab payload. Carried in a Commercial Refrigeration/ Incubation Module, a temperature change initiates the crystallization process. The facility contains four cylindrical crystallization containers that are kept at 40 °C until the Shuttle reaches orbit; at that time, they are gradually cooled to 22 °C over a 24-hour period. Crystals form as the chamber cools, and crystal growth continues at 22 °C for the remainder of the mission.

### **Ambient Temperature Recorder (ATR-4)**

(STS-40, 42, 47, 65, 78) NASA

The Ambient Temperature Recorder (ATR-4) is a self-contained, battery-powered instrument, approximately the size of a deck of cards. It may be placed in almost any environment (not submersible in liquid) to provide recording of up to four channels of temperature data. Channel 1 is selectable for either internal or external probe temperature sensing. Channels 2–4 are external only and require individual external temperature probes. External probes are flexible to allow the user to place probes at various locations within the sensed environment. Standard length for probes is 3 feet, but they may be longer or shorter, if required. Data sample rate and number of channels are user-selectable. The total number of samples (32400) is limited by the size of the solid-state memory in the ATR-4. When the memory is full, the recorder stops recording. Stored data may be accessed postflight using a serial interface unit and an IBM-compatible computer. Power for the ATR-4 is provided by two internal batteries. An O-ring seal protects the internal electronics of the ATR-4 from fluids in the environment and permits operation in damp or humid environments, such as an animal habitat.

#### *Specifications:*

Dimensions: 23 x 41 x 86 mm

Weight: ~135 g

Power: Lithium thionyl chloride batteries, 1 year life

Temp: Range: -40 to +60 °C

Accuracy: ±1 °C

Probes: Integrated circuit sensor, standard length, 3 feet

Data Acquisition

Sampling: every 1.87, 3.75, 7.5, or 15 minutes selectable; internal/external measurement (selectable on 1 channel only); 1 channel: 42 days @1.87-min sampling; 342 days @15 min; 4 channels: 10 days @1.87-min sampling; 85 days @15 min

### **Ames Research Center (ARC) Life Sciences Payload**

(STS-51B) NASA

See also descriptions of individual test hardware. During Spacelab 3, the ARCLSP consisted of five main test hardware: the Research Animal Holding Facility (RAHF), Biotelemetry System (BTS), Dynamic

Environment Measurement System (DEMS), Autogenic Feedback Training Experiment (AFTE), and the Urine Monitoring System (UMS). It was housed partially in rack 5, a single portside rack (Ames Single Rack –ASR) which contained a primate RAHF which houses and provides life support for four squirrel monkeys, each within their individual cages. (Due to complications preflight, only two monkeys were actually flown. These two monkeys were both unrestrained and free to move about their cages, as opposed to be restrained.) Spacelab 3, rack 7, is a double portside rack (Ames Double Rack-ADR). It contains a rodent RAHF which houses 24 rodents and that RAHF is equipped with a 16mm camera/mirror system to enable photography of the rodents contained within the bottom four cages. These photographic images are reflected by the mirror system to the camera mounted above and the camera is controlled by a camera control box which has preset switches that can be and are changed on-orbit. Four of the rodents are implanted with biotelemetry transmitters which permits four signals to be received by an installed cage antenna and transmitted via cabling to a Biotelemetry System (BTS). The right side of the ADR contains the BTS receivers and demodulators, a Dynamic Environment Measurement System (DEMS), two condensate collectors (one for the rodent RAHF and one for the primate RAHF, an intercom remote panel and the Life Sciences Laboratory Equipment (LSLE) microcomputer which accepts data from the BTS systems and transmits that data to the Spacelab High Rate Multiplexer (HRM) for transmission to the ground. Other than visual and photographic observation of the animals, no interface with the animal payload will be required except normal housekeeping operations. RAHF operation and animal/RAHF interfaces are fully documented by visual means, by taped verbal comments, by written notes, and photographically by using 16-mm motion picture and 35-mm still cameras. After recovery of animals, behavior is monitored, and physiological data are obtained to compare with inflight data and ground control animals. In conjunction with the RAHF experiment there are two measuring systems, the Dynamic Environment System (DEMS) and the Biotelemetry System (BTS). The DEMS, designed to measure noise, vibration, and acceleration forces is mounted between the two RAHF units. The BTS measures the deep body temperature, heart rate and ECG pattern of the four squirrel monkeys and of four of the rats. Wireless sensors are implanted in the animals before flight. The AFT and UMS, used for human research, were housed separately within the Spacelab module.

### **Animal Enclosure Module (AEM)**

(STS-40, 78) NASA

The Animal Enclosure Module (AEM) supports up to six 250-grams rats and fits inside a standard middeck locker with a modified locker door. It is composed of a stainless steel grid cage module, fan blowers, a layered filter system, interior lamps. Food bars are glued on cage walls. Total animal floor space is approximately 863 cm<sup>2</sup>. A removable divider plate provides two separate animal holding areas (if required). The AEM remains in the stowage locker during launch and landing. In orbit the AEM may be removed from the locker and the interior viewed or photographed through the clear Lexan cover which is over the cage; the AEM must be pulled out of the locker approximately three quarters of its depth to allow crew observation of the rodents. Temperatures are read from a built-in thermometer. The Main Breaker protects and distributes power to fan and lighting subsystems. Additional circuit breakers independently protect lights and fans in diagonally opposed corners to assure light and air circulation on each side of the AEM should one breaker fail. The AEM is moved into the Orbiter approximately 12 hours before launch and removed approximately 1 hour after landing. The original AEM unit was developed for the Student Shuttle Flight Program (SSIP) by the General Dynamics Company. Units flown initially utilized potatoes as a water source.

*Air Quality:* Cabin air is exchanged with the unit through a filter system. Four fan blowers, operated by a switch on the front panel, create a slight negative pressure inside the cage, causing an air sweep to pull animal waste products into a collection filter. Cabin air is drawn through the front panel inlet slots, then along the side plenum walls, to be directed through the inlet filter located at the rear of the AEM, into the

animal habitat. High efficiency particulate air filters (electrostatic and phosphoric acid treated fiberglass pads) prevent any microbiological escape into the cabin atmosphere. Treated charcoal, within the unit, confines animal odors within the closed system. After exiting the habitat through the exhaust filter, located at the front of the unit between the rodent cage and fans, the filtered air is drawn through the fans into the cabin and directed by the air deflector. Air flow indicator ribbons are attached to both sides of the air deflector for visual confirmation of AEM air flow.

*Lighting:* The four internal lamps provide an average of 14 lux illumination and are controlled by an automatic timer to provide a 12-hour lighting cycle. The lamps are mounted two to a side in the rear corners of the AEM, between the animal habitat and inlet filter, and are covered with a clear cap to protect each lamp from animal debris and to contain glass if lamp breaks. Although the 12-hour cycle is fixed, the starting hours, minutes, and day/night sequence can be selected.

*Water:* The basic unit was not equipped with a drinking water system. Animals obtained fluids by eating potatoes which were placed in the cage.

*Food:* Standard rodent food bars are attached to four slide-in food bar plates inside the rodent cage. The food, a sterilized laboratory formula, is molded into rectangular bars (approx. 1.875 x 1 x 8 inches) accessible to the animals at all times during the mission.

*Upgraded Version Modifications:* After the Student Shuttle Flight Program, a water box, described above, was added to provide a better source of hydration. A major modification was made later to allow in-flight refilling of this water box. This modification added connections on the front panel, appropriate controls and tubing to transfer the water being added to the water box. New fans were also installed to provide better acoustics and new inlet and outlet filters were provided for better odor control. Cloth mufflers, attached to the outside of the AEM, were also added in order to further reduce the middeck noise level. The inside cage divider was removed. Finally, a holder was made at the rear of the AEM to contain an Ambient Temperature Recorder (ATR-4) with holders for two remote ATR temperature sensors. New timers were also installed when it was determined that the originals were no longer available.

## **Ankle Torque Device**

(STS-40) NASA

To measure force output from the lower leg a force measuring apparatus was needed. Constant force, isometric contraction of the leg muscles were implemented using a specially designed ankle-torque device attached to an adjustable knee brace. Flexion and extension forces about the right ankle were recorded by two low-compliant force transducers, whose sum was displayed to the subject for visual feedback using an LED array configured as a zero-null meter. Subjects were seated during the tests and their right leg was flexed to 15 degrees at the knee and 5 degrees plantarflexion at the ankle.

## **Anthrorack (AR)**

(STS-55) ESA

This payload was designed to investigate human physiology under microgravity conditions. AR provided a set of common user stimulation and measurement instruments, supported by centralized services including power supply, control and data handling. The AR was comprised of the following elements: Blood Sample Collection Kit, Urine Monitoring System, High Speed Centrifuge, Respiratory Monitoring System, Ergometer, Peripheral Blood Measurement System, Manual Blood Pressure Measurement System, Limb Volume Measurement Device, Electrode Contact Impedance Meter, and Ultrasound Monitoring System. The following experiments were performed: (1) Cardiovascular Regulation at Microgravity - examined cardiovascular adaptation to microgravity; (2) The Central Venous Pressure During Microgravity - measured CVP in two crew members before launch and during the mission; (3) Leg Fluid Distribution at Rest and Under LBNP; (4) Determination of Segmental Fluid Content and Perfusion; (5) Left Ventricular Function

at rest and UserStimulation; (6) Peripheral and Central Hemodynamic Adaptation to Microgravity During Rest Exercise and Lower Body Negative Pressure in Humans - investigated cardiovascular reflexes during weightlessness measured by ECG and blood pressures; (7) Tonometry-Intraocular Pressure in Microgravity; (8) Tissue Thickness and Tissue Compliance Along Body Axis Under Micro-g Conditions; (9) Regulation of Volume Homeostasis in Reduced Gravity/Possible Involvement of Atrial Natriuretic Factor Urodilatin and Cyclic GMP - investigated the involvement of hormonal systems in the readaption of humans to weightlessness; (10) Effects of Microgravity on Glucose Tolerance; (11) The Influence of Microgravity on Endocrine and Renal Elements of Volume Homeostasis; (12) Effects of Spaceflight on Pituitary-Gonad-adrenal Function in Humans; (13) Adaptation to Micro-g and Re-adaptation to Terrestrial Conditions; (14) Pulmonary Stratification and Compartment Analysis with Reference to Microgravity; (15) Pulmonary Perfusion and Ventilation in Microgravity Rest and Exercise; (16) Ventilation Distribution in Microgravity; (17) Effects of Microgravity on the Dynamics of Gas Exchange, Ventilation and Heart rate in Submaximal Dynamic Exercise; (18) Cardiovascular Regulation in Microgravity.

### **ANTIBIO (Studies on Penetration of Antibiotic in Bacterial Cells)**

(STS-42) ESA

The hardware for this Biorack experiment consisted of culture chambers containing 0.7 ml of culture medium, 2 micro g/ml of the antibiotic Dihydrostreptomycin 3H, and a glass ampoule filled with the E. coli bacterial suspension. At the start of the growth experiment in the Biorack, the glass ampoules, prepared to obtain inoculi containing a pre-determined number of bacteria per milliliter, were broken in the glovebox by the astronauts. The ESA Type I containers in which this operation was accomplished were placed in the Biorack at 37degC, either on the static rack or on the 1g centrifuge. At time t5 (291 minutes of growth culture) the first sample was extracted and moved back to 5degC to stop growth. The other containers from the static rack were removed at 1 hour intervals and stored at 5degC. The cultures for electron microscopy were fixed by breaking the ampoules containing the fixative at time t8. The containers placed in the 1g centrifuge were removed at times t6 and t9 which correspond respectively to 347 and 537 minutes of incubation. Cell suspensions for electron microscopy were fixed with 0.5% formaldehyde and post-fixation with osmium tetroxide.

### **Applied Potential Tomographer (APT)**

(STS-90) NASA

The Applied Potential Tomographer (APT) uses electrical resistivity measurements to monitor the fluid distribution in the subject's thigh. The APT (used in conjunction with the Thigh Cuff Test and Lower Body Negative Pressure (LBNP)) measures volume changes in the leg while the leg is subjected to positive and negative pressures. The APT is a double-measurement technique that collects transfer resistance measurements from 16 electrodes spaced around the boundary of the upper leg cross section. Data used to construct images of resistivity changes in the cross section are defined by the electrode plane. High-frequency ac (50 kHz at 2.8 mA rms) is applied through one pair of electrodes (A and B), and the induced voltage is measured across another two electrodes (C and D). This induced voltage should be identical to the induced voltage measure across A and B if the same current is applied to C and D. Each voltage measured in one direction is compared with the voltage measured in the reciprocal direction. This procedure is repeated multiple times with current supplied through a different electrode pair for each cycle. The system consists of the following:

1. Data Acquisition System (DAS) - generates current to be applied to the electrodes and provides timing information, measurement and signal Analog-to-Digital (A/D) conversion, and electrode multiplexing. It interfaces with the LSLE Microcomputer II (LM2), battery box, and electrode assembly.
2. Optical Link - interfaces the DAS and decoder module in the LM2, which displays and stores data. It includes a transmitter module which converts parallel data to serial data and electrical pulses to light pulses.

3. Battery Package - the battery box and power cables provide power to the DAS.
4. APT Electrode Belt - APT electrode belts are custom fit to each subject and contain 16 electrodes equally spaced around the leg.
5. Test Adapter - with resistor network replaces the electrode assembly for quick verification of basic system functions.
6. Thigh Cuff System - a stimulation device designed to produce blood flow occlusion by compression in the thigh of the subject.

*Thigh Cuff System:* The Thigh Cuff System applies different pressure values to the subject's limbs. The System consists of a cuff controller, pump unit, thigh cuff, and two umbilicals (one for 12V power, the other for control and command lines). The cuff controller inflates and deflates the thigh cuff in a constant, controlled manner by command. It interfaces to the LSLE Microcomputer II (LM2 #2) for receipt of analog signal of pressure and of commands and for outputting of data. It has a set operating pressure of 0 to 180 mmHg. The cuff pump has a pressure range of 20 to 600 mmHg with an accuracy up to 2 mmHg. It is limited to 210 mmHg  $\pm$  10 mmHg by a safety switch. The thigh cuff is suitable for application around the subject's thigh and is capable of sustaining pressures of up to 180 mmHg above the external ambient.

### **Aquatic Animal Experiment Unit (AAEU)**

(STS-47, 65) NASDA

AAEU consists of the main unit, Aquarium Package (A/P) for newts and Medaka fish, and Fish Package (F/P) for goldfish. A/P and F/P each have an independent life support system. The water in the AAEU is kept clean by filtration devices that trap waste materials from the animals. Oxygen circulates water at appropriate rates and the temperature is controlled independently. A water accumulator compensates evaporation. This aquarium, which was flown successfully on the Spacelab J mission, consists of two independent life-support systems, called fish and aquarium packages. Using this unit, scientists can study small aquatic animals for the duration of the mission. It permits observations of spawning, fertilization, embryonic stages, vestibular function, and behavior in microgravity. Animals, such as newts, live in four cassette-type aquariums, and there is a water tank designed for fish. A special life-support system supplies oxygen, removes carbon dioxide and waste (such as ammonia and organic substances), and regulates temperature from 15 to 25 C. The crew can view the animals through a window and access them via a port. A video system can be attached to the viewing port for recording observations of animal behavior, such as swimming patterns. Closeup observations can be made of fertilization and embryonic development. These images, along with housekeeping data on water temperature and pressure and other parameters, are downlinked to scientists working on the ground.

### **Assembly Concept for Construction of Erectable Space Structures (ACCESS)**

(STS-61B) NASA

The Assembly Concept for Construction of Erectable Space Structures (ACCESS) experiment was a validation of ground-based timelines based on the neutral buoyancy water simulator at the Marshall Spaceflight Center, Huntsville, Alabama. Crewmembers manually assembled and disassembled a 45-foot truss to evaluate concepts for assembling larger structures in space.

### **Astroculture<sup>TM</sup>**

(STS-50, 73) WCSAR

The Astroculture<sup>TM</sup> system contains three subsystems that provide environmental control for plant growth in a spaceflight package. First, the water and nutrient delivery system uses porous tubes with different pressures to ensure a proper flow through the rooting matrix. This system has proven itself to be effective during long-duration flights in the microgravity environment. Second, the efficient subsystem for controlling

moisture in the growth chamber humidifies and dehumidifies the air without needing a gas/liquid separator, which is required by all other systems currently in use, to recover the condensed water. Third, the lighting subsystem uses light-emitting diodes (LEDs) to provide high levels of light within the limits of electrical power available on orbit and with greater safety than any other light sources currently used by space-based plant growing facilities. The experiment package is sealed, with cooling provided by an experiment heat exchanger and carbon dioxide (necessary for photosynthesis) supplied from a storage tank.

For STS-50, the Astroculture™ plant growth chamber (ASC-GC) was a single middeck locker insert space flight payload. ASC-GC, designed to operate autonomously, provides temperature control, humidity control, lighting control, nutrient delivery, atmospheric control and video/data downlink. ASC-GC can be configured with a single chamber or dual chambers in which the environmental conditions for each chamber are independently controlled.

#### *ASC-GC Specifications*

##### Growing Space

Single chamber Configuration:

shoot area: 178 cm<sup>2</sup> shoot height: 23 cm

root area: 178 cm<sup>2</sup> root height: 5 cm

Dual chamber Configuration (each chamber):

shoot area: 130 cm<sup>2</sup> shoot height: 15 cm

root area: 130 cm<sup>2</sup> root height: 5 cm

##### Temperature

Method: active control using thermoelectric coolers Control: 19 - 45 °C

Accuracy: ± 0.5 °C from the set point Uniformity: ± 1 °C within plant canopy plan

##### Humidity

Method: active control using Astropore® technology Control: 55 - 95 % RH

Accuracy: ± 3 % RH from the setpoint Uniformity: ± 5 % RH within plant canopy plan

##### Lighting

Method: high intensity red (670 nm) and blue (470 nm) light emitting diodes (LEDs)

Intensity: 450 μmol/m<sup>2</sup>/s (red), 50 μmol/m<sup>2</sup>/s (blue), measured at bottom of the chamber

Control: photon flux controlled within ± 5% of setpoint

Uniformity: ± 10% within plane, 10 cm from the light source

##### Water/Nutrient Delivery

Method: capillary mass transfer through rooting matrix via porous materials

Control: solution pH range 4.5-7.5, ± 0.2

##### Atmosphere Composition

CO<sub>2</sub>: 300-2000 ppm ± 50 ppm or ± 5% setpoint Ethylene: < 50 ppb by photocatalytic oxidation

On STS-73, the objectives of the experiment were to evaluate the performance in microgravity of the Astroculture™ system and to study how starch accumulation in plants is affected. Leaf cuttings were taken from potato plants and placed in the Astroculture™ hardware approximately 36 hours before launch. On orbit the crew monitored the automated operation and status of the plant material via a video camera. Results showed that the Astroculture™ hardware, a totally enclosed chamber, provided the environment required to support plant growth in microgravity during the 16-day mission. This was the first time plant material had been grown in microgravity in such a totally enclosed controlled environment chamber. This is significant since any plant growth response could be attributed to microgravity rather than lack of environmental control of critical factors such as temperature, lighting and humidity. Downlink ability allowed real-time monitoring of development of the tubers. The Astroculture™ hardware provided remote site capability for

monitoring mission activities to involve the scientists in the ongoing mission activities and increasing the science information learned for application to future missions.

### **Astro/Plant Generic Bioprocessing Apparatus (Astro/PGBA)**

(STS-83/94) Bioserve

The Astro/PGBA experiment hardware is contained in a double locker installed into the EXPRESS Rack after the Shuttle is in orbit. The hardware consists of a plant growth chamber with a 10-inch by 12-inch growth area that allows 10 inches of plant height and 2 inches of roots. Fluorescent lighting will simulate sunlight, and an atmospheric control system will maintain set levels of carbon dioxide and humidity while scrubbing volatile organic compounds, such as ethylene, that can accumulate and inhibit plant growth. Plant transpiration water, collected from a dehumidifier system, can be recirculated back into the root matrix. A computer system will control experiment operations and provide engineering and video data for downlink to investigators on the ground. Several weeks before launch, seeds or cloned cuttings of the plants to be studied will be established in conditions matching those of flight. The plants will be staged at different points in their development to optimize the particular properties being evaluated. Approximately 1 week before launch, the plants will be loaded into the growth chamber and established on the day/night cycle to be used on the mission. After the mission, the plants will be photographed to record plant size and shape, as well as leaf and root system size and shape, before being dissected and preserved. Frozen samples of leaf, stem, and root materials will be shipped to industry investigators for detailed analysis of lignin and secondary metabolite composition. The data gathered from these and other investigations will be compared with data from plants grown on the ground under near-identical conditions.

### **Atmospheric Emission Photometric Imaging (AEPI)**

(STS-9, 45) NASA

The equipment consisted of (1) a dual-channel video system with associated optics and data handling electronics mounted on a stabilized platform for pointing and control, (2) SEC vidicon for high-sensitivity, high-resolution operation, (3) a low-resolution microchannel plate array operating in a photon counting mode, and (4) command and data management systems and onboard recorders utilized for data display and recording. The magnesium positive ion resonance line was imaged at 279.5 and 280.2 nm.

### **Atmospheric Trace Molecule Spectroscopy (ATMOS)**

(STS-51B, 45, 56, 66) NASA

The Atmospheric Trace Molecule Spectroscopy (ATMOS) experiment was flown to demonstrate the capability to monitor environmental quality by surveying the atmosphere for trace constituents and by identifying their sources, flow patterns, and decay mechanisms. In its most general form, the ATMOS experiment objective was to determine concentration profiles for a large number of stratospheric species for altitudes from 20 to 80 km, with a vertical resolution of 2 km. The ATMOS instrument viewed the sun through the stratosphere and measured the spectral absorption of solar energy. Each data-taking run was initiated before the sun emerged from or disappeared behind the earth. Data from the instrument for these sunrise and sunset limb encounters were interferograms that were processed on the ground to provide absorption spectra. The instrument was a continuous-scanning Fourier spectrometer that operated in the 2- to 16-micrometer wavelength region and generated one interferogram each second, with a spectral resolution of 0.01 (1/cm). The ATMOS consisted of four major systems: a suntracker for precise solar pointing, an input optical system that included a telescope and a data handling system, an interferometer for wavelength measurements, and an infrared detector sensitive to radiation in the 3- to 16-micrometer wavelength range. The data, in conjunction with engineering and housekeeping data, were converted into a serial PCM bit stream in a format compatible with the Spacelab high-rate, real-time telemetry system.

### **Atmospheric Lyman-Alpha Emissions (ALAE)**

(STS-9, 45) NASA

The ALAE instrument detects a particularly intense wavelength of ultraviolet light, called Lyman-alpha, which is radiated by both hydrogen and deuterium. The atoms emit this radiation at slightly different wavelengths, however; hydrogen emits at 121.566 nm, while deuterium produces a 121.533-nm emission. Because Lyman- alpha radiation is absorbed in the lower atmosphere, it can only be observed from space. In 1983 aboard Spacelab 1, the ALAE instrument consisted of a spectrophotometer with an atomic hydrogen absorption cell and an atomic deuterium absorption cell, and a solar-blind photomultiplier for the detector. Various combinations of switching the cells on and off allow observations of the atmospheric deuterium layer, the atomic geocorona, and the Lyman-alpha interplanetary medium. During the ATLAS 1 mission, the ALAE instrument, which is five times more sensitive than the equipment that flew on Spacelab 1, will measure Lyman-alpha emissions from the deuterium layer, the hydrogen geocorona (a region of Earth's atmosphere extending out to about 100,000 km [62,000 mi]), and even from the space between planets. The instrument can also be used in the study of other geophysical phenomena. It detects Lyman-alpha wavelengths produced by hydrogen nuclei (energetic protons) that combine along magnetic fields to form hydrogen atoms.

### **Atomic Oxygen Exposure Tray (AOET)**

(STS-55) DARA

The Atomic Oxygen Exposure Tray (AOET) is a self-standing facility located on the support structure that performs experiments in the field of material science. The AOET uses the orbiter as an exposure laboratory to obtain inside reaction rate measurements for various materials interacting with atomic rate measurements for various materials interaction with atomic oxygen with the low-Earth orbital environment. AOET is dedicated to investigate the erosion effects on a technological basis. The AOET is a quasi-passive sample array mounted onto the Unique Support Structure within the cargo bay such that the samples are facing the incoming atmospheric flow. The 124 sample plates are either circular or rectangular sized, depending on post mission analysis needs.

### **Auroral Imaging Experiment**

(STS-51B) NASA

In this investigation a sensitive B/W television camera (standard flight equipment in the Shuttle) is used to record changing auroras over the Northern Hemisphere (primarily North America). Auroras within 3200 km of the Shuttle should be visible. During more than 40 prime observation opportunities, the Shuttle passes within 800 km of the auroras, and its path allows observations of hundreds of kilometers of auroras in a few minutes. The observations occur in periods of 10 min or less and in groups of up to 10 consecutive orbits each day. The video images are supplemented with color still photographs taken by crew members. Since different colors represent different interactions, these photographs provide information about auroral chemistry and physics. The orbital velocity is such that images made a fraction of a second apart form stereo pairs from which the three-dimensional structure and form of most of the aurora can be constructed. The principal investigator provides the crew with current information on predicted auroral activity, types of observations with priority for the day, and evaluations of previous ones.

### **Autogenic Feedback Training Experiment (AFTE) System**

(STS-51B, 47)

The Autogenic Feedback System-1 (Spacelab-3) is a self-contained, battery-powered, ambulatory, physiological-monitoring system. It can continuously monitor, display, and record up to nine channels of physiological data continuously for up to seven hours on a single cassette tape and change of batteries.

The Autogenic Feedback System (AFS-2, Spacelab J) is a lightweight, self-contained, battery-powered ambulatory physiological monitoring system. It can continuously monitor, display and record 9 channels of physiological data for up to 12 hours on a single change of batteries. The Belt Assembly features both a Treatment Mode and a Control Mode. The Treatment Mode permits display of physiological data on a small wrist display while the Control Mode allows only system status and malfunction indications to be displayed. Acquired data is stored on a standard audio cassette using special instrumentation tape. The AFS-2 system may be divided into three general subsystems: the Sensor Group, Garment and Cable Harness Assembly, and the Belt and Recorder Assembly.

*Sensor Group:* Through a unique combination of sensors and transducers, the AFS-2 can acquire skin temperature ( $70-99.9$  degrees F  $\pm 1$  degree F), blood volume pulse ( $1-200 \pm 0.5$  ), skin conductance level ( $0.5-50 \mu\text{MHOs} \pm 2$  percent), electrocardiography ( $40-180$  beats/minute), respiration ( $4-60$  breaths/minute), and acceleration in three axes ( $\pm 0.25$  G  $\pm 5$  percent). These signals are transferred to the Belt Electronics for signal conditioning prior to recording.

*Garment Assembly:* The Garment Assembly consists of a Garment, a Cable Harness, Sensors and Transducers, and a Wrist Display Unit. The garment is a cotton jumpsuit featuring velcro attachment points to secure the Cable Harness. The Garment also serves as a support structure for the various system sensors and transducers. A custom-designed liquid crystal display is attached with velcro to the left sleeve of the AFS-2 garment. The Wrist Display Unit not only provides display of physiological data, but also indicates malfunctions and low battery conditions. Data and power for the Wrist Display Unit are provided by the Belt Electronics via the cable harness.

*Belt and Recorder Assembly:* This group consists of a Belt Electronics Package, a Battery Pack, and a TEAC Data Recorder. The Battery Pack provides power for the entire system using four alkaline 9V transistor-type batteries. The TEAC Data Recorder, a modified nine-channel TEAC HR-40J FM, records analog and digital signals from the Belt Assembly. Data and power for the Data Recorder are provided by the Belt Electronics via the TEAC Interface Cable.

### **Automated Directional Solidification Furnace (ADSF)**

(STS-61C) NASA

See also Advanced Automated Directional Solidification Furnace (AADSf). The furnace is specially designed to melt along a plane in a long, slim magnetic composite sample and then cool the molten metal behind the melt. The furnace module traverses the sample in a single direction, melting and then resolidifying the material as it goes. The ADSF flight hardware is housed in three separate containers connected by power and data cables. The four furnaces are housed in one container; another contains electronics which control furnace operations; and the third houses control switches, status indicators, and a system which records data produced during operation of the furnaces. The total flight package weighs about 250 pounds and occupies the space of five crew lockers in the orbiter middeck. Crew interface is through two switches and three indicators which provide operational and safety status.

### **Awareness of Position Setup**

(STS-40) NASA

To measure changes in proprioception (awareness of body position), the subject points at remembered targets with eyes closed. The Awareness of Position experiment is configured with a 40 by 40 inch Nomex reference screen supported between two handrails. Equipment utilized includes the reference screen, light pointer, data sheets, ear plugs, velcro straps (used as restraints for the test subject), and the Spacelab video camera. The test subject sits before the reference screen with eyes closed and points to certain coordinates with the light pointer. Deviations from the intended position are recorded by the observer on data sheets.

### **Bag-in-Box (BIB) Assembly**

(STS-40, 58, 78, 90) NASA

The Bag-in-Box is designed to permit monitoring of inspired and expired flow and volume by electronic integration of the flow signal, while the subject breathes either cabin air or a test gas mixture through the breathing assembly mouthpiece. By proper positioning of the valves, it is possible to make a transition from air breathing to either single breaths, multiple breaths, or rebreathing of the test gas mixture. It is possible to deliver a sample of a separate tracer gas at residual volume during the single breath N<sub>2</sub> wash-out test gas inspiration. This item consists of a mix gas bag, oxygen bag for inspiration, and an exhaust gas bag. The mix gas bag and oxygen bag are filled from the Gas Cylinder Assembly upon computer command or manually through solenoid valves and tubing. The subject interface to the bags is through a mouthpiece and rotary valves on a Breathing Assembly. The breathing paths are controlled by manually operated or automatic solenoid valves which are driven by the Electronics Control Assembly. The bags are vented by the Spacelab vacuum at the conclusion of each test sequence. A pneumotachograph with a separate mouthpiece is included for forced expirations and an additional pneumotachograph measures flow into and out of the box. The unit is rack-mounted with data and electrical connections to the Electronics Control Assembly and gas line connections to the Gas Cylinder Assembly. Forced expiration spirometry measurements are performed by blowing directly through the pneumotachograph using the separate forced expiration spirometry assembly.

### **Ballistocardiography Package**

(STS-9) ESA

The equipment consisted of three mini-accelerometers and a four-track miniature recorder. A ballistocardiogram is a record of the body's recoil caused by cardiac contraction, the ejection of blood into the aorta, and ventricular filling forces. It has been used as a basis for calculating the cardiac output in man, but its lack of accuracy and reproducibility has caused it to be discarded.

Due to fundamental weight and feeding requirements, researchers used the ENTRM damped piezoresistive accelerometric sensors, though their thermal and aging characteristics were known. Both flight equipment and identical models for ground training and simulation purposes were designed, manufactured and calibrated in Rome by the CONEL company, under the supervision of the Project Manager. The general feature of the equipment were: "dural" plate suitable secured to the back of the subject, supporting the three sensors set in a triaxial configuration, their respective preamplifiers plus one ECG preamplifier box containing the amplifying system, active filters (passing band 0.2 to 30 Hz), control systems and a 4-track miniature tape recorder connected to the other small box by means of a shielded cable measuring 3 meters in length recording time of approximately four hours (three standard cassettes of 90 min each) overall weight of 2,700 grams, alkaline batteries included. Ground recordings were carried out by means of a suspended camp bed secured to four thin steel cables having a natural frequency of about 0.29 Hz. The recordings of the triaxial BCG sequences plus one chest ECG lead (each having an average duration of about 10 min) were carried out 11 days before (F-11) and then again 24 hours prior to the flight (F-1), as well as 24 hours after reentry (R+0) and six days after (R+6). During the first 8 days inflight some recordings were carried out on the PS's starting from the 16th hour after lift-off (F-I), while the recordings carried out on the MS's began on the 5<sup>th</sup> day (F-E). The total number of performances summed up to 14. The sequence was inclusive of periods of approximately 30 sec of spontaneous breathing, of breath-holding, of a Valsalva maneuver lasting about 15 sec, of a light physical showed a normal pattern with high levels in the morning and decline during the day for both subjects.

## **Ball Launcher**

(STS-90) CNRS

The Ball Launcher is designed to launch the experiment ball toward the subject's catching arm. The device uses the release of a compressed spring to launch the attached ball. Changes in spring stiffness or compression are used to vary the initial velocity of the ball. The Ball Launcher can launch the ball at three different velocities between 0.5 and 3.3 meters per second. The ball launcher is clamped to a launcher plate, which is attached with velcro to an overhead locker in the Spacelab. As secondary support, there are also 2 straps which secure the launcher and plate to the overhead handrails. Two LEDs are located on the bottom of the Ball Launcher as indicators of launcher status during operational sessions. Protective goggles were worn during experiment operations.

*Ball Launcher Prolongator:* The Ball Launcher Prolongator is an adapter used to decrease the distance between the subject's catching arm and launcher from 1.6 meters to 0.8 meters. The prolongator is attached between the Ball Launcher and the launcher plate.

*Ball Launcher Loading Device (Ball Wand):* The Ball Launcher Loading Device is a telescoping rod used to load the ball into the launcher. The Ball was attached to the Ball Wand using a quick disconnect which was automatically released by pushing the ball into the launcher. The Loading Device enabled the subject to load the ball without assistance and without having to leave the Body Restraint System (BRS).

*Ball:* The Ball is silicon rubber coated, weighs 400 grams, and measures 9 centimeters in diameter. Attached to the Ball are four reflective markers that allow the Ball to be tracked by the four Camera Illuminator Equipment (CAMILLE) units. A small hole located amid the reflective markers allows the Ball to be attached to the Ball Launcher Loading Device. A small magnet holds the ball in the launcher.

## **Baroreflex Measurement System**

(STS-40, 55) NASA

The centerpiece of this system is a neck chamber made of silicone rubber molded to fit the contour of the anterior three-fourths of the subject's neck. There is a Silastic rubber diaphragm inside the chamber which seals against the neck when pressure is applied. The chamber is connected by means of flexible tubing to a bellows driven by a stepping motor. Bellows movements are controlled by a microprocessor, which also analyzes pressure changes within the system, and analyzes ECG (R-R interval) changes. The system works on the principle that a vacuum applied to a chamber encircling the neck slows heart rate by stimulating the carotid baroreceptors. Pressure changes are transmitted from outside the neck to internal structures; therefore, carotid distending pressure is altered, the carotid artery stretches, baroreceptor nerves change their firing rates, and a baroreceptor-cardiac reflex response is produced. The neck chamber system kit contains eight custom-fitted neck chambers (a backup is carried for each crewmember), two umbilicals and a backup digital display module (DDM). The neck chamber system is worn by the test subjects during experiment operations. The pressure system consists of two microprocessor controlled, stepping motor-driven bellows and a calibration canister. Either of these bellows systems is able to furnish a complex stimulus to the neck chamber system between the pressures of +40 and -65 mmHg. The pressure system is calibrated with a pressure gauge.

## **Bearing Lubricant Wetting Experiment**

(STS-9) NASA

The equipment consisted of plates for lubricant wetting and spreading tests, various journal bearings, and a flight camera to record lubricant responses. Two types of experiments were planned: wetting and spreading on stationary surfaces, and two-phase boundary in a journal-bearing configuration. In each case, the fluid-surface combination was the primary control parameter.

### **Bicycle Ergometer**

(STS-40, 58, 71, 78) ESA

The Bicycle Ergometer is an exercise bicycle that provides a quantitative measure of work done by a subject for experiments evaluating the effects of 0-g upon the cardiovascular system. The equipment consists of a variable workload cycle ergometer, driven by hands or feet, and controlled by the subject's heart rate, manual adjustment or computer control through the use of an ergometer control box mounted to the side of the ergometer. The workload is 10 to 350 W + 5 W, pedal speed is 40 to 80 rpm, and the heart rate control range is 40 to 200 bpm.

### **Biolabor (BB)**

(STS-55) DARA

This facility was used to perform research on electrofusion of cells, cell cultivation, botany experiments and zoological experiments. Biolabor consisted of a cell electrofusion workbench equipped with a microscope, a cell electrofusion control unit, two cell cultivation incubators, a 41 degree C cooler, and two mid-deck mounted cooling boxes. Biolabor experiments consisted of the following: (1) Development of Vestibulo-ocular Reflexes in Amphibia and Fishes with Microgravity Experience; (2) Comparative Investigations of Microgravity Effects on Structural Development and Function of the Gravity Perceiving Organ of Two Water Living Vertebrates; (3) Structure- and Function-Related Neuronal Plasticity of the CNS of Aquatic Vertebrates During Early Ontogenetic Development Under Microgravity Conditions; (4) Immunoelectron Microscopic Investigation of Cerebellar Development at Microgravity; (5) Gravisensitivity of Cress Roots - investigated gravity sensitivity in cultivated cress roots; (6) Cell Polarity and Gravity; (7) Influence of Gravity on Fruiting Body Development of Fungi; (8) Significance of Gravity and Calcium-Ions on the Production of Secondary Metabolites in Cell Suspensions; (9) Influence of Conditions in Low Earth Orbit on Expression and Stability of Genetic Information in Bacteria; (10) Connective Tissue Biosynthesis in Space: Gravity Effects on Collagen Synthesis and Cell Proliferation of Cultured Mesenchymal Cells; (11) Antigen-Specific Activation of Regulatory T-Lymphocytes to Lymphokine Production/Growth of Lymphocytes Under Micro-G Conditions; (12) Enhanced Hybridoma Production Under Microgravity; (13) Culture and Electrofusion of Plant Cell Protoplasts Under Microgravity: Morphological/Biochemical Characterization; (14) Yeast Experiment HB-L29/Yeast: Investigations on Metabolism.

### **Biomedical Instrumentation Port (BIP)**

(STS-40) NASA

This item serves as a way to route both electrical and fluid lines out of the Launch-Entry suit (LES). This item is a special harness which contains signal wires, a small fluid tube, and an air hose. It is used to pass electrical signals, saline, and air. The electrical and saline lines are for the System for Measurement of Central Venous Pressure (SMCVP), a medical device that measures central venous pressure. Data collected during launch include indirect arterial blood pressure, a standard three lead ECG, and CVP.

### **Biomolecules in the Space Environment**

(STS-9) ESA

The equipment was a box accommodating 350 biological samples. The samples were exposed to selected combinations of space vacuum and solar radiation of various wavelengths and intensities. An exposure tray was mounted on a cold plate on the pallet of Spacelab 1. Of the four experimental compartments available, two were vented to the outside, the other two hermetically sealed with internal pressure of 1atm. In each compartment 79 dry samples of spores were accommodated in the layers, with 10E(5) to 10E(7) organisms per sample. Samples that were exposed to UV solar radiation were placed beneath an optical filtering system. An opaque shutter with optical windows was used to achieve precise irradiation intervals during the hot

phase of the seventh day of the mission. Each compartment was equipped with a recording thermometer. The experiment was activated in orbit twelve hours after launch. On mission day 7 the shutter was moved to positions allowing access to solar UV radiation to the four compartments for 19 minutes, 23 minutes, 43 minutes or 4 hours and 17.5 minutes, respectively. The experiment was deactivated on hour 10 of mission day 9. Two kinds of ground controls were used: a simulation experiment before the flight, and an identical experimental set-up in parallel with the flight, but with 1 day phase shift.

## **Biorack**

(STS-61A, 42, 55, 65) ESA

The Biorack is a multi-purpose facility for experiments in cell and developmental biology and radiation biophysics located in a single Spacelab rack with one incubator mounted in another rack. Biological samples are stored in the middeck during launch and in the middeck and the Life Sciences Laboratory Equipment (LSLE) refrigerator/freezer during landing. It had its first flight on the German Spacelab Mission D-1 (STS-61A) in 1985. The main elements of the Biorack are experiment containers, incubators, a cooler/freezer and a glovebox.

On STS-61A, the equipment consisted of a cooler/freezer, two incubators (one for the 18-30 degree C range, and a second one for the 30-40 C range), and a glovebox; experiments included Effect of microgravity on hybridoma mammalian cell behaviour and structure; Embryogenesis and organogenesis of *Carausius morosus* under spaceflight conditions; Dosimetric mapping inside Biorack; Effects of microgravity on genetic recombination in *Escherichia coli*; Effects of microgravity on lymphocyte activation (ex-vivo); Effects of microgravity on lymphocyte activation (in-vitro); Embryogenesis of *Drosophila melanogaster*; Growth and differentiation of *Bacillus subtilis* under microgravity conditions; The circadian clock of *Chlamydomonas reinhardtii* in space; The *Paramecium* experiment; Contraction behaviour and protoplasmic streaming in the slime mould; Antibacterial activity of antibiotics in space conditions; The role of gravity in the establishment of the dorso-ventral axis in the amphibian embryo; and Gravireception of cress roots (*Lepidium sativum* L.).

On STS-42, the equipment included the Dynamic Cell Culture System (DCCS), and the ANTIBIO, BONES, CELLS, DOSIMTR, EGGS, FLY, FRIEND, HYBRID, MOROSUS, PROTO, RADIAT, ROOTS, SHOOTS, SLIME, SPORES, and YEAST experiments, as well as the standard Biorack equipment.

On STS-55, Biorack carried the following experiments: Influence of conditions in space on expression and stability of genetic information in bacteria; Fluctuation test of bacteria cultures; Graviperception and neuronal plasticity: comparative investigations of weightlessness effects on structural development and function of the gravity perceiving organ of two water living vertebrates (*Xenopus laevis*, *Oreochromis mossambicus*); Graviperception and neuronal plasticity: structure and functional related neuronal plasticity of the central nervous system of aquatic vertebrates during early ontogenetic development under microgravity; Antigen-specific activation of regulatory T-Lymphocytes to Lymphokine production; Growth of T-Lymphocytes; Gravisensitivity of cress roots; and Electrofusion and regeneration of sunflower protoplasts under microgravity considering the ultrastructure.

On STS-65, Biorack's experiments were Effect of microgravity on cellular action: the role of cytokines; The role of gravity in the establishment of embryonic axes in the amphibian embryo; Cell microenvironment and membrane signal transduction in microgravity; Lymphocyte activation, differentiation, and adhesion-dependence of activation; Antigen presentation and T-cell proliferation in microgravity; Effect of stirring and mixing in a bioreactor experiment in microgravity; Lymphocyte movements and interactions; Radia-

tion repair kinetics in bacteria and mammalian cells; Efficiency of radiation repair in prokaryotes; Root orientation, growth regulation, adaptation, and agravitropic behaviour of genetically transformed root; Plant growth and random walk; Investigation of the mechanisms involved in the effect of space microgravity on *Drosophila* development, behaviour and aging; The sea urchin larva, a potential model for studying biomineralization and demineralization process in space; Effect of microgravity on lentil morphogenesis; Dosimetric mapping inside Biorack; Gravireaction of Chara; and Gravisensitivity of Cress Roots.

*Experiment Containers:* Experiments designed to fly in the Biorack are contained in sealed experiment containers made of black anodized aluminium. Two types of container are available: Type I, with a volume of approximately 65 ml and internal dimensions of 81x40x20 mm; and Type II, with a volume of approximately 385 ml and internal dimensions of 87x63x63 mm. Each container can be fitted with a standard electrical connector to interface with the power and data lines provided by Biorack. Type I containers fit into standard racks inside: the freezer (maximum 12 containers); the cooler (maximum 18 containers); the incubators (maximum 24 containers each); as well as on the control centrifuges which can take up to 8 containers each. Limited space is available for Type II containers in: the cooler (maximum 4 containers), and the incubators (maximum 3 containers each). No in-flight 1g control experiments can be carried out with the Type II containers which cannot be fitted onto the centrifuges.

*Incubators:* Incubators A and B are of a similar design. The temperature control of these units, and of the cooler, is achieved by means of thermo-electric pumps and forced air circulation which ceases when the door is opened. Container racks for both the incubators and the cooler are mounted on trays that slide out of the opened unit thus giving easy access to each of the stowed containers. Two fixed-speed, 1g centrifuges are mounted on each incubator tray. The incubators can be set at an accurate temperature in the range of 18 to 30 degrees C, depending on the type of incubator. Control samples, identical to those being exposed to microgravity conditions, are placed in the centrifuges.

*Cooler/Freezer:* The cooler is capable of maintaining samples just above the freezing point (4 degrees C), and the freezer section can conserve samples at temperatures as low as -15 degrees C. The Biorack which flew on the Spacelab D1 mission consisted of: a cooler/freezer unit with the cooler operating at +4 °C ( $\pm 0,5$  °C) and the freeze at -15 °C ( $\pm 0,5$  °C); two incubators, A and B, operating respectively at +22 °C ( $\pm 0,5$  °C) and +37 °C ( $\pm 0,5$  °C); and, a glovebox. They were all mounted in a standard Spacelab Single Rack and provided with sensors giving information on the status of each unit and on the experiments via the Spacelab Experiment Computer Operating System. Temperature control in the freezer - which is located inside the cooler - is maintained by means of thermo-electric heat pumps and heat conduction via the inner metal wall. Unit status information is acquired and transmitted during flight at a sampling rate of one reading per second per data channel. Common information acquired from the incubators, cooler and freezer is: temperature (4 sensors per unit); temperature status, which shows if the temperature is outside the nominal approx. 0,5 °C (1 sensor per unit); and, air circulation, which indicates whether the fans are switched on or off (1 sensor per unit). Other sensors provide information on the angular velocity of each centrifuge and yet others safeguard operation conditions.

*Glovebox:* The glovebox is a small working area for handling and observing biological specimens. The observations can be made through a microscope connected to photo, film, or TV cameras. This provides a better than class 100 particle-free working environment and safe conditions for the handling of toxic materials such as chemical fixatives. An air circulation system ensures that air continuously passes from the work area over a filter bed and then back into the work area. Air pressure inside the work area is always lower than in the Spacelab cabin so that, should small leakages occur, no air can escape into the cabin. The glovebox work area: can be lit up; is provided with drawers for tools and alcoholic wipes; has bungee cords to attach containers to its walls; and, is provided with double-sided adhesive tape on the base to attach small items. A specially adapted Zeiss microscope (Bradford) (bright field, 12,5x16 magnifications) can be mounted in the glovebox door opening for the observation of specimens inside. In addition, an automatic mini-Pentax

camera, provided with a macro lens, can be fitted above the glovebox door if photographs of experiment samples are required; both the shutter release and the film transport are activated by a lever which the astronaut presses with his or her chin, thus leaving the hands free for work inside the glovebox.

*Passive thermal conditioning units (PTCU's):* For operational reasons, biological specimens have to be stored in Spacelab at least 33 hours before being activated in orbit. The 33-hour period can be broken down as follows: 24 hours prior to launch during which there is no access to Spacelab; a 3-hour launch window; and, 6 hours after lift-off before the crew can activate the experiments. In many cases, this is too long a period for biological specimens. However, access to the Shuttle middeck lockers is possible between 12 and 6 hours before launch which reduces storage to an acceptable length of time for most experiments provided they are maintained at certain temperatures. In this way, experiment storage time can be considerably reduced not only prior to launch but also during the landing and post-landing periods. Storage containers, or Passive Thermal Conditioning Units (PTCU's), which fit into the middeck lockers and maintain a pre-determined temperature over a twelve-day period were therefore developed. The principle of the PTCU's is the application of the latent heat capacity at the melting point of selected waxes and the insulation of the wax from the warm environment by means of specially developed, double, stainless steel Dewar vessels, sliding one over the other. Racks for 16 Type I and 1 Type II experiment containers can be placed inside each PTCU. Three levels of temperature:  $-10^{\circ}\text{C} (\pm 2^{\circ}\text{C})$ ,  $+5^{\circ}\text{C} (\pm 2^{\circ}\text{C})$  and  $+10^{\circ}\text{C} (\pm 2^{\circ}\text{C})$  were successfully maintained for over 13, 23, and 20 days respectively.

*Hardware Description:* Biorack is a reusable, multiuser facility, developed by the European Space Agency (ESA), designed for studying the effects of microgravity and radiation on cellular functions and developmental processes in plants, tissues, cells, bacteria, and small invertebrates. The facility is equipped with a cooler/freezer, two incubators, and a glovebox. Experiment hardware must fit in one of two types of sealed, anodized aluminum containers. Type I containers are 90 x 58 x 24 mm and Type II containers are 79 x 79 x 99 mm.

The US1 hardware is designed to study the effects of high-energy ionized particle (HZE) radiation in a biological dosimeter. Organisms can be flown in the configurations described below. US1 hardware made use of both Type I and Type II containers.

*Subsystems:*

**Lexan Tubes:** Lexan polycarbonate tubes are assembled in four-tube and eight-tube configurations in Type I containers. These tubes maintain the nematodes in liquid buffered saline. The containers also feature CR-39 film to document the tracks made by the radiation, kimfoil sheets to keep the film oxygenated, and Thermoluminescent Detector assemblies to measure radiation received.

**Radiation Cartridge Belt:** The belt made of Nomex fabric consists of pockets lined with Pyrell foam. Velcro tabs secure the experiment packages. The belt is attached to the Spacelab tunnel to absorb radiation and contains five Type I containers with specimens and one ambient temperature recorder.

**Nematode Stack Assembly:** Twenty-eight layered assemblies are contained within each Type II container. These assemblies consist of a base support, worm/agarose layers on millipore filter paper, CR-39 film to track the path of radiation, kimfoil sheets, and Teflon sheets to act as a non-stick surface to prevent dislodging the worm/agarose layer postflight when removing the CR-39 film.

The US2 hardware is designed to study the effects of microgravity and radiation on cellular and genetic structures. US2 hardware used only Type I containers.

*Subsystems:*

**Cell Chambers:** Each double chamber has two culture wells consisting of a Lexan chamber fitted with a movable piston and a molecular layer of silicone to ease piston travel. The yeast plate has two grooved areas into which Lexan rings fit. Prior to fixation, the piston is pushed down to vent the air inside the chamber. Fixative is injected through the piston with a hypodermic syringe.

Culture Assemblies: Four of the double chambers (total of eight culture wells) are placed into a tray and inserted into Type I containers. The tray holding the chambers is fitted with a pad to ensure that the chambers are held adequately in place. These containers are opened only inside the Biorack glovebox.

The US3 hardware is designed to study the effects of microgravity on cell cultures. US3 hardware used only Type I containers.

#### *Subsystems:*

Cell Chambers: The chamber is a Lexan polycarbonate with two wells. In each well is a bubble of a gas exchanging material that expands or collapses as medium is added or removed. A silicon rubber gasket and bottom plate hold cells cultured on coverslips. A deflector ring in the bottom of the chamber prevents fluid forces from dislodging or shearing the cells.

Chamber Assemblies: Four culture chambers (eight wells) are inverted and placed onto a tray inserted in a Type I container. The chamber units are held in place by double-sided tape. Medium exchange and fixation are performed by inserting a hypodermic needle through the gasket and onto the cultures.

The Syringe Racks are storage devices for use with the Biorack US3 experiment hardware. The racks are designed to hold the syringes that are used to perform medium exchange and fixation on the cell cultures. The racks, made of Lexan polycarbonate, are designed in three different configurations. Each fits in a different location: the Middeck Locker Stowage Insert, the cooler, and the freezer. The Cooler Rack is designed to hold 40 syringes filled with replacement medium. The Stowage Rack is designed to hold the replacement medium syringes that are transferred from the Cooler Rack following Biorack activation. The Freezer Rack is designed to store the syringes containing removed conditioned medium.

### **Biostack**

(STS-9, 61A, 42, 65) DLR

The STS-9 experimental packages consisted of layers of different biological objects sandwiched between different types of HZE detectors. This arrangement permitted correlations between HZE particle trajectories and biological injury.

On STS-61A, three detector systems, LiF-thermoluminescence dosimeters (TLD), nuclear emulsions, and plastic nuclear track detectors, were combined. Each dosimetric stack consisted of a total of 20 to 100 sheets of plastic detector foils (cellulose nitrate, Lexan and CR 39) of a thickness between 0.1 and 0.6 mm and a size of 38x81 mm<sup>2</sup> and nuclear emulsions of different radiation sensitivity. The overall height of each stack was 16 mm including the 2 layers of 18 LiF chips covering the bottom and top. The stacks were placed inside aluminum containers with 1 mm thick walls. Two such containers were installed in the 22degC Biorack incubator, and 4 stacks in the 37degC incubator, 2 of which were placed in the 1 g centrifuge. Additional stacks were included in the experiment on embryogenesis and organogenesis of *Carausius morosus*, 2 on the 1 g centrifuge and 1 in the static rack.

The four Biostack packages on STS-42 contained single layers of bacteria and fungus spores, thale cress seeds and shrimp eggs sandwiched between sheets of nuclear emulsion and plastic radiation detectors.

On STS-65, Biostack employed radiation detectors to monitor incoming particles. Within sealed aluminum containers, biological specimens are arranged in fixed positions between nuclear track detectors. This allows scientists to localize the trajectory of each heavy ion in the biological layer and to identify the site of penetration inside the biological subject. The precision for reconstructing the geometric relation between the particle trajectory and the organism can be as low as 0.2 microns for the smallest objects, bacterial spores. The experiment uses a wide spectrum of biological specimens, such as spores, yeast cells, shrimp

eggs, and plant seeds, with different levels of biological organization and radiation sensitivity. The species are well known and have shown at least one typical genetic or somatic radiation effect. The specimens will be studied postflight to identify any changes in cellular and organic development, damage to nuclei and other subcellular organs, and induction of mutations leading to somatic or genetic changes of biological significance. Information will also be obtained on the spectrum of charge and energy level of cosmic radiation inside Spacelab.

### **Biotelemetry System (BTS)** (STS-51B) NASA

The Biotelemetry System (BTS) monitors physiological functions of mammals on board the Spacelab. This rack-mounted system is designed to be used primarily with the Research Animal Holding Facility (RAHF). Each unit of the BTS can monitor one animal for one to four physiological parameters. Transmission of data from the BTS data-handling system to Spacelab data systems is accomplished through a Life Sciences Laboratory Equipment (LSLE) Microcomputer.

*Implantable Sensors and Transmitter:* The implants for SL-3 included a transmitter as well as the sensors for deep-body temperature, heart beat count and signal strength which are sampled once a second and heart rate (ECG) which is sampled at 320 times per second. The range of the transmitter is at least one foot. Implantation typically occurs three weeks prior to launch.

*Antenna/Receiving System:* The antenna is capable of being installed within one cage of the RAHF and is connected via cables to a receiver/demodulator system compatible with the BTS Data Handling System. Sensor data are transmitted from the implant to these antennae within selected rodent cages. A pulse interval modulated FM radio signal is received from each animal cage being monitored.

The four receivers, two demodulators, four QRS signal conditioners and one power supply comprise this part of the Biotelemetry (BTS) system. This part of the system is mounted in a rack space next to the rodent RAHF.

*BTS Receivers:* These receivers are designed to distinguish between proper transmitter signals and outside RF signals. Each receiver has controls suitable for interfacing with an associated demodulator system. The Automatic Frequency Control (AFC) switch enables the automatic frequency control function. The display switch enables the numerical LED display which is tuned to a specific frequency between 88-108 MHZ. A tuner knob located in the lower center part of the receiver is used to adjust the signal strength and center tune the frequency of the transmitter. The left 10 diodes above the LED display verify optimal signal strength. The right 10 diodes and the dropout light located on the left side of the receiver verify correct adjustment of signal frequency. Squelch control is preset to minimum but can be adjusted on orbit. The level, logic and video output connections are used for test only. Output signals from these receivers are sent to the demodulators.

*Demodulators/QRS Boards:* The demodulator is designed to accept the received signal and encode the ECG and deep body temperature information from the pulse train and convert them to analog outputs. A QRS board (not shown, contained within receiver module) receives the waveform, a portion of the ECG, from the receiver to enable counting of heart beats. The QRS board is an event accumulator that counts heart beats to 255 and then resets to zero to resume accumulation. This heartbeat count is sent to the Life Science laboratory Equipment (LSLE) microcomputer with the ECG and deep body temperatures. In the event of a signal dropout, the demodulator is capable of holding the last value received for temperature until an adequate quality signal is again received.

## **Biowissenschaften (BW)**

(STS-61A) DARA

This life sciences payload experiment package combines a group of three-element botanical or biological and two medical experiments in which a small botanical garden will be tended during the mission (BO-TEX). Experiments included Differentiation and Embryogenesis in Aniseed Cell Cultures in Microgravity; Gravisperception of lentil seedling roots grown in space; and an experiment entitled Geotropism (PI - J. Gross, Univ. Tübingen Germany - no information available, may not have flown). Frog larvae development was investigated in the “frog statolith” experiment (STATEX). The third experiment in the field of life sciences continued the first Spacelab’s medical experiments of the central venous pressure, measuring for the first time the internal pressure of the eye. This experiment is designed to study fluid shifts under the effect of microgravity, as well as the adaptive behavior of the related human organs. The two other medical experiments were Tonometry (TOMEX) and Early adaptation to body fluid and cardiac performance (body impedance measurement).

## **Blood Holding Kit (Freezer/Refrigerator)**

(STS-40, 78) NASA

The Refrigerator Blood Holding Kit is designed to hold refrigerated or frozen blood samples. This metal tray has multiple holes that hold vacutainer blood tubes. The Refrigerator Blood Holding Kit is stowed in the Spacelab freezer or refrigerator for temporary stowage of samples before centrifuging or for return of samples for postflight analysis.

## **Blood Pressure Monitor (Continuous/Intermittent)**

(STS-40) NASA

Continuous blood pressure can be measured noninvasively using the Penaz technique. This pressure monitor is an Ohmeda 2300 Finapres. It provides continuous measurement of finger arterial blood pressure displaying the pressure waveform, digital values of systolic, diastolic and mean pressure as well as pulse rate and a time annotated trend display. The Blood Pressure Monitor requires only electrical power to operate. A small, quiet pump in the monitor unit provides the finger cuff with required air pressure. The intermittent monitor is designed to monitor indirect blood pressures on a wide variety of physiological subjects. This item is a NARCO Biosystems Model PE-300. The unit incorporates a K-sound microphone and a brachial cuff. The front panel allows for adjustment of cuff inflation rate, maximal cuff inflation pressure and K-sound amplitude.

## **Body Impedance Measurement (BIM) Device**

(STS-55, 90)

The origin of the hardware is unconfirmed, but both experiments using it were sponsored by DLR. On STS-55, The BIM also included the BIM Recorder and pouch, a belt to fix the pouch and the BIM Control Box around the subjects waist, and an umbilical cord. BIM measurements were performed during the launch and landing phases (using the BIM harness) and during Anthrorack operations (using the LOBO suit). During launch and landing, the subjects wore the Harness with 6 attached electrodes with two impedance segments. The Harness integrated the sensor cables for the electrodes, which were positioned on the subjects forehead, the front of the neck, to the hip (2 electrodes), just above the knee and just below the knee. The positioning of the electrodes was part of the suit-up procedure before launch and the Harness was worn below the Launch and Entry Suit (LES). The BIM Recorder was mounted under the subject’s seat and signals were recorded using a 24-hour audio-tape. During flight, the electrodes were part of the LOBO suit. The LOBO suit integrated the 8 electrodes with 3 impedance measurement segments. During measurements, the BIM Recorder was worn in the pouch using the waist belt.

For STS-90, the Body Impedance Measurement (BIM) device measures the electrical impedance of the body during Lower Body Negative Pressure, providing body fluid distribution information and determining physiological variables. The BIM includes the BIM Control Box and the BIM Harness containing eight electrode leads. The 8 electrodes are positioned on the forehead, the front of the neck, the waist (2 electrodes), just below the groin, below the knee, above the shinbone at the lower end of the calf, and on the upside of the foot. The Control Box supplies a current between two electrodes (placed at the head and foot) for impedance calculation. During use, the Control Box is connected to the Harness and a recording device.

### **Body Mass Measurement Device (BMMD)**

(STS-40) NASA

Body mass determinations are made using a linear spring / mass pendulum platform. The mass measured determines the period of the pendulum. The period is electronically timed and is converted to a mass measurement. The equipment consists of a frame, a seat, springs, a release and lockout mechanism, specimen restraint, and an electronics module with display system. The BMMD comprises a Mechanical Subsystem and an Electronics Subsystem. This device is completely self-contained, with the exception of requiring a DC power source (nominal 28 volts) and a plane stable supporting surface. Immediately adjacent to the seat is the display face of the Electronics Subsystem.

### **Body Restraint System (BRS)**

(STS-9, 40, 58, 90) NASA

The BRS resembled a backpack frame and consisted of a lounge-type chair, a bearing assembly to allow manual rotations, a cage assembly to hold the bearing assembly, and a system of tethers to loosely attach the chair to Spacelab rack handrails. The chair could be used without the bearing connection allowing linear translations within the constraints of the tethers. An adapter plate was provided for attaching the cage assembly to the Spacelab floor and for rotating the cage to the side when needed. The cage could also be completely removed from its location when necessary to avoid interference when performing other experiments. During SLS-1 and SLS-2, the BRS was used to rotate the subject so that the characteristics of vestibulo-ocular reflex (VOR) in zero-g and the influence of head tilt on VOR could be studied. Used for the Neurolab flight, the Kinelite BRS is a custom-made aluminum chair with restraining belts for the shoulders, hips, and thighs. Velcro is used to secure the restraining belts. The BRS can be oriented facing the port or starboard side of the Spacelab to satisfy either right- or left-handed subjects. The Underseat Stowage Bag is attached to the underside of the BRS and stores the reflective marker sets, the Hand Sensor Set, two Balls, and the EMG Harness. The reflective marker sets include the shin, body, hand, and head marker sets. The BRS Mounting Plate provides an on-orbit installation location for the BRS. The BRS chair legs fit over brackets on the plate, and pins hold the chair in place. The plate is attached to the center aisle of the Spacelab floor with four bolts. The plate weighs 6.6 kilograms.

### **Body Rotating Device (BRD)**

(STS-90) NASA

The Body Rotating Device (BRD), a component of the Visual and Vestibular Investigation System (VVIS), is a chair mounted on an arm that rotates around a shaft such that the head trajectory of a subject seated upright is a circle of 50 cm radius. When a subject is rotated in the supine position (lying on back or LOB), the head is rotated in a circle of 62 cm radius. In the upright position, the chair can be configured so that the subject is in a left-ear-out (LEO) or right-ear-out (REO) orientation relative to the center of the circle. Off-axis rotation generates a steady-state level of linear acceleration (0.5-g or 1-g, depending on the rotational velocity) on the vestibular organs of the subject. For the left-ear-out (LEO) and right-ear-out (REO) chair orientations, the rotation velocities are 254°/s and 180°/s for 1.0-g and 0.5-g, respectively. In the lying-on-

back (LOB) orientation, the velocity is 223°/s for 1.0-g and 158°/s for 0.5-g. Subjects are rotated either clockwise (CW) or counter-clockwise (CCW) when viewed from above the chair. When the chair is in LEO, CW rotation results in the subject rotating “facing” the motion (rotating “face first”) while CCW rotation results in rotation with the subject’s “back” to the motion (rotating “back first”). The reverse is true for the REO orientation. Rotation in LOB is conducted in the CW direction. The orientation of the chair can be changed between LEO, REO, and LOB by a single operator. The BRD includes an audio subsystem which isolates the subject from noise orientation cues coming from the Spacelab environment, provides a means of communication between the operator and subject, and allows recording of subject perceptual reports. When flown on a Spacelab mission, the BRD is located in the center aisle at the aft end of the Spacelab. It measures 161 x 62 x 150 cm (63.4 x 24.4 x 59.1 inches) in the LOB position and weighs 160.6 kg (353.3 lb). The various components of the BRD are detailed below.

*Baseplate and Fixed Support Structure:* The baseplate supports the rotating platform and the mounted electronics through the shaft assembly housing. It distributes the loads to the floor attachment points. The baseplate is a machined frame (aluminum alloy) composed of one central section and two lateral sections. The central section consists of a bottom plate, a circular stiffener web, and an upper flange used to attach the Fixed Support Structure to the baseplate. Each lateral section has a lower plate, an upper plate, walls, and a longitudinal stiffening web. The baseplate is fixed to the Spacelab floor using one bolt in each of 8 feet.

*Shaft and Rotating Platform:* The aluminum alloy shaft assembly transfers the rotational motion to the rotating platform. It includes the motor, slip rings, brake, encoder units, and the harness support. The shaft is fixed in the hub of the rotating platform. The rotating platform is mounted on the shaft assembly housing with two sets of ball bearings. The platform supports the Eye Movement Recording Subsystem (EMRS), two Video Tape Recorders (VTRs), the LOB back support, the BRD Rotating Electronics Box (E-Box), the Eye Stimulation Subsystem (ESS) E-Box, and the Body Restraint System. Two platform locking pins (BRD locking pins) are present which can be inserted to prevent rotation of the platform. Two additional pins (LEO/REO pins) inhibit rotation of the Body Restraint System (swivel of the seat from LEO to REO position). When not in use, the rotating platform is aligned with the center line of the Spacelab and locked in place with the locking pins.

*Head Restraint System (HRS):* The HRS is required to maintain accuracy in the measurement of eye movements and a constant position of the vestibular organs during experimentation. The system is adjustable to accommodate different subjects and the fluid shifts associated with weightlessness. The HRS consists of a subject-specific mask (shell) divided into front and back molded pieces. The back shell is attached to the seat back and fixed with a captive screw. The front shell is connected to the front part of the Eye Stimulation Subsystem (ESS) support structure, which is positioned on a sliding mechanism. The slide is manually released by the subject by pulling down on a bar (egress bar). This allows the entire structure (head unit) to be moved 10 cm in or out. A fine slide, operated by the subject with a knob, allows the final approach after the head unit is closed. The fine adjustment is  $\pm 2.5$  cm about the nominal zero. A minimum distance of about 5 cm is permanently free in front of the subject’s mouth. Proper closure of the head unit structure is monitored by two microswitches which are mounted on the Body Restraint System chair on either side of the subject’s head. Rotation is disabled until both of the microswitches are engaged. The HRS is constructed of carbon fiber with methyl-methacrylate resin and silicone cushioning. Each of the payload crewmembers has his or her own shell set (front and back). These are stowed when not in use and are mounted on the BRD when the chair is being prepared for that individual as a subject. Each front shell is 26.6 x 23 x 12 cm (10.5 x 9.1 x 4.7 inches). Each back shell is 21 x 16 x 15 cm (8.3 x 6.3 x 5.9 inches). Each shell set weighs 1.3 kg (2.9 lb).

*Body Restraint System (BRS):* The Body Restraint System (chair with restraints) is provided to avoid undue forces on the subject’s neck and to keep the subject’s limbs within the rotational envelope. The chair seat height, shoulder restraint height and width, hip restraint width, foot restraint height, and lumbar sup-

port are fully adjustable to fit a variety of subject sizes. The subject is secured to the chair with a 5-point body restraint system (seat belt). This Nomex strap consists of a main strap that encircles the thighs, two side straps that clip to slots on the arms on either side of the chair below the handgrips, and a third thin strap perpendicular to the main strap that encircles the subject's ankles. The main strap and side straps have buckle closures and are of adjustable length. The ankle strap is secured with Velcro™ and its length is not adjustable. A knee cushion (Nomex-covered foam) is placed between the subject's knees to increase subject comfort and provide a more secure fit of the knee/ankle strap. The subject's feet are secured to a footplate with kick-through Velcro™ straps. Both the knee/ankle strap and foot holders are designed to allow rapid egress of the subject in the event of an emergency. The chair is mounted on the rotating platform via an interface mechanism that accommodates the three required chair orientations (LEO, REO, and LOB). Chair swivel between the LEO and REO positions is accomplished by release of two LEO/REO pins. These pins are located below the seat on either side of the chair. The BRD tie-rod, used to brace the chair when rotating in the upright position, must be also be removed when the chair is repositioned (it is resecured when switching between LEO and REO and is stowed at the baseplate when the chair is put into the LOB position). Backward tilt of the chair into the LOB position is enabled by release of two LOB pins. These pins are located on the rotating platform below the chair seat. To secure the chair in the LOB position, two backrest pip pins are engaged. The brackets for these pins are located on the rotating platform near the BRD Rotating E-Box. These same pip pins are used to secure the BRD tie-rod when the chair is in the upright position. The status of the LEO/REO and LOB pins is monitored via microswitches which prevent chair rotation if not properly engaged. Microswitches on the back of the chair must be engaged by the backrest pip pin brackets to enable rotation in LOB. The chair also includes two handles with handgrips. Each handgrip has a switch. The left handgrip has a button which the subject can use to stop rotation. The right handgrip has a toggle switch that is used for calibrations.

*Failsafe Brake:* The failsafe brake stops the BRD in less than 8 seconds in emergency conditions and automatically engages if power is cut off. The failsafe brake is not used for a nominal stop of rotation. The brake is an external shoe brake with a rigid approach. A compression spring connects the two arms of the brake and pushes them against the shaft. When an electromagnet is powered, it pulls a triangular lever which opens the brake arms leaving the shaft free to rotate. The failsafe brake can also be manually disengaged to allow the rotation of the platform during experiment set-up. Three microswitches are used to control brake function. One supplies housekeeping data of brake status. The other two prevent powering of the motor during platform handling (when the failsafe brake is manually disengaged). In the event of a microswitch malfunction, a bypass adapter can be installed to enable rotation.

*Accelerometer:* The servo accelerometer is fixed to the rotating platform next to the BRD Rotating E-Box and is used to measure the radial acceleration of the platform. The acceleration data is then provided to the BRD Rotating E-Box which detects any overspeed condition.

### **BONES (In Vitro Mineralization and Resorption of Fetal Mouse Long Bones)** (STS-42) ESA

The equipment for this Biorack experiment consisted of eight containers, each of which contained culture bags filled with medium, including 10 percent rat serum. At the beginning of the experiment the containers were placed in a 36 degree C incubator to initiate biological activity and in the containers used for biochemical studies a glass ampulla was broken. After the 4 day experimental period the containers used for biochemical purposes were placed in a -15 degree C freezer to stop biological activity, and the containers used for histological studies were placed in a 4 degree C cooler after a ampulla of the fixative formaldehyde was broken inside. The pressure of the culture bags was then monitored using the PROD (Pressure Read-Out Device) which was attached to the container and was connected, on one side, to the data and power lines of Biorack. The long bones were individually cultured in double layered, gas perme-

able, polyethylene culture bags containing 675 microliters of culture medium with additives (serum and antibiotics). The medium is sodium bicarbonate buffered. Each culture bag contained one long bone and a glass ampulla, which, for the biochemical experiments using radioactive labels, contained either proline marked with calcium 45/phosphorus 32/hydrogen 3-proline or hydrogen 3-proline only. The containers were stored in the cooler.

### **Broad-Band X-Ray Telescope (BBXRT)**

(STS-35) NASA

The BBXRT consists of a pair of coaligned thin foil conical X-ray mirrors, with a cryogenically-cooled, Si(Li) spectrometer at the focus of each. The X-ray mirrors have a focal length of 3.8 m and a diameter of 40 cm. Each mirror consists of 118 nested pairs of reflectors. Each reflector consists of 0.017 mm thick aluminum shaped into a cone, coated with an acrylic lacquer to form a microscopically smooth surface, which is overcoated with gold to enhance X-ray reflectivity. The spatial resolution of the telescope is 1.3 arcmin (half power radius) and the plate scale is 0.91 arcmin per cm. The detectors are segmented into five discrete Si(Li) detection elements. The circular central element has a diameter (field of view) of 4.0 arc minutes; the outer ring, of diameter 17 arcminutes, is divided into four 90 degree segments. Each is located in a cryogenically-cooled vacuum cryostat. Attached to each cryostat is a solid argon cooler with a 90 lb capacity. Experiment mass: 680.4 kg

### **Bubble, Drop and Particle Unit (BDPU)**

(STS-65, 78) ESA

For STS-65, crew members exchanged interchangeable experiment test containers with dedicated fluid cells located in the Bubble Drop and Particle Unit. The fluid cells incorporate mechanical or acoustic stirrers for fluid mixing, injectors for bubbles or droplets, and heating and cooling elements to impose temperature differences within the fluid. Modular optics components support several different diagnostic techniques, including Schlieren (shadowgraph), interferometric and infrared imaging. The sample can be illuminated using fluorescent lamps, or a Helium-Neon laser. Experiments are automatically controlled by a microprocessor. Investigators on the ground can monitor the processing of their experiments and can change parameters. Crew members can also adjust and modify conditions. Cameras and sensors will observe and record temperature, density, position and interactions within the liquid-filled test cells. On STS-78, commands will be sent from the ground to inject bubbles or drops into liquid-filled test cells and then to subject the cells to predetermined changes in temperature. Cameras and sensors will observe and record temperature, density, and position of the bubbles or drops. The various test cells will be used to study how bubbles and drops react in liquids with varying temperatures and concentrations, how they affect the process of solidification, how convection affects liquid layers under different temperature conditions, and how evaporation and condensation affect bubble creation and growth.

### **Camera Illuminator Equipment (CAMILLE)**

(STS-90) CNRS

CAMILLE consists of four cameras used to track markers on the subject and the ball, as well as the reference marker attached to the Body Restraint Device (BRS). Each CAMILLE unit consists of a video camera, an infrared illuminator, and a mounting bracket. The cameras serve as mounting for the illuminators. Data for the cameras are transmitted to the Kinelite Processing Module (PM) for later calculation of 3-D data. The cameras are mounted to handrails in four locations in the Spacelab using the camera fixation devices (clamps). The CAMILLE units are powered by the PM. The Camera Fixation Device is a clamping device that attaches the CAMILLE cameras to the Spacelab handrails. They provide a swivel for orientation adjustment. Knurled knobs ensure mounting adjustments and dismounting without the need for additional

tools. The Reflecting Markers are reference and body markers tracked by the CAMILLE for generation of 3-D data. The markers are made of reflective paper attached to small half spheres about 13 mm in diameter. The markers are visible in a 180-degree field of view. Nine markers are worn by the subject: two on the head, two on the catching hand, and two on the shin of the leg; the remaining three are snapped over the electromyograph (EMG) electrodes that are also attached to the catching arm. Four reflective markers are also attached to the ball for later reconstruction of ball trajectory. The OBCO (On-board Correspondence Object) is the Kinelite calibration device. It is a flat, square, aluminum frame with a handle down the middle. Reflective markers are precisely mounted at each of the four corners of the frame. The OBCO is filmed at the beginning of an experiment session to provide the data needed to reconstruct positional (2-D and 3-D) data.

### **Candle Flames in Microgravity (CFM) Package**

(STS-50) NASA

There were two modules used in the experiments:

- a candle parts box, containing such items as cables, igniters, and a candle holder
- a candlebox in which astronauts mounted the candles

The faces of the plastic candlebox were 4 1/2" by 4 1/2" by 3/8" thick. There were approximately 100 1/8" holes in each of the six faces. The holes permitted fresh air to reach the candle, but prevented other material from being accidentally ignited. The box itself provided thermal mass to keep the combustion products diffusing through the holes and the candle box itself from becoming too hot to touch.

*Candle mounting:* For single-candle experiments, researchers mounted a candle in the right-hand face of the candle box. For two-candle experiments, they mounted a second candle—whose position is adjustable so the distance between the candles can be varied—was mounted in the center of the left-hand face (as shown in the photo on the right). Also on the right face of the candlebox is a soft-covered opening through which the igniter can be pushed. The experiment module was equipped with two thermocouples that the crew could move in two dimensions by means of a translation stage. The purpose was to measure the temperature profile in and around the flame. The crew did not, however, have time to perform the thermocouple experiments. The candles were 3/16" in diameter and approximately 1/2" long. The candle composition was 80% paraffin wax and 20% stearic acid ( $C_{18}H_{36}O_2$ ); the latter imparts toughness and reduces dripping characteristics. The candle was similar to a typical birthday cake candle, but without coloring or perfume. The melting temperature of the candles was about 155 degrees F.

*The ignition and mounting systems:* The ignition system was a manually operated, electric-powered, hot-wire igniter. The crew ignited the candle by pushing the igniter through a soft-covered opening on the candlebox's right face. The igniter required simultaneous closing of two remotely located switches. The candlebox was permanently mounted on an aluminum stand 2" to 3" high to ensure that it would be centered in the glovebox. The stand contained thermocouple displays and electrical connectors.

*Cameras:* Experiment data came from two black-and-white video cameras. The Spacelab's 35-mm single lense reflex camera provided color, still photographs of the flame for several tests.

### **Cardiopulmonary Control Unit (CCU)**

(STS-40) NASA

The CCU is needed to perform experiment control, digital data interfacing, analog data interfacing, keypad data recognition, signal processing and preparation for downlink, data computation, and data presentation on the Video Monitor. The CCU initiates the calibration of the experiment system on command from the keyboard. It accepts input data from the operators and allows them to sequence through the steps of the experiment. The CCU also receives flowmeter signals from the Cardiopulmonary Rebreathing Unit (CRU) and from the Gas Analyzer / Mass Spectrometer (GAMS). It uses this data to calculate experimental results

which are displayed on the Video Monitor and telemetered to JSC. The results inform the operators about the status of the experiment. The CCU automatically computes the correct volume of gas for the rebreathing bag and initiates automatic filling of the bag. The duration of the rebreathing portion of the experiment is predetermined and automatically controlled by the CCU. The CCU monitors the ergometer output which indicates when the subject fails to maintain adequate effort or workload. It is possible to calibrate the Gas Analyzer / Mass Spectrometer (GAMS) using a separate supply of calibrating gas of known content and pressure, supplied by the Gas Tank Assembly (GTA) and controlled by the CCU.

### **Cardiopulmonary Rebreathing Unit (CRU)**

(STS-40) NASA

This item consists of a rebreathing bag, a system of electronically and pressure operated valves controlled by the CCU, a mouthpiece, a probe and capillary line leading to the GAMS, a flowmeter in the breathing pathway, thermistor, indicator lights, and control switches. During the experiment the rebreathing bag is filled with a known volume of test gas. The valves control the filling of the bag and also select whether the subject breathes cabin air or test gas. During rebreathing, no cabin air enters the air system. The air system is comprised of the bag, valves, mouthpiece, and subject. After rebreathing, the valves switch the subject to cabin air. The rebreathing bag then is exhausted by exposure to space vacuum. The bag has a special spring valve, to facilitate complete emptying. The mouthpiece holder accepts a mouthpiece through which the subject breathes. When the subject uses the mouthpiece an airtight seal is formed. The GAMS probe is located in the breathing pathway and samples breathing air, diverting 60 ml/min. to the GAMS via the capillary line. The CRU is mounted on top of the bicycle ergometer, positioned between the shoulder restraints. The CRU receives signals from the CCU to close the air system to cabin air and open it to the rebreathing bag, at the appropriate time after subject switch activation. The CRU also switches the subject back to cabin air at the end of the rebreathing period.

### **Cell Culture Chamber Kit**

(STS-47, 65) NASDA

On STS-47, the NASDA provided Cell Culture Chamber was an aluminum, petri-dish-like chamber 101 mm in diameter and 32 mm high. The interior of this chamber is coated with PTFE. A honey-combed matrix is inserted into the base of the chamber in order to provide structural support to the agar/cells. This honeycomb matrix is constructed from an unspecified aromatic polyamide. In order to provide for gas exchange, the top of the chamber has a 45m, polysulfone, gas-permeable membrane. This membrane is a commercially available filter.

Each kit provided for STS-65 included a main chamber, containers for culture mediums, waste collectors, applicators, syringes and containment bags. For IML-2, three different types of kits will support animal cell-culture and electrophoresis experiments. Petri-dish-type chambers will be used for the slime mold and plant cells. Animal cell culture kits have transparent windows which allow crew members to observe cell cultures grown in orbit with a Biological Microscope. They will use a 35-mm camera, which attaches to the microscopes, to make still photographs of the samples. For the slime mold culture, a video system will record and downlink real-time images of specimens to scientists at Spacelab Mission Operations Control in Huntsville. The Thermoelectric Incubator will operate at around 98.6 degrees Fahrenheit (37 degrees C). Experiment samples within the incubator are secured by a bungee cord to prevent damage from vibration and keep them from floating away when the door is opened.

*Plant Fixation Chambers (PFCs):* The Plant Fixation Chambers (PFCs) were provided by NASDA. They are aluminum, petri-dish like containers which are approximately 100 mm in diameter by 35 mm high. Each chamber has a 15 mm septum port which extends 22 mm above the top of the container. These

containers are completely sealed. The PFCs allow plant cells exposed to space flight to be fixed on orbit by insertion of a chemical fixative via syringe through the septum port. The fixative used was a 3% glutaraldehyde (balance water) solution. 20 ml of fixative was contained within each chamber.

### **CELLS (Chondrogenesis in Micromass Cultures of Embryonic Mouse Limb Cells)**

(STS-42) ESA

Stored in Biorack, the hardware consisted of several Type I containers which consisted of four culture units, each of which contained two non-communicating wells. Within each culture chamber was a “bubble” of a gas exchange material (Silastic) used to suspend the medium. Prior to flight the cells were inoculated into the hardware at high densities which promoted cartilage differentiation. In flight, the cultures were placed in 4 degree C PTCUs and were stowed on the middeck. Also stowed in middeck were 40, 5 ml syringes with medium at ambient temperature, and 30 syringes with fixatives (20, 3 cc with 1% glutaraldehyde; 10, 2 cc with 1% formalin in 95% ethanol) at 4 degree C. Medium changes took place at launch + 15 hours and were repeated at 26 hour intervals. During each change, one container from 1 g and one from 0 g were fixed and refrigerated.

*Cell Chambers:* The hardware containing the limb bud cell cultures is a Lexan polycarbonate chamber with two wells. In each well is a “bubble” of a gas changing material, which expands or collapses as medium is added or removed. A silicon rubber gasket and bottom plate complete the basic assembly. Cells are cultured on coverslips inserted between the gasket and bottom plate. A deflector ring in the bottom of the chamber prevents fluid forces, produced during the medium injection and withdrawal, from dislodging or shearing the cells on the coverslip.

*Chamber Assemblies:* Four culture chambers (eight chamber wells) are inverted and placed on a tray designed to fit into a European Space Agency (ESA) Type I/O container. This allows the four culture chambers to be removed as a unit. The chamber units are held in place in the tray by double-sided sticky-back tape. The medium exchange and fixation are performed by inserting a hypodermic needle through the gasket and onto the cultures on the cover slip.

*Syringe racks:* One rack is designed to hold 40 syringes filled with replacement medium and is stored in an ambient stowage insert on the middeck. A second rack, designed to hold 60 empty syringes, which are used for removal of used medium, is stored in Biorack stowage in the Spacelab. The racks are made of Lexan polycarbonate, as are the end plates that hold the syringes in place in these racks. Additional syringe assemblies in groups of three syringes are stored in Type I/O containers provided by the European Space Agency (ESA). Additional items provided for this experiment include extra syringe needles, a dummy Type I/O container and a syringe plunger.

### **Charged Particle Beam Phenomena**

(STS-9) CNRS

The experiment objectives were to use electron- and ion-beam guns (up to 10 keV), an associated wave receiver (up to 100 MHz), an electron-temperature probe, and three particle detectors (1) to study ionospheric neutralization processes by studying the stability of the electronic potential of the gun with respect to the plasma, (2) to study plasma instabilities by measuring electric (up to 100 MHz) and magnetic (200 Hz to 20 MHz) wave components, (3) to use the Shuttle motion to perform ion-bounce experiments, and (4) to monitor the secondary electron flux. The equipment consisted of an active package containing an electron gun, an ion gun, and a particle detector; and a passive package containing an electric antenna, a magnetic antenna, and two particle detectors.

## **Coarsening in Solid-Liquid Mixtures (CSLM)**

(STS-83/94) NASA

The experiment will be performed in an electric furnace in the Middeck Glovebox, located in Spacelab rack 10. The furnace heats the samples held in eight cartridges and melts the matrix surrounding the solid particles. The eight cartridges will be loaded sequentially into the compact oven. Each cartridge is 11.5 cm in diameter and holds 7 samples that are 10 mm in diameter and 5 mm long. Hundreds of thousands of solid particles are dispersed in these small specimens. The samples are designed to produce various volume fractions of solid at the coarsening temperature of 185 °C. Each of the specimens in each cartridge will have compositions chosen to yield volume fractions of solid of 0.05, 0.1, 0.2, 0.3, 0.5, 0.7, and 0.8. One cartridge will be processed at each of the following times: 0, 150, 375, 940, 2,340, 5,860, 14,600, and 36,600 seconds. Then, the samples will be quenched rapidly, freezing the high-temperature particle structure. After the mission, quantitative metallographic analysis will be used to determine the coarsening kinetics. The samples will be sectioned, polished, and etched. The images of each section will be digitized for analysis and stored on compact disks for future use. To compare the results to theory, investigators will measure the average radius of the sectioned particles and the particle size distribution as a function of time for each volume fraction of solid. The rate at which the average section radius changes with time then will be compared with theoretical predictions with no adjustable parameters, the first time this has been possible. To understand the morphology of the solid-liquid mixtures in more detail, scientists will use an electron microscope to analyze the particle contacts that may form during the coarsening. By digitally stacking many two-dimensional images, much in the same way standard medical X-ray tomographic and magnetic resonance images are produced, investigators will be able to reconstruct the full 3-dimensional morphology of the solid-liquid mixtures.

## **Cold Pressor Glove Assembly**

(STS-90) NASA

The Cold Pressor Glove Assembly duplicates the effect of immersing the hand in ice-water. This rapid, sustained, severe cooling of the hand elicits a blood pressure and heart rate increase. The assembly is comprised of a cold gel pack of Crylon Gel / Metho gel enclosed in a Linear Low Density Polyethylene bag and stowed inside a Nomex cover. The subject inserts the hand into bag, closes the strap and wraps the manual blood pressure cuff around the bag, applying 50mmHg pressure to ensure good contact between gel pack and hand.

## **Combustion Module**

(STS-83/94) NASA

The Structure of Flame Balls at Low Lewis-number (SOFBALL) and the Laminar Soot Processes (LSP) experiments were completed successfully during the STS-94 mission. CM-1 requires two Spacelab racks, one double and one single rack, with a combined weight of more than 1,600 pounds or 730 kilograms. At the heart of CM-1, the double rack houses the Experiment Package (EP), which contains the 90-liter combustion chamber, the gas chromatograph, and seven cameras. The EP chamber slide rails and quick disconnects enable the crew to insert and connect the EMS for each investigation. Also housed in the double rack are experiment computers and support equipment, including the Video Interface Package (VIP), the Diagnostic Processor Package (DPP), the Dedicated Experiment Processor Package (DEPP), the Exhaust Vent Package (EVP), the Power Distribution Package (PDP), the Experiment Power Switch Panel (EPSP), and the Remote Acquisition Unit (RAU). The single rack contains the Video Cassette Recorder Package (VCRP) and the Fluid Supply Package (FSP). The FSP contains 20 bottled gases and supplies gas for combustion, combustion chamber purges, soot sampler actuation, chemical diagnostics, on-orbit system leak tests, and pure air in the combustion chamber for science and crew access. For SOFBALL, 14 bottles

contain a range of premixed gases consisting of oxygen, hydrogen fuel, and a diluent. For LSP, two bottles contain the propane and ethylene fuels, and another bottle provides the pure air. The last three bottles are used for other functions listed above. All waste gases flow through the EVP and are vented overboard using the Spacelab vacuum vent system. The two EMS units will be launched in the Spacelab center aisle stowage containers. The main components of the LSP EMS are a fuel nozzle, a hot wire ignitor, temperature sensors, a radiometer, and soot samplers. The SOFBALL EMS main components include a variable gap spark ignitor, radiometers, and a mixing fan.

### **Commercial Generic Bioprocessing Apparatus (CGBA)**

(STS-50, 73) Bioserve

The CGBA is a multi-purpose facility that allows scientists to study biological processes in samples ranging from molecules to small organisms. The CGBA payload replaces a standard middeck locker, which can be flown in the Space Shuttle middeck, Spacelab, or in Spacehab. Samples are contained in a Fluid Processing Apparatus (FPA), a device that is essentially a “microgravity test tube.” An FPA is a multi-chambered glass barrel that allows sequential mixing of three fluids. Eight FPAs are housed in a Group Activation Pack (GAP). The CGBA locker provides a uniformly temperature-controlled (37 °C) volume for nine GAPs, data acquisition and control electronics, and optical density measurement capabilities (565 nm) for up to eight FPAs at a time. GAPs also can be stored at ambient temperature in middeck lockers or in the Spacelab module. The CGBA locker and its samples can be loaded as late as 18 hours before launch to maximize viability of the biological samples. Bioprocessing reactions can be initiated using predetermined mixing protocols. Multiple-step reactions involving sequential mixing of fluids are possible for phased processing. Simple optical monitoring of turbidity changes is possible. This capability is a major innovation in the study of biological processes in space. A crewmember can activate experiments by turning a crank on the GAP, thereby initiating the first fluid mixing process. Later in a mission, experiments can be terminated in a similar fashion. Some samples can be monitored for brief periods repeatedly throughout the mission. Both data taken on orbit and the returned samples provide the basis for experimental analyses.

### **Commercial Refrigerator/Incubator Module (CRIM)**

(STS-50, 83/94) Space Industries, Inc.

CRIM temperatures can be programmed before launch. The temperatures are monitored during flight by a feedback loop. Developed by Space Industries, Inc. for the Center for Macromolecular Crystallography (now the Center for Biophysical Sciences and Engineering, Birmingham, Alabama), it provides improved thermal capability and has a microprocessor that uses “fuzzy logic” (a branch of artificial intelligence) to control and monitor the CRIM’s thermal environment. A thermoelectric device is used to electronically “pump” heat in or out of the CRIM.

### **Confined Helium Experiment (CHeX)**

(STS-87) Stanford University

The CHeX hardware is composed of several main components. The container for the instrument is a double-walled facility called a dewar, which is covered on the outside by a magnetic shield. The double walls provide a vacuum between the outside and inside walls for thermal isolation of the instrument. The research instrument is surrounded with a protective metal shroud and contains the very heart of the experiment, the cylindrical sample container (the calorimeter). Thermal controls and heater feedback systems, located in the instrument, regulate the temperature of the calorimeter sample to better than a billionth of a degree over several days. In space, the experiment is controlled by its on-board computer, and data from the experiment is routed to the investigator team on the ground. The CHeX experiment is extremely sensitive to environmental changes, so the most “quiet” times of Shuttle orbits will be used for collecting the most sensitive science data.

### **Contamination Monitor**

(STS-3) NASA

The Contamination Monitor Package (CMP) measured mass accretion emanating from sources on and around the OSS-1/STS-3 pallet. Quartz crystal microbalances (QCM) viewed orthogonally in three directions and measured the accumulated mass of molecular and gas contaminant. They were not affected by particulate contaminants. Correlation studies of the data obtained here with those from other pallet instruments were undertaken. Two monitor mirrors were mounted on the front face of this CMP, and were coated with magnesium fluoride over aluminum, a material commonly used for optics in ultraviolet instruments. The mirrors' UV reflectivity was measured prior to and after flight.

### **Continual Flow Electrophoresis System (CFES)**

(STS-7) McDonnell Douglas Astronautics Co.

In continuous flow electrophoresis (CFE) a stream of sample material is continuously put into a rectangular chamber filled with a flowing buffer solution, or carrier fluid, across which an electrical field is applied. The experimental setup consisted of a cooled separation unit, an experiment control and monitoring unit, and a small refrigerator for sample storage. The separation unit was larger than its corresponding ground-based laboratory version, allowing for increased volume sample separation. Samples entered the lexan separation chamber through a thin-walled glass tube. All fractioned samples and carrier buffer were isolated and exited the separation chamber through an array of 197 tygon tubes. Individual samples were collected and stored in vinyl receptacles within the collection cassettes. Samples consisted of (NASA) (1) a mixture of three different sizes of polystyrene latex particles with a total latex concentration of 5.0% and a conductivity of  $155 \pm 5$  micro-mhos/cm and (2) a mixture of three different sizes of polystyrene latex particles with a total latex concentration of 5% and a conductivity of  $455 \pm$  micro-mhos/cm. (McDonnell Douglas) The four samples were of proprietary tissue culture media with solution concentrations of 7.3%, 10%, and 25% (two samples)

### **Coronal Helium Abundance Spacelab Experiment (CHASE)**

(STS-51F) ESA

The instrumentation is composed of a 1-m, grazing-incidence spectrometer using a 1200-line/mm ruled grating. The sun's image is focused onto the entrance slit plane by means of a 28-cm focal length, grazing-incidence telescope of Wolter type-1 sector design. The slit is oriented tangentially to the solar limb, and can be stepped radially in steps of 1 arc-min from a position on the solar disk to 8 arc-min above the limb by a servo-driven linear traverse on the telescope mirror. Twelve channel electron multipliers are positioned behind different exit slits at pre-selected spectral positions on the Rowland circle. Two positions are at 121.6 nm and 30.4 nm (for H/He abundances). The other slits cover associated parameters, such as the temperature and density of the solar atmosphere. Some slits have attenuating filters for dynamic range of the ratio of the disk intensity to that of the corona at the distance of  $3.5E5$  km. Filters are removed for limb measurements. A small oscillatory rotation of the grating about an axis through the entrance slit permits a small wavelength scan to discriminate against scattered stray light. An auxiliary instrument monitors changes in He II 30.4 nm intensity caused by atmospheric absorption effects resulting from spacecraft height or changes of line of sight to the sun. A zero-order detector monitors the solar limb crossings and gives data on short-term intensity variations in stars for wavelengths shorter than 140 nm. Signals are counted, multiplexed, and interfaced with the Spacelab telemetry system for transmission to the ground. The pointing accuracy is 15 arc-s and the pointing stability is 5 arc-s. Experiment mass: 160 kg; average experiment power: 80 W

## **Cosmic Radiation Experiment Package**

(STS-55) ESA

The Cosmic Radiation Experiments on the Spacelab D-2 mission consisted of detectors worn by the astronauts and detectors near biological specimens (such as plant seeds, insect eggs, and bacterial spores) placed in stacks of trays called biostacks. The experiments were designed to assess the biological effects of specific cosmic radiation and to assist in reducing the health risks for future human space explorations. The experiments consisted of: (1) Biological HZE-Particle Dosimetry with Biostacks; (2) Personal Dosimetry: Measurement of the Astronaut's Ionizing Radiation Exposure; (3) Measurement of the Radiation Environment Inside Spacelab at Locations Which Differ in Shielding Against Cosmic Radiation; (4) Chromosome Aberration; (5) Biological Response to Extraterrestrial Solar UV Radiation and Space Vacuum.

## **Cosmic Ray Nuclei Experiment (CNRE)**

(STS-51F) NASA

The objective of this investigation is to make a precise determination of the charge composition and individual energy spectra of cosmic ray nuclei from lithium to iron, covering the energy range from 50 to 2000 GeV/nucleon. The investigation exposes to deep space an instrument of large volume and considerable mass for an extended time period (without the influence of an overlying atmosphere). The instrument for charge composition is a telescope of two plastic scintillators; for the energy measurements, two gas Cerenkov counters covering the range from 50 to 150 GeV/nucleon and a transition radiation detector system for the region from 400 to 2000 GeV/nucleon are used. The detector elements are contained in a cylindrical pressurized shell with hemispherical top and bottom covers (2.8 m in diameter with a maximum height of 3.7 m). All detector elements comprise areas of 2 x 2 m. The transition radiation detector consists of six radiators (with a total of 10,000 plastic foils of 5-micrometer thickness) and six xenon-filled multiwire proportional chambers, and is positioned in the center of the instrument. One scintillator is adjacent to each end, and housed in a light integration box. The two gas Cerenkov counters fill the remaining space between the scintillators and hemispherical lids of the pressurized container. They are filled with gases at atmospheric pressure, and the inner walls are coated with white, highly reflective paint. There is a geometric factor of 5 sq m-sr for the transition detector and 1 sq m-sr for the Cerenkov counter telescope. To detect the light of an incident particle, 24 photomultiplier tubes with photocathodes 12.7 cm in diameter are used. Fast 5.08-cm photomultipliers are coupled directly to the scintillators, which are used for time delays between responses recorded by each scintillator; particles must penetrate both. Cerenkov radiation is detected by 50 photomultipliers with 12.7-cm windows. An electronics package collects the information from the various sensors and formats it for ground transmission. Experiment mass: 1784 kg; average experiment power: 231 W

## **Critical Fluid Light Scattering Experiment (CFLS-Zeno)**

(STS-62, 75) University of Maryland

The Zeno instrument was built by Ball Aerospace of Boulder, Colorado, for the Institute for Physical Science and Technology at the University of Maryland, College Park, and is contained within two flight modules. The electronics module contains the power-and signal-conditioning circuitry, the communications capability, the correlator, and the computer. This module is mounted on a cold plate for thermal control. The computer controls all data-gathering and analysis functions. The system supports near-real-time communications (both up-and downlink) to the payload operations center through the carrier and shuttle computers. Both autonomous and programmable operation is possible. The optics module contains the optics bench, which holds the primary components of the light-scattering system: laser light source, beam-direction optics, shutters, mirrors and lenses, photocells (for measuring transmitted light to determine turbidity), photomultipliers (for photon counting of scattered light), and the sample cell/thermostat

assembly. All optics components are mounted in nonadjustable hard mounts for thermal and mechanical stability. The more sensitive analog electronic components are mounted in the optics module for added thermal stability, and all high-voltage supplies are mounted near the subsystems they power. The optics module is radiatively cooled by using the top and the out-facing side as integral radiators. Surface heaters help control the internal temperature to within plus or minus 1 K, and the large mass of the optics module box acts as a thermal sink to stabilize the controlled environment. In addition, the heat sources (including laser and photomultipliers) and the thermostat are thermally isolated from the optics bench to better ensure a stable platform for optical alignment.

### **Critical Point Facility (CPF)**

(STS-42, 65) ESA

ESA's CPF is a multi-user facility to investigate near critical point phenomena in transparent fluids under well-defined conditions. The Critical Point Facility consists of an experiment subunit connected to an electronics module, which included the electric power supply (28 V DC), electronics and microprocessors. The experiment unit accommodates the following: an exchangeable thermostat containing the experiment-dedicated fluid cell; different stimuli: thermal (i.e. heating, cooling, quenching) and acoustic stirring; diagnostics (thermal, optical). Several thermostats dedicated to specific experiments can be carried on board for in-orbit exchange so that several experiments (typically four) can be conducted during one mission. The CPF thermostats house one or two test cells that hold sample fluids, and maintain a sample at a precise, stable, and homogeneous temperature (better than 0.0001 K). The facility also quenches samples, cooling them quickly, and provides electrical stimulation, stirring, pressure measurement, and local heating within the fluid sample. The samples are monitored continuously by direct observations via downlinked video images; scattering of laser light at angles ranging from very small ones to 90 degrees; interferometry, which shows the local fluid density changes in various parts of the cell; and turbidity, the transparency of the fluid. Real-time video is available to investigators on the ground along with digitized video snapshots, at 6-second intervals, of the phenomena in progress. Although CPF experiments run automatically, investigators working on the ground can send remote commands to modify their experiments in real time.

### **Cryostat**

(STS-9, 42, 55) DARA

The Cryostat provides a temperature-controlled environment for growing protein crystals by liquid diffusion under two different thermal conditions. The facility can operate in either the stabilizer mode with a constant temperature between 59 and 77 degrees Fahrenheit or the freezer mode where temperatures can be varied from 17.6 to 77 degrees Fahrenheit. Temperatures are controlled by preprogrammed commands, but the crew members can reprogram the computer if necessary. When the experiments are started, solutions of a protein, a salt and a buffer mix via diffusion to initiate crystal growth.

### **Crystal Growth Furnace (CGF)**

(STS-50, 73) NASA

On STS-50, the Crystal Growth Furnace processed samples at temperatures above 2,300 degrees Fahrenheit (approximately 1,300 degrees Centigrade). This reusable equipment will help scientists investigate the different factors affecting crystal growth and explore the best methods to produce better crystals. Four experiments to be conducted in the Crystal Growth Furnace will result in crystals grown from different materials: cadmium telluride, mercury zinc telluride, gallium arsenide and mercury cadmium telluride.

Also flown on STS-73, the CGF is the first space furnace capable of processing multiple large samples at temperatures up to 1800F (1350C). The CGF consists of three major subsystems: the Integrated Furnace Experiment Assembly (IFEA), the Avionics Subsystem and the Environmental Control System (ECS).

The IFEA houses a Reconfigurable Furnace Module (RFM) — a modified Bridgman-Stockbarger furnace with five controlled heating zones — a Sample Exchange Mechanism capable of holding and positioning up to six samples for processing and a Furnace Translation System which moves the furnace over each sample. Sample material is contained in quartz ampoules mounted in containment cartridges. Thermocouples mounted in each cartridge provide temperature data. The Avionics Subsystem monitors and controls the CGF experiments and provides the interface with the Spacelab data system. The ECS maintains and controls the argon processing atmosphere inside the IFEA and provides cooling to the outer shell of the furnace through connections to Spacelab Mission Peculiar Equipment (MPE) fluid loop.

### **Crystallization Observation System (COS)**

(STS-83/94) CBSE

MSL-1 carried new Protein Crystal Growth (PCG) hardware, including the Crystallization Observation System (COS), and the Advanced Crystallization Observation System (A/COS). The COS and A/COS will increase understanding of the crystal growth process by allowing scientists to monitor the crystal growth in each chamber of the experiment apparatus. The COS consists of a specially designed VDA tray with six chambers, a video camera for each chamber, a lighting system, and associated hardware. By observing the crystal growth in each chamber, researchers can identify which conditions and concentrations of proteins and precipitants are best for promoting the crystal growth of a particular protein. The A/COS provides a similar function, incorporating a moveable camera to view 20-chamber VDA trays.

### **Data Acquisition System (DAS)**

(STS-71) NASA

The Data Acquisition System (DAS) is a custom-designed flight data system for use during biomedical experiments, such as LBNP studies, that require access to the Spacelab telemetry stream. The DAS converts the analog signals from the LBNP Controller into digital data, and puts the information into a serial data format compatible with the Spacelab High Rate Multiplexer (HRM). The DAS employs parallel processing technology, and consists of analog signal processing circuitry, a network of analog-to-digital converters, a single-board computer, and a custom-designed interface board with an imbedded processor and special output drivers that send the digital data to the Spacelab HRM. The entire system fits into a compact enclosure measuring 13 x 7.5 x 5.5 inches. The DAS also conditions the analog signals and routes them to a redundant low-rate data system called the Remote Acquisition Unit (RAU). The RAU provides a user time-clock signal to the DAS for data synchronization. Both high- and low-rate data streams are multiplexed into the Orbiter's telemetry system for downlink via the S-band (low-rate) and Ku-band (high-rate) transmitters, and routed to flight surgeons and scientists monitoring the test on the ground.

### **DC and Low Frequency Vector Magnetometer**

(STS-9) ESA

The experiment objectives were to use a three-axis fluxgate magnetometer to study (1) magnetic fields of the ionospheric polar electrojet and its return current, equatorial electrojet, and the solar quiet current, (2) the vector magnetic field as a plasma parameter, and (3) the Spacelab magnetic field background. The equipment consisted of two separate three-axis fluxgate sensors.

### **Diffusion Controlled Crystallization Apparatus for Microgravity (DCAM)**

(STS-73) NASA

This experiment uses liquid/liquid and dialysis methods in which a precipitant solution diffuses into a bulk solution. Each DCAM unit is about the size of a 35mm film can. It has 2 chambers joined by a tunnel. The first cylinder contains the dissolved protein and the second larger chamber holds the precipitant solution.

The 2 chambers are joined by a plug which controls the rate of diffusion. There are no mechanical parts and diffusion starts as soon as the chambers are filled, but at a very slow rate so that crystals do not form during the launch stage. Because of the long time needed DCAM has been used on the longer Mir missions. A normal configuration contains 162 DCAM units mounted in a 3 X 9 array on six trays.

### **Droplet Combustion Experiment (DCE) Apparatus**

(STS-83/94) NASA

The Droplet Combustion Experiment Apparatus (DCE) is an enclosed chamber into which controlled helium-oxygen atmospheres are injected and in which single heptane droplets are burned. The initial droplet diameters range from 1 mm to 5 mm. A droplet will be formed by injecting the fuel through two opposed injectors. The injectors then will be retracted slightly to stabilize the droplet and rapidly removed to deploy the droplet in the field of view of the optical measurement apparatus. Two hot-wire igniters will be brought near the droplet from opposite sides to ignite the flame while providing minimum disturbance to the droplet. After ignition, the igniters will be retracted, and the droplet and its flame will be observed as combustion occurs in the selected atmosphere, away from disturbing influences of walls. Besides recording of temperatures and pressures, there will be backlit droplet views, ultraviolet flame views, camcorder observation, and visual and still-camera photographic observations through different optical ports in the chamber.

*Hardware Subsystems:* the experiment module, the avionics module, and the diagnostics subsystem. The experiment module contains the combustion chamber with provisions to mount the environment gas supply bottles, vent system plumbing to remove the burnt gases, camcorder mounting system, and a crew view port. The heart of the experiment module is the Internal Apparatus (IA). IA contains the droplet deployment and ignition mechanisms which are controlled by onboard microprocessors. The combustion chamber pressure and temperature are recorded during an experiment. The diagnostic subsystem consists of a 35 mm film camera running at 80 frames per second, a UV-sensitive intensified-array camera which captures the radiant emission from excited OH radicals at 310 nm wavelength and a camcorder which is used to monitor the experiment progress. The camcorder and the UV-flame views could be down-linked for examination by the investigators during the mission. The crew view port could also be used to obtain still, color camera pictures of the flame by the crew as needed. The avionics module houses the electronic power supply and control boards. The key components of the avionics module could be replaced on-orbit by the crew member, in case of a failure. There are 21 high pressure, premixed gas supply bottles containing predetermined Oxygen/Helium mixtures that are used to fill the combustion chamber according to DCE test matrix specifications.

### **Dissecting Microscope**

(STS-47) NASA

The Dissecting Microscope supports general life sciences experiments requiring capabilities such as examination, dissection, and image recording of tissues and other specimens. It is a modular unit that supports inflight dissections and is stowed when not in use. During operations, it is deployed in the General Purpose Work Station and secured using Velcro. It has image recording capabilities as well as a fiber optic lighting system. Magnification is continuously variable from 8x to 64x.

*Zeiss Stereomicroscope, Model SV 8:* The microscope features a continuously variable zoom of 8–64 X magnification. It includes an adapter to accommodate a video camera.

*Video Camera:* The video camera records images during inflight experiment operations, which can be downlinked in real time.

*Video Interface Unit (VIU):* The VIU supplies power to the video camera and converts the Spacelab-provided video synchronization signal from balanced to single-ended format for use by the camera. Addi-

tionally, the VIU simultaneously converts the video output of the camera to a balanced, differential output for recorders and downlink.

*Dissecting Microscope Lighting System:* The lighting system provides the incident lighting required for viewing through a bifurcated fiberoptic bundle. A cooling system, prime and backup 160 W halogen lamps, and protective inlet and outlet screens are included.

### **DOSIMTR (Dosimetric Mapping Inside Biorack)**

(STS-42) ESA

Eight track-detector stacks (Dos 1 to Dos 8) flown inside Biorack Type I containers were used for the measurements. Dosimetric stacks, each with 20 to 100 sheets of plastic detector foils (cellulose nitrate, Lexan, and CR 39) and nuclear emulsions of different radiation sensitivity are packed inside aluminum containers with 1-mm (0.04 in.) walls, together with Thermoluminescence dosimeters (TLDs). Each detector set consisted of up to 200 detector layers, each of thickness between 0.1 and 0.6 millimeters. Chips of LiF detectors were welded between two polyethylene foils which formed the top and bottom layers of the detector stacks. They are placed in different parts of Biorack, with two of the stacks placed in a 37 deg Celsius incubator, four in a 36 deg incubator (two of which were placed on a 1-g centrifuge), and two of the stacks in a stowage position at ambient temperature. After the mission, particle hits recorded by the dosimeters are measured to reveal absorbed doses from medium-energy neutrons up to about 1 million electron volts. The plastic detectors are developed like photographic emulsions, and particle tracks can then be seen under a microscope.

### **Drop Dynamics Module**

(STS-51B) NASA

The module consists of an acoustical chamber with three sources that generate, in three different directions, sound waves of variable frequency and amplitude. The sound waves will be used to rotate and oscillate water and silicone drops and to position the drops in a field of view. Detailed objectives of the rotation experiment are to determine (1) bifurcation points, (2) instability at bifurcation points, (3) hysteresis of bifurcation points, (4) equilibrium shapes of drops, and (5) oscillations of the rotating drops. Objectives concerning oscillations of rotating drops are to determine (1) frequency of large-amplitude oscillations, (2) damping of large-amplitude oscillations, (3) shaping of these oscillations, (4) mode coupling in oscillations, and (5) effect of turbulent flow on relationships between amplitude and frequency/damping of a mode. This equipment was refined, and later flew as the **Drop Physics Module**.

### **Drop Physics Module**

(STS-50, 73) NASA

The Drop Physics Module has been developed so scientists can study several fluid physics phenomena. A crewmember conducts all experiment in the Drop Physics Module by directly selecting commands from menus on the two video displays or by selecting a sequence of preprogrammed commands. The crewmember monitors the response of the drop on an adjacent video display, choosing one of two views of the drop. All selections are made through a novel integrated video menu display/infrared touch grid. Liquid samples deployed into the rectangular experiment chamber are positioned by the sound waves so that film and video cameras can record the liquid's behavior. Small particles, mixed before the flight with most of the fluids, make the fluid motion inside the drop visible. The crewmember operating the experiment may manipulate the sound waves in the experiment chamber so that the sample is rotated, oscillated, or moved in some other way.

### **Dual Energy X-ray Absorptiometry (DEXA)**

(STS-71, 78) NASA

Dual Energy X-ray Absorptiometry (DEXA) is a noninvasive technique that employs low dose radiation to measure bone, fat and lean tissue composition. DEXA is used in clinical applications to determine bone mineral content in the skeletal system, particularly the lumbar spine and hips. A DEXA unit consists of a whole-body scanner frame, an x-ray source and detector, and a control computer. The subject is positioned on top of the scanner frame, in a supine position. The scanner moves above and below the subject, along the scanner frame. The method is based on measurements of the attenuation coefficients of different radiation energies through a medium consisting primarily of two materials, bone and soft tissue. The dual energy method employs both high and low energy x-ray beams. By comparing the absorption of the low and high energy x-rays, the contribution of soft tissue can be identified, and eliminated for bone measurements. This allows for accurate measurements of bone mineral content (BMC) and bone mineral density (BMD) even in areas where the amount of soft tissue can be large and variable, such as the hip or spine.

### **Dynamic Augmentation Experiment (DAE)**

(STS-41D) NASA

See: **Solar Cell Calibration Facility (SCCF).**

### **Dynamic Cell Culture System (DCCS)**

(STS-42) Space Biology Group, Zurich, Switzerland

The dynamic cell culture system (DCCS) was developed by the Space Biology Group and manufactured by Contraves AG. The DCCS consisted in principle of an osmotic pump with a reservoir volume of 230 microl and a flow rate of 1 microl/h at 37degC. A polyvinylchloride tubing serving as medium reservoir (360 microl). A stopcock that allows to turn on and off the medium flow. A perfusion and a batch cell chamber with a volume of 200 microl each, closed by a glass inspection-window. The system can operate completely unattended for a period of 7 to 14 days, depending on the cell type, pump model and culture conditions. 26 Hours before launch, the culture chambers of the DCCS were filled with the cell culture (105 cells/ml) and the osmotic pump with the medium reservoir were placed into the DCCS. An osmotic pump automatically supplies fresh nutrients needed for cell production. The osmotic pump, a rubber container, is gradually squeezed empty of cultural medium by osmotic pressure. As culture nutrients flow into the cell container, old medium is forced out. The cultures in the DCCS were equilibrated for 2 hours in a 5% CO<sub>2</sub> atmosphere at 37degC before the units were sealed and inserted into the type I containers. Two Dynamic Cell Culture Systems fit in each of four Biorack Type I containers. The containers were stored at room temperature until activation in space. Each system has a 0.2-ml (0.006-oz) culture chamber with a window. The cell chamber contains Syrian hamster kidney cells and microcarriers consisting of collagen-coated, dextran beads, used as the growing surface. Two containers were incubated in microgravity and 2 on the 1 g reference centrifuge at 37degC. After 7 days of incubation the pump was shut off and the containers stored at room temperature for 30 hours until recovery. The system is designed to operate automatically for 2 weeks.

### **Dynamic Environment Measuring System (DEMS)**

(STS-51B) NASA

The Dynamic Environment Measuring System (DEMS) is an instrumentation package that monitors and records Spacelab vibration, acoustics, and acceleration levels during launch and reentry. Data are used to monitor the stimuli various biological systems experience under launch and reentry loads. A microphone, a triaxial-vibration sensor unit, and a triaxial-accelerometer unit function, respectively, as the acoustic, vibration, and acceleration transducers. One other device, the DEMS MET (Mission Elapsed Time) Slow

Code Generator, converts the orbiter's pulse width modulated time code (100 Hz) to an amplitude modulated "slow code" (10 Hz) which is recorded by the DEMS tape recorder. The DEMS Signal Conditioner passes only certain frequency ranges from the sensors to the recorder. The axes and frequency ranges of the various signals are as follows:

Acceleration: X,Y, and Z axes, low frequency only (DC-20 Hz) for three unique signals.

Vibration: X,Y, and Z axes, low and high frequencies (20-160 Hz, 50-2,000 Hz) for six unique signals.

Acoustics: low and high frequencies (20-160 Hz, 50-6,000 Hz) for two unique signals.

MET Slow Code: low frequency (10 Hz) for one unique signal.

During launch and reentry, the DEMS cassette recorder collects the signal on two cassette tapes, seven tracks per tape (the eight channel is not used). The twelve DEMS signals are distributed on the two cassette tapes within the DEMS; X-acceleration and MET signals are recorded on both tapes to help synchronize the two separate groups of data. The DEMS is designed to activate automatically at launch and reentry, but can also be manually controlled. Once activated, the DEMS records data automatically for ninety minutes. The DEMS, located in Spacelab rack 7 adjacent to the RAHF, measured three-axis vibration, three axis acceleration, and acoustic noise levels. The unit was turned on by manual switch activation by the crew in the aft-flight deck prior to launch. Recorded tapes of the ascent were removed by the crew during orbit and exchanged with new tapes to record conditions associated with reentry and landing. For data reduction, digital information on the tapes was decoded using a special cassette playback unit. The output of the cassette unit was fed, one cassette at a time, into a 14-track recorder. Along with the MET pulses, the most apparent and readable signals were acceleration values with respect to the gravity vector: the X-acceleration at launch (Shuttle length) and the Z-acceleration at descent (Shuttle height). DEMS information was correlated with reactions of the animals and performance of the hardware.

### **Dynamic Posturography System**

(STS-71) NASA

The Dynamic Posturography System is based on a posture platform, which tilts up or down to create a postural disturbance as a subject stands on it. A microcomputer controls the movement of the platform. As the subject reacts to maintain balance, data can be recorded from the muscles and other parts of the body. The EquiTest Dynamic Posturography System Version 4.0 (NeuroCom International, Clackamas, Oregon), used by clinicians for the assessment of disorders of balance, was modified for NASA use. The following features were added to the commercial system: (1) an electromyography (EMG) system for monitoring activity in the 4 major weight-bearing muscle groups in the left leg, (2) sway bars for monitoring the anterior-posterior movement of the hips and shoulders and (3) a head set with sensors for monitoring the head's angular velocity in the pitch and roll planes, and headphones for providing pink noise to block external auditory cues. Force transducers provided data used to compute the location of the instantaneous anterior-posterior center of mass. The subject stood in stocking feet on a dual foot plate capable of tilting and shifting, inside a visual surround capable of tilting. The visual surround completely filled the subject's visual field. The foot plate and visual surround were tilted forward or backward by servomotors about an axis through the subject's ankles. The maximum tilt angle was  $\pm 10$  degrees. The subject wore a safety harness fastened to two suspension rings mounted to a safety bar during the testing procedures, to prevent falling. Force transducers mounted beneath the foot plate were used to measure the vertical and horizontal forces exerted by the subject's feet under the force of gravity.

Position of the center of force was used as an estimate of the sway of the body's center of mass. Anterior-posterior position and displacement were measured using a sway bar and potentiometer at the pelvis (center of mass) and shoulder. Rate sensors monitored head movements. While sensory organization tests were

conducted during the experiment, either the support surface or the visual surround, or both simultaneously, could be tilted in proportion to the postural sway of the subject as estimated by the subject's center of force. Data from the force transducers (50-hertz sampling rate) were digitized with 12-bit accuracy and stored in a digital computer for subsequent analysis. This computer system was used to control all aspects of the experiment protocols, including data acquisition and storage, support surface and visual surround servomotor commands, data reduction and analysis and operational displays.

### **Echocardiograph**

(STS-40) NASA

The echocardiograph uses ultrasound, computer image processing, and data storage to generate a two-dimensional real-time video display of the heart. The LSLE echocardiograph is a Hewlett-Packard 77020A Echocardiograph specially modified for flight. The echocardiograph incorporates an operator video display image processor unit, a digital scan converter, video recorder, and a telemetry downlink interface. In addition to the Hewlett-Packard unit, another echocardiograph was also flown to serve as a backup. This unit, called the American Flight Echocardiograph, is a ADR 5000 portable echocardiograph unit.

### **EGGS (Establishment of the Dorso-Ventral Axis Amphibian Embryos)**

(STS-42) ESA

The equipment consisted of six Automatic Experiment Containers (AEC) (79.5 x 19.0 x 33.1 mm) each of which consisted of six compartments that were able to interchange contents through use of an automatic plunger system. The compartments contained one of the following: 0.7 ml full strength MMR (a solution of 100 mM NaCl, 2 mM KCl, 1 mM MgSO<sub>4</sub>, 2 mM CaCl<sub>2</sub>, 5 mM Na-Herpes buffer, 0.1 mM EDTA, and 230 m Osmolarity, pH 7.8) with one testis; 1.5 ml 10% MMR; 0.6 ml 10% MMR; 2.0 ml 25% MMR; 0.24ml 25% MMR, with 7% glutaraldehyde; and 0.9 ml full strength MMR with 2 groups of 15 eggs each from two different females. Upon activation, the six containers were transferred from the 10 degree Celsius middeck locker to the 22 degree incubator, four on the static rack and two on one of the 1-g centrifuges. The plunger system then, at various intervals, caused the contents to be automatically fertilized and then fixed. Embryos from two different females in each of the two static containers and in one AEC on the 1g centrifuge were fixed at the time at which gastrulation would be expected to occur on Earth, under similar conditions.

### **Electromagnetic Levitator (EML)**

(STS-61C) NASA

Six samples will be suspended in the electromagnetic field of a cusp coil and melted by induction heating from the coil's electromagnetic field.

### **Electromyograph (EMG)**

(STS-40, 47, 58, 71, 78, 90) NASA

An electromyograph (EMG) graphically records the electrical activity of muscles. Normal muscle is electrically silent when at rest, but when it is active, as during contraction or stimulation, an electrical current is generated. The successive action potentials are measured through surface electrodes that are connected to a signal amplifier and recording device.

For the STS-71 mission, the following hardware was used with the EMG. The Belt Pack Amplification System (BPAS) Vest Kit contains a vest assembly, electromyogram (EMG) electrodes, a preamplifier electrode adapter cable assembly, the BPAS power supply, BPAS battery cable assembly, BPAS data cable assembly, an Accelerometer Glove, and the BPAS signal conditioner and amplifier. The BPAS vest assembly

is composed of royal blue Nomex material. Two strips of elastic, encased within layers of Nomex, are used for proper fit around a crewmember's waist. Stainless steel snaps are used for proper fit of the shoulder straps on the crewmember. Velcro hook and pile attached to Nomex straps are used to secure the rear section of the vest to the front. Teflon windows (quantity = 4) are used to contain paper labels for proper labeling. A plastic (polypropylene) buckle is used to attach a strap at the waist. The BPAS power supply provides a maximum of +15 Vdc to operate the BPAS. The battery pack contained inside the power supply consists of ten 1.2 volt, 1500 mA-hour Nickel-metal Hydride batteries, constructed of sealed steel cases, encased in Teflon tape. Two items, a thermostat and "polyswitch" are soldered in series to provide two-fault tolerance during charging and discharging. The thermostat is hermetically sealed, and is set to disengage the circuit if the batteries reach a temperature of 45 degrees Celsius. The power supply will provide power to the BPAS for a maximum of 2.5 hours. The power supply will interface with the Universal Battery Charger for charging using the UBC Charger Cable located inside the Postural Kit; the charging procedure will take a maximum of 3 hours to perform, depending upon amount of discharge. EMG electrodes are sensor used to measure the surface potential at the skin surface and amplify the signal ( $G=350$ ); frequency response is 10 Hz to 10 KHz. The electrode housing is composed of Nylon 6/6 with carbon additive. The accelerometer cable is 2 meters in length, encased in a Teflon jacket. The cable connector, which attaches to channel 8 of the BPAS Signal Conditioner and Amplifier, is a 7-pin Microtech EP-7S-1 connector. The BPAS Battery Cable Assembly connects the BPAS Signal Conditioner to the BPAS power supply. The connectors used are two 6-pin Lemo connectors, P/N Fgg.1B.306.CLYD52. The cable length is 0.25 meters. The cable is encased in a Teflon jacket. The BPAS Data Cable Assembly connects the BPAS signal conditioner to the TEAC Data Recorder. The connectors used are a 15-pin D-subminiature (male) and 24-pin Amphenol connector, P/N 57-33240-1. The cable length is 0.5 meters. The cable is encased in a Teflon jacket. The Accelerometer Glove consists of a wrist splint (glove) with an accelerometer mounting cube attached by a small aluminum plate. One K-Beam Accelerometer is mounted on the mounting cube. The accelerometer data is obtained by placing an accelerometer, which is attached to the glove, on the right wrist, then raising and lowering the glove. The signal passes to the BPAS unit, which amplifies and conditions the signal. The BPAS signal conditioner and amplifier is used to configure EMG signals, voice and accelerometer data into a format which may be used for ground-based analysis following the Mir mission. The unit is composed of aluminum alloy with clear anodize. The front panel is black anodized. The unit contains one accelerometer circuit board, seven active EMG amplifier/filter circuit boards, and one spare non-active EMG circuit board. All boards, which are 0.62 inches thick and comprised of glass-filled epoxy, are conformably coated and chassis-isolated.

### **Electronics Control Assembly (ECA)**

(STS-40, 58, 78, 90) NASA

The Astronaut Lung Function Experiment (ALFE) Electronics Control Assembly (ECA) has three major functions: experiment control, signal processing, and data interfacing. The ECA was rack-mounted above the Bag-in-Box Assembly. All solenoid valves were operated by switches on the front panel. In normal operation, they were in the "AUTO" position and under control of a microcomputer. The ECA has a calculator-style keypad to allow data entry and procedure control and has an alphanumeric display. All prompts to the crewmembers appeared on the display. Above the alphanumeric display was a bar graph display providing a visual feedback for the gas flow.

### **Electrophysiological Tape Recorder**

(STS-9) Clinical Research Center, Harrow, England

The experiment objective was to study acclimatization of astronauts to zero gravity by means of electrocardiograms (ECG), electroencephalograms (EEG), and electro-oculograms (EOG) obtained before launch,

throughout the mission, and after the flight. The equipment was a standard Oxford Instruments Medilog four-channel tape recorder with electrodes, spare batteries, and tape cassettes. The recorder was attached to the belt of a crew member.

### **EMG Amplifier**

(STS-40) NASA

This hardware is used to measure activation of the tibialis anterior and gastrocnemius muscles during the drop session, electromyography was used. The device is an electrically-isolated amplifier specially modified for spaceflight. The EMG signals are amplified differentially and band-pass filtered between 50 and 350 Hz. The amplifier was built by the Denver Research Institute.

### **Enclosed Laminar Flames (ELF)**

(STS-87) NASA

The major hardware components are an experiment module, electrical cables, a control box, fuel bottles, and a set of ignitors. The ELF module is a miniature, fan-driven wind tunnel, equipped with a gas supply system. A small nozzle, located on the duct's flow axis, has a thermocouple at its outlet to indicate extinction of the flame. The air velocity is measured by a hot-element anemometer, and the fuel flow is set with a mass flow controller. The duct is also equipped with a temperature rake, containing silicon carbide fibers and thermocouples. It can be positioned by the astronaut so that temperature measurements can be made at appropriate flow conditions. A hot-wire ignitor is activated by a lever on the ELF module. The fuel flow, air velocity, rake position, fan voltage, and two temperatures are displayed for astronaut viewing on the module. Video imaging and data from the rake thermocouples is recorded by the MGBX video system. A second image of the flame will be recorded with a video camera through the top viewing window. During operations, the investigator team will monitor the downlinked data, so they can recommend appropriate conditions for subsequent tests. Having this capability will allow the ELF science team to further enhance the scientific return available after the combustion tests are conducted during USMP-4.

### **EXpedite the PROcessing of Experiments to Space Station (EXPRESS) Rack**

(STS-83/94) NASA

The EXpedite the PROcessing of Experiments to Space Station (EXPRESS) Rack is a Space Station International Standard Payload Rack (ISPR) being flown on MSL-1 as a precursor payload. The Spacelab program provides the structure and subsystem hardware to accommodate the EXPRESS Rack with interfaces like those on Space Station. The EXPRESS Rack provides standard and simple interfaces to payloads, thereby simplifying the integration process of payloads into the rack. The EXPRESS Rack accommodates payloads compatible with the Space Shuttle middeck, Spacehab, and Standard Interface Rack (SIR) drawers, developed by NASA's Life Sciences division. Eight single middeck lockers and two SIR drawers are provided by the EXPRESS Rack for payload use. The Physics of Hard Spheres Experiment (PHaSE) will be housed in four of the middeck lockers and one of the SIR drawers, demonstrating the accommodations for modular, as well as small, payloads. A double-locker payload, the Astro/Plant Generic Bioprocessing Apparatus (PGBA), will be located in the orbiter middeck for launch and relocated to the EXPRESS Rack for operations once on orbit, just as late access payloads will be during the Space Station era. The rack provides for resource distribution to and command and control of the payloads installed in it. It utilizes a Space Station program-provided ISPR, Avionics Air Assembly (AAA), and coldplates. The primary subsystems for the EXPRESS Rack are the AAA, the Solid State Power Controller Module (SSPCM), and the Rack Interface Controller (RIC). The AAA will provide avionics air cooling for payloads on Space Station. Payload exhaust heat will be drawn to the rear of the rack and passed across an air-to-water heat exchanger. The heat then will be transferred to the Spacelab Mission Peculiar Equipment water loop, and the conditioned air will

be returned to the Spacelab cabin. The SSPCM provides power distribution and protection to subsystems and payloads in the rack. The RIC provides the communication link between payloads and the Spacelab data system and ground controllers, mimicking the command and control link for the International Space Station. The RIC communicates with payloads via standard data protocols (RS232, RS422) and with the Space Shuttle-provided laptop via ethernet. The RIC will route the payload data in packets, with headers to identify the payload, and will transmit them through the Spacelab data system just as it will with the Space Station data system. The subsystems are coldplate cooled to preserve air cooling for payloads in the rack. Payload power and data connections for the SIR drawers are on the rear of each drawer so that when one is inserted into the rack the connectors will engage. Payload power, data, and water loop connections for the middeck locker payloads are made on their front faces by jumper cables that connect to the appropriate utilities on the EXPRESS Rack connector panels at either the top or mid-section of the rack. A Shuttle program-provided laptop computer will be attached to the rack on orbit, allowing crew control of the rack and its payloads. The EXPRESS payloads may be operated from the payload front panels, the rack front control panels, the EXPRESS Rack laptop, the Spacelab crew workstation, or the ground.

### **Experiment Assembly of Structures in Extravehicular Activity (EASE)**

(STS-61B) NASA

The Experiment Assembly of Structures in Extravehicular Activity (EASE) is a study of EVA dynamics and human factors in construction of structures in space. In the orbiter's payload bay, Ross and Spring will assemble and disassemble an inverted tetrahedron consisting of six 12-foot beams. They will connect two of the beams to simulate Space Station construction and manipulate the assembled beam using the foot restraint and the Remote Manipulator System.

### **Experiment Control Subsystem (ECS)**

(STS-90) NASA

The Experiment Control Subsystem (ECS), a component of the Visual and Vestibular Investigation System (VVIS), coordinates the actions of the other subsystems and controls and monitors the supervision of the Body Rotation Device (BRD) experiment by the LSLE Microcomputer II (LM2). The ECS contains electronic cards and a microprocessor, and communicates with other subsystems. The electronic rack is connected by a cable to a video monitor which displays the image of the eyes to the operator. Experiment runs are interpreted from protocol profiles uploaded by the LM2 to the ECS. The ECS also provides a video signal for downlink to the ground and provides experiment status information to the LM2. The major components to the ECS include the following.

*Electronic Rack (ECS Panel):* Switches on the front panel of the ECS electronic rack enable powering of the ECS and the Video Monitor. A switch to enable rotation is also on this panel as is a push button to stop the rotation without braking (slow stop). Light Emitting Diodes (LEDs) enable monitoring of the status of the various subsystems (ESS, BRD, EMRS, ECS, and VTRs). The two cables from the ECS Video Monitor are also connected to this panel. It weighs 17.762 kg (39.1 lb). The ECS panel has an operating power requirement of 42W and has a single 250V 3.15A fuse. There are two spares located on the ECS next to the active fuse. The REBO (see below) also contains an identical fuse which can be utilized as a spare, if necessary.

*Video Monitor (ECS VM):* The ECS Video Monitor is a screen monitor used by the Body Rotation Device (BRD) operator to monitor the subject's eyes during the experiment. It is connected to the ECS panel (L5K) via data and power cables and is mounted with a bracket assembly to a Spacelab rack during experiment operations. The bracket assembly allows placement of the monitor wherever convenient for the operator. In addition to contrast and brightness controls, the ECS VM has an Emergency Movement Stop pushbutton. Rotation is stopped when this button is pressed. Rotation remains disabled until the button is

pressed again. A Light Emitting Diode (LED) on the ECS VM lights a violet color to indicate this condition. Rotation is also disabled (and the LED is lit) if the ECS VM data cable is not completely engaged as the ECS senses this disconnect as a push of the Emergency Movement Stop pushbutton. An Emergency Equipment Shutdown pushbutton is also available on the ECS VM. Pressing this button stops chair rotation and shuts off power to both the ECS and BRD-RME. Crewmembers were instructed to use this button if an emergency egress of the Spacelab was required.

*Remote Box (REBO):* The REBO is used to control and monitor the Body Rotation Device (BRD), Eye Stimulation Subsystem (ESS), and Eye Stimulation and Movement Recording Subsystem (EMRS) only in the event of a failure in the ECS computer or the LM2. The REBO functions as a backup unit to the ECS or the LM2. The REBO consist of a CPU card, a power supply card, a front panel with light indicators, selectors, and switches, and two connection cables which connect the REBO to the ECS panel. The complete experiment protocol can be run; however, the automation of the LM2 interface is lost. The REBO has an operating power requirement of 34W and has a single 250V 3.15A fuse. There are three of these fuses on the ECS panel at L5K: one is the primary fuse for the ECS, the other two are spares located on the ECS next to the active fuse.

### **Exposure Tray**

(STS-9) ESA

See **Biomolecules in the Space Environment.**

### **Extended Data Tape Recorder (EDTR/TEAC)**

(STS-71, 78) TEAC Corporation, Japan

The Extended Data Tape Recorder (EDTR) Recorder is a cassette tape recorder used to record such data as ultrasonic Doppler blood flow data, pressure, electromyographic (EMG) data, accelerometer data, and audio records of data collection sessions. The EDTR is a modified TEAC Recorder manufactured by TEAC Corporation, Japan. The EDTR hardware consists of three major parts:

- an analog recording device,
- the EDTR Recorder Kit, and
- the EDTR Monitor Unit.

The analog recorder is unidirectional record-only device, capable of recording up to nine separate signals simultaneously at a tape speed of 0.30 cm/sec. This speed allows sufficient bandwidth (50 to 560 Hertz) to record a variety of physiological input signals with 12 hours of uninterrupted recording. Nine channels allow researchers the convenience of using one channel for time encoding and eight channels for data recording. The EDTR is mainly used to record data such as electromyography (EMG) data, accelerometer data or the voice of a subject. The recorder uses battery power (one 9-volt battery) for complete portability. The EDTR Recorder Kit holds 40 TEAC Data Tape Cases in 2 rows of 17, and 6 tapes secured in the lid by elastic straps. Two strips of Velcro pile (female) on the bottom of the kit and interface with small pieces of Velcro hook (male) on the tapes to hold the tapes in the kit when the lid is lifted. The EDTR Recorder Kit is made out of Nomex and measures 36 cm x 11.5 cm. The EDTR Monitor Unit, operated by a 9-volt battery, is used to verify the 0-10 volt analog output from the BPAS. Each channel (1-8) can be individually verified using an analog gauge. The unit has a power switch to turn the unit power on and off; a channel select switch to select the channel to be monitored; a "CAL & ATT" switch to allow the crewmember to select a gain of 0.1, 1 or 10 (typically set on 1); a "CAL & METER" switch that allows the crewmember to check the battery charge; and an "OPEN (BATT)" switch that allows the crewmember to open the bottom panel to replace the battery. The unit also has an input connector which allows signals to be input to the monitor unit; a monitor connector for ground use only; and an output connector to allow data out of the monitor unit (not used inflight).

## **Extended Duration Orbiter Medical Project (EDOMP)**

(STS-50, 65) NASA

The EDOMP is a series of Detailed Supplementary Objective (DSO) investigations designed to assess the medical status of the crewmembers and the environment where they work. Hardware used in this experiment on STS-40 and 65 included the Acetylene Rebreathing Cardiac Output System, American Echocardiograph Research Imaging System (AERIS), Biomedical Instrumentation Port (BIP) – Launch, Biosensor Harness, Cardiopulmonary Control Unit (CCU), Chibis Lower Body Negative Pressure (LBNP) Device, Collapsible Lower Body Negative Pressure (LBNP) Device, Continuous Blood Pressure Device (CBPD), Data Acquisition System (DAS), Digital Sleep Recorder (DSR), Extended Data Tape Recorder (EDTR) / TEAC, Eye Movement Recording Subsystem (EMRS), Eye Stimulation Subsystem (ESS), Gamma-1 Medical Monitoring Device, Hematocrit Minicentrifuge, Holter Electrocardiograph (ECG) Monitor, Immunization System, Inflight Medical Equipment Kit, Inflight Medical Support System (IMSS), Instrumented Vest Assembly (IVA), Life Sciences Laboratory Equipment (LSLE) Refrigerator / Freezer, Lower Body Negative Pressure Device (LBNP), Magnetic Resonance Imaging (MRI) Device, Microneurography System, Mir Blood Collection System, Mount Sinai Human Tilt Chair, Operational Bioinstrumentation System (OBS) - Electrocardiograph (ECG) Monitor, Orbiter Centrifuge, Orbiter Refrigerator / Freezer (OR/F), Percutaneous Electrical Muscle Stimulator (PEMS), Physiological Monitoring System (PMS), Plant Growth Unit (PGU), Rack Mounted Centrifuge, Saliva Collection Kit, Sample Slicing Device, Spacelab Thermoelectric Freezer (STEF), System for Measurement of Central Venous Pressure (SMCVP), Thermoelectric Freezing Module (TEFM), Thermoelectric Holding Module (TEHM), Thermoluminescent Detector (TLD), Urine Monitoring System (UMS), Visuo-Motor Coordination Facility (VCF), Water Experiment Kit (WEK).

Experiments during the STS-50 flight were a series of medical investigations to assist in the continuing development of countermeasures to combat adverse effects of space flight. These used hardware including the Lower Body Negative Pressure (LBNP) device, an Automatic Blood Pressure Monitor and Holter Recorder system (which continuously records ECG while periodically monitoring blood pressure in the arm), a Microbial Air Sampler (uses agar strips inserted into the device for collection of microbes), an Isolated/Stabilized Exercise Platform (ISEP) which supports the use of exercise equipment such as the bicycle ergometer while canceling out the inherent vibrations (the ISEP consists of four rectangular stabilizers attached vertically to a frame, which rests on shock absorbers called isolators; the equipment, in this case an ergometer, attaches to the frame, and the stabilizers hold each corner of the frame stationary while a motor inside each stabilizer uses inertial stabilization to counteract the disturbances caused by exercise), and a Polymer Membrane Processing investigation (using two IPMP units and a stowage tray stored in a Middeck locker).

## **Eye Movement Recording Subsystem (EMRS)**

(STS-90) NASA

The Eye Movement Recording Subsystem (EMRS), a component of the Visual and Vestibular Investigation System (VVIS), is used to film the movement of the subject's eyes, acquire experiment data, and provide video signal to the Video Tape Recorders (VTRs). This is accomplished with the use of infrared cameras that capture eye images, and image and data processors that compute eye movements. The EMRS is composed of two camera units, and an Image and Data Processing Unit (EMRS E-Box). The cameras, one for each eye, are mounted on the Eye Stimulation and Movement Recording Subsystem Head Unit (ESMRS-H/U), which is stowed during launch and landing. The cameras function to capture images of both eyes without disturbing the subject's vision. This is accomplished by the use of infrared light, a dichroic mirror (Beam Splitter), and a camera sensor unit.

*Light Emitting Diodes (LEDs):* The LEDs light the eyes with an invisible infrared wavelength (950 nm). Each eye is lighted by two arrays of nine LEDs. Each array is alternately powered during a video field.

The maximum duration of each pulse is 16 milliseconds. There are several constraints responsible for the design of the LEDs:

**Reflection cancellation** - Every light source provides a corneal reflection and a missing area in pupil detection. To complete the pupil, two successive frames with non-overlapping corneal reflections are used. The non-overlapping reflections are achieved by two separate LED arrays that are cycled such that only one is lit at a time. Cycles are approximately 62.5 Hz.

**Corneal reflection measurement** - This measurement is used to cancel errors of measurement produced by slipping of the mask with respect to the head. In order to achieve good accuracy in corneal reflection position, it must cover a minimum area on the camera sensor (i.e., from the eye point of view, the LED array must cover a minimum angle).

**Shadow canceling and pupil detection** - The pupil is the darkest part of the eye picture; however, since the eyeball is spherical, the contrast between the pupil and other parts of the eye are not clear. This implies the need for non-uniform lighting sources and higher intensity on the sides of the eyeball.

**Beam Splitter:** The Beam Splitter is a dichroic mirror which reflects infrared light from the LEDs to the eye and from the eye to the camera lens. It also transmits visible light from the Eye Stimulation Subsystem (ESS) display to the eye. The beam splitter is mounted to a bracket on the ESMRS-H/U with a long screw before the Head Restraint Subsystem (HRS) front shell is installed. Each subject is assigned to a particular beam splitter based on visual acuity (0, +1, or -2 diopter). The beam splitter has two halves, one for each eye. The position of each half is individually adjustable by turning a knob on the beam splitter. The correct adjustment for the left and right graduation (based on interpupillar distance) was determined pre-flight and is recorded on a cue card for easy reference. Six beam splitters are stowed in individual protective cases. Three cases (one each of 0, +1, and -2 diopter) are physically attached to form a set. There are two duplicate sets: one labeled "primary", the other "backup". The backup set is to be used in case of a failure in the primary set. Both beam splitters function the same; however, post-flight data processing requires knowledge of which beam splitter was used for each session by each subject. Use of only the primary set is intended to ensure that the identity of the beam splitter used is known. Each set of three beam splitters is 30 x 15 x 7 cm (11.8 x 5.9 x 2.8 inches) and weighs 1.723 kg (3.8 lb). Each beam splitter is made of polycarbonate overlapped by a glass sheet, 0.5 mm thick. The coating of the beam splitters is highly sensitive to pressure, temperature, and skin oils. Careful handling is extremely important.

**Camera Sensor Units:** The camera sensor unit converts the luminous image of the eye into an electronic analog image. Each of the two camera units is controlled by an electronic box fixed on the side of the ESMRS-H/U and consists of a Charge Coupled Device circuit, a lens, and an infrared filter. The cameras are mounted on the ESMRS-H/U before launch. They are protected during launch and landing by removable lens caps.

**Image and Data Processing Unit (EMRS Electronics Box):** The EMRS E-Box is permanently installed on one end of the BRD Rotating Platform. It's main function is to provide a recording signal on which all scientific data are available. It controls the Light Emitting Diodes (LEDs), the cameras, the Video Tape Recorders (VTRs), and the Experiment Control Subsystem (ECS) Video Monitor. It also processes eye images, computes eye movements, digitizes analog signals from the Eye Stimulation Subsystem (ESS) and Body Rotating Device (BRD), inserts digital data in the video signals, powers the cameras and VTRs, and provides a copy of the video signal to the ECS for downlink. The EMRS E-Box includes a back-up capability in the event of a hardware malfunction. A recovery control panel with switches accessible from the top, allows switching of the infrared illumination in a continuous mode (with only one corneal reflection), direct video channeling to the VTRs and ECS for downlink (without insertion of digitized data), and manual selection of the eye image (left or right) for downlink. The EMRS E-Box contains two power supply boards and a back plane supporting seven Personal Computer/AT (PC/AT) electronic boards. The EMRS E-Box has three 125V 15A fuses.

*Eye Stimulation and Measurement Recording Subsystem Head Unit (ESMRS HU):* The Eye Stimulation and Movement Recording Subsystem Head Unit (ESMRS-H/U), a component of the Visual and Vestibular Investigation System (VVIS), is attached to the top of the Body Rotation Device (BRD) and in front of the subject's head. The head unit provides a mounting structure for the Eye Stimulation Subsystem (ESS) and the Eye Movement Recording System (EMRS). The ESMRS-H/U includes: the Eye Stimulation Subsystem (ESS) Vision Unit, the Eye Movement Recording System (EMRS) camera sensor units, a mounting bracket for the Beam Splitter, the front mount for the Head Restraint System (HRS) Shells, the ESS slides (for attachment to the BRD), an egress bar, and a darkness system. The ESS and EMRS are described separately. The following are the other components of the ESMRS-H/U:

*Eye Stimulation Subsystem (ESS) Slides and Egress Bar:* The ESS Slides provides for attachment of the ESMRS-H/U to the BRD. The interior of the slides is coated with teflon. The slides fit onto two bars that protrude from either side (left and right) at the top of the rotating chair. One pip pin and one knurled knob attach each of the slides to the BRD. The ESMRS-H/U is secured to brackets on each of the slides by two additional knurled knobs. Once the head unit is attached to the slides, the egress bar is screwed on. When pulled down, this bar releases the head unit from the locked position. The bar is easily reached and operated by the subject. Two microswitches located on the BRD sense when the head unit is released which disables rotation immediately. If the egress bar mechanism becomes jammed, the head unit can still be moved away from the subject by removing the pip pins on the ESS slides (the knurled knob will prevent the slides from coming off the BRD).

*Darkness System:* The Darkness System is a collection of black cloth pieces that connect together and to the front of the ESMRS-H/U. The Darkness System blocks outside light from the subject so the visual stimulation pattern on the head unit can be easily seen. It also limits outside visual cues to the subject. A portion of the darkness system is glued to the HRS front shell. Velcro™ is used to secure the various pieces together.

*Eye Stimulation Subsystem (ESS):* The Eye Stimulation Subsystem (ESS), a component of the Visual and Vestibular Investigation System (VVIS), is an eye movement stimulator that presents the subject's eyes with either moving stripe patterns, moving smooth pursuit targets, or stationary calibration targets. The ESS optical system is composed of a wide aperture, three lens optic with its focal plane focused on a 640 x 480 standard VGA computer display. The lenses are spherical and are made of plexiglass in order to minimize both weight and risk of damage to subject and equipment. The optics function as a magnification lens which projects the display surface in parallel beam towards the subject's eyes. The parallel beam projection locates the image of the display at infinity, which allows comfortable viewing of the computer-generated patterns. The diameter of the lenses is large enough to allow binocular observation by individuals of varying size. The ESS consists of two parts: the Vision Unit and the Power Box. The Vision Unit is contained within the Eye Stimulation and Movement Recording Subsystem Head Unit (ESMRS-H/U). It consists of the following: Display unit - generates the optical stimulation patterns; Computer Processing Unit (CPU) module - controls operation and processing of the display unit; Analog to Digital, Digital to Analog and Input/Output (I/O) module - acquires the position of the manual focusing regulation and housekeeping voltages, controls the global brightness of the display, and generates synchronous information for the EMRS; Service module - contains electrical level adapters, power monitoring circuits, and brightness interface controls; Mass storage unit - 40 MB solid state flash drive that stores the stimulation patterns; Focus linear position transducer - a linear potentiometer which is used to measure the relative position between the display and the optical system; Fan; Thermoswitch - reads temperature of the connector baseplate; and Temperature transducers - CPU heat-sink and Display Module.

The Power Box is located under the arm of the BRD Rotating Platform. It is composed of a power filtering stage (used to reject externally generated electrical noise on the power line and prevent electrical noise

generated by the power supply circuits or by the electronic unit), a DC/DC converter section (generates the main secondary voltages which power the Vision Unit), output filters, a thermoswitch which reads temperature of the box structure, and a temperature transducer (base platform of DC/DC converters). The Power Box also contains three fuses. F1 and F2 are 250V 3A fuses while F3 is a 250V 0.5A fuse.

### **Far Ultraviolet Space Telescope (FAUST)**

(STS-9, 45) NASA

The equipment consisted of a far ultraviolet space telescope (FAUST) and an electronic interface module. The instrument was an f/1.12 Wynne camera with an effective collecting area of 150 sq cm and a field of view of 7.5 deg. The imaging capability was better than 2 arc-min in the entire field of view. The detector system used a microchannel plate image intensifier in conjunction with a 60-exposure, 35-mm film pack of Kodak IIA0. For the STS-45 mission, the detector system used on the Spacelab 1 FAUST was replaced with a new all-electronic photon counting imaging detector for the ATLAS 1 payload. When used in a photometric mode with a bandpass of 500 Angstroms, the limiting magnitude for a 20-minute observation is  $V=17$ . Diffuse sources as faint as 27th magnitude per square arc second can be detected. The instrument can operate manually (if necessary) or automatically by computer.

### **Feature Identification and Location Experiment (FILE)**

(STS-2, 41G) NASA

The Feature Identification and Location Experiment (FILE) system consisted of a sunrise sensor, two TV cameras, a decision-making electronics unit, a buffer memory, a tape recorder, and a 70-mm Hasselblad camera. This equipment was mounted on the experiment pallet shelf. The sunrise sensor would activate the experiment when the sun was 60 deg from the Space Shuttle's zenith. The two TV cameras were equipped with optical filters for visual red (0.65 micrometer) and near infrared (0.85 micrometer) to determine the ground track.

### **Fiber Pulling in Microgravity (FPM)**

(STS-50) UAH

Simulated glass melts of different viscosities will be extruded from syringes to simulate the drawing of a fiber. There are six syringe sets with decreasing ratios of viscosity to surface tension. One video camera will observe the apparatus, while another camera will use a high resolution macro lens to focus on the pulled fibers.

### **Fiber Supported Droplet Combustion (FSDC)**

(STS-73, 83/94) NASA

The FSDC hardware consists of an experiment module and a separate parts box. The experiment module contains the fiber support, deployment needles, hot-wire igniter arm, and the fuel accumulators. The bottom section of the experiment module houses the electronics that control the experiment. There are eleven different fuel accumulators, each feeding a separate fuel line, including a cluster of three accumulators that are operated simultaneously using a gear-head to form a three- droplet array. The accumulators are operated individually to feed a single-pair of needles and form a single droplet at various set locations along the support fiber. The supporting silicon-carbide fiber is 70m in diameter. An electric fan located on one end of the experiment module draws air along the fiber through a metal screen located on the other end. Flow straighteners positioned in front of the fan produce a uniform flow. A linear array of red, light-emitting diodes (LED's) backlight the droplet so that its size can be captured during combustion with a video camera attached to the Glovebox-supplied microscope. The flame images are captured via another CCD camera mounted to the front door of the Glovebox. The Shuttle crew will set up the FSDC experiment inside the

Glovebox, remove the front cover, and install the fiber support and the igniter arm within the experiment module. Then they will hook up the power cables to energize the experiment. Depending on the particular test, they will select the appropriate fuel accumulator and attach it to the fuel-feed line. The droplet-view camera with the microscopic lens and the flame-view camera will then be installed and focused at the appropriate location along the fiber. At this point, the experiment will be ready to be activated. By turning the knob on the fuel accumulator head to a preset number of clicks, the crew will be able to dispense measured amounts of fuel onto the fiber. The dispensing needles will be separated by a small distance to stretch the droplet or droplets, and then the needle arms will be swung open to deploy the droplet or droplets onto the fiber. Following deployment, the igniter will be energized to ignite the droplet or droplets. Then the igniter will retract. For tests that require forced convection, the fan will be turned on prior to ignition. Both the backlit droplet image and the flame view will be recorded on video tapes during each experimental run.

### **Fluids Experiment System (FES)**

(STS-51B, 42) NASA

The Fluids Experiment System is a facility that has sophisticated optical systems for imaging fluid flows during materials processing. The facility contains an enclosure for experiment processing inside an optical bench. The optics include a laser system for making holograms of samples and a video camera for recording images of fluid flows in and around samples.

### **Fluid Physics Module (FPM)**

(STS-9, 61A, 55) ESA

The Fluid Physics Module consists of a cylindrical structure fitted with two piston discs. The fluid to be studied can be injected through one of the discs. This disc can be moved axially, thereby enabling the length of the floating zone to vary. The discs can be rotated separately, at the same or at different speeds, and in either direction. One disc can be vibrated axially at different frequencies and with different amplitudes. The form and diameter of the end plates can be modified according to the experiment objectives. Special containers can be mounted and rotated with the help of the end plates. Temperature gradients and a difference in electric potential can be established between the two discs. The test chamber is air tight and will accept different fluids, with and without tracers. An air circulation and liquid recovery system is provided to clean out the test chamber in case the floating zone is broken and to control temperature and moisture inside the test chamber.

### **Fluid Therapy System**

(STS-65) NASA

The Fluid Therapy System will be used to purify and deliver intravenous fluids in microgravity. This multipurpose unit produces sterile water from onboard water sources, formulates and stores solutions and infuses the appropriate solution into the patient. The test will purify 10 liters of water with known contaminants into sterile water, which will be formulated into solutions. To test its operation in microgravity, the solutions then will be administered to a mannequin's arm with simulated veins. After the flight, the quantity and quality of the water and solutions will be analyzed.

### **FLY (Development and Aging of Flies)**

(STS-42) ESA

Part of this Biorack experiment used four containers holding both male and female flies, two of which were held at 0-g and two at 1-g. Each container had a slot through which feeding/egg collecting trays were exchanged at various times throughout the mission. The trays were shallow containers coated with agar containing a fly nutrient (yeast extract and sucrose). The eggs were laid on the surface of the agar. In ad-

dition, four containers were used to study another aspect of the experiment, each of which held a group of 60 adult male flies; two of these containers were held under 0-g conditions and two were placed on centrifuges and held under 1-g conditions. Again, the collecting trays on the bottom of the containers were periodically exchanged throughout the duration of the experiment. The feeding trays with the embryos deposited during the flies' previous incubation time were to be stored in the freezer to be studied upon recovery, to count, classify and describe the morphology of the different embryos and larvae. The motility response of flies was to be video-recorded for later study. A new step, ethylene oxide sterilisation of the plastic containers harbouring the flies, was introduced a month before the IML-1 launch and caused fatal toxicity in the specimens during launch.

### **Forced Flow Flame Spreading Test (FFFT)**

(STS-75) NASA

The space-flight hardware consists of three test modules, which are miniature, low-speed wind tunnels; a hand-held control box; and a set of 24 fuel sample assemblies. Two of these modules will fly on the shuttle and one on the Russian Space Station Mir. This hardware will be operated inside of the Microgravity Glove-box (MGBX). The test modules are metallic ducts with an inlet section, where air velocity measurements are made, and an outlet section where the fan that moves the air is located. The test section in the middle is isolated from the inlet and outlet sections by small mesh screens that condition the air flow, absorb the heat of the flame, and prevent the escape of any particulates (like soot) created during the burning. The front of a test module is a window that opens to provide access for installing and removing fuel samples. An additional fixed window is located on the top of the duct. Thermocouples located near and inside each fuel sample will provide measurements of both fuel and flame temperatures. The temperature values are presented on digital displays in the front window of the test module. A video camera will simultaneously image the flame, the six thermocouple displays, and the anemometer display by viewing the front window of the module. A 35mm camera will provide high-resolution still images of the flame through the top window of the module. Two types of fuel will be flown. The first type is flat paper (cellulose) samples lying in a plane parallel to the flow; the second is cylinders of either polyethylene or paper formed around an inert core that can be heated electrically. A test module is operated using the control box, located outside the MGBX and linked to the test module through a connector in the MGBX front door. FFFT is one of three combustion MGBX investigations to fly on the shuttle with two experiment modules and 16 samples: eleven flat sheets of paper (having the same thickness) and five cylindrical paper samples.

### **Free-Flow Electrophoresis Unit (FFEU)**

(STS-47, 65) NASDA

Several different biological materials will be tested separately in the electrophoresis unit. They are injected into one of three types of buffer solutions contained in separate tanks. One type of buffer solution is specifically used to test isoelectric focusing by creating a pH gradient in the flow for a separation of small charge differences. An electric charge applied in the main separation chamber causes the individual components in each mixture to separate into substreams, and the flow will be divided into up to 60 separation collection tubes. At the bottom of the separation chamber, a window linked by optical fibers detects the sample streams in different intensities of ultraviolet light passed by the sample. The crew in space and scientists on the ground examine the intensity and monitor the readings.

### **FRIEND (Friend Leukemia Virus Transformed Cells Exposed to Microgravity in the Presence of DMSO)**

(STS-42) ESA

The hardware, i.e. cell culture flasks and syringes, was identical to those used in a previous experiment in Biorack. Cultures of Friend cells (0.75x10<sup>5</sup>/ml) suspended in minimum essential medium Iscove contain-

ing 2 mM L-glutamine, 25 mM HEPES, supplemented with 10 mM sodium bicarbonate, 50 microg/ml gentamycin and 10% fetal calf serum (pH 7.35) were filled into 16 culture flasks, 5 ml each (8 flask for the flight experiment, 8 for the ground control). A gentle flow of carbon dioxide (5% CO<sub>2</sub>) was flushed through the medium before sealing the culture flasks. In flight, i.e. 8 hours after launch the cultures were transferred to the 37degC incubator, 4 in the static rack at 0 g and 4 on the 1 g centrifuge. Five hours later, hemoglobin synthesis was induced by injection of dimethylsulfoxide at a final concentration of 1.3%. Incubation continued for 140 hours at 37degC. Finally, 2 of the 4 cultures at 0 g and 2 from the 1 g centrifuge were fixed with glutaraldehyde (final concentration: 1%). All cultures were stored at 4degC.

## **Frog Environmental Unit (FEU)**

(STS-47) NASA

The Frog Environmental Unit (FEU) provides a ventilated and temperature-controlled habitat (18 degrees Celsius for the ovulation phase of the experiment) for four female frogs as well as groups of developing embryos. This temperature is reset to 21 degrees Celsius after egg fertilization in the General Purpose Work Station (GPWS). A 1-g centrifuge is part of the FEU and provides a simulated on-Earth condition for up to 28 Egg Chamber Units (ECUs). A zero compartment in the FEU provides exposure to microgravity conditions for two racks of ECUs (up to 28 ECUs). Together, these systems offer the capability for simultaneous side-by-side experiments consisting of both a 0-G “treatment” group and a 1-G “control” group. Another part of the FEU is a chamber to house an Adult Frog Box. Completing the FEU system is a mainframe control panel and a power conditioning unit with front panel.

*Egg Chamber Units (ECU):* Egg chamber units consist of three Lexan pieces assembled to form an incubation chamber for the growing embryos. The eggs are placed on a stainless steel grid inside an egg basket and fitted onto the eyepiece unit. The eyepiece features a viewport for examining embryos using a microscope and video equipment. The chambers may be filled with Ringer’s solution and can accommodate injections of fixatives or other materials.

*Power and Control Systems:* The Power Conditioning Unit (PCU) provides 28 volts DC from Spacelab and distributes this power to the various sub-systems. The PCU switches and indicators provide for set-up, monitoring and operation of the unit. The six sub-systems controlled by the Pulse Code Modulation (PCM) include the thermoelectric temperature control system, the air circulation fans, the adult frog box air pumps, the centrifuge, the temperature monitoring system and the digital PCM electronics. The main power switch provides 28 volts DC to all systems; however, the T.E. MAIN power switch must be placed in the ON position to power the thermoelectric unit.

The *Mainframe Control Panel* is divided into four subsections: the Thermoelectric Unit (TEU) control, the centrifuge control, the data acquisition control and the temperature monitor. The TEU provides heating and/or cooling as required by the set point on the thermal unit panel and as modified by the proportional controller that modifies the set point. The TEU interfaces with the Spacelab coolant loop through two disconnects in the rear of the FEU. The centrifuge control allows centrifuge run or stop operations and indicates status. Automatic sensors stop the centrifuge when the door is opened to permit changing of Egg Chamber Units (ECU). A power cut-off switch engages when the door is opened and may be manually disengaged in order to manually rotate the centrifuge for experiment work. The data acquisition panel permits the following three alternatives: Normal operation of all 12 temperature channels, High Cal operations with temperature sensor channels fed into the signal conditioners reading the high range and Low Cal operations with temperature sensor channels fed into the signal conditioners reading the lower temperatures. The temperature monitor permits individual display of any of the 12 temperature channels on a liquid crystal display. This permits a check of the calibration of the sensors.

*Frog Box Chamber/Centrifuge/0-g Stowage:* The adult frog box chamber holds the frog box with four adult female frogs (two per compartment) that will provide eggs for the experiment. It is connected at the

rear of the compartment with a quick disconnect air supply to sustain the frogs in the box. The centrifuge provides an artificial gravity force of 1-g for selected egg chambers. It has a double row of slots, color-coded to match the egg chambers. The 0-g stowage compartment is a holding chamber to maintain embryos in the microgravity environment of the orbiter; it houses two racks, A and B. The adult frog box contains four adult female frogs housed in a box with soft absorbent material, kept moist with Ringer's solution, a solution of chlorides of sodium, potassium, and calcium that is isotonic to animal tissue, and fits in the FEU. The egg chamber units are composed of three Lexan parts that fit together to form an incubation chamber for growing embryos. Chambers can be viewed with a microscope and video equipment. The eyepiece unit has an injection port through which chambers can be filled with Ringer's solution, or fixative. An aquarium-style air pump provides ventilation. Several kits are used to perform experiment operations.

*Kits:* The Human Chorionic Gonadotrophin (HCG)/Sperm Kit contains separate syringes filled with HCG and Ringer's solution and Sperm Packages for holding sperm suspension and whole frog testes. The Egg Chamber Operations Kit holds forceps and petri dishes for egg handling. Ringer's Kits contain separate syringes for Ringer's solution and a mixture of Ringer's and Ficoll. Fixation Kits contain separate syringes for two types of fixative: a dilute acetic acid/dichromate buffer and formaldehyde. The Fixed Egg Chamber Kits contain boxes for holding egg chambers after fixation, as well as extra syringes for fixation.

### **Galactic Ultrawide-Angle Schmidt System Camera (GAUSS)**

(STS-55) DLR

This device was an ultraviolet camera which provided wide-angle, photographic coverage of the galaxy. The camera also photographed the Earth's atmosphere when the orbiter faced the Earth. The GAUSS field-of-view was 145 degrees and about 100 exposures of the Milky Way and upper atmosphere were taken.

### **Gas Analyzer System for Metabolic Analysis Physiology (GASMAP)**

(STS-78, 90) NASA

The Gas Analyzer System for Metabolic Analysis Physiology (GASMAP) device is used to monitor and analyze inhaled and exhaled breath streams to determine their gas concentrations. The primary gases of interest are nitrogen ( $N_2$ ), oxygen ( $O_2$ ), carbon dioxide ( $CO_2$ ), argon (Ar), acetylene ( $C_2H_2$ ), sulfur hexafluoride ( $SF_6$ ), helium (He), and carbon monoxide ( $C_{18}O$ ). The GASMAP flight hardware consists of two components: an analyzer module and a calibration module, both of which are housed in drawers inside the Spacelab. The analyzer module contains all the sensor and electronic hardware of the GASMAP. The major sub-assemblies of the analyzer module are the Random Access Mass Spectrometer (RAMS), the Roughing system, the Gas Delivery system, the Interface Shell (IS) computer and the power connection. The module is controlled via the keypad and LCD display of the front panel, or via a laptop computer. The Random Access Mass Spectrometer (RAMS) is the largest assembly of the analyzer module. Through software control, the RAMS can measure molecular mass-to-charge ratio in the range of 1 to 250 AMU (atomic mass unit) with a resolution of 1 AMU and a sensitivity down to 250 ppm (parts per million). A Single Board Computer resides in the RAMS and is dedicated to performing housekeeping functions and calculating gas concentrations. The gas data are sent out on ten analog outputs, reading gas and range. In addition, data transfer through two computer ports is available. The analog RAMS readings are displayed on the front panel of the GASMAP device and a second signal is prepared for data downlink by the Interface Shell computer. The functional components of the RAMS include a gas inlet valve, an ionizer, a mass filter, a collector, an ion pump, a roughing system and a gas delivery system. The gas inlet valve controls the inlet of small amounts of gas into the ionization chamber (in the range of microliters), independent from the outside pressure. In the ionization chamber the gas molecules are ionized by electron bombardment and released to the mass filter system, which consists of electrically charged rods. The electrons are neutralized when brought into contact with the rods. This allows the calculation of (gas) concentrations.

The process must be repeated separately for each analyzed gas. The Gas Delivery system provides constant gas sample flow rates in the range of 10 to 150 cc/minute to the RAMS for analysis. The system contains a micron screen to protect the analyzer from debris and liquid and a flowmeter to provide the desired target flow. To eliminate any pulsating effects, a surge chamber is added just before the gas enters the RAMS through the inlet valve. The Roughing system provides the necessary hardware and vacuum interfaces to pump down the analyzer in the event of a loss of vacuum, which is necessary for nominal operations. The Interface Shell computer also controls the GASMAP subcomponents, acquires data, and transfers data to display devices, to the rack controller, and to analog outputs. The calibration module is compatible with the analyzer module and is used to calibrate the RAMS readings on a regular schedule. Three cylinders, filled with a known gas mixture, are installed in the calibration device. By knowing the mixture, the readings of the GASMAP system can be compared and adjusted if necessary.

### **Gas Cylinder Assembly (GCA)**

(STS-40, 58, 78, 90) NASA

The Astronaut Lung Function Experiment (ALFE) Gas Cylinder Assembly (GCA) consists of two rack mounted units, a Mix GCA and an Oxygen/Argon ( $O_2/Ar$ ) GCA. The units store gas mixtures for the various test sequences performed by the astronauts during experiments investigating lung function and lung perfusion. The gases are stored in aluminum Kevlar wound cylinders at 2750 psi and are reduced by a pressure regulator to 50 psi during the bag fill sequence. Gas pressures inside the Bag-In-Box (BIB) bags are near ambient. The solenoids are controlled by an on/off/auto switch located on the GCA for manual operation or automatic control by the experiment computer. The Mix and  $O_2/Ar$  GCAs interface via power cables and Mix Gas Interconnect Tubes for power, data and gas transfer. The  $O_2/Ar$  GCA interfaces to the BIB device via the Argon Hose, Oxygen Hose and Mix Gas Hose to provide the test gases for inspiration. The gas being used at a given moment depends on the activity being performed and the measurement being sought. The experiment computer controls the supply of gases to the BIB via signal routing to the GCA solenoid control circuits located inside the Electronics Control Assembly (ECA). The GCAs also receive power from the ECA.

### **General Purpose Rocket Furnace (GPRF)**

(STS-7, 61A) NASA

General Purpose Rocket Furnace has three furnace chambers, and was used on STS-7, and on STS-61A processed an Al-40 wt.% In alloy. The alloy was to be contained in a crucible which also held a plunger to prevent the formation of a free surface (gas/liquid interface) during sample processing. It was anticipated that the crucible would be heated to 970 (+/- 10) °C at a rate which would avoid thermal shock to the ceramic components (>15 minutes). The cartridge was to be held at this temperature for 12 hours and then cooled at a rate of 6.0 (+/- 0.5) °C to below 600 °C. Cooling from 600 °C to below 100 °C was expected to occur at a rate near 6 °C/min. The Gradient-GPRF had a maximum operating temperature of approximately 1000 °C which accommodated the processing temperature of the sample (904 °C). Directional solidification was achieved in the G-GPRF via (1) three independently programmable temperature zones and (2) a water-cooled heat exchanger located at one end of the furnace. No ampoule or furnace translation was required (or possible) using this G-GPRF experimental setup. An isothermal heating and cooling module is also available (the Isothermal-GPRF).

### **General Purpose Transfer Unit (GPTU)**

(STS-40, 47, 58) NASA

The General Purpose Transfer Unit is specifically designed to provide a second level of particulate containment during transfer of rodents in cages between the Research Animal Holding Facility (RAHF) and the General Purpose Work Station (GPWS). The GPTU has a Lexan frame with a sliding access door that

interfaces with both the RAHF and the General Purpose Work Station (GPWS). A Tyvek sock is attached to the frame and encloses the rodent cage during transfer. The GPTU interfaces with the Side Access Window (SAW) of the GPWS. Two fasteners connect the two units and a tab on the GPTU sliding door fits into a slot in the SAW, allowing both doors to open simultaneously. The GPTU interfaces with the RAHF through a special adapter attached to the RAHF. The adapter enables the GPTU to slide horizontally and vertically across the face of the RAHF to align with any rodent cage. The GPTU has two fasteners that mate and align with dowels on the RAHF adapter. A slight pressure is applied to compress the GPTU face gasket. The fasteners are then turned to lock the two components together. Releasing the fasteners allows the GPTU to slide to another designated cage location.

### **General Purpose Work Station (GPWS)**

(STS-40, 47, 58) NASA

The General Purpose Work Station (GPWS) is designed to provide containment of particulates, urine, blood, feces and other contaminants when it is being used to perform scientific procedures on rodents or other specimens. It is, in effect, a large, sophisticated glovebox. The GPWS supports biological experiments, biosampling, and microbiological experiments, and it serves as a closed environment for containment while routine equipment repair or other inflight operations are performed. The GPWS provides the essential working space and accommodates the laboratory equipment and instruments required for many life sciences investigations. Housed in a Spacelab double rack, the GPWS is self-contained, apart from power, data, and cooling interfaces.

*Cabinet:* The rack-mounted, retractable cabinet provides laboratory work bench accommodations, including airflow, power, and lighting. The front door of the cabinet allows large experimental hardware to be transferred inside during flight. Ports on the front and side of the cabinet allow two crew members to simultaneously perform tasks inside the cabinet using gauntlets. The entire cabinet may be locked into one of three extended positions during use or fully recessed into the rack for stowage. Waste may be deposited in a disposal compartment through rubber slits on the rear wall of the internal work volume.

*Containment Control System:* The system is designed to clean the air within the work volume and provide biohazard protection. It includes a circulation blower, a main Trace Contaminant Control System (TCCS) canister, a vent canister, High Efficiency Particulate Air (HEPA) filters, absorbent fiberglass blotter pads, and a manually-operated Air Diverter Valve. The GPWS incorporates two modes of operation: normal, for nominal operations, and recirculation, to facilitate cleanup in the event that fluid and debris are released into the cabinet.

*Electrical System:* The electrical system accepts AC/DC power from the Spacelab for experiment-related equipment. Panels on the front and inside the cabinet volume contain power switches and temperature controls.

*Thermal Control System:* The Thermal Control System controls air temperature inside the cabinet, which can be maintained between 20 and 29 °C. Caution indicators are illuminated when the system fails to maintain the cabinet air temperature to within 2 °C of a set point.

### **Geophysical Fluid Flow Cell (GFFC)**

(STS-51B, 73) University of Colorado

The purposes of this experiment on STS-51B are to simulate density stratified flows which occur naturally in the atmospheres of rotating planets and stars, and to gain insights and answers to basic questions concerning large-scale fluid flows in oceans, atmospheres and stars. Simulation is accomplished through the use of a dielectric fluid that is temperature-dependent and confined between concentric, rotating, electrically conductive spherical shells. The apparatus includes a convection cell, temperature controllers, rotation drive, and a high voltage supply. A camera is used to view the flow pattern made visible by injection of dyes, or from

the distortion of a set of ruled lines on the outer shell caused by refractive index changes in the fluid. The experiment on STS-73 uses two hemispheres. One, made of stainless steel and about the size of a baseball, is placed inside a transparent sapphire hemisphere, and a layer of silicone oil fills the space between the two. They are mounted together on a turntable. The transparent sapphire allows a clear view of the oil and conducts heat well so precise temperature control of the sapphire dome can be maintained. The temperatures of the inner and outer hemispheres are controlled by the experiment computer, as is the speed of rotation. The heating creates a thermally driven motion in the oil, while the rotation mimics that present on rotating planets and stars. A high-voltage electric field is applied across the silicone oil, creating a buoyancy force identical to buoyant forces on Earth and in other atmospheres being modeled. The basic variables for the experiment are hemisphere rotation speed, voltage charge and temperatures. Once the variables are set and the experiment is running, thermally driven fluid flows within the rotating silicone oil are monitored. Dr. Hart and his team will study variations in the fluid's thermal patterns for a wide range of external forces. Different combinations of voltage, speed and temperature will be used during each run, creating unstable and turbulent flows in the rotating sphere shell that will help researchers better understand the dynamics of oceans, planetary atmospheres and stars.

### **Glovebox (MGBX)**

(STS-50, 73, 75, 87, 83/94) ESA

The Microgravity Glovebox offers an enclosed cabinet area which helps maintain a controlled workspace. A wide range of support systems are available to microgravity researchers using the Glovebox. Real-time downlink of color and black-and-white video images, 35 mm photos, a high-magnification stereomicroscope which allows images to be recorded by the video, and still cameras are among the resources investigators can use to collect experiment data. The Glovebox allows researchers to view and interact with their investigations. A central port allows equipment to be installed and extracted from the facility. Experiments can be mounted to the Glovebox floor, elevated by jacks, held down with magnetic bases or strips, bolted to the inside wall or even attached to the outside of the facility. Two doors located on the sides of the cabinet are equipped with rugged gloves and provide an airtight environment in which the crewmembers can manipulate their investigations. Surgical gloves can be worn by the crewmembers to facilitate more delicate procedures. A large window on top of the cabinet allows Glovebox activity to be viewed by the crew and recorded by the imaging devices. The Middeck Glovebox consists of an Interface Frame (IF) and Glovebox (GBX). The facility was developed for use in the middeck but was mounted in Spacelab rack 12 for the MSL-1 mission. The IF furnishes structural, thermal, and electrical interfaces to the orbiter and to the Glovebox, as well as operational capabilities for the data and video recording equipment. The Glovebox provides a sealed work area that presents a clean working space and minimizes contamination risks, both to Spacelab and to experiment samples. It provides two types of containment: physical isolation and a negative air pressure differential between the enclosure and the rest of the Spacelab working area. The facility has a filter system designed to contain fluids, powders, and other solid particles, preventing them from entering the Spacelab environment. Also, the Glovebox protects samples from contamination from external sources when experiment procedures call for containers to be opened. The crew manipulates samples or experiment equipment through three doors: two glovedoors and a central port through which experiments are placed in the Glovebox. The glovedoors are located on each side of the central port and serve three functions. When an airtight seal is required, crewmembers can insert their hands into rugged gloves attached to the glovedoors, allowing no airflow between the enclosure and Spacelab. If the experiment requires more sensitive handling, crewmembers may put on surgical gloves and insert their arms through a set of adjustable sleeves. In addition, each of the doors serves as a viewport for the facility's video cameras.

(STS-50) - Experiments in the Glovebox on this mission include the Passive Accelerometer System, Interface Configuration Experiment, Protein Crystal Growth Glovebox Experiment, Solid Surface Wetting

Experiment, Marangoni Convection in Closed Containers, Smoldering Combustion in Microgravity, Wire Insulation Flammability Experiment, Candle Flames in Microgravity, Fiber Pulling in Microgravity, Nucleation of Crystals from Solutions in a Low-g Environment, Oscillatory Dynamics of Single Bubbles and Agglomerations in an Ultrasonic Sound Field in Microgravity, Stability of a Double Float Zone, Oscillatory Thermocapillary Flow Experiment, Particle Dispersion Experiment, Directed Orientation of Polymerizing Collagen Fibers, and the Zeolite Glovebox Experiment.

(STS-73) - Experiments in the Glovebox on this mission include the Interface Configuration Experiment, Oscillatory Thermocapillary Flow Experiment, Protein Crystal Growth - Glovebox (PCGG), Colloidal Disorder-Order Transitions (CDOT), Fiber Supported Droplet Combustion (FSDC), Particle Dispersion Experiment (PDE), and Zeolite Crystal Growth - Glovebox (ZCGG).

(STS-75) - Experiments in the Glovebox on this mission include Comparative Soot Diagnostics, Forced Flow Flamespreading Test, and Radiative Ignition and Transition to Spread Investigation.

(STS-87) - Experiments in the Glovebox on this mission include Enclosed Laminar Flames (ELF), Particle Engulfment & Pushing (PEP), and Wetting Characteristics of Immiscibles (WCI).

(STS-83/94) - Experiments in the Glovebox on this mission include Coarsening in Solid-Liquid Mixtures (CSLM), Bubble and Drop Nonlinear Dynamics (BDND), Capillary-driven Heat Transfer Device (CHT), Internal Flows in a Free Drop (IFFD), and Fiber Supported Droplet Combustion (FSDC-2).

## **GN<sub>2</sub> Dewar**

(STS-71) NASA

Dewars carry 250 to 500 samples of proteins contained in Tygon plastic tubing (sealed at each end) or Nunc storage tubes. The protein solutions (proteins mixed with precipitants that cause them to form crystals) are loaded and flash frozen on earth, then installed in a Dewar which uses liquid nitrogen (GN<sub>2</sub>) to keep them frozen. After arrival aboard the Mir space station, the liquid nitrogen slowly evaporates and the protein samples warm to cabin temperature. This allows each sample to start crystallizing over a period of weeks in Mir's weightless environment.

Equipment for the Mir experiment is simple and requires virtually no crew activity. A total of 250 to 500 samples (depending on the mix of tubes and sizes chosen) will be divided into three bundles. The bundles will be stacked in a sealed aluminum cylinder, 3.5 inches (8.9 cm) wide and 13.5 inches (34.3 cm) long. The cylinder then will be placed inside an aluminum vacuum jacket, or dewar, lined with a calcium silicate absorbent. The absorbent will be filled with liquid nitrogen at -320 degrees Fahrenheit (-196 degrees Celsius) to flash freeze the samples, blocking diffusion and crystal growth until thawing occurs aboard Mir. Because the dewar has no active refrigeration, the liquid nitrogen will begin warming slowly and boiling off when the dewar is filled before launch. After Atlantis docks with Mir, the crew will secure the dewar in a quiet area of the Mir station to minimize vibration. The liquid nitrogen will continue to boil off into Mir's oxygen/nitrogen atmosphere. In orbit, the samples will thaw after the nitrogen evaporates (over a period of 10 days). This ensures that all crystallization will occur in the microgravity environment of space. The proteins will crystallize over the next few months at cabin temperature, 72 degrees Fahrenheit (22 degrees Celsius). The dewar will remain within a few degrees of that temperature through STS-74 landing and return of the samples to science investigators.

## **Grab Air Sampler**

(STS-71) NASA

The Grab Sample Containers (GSC) are purchased from Scientific Instrumentation Specialists in Moscow, Idaho. The GSC is a stainless steel sphere with an 8.9 centimeter diameter and a 350 cubic centimeter volume. It weighs approximately 0.45 kg. The canisters are equipped with a special modification that includes

a clutched-closure valve and a clutch handle retainer. Each canister weighs 0.5 kg and retains a volume of 358 ml. The interior surfaces are SUMMA-treated to minimize retention of compounds on the walls. The sampler is evacuated prior to launch. To collect a grab air sample, the valve (type 316 SS Nupro) is opened and the sampler is filled until pressure equilibrium exists. (Procedures call for the valve to remain open for 10 seconds). The valve is closed to seal the device. A torque limiting device is incorporated into the valve handle to prevent over-tightening and possible damage to the valve. There is a dust cap over the valve, and the valve has a Valve Protection Device. Once the canister is received at JSC, the tether is added to prevent loss of the dust cap.

### **Gravitational Plant Physiology Facility (GPPF)**

(STS-42) NASA

The Gravitational Plant Physiology Facility (GPPF) occupies a Spacelab double rack and is designed to support plant experiments in space. The GPPF contained a Mesocotyl Suppression Box (MSB), two Video Tape Recorders (VTR-F and VTR-G), and a plant cube support panel, a control unit, plant growth containers (Cubes), two culture rotors, a recording and stimulus chamber (REST), and a plant holding compartment. The seedlings were cultured in growth “cubes” which consisted of a black anodized aluminum body 70 x 65 x 65 mm fitted with two acrylic plastic viewing windows made from an infrared (pass > 800 nm) filter material. For the GTHRES experiment, as seedlings grew, infrared radiation confined to a narrow wavelength band centered at 890 nm was directed from a bank of emitting diodes through the cube windows. The contents of the cube, including the plants, reflected this light and the resultant infrared image was recorded by a video camera. The first growing phase was performed on a 1 g centrifuge and lasted until the seedlings were at an optimal growth stage for responding to a g-force in the direction transverse to the coleoptile axis. When the plants were ready, the cubes were placed in another centrifuge, called a test rotor, and were exposed to a centripetal g-pulse which could be varied from set to set over a range of both g forces (0.1 - 1.0 g) and pulse durations (2 min - 2 hr) in various combinations. A maximum of 20 g-pulse combinations were possible. After the g-pulses, the responding plants were monitored using time lapse video imagery. Tropistic responses were followed for several hours. These time lapse response data were stored on video tapes to be analyzed after landing. Gas samples and other variables, such as experiment temperature, centrifuge speed, and the time of the events were also recorded. The FOTRAN experiment fitted a clear acrylic window to the front face of the seed tray that allowed entry of the photostimulus light beam. The complete assembly was not gas-tight, but diffusive gas exchange was restricted. For the FOTRAN experiment wheat seedlings (*Triticum aestivum*) weighing between 30.1 and 40.0 mg were first placed in Cubes and were maintained at a constant (22.5 degree C) temperature and an artificial 1 g centrifugal field for 75 hours. For the next stage they were transferred to the REST unit where they were recorded on time lapse video using physiologically inactive IR illumination for a five hour period and then subjected to photostimulations of predetermined duration under control of the GPPF control unit microprocessor. The seedlings were then recorded on video tape for another 7 hours after which they were transferred to the Biorack Glove Box where gas samples from the cube interiors were taken for later analysis and a sample of the coleoptiles were chemically fixed. This process was repeated for five batches of four cubes giving a total of 20 different programmable photostimulus doses. Light doses ranging from 0.34 J m<sup>-2</sup> (1.15 umol m<sup>-2</sup>) to 113.9 J m<sup>-2</sup> (380 umol m<sup>-2</sup>) were given. Different doses were achieved by varying the duration of exposure from 3 to 999 s at a constant intensity of 0.114 W m<sup>-2</sup> (0.38 umol m<sup>-2</sup> s<sup>-1</sup>).

*Control Unit:* The control unit (CU) manages power to experiment hardware and controls the functions of the rotors, cameras, REST, etc. It also has a TV monitor system that displays such functions as rotor and REST speeds and temperature. Commands to the system are entered on a panel keyboard with a one-line, 24-character display that shows messages prompted or for confirming inputs. These commands initiate

inflight activities. The one-line display and video monitor also generate/display warning messages such as over temperature, door opened, etc. It also includes four circuit boards behind a front panel hatch.

*Culture Rotor:* The culture rotor (CR) is located immediately beneath the control unit. It contains two 1-g centrifuges (rotors) that simulate Earth gravity. Each rotor contains 16 plant cubes. The rotors are individually controlled (start and stop) by the control unit. Plant cubes are placed on these rotors prior to their transfer to the Mesocotyl Suppression Box (MSB), the Test Rotor (TR) or the Recording and Stimulus Chamber (REST).

*Test Rotor:* The test rotor (TR) is located directly beneath the culture rotor. It operates within the range of zero gravity to 1.5-g. The system includes an internally mounted infrared-sensitive video camera head. The plant cubes rotate on the rotor and move in succession across the video camera field of view to permit time-lapse video recording of plant bending. The control unit commands the rotors to operate in a slow-scan mode, which is followed by a g-pulse/time stimulus and a return to the slow scan mode when video recording of the response to the stimulus takes place.

*Recording and Stimulus Chamber:* The Recording and Stimulus Chamber (REST) provides the capability for time-lapse infrared video recording of plants in four plant cubes, before and after an exposure to blue light. The light pulse is provided by a 10-watt tungsten filament lamp. A camera and recorder, controlled by the microprocessor, take nine-second pictures every ten minutes.

*Video Tape Recorders:* Two redundant video tape recorders (VTR-G and VTR-F) are located on the side of the rack above the Recording and Stimulus Chamber (REST). They are used to record images from the REST and from the Test Rotor (TR) cameras. They record the same information to ensure successful data collection.

*Mesocotyl Suppression Box:* The Mesocotyl Suppression Box (MSB) is located in the upper left of the GPPF double rack. It is used only with oat seedlings that are exposed to a red light spectrum for up to ten minutes. The red light permits the seedlings to grow straight, enhancing viewing. If no red light were used, the mesocotyl tissue of the plants would undergo extensive growth and cause bending and elongation. Four soil trays containing seedlings are removed from their plant cubes and loaded into the MSB at one time. The empty plant cubes are attached temporarily to the Cube Support Panel (CSP) directly above. The MSB features a power switch, a timer to regulate the exposure of red light and indicator lights.

*Plant Holding Compartment:* The Plant Holding Compartment (PHC) is located in the lower left side of the double rack. It is thermally regulated and contains a seed planting kit, gas sampling syringes, rotor counterweights, and plant cubes. The seed planting kit contains oat and wheat seeds wrapped in aluminum foil, a dibble to plant the seeds in soil tray wells and a seed planting fixture to aid the planting process. Both the Middeck Ambient Stowage Insert (MASI) and the Plant Carry On Container (PCOC) are support hardware for the Gravitational Plant Physiology Facility (GPPF) experiments. The MASI is designed to hold soil trays, while the PCOC holds plant cubes. Each is constructed of a standard aluminum box, with a hinged cover and latches mounted inside the lid. Inside the lid of the box is an Ambient Temperature Recorder to automatically sense and record internal temperatures during the mission, a hex key, and seed strips. The portion of the box below the lid contains five layers of experiment support hardware. These are packages of experiment soil trays and experiment plant cubes, which are used within the GPPF. The entire package is protected by Pyrel foam into which the soil trays and plant cubes are inserted. They are further contained by Nomex straps and tape.

## **GRILLE Spectrometer**

(STS-9, 45) Institut d'Aeronomie Spatiale de Belgique

The Grille Spectrometer measures the absorption of infrared radiation during orbital sunrises and sunsets. Two detectors collect two infrared wavelength ranges so that scientists can make simultaneous observations of atmospheric components linked by chemical and/or dynamic processes. The equipment contained

an infrared spectrometer with a telescope and a cooled infrared detector. The spectrometer operated in the wavelength range from 2.5 to 13 micrometers. During Spacelab 1 (STS-9), the Grille measured chemicals up to 130 km (81 mi), noting concentrations of chemicals like carbon monoxide, carbon dioxide, nitric oxide, water vapor, methane, nitrous oxide, hydrogen chloride and hydrogen fluoride changed with altitude and latitude, and as the seasons change. During ATLAS 1 (STS-45), the Grille Spectrometer observed the global distribution of active trace gases at altitudes between 15 and 140 km (9 to 87 mi), studying those molecules that absorb infrared radiation in the 2.5 to 10 micron spectral band. The Grille Spectrometer observes ozone, carbon monoxide, carbon dioxide, methane, water vapor, nitrogen dioxide, nitrous oxide, nitric oxide, hydrogen fluoride, and hydrogen chloride.

### **Hand Grip Dynamometer (HGD)**

(STS-78, 90) NASA

The Hand Grip Dynamometer (HGD) is a device used to measure any applied compressive force. It is used to measure grip strength capabilities through the establishment of a muscle force/time relationship. The HGD is a stowable, hand held device that is battery powered. It is able to measure forces from 0 to 100 pounds, and its outer dimensions are approximately 207 x 89 x 32 millimeters with a weight of about 900 grams. The HGD consists of two components, the handgrip module and the conditioner module. The load cell arrangement of the handgrip module generates a voltage signal when a compressive force is applied. The signal is transferred to an amplifier via a signal and power transfer cable and from there to the LSLE Microcomputer-2 for recording.

### **Hand Held Diffusion Test Cell (HHDTC)**

(STS-83/94) NASA

The Handheld Diffusion Test Cell apparatus uses liquid diffusion. Four HHDT units containing four test cells each are flown for a total of 16. The end of the test cells where crystals will grow and the containment housing are made of clear plastic, so the crew can photograph growth during the mission. Three HHDT units can be housed in lockers, and another can be mounted on the module wall for periodic video recording. Each test cell has three chambers: protein solution, buffer solution, and precipitant solution. The buffer solution chamber cuts across the width of a shaft between protein and precipitant solutions. Before the experiment, a valve is positioned so each fluid is isolated from the others. An astronaut will activate the experiment by rotating the valve 90 degrees, so the buffer contacts the protein and precipitant and the three form a single volume. The rotating valve minimizes liquid movement, limiting alteration of the liquids' shapes and volumes. When the three liquids are in contact, they will slowly diffuse into each other. The crew will close the valves before return to Earth. . The HHDT experiments are recorded on video and/or 35-mm film.

### **High Resolution Telescope and Spectrograph (HRTS)**

(STS-51F) US Naval Research Laboratory

The observations of this instrument are made through intensity measurements, Doppler measurements, and line-profile analysis of high spatial resolution (1 arc-s) and high spectral resolution (5 pm) of UV spectra (wavelengths 117.6-170 nm) covering a wide variety of continua and emission lines that originate in different temperature regimes of the solar atmosphere. The instrumentation consists of a stigmatic spectrograph with a slit that covers the full solar radius simultaneously with 1000 resolution elements. Thus, the slit covers many different solar features at the same time. One spectrum contains enough information for a statistical analysis. Photographs of a series of spectra over a period of at least 15 min are made in order to follow the changes in the intensity, Doppler velocities, and line profiles as they are caused by disturbances moving through the solar atmosphere. Spectroheliograms of two dimensions as a function of time are con-

structed in order to investigate the three-dimensional structure of the chromosphere and transition zone. A systematic mapping of the coronal velocity field over the whole sun is also made, along with a series of limb spectra at different altitudes for studies of the structure and dynamics of spicules. The slit is pointed within a tolerance of half a slit width for a duration of at least 15 min. The slit of the high-resolution telescope and spectrograph (HRTS) is stepped in rapid sequence over a small area of the sun (plus or minus 5 arc-s), which allows the spectroheliograms to be made. The HRTS consists of a 30-cm Gregorian telescope of 90-cm focal length, a UV spectrograph, a 160-nm broad-band spectroheliograph, and an H-alpha split-display system housed in a thermal control canister mounted on the instrument pointing system (IPS). The telescope has an occulting mirror at the primary focus that reflects away all but a 5 x 15 arc-min portion of the solar image that then passes through an aperture to strike a secondary mirror that re-images it onto the UV Wadsworth spectrographic slit plate. The secondary mirror receives less than one solar constant of illumination. The spectral resolution is 50 mÅ, and the spatial resolution is 1 arc-s. The roll film camera holds 1000 exposures of type-101 film. Experiment mass: 184 kg; average experiment power: 340 W

### **HI-PAC Digital Television**

(STS-73, 83/94) NASA

Designed to operate from the Spacelab, high-packed digital television will provide researchers on the ground with up to six channels of video. Using Spacelab's high-rate data system, HI-PAC converts standard analog video signals into digital signals, compressing the signal in the process and downlinking it in the same way as other digital data. When the signal is received in the Spacelab Mission Operations Control Center at the Marshall Space Flight Center, the digital data are converted back into an analog signal and distributed to scientists for viewing on monitors in the Science Operations Area. Once on orbit, a crewmember will switch the closed-circuit television system from the standard analog video to the HI-PAC system. After the system has been checked out, the equipment will operate in the HI-PAC mode unless analog mode is required. The system can be switched easily from one mode to the other when necessary.

### **Holographic Optics Laboratory (HOLOP)**

(STS-61A, 55) ESA

The Holographic Optics Laboratory (HOLOP) was a multi-user experiment facility for conducting fluid physics experiments under microgravity conditions. The objective of HOLOP was to investigate transient phenomena such as heat transfer, mass transfer, surface convections and particle motion through holographic methods. The following experiments were included on HOLOP: (1) Marangoni Convection in a Rectangular Cavity (MARCO) - investigated thermocapillary convection driven by temperature gradients applied parallel to free liquid-gas surface; (2) Interferometric Determination of the Differential Interdiffusion Coefficient of Binary Molten Salts - measured diffusion coefficients by means of holographic real-time interferometry using a Potassium Nitrate/Silver Nitrate system at eutectic composition; (3) Measurements of Diffusion Coefficients in Aqueous Solution (IDLE) - measured diffusion coefficients through interferometric holography of refractive index changes; (4) Phase Separation in Liquid Mixtures with Miscability Gap (NUGRO) - used a pressure jump technique to induce phase transition observed by holographic image recording; (5) Radiation Detector (RD) - was a set of four experiments designed to expose different types of material and biological probes to space environmental conditions.

### **Hopkins Ultraviolet Telescope (HUT)**

(STS-35, 67) Johns Hopkins University

The HUT consists of a 0.9 meter f/2.0 primary mirror and a prime focus, "Rowland-circle" design spectrograph. The primary mirror is coated with iridium, thus providing good reflectivity through the extreme and far ultraviolet (EUV/FUV) range, has a collecting area of 5300 sq cm, and at the focal place the scale

is 115 arcsec/mm. The telescope is focused and aligned using three motors which can drive the primary mirror in and out. The spectrograph consists of an aperture wheel assembly, a concave grating and a photon-counting detector. The grating diameter is 200 mm with a radius of curvature of 400 mm, a groove density of 600 lines/mm, Osmium coating, 41.4 A/mm (order 1) dispersion, and the wavelength coverage is in first order 840-1850 Å, and in second order 420-925 Å. The detector includes a microchannel plate intensifier with a Cesium Iodide photocathode array (pulse counting) with 1024 channels. The pixel size is 25 microns x 2.5 mm (about 1 Å/pixel). The active length is 25 mm. Photon events are electronically centroided to half a channel, providing a 2048-element spectral array. The spectrograph resolution is 75 microns. Using the first order of the grating permits observations in the 850 to 1850 Angstrom Å region with a resolution (full width half maximum) of about three Å. In addition, the second order of the grating can also be used, providing access to the 425 to 925 Å region with 1.5 Å resolution. The time resolution is 1 millisecond in high time resolution mode, 2 sec in histogram mode. Absolute timing is accurate to 3 milliseconds. The maximum event rate (point source) is: 5000 cts/sec across the array, 20 cts/pixel/sec for emission lines, and a 0.001 cts/pixel/sec dark count rate. The instrument sensitivity is such that HUT will be able to observe unreddened B stars to a visual magnitude of 17. Within HUT's photon counting detector system events are recorded in a 1024 channel photodiode array which is read out once per millisecond. Individual photons excite 10-20 diodes and under normal conditions these events are centroided in the SP. The spectrometer/SP operates in four distinct modes: [A] Histogram mode, [B] High-time resolution mode, [C] Cumulative unprocessed mode, and [D] Single scan mode. The first two modes will be used in flight for observations of astrophysical objects. The last two modes are unprocessed modes which are used only for diagnostic purposes; they are not discussed further. In the histogram mode, a 2048 bin histogram containing the spectrum of the target is sent to the ground every two seconds. The spectrum of the target accumulates throughout an observation (which provides redundancy if there are telemetry dropouts). By differencing two successive histograms, the events detected in a two second interval can be recovered. In this mode, event rates as high as 5000 events/s can be accommodated (the count rate limitation is set by the rate at which the SP can centroid events, plus concerns about the ability of the intensifier to handle very bright sources, and the number of events on a single scan of the photodiode array that can be tolerated). This is the normal observing mode for observations of bright sources. In the high-time resolution mode, the individual centroided events are encoded into the data stream in such a way that the time of the event can be recovered (to an accuracy of approximately 3 ms). Because of telemetry limitations, the high-time resolution mode is only useful for sources with counting rates less than 500 events/s. A histogram of the source is also accumulated in high-time resolution mode and periodically sent to the ground. This is the normal observing mode for low count rate sources.

## **HYBRID (Proliferation and Performance of Hybridoma Cells)**

(STS-42) ESA

The hardware, i.e. cell culture flasks and syringes, were identical to those used in a previous experiment in Biorack. Cultures of Hybridoma cells ( $0.75 \times 10^5$ /ml) suspended in minimum essential medium Iscove containing 2 mM L-glutamine, 25 mM HEPES, supplemented with 10 mM sodium bicarbonate, 50 microg/ml gentamycin and 10% fetal calf serum (pH 7.35) were sealed into 16 culture flasks, 5 ml each (8 flask for the flight experiment, 8 for the ground control). Incubation at 37degC was started 8 hours after launch (4 cultures at 0 g and 4 on the 1 g reference centrifuge). After an incubation time of 49 and 102 hours, 3H thymidine was injected into 4 cultures, two at 0 g and two at 1 g, respectively (final concentration: 8 microCi/ml). Incubation was continued for another 5 hours. Finally, dimethylsulfoxide was injected prior to storage at - 20degC. The other containers were cultured for 88 hours after which they were labeled and preserved as described above.

### **Imaging Spectrometric Observatory (ISO)**

(STS-9, 45) University of Michigan, Ann Arbor

The flight instrument was designed for high-speed operation as an imaging device, and was composed of five modules containing identical spectrometers, each of which was restricted to a given spectral range within the 20- to 1200-nm region. Each module was an imaging scanning spectrometer, and the modules had coincident 0.5- x 0.007-deg fields of view. Imaging capability was obtained along the length of the observational field by use of an area array detector comprising 190 x 244 elements. Thus, a single measurement produced adjacent spectra in a given module obtained from adjacent observational fields. Wavelength resolution varied between 0.2 and 0.6 nm over the spectral range. A scan mirror was used, and a single exposure at one scan position covered a 250-nm region. The telescope was baffled, and it had several operating modes. On STS-45, it also made observations for the Energetic Neutral Atom Precipitation (ENAP) Experiment. The objective of the ENAP experiment is to measure very faint emissions at nighttime arising from fluxes of energetic neutral atoms in the thermosphere. The experiment will measure the optical emission produced by neutral atoms on trajectories that intersect the thermosphere. The ISO was designed to for daytime spectral observations, and the ENAP will use ISO for nighttime measurements because of the faintness of the emissions and the relatively low level of magnetic activity expected.

### **IMAX Cargo Bay Camera**

(STS-41D, 41G, 61B) IMAX Corporation, Canada

The IMAX project is a cooperative effort between the Canadian IMAX company and NASA. The system uses a specially designed 70mm film camera to record color motion images on specially sprocketed film. During this flight, the IMAX camera will be used to document payload bay activities associated with the EASE/ACCESS assembly during the two planned space construction walks. The camera is mounted in the payload bay in a pressure-sealed container with a viewing window. The window has a sliding door which opens when the camera is in operation. The camera is controlled from the aft-flight deck, exposing the film through a 30mm fisheye lens.

### **Inflight Blood Collection System (IBCS)**

(STS-9, 51B, 51F, 40, 58, 71, 78, 90) NASA

The Inflight Blood Collection System (IBCS) is a system designed to collect blood samples from crewmembers in flight. The system is composed of Flight Day Assemblies and Work Trays. The trays include laboratory blood drawing items such as catheters, infusion sets, various sizes of vacutainers, needles, saline syringes, etc. The use of needles has been minimized by replacing sharp needles with blunt tipped plastic cannules and blunted needles where possible (sharp needles are only used for initial venipuncture). The IBCS contains four different types of experiment support kits. These items are used in the collection and processing of blood samples for Spacelab experiments. These kits include:

1. Blood Collection Kit (equipment required for blood collection on each sampling day)
2. Blood Spares Kit (vacutainers, butterfly infusion sets, and syringes for contingency blood draws)
3. Blood Work Kit (slides, hematocrit tubes, hematocrit centrifuge, etc. for hematology workups)
4. Accessories Kit (heparin and small vacutainer tubes needed for sequential blood draws using indwelling catheters).

Preassembled blood collection components are prepackaged and sterilized on the ground for inflight use. Wrist bands are worn by the crew to protect the inserted catheter between blood draws. No sharp objects are exposed and all glass is covered with Teflon tape and shrink tubing to prevent shattering. All IBCS items are restrained within cloth and/or foam assemblies. A glove container is used to dispense gloves worn by the crew during blood collection activities. The configured assemblies are stowed in a middeck or Spacelab stowage locker during flight.

### **Infrared Telescope (IRT)**

(STS-51F) NASA

The instrumentation consists of a small Herschelian telescope (15 cm in diameter with an f/4 off-axis) cooled to 3 deg K. It scans at the rate of 6 deg/s and covers a 90-deg arc across the sky. The focal plane contains 10 detectors, nine of which cover the region from 4 to 120 micrometers in three non-overlapping broad bands (4 to 9, 12 to 24, and 50 to 120 micrometers). One detector has a narrow-band response at the H<sub>2</sub>O and CO<sub>2</sub> band locations (6 to 7 and 14 to 16 micrometers, respectively). The detectors cover a full 3 deg perpendicular to the scan direction. There is also a movable cold shutter to provide an absolute zero flux reference for each band. The stored liquid helium cooling system is composed of a liquid helium Dewar containing liquid helium at 1.5 deg K, a transfer line assembly, a vapor-cooled telescope cryostat, and a cryostat vacuum cover. Experiment mass: 690 kg; average experiment power: 125 W

### **Ingestible Temperature Monitoring System (ITMS)**

(STS-78, 90) NASA

Body temperature is measured using the Ingestible Temperature Monitoring System (ITMS). The ITMS consists of an ambulatory recorder unit with an attachment belt and pouch, antenna harness and disposable temperature sensor. The belt-mounted recorder is connected to the antenna coil worn on the subject. The recorder receives the temperature signals transmitted by the ingested temperature sensor, displays the temperature on a two-line liquid crystal alpha-numeric display, and stores up to 4500 individual time and temperature readings in 16K RAM memory. Selectable features such as sampling rates, temperature scales and limits, filter modes and other settings are keypad programmable. The unit operates on one 9 volt alkaline battery which provides approximately 12 hours of use. The display will flash a warning and an audible tone will sound when the battery is low or when a sensor may have been passed. The recorder dimensions are 20.3 x 13.7 x 7.6 cm and the mass is 1000 grams. The ingestible temperature sensor is a small electronic device that utilizes a temperature sensitive crystal to sense the core body temperature and transmit that temperature to a receiver antenna that is within approximately 25 cm. The sensor is intended to be swallowed. The entire sensor is totally encapsulated first in an inner epoxy shell and then in a dimethyl polysiloxane silicone outer coat. Power is provided by a non-rechargeable silver oxide mini-battery which provides 100 hours of operation. The sensor can be turned on and off by means of an enclosed magnetic switch. The sensors are stored with magnets attached in order to keep the batteries turned off. Prior to use, the battery is activated by removing the small magnet. The sensor dimensions are approximately 16mm long and 10mm in diameter and the mass is 3.0 grams.

### **Interface Configuration Experiment (ICE)**

(STS-50, 73) University of California

The primary vessel components are a single-piece acrylic-plastic (transparent) body, an aluminum piston and control dial, stainless steel drive screw and two-port valve, and magnetized feet for securing the vessel to the Glovebox labjack. One of the test fluids is a blend of hydrogenated terphenyl and an aliphatic hydrocarbon, an "immersion" fluid that has a refractive index matched with that of the acrylic container, thus virtually eliminating optical distortions. Two of the vessels contain this fluid. The interior of these vessels is coated with surface modifier FC-723 to produce a desired contact angle. Distilled water is used in the other two containers, which are not coated. The fluids are lightly dyed in order to enhance visibility of the fluid interface. The diagnostics for the tests include two full-color 1:1 video cameras to record the fluid interface configurations, a Glovebox video camera with audio, and devices for the measurement of ambient Glovebox temperature and local acceleration levels. The general experimental procedure for ICE during the USML-1 flight was to partly fill the selected vessels with prescribed volumes of fluid and to record with two video cameras the fluid interface configurations that result.

### **Ionization States of Solar and Galactic Cosmic Ray Heavy Nuclei Studies (IONS)**

(STS-51B) Tata Institute of Fundamental Research, National Centre of Government of India for Nuclear Science and Mathematics

This experiment was designed to study the recently discovered anomalous component of low-energy galactic cosmic-ray ions of C, N, O, Ne, and Ca to Fe of energy 5 to 100 MeV/u in regard to their ionization states, composition and intensity, and to study the ionization states of heavy elements from O to Fe in energetic solar particles emitted during flare events. The detector system serves for both studies, and consists of stacks of thin sheets of cellulose nitrate and lexan polycarbonate which are efficient low-noise detectors for heavy nuclei. The stacks are in the shape of a cylindrical module with a diameter of 40 cm and a height of approximately 5 cm. An energetic particle stopping in the stack leaves a damage trail along its path that can be revealed optically by postflight chemical treatment in the laboratory.

### **Isothermal Dendritic Growth Experiment (IDGE)**

(STS-62, 75, 87) Rensselaer Polytechnic Institute

The IDGE apparatus consists of a thermostat that contains the dendrite growth chamber. The growth chamber is filled with ultrapure PVA before flight and contains a stinger that is used to begin dendrite growth. The stinger is a hollow tube filled with PVA connected to coolers on the outside of the growth chamber. As the stinger is cooled, the PVA in the tube begins to solidify. The solidification front moves down the tube to the tip of the stinger and emerges into the PVA volume as an individual dendrite. Two television cameras “watch” for the emergence of the dendrite. When software in the IDGE computer detects dendrites, it triggers two 35 mm cameras, which photograph the growing dendrites in a programmed sequence. In addition, a video cassette recorder housed within the IDGE apparatus begins recording the dendrite as it grows. The television images are also transmitted to the IDGE science team on the ground.

### **Isothermal Heating Facility (IHF)**

(STS-9, 61A, 55) ESA

The Isothermal Heating Facility (IHF) flew as part of the Materials Science Double Rack on Spacelab-1 and D-1, and an advanced version on D2. The new heater is made of Pyrolytic Boron Nitride (PBN) with deposited graphite surrounded by the Tantalum insulation. The temperature of the furnace is measured by two WRe thermocouples, one of them a combined noise thermometry thermocouple used for calibration of the furnace before and after the mission. The furnace is operated under vacuum (sample environment). The cooling chamber in parallel to the furnace allows the simultaneous heating and cooling of two different samples. After heating and solidification of one sample, heating chamber and cooling chamber will be rotated and switched over. This combined motion of the chambers will be maintained by the transport mechanism, i.e. torque system, a motor and a spindle. The IHF also provides the possibility to conduct gradient experiments. A chill block will then be inserted into the furnace.

#### *Typical Isothermal Experiments*

- Ostwald ripening in metallic melts
- Melting and solidification of metallic composites
- Separation of immiscible melts

#### *Typical Gradient Experiments*

- Particles at melting and solidification fronts
- Skin technology
- Skin casting of grey cast-iron

## **Isotope Stack**

(STS-9) ESA

The experiment objective was to use a stack of plastic sheets to measure heavy cosmic-ray nuclei (nuclear charge equal to or greater than 3, energies in the range 20 MeV to 1 GeV per atomic mass unit) and to determine the source, acceleration, propagation, and age of cosmic rays. The equipment consisted of a stack of layers of plastic visual track detectors housed in a sealed aluminum container.

## **Jellyfish Kit**

(STS-40) NASA

Jellyfish kits contain the necessary materials to maintain jellyfish during flight. The kits are maintained in the Refrigerator Incubator Module (RIM) to provide a constant 28° environment for the specimens during flight. Various hardware is used to support various experiment activities. These include: 1) commercially obtained polystyrene flasks utilized for jellyfish groups requiring inflight filming; 2) a passive bagging system used to maintain those specimens requiring no inflight manipulation; and 3) a bagging system with attached chemical delivery system for specimens requiring inflight treatments. This experiment consist of four distinct kits.

*Jellyfish Bags/Kits:* Jellyfish are maintained in these bags filled with Artificial Sea Water (ASW), at a concentration of 1:3 ratio of air to solution. Kapak bags of polyester with polyethylene lining are utilized. Bags are carefully cleaned and tested for biocompatibility prior to use. Lithium fluoride (LiF) radiation rod dosimeters are added to 6 of the 18 bag configuration in Kit #1 before heat-sealing the bags. Kit #1 contains nonoperative single compartment bags that do not require crew operation on orbit. Kit #2 contains 8 multicompartment syringe/bag assemblies with one to three syringes attached. Each syringe bag has two outer bags for containment and are individually tetherable. Kit #3 is empty and is stowed in the Spacelab refrigerator. The fixed specimens from kit #2 are transferred to the empty kit during the last in-flight procedure and returned to the refrigerator. Kit #4 contains the small culture flasks containing ASW and Jellyfish. The flasks are made of optically clear polyethylene and are used for filming Jellyfish swimming patterns in zero gravity.

*Chemical Delivery Systems (CDS):* Chemical Delivery Systems (CDS) were developed for the introduction of chemicals to the jellyfish in space. Kapak bags of polyester with polyethylene lining were modified for attachment to syringes via plastic housings. These are carefully cleaned and tested for biocompatibility before launch. Three days before flight, chemicals are placed in small plastic bags inside the syringe barrels of the CDS. Iodine and thyroxine are injected into the bags containing the animals during the flight, to achieve a final concentration of 10 to the -5th M in ASW. The CDSs are contained within inner and outer plastic bags to achieve triple containment.

## **Kinelite Processing Module (PM)**

(STS-90) CNRS

The Kinelite Processing Module (PM) is a rack-mounted computerized video system designed to record and analyze complex body movements. It consists of real-time processing of TV images and is used to recognize and provide coordinates of multiple passive markers. Infrared flashes illuminate the markers that are recognized in the images by using a brightness threshold. The computer can then calculate the 3-D coordinates of the reflective markers and all the cinematic data off-line. Signal cables connect the PM to the Ball Launcher, the Camera Illuminator Equipment (CAMILLE), and the Electromyograph (EMG) Unit. There are 4 camera cables, one Ball Launcher Cable, and one EMG Unit cable. Experiment control and tracking of the status of all key system components is done by the PM. Data from the CAMILLE is digitized and compressed then stored on the removable hard drive, while control views are recorded on a Hi8 video recorder. The removable hard drive is a standard SCSI-2 Toshiba 810 megabyte disk, model

MK2628FB, with a transfer data rate of 1 megabyte per second over a fast SCSI-2 bus (10 megahertz maximum throughput). The disk is powered by the PM with a maximum consumption of 3 Watts.

### **Lambda Point Experiment (LPE)**

(STS-52) Stanford University

See also: Confined Helium Experiment (CheX).

A sample of helium cooled far below its lambda point will be placed in a low-temperature cryostat (an apparatus used to keep something cold, such as a thermos bottle). During a series of 2-hour runs controlled by an onboard computer, the helium's temperature will be raised through the transition point by a precision temperature-control system. Sensitive instruments inside the cryostat will measure the heat capacity of the liquid helium as it changes phases. The temperature of the helium sample will be maintained to within a billionth of degree during the experiment.

### **Large Format Camera (LFC)**

(STS-41G) NASA

The Large Format Camera (LFC) was a photographic camera with a 305-mm focal length, an F/6 aperture, and a film format of 23 by 46 cm. The objective was to evaluate the utility of orbital photography for cartographic mapping and land use studies at scales of 1:50,000. To minimize smearing effects, the camera's film platen moved horizontally along the Shuttle's line of flight when the shutter was open. A ground resolution of 10 m was achieved at altitudes of 200 to 250 km with standard photographic films. The LFC was able to obtain overlapping stereoscopic coverage along the Shuttle's flight path with base-to-height ratios of 0.3, 0.6, 0.9, and 1.2.

### **Large Isothermal Furnace (LIF)**

(STS-47, 65, 83/94) NASDA

This furnace heats large samples uniformly at a maximum temperature of 1600 C. The furnace flown on STS-47 consisted of a sample cartridge and a heating element surrounded by a vacuum chamber. A crew-member inserts a sample cartridge into the furnace, and then the experiment operations are controlled automatically by computer. At the end of the experiment, the sample is cooled by a water jacket and/or by a continuous flow of helium through the furnace, which will cool samples rapidly.

For STS-65, the furnace had a similar setup to the one flown on STS-47. A screw-type connector secures the sample in the furnace. Air within the chamber is evacuated through the Spacelab vent system. The furnace control equipment runs through a pre-programmed heating/cooling cycle to process the sample, and data from temperature sensors are recorded. A gas-driven piston within the sample cartridge can be used to apply pressure to the sample during the experiment. At the end of the experiment, helium gas is injected into the furnace to allow rapid cooling of the sample. The cartridge is then removed and another can be installed to start a new experiment. Sample cartridges are returned to Earth for analysis.

For MSL-1 (STS-83/94), the furnace has been modified to allow ground commanding of the heating and cooling processes so that investigators can make real-time changes to enhance science operations. The furnace consists of a sample container and heating element, surrounded by a vacuum chamber. A crew-member will insert a sample cartridge into the furnace, locking it in place. The furnace will be activated, and operations will be controlled automatically by a computer in response to an experiment number entered on the control panel. At the end of operations, helium will be discharged into the furnace, allowing cooling to start. Cooling will occur through the use of a water jacket, while rapid cooling of samples can be accomplished through a controlled flow of helium. Two of the five LIF experiments that study diffu-

sion will use the Shear Cell Method, which involves two sample columns with different concentrations of materials. The two columns will be melted, then rotated into contact with each other for a predetermined amount of time. The single column will be sheared into segments and allowed to cool. One experiment will make use of the Middeck Glovebox to take preliminary resistance measurements of its shear cell samples, so that the processing of the next sample can be modified based on these results.

### **LIDAR In-Space Technology Experiment (LITE)**

(STS-64) NASA

The LITE instrument was carried in the Shuttle cargo bay on a standard Spacelab pallet. The instrument was mounted on an orthogrid platform attached to the pallet by 52 struts. The orthogrid is a support platform for the instrument subsystems and was designed to be immune to thermal deformations which could affect optical alignment. A description of the major LITE subsystems follows.

*Receiver Assembly:* The receiver includes a one meter telescope and an aft-optics package. The telescope collects laser light scattered from the atmosphere, and brings it to focus in the aft optics. The aft optics includes wavelength selective optics to separate the return signal into its three color components. The 532 nm and 355 nm detectors are photomultiplier tubes, while the 1064 nm detector is a silicon avalanche photodiode.

*Boresight Assembly:* The boresight assembly consists of a two-axis motor-driven prism. Its purpose is to align the laser beam to the telescope field-of-view so that both point to the same column of atmosphere.

*Laser Transmitter Module (LTM):* The LTM consists of two flash lamp-pumped, Q-switched Neodymium:YAG lasers which emit simultaneously at the three harmonically related wavelengths of 1064 nm (infrared), 532 nm (visible green), and 355 nm (ultraviolet). The two-laser system provides redundancy in case one laser fails. Only one laser operates at a time.

*Orbiter Experiments Autonomous Support Instrumentation System (OASIS-I):* The OASIS-I is a data-logging, subsystem which was used to record accelerations, acoustic loads, strains temperatures, thermal flux and pressures during the launch, ascent, on-orbit, descent, and landing phases of the LITE mission.

*Camera Assembly:* The LITE camera is a modified half-frame 35 mm camera originally used for aerial reconnaissance. It was used to photograph the Earth's surface and cloud cover during the daylight portions of orbits when lidar data were acquired. A 25 mm focal length lens was used, giving a coverage of 200 X 200 km<sup>2</sup>. The time interval between photographs is approximately 21 seconds, giving roughly 20% overlap between successive frames. A GMT time stamp recorded on each frame was used to determine the latitude and longitude on the surface of the Earth that corresponds to the center of each frame.

*Instrument Controller:* The Instrument Controller (IC) handles all command and data interfaces of the LITE instrument. All subsystems could be commanded and controlled via the IC. Health and status of the LITE instrument are monitored and transferred to the Spacelab's Smart Flexible Multiplexer/Demultiplexer (SFMDM). The IC software consists of over 18 real-time Ada tasks that perform all commands and data interfaces for the IC as well as autonomous operations.

### **Life Sciences Laboratory Equipment (LSLE)**

(STS-51B, 40, 42, 47, 58, 71, 78, 90) NASA

(STS-90) *Actigraph:* The LSLE Activity Monitor (Actigraph) is a wrist-worn instrument that records body motion. The device uses a piezoelectric sensor to detect zero crossings. The zero crossing counts are stored in a 64K RAM memory chip that uses an interface unit to a PC for initialization and memory download. The interface unit is not flight-qualified so the analysis and initialization is performed on the ground. Memory capacity depends on the data packing option selected. The number of counts stored during a time period or epoch is programmed pre-flight. The packing options are optimized for expected activity (awake or sleep), memory capacity and battery life. The unit is powered by two 160 mAH lithium cells powers.

The actigraph uses a wristband made of Nomex and Velcro to meet flight material requirements and ease of attachment in microgravity.

(STS-51B, 40, 78, 90) *Microcomputer I/II*: The Biotelemetry System (BTS) animal ECG rate is up to 320 samples per second; the other parameters are sampled at a rate of one sample per second by the LSLE Microcomputer. Data can be stored for later transmission or down-linked to Earth by radio transmission in realtime or near-realtime. Life Sciences Laboratory Equipment (LSLE) Microcomputer: The JSC developed LSLE Microcomputer is designed as a stand-alone computer for use with flight experiments onboard the Shuttle. A flexible system design allows the experimenter to use the microcomputer to accomplish a variety of experiment computer operations, by interfacing with Spacelab data systems for telemetry and/or onboard interaction. It is designed to assemble and format data into uniform major and minor frames for transmission through the Shuttle high rate multiplexer (HRM) to the ground. During SL-3, the microcomputer assembled, formatted and time-coded the BTS data for HRM transmission, after converting the signal from analog to digital. It is operated only during orbit, and was activated by the crew via a front panel switch. This is the only switch manipulated on-orbit and activation is verified on the RUN LED displaying four sevens (7777) when the switch is turned on. It is turned off following deactivation of the Biotelemetry System (BTS).

(STS-40, 58, 71, 78, 90) *Rack Mounted Centrifuge*: The Rack Mounted Centrifuge provides processing of up to 48 samples per operation. It gives a variety of centrifuge capabilities for separating biological samples during flight. This item is rack-mounted on slides and is pulled out for loading/unloading of samples. It is operated only when pushed back into the rack. It has protective circuitry that regulates both the speed and duration of acceleration; this circuitry also prevents excessive speed or continued operation with the rotor out of balance. There is an automatic shut-down timer that may be manually set for operating durations selectable up to 60 minutes. An override is provided that enables manual start and stop without intervention of the timer. Rotors: Two types of rotors are interchangeable in the centrifuge, each providing different capability. The bucket rotor is used for specimens requiring acceleration from 50 to 1600 times gravity. This rotor can hold four buckets containing tube holders that swing out 90 degrees during centrifugation. A retention knob holds the rotor in a secure position in the centrifuge. Each bucket with tube holder can accommodate 12 tubes containing 5, 10 or 15 ml of a sample, or one bucket may contain all three size tubes. The Fixed Angle Rotor provides acceleration speeds from 35 to 4000 times gravity. The specimens are centrifuged at 35 degree fixed angle. Several rotors are available which have holes for placement of twenty-four 10 or 15 ml tubes or ten 50 ml tubes.

(STS-40, 42, 47, 58, 71, 78, 90) *Refrigerator / Freezer* : The Life Sciences Laboratory Equipment (LSLE) Refrigerator / Freezer (also known as the Spacelab Refrigerator / Freezer) was designed by Johnson Space Center (JSC) to support a wide variety of life sciences investigations. It is normally used to freeze perishable samples such as blood, urine or saliva and preserve them for postflight analysis. It can also be used to house small animals, to incubate amphibian zygotes, or to stow animal food supplies. The Refrigerator / Freezer functions either as a refrigerator or as a freezer and has a temperature range from -22 degrees Celsius to +10 degrees Celsius. The unit has an internal volume of 2.5 cubic feet (larger than its equivalent in the Orbiter) and is designed to accept experiment racks, shelves and containers. The Refrigerator / Freezer is integrated into a standard Spacelab double rack. The entire unit measures 42 inches in height and 19 inches in width. The control panel is allocated in the upper front, while the cooling chamber itself is below. It has a modified double-headed commercial compressor and a specially designed condenser and evaporator. The Freon loop of the LSLE Refrigerator / Freezer is double contained. It has a thermal load to the Spacelab cabin of 345 BTU/hour in the refrigerator mode, 235 BTU/hour in the freezer mode and

the electronics contribute another 315 BTU/hour each for the refrigerator or freezer modes. Air for the compressor/condenser and for electronics enters through inlet ducts at the top of the unit and is exhausted through outlet ducts at the bottom. Several controls and displays allow the astronauts to monitor the unit. A Selector Switch designates between refrigerator or freezer operations, and is normally set by the ground crew prior to launch. The Readout Temperature Display (RTD) is a digital readout of the temperature inside the cooling chamber (display ranges from +99 to -99 degrees Celsius). The RTD is constantly powered during nominal operations. Three indicator lights monitor the compressor operations, the Freon pressure (lights up in case of low pressure), and pressure in the cooling system (indicating leaks from the outside). An Emergency Switch allows activation of the emergency mode during power failure. During this mode, spacecraft power is directly applied to the compressor and cooling fans, while the control elements such as the RTD are removed from the circuit. To obtain a quick temperature reading, the RTD can be momentarily powered by the Momentary Temperature Readout push button.

### **Lower Body Negative Pressure Device (LBNP)**

(STS-40, 47, 50, 65, 71, 73, 90) NASA

The lower body negative pressure device provides a controlled, measured orthostatic stress to the cardiovascular system. This item is configured as a cylindrical chamber made of anodized aluminum, with nominal measurements of approximately 51 cm in diameter and 122 cm in length. The cylinder separates longitudinally to provide access to the legs and to provide ease of installation of the leg band; closure of the cylinder is effected by bringing the two parts together and fastening with a Marmon clamp. To maintain negative pressure within the chamber, movable superior and lateral iris-like aluminum templates, installed around the elliptical opening, are adjustable to fit snugly to the subject's lower waist at the iliac crests. An adjustable padded post, which serves as a saddle or crotch restraint, is located within the chamber. It can be adjusted headward or footward so that the iliac crests of the subject are at the level of the metal templates. The movable upper torso restraint assembly supports the person's upper torso while his/her lower body is within the LBNP Device. It retracts to a stowed position beneath the chamber when not needed. When deployed, it extends outward from the LBNP Device opening for 63.5 cm. Decreased pressure within the device is provided by a vacuum plenum. Safety features include a quick-release valve, easily accessible to subject and observer, and an automatic mechanism to prevent negative pressure from exceeding 65 mm Hg. Pressure within the LBNP Device is vented to the room via the vacuum release valve. The pressure is maintained by setting the vacuum regulator at 0 to 50 mm Hg below ambient pressure. For the STS-71 flight, the Automatic Blood Pressure Monitor was added.

The Automatic Blood Pressure Monitor (ABPM) is designed to calculate and record blood pressure of a subject. It can be programmed to measure absolute blood pressure (10 to 250 millimeters of mercury) at almost any interval. The method of measurement is auscultatory, using Korotkoff sounds (K-sounds) to determine systolic and diastolic blood pressure. R-wave gating reduces the effects of motion so that use by ambulatory patients produces accurate readings. This monitor is manufactured as the Accutacker II by SunTech Medical Instruments. The ABPM receives power from four (4) "M" alkaline batteries, and provides backup memory through a small lithium cell. Its dimensions are 120 mm long x 90 mm wide x 33 mm high, and its mass is 0.36 kg.

### **Magnetic Resonance Imaging (MRI) Device**

(STS-47, 55, 78) NASA

Magnetic Resonance Imaging (MRI) is a technique that allows imaging of the interior of the body without the use of ionizing radiation. MRI technology is based on the fact that the nuclei of certain atoms, when placed in a magnetic field, will tend to align with the magnetic field. This is true in general of any nucleus

with a non-zero magnetic moment, but hydrogen is the element used almost exclusively in medical applications. This is because of its abundance in biological tissues and large magnetic moment that makes it by far the easiest element to image. Several other biologically important elements (carbon, oxygen, and calcium) do not have a magnetic moment and therefore cannot be used in MRI. In the presence of a strong magnetic field, the hydrogen nucleus can be likened to a top precessing about the gravitational field; the nucleus precesses about the applied magnetic field of the magnet. This precession has a frequency that is determined by the strength of the magnet and the magnetic moment of the nucleus that is characteristic of a particular element. For magnets used in medical imaging this frequency is typically in the range of FM radio waves. By controlling the magnetic field and the frequency and phase of the radio frequency (RF) pulses, images can be obtained in any desired orientation. Information regarding a particular part of an object is obtained by applying magnetic field gradients (which are small relative to the main field) so that the hydrogen in different slices will precess at different, but known frequencies. By applying RF pulses at a particular frequency, the nuclei in a particular slice can be excited. As the energy from this slice is dissipated, a receiver measures the resulting signal to obtain information unique to this region of the object. Image contrast is achieved by varying the sequence and types of RF pulses. For each image, a series of pulses are required (typically 256) with a period between the pulses (typically 1 second) to allow the system to return to its original state. The decay characteristics of the MRI signal are determined by the chemical and physical state of the hydrogen. This property allows to easily distinguish between various tissues such as fat, muscle and spinal disks, and by adjusting the imaging parameters the sequence for the tissue of particular interest can be optimized.

### **Marangoni Convection in Closed Containers (MCCC)**

(STS-50) UAH

Two glass ampoules will be tested, one with water and one with silicone oil, both containing glass tracer beads. Each ampoule has a set of heaters and thermistors. The crew will record the onset of Marangoni convection during heating with video and the 35mm camera.

### **Materials Experiment Assembly (MEA)**

(STS-7, 61A) NASA

The MEA is a self-contained facility that provides accommodation for multidiscipline experiments in the materials processing field. MEA was developed for NASA's OSTA-2 (STS-7) mission, on which it housed (1) the SAAL, (2) the GPRF, and (3) a three zone electric furnace. On STS-61A, the MEA held the following experiment facilities: (1) SAAL, (2) Gradient GPRF and (3) Isothermal GPRF, supporting experiments in vapor crystal growth, immiscible alloy solidification, and containerless processing of glass forming melts.

### **Materials for the Study of Interesting Phenomena of Solidification on Earth and in Orbit (Material pour l'Etude des Phenomenes Interessant la Solidification sur Terre et en Orbite) (MEPHISTO)**

(STS-52, 62, 75, 87) CNES

The cylindrical-shaped MEPHISTO furnace experiment contains three identical rod-shaped samples of a tin-bismuth alloy. MEPHISTO will process the samples using two furnaces, one fixed and one moving. As a run begins, the mobile furnace will move outward from the fixed furnace, melting the samples. The mobile furnace then moves back toward the fixed furnace, and the sample resolidifies. The fixed furnace contains a stationary solid/liquid interface to be used as a reference for studying the mobile solid/liquid interface. During the experiment runs, a small electrical voltage will constantly measure the temperature changes at the interface to verify solidification rates. During the last experimental run, electrical pulses will be sent through one sample, "freezing" the shape of the interface for post-mission analysis. During

the mission, scientists will compare the electrical signal to data from a SAMS sensor to see if the Shuttle's movement is disturbing the interface. They then can make adjustments to the experiments if necessary. Post-mission analysis of the space-solidified sample will allow correlation between the electrical measurements and changes in the sample.

### **Material Science Autonomous Payload (Materialwissenschaftliche Autonome Experiments unter Schwerelosigkeit) (MAUS)**

(STS-7, 55) BMFT

The Material Science Autonomous Payload (MAUS) on OSTA-2 held four experiments, including (1) Critical Marangoni Number; (2) Fundamental Studies in the Manganese-Bismuth System; (3) Particle Transport Induced by Directional Solidification; and (4) Stability of Metallic Dispersions. The MAUS consisted of three instruments; each was contained in a get-away-special (GAS) canister. Each cylindrical canister carried an experiment furnace, which was thermally insulated, and had its own service module. On Spacelab D-2 the MAUS experiments consisted of the following: (1) Pool Boiling; (2) Gas Bubbles in Glass Melts; and (3) Reaction Kinetics in Glass Melts.

### **Materials science Experiment Double rack for Experiment modules and Apparatus (MEDEA)**

(STS-61A, 55) DFVLR

The Material science Experiment Double rack for Experiment modules and Apparatus (MEDEA) is composed of three largely autonomous experiment facilities, including the Gradient Heating Furnace with quenching capability for metallurgical and directional solidification, a Monoellipsoidal Mirror Furnace for crystal growth, and a High Precision Thermostat. The high precision thermostat measures specific heat at the critical point of a specimen.

### **Materials Science Facility (Werkstofflabor)**

(STS-9, 61A, 55) DFVLR

See: **Werkstofflabor**

### **Measurement of Air Pollution from Satellites (MAPS)**

(STS-2, 41G, 59, 68) NASA

The Measurement of Air Pollution from Satellites (MAPS) equipment consisted of an electro-optical head, an electronics module, a digital tape recorder, and an aerial camera. The core of the MAPS instrument was a nadir-viewing gas filter radiometer operating at the 4.67-micrometer CO band. The instantaneous field of view was approximately 20 by 22 km. The equipment was coupled to a cold plate and mounted on the experiment pallet shelf. The aerial camera was mounted alongside the MAPS electro-optical head to provide information on cloud cover and the terrain over which the data were gathered.

### **Measurements of Solar Spectrum Package**

(STS-9) CNRS

The experiment objective was to measure the solar spectral irradiance between 170 and 3200 nm with an accuracy of 0.1% in order to determine the solar constant, variations in the solar constant with solar cycle using Spacelab/STS flights over a 10-year period, and variations of irradiance within each spectral region. The equipment consisted of three grating spectrometers covering UV (170 to 370 nm), visible (350 to 900 nm), and IR (800 to 3200 nm).

### **Mental Workload and Performance Experiment (MWPE)**

(STS-42) Massachusetts Institute of Technology (MIT)

The Mental Workload and Performance Experiment examined the effect of microgravity on the ability of crew members to perform tasks requiring interaction with a computer workstation. The IML-1 crew has a redesigned microgravity workstation with an adjustable surface for their daily planning sessions and record keeping. Cameras record the crew's range of motion and variety of positions while at the workstation. Films and videotapes, reports from the crew, and measurements of the locations of the adjustable surface will influence the design of workstations for future missions and for Space Station Freedom. A second piece of equipment is evaluated during tests of mental function, reaction times, and physical responses. A portable microcomputer with its display monitor and keyboard are attached to a Spacelab rack handrail and positioned in the most convenient location by a crew member who then follows a program displayed on the computer monitor. After memorizing a sequence of characters, the crew member moves a cursor to corresponding targets on the screen using three different devices: keyboard cursor keys, a two-axis joystick, and a trackball. The microcomputer records the speed and accuracy of the movements and the time needed to interpret the instructions. These data are complemented by the crew's evaluations of the equipment. Because different fine motor skills are involved in manipulating the devices, the results of the exercise will shed light on the most efficient design for performing specific computer tasks in space.

### **Mercury Iodide Crystal Growth (MICG)**

(STS-9, 51B, 42) CNES

On Spacelab 1, a simple furnace heated a mercury iodide source and caused it to evaporate and condense in a cooler part of the container to form small crystals. The experiment was repeated on Spacelab 3, with the crystal growth occurring within ampoule cartridges in a two-zone furnace having different temperatures at each end, and with differing pressure conditions. The instrumentation included two heat-pipe furnaces, each holding three cartridges, and six ampoule cartridges enclosing mercuric iodide seed crystals and source material. The IML-1 investigation uses six single-seed crystals obtained from mature crystals grown on the ground. They are placed in separate containers to grow large crystals under controlled conditions. The furnace holds three samples, each inside a clear ampoule surrounded by stainless-steel cartridges, with the heating element located between the ampoule and the steel container. At the beginning of the experiment, a crew member inspects the ampoules, places them in the facility, and turns it on. Periodic checks are made of furnace temperature, and adjustments are made at the request of the investigator. Three temperature zones exist between the hot end (source) and the cold end (sink) of each ampoule. The payload scientist increases the temperature at the mercury iodide source in 1-C increments from 107.5 to 111.5 C. As the source is heated, it evaporates and moves through the cartridge. Some source material is distributed symmetrically around a 2-mm (0.08-in.) seed in the center of the ampoule; the seed is mounted on a small pedestal kept slightly cooler. Additional source matter is deposited in the cold sink so that it does not condense and form small crystallites near the seed crystal.

### **Metric Camera Experiment**

(STS-9) ESA

The purpose of the metric camera experiment was to test the mapping capability of high-resolution space photography. The experiment used a Zeiss RMK A30/23 aerial survey camera and a Skylab optical window having the following characteristics:  $f = 305$  mm;  $f$ -stops available-- $f/5.6$ ,  $f/8$ ,  $f/11$ ; shutter speeds-- $1/100$ ,  $1/250$ ,  $1/500$ , and  $1/1000$  s; negative size-- $23 \times 23$  cm (length for 550 photos per magazine); angle of field-- $56^\circ$ ; and ground resolution-- $20$  m. Black-and-white, color, and color IR films were used. To obtain 80% longitudinal overlap of subsequent photographs at a Spacelab velocity of  $7.7$  km/s, there was a time interval of about  $5$  s between two successive exposures. Strips  $1800$  to  $2300$  km in length were covered on the ground in each sequence.

### **Microabrasion Foils (MFE)**

(STS-3) University of Kent, Canterbury

The MFE comprises a double layer foil structure of one square meter total area. The top layer of 5 micron aluminum foil is held 1.0 mm above a Kapton sheet by a gold-coated brass grid and forms an array of capture cells – effectively a miniature meteoroid bumper.

### **Microgravity Analysis Work Station (MAWS)**

(STS-73, 75, 78, 87) NASA

The Microgravity Analysis Work Station (MAWS) is an analytic solution of the microgravity environment. It is a PC-based program that receives telemetry from the Shuttle and presents the computed acceleration values in a graphical format. The telemetry used is a standard product on the Shuttle with items such as the position and velocity along with attitude information. These items are sent to the ground via the TDRS network and then sent to the POCC located at MSFC in Huntsville, Alabama. The MAWS pre-mission simulation uses a 6 degree-of-freedom (6 DOF) model of the Shuttle to calculate the accelerations. During the mission the 6 DOF model is replaced by the real-time telemetry data. MAWS is able to determine the microgravity environment at any point on the orbiter. On USML-2 MAWS analysis proved invaluable for calibrations and testing on several on-board sensors. One of the on-board sensors (OARE) downlinked their actual sensor data of the accelerations and sent it to the MAWS via the Internet.

### **Microgravity Measurement Assembly (MMA)**

(STS-55, 78, 83/94) ESA/DLR

This was the core acceleration measurement system on the Spacelab D-2. It consisted of 6 tri-axial accelerometers, four of which were permanently mounted in the equipment rack. The following were experiments included on MMA: (1) Residual Acceleration in Spacelab D-2 - examined deviations in the spacecraft dynamic state which result in residual gravity-like accelerations; (2) Transfer Function Experiment - covered the empirical and systematic investigation of the disturbance transmissibility characteristics and transfer functions of the spacecraft structure under microgravity conditions. The MMA on MSL-1 was a microgravity monitoring system capable of providing real-time display of accelerations detected by seven sensor heads that measure accelerations in three axes. Four of these sensor heads will be deployed in Spacelab racks, where many gravity-sensitive investigations are located. Most of the MMA sensors can detect accelerations in the 0.1- to 100-Hz range. One sensor, called the Accéléromètre Spatial Triaxial Electrostatique (ASTRE) measures accelerations below 1.0 Hz. The ASTRE working principle is based on keeping a proof-mass motionless in a fixed position and attitude by electrostatic suspension. By measuring the strength of the electrostatic force that is required to keep the proof-mass stationary, scientists can measure the acceleration levels in three dimensions. The analog data from the sensors are routed to the instrument's central Microgravity Measurement Electronics computer for processing, formatting, and downloading.

### **Microgravity Vestibular Investigations**

(STS-42) NASA

The Microgravity Vestibular Investigations use equipment specially designed or modified for Spacelab. A rotating/oscillating chair system tests the crew member's visual and vestibular responses to head and body movements. The chair's position on the rotator/oscillator can be changed so that a crew member is seated upright and turns around the yaw axis (from left to right), lies on one side and moves around the pitch axis (backward and forward), or lies on the back and moves around the roll axis (head over heels). The chair system also has three velocity patterns: sinusoidal (traveling predictably back and forth over the same distance at a constant speed), pseudorandom (moving back and forth over varying distances and at changing velocities), and stepped (beginning and stopping suddenly). The system is located in the Spacelab

rear center aisle and is controlled by a crew member using a computer. Each crew member being tested wears a helmet assembly with accelerometers to measure head movements and two moveable visors that fit over the left and right eyes independently. Two helmet modules can be mounted on the visors. The camera module contains a video camera that records vertical, horizontal, and torsional eye movements. (Torsional eye movements are produced when the head rotates in the roll axis.) On one eye, the subject wears an opaque contact lens marked with two white dots. The lens shuts out light, and the dots provide a reference to determine how much the eye torsions in its socket when the subject is rotated. The video camera recordings of the movement of the dots on the lens measure eye movements. The optokinetic stimulus module contains a motor-driven, black-and-red checkerboard pattern that moves at variable speeds and directions (horizontal, vertical, and oblique) to provide a moving visual display in front of the eye. In addition, when free-floating, the subject wears a pair of binocular optokinetic stimulus goggles. The goggles contain a motor-driven, black-and-red-striped pattern that also moves at variable speeds and directions. The helmet interface box, an electronics package mounted on the rotator/chair assembly, sends experiment sensor data to the experiment control and display interface located in a Spacelab rack. This equipment sends control signals to the helmet interface box, displays data for the experiment operator, and has a data downlink through Spacelab equipment to scientists on the ground.

### **Microneurography System**

(STS-90) Vanderbilt University

Adapted specifically for the constraints of spaceflight, the Neurolab microneurography system (MNS) provides for detection of the Muscle Sympathetic Nerve Activity (MSNA) of a crewmember via an electrode recording of the peroneal nerve traffic. The raw nerve traffic signal (5-20mV) is amplified 40,000 to 100,000 times to produce a bandwidth filtered (0.5-2 kHz) neurogram, which is then rectified and integrated to produce the final neurogram recording. The system is used in conjunction with Lower Body Negative Pressure (LBNP). The subject is placed in the LBNP Bag with the leg restrained with LBNP leg straps and knee brace. The LBNP Mylar layers serve as a Faraday cage, thus shielding the sensitive microneurography needle from electromagnetic interference. For positioning of the microneurography electrode (a thin needle with a diameter of approximately that of a human hair — 200 microns), the operator is aided by the bandwidth filtered neurogram display on an LM2 screen, acoustic cues to the nerve location through a set of headphones, and visual foot movement generated by the H-Reflex Stimulator.

The system consists of the following:

*Control Box* - The microneurography control box can be strapped to the leg of the operator and provides necessary controls (gain, low and high pass, offset, discriminator, and volume) to “fine tune” the signal. It has connectors for pre-amp, power, LM2 interface, and headphones.

*Pre-Amp* -The pre-amp system is a 1000 gain amplifier grounded to the thigh of the subject, and it is 2-fault tolerant with an inline current limiter of at least 100 microAmps. Analysis shows that a stronger current limiter (10 microA) introduces enough noise into the signal to mask the nerve traffic completely.

*Headphones* - Commercial-Off-The-Shelf (COTS) Headphones provide the operator acoustic cues to locate nerve signal and are stowed in the Transcranial Doppler (TCD) kit.

*Microneurography System (MNS) Support Kit* - The Microneurography Kit comprises H-Reflex Probes, H-Reflex Ground/Lead, MNS Ground, Autonomic Neurography Diagnostic Instrument (ANDI), 1 Hertz (Hz) Pulse Generator, and Sharpie pen. ANDI is used to verify operation of the MNS prior to electrode insertion. It is powered by an “AA” battery.

*H-Reflex Stimulator* - The H-Reflex Stimulator (stowed in MNS Support Kit) assists in locating the peroneal nerve path for microneurography recordings. This stimulation produces a single square wave pulse (600 microseconds in duration and up to 100 V in amplitude) when activated manually or by the 1 Hz Pulse Generator trigger signal.

## **Microwave Remote Sensing Experiment**

(STS-9) ESA

The objectives of the microwave remote sensing experiment were to develop all-weather remote sensing methods, study sensor-object interaction by measurement of ocean surface wave spectra with a two-frequency scatterometer, and verify synthetic aperture radar behavior. The microwave remote sensing experiment instrumentation was a radar facility. In the active modes, the instrument transmitted microwave energy in X-band (9.65 GHz) to earth targets. A sensitive low-noise receiver detected the backscattered radar signals. The instrument operated in three modes: (1) a main mode as a two-frequency scatterometer (2FS), (2) a high-resolution mode as a synthetic aperture radar (SAR), and (3) a passive mode as a passive microwave radiometer. In the 2FS mode, the instrument measured the ocean surface wave spectra at wavelengths within a range of 5 to 500 m by using the complex backscattering of the ocean surface at two adjacent microwave frequencies. In the SAR mode, areas of the earth's surface were imaged. The backscattered data were coherently recorded and off-line processing provided imagery with a ground resolution of 25 m by 25 m. The radiometer mode, which measured naturally emitted microwave radiation from the earth to provide ocean surface temperatures, was used in time multiplex with other modes.

## **Millimeter Wave Atmospheric Sounder (MAS)**

(STS-45, 56, 66) ESA

The Millimeter Wave Atmospheric Sounder (MAS) experiment on the ATLAS missions was to study the composition and dynamic structure of the stratosphere, mesosphere, and lower thermosphere in the 20 to 90 km altitude range (middle atmosphere) with a height resolution as low as 4 km. MAS provided simultaneous information on the temperature and ozone in the 20 to 90 km region information on water vapor and chlorinemonoxide (CLO). The MAS was a passive limb-sounding total power microwave radiometer-spectrometer. The equipment consisted of a steerable parabolic antenna which focused the radiation into the MAS Reciever Electronics (MRE). The MRE consisted of three radiometers operating at frequencies 61 to 64 GHz, 183 GHz and 204 GHz. The signals were converted to intermediate frequencies below 6 GHz which were then analyzed by five filter banks in the Filter Electroic Box (FEB) which consisted of 240 filters. The antenna can position in elevation about 4 degrees with a total scan of about 13 degrees.

## **Mir Kits**

(STS-71) NASA

Several NASA-designed kits were provided for the NASA/Mir avian developmental biology experiments collectively titled "Incubator," which used the Russian IMBP incubator, and the plant biology experiment titled "Greenhouse," which used the Russian Svet Greenhouse and the NASA/P.I.-provided Gas Exchange Measurement System (GEMS).

*Fixative Kits (Incubator):* Fixative Kits consist of double-layered, double-clamped plastic bags that hold the required volume of paraformaldehyde fixative. The design allows the crew member to introduce into the bag the quail egg to be fixed while precluding exposure of the crew member to the fixative. Each of the fixative bags are enclosed in turn by a large outer bag, also clamped. The bags are stored within an aluminum box. Each box holds 16 fixative bags.

*Harvest Kit:* The kit includes instruments for harvesting the plants. Among other elements, these instruments include long probes (overall, 40 cm; probe arm, 32 cm) with small scissors or tweezers on one end.

*Fixative Kit (Greenhouse):* These bags of chemical fixative contain a solution developed and tested by Dr. Campbell at Utah State University, based on a formula of MacDowell and Trump: 4 parts formaldehyde; 1 part glutaraldehyde, buffered with Na<sub>2</sub> PO<sub>4</sub>, adjusted to pH 7.2 with NaOH; and sodium azide added to prevent fungal growth. Like the incubator fixative bags, each bag is triple sealed to prevent the release of hazardous chemicals into the cabin atmosphere.

*Glovebag Kit:* The glovebag is a large, clear plastic bag that allows a single user access to its interior through two rubber gloves on the front surface of the bag. A small airlock entry port is located at the rear of the bag, which allows the crew member to insert samples into the glovebag. The entry port can be rolled up and clamped shut, if necessary.

*Filter/Pump Kit:* The kit consists of a filter and pump for evacuating the air inside the glovebag, in case of a hazardous fixative spill.

*Dry Stowage Kit:* The dry stowage kit includes plastic bags containing silica gel as desiccant. The kit stows plant samples not placed into chemical fixatives.

*Observation Kit:* The kit includes the camera bracket and ruler/color chart to be included in photographs. The camera itself is not part of the kit.

*Logbook Kit:* The logbook is used to record crew observations.

### **Modular Optoelectronic Multispectral Stereo Scanner (MOMS)** (STS-55) DLR

The MOMS-02 provided imaging data for photogrammetric mapping and thematic mapping applications in cartography, land-use, ecology, and geology. MOMS-02 was an improved instrument based on the MOMS-01 which flew on the Shuttle in 1983 (STS 7) and 1984 (STS 41B). The MOMS-02 performed the following experiments: Triple Stereoscopy, Along-Track Stereoscopy, High Resolution Imagery, Multispectral Observation, and Combination Stereo-Multispectral Imagery. The MOMS-02 camera consisted of modular optics and optoelectronic charge-coupled device (CCD) detectors. MOMS-02 consisted of 7 channels and five optical systems, three for stereoscopic imagery and two for multispectral imagery. The central lens, which formed the core of the camera system, had a focal length of 600 mm for high resolution imagery. Two other lenses, each with a focal length of 220 mm, were used for multispectral imaging. The first four channels were Multispectral bands (MS): (1) 440-505 nm, (2) 530-575 nm, (3) 645-680 nm, (4) 770-810 nm. Channels 5-7 were the high resolution panchromatic and stereo bands (HR+ST): (5) 520-760 nm nadir-looking, (6) 520-760 nm, +21.4 deg forward tilt, (7) 520-760 nm, -21.4 deg backward tilt. The ground pixel size for channels 1-4, 6-7 was 13.5 x 13.5 m while channel 5 was 4.5 x 4.5 m. The swath width for channels 1-4, 6-7 was 78 km and for channel 5 it was 37 km. Channels 1-4 had a 10 deg FOV, channels 6 and 7 had 15 deg FOV, and channel 5 had an 8 deg FOV. MOMS-02 operated in the following modes: Mode 1, channels 5,6,7 HR+ST, full stereo; Mode 2 channels 1-4 MS, full multispectral; Mode 3 channels 3,4,6,7 2MS/2ST; Mode 4, channels 1,3,4,6 3MS/1ST; Mode 5, channels 1,3,4,7 3MS/1ST; Mode 6, channels 2,3,4,5 3MS/HR; and, Mode 7, channels 1,3,4,5 3MS/HR. Data processing consisted of on-board recording onto High Density Tape (HDT). The on-board tape recorder allowed a maximum of 5.5 hours recording time.

### **Modular Support Structure (MOSO) with Automated Blood Pressure (ABP)** (STS-90) NASA

The Modular Support Structure (MOSO) accommodates the Automated Blood Pressure (ABP) unit, converts Spacelab power into secondary power, provides an electrical interface between ABP and the Command and Data Acquisition System (CDAS), and a thermal interface between ABP and rack forced air cooling system. The ABP provides a continuous blood pressure signal, as well as systolic and diastolic pressure signals. The Life Sciences Laboratory Equipment (LSLE) Microcomputer II (LM2) #2 collects the signals and provides calculated values of mean blood pressure and heart rate. The ABP consists of: Finger Cuff - worn on subject's finger, applies pressure to the finger arteries and optically measures blood circulation. The Pressure Regulator prevents the cuff pressure from exceeding 280 mmHg (+7mmHg); Front-End Box (FEB) - worn on subject's hand, provides pressurized air to the finger cuff and receives and processes signals from the finger cuff; Plug-In Module (PIM) - controls FEB and air supply; it interfaces between the

CDAS and the test operator; The ABP Kit comprises a Nomex container with finger cuffs (three small, six medium, and three large) to support ABP use during Early, Mid, and Late Mission Protocols. The Utility Panel powers the MOSO.

#### **MOROSUS (Embryogenesis and Organogenesis of *Carausius Morosus* under Spaceflight Conditions) (STS-42) ESA**

Four experiment packages were prepared for this Biorack experiment, each consisting of nuclear track detectors of cellulose nitrate and CR 39, interleaved with sheets on which the deposited eggs of the stick insect (*Carausius morosus*) were developing. An egg sheet consists of a perspex plate with holes of 3 mm in diameter, in which the eggs have been placed. This arrangement of detectors and biological layers allows the heavy ion path through the biological layer to be determined with an accuracy of about 150 micrometers. With cellulose nitrate detectors, particles with atomic number greater than 8 and LET greater than 1.7 GeV per centimeter in water were selected. The top of two packages was formed by the YEAST experiment trays, in which the yeast cells were fixed on a salt agar medium (a non-growth medium). The packages with the yeast cells were mounted in the Type II containers. The IML-1 mission was flown at an altitude of 302 Km and an inclination of 57deg. The total dose of radiation exposure, during the 8-days mission was measured to be 1mGy the number of heavy ions varied between 7+/-0.5 per square centimeter and 3.9+/-0.4 per square centimeter for LET greater than 1.3 MeV per centimeter.

#### **Mount Sinai Human Tilt Chair**

(STS-90) Mount Sinai Hospital, Toronto, Ontario, Canada

The Mount Sinai Human Tilt Chair is composed of a Tilt Stand, a Tilt Chair, an Optokinetic Projection Apparatus and a ten foot diameter fiberglass dome which is mounted on aluminum struts. The chair was designed to carry humans spanning a wide range of weight. To accomplish this, a slide-mounted counterweight is positioned above and behind the subject. The amount of counterweight, chosen by positioning the weights through an arc, should be equal or close to the subject's weight. The counterweights are 30-pound lead bricks housed in an aluminum frame. The subject sits in a modified racing car seat facing the fiberglass dome. The chair can be tilted in 10° increments from 0° to 90° to the left or right. The dome is featureless and white, and provides a screen onto which the optokinetic stripes are projected. Above the subject's head is a computer-controlled, three-axis optokinetic stimulator (a rotating, slotted metal ball with an interior light source) which can project the stripes in any orientation and at velocities of 0° to 90° per second. Stops are positioned to limit rotation to 90° in either direction. The entire unit is bolted to the floor. Eye movements are recorded using an ISCAN system. A headband (plastic front with elastic back) is worn by the subject. Two miniaturized infrared cameras are mounted on the headband pointing downward. Two beam splitters are attached to the apparatus and are placed in front of the subject's eyes to reflect the eye image. A cable connects the cameras to a control box which routes the video signal to two Video Tape Recorders (VTRs). Each VTR records the image of a single eye.

#### **Navigation Experiment (NAVEX)**

(STS-61A) DARA

The single navigation/communications investigation (NAVEX) included a clock synchronization and time distribution experiment, and a one-way distance measurement experiment.

#### **Niedergeschwindigkeits-Zentrifugen-Mikroskop (NIZEMI): Slow Rotating Centrifuge Microscope (STS-65) DARA**

The NIZEMI (Niedergeschwindigkeits-Zentrifugen-Mikroskop) is a Spacelab facility for optical investigations of small biological and non-biological specimens under variable accelerations from .001 to 1.5-g.

It consists of a microscope for investigations in microgravity (no rotation) and under “selected” gravity (with rotation). The minimum and maximum gravity levels correspond to an effective radius of the samples of 110 mm and rotation speeds of 2.6 and 120 rpm, respectively. The equipment mounted on the NIZEMI centrifuge consists of a micro and a macro observation unit. The micro observation unit is a microscope using various contrast-enhancing methods and filters. Relevant functions such as object selection, magnification, and focusing adjustments are remotely controlled during centrifuge rotation. The object planes of the micro and macro units have a defined distance to the rotation axis of approximately 125 mm. Video displays can be downlinked in real-time or recorded. Normally the micro and macro observation units are not used concurrently. Individual micro and macro chambers can be customized within the standard interfaces. The prepared specimen, stored in a special micro chamber, can easily be positioned on the stage by a crew member. The facility is automatically controlled via dedicated processor electronics. Visual observation is possible via onboard monitoring, onboard video recording and optional video downlink or via in-situ photography. Cuvette temperature is automatically controlled between 18 and 37 degrees Celsius. Micro chambers with samples can also be stored onboard within a Biorack experiment container Type I (i.e., cooler, reference centrifuge, incubator or freezer).

### **Night/Day Optical Survey of Lightning (NOSL)**

(STS-2) NASA

The Night/Day Optical Survey of Lightning (NOSL) equipment consisted of the camera, the attached photocell sensor, and the connected tape recorder. In orbit, the equipment was retrieved and assembled for use in the crew cabin. The motion picture camera was a 16-mm data acquisition camera, a model flight tested on Apollo and Skylab missions.

### **Norepinephrine (NE) Spillover System**

(STS-90) NASA

The Norepinephrine (NE) Spillover System consists of the following: Drug Infusion Pump - The hand-held commercial-off-the-shelf (COTS) Drug Infusion Pump straps to the subject’s arm during operation and automatically administers a 60cc syringe of NE into a subject’s arm via a venous catheter. The pump consists of a microprocessor-controlled linear motor that drives a plunger on the syringe, which is clamped to the pump. Sensors in the motor monitor the delivery rate, and sensor information verifies proper delivery and occlusion problems in the syringe and attached intravenous (IV) tubing. The initial bolus delivers 13.5 mL/min for 1.5 minutes, and the maintenance dose rate is 0.45 mL/min until the end of LBNP protocol or until the syringe is empty, whichever comes first. Upon reaching the end of the syringe, the motor stops and signals completion of the infusion. The compact pump does not interfere with subject movement and can be preprogrammed so that once the drug infusion has begun, the two infusion rates follow concurrently without operator monitoring. The Drug Infusion Pump Battery Pack is an external, replaceable battery pack (four C alkaline batteries) used to power the Drug Infusion Pump. Frozen NE Kit - The Kit contains 5 mL vials with a mix of 1 mL frozen NE and 1 mL alcohol. NE Support Kit - The Kit comprises 5 ziplock bags, each containing 30 mL saline vials and saline injector; 5 ziplock bags, each containing an NE injector, 3-way stop cock, 60 cc infusion syringe, and return sample vial; and 5 ziplock bags, each containing a sterile extension kit, and syringe and extension coverings. NE Support Kit is used in mixing NE solution and the return sample vial is used to obtain a sample on the infused solution prior to use, covered in foil, and frozen after use.

### **Plant Nutation Experiment Package**

(STS-9) University of Pennsylvania

The equipment consisted of a dark box, within which four test plants illuminated by infrared light could be located in the field of view of a video camera; rotor compartments; battery pack; video tape data recorder;

control electronics; and a carry-on container of 28 plant modules, each containing one plant. Plants at various stages of growth were kept in a rotor compartment under a 1-g acceleration until it was their turn to be tested in front of the camera.

### **Ocean Color Experiment (OCE)**

(STS-2) NASA

The Ocean Color Experiment (OCE) instrument was a modified version of a NASA high-altitude aircraft sensor known as the U-2-borne ocean color scanner and similar to the coastal zone color scanner (CZCS) on the Nimbus 7 satellite. It consisted of two main modules: the scanner and the electronics. The scanner was mounted on the experiment pallet shelf, and the electronics were coupled to a cold plate on the pallet deck. The rotating mirror on the OCE instrument scanned plus or minus 45 deg from nadir across the direction of flight with a ground resolution of 3 km. The scanner operated in eight spectral intervals: 486 nm (blue), 518 nm, 553 nm (green), 585 nm, 621 nm, 655 nm (red), 685 nm, and 787 nm (near-infrared).

### **Optokinetic Stimulus Goggles (OKS)**

(STS-42, 78, 90) CNES

The Optokinetic Stimulus (OKS) goggles and controller are used for optokinetic nystagmus measurements. The OKS controller is located on the Instrument Vest, worn by the subject, and connected to other interface electronics and data collection systems. The subject is also equipped with electrooculography to measure eye movements. The OKS goggles were developed by the French Space Agency, CNES, and was used during several investigations performed on board the Space Shuttle or the Russian Space Station Mir. The Optokinetic Stimulus (OKS) goggles cover the entire field of view of the subject. Inside the OKS, a pattern of alternating black and red stripes, each stripe is 4 degrees wide, and is viewed through Fresnel lenses placed in front of each eye which provide approximately a 70 by 90 degree field-of-view. The orientation of the stripes can be changed to move in the horizontal (rightward or leftward), vertical (upward or downward) or 45 degree oblique directions rightward/upward or leftward/downward).

### **Orbital Acceleration Research Experiment (OARE)**

(STS-40, 50, 58, 73, 75, 78, 87, 83/94) NASA

The OARE has four component assemblies; each attaches to the mounting shelf provided by the orbiter contractor with 0.64-cm captive fasteners. The four OARE assemblies are the sensor/table assembly, which includes the acceleration sensor subsystem and the motor/table subsystem; the signal processor and the control subsystem, the subplate assembly, which includes the orbiter interface subsystem, the servocontrol subsystem, the power-conditioning subsystem, and the subplate and cable harness; and the cover assembly, which includes the desiccant subassembly, a two-piece cover, interface feed through connectors, and miscellaneous hardware. The OARE instrument was designed to measure, process, and store data according to a functional signal flow diagram. The input section-the acceleration sensor subsystem mounted on the motor/table subsystem portion of the rotary table assembly-provides a triaxial output signal in analog voltage form, proportional to the components of the instantaneous acceleration vector sensed by the electrostatically suspended proof mass. The orientation of the three proof-mass sensing axes (input axes) is determined by the attitude of the sensor base mounted to the dual-axis rotary table. The servocontrol subsystem accepts steady-state position commands to align any proof-mass input axis with any selected orbiter axis for sensitivity axis pointing and bias calibration. The rotary table assembly also rotates the sensor proof mass at a selected angular rate in one of the three orthogonal planes for sensor scale factor calibration. Both the acceleration sensor subsystem and the servocontrol subsystem receive commands from and transmit data and status information to the signal processor and control subsystem (SPCS). The orbiter interface subsystem (OIS) filters and conditions the sensor's output signals and converts both signals and housekeeping

voltages to digitized form for transfer to the SPCS. The OIS also receives mission status discrete signals from the shuttle control system and routes unprocessed high-rate digitized sensor data to the payload data recorder. The power-conditioning system interfaces with the orbiter 28-v dc main power bus and provides regulated power for all OARE subsystems. Other functions of the OARE instrument are to interface with the orbiter-supplied time code, which provides a real-time clock reference, and to interface with the ground support equipment.

### **Orbiter Refrigerator / Freezer (OR/F)**

(STS-40, 47, 55, 58, 71) NASA

The Orbiter Refrigerator/Freezer is designed to provide +4 degrees Celsius cooling as a refrigerator or -20 degrees Celsius cooling as a freezer. The Orbiter R/F fits in two middeck lockers and has an internal volume of 1.27 cubic feet, much more compact than its Spacelab equivalent due to spatial constraints. The R/F is designed to accept experiment racks, shelves, and containers to cool biological samples, solutions, and tracers for Life Sciences experiments. The OR/F was modified prior to the D2 mission in 1993. Enhancements include more reliable electronics, updated compressor and motor, new plenum, modified front panel and additional acoustic padding to muffle sound. Similar to the OR/F, the Enhanced Orbiter Refrigerator / Freezer (EOR/F) can be configured into either a refrigerator or a freezer with a temperature range between -22 and +10 degrees Celsius. The internal cold volume remains 1.27 cubic feet. Blood, body fluids, cell samples, experiment solutions and fluids intended for injections are usually stored in the EOR/F. The EOR/F can also be used to house small animals, incubate amphibian zygotes, and stow animal food supplies. It can accept experiment racks, shelves and containers for a variety of life science specimens. Unlike the OR/F, the EOR/F requires three storage lockers when located in a Shuttle middeck. For that reason, the EOR/F usually flies in the Spacehab module.

### **Organic Crystal Growth Facility**

(STS-42, 47) NASDA

The Organic Crystal Growth Facility has two growth chambers: a large chamber for growing a big crystal and a small chamber with a window for observing the growth of a smaller crystal. A crew member starts the experiment on the first day, and it runs automatically, growing two crystals simultaneously for the length of the mission. Periodically, the crew member uses a 35-mm camera to photograph crystal growth in the small chamber. Temperature and vibration data are automatically recorded for both chambers. A seed crystal is mounted on a gold wire in the center section of each chamber; this chamber also contains acetone, which acts as a solvent. A chamber on one side is filled with the acceptor solution (a nickel solute) and the chamber on the other side is filled with the donor solution (TTF solute). The payload specialist cranks a handle that lowers the seed crystal into the center of the chamber. Two valves are opened in each side chamber allowing acceptor and donor solutions to diffuse into the center chamber and condense on the seed. This reaction of organic crystal growth requires 6 days to complete. At the end of the experiment, a crew member cranks a handle that closes the two valves and raises the crystal into a protective bladder to prevent further growth under 1-g conditions postflight. After the mission, the bladders are given to the principal investigator who removes the crystals and analyzes their structures, perfection, electrical and magnetic properties, superconductivity, and other important parameters. A second goal of the experiment is to monitor g-jitter accelerations that mimic gravity and cause convection and other disturbances. The mounting beam that holds one of the growth chambers is made of damping material (an epoxy-based polymer) and aluminum, whereas the mounting beam of the other chamber is made of aluminum only. Accelerometers mounted on each chamber measure the amplitude and frequency of the accelerations, so that scientists can determine if the jitter is absorbed by the epoxy-aluminum beam.

### **Oscillatory Thermocapillary Flow Experiment (OTFE)**

(STS-50, 73) NASA

Four cell/reservoir modules will be tested (two different sizes, using two different viscosities of silicone oil). Micron-sized aluminum oxide tracer particles will be mixed with the fluid in the reservoir. The fluid will then be transferred to the test cell. The crew member manipulates the cell to obtain a fluid free surface. The fluid then is heated by a wire heating element in the center of the test cell. Three thermocouples measure the temperature at the wall, heater and in the fluid. Three video cameras will record the free surface behavior and the thermocouple readings. Four nearly identical OTFE-2 modules will fly on USML-2. The modules will be operated inside the Glovebox Facility. The modules contain test cells of varying diameters and aspect ratios. Each module is configured around a base plate with a reservoir, and piston pump connected to the copper test cell. A variable power, resistive heating element is located on the centerline of the test cell, which creates the temperature difference across the surface of the fluid. This temperature difference, the primary segment of OTFE-2 data, is measured by placing a thermocouple in the heater and side wall of the test chamber. In addition, a thermocouple extends into the bulk fluid flow, is produced when small particles placed in the fluid, which follow the flow and trace its path, are illuminated. The observation and recording of these particles, and subsequent qualitative flow structure, are accomplished with the use of a microscope and video camera, which are part of the Glovebox Facility equipment. A small control box located outside of the Glovebox is used to vary the power to the heater, and therefore, the resulting temperature difference. This control box is connected to a control circuit inside of the OTFE-2 module by way of an electrical feedthrough in the Glovebox door. The temperature displays for the heater, test chamber, and fluid can be viewed through a small window on the end of each module.

### **Otolith Spinal Reflex / “Drop” Station**

(STS-40) NASA

*Release Mechanism:* (T-Handle) The release handle is activated by command from the ECDS/ Micro-computer System (EMS) after being triggered by the crewmember operated cue switch.

*Harness And Belt:* A shoulder-type safety harness is used in combination with a wide, strong, tight-fitting adjustable belt. The EMG Amplifier secures to a velcro patch on the harness, and the Accelerometry Recording Unit (ARU) Power Pack and Cassette Data Tape Recorder (CDTR) are on a separate belt worn by the subject.

*Foot Switch:* The foot switch sole is attached to the bottom of the boot by double-sided adhesive rings. It signals contact of the crewman's foot with the floor of the Spacelab.

*Bungee Cords:* From three to nine Constant-Acceleration-Fall (CAF) bungees are used. During experiment operation they are attached to the floor and belt to simulate g-forces. Bungees not being used are held back with Velcro straps.

*Electromyogram(Emg) Amplifier And Electrode Kit:* One LSLE amplifier/signal conditioner is used to monitor calf muscle activity. The amplifier is similar to those used with the dome although of much lower gain. Data is routed through the drop cable to the EMS. The EMG Electrode Kit is a ziplock bag and contains three pre-gelled disposable electrodes, one alcohol pad and one sterile needle for scratching the skin. The kit contains electrodes for one experiment run on one subject.

### **Particle Dispersion Experiment (PDE)**

(STS-50, 73) NASA

The PDE consists of a pump unit for generating compressed air and eight small experiment modules. An experiment involves connecting a module to the pump, pressurizing the pump by operation of a hand crank and sudden release of the compressed air into the module which forcefully injects a stream of small particles into the 2 x 2 x 2 inch cubic experiment volume of the module. This process is filmed on video through one of two windows in the module.

## **Particulate Containment Demonstration Test Package**

(STS-40) NASA

Two rodent cages, without animals, and specially modified as described below, were allocated to the SLS-1 mission to verify that redesign efforts have resulted in a Research Animal Holding Facility (RAHF) and General Purpose Work Station (GPWS) that will contain particulates to specified micron particle size. Particulates are released into the Particulate Containment Demonstration Test (PCDT) cages on orbit and one cage is transferred to the GPWS using the General Purpose Transfer Unit (GPTU). An air sampler is also used to verify that particulates accumulated do not exceed specifications. Feeder and waste tray changeouts during these operations also verify that particulates are contained. The design of the PCDT cages includes a dispenser pull knob on the front of the modified cage. It is connected via a center mounting plate to an actuator arm to enable release of particulates from specially designed dispensers. Particulates are dispensed by opening the cage light isolation door and operating the dispenser pull knob. This action pulls cords on each of the dispensers, tearing the aluminum foil cap and inverting a fabric liner to release the particulates. The particulate load for each dispenser consists of food bar crumbs, rodent hair and black eyed peas to simulate feces. This load of particulates simulates a 10 day accumulation of rodent cage debris. Several items of hardware were flown on SLS-1 which were designed, in conjunction with the Particulate Containment Demonstration Test (PCDT) cage, to verify that the design of the General Purpose Work Station (GPWS) is adequate to contain particulates under a simulated 10 day mission of rodent waste materials.

*GPWS Particulate and Fluid Dispensers:* The particle dispensers are manually operated in the GPWS. The balloon dispenser is made up of a pre-filled balloon and attached to an inflation bulb. The balloon dispenser will be inflated to approximately 6 inches in diameter by hand pumping the inflation bulb. The particle load is then dispensed within the GPWS by rupturing with a pin. The fluid dispenser is a standard STS crew cup with a drinking straw as a nozzle. Each crew cup contains 120-150 ml of colored water with approximately 60 ml being dispensed per test. Wipes are used to detect any fluid leakage out the GPWS cabinet by showing a colored stain. The crew member inserts his/her hands inside the GPWS through the side port gauntlets and, using a second crew cup on top of the one containing the colored water, presses down, releasing the colored water into the GPWS work space.

*Volume Simulators:* The volume simulators represent those that were used in the cardiovascular experiment on board the SLS-2 flight. These simulators are for the microscope and flow meter (represented by a zero box containing the particle and fluid simulators). One of the PCDT cages is also placed inside the GPWS, creating a realistic profile in the GPWS by disrupting the cabinet airflow in a way that is representative of a flight configuration. Film and crew voice recording, along with post flight analysis, determine the efficiency of the clean-up and GPWS containment design.

## **Passive Accelerometer System**

(STS-50) UAH

A proof mass (steel ball) will be placed in a glass tube full of water. This tube is contained in a lexan sleeve and will be mounted parallel to the flight direction. An astronaut tracks its position manually every 1-2 minutes, using a ruler and protractor, repositioning the tube if the angular deviation of the proof mass exceeds 10. Each run will take approximately 20 minutes.

## **Percutaneous Electrical Muscle Stimulator (PEMS)**

(STS-78) ESA

The Percutaneous Electrical Muscle Stimulator (PEMS) is a high voltage instrument which provides single pulses or pulse trains according to a preadjusted program. The pulses are square wave signals of 50 microseconds in duration and from 100 to 800 milliamperes (mA) intensity, thereby allowing the hardware to adjust the signal in 50 mA steps. The PEMS is stowed during launch and landing. In orbit, the PEMS Main Box is unstowed and mounted to the rack

handrail via a Multiuse Mounting Bracket Assembly. The connecting cables (power and the cables to the electrodes) have to be unstowed and connected with their ports on the back of the Main Box. The major electronic units of the Main Box are the power supply, the unit adapter, the interface module, and the high voltage stimulator. The power supply converts the 28 volts DC from the Space Shuttle's power source into 5, 12, and 15 volts DC as needed. The main task of the unit adapter (UA) is to generate the selected pre-programmed protocol and its trigger (muscle stimulation). The interface module is designed to select 8 different protocols and 16 different intensities of stimulation, with positions ranging from 100 to 800 mA. It also includes a Protocol Start and a Protocol Stop switch as well as an LED display, indicating the status of the PEMS. The High Voltage Stimulator (HVS) is the outlet of the triggers, and connects to the stimulating and safety electrodes positioned on the astronaut's leg. The electrodes used for the PEMS have the characteristics of auto-adhesive, pre-gelled, and reusable electrodes. The cathode-electrode measures 3 x 5 inches and is positioned above the two heads of the gastrocnemius muscle (approximately 1 inch below the knee on the back of the leg). The anode-electrode is 1.5 x 3.5 inches in size and is positioned over the soleus muscle. The two safety electrodes are 2 inches in diameter and are positioned on the outside thigh, just above the knee.

### **Performance Assessment Workstation (PAWS)**

(STS-65, 78) NASA

The Performance Assessment Workstation (PAWS) was developed and validated for space flight to collect cognitive performance data. The Performance Assessment Workstation tests are based on current theoretical models of human performance. They were selected by analyzing tasks involved in space missions that might be sensitive to microgravity. Subjective questions also are included in PAWS for interpreting fatigue and mood states. The investigation uses a set of six computerized cognitive performance tests taken from the Unified Tri-Service Cognitive Performance Assessment Battery. The series of tests is internationally recognized and has proven sensitive to many environmental stressors. The crew underwent these performance tests using a laptop computer. It consists of an IBM ThinkPad laptop computer with an active matrix color display and a NASA-compatible trackball. The computer used in flight was modified by NASA to enhance its operation in the microgravity/Shuttle environment. These modifications did not affect its functionality. The PAWS requires a Measurement Systems, Inc. (MSI) 2-inch trackball (Model 622) connected to the serial port at 9600 baud and powered by 28 volts DC from the Shuttle power.

### **Personal Melatonin / Placebo Kit**

(STS-90) NASA

This kit consisted of a Nomex container with approximately 16 Melatonin and placebo tablets for administering one tablet per night required for each crewmember. Packages were labeled by flight day only. The records regarding which pill (melatonin or placebo) the crewmember ingested were available to the Flight Surgeon if needed during the mission.

### **Personal Sleep Kit**

(STS-90) NASA

The Personal Sleep Kit was a Nomex bag that contained the following items: 2 Sleep Nets; 4 packages of hydrodotes; 4 packages of Nuprep swabs; 3 Sleep Net chin straps; 3 Sleep Net necks straps; 4 spare snaps; 6 large frontal pads; 1 package collars; 12 ECG electrode packs; 6 nasal thermistors; 1 Pulse Oximeter sensor; 20 alcohol pads; 10 Biocide wipes; Adhesive dots; Micropore tape.

### **Physics of Hard Spheres Experiment (PHaSE)**

(STS-83/94) NASA

The PhaSE experiment will be performed in a multi-angle Light Scattering Instrument (LSI). Within the LSI, seven hard-sphere samples of varying concentrations of three components will be housed in individual

glass cells mounted onto a precision rotary stage. The exact ratio of the three components is dependent on the specific volume fraction of solids to liquids desired; each sample will have a slightly different ratio. During operation, each of the samples will be rotated into position for light scattering/data collection activities using both static and dynamic laser sources. Data will be collected using both a high-definition CCD camera to record images of the cells and photon counters to measure light scattering.

### **Physiological Monitoring System (PMS)**

(STS-40) NASA

The PMS provides EKG, heart rate and indirect blood pressure. In addition, the unit accepts the input from various data detection sources (e.g. the SVOP or SMCVP) and routes these data to the appropriate onboard data display, recording, transmission interface, or manipulation devices. Each data channel input to the PMS has the capability to be output to the body-worn LSLE cassette data tape recorder (CDTR), the Orbiter analog telemetry downlink interface or the LSLE microcomputer. The PMS is capable of being self-powered (battery operated) or spacecraft powered. The main PMS module is subdivided into two major segments, the Basic Parameters Module (BPM) and the Data Control Module (DCM). The BPM contains all equipment and systems necessary to obtain ECG, heart rate, Korotkoff sounds (K-sounds), cuff pressure data, and conditions the same for interface into the DCM. The DCM controls and distributes the data from the BPM and interfaces this data into the various display, recording, transmission interfaces, or computation/manipulation devices. Certain preprogrammed computational and scaling processes can be performed on the input data by the PMS prior to data transmission. The Remote Control Display Unit (RCDU) displays heart rate and blood pressure measurements through an umbilical from the PMS Electronics Module. The unit contains a liquid crystal display (LCD) capable of showing two lines of 32 characters of visual data of any type to the crewmembers. The controls of the unit may be used by the crewmember to control any preprogrammed operation, such as calibration or blood pressure measurements. Note: Additional Experiment Unique Equipment (EUE) may be used in conjunction with this system. For example, the System for Venous Occlusion Plethysmography (SVOP) and System for Measurement of Central Venous Pressure (SMCVP), routed their signals through the PMS.

### **Physiological Signal Conditioner (PSC)**

(STS-78) NASA

The Physiological Signal Conditioner (PSC) is a compact, lightweight, low-power precision instrument designed to monitor physiological signals such as electromyogram (EMG) and electrocardiogram (ECG). The PSC picks up physiological signals from surface electrodes, which are amplified and filtered. The analog output is received by an Electronics Control Assembly (ECA). The PSC is battery powered and uses 2 packs of five 1.5 volt silver oxide batteries. It can operate for more than 100 hours on a single set of batteries and the batteries can be easily changed during the space flight, without the need for tools. The operating status of the PSC is indicated by a small LED; a periodic blinking signal indicates nominal operations, while a fast blinking signal refers to low batteries. The battery power is applied and removed by connecting and disconnecting the output cable. The single-channel PSC, which was used for ECG recording, is approximately 6.2 x 4.7 x 3 centimeters and weighs no more than 300 grams with the batteries installed.

### **Plant Growth Unit (PGU)**

(STS-2, 3, 51F, 78) NASA

The early version flown on the STS-2/OSTA-1 was known as the HEFLEX Bioengineering Test (HBT). The HBT experiment was a suitcase-like container loaded with 85 sealed plant modules varying in soil moisture content from 55% by weight to 77%. This plant carry-on was stored in a locker in the crew compartment of the Space Shuttle. The Plant Growth Unit (PGU) is a self-contained system carried in the

Orbiter middeck and designed to hold six removable Plant Growth Chambers. The PGU consists of the support components and a cavity for growing plants. The PGU is equipped with three 15 W plant growth lamps (Vita-Lite spectrum), a timer to provide day/night cycling, temperature sensors, electronically-controlled fans, heater strips for temperature modification, data-acquisition system, and internal batteries. The few system controls and displays appear on the exterior front panel. These include several status lights, a power switch, and a selectable digital temperature readout. Four switches that set the clock and a digital time display are located inside the unit. Temperatures and lamp status are recorded at intervals in flight by a tape recorder. For environmental control, two thermostatically-controlled variable-speed fans draw air over the plant growth chambers. A temperature gradient decreasing from the top to the bottom of the chambers is maintained to prevent moisture condensation in front of the light. Diurnal temperature cycling is provided, with a chamber temperature of  $78 \pm 1$  °F during the “daylight” and  $74 \pm 1$  °F during the “night.” The PGU replaces a storage locker in the Orbiter middeck and can be placed into the Orbiter approximately twelve hours before launch and removed approximately one hour after landing. Each of the six Plant Growth Chambers hold seeds or seedlings between sheets of moist filter paper-like material and consist of a metal alloy base and a Lexan cover which is sealed to the base using a gasket. Each chamber is airtight. The chamber base is fitted with a temperature probe in the center and two gas-sampling ports toward each end. Seeds or seedlings are planted in a “sandwich” support medium contained in the base. The chambers fit into the Plant Growth Unit which supplies all environmental control and power. The lighting system consists of three fluorescent lamps containing phosphor lenses, reflector, aluminum housing, and associated circuitry. The filament and header designs are ruggedized; the lamp assembly is hermetically sealed with teflon tubing; and an indium-mercury amalgam is substituted for elemental mercury. The light intensity over the four middle plant growth chambers is about  $75 \mu\text{mol}/\text{m}^2/\text{sec}$  and over the two outside chambers about  $48 \mu\text{mol}/\text{m}^2/\text{sec}$ . Diurnal cycles are adjustable.

*Specifications:*

Chamber Size: 19 x 5 x 22 cm

Irradiance:  $75 \mu\text{mol}/\text{m}^2/\text{sec}$  Photosynthetic Active Radiation

Spectrum: Fluorescent (Vita-Lite)

Thermal Control: Temperature in PGU can be controlled only above ambient

Dimensions: 52 x 45.9 x 27.4 cm

Weight: 27.2 kg (59.84 lb)

Power: 28 VDC; day 81.2 W; night 47.6 W

### **Plasma Diagnostic Package (PDP)**

(STS-3, 51F) NASA

The Plasma Diagnostic Package (PDP) is a fully instrumented ejectable subsatellite. During the mission it will operate within the payload bay, on the remote manipulator system (RMS), and as a free flyer. Instruments to be flown include the following: (1) a quadrispherical low-energy proton and electron differential analyzer to provide electron and proton distribution functions from 2 eV to 50 keV; (2) a plasma wave analyzer/electric dipole and magnetic search coil sensors to give components of electrostatic and electromagnetic waves from 5 Hz to 30 MHz; (3) a dc electric field meter for sensing components of the dc electric field over the range from 2 to 2000 mV/m; (4) a triaxial fluxgate magnetometer to measure the dc magnetic field distribution in the vicinity of the Shuttle; (5) a Langmuir probe to measure electron density in the region  $1.E4$  to  $1.E7$  per cc and electron temperature from 500 to 5000 deg K; (6) a retarding potential analyzer and differential flux analyzer to determine the energy distribution and streaming velocity direction for plasma ions with energies less than 16 eV, number densities of  $1.E2$  to  $1.E7$  per cc, temperatures from 500 to  $1.E6$  deg K, and velocities up to 15 km/s within plus or minus 50 deg of the instrument plane; and

(7) an ion mass spectrometer for measuring from 1 to 64 u and densities of 20 to 2.E6 per cc. In addition to the PDP, the experiment consists of a special purpose end effector, a release mechanism, a receiver and data processing assembly, and an rf antenna assembly.

### **Postural Kit**

(STS-71) NASA

The Postural Kit container is constructed of blue Nomex. Inside the kit is a minicell foam assembly. In the foam are appropriately sized and shaped cut-outs that hold the kit contents by friction fit. The kit contains an electrode wrap assembly, a bag of 50 disposable electrodes, adhesive tape, bag of 3 razors, the TEAC monitor unit, BPAS battery, shoe inserts and a UBC charger cable.

### **Pressure Shoe Assembly**

(STS-71) NASA

The Pressure Shoe Assembly consists of a left and right shoe assembly connected by tygon tubing, which in turn connects to a small manually-operated pump with analog gauge. The gauge face shows pressure in millimeters of mercury, and is plastic covered with a clear Teflon window. The left and right shoe assemblies are constructed of aluminum 6061, with anodized finish. The shoe assemblies weigh 2.2 kg and were approximate in size to a man's U.S. size 13 athletic high-top shoe. The "toe" section of the shoe can rotate outward to allow ingress of the subject's foot, by rotating on a hinge, prior to the experiment session. The inside of the shoe is padded with minicell foam for subject comfort and to eliminate any possible exposure to sharp edges. A flexible "bladder" constructed of polyurethane-coated nylon with ultrasonically-sealed edges is placed at the bottom of this shoe, with a plastic orthopedic insert placed on top. The orthopedic insert has two plastic raised sections, covered with neoprene, to simulate the particular subject's one gravity pressure profile (on the bottom of the foot). As the bladders inflated, the elevated surface of the inserts exerted pressure on the balls and heels of each foot. Boots were inflated with a hand-held sphygmomanometer pump attached to hoses leading to the bladders. Crewmembers were trained to inflate the bladders to a level so that the distribution and amount of pressure resembled those obtained during preflight testing in 1-G.

### **Protein Crystal Growth (PCG)**

(STS-42, 47, 50, 73, 83/94) NASA

NASA's Protein Crystal Growth Experiments used various hardware, including ESA's APCF, over several missions to provide different environments for crystal production in microgravity. See entries for the following apparatus:

**Crystallization Observation System/Advanced Crystallization Observation System (COS/ACOS)** - STS-83/94.

**Diffusion Controlled Crystallization Apparatus for Microgravity (DCAM)** - STS-73.

**Handheld Diffusion Test Cells (HHBTC)** - STS-83/94.

**Protein Crystallization Apparatus for Microgravity (PCAM)** - STS-62, 73, 83/94.

**Protein Crystallization Facility (PCF; see Advanced Protein Crystallization Facility)** – STS-73.

**Thermal Enclosure System/Single Locker Thermal Enclosure System (TES/STES)** - STS-73.

**Vapor Diffusion Apparatus (VDA)** - STS-42, 47, 50, 83/94.

### **Protein Crystallization Apparatus for Microgravity (PCAM)**

(STS-62, 73, 83/94) NASA

Protein Crystallization Apparatus for Microgravity (PCAM) uses vapor-diffusion to grow protein crystals. A droplet of solution with protein molecules dissolved in it is isolated in the center of a small well. In orbit, an elastomer seal is lifted so the solution can evaporate and be absorbed by a wick material. This

raises the concentration of the solution, thus prompting protein molecules in the solution to form crystals. Individual samples are carried in trays with 7 samples per tray and nine stackable trays contained in each PCAM cylinder. On the MSL-1 mission, the Protein Crystallization Apparatus for Microgravity (PCAM) experiment uses trays to grow protein crystals in 378 chambers that are housed in a Single-locker Thermal Enclosure System (STES), which is located in a middeck locker. PCAMs also are stowed in the middeck at ambient temperature.

### **PROTO (Cell Growth and Differentiation of Plants from Protoplasts)**

(STS-42) ESA

PROTO used protoplasts from carrots (*Daucus carota*) and a fodder plant, rape (*Brassica napus*), which were injected into 0.6 ml polyethylene bags and placed in aluminum containers prior to flight. In orbit the containers were transferred from their 4 degree C storage PTCUs to the 22 degree C Biorack incubator. Some of the samples were placed on a 1-g centrifuge so that it was possible to distinguish between effects of near weightlessness (ca  $10^{-3}$  g) and effects caused by cosmic radiation and other space flight factors including vibrations. Several times during the mission crew members, by use of a hypodermic syringe and needle inserted through the septum, removed and examined aliquots of the protoplast samples. Various developmental cell stages were recorded and photographed and some of the samples were fixed using glutaraldehyde. During the eight day mission, cell wall regeneration, cell division and formation of cell aggregates of plant protoplasts were simultaneously analysed under microgravity and in the various controls. Microscopic observations in Spacelab were performed with the Biorack light microscope, mounted on the Biorack glovebox with which also colour films and images for a videocamera could be obtained.

### **Prozesskammer (PK)**

(STS-61A) DARA

The PK (or process chamber) was tailored to the requirements of the scientists. It is designed to show and measure flows, heat and mass transport, and temperature distribution occurring during melting and solidification processes, as well as during phase changes of liquids, and included a holographic diagnostic unit (HOLOP), an interdiffusion in salt solutions experiment, and a convection experiment.

### **Quasi-Steady Acceleration Measurement (QSAM)**

(STS-65, 83/94)

The QSAM system is primarily designed to detect steady, very low-frequency, residual accelerations between 0 and 0.02 Hz. In this range, the acceleration level is typically  $10^{-6}$  or even lower, and these low-frequency accelerations affect various physical processes more than higher frequency accelerations. Unlike other measurement systems, QSAM suppresses the sensor's bias and noise to assess this acceleration range with a minimum of on-orbit maintenance. To achieve this, the measurement signal can be modulated by rotating a sensor's sensitive axis. The system employs four rotating sensors to allow 3-dimensional acceleration detection. An additional package with stationary sensors has an upper bandwidth of 50 Hz. For the MSL-1 mission, the QSAM system will be located in the lower left side of Spacelab double rack 3; however, data can be modeled to calculate the low-frequency accelerations at other locations inside the orbiter.

### **RADIAT (Genetic and Molecular Dosimetry of HZE Radiation)**

(STS-42) ESA

This Biorack experiment used two different configurations of hardware, labeled "TYPE I" and "TYPE II," and these were placed in several locations within the Biorack system as well as in the Spacelab tunnel in order to vary temperature, shielding and the force of gravity. Eleven Type I containers were used; two of these were incubated at 5 deg. C, four at 22 deg. C (two of which were placed in a 1 g centrifuge so

that radiation influences could be distinguished from zero gravity influences), and five were placed in the forward Spacelab connecting tunnel. Most tubes contained 1 ml of a suspension of 10,000 - 40,000 larvae in buffer and 1 ml of air. Type II containers were incubated at 5 deg. C in a stiff agarose gel matrix.

*Lexan Tubes:* Lexan polycarbonate tubes containing the daf strain of *Caenorhabditis elegans* are assembled in “four” tube and “eight” tube configurations within Type I/O containers provided by the European Space Agency (ESA). These tubes contain the bulk strain in liquid buffered saline. Also inside the Type I/O containers are CR-39 films to document the tracks made by radiation, kimfoil sheets to keep the CR-39 film from becoming oxygen starved and Thermal Luminescence Detection (TLD) packages to measure the amount of radiation received.

*Solid Agar Sandwiches:* Twenty-eight sandwich assemblies with the eTI strain of *Caenorhabditis elegans* are contained within each Type II/O container provided by the European Space Agency (ESA). These assemblies consist of a base support, worm/agarose layers on Millipore filter paper, CR-39 film to track the path of radiation, kimfoil sheets to protect the CR-39 film from oxygen starvation and Teflon sheets to act as a non-stick surface to prevent dislodging the worm/agarose layer after flight when removing the CR-39 film.

*Radiation Cartridge Belt:* The radiation cartridge belt is made of Nomex fabric. The inside of each pocket is lined with Pyrell foam to act as an insulator for the experiments. Velcro tabs are placed on the cartridge cover flaps to secure the experiment packages. The cartridge belt is attached to the Spacelab tunnel to absorb radiation in that location and contains five European Space Agency (ESA)-provided Type I/O containers with experiment specimens and one ESA Temperature Recorder (ETR).

### **Radiation Environment Mapping**

(STS-9) University of California, San Francisco

The equipment consisted of 12 small, lightweight, passive dosimeter packets and three thick multilayered stacks of plastic detector films attached at sites corresponding to a wide range of spacecraft shielding. Materials used in the dosimeter included plastic nuclear track detectors, AgCl crystal detectors, and thermoluminescent detector chips. The thick plastic stacks consisted of 200 Lexan polycarbonate plastic films.

### **Radiation Monitoring Container Device (RMCD)**

(STS-42) NASDA

Comparative biological specimens were subjected to cosmic irradiation with emphasis on HZE (high atomic number Z and high energy) particles. Mounted in the aft end of the Spacelab, layers of cosmic ray detectors and bacteria spores, maize seeds and shrimp eggs are sandwiched together and enclosed on all sides by gauges that measure radiation doses. The specimens were examined before the flight for their suitability to spaceflight constraints, characteristics of radiation sensitivity, and background information. Modification of previously developed dosimetry equipment was conducted to meet the requirements for biological experiments. After being exposed to cosmic radiation for the duration of the mission, the plastic detectors will be chemically treated to reveal the three-dimensional radiation tracks showing the path the radiation traveled after entering the container.

### **Radiative Ignition and Transition to Spread Investigation (RITSI)**

(STS-75) NASA

RITSI Glovebox engineering hardware consists of a flow duct with screens at both ends and a fan which pulls air through the duct. The transparent lid of the duct opens for access to the sample holder for change out of samples. Some samples are rectangular to allow for 2D flame spread, and some are square to allow for 3D flame spread. A near-infrared radiant heater is used to ignite the samples, and is recessed into the back wall of the duct to minimize disturbances to the flow. Samples are stored in a parts box, along with

cleaning supplies, and the changeable filter. Each thin metal sample holder will contain a cellulose sample. Some samples are doped with a smoldering promoter to study smoldering rather than flaming combustion. Six thermocouples and an ignitor wire are pre-installed on each sample holder. The thermocouple data is recorded along with radiant heater power, ignitor power, and flow velocity. Astronaut experiment controls on the small external control box (attaches to the outside of the Glovebox front door) include fan on/off and variable speed control, ignitor wire activation, radiant heater activation and variable power adjustment, and chamber light on/off. On USMP-3, the crew ignited 15 samples of ashless filter paper using a radiant source. Video and 35 mm cameras record the process of ignition and the flame development. The investigator team will be monitoring the experiment during operations. Between tests, the investigator team will analyze the down-linked data to determine the conditions for subsequent tests.

### **Real-Time Radiation Monitoring Device (RRMD)**

(STS-65) NASDA

This IML-2 device is the first one ever flown that actively measures the high-energy cosmic radiation entering Spacelab on orbit. It rapidly collects data necessary to analyze the influences of radiation on the crew, the payload, and biological specimens. During the flight, each time a cosmic ray particle enters Spacelab, a spectroscopy sensor measures the element energy and incident direction of each cosmic ray particle; these parameters determine the strength of the radiation. An electronics-control unit records signals from the detector and transmits them to the ground during the mission. As a basis for a space weather forecasting network that might be established for future spacecraft, data will also be transmitted to remote centers and compared with other observed radiation information, such as optical and X-ray observations. Bacteria will be used to study their ability to recover and repair themselves after a cosmic ray impact. IML-2 data will be compared to passive track dosimeters attached with biological specimens on top of the active detectors and also with Biostack detectors, which have flown on several previous missions, including IML-1.

### **Rebreathing Assembly (RBA)**

(STS-40, 58, 90) NASA

The Astronaut Lung Function Experiment (ALFE) Rebreathing Assembly (RBA) contained the valving and bags needed to perform rebreathing and other measurements during Pulmonary Function Testing (PFT). Part of the (ALFE) Bag-In-Box Assembly, the RBA has two rotary valves designated left and right. The left handle controls the source of inspired gas. The right handle controls the expiration path.

### **Recherche Appliquee sur les Methodes de Separation en Electrophorese Spatiale (RAMSES): Applied Research on Separation Methods Using Space Electrophoresis**

(STS-65) CNES

The RAMSES electrophoresis unit has a special transparent chamber so that scientists can monitor the progress of samples as they are processed. The chamber has 40 outlets for collecting separated samples. To analyze the fractions, the concentration of each fraction is monitored continuously with an ultraviolet photometer that allows scientists to deduce the sample concentration by measuring how strongly light is absorbed by the samples. Samples will be photographed, and some will be collected and refrigerated for analysis on Earth.

### **Refrigerator/Incubator Module (R/IM)**

(STS-40, 47, 50, 58, 65) NASA

The Refrigerator/Incubator Module (R/IM) is a temperature-controlled holding unit flown in the Shuttle middeck. The R/IM uses a solid-state heat pump to maintain a cooled or heated internal environment. A fan

circulates cabin air through the heat pump/heat sink and is exhausted through ducts in the top and bottom surfaces of the unit's outer shell. Air is not circulated within the internal cavity. A vent valve on the front door automatically controls internal pressure. To accommodate experiments, rail guides and fasteners are provided as a means of mounting up to six shelves of experiment hardware. The refrigerator/incubator module is an active unit with a temperature range from 4 to 40 degrees Celsius. It is flown in place of a standard middeck stowage locker or may be mounted to the Spacelab Middeck Experiment (SMIDEX) rack. Power consumption is 136 watts at 100 percent duty cycle and from 4 to 70 watts at a 70 percent duty cycle (empty). The temperature is set using a front-mounted variable potentiometer, with switching between the refrigeration and incubation modes occurring automatically. Front-mounted heat/cool LED indicators and a power switch are also provided. Stability of the temperature at the reference sensor is maintained within plus or minus 0.5 degrees Celsius of a set point within 20 degrees Celsius of ambient temperature. The unit uses 28 volts of power. A vent valve on the front door automatically controls internal pressure to within 0.5 psi of ambient pressure and can be manually activated to permit venting a negative pressure that may prevent opening of the R/IM door. To accommodate experiments, rail guides and fasteners are provided as a means of mounting up to six shelves of experiment hardware. The interior of the R/IM is composed of two cavities. The primary cavity, on the right, measures 6.46 x 10.19 x 14.56 inches or 958 cubic inches. The smaller cavity, on the left, is 60 cubic inches. The temperature desired is selected by a ten-turn precision potentiometer with a digital turn-counting indicator and locking device. The temperature controller has a time-proportioning output and integral action to bring the desired temperature to equal the set point. Two light-emitting diodes indicate the mode of operation (heat or cool) and the duty cycle of the heat pump. A digital display monitors the internal temperature of the unit. The temperature is derived from a Resistance Temperature Device (RTD) on the left rear wall of the cavity. The original R/IM that was designed and built was flown on four shuttle flights prior to the extensive modifications that resulted in the version flown on SLS-1 and subsequent missions.

### **Research Animal Holding Facility (RAHF)**

(STS-51B, 40, 58) NASA

The Research Animal Holding Facility (RAHF) is an animal habitat for general use within the Spacelab. Animal-specific cages are inserted, as needed, to provide appropriate life support for rodents. Cages can be removed from the RAHF to allow inflight experiment procedures to be conducted. The RAHF is installed in a double rack to provide environment control, food, illumination, and waste management for the animals on board. The data system in the RAHF is designed to interface with the Spacelab data acquisition systems. The RAHF houses twelve rodent cage assemblies. Each cage contains a waste management system, and individual feeders and watering Lixits. Control can be exercised for overall cage module temperature and day/night lighting for each of four cage module quadrants.

*Rodent Cage:* The Rodent Cage Module contains 12 cage assemblies, with each cage housing two rats separated by an internal divider for a total capacity of 24 rats. The cages are removable inflight for transfer to a General Purpose Work Station using the General Purpose Transfer Unit to maintain particulate containment.

*Environmental Control System (ECS):* The RAHF Environmental Control System (ECS) is mounted on the back of the cage module to circulate conditioned air through the cages. Air temperature is controlled. Carbon dioxide is removed and oxygen replenished by exchange of air with the Spacelab. Two propeller fans pull cabin air from the RAHF cage module and return a portion of the circulating air to the cabin through a filter and a charcoal bed, which removes odors and particulate matter. These two filters bacteriologically isolate the animals and crew and ensure that the RAHF maintains a slightly negative pressure with respect to the cabin. Air within the RAHF is circulated by a cluster of four propeller fans. To ensure containment of free-floating particulates, the Single Pass Auxiliary Fan maintains negative pressure within the RAHF when a

cage is removed. The RAHF uses a bang-bang type electronic system with a controllable set point to modulate Thermo-electric Units (TEUs) and fans for cooling and electric resistance elements for heating to provide temperature control. Fans direct bypass air through the cold side of a Pelita-type TEU to cool cage module air, which is remixed with circulating air prior to return to the cages. The Spacelab experiment cooling loop provides a heat sink for the TEU. Water condensing on the TEU is guided by a hydrophilic coating and capillary action to the trailing edges of the TEU cooling fans in the aircore. Water, with some air, is sucked from the trailing edge of the aircore and pumped by a water separator into a condensate collector bottle, which is changed out by the crew as required. A thermoswitch located on the inlet water header of the TEU shuts down the TEU in case of loss of Spacelab cooling water flow and subsequent TEU overheating. The air is warmed, as necessary, by a heater located in the main circulation airflow stream. The RAHF is equipped with its own auxiliary pump, since the Spacelab coolant circulating pump is not on prior to and during launch or during descent. The auxiliary pump is connected to the ECS system to provide cooling during these periods.

*Feeding/Waste Management Systems:* Rodent food bars are supplied automatically on a demand basis. Directed airflow continuously draws liquid and solid wastes into a waste tray at the bottom of each animal cage where bacterial growth is controlled and odors are neutralized. Rodent food is supplied *ad libitum* in the form of a rectangular diet bar mounted in the feeder. The bars are advanced into the feeder alcove as one is consumed by the rat. The removable feeder cassette contains two food bars, one servicing the forward cage, the other servicing the back cage. The crew changes the food bars by removing and replacing the feeder cassette without removing the animals or cages. On a scheduled basis, the crew measures food consumption using built-in measurement tapes. A waste collection tray is attached by slides to the bottom of each cage. For missions longer than 10 days, trays may be changed without removing cages from the cage module. Air-flow through the top of the cage directs waste products into the waste trays. The coarse grid of the cage floor allows animal debris to pass into the waste tray. Below this grid, a feces tray screen traps feces, and urine is trapped by an absorbent Bondina filter located immediately below the feces tray grid. This filter is treated with phosphoric acid to reduce urine pH, thus inhibiting the production of ammonia from the decomposition of urine. Below the absorbent filter is a fibre pad layer into which is bonded charcoal dust. Below the charcoal pad is a Filtrete layer, formed with polypropylene, that serves as a hydrophobic barrier, followed by a final 150-micron stainless-steel mesh. Feces and urine are also dried by recirculating airflow to inhibit decomposition.

*Water System:* The RAHF *ad libitum* watering system consists of a pressurized bladder tank, pressure regulator, water delivery system, and water consumption counters. The delivery system includes 24 sets of solenoids, pressure switches, and accumulators that deliver aliquots of water to lixit valves in the cages for the animals.

*Self-Pressurized Bladder Tank:* A two-camber gas side pressure tank maintains water system pressure and provides the force to move water from the drinking water tank through the system to the cage. As water is used, a flexible diaphragm collapses across the water volume while the gas side expands. The quantity of the water remaining in the tank is monitored via a water pressure transducer.

*Pressure Regulator:* A pressure regulator maintains downstream water pressure to the drinking water manifold.

*Drinking Water Manifold:* Water flows in the manifold assembly and via a solenoid into a 0.5-ml accumulator. When consumption reduces accumulator pressure sufficiently, a pressure switch initiates a refill of the accumulator. When water pressure in the accumulator rises sufficiently, a high pressure switch stops water flow until the next consumption-initiated cycle. A count is registered and sent to the data system each time this cycle is carried out. If there is a loss of electrical power or a failure of a solenoid valve or pressure switch, water can be made available to the cage by manually pulling out a small knob on the affected valve. In this mode, water is made available to the cage but no electrical signals indicate water consumption.

*Lixit Valves:* A lixit provides a “water ball” in the cage, which is replenished as the animal tongues the spigot. Lixits are mounted on a service bar located within the cage side wall.

*Version Modifications:* For SLS-1, water delivered from the tank was forced through an iodinator, an iodine charged resin bed, to provide nominal iodine levels to ensure water was uncontaminated. An additional valve was added in order to bypass the pressure regulator in the event of a malfunction. Also, a valve was added for drain and fill operations. For SLS-2, the iodinator was removed due to drying and flaking of the bed and subsequent contamination of the water. In this case, iodine is manually added to the drinking water before being pumped into the water tank.

*Inflight Refill Unit (IRU):* For SLS-2, the IRU is used to obtain and transport water from the orbiter middeck galley to the RAHF Water System.

*Lighting System:* Rat cage illumination is provided on a 12:12 day/night cycle. Each cage lamp provides approximately 2.1 lumens of light at cage floor level. The light cycle for each quadrant of cage assemblies (four cages) can be independently controlled, manually or via an adjustable timer.

*Data System:* The Data System collects three types of data. Temperature, humidity, water pressure, and air pressure across ECS fans (air flow) are collected as Analog data. Heating, cooling, lighting, and a drinking water out of limit condition are collected as Discrete data. Water delivery and activity are collected as Pulse-code Modulated data. All data are passed to the Spacelab data system for display, recording, and downlink to the ground. Data displayed on board include environmental status, water consumption, and activity. A special subset of data is routed to launch control center computers for display during late access loading and until launch.

On STS-58, the following hardware adaptations were made to the various subsystems of the RAHF. If necessary, refill water for the Research Animal Holding Facility (RAHF) drinking water system is obtained from the orbiter middeck galley using the Inflight Refill Unit (IRU) for transport to the Spacelab. Excess water is disposed of through the Middeck Waste Collections System. The IRU consists of two major subsystems: the Fluid Pumping Unit and the Collapsible Water Reservoir. A tether for the IRU is provided to meet Shuttle safety requirements.

*Fluid Pumping Unit (FPU):* The FPU is contained within a Nomex cloth pouch for ease in storage and transport. It is composed of the pump/motor, piping, sensors, and supporting structure required to pump water through the IRU system. The FPU's positive displacement pump contains an integral motor designed for continuous operation. A motor drive control governs pump speed by regulating the motor input voltage. A current limiting device is also provided. Power is not required when filling the system but is required at the RAHF when transferring water to the water tank and when disposing of excess water. Two counters are provided that mechanically indicate the number of liters of water pumped (resettable) and total liters pumped (not resettable).

*Collapsible Water Reservoir (CWR):* The CWR, also contained within a Nomex cloth, is a flexible, stowable bag, which contains the water for transfer. The main body is constructed of two layers. The inner bladder is made from a polyether polyurethane material compatible with potable water and the outer bladder is made of a Kevlar reinforced urethane to provide pressure holding capability and to provide protection against accidental cuts and tears. A panel of urethane is attached to both sides of the CWR to limit its expanded height. A thermoplastic hose with a quick disconnect mates with the FPU.

*Hose/Adapter Accessories:* An adapter is provided to enable the dumping of excess water into the orbiter Waste Collection System with a quick disconnect at the IRU end and a twist lock connection to the waste system.

*Cages:* Each rodent cage houses two rats. Cages are constructed of anodized aluminum side and rear walls, perforated metal floors, and screened-top doors to permit air circulation (top to bottom). Rodent cages are designed with a polycarbonate front window backed with a stainless mesh to keep rodents from rubbing against the window. The cages have a stainless steel mesh partition creating two compartments, one for each rat. Both front and back rats may be viewed by opening a front cover. Cage tops are hinged to allow access

to the animals. Each cage also contains a feeder and a waste tray to contain urine and feces (see separate records). Each rat cage contains activity monitors to record general movement using an infrared light source and sensor. Each time an animal breaks the light beam, a counter automatically advances one count. These signals are recorded and periodically transmitted to the ground to ensure animal well-being.

### **Respiratory Inductive Plethysmograph (RIP) Suit**

(STS-78, 90) Institut de Recherche Interdisciplinaire (Free University of Brussels), Brussels, Belgium

The Respiratory Inductive Plethysmograph (RIP) Suit, also called the Respitrace Suit, allowed for the measurement of respiration without any direct communication to the airway. It measured the change in the volume of the subject's torso, where the change in volume is produced by the motions of respiration. These measurements were used to determine respiration by assuming that the length of the subject's trunk does not change, but that change in trunk volume is reflected by the change in area of the cross-section. During torso volume changes, the inductance changes and the motion can be measured. The main assembly of the RIP system is a Lycra-Spandex suit worn by the astronaut, in which two wires are stitched in a zig-zag pattern into the suit, one wire at the chest level and the other at the abdomen. Each wire acts as a single-turn coil of wire, forming the inductance in a tuned circuit which determines the oscillatory frequency of the system. ECG electrode leads are also sewn into the suit to allow for proper placement of ECG electrodes. The Respitrace Electronics Module (REM) is stowed hardware. The REM receives a signal from the Respitrace Suit, converts the signal into analog data describing lung capacity, and provides it to the Electronic Control Assembly (ECA) for downlinks via the experiment computer. The data is also stored on a disk in the Microcomputer II. The REM requires a 12 volt DC power supply, which is converted from the 28 volt DC Spacelab power routed through the ECA. The conversion from 28 to 12 volt DC is performed by a DC-to-DC Converter located inside the ECA. Power to the Respitrace Suit is supplied by the REM.

### **Robotics Experiment (ROTEX)**

(STS-55) DARA

This was a robotic arm that operated within an enclosed workcell in the Spacelab D-2 module and used teleoperation from both an on-board workstation and on the ground. The robotic arm used teleprogramming and artificial intelligence to examine the design, verification and operation of advanced autonomous systems to be used in future applications. ROTEX was comprised of (1) a robot arm with six joints; (2) two torque sensors located at the back of the gripper to prevent overloading; (3) a gripping assembly containing laser distance-measuring devices, tactile sensors and stereo television cameras; (4) two fixed video cameras that provided stereo pictures of the whole assembly.

### **ROOTS (Transmission of Gravistimulus in the Statocyte of the Lentil Root)**

(STS-42) ESA

The experiment consisted of two minicontainers each containing six seeds. The dry seeds, with their coat removed in order to facilitate root growth, were placed in a small growth chamber which had a transparent cover and a cellulose sponge upon which the seeds were held. Water was injected into the sponge to activate the experiment, after which the containers were placed into a 22 deg C Biorack incubator where they were kept for 27 hours. The mini growth chambers permitted gas exchange between the seeds and the incubator, kept at = 22degC. The seedlings were grown in darkness for 28 hours, then placed on a 1g centrifuge for various times (5, 10, 15, 20, 35 and 60 minutes) in such a way that the root axis was either perpendicular or oblique to the 1g acceleration. Six of the seeds were fixed with glutaraldehyde (using a spring-driven piston) after 5, 10, 15, 25, 40 and 60 minutes of stimulation. Then the minicontainers were placed in front of a photcamera, and photographs were taken at 10 minutes intervals. A green filter (560 nanometers) was interposed between the flash and the seedlings. The analysis of the gravitropic reaction as a function of time was done from time-lapse colour prints.

### **Rotating Dome**

(STS-9, 40, 58) NASA

The Rotating Dome is a motor-driven variable-speed drum-like apparatus which provides a rotating visual field to the test subject. A removable bite board with a built-in strain gauge for each crewmember provides proper head positioning in the Dome and provides a measure of neck torque. EMG electrodes measure the activity of the neck muscles. A joystick mounted on the dome is used by the test subject to indicate his/her perception of direction and velocity of rotation. Joystick output is routed to the ECDS/ Microcomputer System (EMS). Rotational velocity and direction are varied by commands from the EMS. A black and white Spacelab video camera, with an adapted 105mm zoom lens, is mounted on the Dome along its rotational axis to record eye movements. A second video camera is mounted to a rack handrail, behind the subject, by means of an STS camera mount with clamp adapter (Bogen bracket), to monitor neck angle and body position for all runs.

### **Saliva Collection Kit**

(STS-40, 71, 78, 90) NASA

Several configurations of the Saliva Collection Kit have been developed. Each consists of a cloth (Nomex) pouch in which a quantity of collection vials is secured by means of foam inserts or elastic straps. Each vial contains a sterile dental cotton roll. The vials are labeled and color-coded, and contain a space for the crew member to record the time at which the sample was taken. The kits also contain a marking pen, a pair of tweezers to facilitate removal of the cotton roll from the vial, and strips of an inert rubbery film (Parafilm) that the crew members can chew to stimulate salivation if necessary. During use, the subject removes the cotton roll, places it in his/her mouth until it is saturated with saliva, and then returns it to the vial. Two different types of collection vial are used. For studies in drug pharmacokinetics, plastic "Salivette" vials (developed for NASA by Sarstedt) are used. The Salivette is a test-tube system designed for standardized hygienic collection of mixed saliva in the mouth. After flight, each vial is placed in a plastic adapter that allows it to fit into a standard centrifuge test-tube holder. The saliva samples are then removed from the vials by centrifugation and stored for subsequent analysis. For studies involving the calculation of total body water, saliva samples are typically taken after ingestion of a tracer, such as water labeled with "heavy oxygen" and deuterium (heavy hydrogen). In these cases, glass lyophilization vials are used in place of the plastic Salivettes. This is because the concentrations of isotopes involved are extremely low, and the plastic vials are just porous enough that isotope transport through the vial walls is possible. Thus, the samples could be altered by evaporation of the tracer dose. When the glass vials are used, each vial is wrapped in protective Teflon shrink-wrap and adhesive tape. This reduces the chance of breakage and would contain the glass fragments if breakage did occur.

### **Self-tonometer (TOMEX)**

(STS-55) DARA

Microgravity leads to an increase in intraocular pressure due to a fluid shift from the lower to the upper part of the body. Up to now little was known about the peak values and the adaptation process. The greatest alteration in intraocular pressure is expected during the early phase after launch. Because the astronauts are fastened in during this phase, measurements have not been performed. To solve this problem and to save crew time, a tonometer was developed which enables self tonometry.

### **SHOOTS (Growth, Differentiation and Development of *Arabidopsis Thaliana* Under Microgravity Conditions)**

(STS-42) ESA

Seeds of *Arabidopsis thaliana* wild type and seeds of its agravitropic mutant aux-I were attached to a strip of cellulose nitrate filter, supported on a piece of filter paper, arranged so that it would absorb injected water

and conduct it to the seeds. In each growth chamber (18 x 20 x 80 mm) 23 seeds each of the wild type and of the mutant were contained. The tops of the chambers were transparent to allow a light stimulation period, since the seeds have a light requirement for germination. The seeds were then kept in darkness for the rest of the experiment. Two growth chambers were contained in one Type 1/0 BR container. The space-flown part of the experiment, carried in the Biorack, comprised six Type 1/0 containers, four of these housed in the Biorack Incubator A racks, at 22degC, the remaining two on the Incubator A centrifuge. At the start all material was hydrated before being exposed to the glovebox light for 30 minutes. The growth chambers were then replaced in their Biorack containers, four in the Biorack 22 degree C incubator in microgravity and two on the 1-g control centrifuge. Fifty hours after the initial hydration two growth chambers from microgravity and one from the 1-g centrifuge were removed, photographed in stereo, then fixed with an injection of glutaraldehyde. These fixed samples were then placed in storage at 5 degrees C. This sequence was then repeated three more times at 15 hour intervals.

### **Shuttle Imaging Radar (SIR-A, B, and C)**

(STS-2, 41G, 59, 68) NASA

The SIR-A experiment on STS-2 used a sidelooking, synthetic aperture radar operating at L-band (1.278 GHz) with a viewing angle of 47 deg to create two dimensional images of the earth's surface. The imaging radar was independent of sunlight and was able to penetrate cloud cover. A swath width of 50 km and a resolution of 40 m both across and along the track of the beam was attained by this system. The sensor was in operation for 8 h during the 2-1/2 day flight, acquiring images of about 10 million sq km between 38 deg N and 38 deg S latitude. Landsat multispectral imagery was used to provide supplementary information necessary to identify rock types and types of vegetation.

The primary purpose of the Shuttle Imaging Radar-B (SIR-B) experiment on STS-41G was to provide data for studies of geography, geology, hydrology, oceanography, vegetation, and ice applications. The SIR-B was a side-looking, synthetic aperture radar that illuminated the earth's surface with horizontally polarized (HH) microwave radiation transmitted at L-band frequency 1.28 GHz (wavelength 23 cm). The SIR-B antenna was mechanically tilted while the Shuttle's payload bay was facing the earth. This enabled researchers to obtain radar imagery of a specific area at up to six incidence angles ranging from 15 to 60 deg. Multiple-incidence-angle radar imagery was used to distinguish surface materials on the basis of their roughness characteristics. With a 12-MHz bandwidth and 20% degradation in the pulse, the ground range resolution was 17 m at a 60-deg incidence angle and was 58 m at 15 deg. The azimuth resolution was 25 m at all incidence angles. The swath width of the SIR-B imagery was 20-50 km. The original plan was to obtain 42 h of digital data and 8 h of optical data. A number of problems severely impacted the SIR-B data collection. They included the Ku-band antenna failure, a TDRSS link lost for more than 12 h, and anomalies in the RF feed system to the antenna. As a result, only 7 1/2 h of digital data and 8 h of optical data were collected. The digital data were transmitted from the Shuttle through the TDRSS to White Sands, New Mexico. White Sands relayed the SIR-B data via Domsat to GSFC. The digital tapes were then sent to JPL to be processed to imagery. The optical data were processed by an optical correlator at JPL.

Shuttle Imaging Radar-C (SIR-C) instrument on STS-59 and 68 was to investigate characteristics of the Earth's surface such as (1) vegetation extent and biomass condition, (2) soil moisture and snow properties, (3) recent climate change and tectonic activity, and (4) ocean wave spectra. The SIR-C was jointly operated from the Space Shuttle with the X-band Synthetic Aperture Radar (X-SAR), provided by the German Space Agency (DARA)/German Aerospace Research Establishment (DLR) and the Italian Space Agency (ASI), on the same Space Radar Laboratory (SRL) platform. The SIR-C radar operated at L-band (24-cm wavelength or 1250 MHz) and C-band (5.6-cm wavelength or 5300 MHz) in multiple polarization modes

(HH,HV,VH,VV). The antenna was composed of two planar arrays, one for L-band and one for C-band, in dual-polarized operation. Each array was composed of a uniform grid of dual-polarized microstrip antenna radiators. The SIR-C antenna was 12.2 meters, weighed over 10,500 kg and filled the Shuttle cargo bay. SIR-C provided images of the magnitudes of HH,VV,and cross-polarized returns, images of the relative phase difference between multiple polarization returns, and derivation of linear, circular, or elliptical polarization. Image resolution was 25 m (20 MHz bandwidth) and 40 m (10 MHz bandwidth). The swath width ranged from 15 to 65 km for calibrated images and 40 to 90 km for mapping mode (SCANSAR) images. In SCANSAR mode, the antenna was steered electronically or mechanically to acquire data at various incidence angles (15 to 55 degrees) increasing the swath width at reduced resolution. Data was acquired at 8 bits per sample or 4 bits per sample in 16 primary modes. SIR-C used four solid state receivers, two each for C-band and L-band. The SIR-C data was recorded on-board on the Shuttle Payload High Rate Recorder.

### **Shuttle Multispectral Infrared Radiometer (SMIRR)**

(STS-2) NASA

The Shuttle Multispectral Infrared Radiometer (SMIRR) system consisted of a Cassegrain telescope, a filter wheel, two Hg-Cd-Te detectors, two film cameras, and supporting electronics. The telescope was a modified version of the Mariner telescope that gathered images of Venus and Mercury in 1973. Since SMIRR was not an imaging device, photographs were necessary to locate the 100-m-diameter radiometer reading within the cameras' ground view (20 by 25 km). The two cameras, one color and one black-and-white, were aligned with the telescope. The filter wheel allowed 10 filters to sample the following spectral bands: filters 1 and 2 at 0.5 and 0.6 micrometer for correlation with Landsat; filters 3 and 4 at 1.05 and 1.2 micrometers for field measurements; filter 5 at the 1.6-micrometer Landsat 4 band; filter 6 at the 2.1-micrometer NO hydroxyl absorption band; filters 7, 8 and 9 at the 2.17-, 2.20-, and 2.22-micrometer hydroxyl ion absorption bands; and filter 10 at the 2.35-micrometer carbonate absorption band.

### **Shuttle Solar Backscatter Ultraviolet (SSBUV)**

(STS-45, 56, 66) NASA

SSBUV flies aboard the Space Shuttle and compares its data with observations of several ozone-measuring instruments on the National Oceanic and Atmospheric Administrations's NOAA-9 and NOAA-11 satellites and the NIMBUS-7 satellites. During the ATLAS series of missions, concurrent measurements are also being taken with the Upper Atmosphere Research Satellite. The same location is mapped by the Upper Atmosphere Research Satellite, Shuttle Solar Backscatter Ultraviolet Spectrometer and other ATLAS instruments within a 60-minute timeframe to verify the accuracy of the data collected. The SSBUV spectrometer is located in a Get-Away-Special canister, attached to the side of the Shuttle's cargo bay. A motorized door assembly, which opens up to allow the SSBUV to view the Earth and sun, closes to protect the instrument from contamination when it is not in use. Data, command and power systems are housed in an adjacent canister and connected to the spectrometer by a communications-link cable. During SSBUV operation, light enters the instrument and travels through a system of mirrors and gratings to a photomultiplier. The photomultiplier converts sunlight into an electric current, which is then magnified by a three-range electrometer amplifier. The desired wavelength is selected by a grating, which is controlled by a microprocessor. The gratings allow the SSBUV instrument to scan through 12 discrete channels in the ultraviolet range. The four longest channels are used to calculate the total amount of ozone in the instrument's view, while the remaining channels determine how the ozone is distributed by height between 15.5 and 31 miles (25 and 50 km).

### **Shuttle/Spacelab Induced Atmosphere Experiment (SSIA)**

(STS-3) University of Florida

The primary objective of the Shuttle/Spacelab Induced Atmosphere Experiment (SSIA) was to provide an early assessment of the effect of the Orbiter-induced atmosphere on astronomical observations, using measurements of the brightness and polarization of light scattered in the vicinity of the Orbiter at ten wavelengths between 400 and 820 nm. Secondary science objectives were to use repeated or continuous measurements of the optical properties of the Shuttle environment to characterize decay rates for contamination resulting from outgassing, thruster firings, water dumps, and flash evaporation operations, and to determine the brightness, polarization, and color of the diffuse astronomical background (zodiacal light and background starlight). The existing Skylab photometer/camera system was used. A photoelectric polarimeter measured the intensity and polarization of sky brightness in ten colors. It had a self-contained pointing system and automatic shutdown and startup provisions to allow maximum viewing time. A boresighted 16-mm camera provided concurrent photographic records of star fields to establish instrument pointing direction. The instrument operated in a single-axis scan mode, sweeping fore and aft through the Orbiter's vertical axis. A photometer mount provided adaptation of the existing instrumentation to the pallet mounting surface.

### **Single Axis Acoustic Levitator (SAAL)**

(STS-7, 61A) NASA

The SAAL is a commercial payload developed by Marshall Space Flight Center for use on the OSTA-2 and D1 missions. During the D1 mission, the processing procedure was fully automated. Samples are released into the furnace, positioned by sound, heated to the appropriate temperature, cooled to the appropriate temperature, and retrieved from the furnace. A high quality photographic record of the processing of the samples was used to determine that the release of the samples went as planned. After the release, the samples oscillated in the acoustic field for 40-50 seconds and then became almost stationary in the acoustic energy well. The samples remained stationary during and after melting but began to oscillate again during the cooling sequence.

### **Sleep Net**

(STS-90) NASA

The Sleep Net is a neuromonitoring system based on a commercially available system for use in conventional electroencephalogram (EEG) recording. The Sleep Net comprised a reusable headpiece and disposable biosensors secured to the scalp with an adhesive gel that does not leave residue after sensor removal. A Borg cable linked the Sleep Net and Respiratory Inductive Plethysmograph (RIP) Suit to the Digital Sleep Recorder (DSR) for data transmission.

### **SLIME (Gravity Related Behavior of the Acellular Slime Mold *Physarum Polycephalum*)**

(STS-42) ESA

The equipment consisted of four standard Biorack containers each of which held two small culture chambers made of aluminum (64 x 20 x 9.5 cm). The culture chambers each had two small windows, one red and one clear, the latter covered with a removable red transparent tape as a protection against light of the shorter wavelengths. The experiment was initiated when the four containers were transferred to a 22 deg C incubator, two of them being placed on a 1-g centrifuge. SLIME was composed of four different parts, the first of which concerned the measurement of the movement of the slime mold (caused by a network of protoplasmic strands performing rhythmic contractions in the minute range). One of the cultures was transferred from the the 1-g centrifuge and its response to the 1-g to 0-g transaction was recorded using a microscope and video. The second part of SLIME concerned the photoreaction measurement with simultaneous induction of the 0-g and light reactions: Another culture chamber was taken from the centrifuge

and, immediately before its insertion in the microscope, its red light protection filter was removed to allow the light stimulation of the slime mold. The third part of SLIME was similar to the second except that it concerned the photoreaction measurement of a 0-g adapted slime mold culture. The fourth part of the experiment concerned the measurement of a 0-g adapted slime mold without light stimulation.

### **Small Mass Measuring Instrument (SMMI)**

(STS-40, 58) NASA

The Small Mass Measuring Instrument (SMMI) has the capacity of accurately weighing specimens in a zero gravity environment. It uses a fulcrum principal and has various weight ranges which can be calibrated into the system for accuracy. The upper limit weight range or capacity of the SMMI is reduced to 1,000 grams for all one gravity operations. It can be integrated into a standard Spacelab single rack or on one side of a double rack. The SMMI determines the weight of a specimen through the use of its mass properties, thereby minimizing the influence of any gravity field. Mass measurements can be obtained when the specimen is placed on the tray assembly and restrained with the perforated rubber cover to minimize relative motion. The measurement process begins with the semi-automatic release of the specimen and tray assembly from an offset position, so that they oscillate mechanically. A set of plate fulcrum springs support the tray assembly and provide the oscillatory forces for motion. The zero crossover detection assembly precisely measures the period of oscillation, which is a function of the mass of the tray assembly, specimen, and part of the plate fulcrum springs. The measurement process ends with the semi-automatic recapture of the specimen and tray assembly and return to its original offset position. The SMMI controller then calculates and displays a mass value for the specimen. A set of 12 stackable calibration weights are provided with each instrument. In addition to the calibration and measurement modes, multiple non-standard diagnostic functions are available, such as inspection of calibration values stored in memory, inspection of equations used to calculate the specimen weight, testing of the oscillation function of the tray assembly, and an option to display period-of-oscillation measurements in seconds.

### **Solar Array Experiment (SAE)**

(STS-41D) Lockheed Missiles and Space Flight Co.

The OAST-1 Solar Array Experiment was fabricated by Lockheed Missiles and Space Flight Company from 3-mil thick Kapton and consisted of 84 panels, each 15 inches wide by 13 ft long, joined edge to edge to form a 105 foot tall array. For launch and reentry, the array had to be folded accordion like into a 7-inch thick stack. Deployment was accomplished using a triangular-shaped coilable mast.

### **Solar Cell Calibration Facility (SCCF)/ Dynamic Augmentation Experiment (DAE)**

(STS-41D) NASA

The shuttle orbiter closed circuit television (CCTV) was used to provide recorded video images of the solar array from four locations in the payload bay. White reflective targets were placed on the array to provide discrete points at which to track the array motion. A dynamic test consisted of a quiescent period in which crew and orbiter operations were restricted, followed by an excitation period using the vernier reaction control jets on the Shuttle, and a free-decay period. By tailoring the thruster firings, different modes of the structure were excited. Analysis of the flight data was done on the ground and required three major steps: each video tape is analyzed to determine motions of target in the camera image plane, triangulation of four camera images to determine 3-D motion in the orbiter coordinate system, and the last step was to process the data using system identification algorithms. Two algorithms were used in the data analysis, the standard FFT analysis and the ERA system identification program.

### **Solar Flare X-Ray Polarimeter Experiment**

(STS-3) Columbia University

The flight instrument, a scatter block polarimeter, consisted of three detectors mounted in an equilateral configuration to provide redundant observations of X-ray polarization. There were four counters and four rectangular lithium scattering blocks per detector assembly designed to detect anisotropic X-ray scattering if the incoming beam was polarized. The polarimeter was pointed at the sun during the occurrence of solar flares, and when sun-pointed, it had a 3-deg field of view.

### **Solar Constant Measurement Experiment (SOLCON)**

(STS-45, 56, 66) ESA

The SOLCON instrument was an absolute self-calibrating radiometer. The radiometer had two channels which enabled the detection of and compensation for any degradation of the black surfaces, and the determination in space of the self-consistency of the radiometric system. Radiation measurements were made by using a heat balance system automatically driven by a feedback system. The two sensors were independently shuttered. The radiometer produced solar measurements with an accuracy of better than 0.05 %.

### **Solar Optical Universal Polarimeter (SOUP)**

(STS-51F) Lockheed Solar Observatory

The instrumentation consists of a solar optical universal polarimeter mounted on the IPS. The polarimeter is composed of a tunable birefringent filter with a bandpass of 60 nm using associated blocking filters to permit the filter to operate in eight spectral bands, each about 0.8 nm wide. A film camera takes direct filtergrams through the tunable filter. A charge injection device (CID)-array camera takes photoelectric filtergrams with a high signal-to-noise ratio through the tunable filters. A video processor stores images in digital memory and a high-resolution, white-light system with film camera and video display is used for acquisition of accurate pointing data. The filter systems are interfaced to a 30-cm Cassegrain telescope with offset pointing capability. Rotatable wedges are placed in front of the telescope to allow it to observe any desired point on the sun. A guider assembly compensates for high-speed image motion. To record a complete line profile, filtergrams are taken in orthogonal polarizations at 15 wavelengths spaced 2 to 3.5 nm apart and in the near continuum. They are recorded on S0115 film with a resolution element of 50 micrometers per side. Experiment mass: 183 kg; average experiment power: 322 W

### **Solar Spectrum (SOLSPEC) Measurement**

(STS-45, 56, 66) ESA

The experiment consists of three double grating spectrometers covering the UV (180 to 370 nm), visible (350 to 900 nm) and IR (800 to 3000 nm) and an onboard calibration device. The three spectrometers use concave holographic gratings of 10-cm focal length with a spectral positioning accuracy of 0.01 nm. The onboard calibration device consists of two deuterium lamps, two tungsten ribbon lamps, and one hollow cathode lamp. The instrument is calibrated against a 3300 K black body and a set of tungsten ribbon lamps.

### **Solar Ultraviolet Spectral Irradiance Monitor (SUSIM)**

(STS-3, 51F, 45, 56, 66) Naval Research Laboratory

There are two SUSIM instruments, one flown on the ATLAS mission, the other part of the UARS satellite system. The SUSIM ATLAS better measures the absolute solar UV intensity while the SUSIM UARS tracks relative solar variability.

The instrumentation consists of a solar UV spectral irradiance monitor. The monitor consists of two identical double-dispersion scanning spectrometers, seven detectors (five photodiodes and two photon counters),

and a UV calibration light source. They are sealed in a canister filled with 1.1 atm of argon to eliminate the effects of contamination from high vacuum out-gassing. One spectrometer is used almost continuously during the daylight portion of the solar-pointed orbit for measuring short-time variations of the UV solar flux (flare-related and slowly varying component). The other spectrometer is used only once a day to track any change in sensitivity of the first spectrometer. Two of the five photodiodes are used only once a day. A deuterium lamp calibrated in spectral irradiance is used as the transfer standard source for daily inflight calibration and stability tracking of both spectrometers and all seven detectors. The two photon counters obtain a spectral resolution of 0.1 nanometer over the whole wavelength range, while 5-nm resolution is obtained with the five photodiodes. A microprocessor controls all instrument functions by program instruction. Channels monitor the 121.6-nm line (Lyman alpha) and seven segments of the continuum from 145 to 390 nm. Eight narrow-band channels (0.1-nm resolution) are monitored continuously and scanned in five 0.1-nm steps. In the spectral scan mode (once a day) the spectrum from 120 to 400 nm is scanned at 0.1-nm resolution. In the narrow-band mode the solar spectrum and the deuterium lamp are scanned with both spectrometers; both are monitored in the broad-band mode. Experiment mass: 20 kg; average experiment power: 20 W

### **Solid Sorbent Air Sampler**

(STS-71) NASA

The Solid Sorbent Air Sampler (SSAS) consists of a cylindrical anodized aluminum enclosure encasing a gas flow subassembly and an electronic subassembly. The gas flow subassembly consists of 8 silica-lined stainless steel tubes containing 3/4 Tenax-TA sorbent (0.5 gm) and 1/4 Carboxen 569 (by volume) separated by a plug of glass wool for sample adsorption. The tubes are connected at one end to a mechanical 8-position, zero-dead-volume valve for on/off switching between tubes. One of the tubes (tube 8, labeled "Park") is used as a parking position between sample collections. The tubes are connected at the other end to the electronic subassembly. The electronic subassembly consists of a pulse pump used to pull air into the sampling device, a battery clip to hold the batteries in position, and four disposable C-sized dry-cell batteries to provide power. The small single-diaphragm pulse pump draws air at an adjustable rate (from 0.5 to 3.0 liters of air per 24-hours). A timer printed circuit board is used to deliver a timed power pulse to the motor. This allows air to be sampled slowly, so that sufficient time is allowed for atmospheric volatile organic compounds to be absorbed evenly throughout an adsorption tube, without saturation in any particular section. The entire unit weighs approximately 2.3 kg. A recent modification to the inlet screen provides a 5-fold increase in the inlet area to minimize chances for obstruction of the inlet.

### **Solid Surface Combustion Experiment (SSCE) Module**

(STS-50) Mississippi State University

The SSCE is designed to fly in either the Space Shuttle middeck or in Spacelab and is capable of withstanding the rigors of several launches. It occupies four standard middeck locker spaces and can be mounted either in place of these lockers, or in a Spacelab middeck experiment (SMIDEX) rack designed to simulate the middeck locker interface. The SSCE consists of two modules -- a chamber module and a camera module. The chamber module houses the sample to be burned inside a sealed container filled with oxygen and nitrogen at the desired atmospheric pressure and concentration. Two viewports are provided to permit the sample to be filmed during combustion from a side and a top view. The camera module consists of the instrumentation package for controlling the experiment and collecting data. Two 16-millimeter color cameras mounted on a camera mast film the entire combustion process. In addition, thermocouples and temperature sensors monitor the temperature of the combustible sample, the flame, and the surrounding air. A pressure transducer monitors changes in chamber pressure. The SSCE computer stores all data for postflight retrieval and analysis. The experiment is entirely self-contained, requiring little in the way of

shuttle services. Electric power is supplied by a battery. The SSCE battery pack consists of 14 D-sized, sealed, lead-acid batteries housed in a specially designed case. The unit can provide up to 75 watt-hours at 28 volts dc to meet the 160-watt peak power requirement of the experiment. The SSCE electrical box houses the data acquisition and storage unit and controls the operation of the experiment. A crewmember activates the experiment by depressing switches on the electrical box panel. Light-emitting diodes provide feedback on the experiment status.

### **Solution Growth of Crystals in Zero Gravity**

(STS-51B) NASA

In this investigation triglycine sulfate (TGS) crystals are grown by a low-temperature solution growth technique. Growth is accomplished by slowly extracting heat at a controlled rate through a seed crystal of TGS suspended on an insulated string in a saturated solution of TGS in a test cell. Variations in the liquid density, solution concentration, and temperature around the growing crystal are studied using schlieren, shadowgraph, and interferometric techniques.

### **Space Acceleration Measurement System (SAMS)**

(STS-40, 42, 47, 50, 52, 58, 62, 65, 71, 73, 75, 78, 83/94, 87) NASA

The middeck/Spacelab SAMS configuration was designed for installation in the habitable environments of the space shuttle middeck and the Spacelab module. From the front panel of the main unit, the crew can access the control switches, indicators, and hard drives during the mission. The three remote sensor heads are connected to the main unit by three sensor head cables. The main unit contains the electronics for control and data processing. The two hard drives provide unlimited data-recording capacity during a mission. Triaxial sensor heads (TSH's) detect accelerations with three single-axis acceleration sensors. These single-axis sensors use a pendulous proof mass and force-rebalance coils to sense the accelerations. The TSH structure maintains the three single-axis sensors in an orthogonal relationship. Each sensor's output is independently amplified and filtered by a multigain amplifier contained within the sensor head. The sensors have an advertised sensitivity of  $1\text{ }\mu\text{g}$  ( $10^{-6}$  times normal gravity). They can be mounted on or near an experiment to measure the accelerations experienced by the experiment. The SAMS instrument has three remote tri-axial sensor heads. Each sensor head has three accelerometers that are oriented at right angles to each other, allowing each sensor head to detect 3-dimensional accelerations in the 0.01- to 100-Hz range. For the MSL-1 mission only, one SAMS sensor head will detect accelerations up to 2.5 Hz, while the others will detect accelerations up to 25 Hz. Each accelerometer consists of a mass suspended by a quartz element so that movement is allowed along one axis only. A coil is attached to the mass, and the assembly is placed in a magnetic field. An applied acceleration moves the mass from its rest position, altering the magnetic field and causing current to flow in an electrical circuit. The current is proportional to the force of the acceleration. The instrument's electronics convert the current into voltage and then into digital data for processing by its computer. These data will be transmitted to scientists on the ground for near real-time processing and science support and also will be recorded for postflight analysis.

### **Space Experiments with Particle Accelerators (SEPAC)**

(STS-9, 45) ISAS

The equipment consisted of an electron beam accelerator, magneto plasma dynamic (MPD) arcjet, battery/capacitor bank to provide high discharge current, monitor and diagnostic devices, and control, display, and data management systems. The electron beam accelerator, MPD arcjet, and neutral gas ejector were contained in the accelerator subsystem. The electron beam accelerator was capable of operating at voltages from 1 to 7.5 kV at a maximum of 1.5 A and with a variable pulse width of from 10 ms to 1 s. The MPD arcjet used argon gas and had an energy input of 2 kJ per pulse. The third accelerator component was a neutral gas plume generator which used nitrogen as the gas.

## Spacelab Modules

(STS-2, 3, 7, 9, 41D, 41G, 51B, 51F, 61A, 61B, 61C, 35, 40, 42, 45, 47, 50, 52, 56, 55, 58, 59, 62, 65, 64, 66, 67, 71, 73, 75, 78, 83/94, 87, 90) ESA

Spacelab was developed by ESA as the European component of the United States' STS program and works on a modular basis. It can be varied to meet specific mission requirements. Its four principal components are the pressurized module, which contains a laboratory with a shirt-sleeve working environment; one or more open pallets that expose materials and equipment to space; a tunnel to gain access to the module; and an instrument pointing subsystem. There were also units called Mission Peculiar Experiment Support Structures (MPRESS) designed to accommodate particular pieces of hardware for specific missions (used on missions STS-7, 41D, 41G, 51B, 61B, 61C, 52, 59, 62, 68, 75, and 87). Spacelab is not deployed free of the orbiter.

*Instrument Pointing System:* Flown on STS-51F, 35, and 67. Some research to be accomplished on Spacelab missions requires that instruments be pointed with very high accuracy and stability at stars, the sun, the Earth or other targets of observation. The IPS provides precision pointing for a wide range of payloads, including large single instruments or a cluster of instruments or a single small-rocket-class instrument. The pointing mechanism can accommodate instruments of diverse sizes and weights (up to 15,432 pounds) and can point them to within 2 arc seconds and hold them on target to within 1.2 arc seconds. The IPS consists of a three-axis gimbal system mounted on a gimbal support structure connected to the pallet at one end and to the aft end of a payload at the other, a payload clamping system to support the mounted experiment elements during launch and landing, and a control system based on the inertial reference of a three-axis gyro package and operated by a gimbal-mounted minicomputer. The basic structural hardware is the gimbal system, which includes three bearing/drive units, a payload/gimbal separation mechanism, a replaceable extension column, an emergency jettisoning device, a support structure and rails, and a thermal control system. The gimbal structure itself is minimal, consisting only of a yoke, an inner gimbal and an outer gimbal to which the payload is attached by the payload-mounted integration ring. The three identical drive units are so arranged that their axes intersect at one point. From pallet to payload, the order of the axes is elevation, cross-elevation and azimuth. Each drive assembly includes three wet-lubricated ball bearings, two brushless dc-torquers and two single-speed/multispeed resolvers. The gimbal/payload separation mechanism is located between the outer gimbal and the payload integration ring. This device prevents the payload and the pointing mechanism from exerting excessive loads on each other during launch and landing. For orbital operations, the outer gimbal and integration ring are pulled together and locked. The operating modes of the different scientific investigations vary considerably. Some require manual control capability, others long periods of pointing at a single object, others slow scan mapping, still others high angular rates and accelerations. Performance in all these modes requires flexibility, which is achieved by computer software. The IPS is controlled through the Spacelab subsystem computer and a data display unit and keyboard. It can be operated either automatically or by the Spacelab crew from the pressurized module and also from the payload station on the orbiter aft flight deck. The IPS has two operating modes, which depend on whether the gimbal resolver or gyro is used for feedback control of attitude. An optical sensor package consisting of one boresighted fixed-head star tracker and two skewed fixed-head star trackers is used for attitude correction and also for configuring the IPS for solar, stellar, or Earth viewing.

*Pressurized Laboratory Module:* Flown on STS-9, 51B, 51F, 61A, 40, 42, 47, 50, 55, 58, 65, 71, 73, 78, 83/94, and 90. The laboratory, or pressurized module, is available in two segments. One, called the core segment, contains supporting systems, such as data processing equipment and utilities for the pressurized modules and pallets (if pallets are used in conjunction with the pressurized modules). The laboratory has fixtures, such as floor-mounted racks and a workbench. The second, called the experiment segment, provides more working laboratory space and contains only floor-mounted racks. When only one segment is needed, the core segment is used. Each pressurized segment is a cylinder 13.5 feet in outside diameter and 9 feet long. When both segments are assembled with end cones, their maximum outside length is 23 feet. The pressurized

segment or segments are structurally attached to the orbiter payload bay by four attach fittings consisting of three longeron fitting sets (two primary and one stabilizing) and one keel fitting. The segment or segments are covered with passive thermal control insulation. The ceiling skin panel of each segment contains a 51.2-inch-diameter opening for mounting a viewport adapter assembly, a Spacelab window adapter assembly or scientific airlock; if none of these items are used, the openings are closed with cover plates that are bolted in place. The module shell is made from 2219-T851 aluminum plate panels. Eight rolled integral-machined waffle patterns are butt-welded together to form the shell of each module segment. The shell thickness ranges from 0.6 of an inch to 0.14 of an inch. Rings machined from aluminum-roll ring forgings are butt-welded to the skin panels at the end of each shell. Each ring is 20 inches long and 195.8 inches in diameter at the outer skin line. Forward and aft cones bolted to the cylinder segments consist of six aluminum skin panels machined from 2219-T851 aluminum plate and butt-welded to each other and to the two end rings. The end rings are machined from aluminum-roll ring forgings. The end cones are 30.8-inch-long truncated cones whose large end is 161.9 inches in outside diameter and whose small end is 51.2 inches in outside diameter. Each cone has three 16.4-inch-diameter cutouts: two located at the bottom of the cone and one at the top. Feedthrough plates for routing utility cables and lines can be installed in the lower cutouts of both end cones. The Spacelab viewport assembly can be installed in the upper cutout of the aft end cone, and the upper cutout of the forward end cone is for the pressurized module vent and relief valves. The pressurized modules are designed for a lifetime of 50 missions. Nominal mission duration is seven days. Because of the orbiter's center-of-gravity conditions, the Spacelab pressurized module or modules cannot be installed at the forward end of the payload bay. Therefore, a pressurized tunnel is provided for equipment and crew transfer between the orbiter's pressurized crew compartment and the Spacelab pressurized module or modules. The transfer tunnel is a cylindrical structure with an internal unobstructed diameter of 40 inches. The cylinder is assembled in sections to allow length adjustment for different module configurations. Two tunnel lengths can be used—a long tunnel of 18.88 feet and a short tunnel of 8.72 feet. The joggle section of the tunnel compensates for the 42.1-inch vertical offset of the orbiter middeck to the Spacelab pressurized module's centerline. There are flexible sections on each end of the tunnel near the orbiter and Spacelab interfaces. The tunnel is built by McDonnell Douglas Astronautics Company, Huntington Beach, Calif. The airlock in the middeck of the orbiter, the tunnel adapter, hatches, the tunnel extension and the tunnel itself permit the flight crew members to transfer from the orbiter middeck to the Spacelab pressurized module or modules in a pressurized shirt-sleeve environment. The airlock, tunnel adapter, tunnel and Spacelab pressurized module or modules are at ambient pressure before launch. In addition, the middeck airlock, tunnel adapter and hatches permit crew members outfitted for extravehicular activity to transfer from the airlock/tunnel adapter in space suits to the payload bay without depressurizing the orbiter crew compartment and Spacelab module or modules. If an EVA is required, no flight crew members are permitted in the Spacelab tunnel or module.

*Pallets:* Flown on STS-2, 3, 9, 41G, 51F, 35, 45, 56, 59, 64, 66, 68, 67. Each pallet is more than a platform for mounting instrumentation; with an igloo attached, it can also cool equipment, provide electrical power and furnish connections for commanding and acquiring data from experiments. When only pallets are used, the Spacelab pallet portions of essential systems required for supporting experiments (power, experiment control, data handling, communications, etc.) are protected in a pressurized, temperature-controlled igloo housing. The pallets are designed for large instruments, experiments requiring direct exposure to space or systems needing unobstructed or broad fields of view, such as telescopes, antennas and sensors (e.g., radiometers and radars). The U-shaped pallets are covered with aluminum honeycomb panels. A series of hard points attached to the main pallet structure is provided for mounting heavy payload equipment. Up to five segments can be flown on a single mission. Each pallet train is held in place in the payload bay by a set of five attach fittings, four longeron sill fittings and one keel fitting. Pallet-to-pallet joints are used to connect the pallets to form a single rigid structure called a pallet train. Twelve joints are used to connect two pallets. Cable ducts and cable support trays can be bolted to the forward and aft frame of each pallet to support and route electrical

cables to and from the experiments and subsystem equipment mounted on the pallet. All ducts mounted on the starboard (right) side of the pallet are used to route subsystem cables, and all ducts on the port (left) side carry experiment utility cables. The ducts and cable trays are made of aluminum alloy sheet metal. In addition to basic utilities, some special accommodations are available for pallet-mounted experiments. The igloo is attached vertically to the forward end frame of the first pallet. Its outer dimensions are approximately 7.9 feet in height and 3.6 feet in diameter. The igloo is a closed cylindrical shell made of aluminum alloy. A removable cover allows full access to the interior. The igloo houses subsystems and equipment in a pressurized, dry-air environment at sea-level atmospheric pressure (14.7 psia). Two feedthrough plates accommodate utility lines and a pressure relief valve. The igloo is covered with multilayer insulation.

### **Space Physiology Experiment (SPE) Package**

(STS-42) CSA

The Canadian Space Physiology Experiments (SPE) on IML-1 investigated human adaptation to weightlessness and other phenomena. The human vestibular and proprioceptive (sense of body position) systems, energy expenditure, cardiovascular adaptation, nystagmus (oscillating eye movement) and back pain in astronauts were studied. Experiments included Space Adaptation Syndrome Experiments (SASE) (Sled Experiment, Rotation Experiment, Visual Stimulator Experiment), and the Proprioceptive Experiments (Energy Expenditure in Spaceflight (EES), Position and Spontaneous Nystagmus (PSN), Measurement of Venous Compliance & Evaluation of an Experimental Anti-Gravity Suit (MVC), Assessment of Back Pain in Astronauts (BPA), and the Phase Partitioning Experiment (PPE)).

### **Spinal Changes in Microgravity (SCM)**

(STS-65) CSA

Physiological measurement equipment has been developed to allow coordinated measurements of changes that occur during spaceflight in the spine, spinal cord function, and several related physiological systems. The specialized equipment includes nerve stimulation and recording, ultrasound imaging, cardiovascular function recording, and stereophotography. For the first time, this experiment hardware will allow a unified approach to examination of the spine and autonomic nervous system during spaceflight.

### **SPORES (Growth and Sporulation in *Bacillus Subtilis*)**

(STS-42) ESA

The bacterial cultures in this Biorack experiment were grown in type II experiment containers, these being either kept “stationary” in microgravity or in the reference 1g centrifuge. Type II containers (63x63x87 mm<sup>3</sup>) provide approximately 345 milliliters internal usable volume, Type I containers (20x40x81 mm<sup>3</sup>) provide approximately 65 milliliters internal usable volume. Both types have leak-tight sealed covers. Bacterial cultures were grown at 37degC. The experiment hardware consisted of a culture chamber (15 ml) made from titanium and closed by a membrane permeable for gases but not for water. Four pistons were attached: the first was used to inoculate the spores and was operated manually; the second added antibiotics to halt metabolism (which caused sporulation to occur) and was also operated manually; the third and fourth were both motor-driven and were used to periodically take samples and to apply a fixative, respectively. Growth of the bacteria was monitored by continuously measuring the optical density with a built-in miniaturized photometer. Other parameters such as viability, sporulation, fine structure, size distribution of cells and spores, and growth kinetics, were measured on the fixed samples and on those where metabolism was temporarily halted. Another set of experiment containers was also used in which all of the pistons were operated manually. Half of the containers were placed on a 1-g centrifuge as controls.

## **Stability of Metallic Dispersions**

(STS-7) DLR

The experiment unit consisted of an X-ray unit working at 80 kV, supplied through a cascade system, an X-ray transparent Teflon oven, and a motorized advance mechanism for double-layered continuous X-ray film. The sample, consisting of gallium with 20 atom percent of mercury, was sealed within the oven. This experiment occupied two GAS canisters. The experiment configuration was identical in each canister, but the experiments had different heating and cooling cycles.

## **Structure Of Flame Balls At Low Lewis-number (SOFBALL)**

(STS-83/94) NASA

The SOFBALL Experiment Package is an aluminum combustion chamber with diagnostic equipment. Six fused-silica windows let external diagnostic instruments view and measure events inside the chamber. Diagnostic instruments include color and image-intensified cameras, and a gas chromatograph to measure combustion product composition. The SOFBALL-2 Experiment Mounting Structure (EMS)—which includes experiment-specific diagnostic equipment—is cylindrical and about 62 cm long and 40 cm in diameter (24.4 x 15.7 in), and weighs approximately 39 kg (87 lb.) The main components are the spark igniter; temperature sensors (arranged as a rake of six thin thermocouple wires); two pairs of radiometers; a mixing fan; and volume compensators to reduce the amount of gas needed for each experiment.

## **Superfluid Helium in Zero-G**

(STS-51F) NASA

The instrumentation consists of an instrumented cryostat or dewar (containing an investigation package inside) and a support electronics package. The cavity is surrounded by a 90-l superfluid helium toroid and a multilayer super insulation system spaced by helium vapor-cooled shields. The Dewar operates in both upright and horizontal configurations. The cryostat is instrumented with germanium and thermocouple temperature sensors to monitor the chamber temperatures and the superfluid plug and insulation performance. Accelerometers monitor vibration effects in order to cross-correlate with the bulk behavior observations. Experiment mass: 205 kg; average experiment power: 20 W

## **Surface Tension Driven Convection Experiment Apparatus (STDCE)**

(STS-50, 73) Case Western Reserve University

The Surface Tension Driven Convection Experiment Apparatus consists of an experiment package and an electronics package located in a double Spacelab rack. The experiments are carried out in a cylindrical container (10 cm in diameter and 5 cm high). A lightweight silicone oil is used as the test fluid because it is not susceptible to surface contamination, which can ruin surface tension experiments. The experiment package contains the test chamber, made of copper to assure good thermal conductivity along the walls, and the silicone oil system, consisting of a storage reservoir and a fluid management system for filling and emptying the test chamber. Two heating systems, which provide the different thermal signatures, are part of the test chamber. A submerged cartridge heater system will be used to study thermocapillary flows over a range of imposed temperature differences. A surface heating system will be used to investigate fluid flows generated by various heat fluxes distributed across the surface of the liquid. This heating system consists of a CO<sub>2</sub> laser and optical elements that direct the laser beam to the test chamber and vary the imposed heat flux and its distribution. To visualize the fluid flows in the test chamber, a laser diode and associated optical elements will illuminate aluminum oxide particles suspended in the silicone oil, and a video camera, attached to a chamber view port, will record the particle motion. A scanning infrared imaging system records oil surface temperature. Thermistors inside the test chamber measure bulk oil

temperatures. The crew can use a Spacelab camera mounted to the front of the chamber to monitor oil filling and draining, submerged heater positions and oil surface shapes and motions.

*STDCE-1:* The basis of Surface-Tension-Driven Convection Experiment 1 (STDCE-1) flight experiment on STS-50 was a copper test cell 10 cm in diameter and 5 cm deep, filled with silicone oil that provided both flat and curved free surfaces in a microgravity environment. The outer wall of the test cell was water-cooled. The silicone oil was centrally heated, either externally by a carbon dioxide laser (constant heat flux, CF), or internally by an immersion heater (constant temperature, CT). The cross-section was illuminated by a 1-mm-thick sheet of light, which scatters from small aluminum oxide particles mixed into the oil. This allowed observation and measurement using a particle-tracking technique of the axisymmetric flow velocity. An infrared imager was used to measure surface temperature, and thermistors were used to measure fluid and wall temperature.

*STDCE-2:* The center of Surface-Tension-Driven Convection Experiment 2 (STDCE-2) on STS-73 is an interchangeable module containing a test cell and fluid reservoir. Six modules containing copper test cells of 1.2, 2.0 and 3.0 cm diameter, each with the depth equal to the radius, were filled with 2 centistoke silicone oil, which provided both flat and curved free surfaces in a microgravity environment. In three of the modules, one of each size, the fluid was heated by a carbon dioxide laser, with a Gaussian heat flux imposed on the free surface. In the remaining three modules, the fluid was heated internally by an axially-located heater that was ten percent of the chamber diameter. The outer walls of the test chambers were also cooled. This modular approach was taken to accommodate the large test matrix.

### **“Svet” Greenhouse Facility**

(STS-71) Institute for Biomedical Problems (IBMP) and the Space Research Institute of the Bulgarian Academy of Sciences

The Greenhouse experiment was conducted in the Russian/Bulgarian-developed plant growth facility called the “Svet”. The Svet is a greenhouse designed jointly by the Institute for Biomedical Problems (IBMP) and the Space Research Institute of the Bulgarian Academy of Sciences for the study of plant growth in space. It was located in the Krystal module of the Mir Space Station and was first used on Mir in 1990 in an experiment using cabbage and radish seedlings. The Svet consists of four basic units: the plant growth chamber, root module (also called vegetation module), light unit and control unit, and the Gas Exchange Measurement System (GEMS). Recent modifications to the Svet include improved lighting and watering systems to enhance plant growth conditions and the addition of an instrumentation system to gather information on how microgravity affects the gas exchange process in plants. STS-71 delivered the root module and seeds to the Mir Space Station for the experiment to be started during the Mir 19 mission. Facility modifications were performed during Mir 18, including the addition of US provided water sensors for the root module, infrared sensors for leaf temperature, illumination sensors to measure light levels and application of reflective mylar film to the Svet chamber walls to enhance light levels. The GEMS, designed and built by Utah State University, offers a means for measuring photosynthesis, respiration, transpiration and other plant-related environmental parameters. These measurements provide documentation of plant growth conditions within the Russian SVET Greenhouse. It is an interactive system for monitoring and collecting data on plant growth and controlling some aspects of the environment within the SVET system designed for the Mir space station.

*Leaf Bag Assemblies:* Within the Svet growth chamber, these assemblies enclose the aerial parts of the plants and the gaseous environment immediately around them. Each assembly consists of a biax nylon bag with a hard polycarbonate top, held to its base by telescoping aluminum legs. Sensors within the bags measure light levels, leaf temperature, and air temperature.

*Air Filtration and Integration Assembly:* Located outside of the Svet growth chamber, this assembly ensures that the concentration of gases in the air leading to the Leaf Bags is uniform. It consists of an aluminum top holding a biax nylon integration bag, an air filter, and a blower fan.

*Gas Analyzer System (GAS):* The GAS measures infrared absorption of CO<sub>2</sub> and H<sub>2</sub>O in the air entering and exiting the Leaf Bag Assembly. It can also measure air flow rate, air temperature, and air pressure. Measurements are made every 3 seconds and detect CO<sub>2</sub> and H<sub>2</sub>O differences of 1/5000 for accurate net photosynthesis (Pn) and transpiration determination.

*Moisture Probe Packing Bundle (MPPB):* The MPPB contains sensor probes placed in groups along the plant rows of the Svet root module. Each sensor probe contains an internal heater and temperature sensor. The heating and cooling profiles of the probes allow determination of soil moisture content.

*Environmental Data System (EDS) and Data Collection and Display System:* The EDS receives, encodes, and stores data from environmental sensors in various GEMS subsystems, including the Leaf Bag Assemblies, the GAS, and the Svet root module. It also controls fan speed and collects data from the soil moisture probes, once inserted in the Svet root module. All data are stored in and displayed on the Data Collection and Display System, an IBM model 750c notebook computer with software to control GEMS functions. Calibrated data are displayed in English and Russian.

*Power Distribution System:* This system transforms 27 VDC Mir power to the various voltages required by the GEMS electronic units and provides switchable control of other electronic components.

*Water Flow Meters:* The meters measure Svet water injection volume, allowing accurate water balance measurements to be made on the Svet root modules.

### **System for Measurement of Central Venous Pressure (SMCVP)**

(STS-40) NASA

The apparatus consists of three parts, the electronics module, the pump chamber and the transducer block. The transducer block is mounted in the armpit at the level of the right atrium. Pressure is transmitted to the transducer through a 4 French polyurethane catheter inserted through an arm vein. Electrical isolation from the transducer face is provided by two latex diaphragms and a non-conductive fluid covering the transducer (Dow Corning 360 medical fluid). The pump chamber provides a slow, continuous infusion of heparinized saline at 1.5 ml/hour. The electronics box contains the circuitry to amplify the transducer output and send it to the PMS for recording or downlink. The signal is recorded on the Cassette Data Tape Recorder. The SMCVP provides an analog output signal of 0-5 volts DC corresponding to a catheter pressure of -10 to 40 mmHg. This signal may be downlinked for monitoring experiment operations.

### **System for Venous Occlusion Plethysmography (SVOP)**

(STS-40) NASA

Occlusion of venous flow is accomplished by step increases in pressure in a cuff above the elbow or thigh. For a flow measurement, an occlusion pressure of 60 mmHg was used. For compliance measurements, pressure was increased as follows: 20 mmHg for one minute, then one minute at 0 mmHg, 40 mmHg for 2 minutes, one minute at 0 mmHg, 3 minutes at 60 mmHg, one minute at 0 mmHg, then 80 mmHg for 4 minutes. The SVOP system has the capability to accurately measure changes in limb circumference as small as .0199 mm. An analog signal (0 to +5VDC) from the SVOP is transmitted to the NASA-provided Physiological Monitoring System (PMS) for recording and downlink. On the ground the signal is recorded on a strip chart recorder and analog recorder. Equilibrated calf volumes are calculated using limb circumference values to provide a measure of venous compliance. An accessory to the SVOP is a NASA-provided blood pressure cuff with a bulb and gauge (0-300 mmHg) for occluding arterial circulation to the foot.

*Venous Occlusion Cuff Controller (VOCC):* The unit consists of a pump, electronic controls and a cuff. The electronics control inflation, deflation, and the rate of inflation, deflation. The source of power for the unit is a battery powered air pump. This device inflates the occlusion cuff around the thigh. The mode button cycles the device through three modes. Mode 1 is flow mode. Mode 2 is compliance mode, which inflates the cuff to pressure levels stated in the compliance protocol (20 mmHg - 40 mmHg - 60 mmHg

- 80 mmHg - 100 mmHg). Mode 3 is the programming mode wherein the flow and compliance pressures can be changed.

Safety features included:

1. Manual start and abort
2. Automatic abort above 300 mmHg, fixed time interval
3. Warning before start of cycle
4. Deflation of cuff during power loss

### **Thermal Canister Experiment**

(STS-3) NASA

To achieve the experiment objectives, the investigator flew a canister measuring 1 m x 1 m x 3 m and weighing 160 kg; fixed conductance canister heat pipes; variable conductance heat pipes; a radiator and radiator heat pipes; a control electronics and data acquisition and command system; and simulated instrument heat loads (heaters) within the canister. The thermal canister was built as close in configuration as possible to the flight application and mounted on a structure together with support electronics. Heaters within the canister simulated instrument power dissipation. Canisters developed for flight instruments are a standard inventory item for future use as required.

### **Thermal Enclosure System (TES/STES)**

(STS-62, 73) CBSE

The new PCG hardware consists of a variety of experiment equipment including improved Vapor Diffusion Apparatus (VDA) trays, hand-held Protein Crystallization Apparatus for Microgravity (PCAM) units, the Crystallization Observation System (COS), and the Advanced Crystallization Observation System (A/COS) which is inserted in special thermal enclosures that are installed in place of lockers in the Orbiter middeck. The two configurations available are the dual-locker Thermal Enclosure System (TES) and the Single-locker Thermal Enclosure System (STES). Internal temperature measurements are recorded by a data logger.

*Thermal Enclosure System (TES)* - Can be operated as a refrigerator, with a minimum set point temperature of 4 degrees C, or as an incubator, with a maximum set point temperature of 40 degrees C. It can maintain the temperature at the controlling sensor location within +0.2 degrees C of the set point. It can be set to maintain a constant temperature or pre-programmed to change temperature settings over time. Larger equipment like the COS and the A/COS must fly in the TES.

*Single Locker Thermal Enclosure System (STES)* - The STES, a commercially derived refrigerator incubator module, provides many of the same features as the TES. It is an incubator capable of heating or cooling to a constant temperature in the 39 to 104 degrees Fahrenheit (4 to 40 degrees Celsius) range. Temperatures are controlled within 0.5 degrees.

### **Thermoelectric Freezing Module (TEFM)**

(STS-78, 90) NASA

The Thermoelectric Freezing Module (TEFM) is a temperature-controlled storage unit used to quickly cool or freeze biological samples at a selected temperature. It is stowed in a middeck locker. The TEFM has a temperature control knob with three modes:

Refrigerator - for a temperature of +4 degrees Celsius (39.2 degrees Fahrenheit)

Freezer - for a temperature of -22 degrees Celsius (7.6 degrees Fahrenheit)

3rd - for a mission-unique temperature selection (the third choice is adjustable by ground crew only and cannot be changed during flight).

The TEFM downlinks data via an interface to the Thermoelectric Holding Module (TEHM). During operations a liquid crystal display (LCD) continuously shows the temperature of the internal volume with an

accuracy of + 0.5 degrees Celsius (1.2 degrees Fahrenheit). In case of a power failure the LCD is powered by a backup battery. Power (28 Volt dc) is provided by the Orbiter Middeck Utility Panel (MUP).

### **Thermoelectric Incubator (TEI)**

(STS-65) NASDA

This general-purpose incubator maintains constant temperature, humidity, and carbon dioxide concentration, providing an environment for cultures of mammal and plant cells. The incubator will be operated at 37 C.

### **Three-Axis Acoustic Levitator (3AAL)**

(STS-61C) NASA

This apparatus permits a liquid specimen to be positioned and manipulated by a three-dimensional acoustic energy well. Three acoustic drivers positioned along orthogonal axes are used to suspend the droplet. Manipulations include rotation, oscillation and drop fusion/fission. The oscillation and rotation can be used to stir the liquid as well as center gas bubbles in the liquid drop. Multiple samples can be injected and controlled while color or black and white motion pictures are obtained, which provide one direct view and two reflected views on orthogonal axes. Temperature, acoustic pressure, and driver power can be monitored. Pulsing or phasing of the drivers permits controlled oscillation or rotation. An injector deploys the liquid sample into the containment area with low velocity and little circulation within the liquid. The primary data recorder is a 16mm movie camera which employs a mirror system to obtain a three view record. Synchronized strobe lights allow the investigator to obtain either a color or a black and white rendition of the experimental sequence.

### **Three Dimensional Microgravity Accelerometer (3DMA)**

(STS-73) UAH

This instrument uses three special accelerometers, located in its central housing, to measure the level of absolute microgravity in three separate axes, or dimensions. The instruments are invertible accelerometers because they invert periodically to allow bias--or inaccuracies present in all accelerometer data--to be eliminated. This allows the absolute level of microgravity to be determined. In addition, three remote sensors record the different vibrations and accelerations caused by experiment and orbiter operations. On board, the data will be recorded automatically on hard disc drives in the central unit for analysis after the mission. In addition, the data will be sent to the ground in real time. Principal Investigators can call up displays that show absolute gravity for each axis and microvibrations in each axis for the four locations. The absolute level of microgravity and data from the three remote sensors will be recorded on three different scales, allowing quantification of disturbances. All three scales will be displayed simultaneously in the data package.

### **Tiegelfreies Elektromagnetisches Prozessieren Unter Schwerelosigkeit (TEMPUS): Electromagnetic Containerless Processing Facility**

(STS-65, 83/94) DARA

TEMPUS, an electromagnetic levitation facility that allows containerless processing of metallic samples in microgravity, first flew on the IML-2 Spacelab mission. During the MSL-1 mission, scientists will perform refined IML-2 experiments, studying various thermodynamic and kinetic properties of up to 22 samples. For each investigation, a spherical 7- to 8-mm sample will be positioned by the electromagnetic coil, melted, and then cooled. Melting points of the samples range between 760 and 1,850 °C, with the maximum sample temperature about 2,100 °C. The TEMPUS operation is controlled by its own microprocessor system, although commands may be sent remotely from the ground, and real-time adjustments may be made by the crew. Two video cameras, a two-color pyrometer and a fast Si-based single color pyrometer for measuring

sample temperatures, and a fast infrared detector for monitoring solidification spikes, will be mounted to the process chamber to facilitate observation and analysis. In addition, a dedicated high-resolution video camera can be attached to TEMPUS to measure the sample volume precisely. The MSL-1 TEMPUS facility has been upgraded with a new levitation coil system to improve positioning stability of the levitated samples. Sample stability can be improved further by automated real-time video analysis, allowing the electronics to recalibrate power to damp excursions actively within the levitation coil. Also, the facility will have a new sample holder to prevent sample contamination and metal vapor deposition on the coils, a residual gas analyzer for in-situ monitoring of the processing environment, and improved data-handling techniques for better on-line operation of the experiment process.

### **Tissue Culture Incubator**

(STS-40) Space Biology Group, Zurich, Switzerland

Two of these items were flown together. The incubators are capable of housing four cultures in either the unitized or modular cell culture blocks described in the preceding descriptions. A regulated heating system provides a temperature of  $37 \pm .5$  degrees when electrical power is available. Sensors are incorporated into the incubators to record temperature and power on-off status and data is transmitted through the Remote Acquisition Unit (RAU). Both incubators are attached to mounting panels which provide electrical and data transmission circuits through a cable and connector designed for easy attachment.

### **Torso Rotation Experiment (TRE)**

(STS-78) CSA

The Torso Rotation Experiment (TRE) head-mounted unit contains a 3-axis Watson angular velocity transducer, an electro-oculogram (EOG) preamplifier, an isolation amplifier for electroshock protection, and temperature sensors to monitor transducer temperature. The head unit is worn on top of the subject's head and secured with the Head Interface consisting of a strap assembly placed over the top of the skull, under the chin and around the back of the head. The unit including cables measures  $12.7 \times 7.6 \times 7.6$  cm and weighs 2.43 kg. The unit will be firmly attached to the head by means of a head-band interface. Two cable sets are fixed to the head unit, one coming from three surface electrodes used to record the eye movements and one going to the back-mounted package. The head unit is connected to the torso unit by means of a flexible shielded cable to transfer data for storage. One Electrode Kit is flown containing 40 disposable surface monitoring electrodes, 40 alcohol wipes and one metal mirror to aid in electrode placement. The interface to the head unit consists of an adapter that includes flexible metal straps running across the top and back of the head and an adjustable chin strap of Nomex webbing and velcro. The relative angles of the straps are fixed by locking knobs on the sides of the head. The head interface measures  $20.3 \times 15.2 \times 3.8$  cm and weighs 0.66 kg. The Torso Rotation Experiment (TRE) torso- or back-mounted unit contains a 3-axis Watson transducer, a temperature sensor, a calendar clock, an auto-resetting electro-oculogram (EOG) amplifier, other signal conditioning amplifiers, anti-aliasing filters, a 12-bit A/D converter, and a Motorola 68000 series microprocessor. It also has a single LED and a beeper to provide certain information to the operator. This unit contains the majority of the electronics used in the TRE experiment. The power supply for all the electronics is located in the back-mounted unit, and consists of eight 9-volt batteries, three for +15 and +12 volt, three for -15 volt, and two for +5 volt. All are regulated down to the desired voltages and have sufficient capacity to complete 8 full experiment runs without being changed. The power supply is fused at the batteries. All electronic circuits use CMOS technology and all are floated from their machined aluminum cases. The unit is gold plated over nickel, inside and out. The interface to the torso is a modification of a device used to immobilize the head and neck of accident victims. In this case, only the chest and back plates are used, connected together by two straps over the shoulders and two others around the sides of the chest (under the arms). It is somewhat difficult to fix equipment onto the upper back in a

secure fashion but this method has been shown to work when a subject is upside down in a 1-g environment. The torso interface measures 35.6 x 25.4 x 5.1 cm and weighs 2.21 kg.

### **Torque Velocity Dynamometer (TVD)**

(STS-78) ESA

The main unit of the dynamometer is located on the floor of the Spacelab center aisle. Inside are the torque sensor, motor, gears, and electronics that drive the device. Special knee, foot, and arm restraints, called Human Interfaces (HIFs), mechanically connect the subject to the TVD. A movable plate attached to the outside of the main unit positions and fixes the HIFs to restrain any limb movement that may compromise the experiments. The leg HIFs have knee and shin restraints, while the arm HIFs prevent wrist rotation and upper forearm movement. Another restraint prevents the shoulder from reacting to the torque produced by a flexing elbow. The subject support plate, a cushioned platform outfitted with shoulder and waist belts to restrain the torso, can be positioned so that it allows the test subject to perform the experiments in comfort and without unnecessary movement. To perform the musculoskeletal experiments, the subject lays on the support plate, with torso and limbs secured to the appropriate HIF. Following instructions displayed on the TVD control/display panel, the subject then performs a safety check of the dynamometer. After the safety test is completed, the subject uses either the TVD control/display panel or an external microcomputer to begin the experiment run. The microcomputer captures and displays the resulting measurements.

### **Tracer Kit**

(STS-40, 71, 78) NASA

See also: **Mir Kits**. The tracer kit is designed to stow injectable and ingestible isotopes. The tracer kit contains all prepackaged tracers used in flight. Oral capsules are in foil packets. Injectable tracers are preloaded in glass syringes wrapped with tape. Each syringe is foil wrapped with a clear viewing window for leak detection.

### **Transcranial Doppler (TCD)**

(STS-71, 90) NASA

The Transcranial Doppler (TCD) measures transcranial blood flow in the middle cerebral artery of the brain. The device provides ultrasonic waves, which produce echoes when they are reflected from body tissues. Shifts in frequency (Doppler) between the original waves and their echoes are used to measure the velocities of moving objects.

### **Ultraviolet Imaging Telescope (UIT)**

(STS-35, 67) NASA

The Ultraviolet Imaging Telescope instrument was a 38 cm f/9 Ritchey Chretien telescope with two selectable cameras mounted behind the primary mirror. The focal length was 352.9 cm, the field of view 40 arc min, the angular resolution 2 arc sec, and the nominal pixel size after digitization was 20 microns. Each camera has a 6 position filter wheel, a two stage magnetically focused image tube, and a 70 mm film transport fiber optically coupled to each image tube. One camera (B) is designed to operate in the 1200-1700 Å region and the other (camera A) in the 1250-3000 Å region. Camera A had a CsTe photocathode, and camera B had a CsI photocathode. The film used was 70 mm IIAO with 1000 frames/camera. The magnitude limit was  $V=25$  for a  $S/N = 10$  image in a 30 minute exposure of a star with  $T_{\text{eff}} = 30000\text{K}$ .

### **Urine Collection System (UCS)**

(STS-78, 90) NASA

The Urine Collection System (UCS) consisted of four different assemblies, namely, the (1) Contingency Urine Collection Assembly, (2) Urine Cage Assembly, (3) Frozen Syringe Kit Assembly, and (4) Preserved Syringe Kit Assembly.

*Contingency Urine Collection Assembly:* The Urine Collection Assembly was designed to collect urine samples for analysis. Each kit consisted of a Nomex container that holds 40 Urine Collection Devices (UCD). The UCDs were fitted with a external male catheter. They were composed of urine collection bags and one plunger tool. The bags and tool are stowed in a Nomex stowage bag. Each bag was filled with 1 milliliter of 2.5M lithium chloride (LiCl), which acts a volume marker. One bag was used per urine void and the bag was discarded following sample collection. After the urine collection bag is filled, a 7.5 or 10 milliliter aliquot of urine was drawn from the bag through a silicone septum with a syringe.

*Urine Cage Assembly:* The Urine Cage Assembly was designed to stow frozen urine samples for post-flight analysis. Three different sizes were available. The long cage assembly has nine rows of Urine Sample Holders two tiers high for a total of 18 Urine Sample Holders. The short cage assembly has three rows of Urine Sample Holders two tiers high for a total of 6 Urine Sample Holders. The center cage assembly has four rows of Urine Sample Holders two tiers high for a total of eight Urine Sample Holders. The urine sample syringes were placed on the Urine Sample Holders, which were then inserted into the cage assembly which was placed inside the Thermoelectric Freezing Module (TEFM). Once frozen, the filled cage was transferred to the Thermoelectric Holding Module (TEHM) or the Life Sciences Laboratory Equipment (LSLE) Freezer until after flight.

*Frozen Syringe Kit Assembly:* The Frozen Urine Syringe Kit contains 100 Monovette Syringes used to collect frozen urine samples from the Urine Collection Devices (UCDs). The syringes are restrained on Nomex pallets by elastic straps. There are five pallets that hold 18 syringes each and one which holds 10 syringes. Each syringe had a Velcro dot (Velcoin), and the pallets were removable so that they could be placed on the wall for easy access.

*Preserved Syringe Kit Assembly:* The function of the Preserved Urine Syringe Kit was to hold syringes needed to obtain urine samples that required the presence of a preservative for stowage at room temperature. EDTA/Sodium Meta Bisulfite was used as the preservative. Each kit contains 90 safety Monovette syringes and 90 adapters used to collect urine samples from the UCDs. The syringes are restrained on Nomex pallets by elastic straps. There were five pallets that held 18 syringes each and two which held 45 adapters each. Each syringe had a Velcoin and the pallets were removable so they could be placed on the wall for easy access. After samples were obtained, the syringes were placed in a Preserved Urine Kit. This kit contained two pallets to store the first urine syringes collected.

## **Urine Monitoring System (UMS)**

(STS-51B, 40, 55, 78, 90) NASA

The UMS includes a mechanical assembly connected to an electronic control assembly with a urine collection hose and a urine discharge hose. It also includes a flush water hose and microbial check valve. Water for flush is obtained by connection to the Shuttle Cross-Tie QD. The UMS urine discharge hose is connected to the Shuttle Waste Collection System Urine inlet port during inflight operations and the UMS itself is attached to the middeck hatch by velcro and a strap assembly. The UMS operates off of 28 volts DC Shuttle Power and is protected by a 5amp fuse. The operation of the UMS is semiautomatic. A microprocessor is used to provide for software controlled automatic functions. Components that include moving parts are the phase separator, the urine pump, the flush water solenoid valves and the urine discharge solenoid valve. The rotation of the phase separator is required to produce the centrifugal forces to separate the liquid from the air. The urine pump is used to pump the urine from the separator through a line which runs parallel to the air discharge hose and then connects near the end of the air discharge hose just before it enters into the waste collection system inlet port. The flush water solenoid valves (normally closed) are used to introduce flush water into the system to flush out the interior surfaces of the UMS hoses and separator before being pumped out through the urine discharge line. The urine discharge solenoid valve is used to control the out flow of urine from the UMS to the Waste Collection System (WCS) when the urine pump is running and is opened during the urine pump out

and closed during sample collection. During in-orbit operations, the UMS is installed in the middeck hatch and is stowed in a middeck locker during launch and landing. Samples can be preserved with chemicals or by freezing. The UMS interfaces with Orbiter Waste Collection System (WCS).

### **US Lab Sled**

(STS-40) NASA

The sled provides measured linear accelerations to the subject, a useful stimulus in vestibular studies. The sled consisted of a chair and instrumented head restraint mounted on a cart guided along two horizontal rails. The subject was seated in a chair which was mounted on the cart in one of two orientations: 1) upright with motion along the lateral or inter-aural direction (y-axis) or 2) supine with the motion along the longitudinal or rostral-caudal direction (z-axis).

### **Vacuum Interface Assembly (VIA)**

(STS-40, 58, 78, 90) NASA

The Vacuum Interface Assembly (VIA) allowed access to the space vacuum by interfacing with equipment through vacuum lines.

### **Valsalva Assembly**

(STS-71, 90) NASA

The Valsalva Assembly allows for the execution of the Valsalva Maneuver during testing. The assembly contains a Valsalva Unit and an Umbilical. The Valsalva Unit is a pressure transducer that measures Valsalva pressure through a valve that opens during Controlled Breathing exercises and closes during Valsalva maneuvers. The crewmember attaches a mouthpiece and Saliva Filter to the unit during use. The Umbilical contains the cables needed to connect the Valsalva Unit to data measurement and recording devices.

### **Vapor Crystal Growth System (VCGS)**

(STS 51B, 42) NASA

The purpose of this experiment is to grow more perfect mercuric oxide crystals by diffusion-controlled growth conditions. On STS-51B, the mercury iodide source material is mounted to the inner wall of the ampoule. The ampoule is put in a heater assembly and installed in the furnace enclosure, a belljar-shaped container. In space, a crew member inspects the seed crystal, grown on Earth, and installs the bell jar in the experiment enclosure in the Vapor Crystal Growth System. Heaters are started, and the ampoule is warmed to temperatures of around 100 C. At this point, the ideal growth temperature is established, and the mercury iodide source evaporates and condenses on the seed, which is maintained at a temperature around 40 C. The vapor molecules follow the structure of the seed to produce a larger crystal. Growth continues for approximately 100 hours, with crew members and investigators monitoring and changing temperatures as necessary to enhance growth. At the end of the experiment, the ampoule is cooled, and the module is removed and stowed.

On STS-42, the crystals are grown by vaporization at 110 deg C and by recondensation at 40 deg C in a specially designed furnace in the Vapor Crystal Growth System. Crew members can reverse the growth procedure if polycrystalline growth begins (which is a common problem on the ground). Growth is observed through an optical assembly.

### **Vapor Diffusion Apparatus (VDA)**

(STS-42, 47, 50, 62, 65, 83/94) CBSE

The complement has three trays that each contains 20 experiment chambers. Each chamber contains a double-barreled syringe. A protein solution is in one barrel and a precipitating agent is in the other bar-

rel. The surrounding chamber holds an absorbent reservoir that contains a solution of the precipitant. The VDA trays extend on slides for operations such as observation, photography, and seeding. VDA-2 has a triple barreled syringe which replaces the double barrel design. This design is used to improve mixing of experiment solutions. Vapor diffusion is used to grow protein crystals. Each chamber uses the improved triple barreled syringe to mix tiny amounts of chemicals. One barrel contains a protein solution, another a precipitant solution, and the third is used as the mixing chamber. The Commercial Vapor Diffusion Apparatus consists of 32 banks of sample holders, each containing four separate experiment chambers. This hardware is an adaptation of the most common laboratory method for growing protein crystals. Each chamber contains a double-barreled syringe which is loaded with protein and precipitant, prior to launch. The bottom of the chamber is fitted with a cylinder of polymer wicking material which holds a more concentrated reservoir solution. On the MSL-1 mission, the Second Generation Vapor Diffusion Apparatus (VDA-2) occupies a Single-locker Thermal Enclosure System (STES) and grows large quantities of crystals in 80 chambers. The VDA-2 experiments are recorded on video and/or 35-mm film. The new PCG hardware consists of a variety of experiment equipment including improved Vapor Diffusion Apparatus (VDA) trays, hand-held Protein Crystallization Apparatus for Microgravity (PCAM) units, the Crystallization Observation System (COS), and the Advanced Crystallization Observation System (A/COS). This equipment is inserted in special thermal enclosures that are installed in place of lockers in the Orbiter middeck. The two configurations available are the dual-locker Thermal Enclosure System (TES) and the Single-locker Thermal Enclosure System (STES). The most often employed method of growing protein crystals is vapor diffusion. The VDA trays, PCAMS, COS and A/COS use this process, which relies on water vapor pressure differences within a chamber, to create optimum growth conditions. Each vapor diffusion device has a number of experiment chambers, and each chamber contains a protein solution and a precipitating (or crystallizing) agent. Various methods--from a double-barreled syringe (VDA tray) to a pedestal in the center of a circular chamber (PCAM)--are used to contain the solutions. In each case, the surrounding chamber holds an absorbent reservoir that contains a solution of the precipitant. Vapor pressure differences between the protein solution and the reservoir solution force water to move from the protein solution to the reservoir. As protein concentrations increase, protein crystals begin to nucleate and grow.

### **Vehicle Charging and Potential (VCAP) Experiment**

(STS-3, 51F) NASA

This multiple experiment uses several instruments for the data acquisition. The instruments to be used are (a) a charge and current probe (CCP), (b) an spherical retarding potential analyzer/Langmuir probe (SRPA-LP), (c) a fast-pulse electron gun (FPEG), and (d) a digital control and interface unit (DCIU). The electron generator emits a stream of electrons, and the effects of the emissions on the plasma environment are recorded by the three plasma probes.

### **Vapor Growth of Alloy-Type Semiconductor Crystals**

(STS-7) Rensselaer Polytechnic Institute

The objective of this experiment was to grow crystals of alloy semiconductors to provide data for a better understanding of the fluid dynamics of vapor transport systems in space. A quantity of germanium selenide was placed in a sealed glass tube. Both ends of the tube were heated at different temperatures. The substance turned into a vapor when heated and moved to the cooler end of the tube to crystallize.

### **Very Wide Field Galactic Camera**

(STS-9, 51B) CNRS

A camera with a very wide field of view was used in two modes on STS-9. In the photometric mode, observations were made at 155, 190, and 250 nm and the field of view was 54 deg. In the spectrometric

mode, a narrow slit 10 deg by 10 arc-min was used and measurements were obtained in the 130- to 270-nm range.

On STS-51B, the camera-telescope is mounted in the Spacelab scientific airlock, from which it takes wide-angle pictures of the sky at UV wavelengths (1300 to 3000 Å). The instrument can operate in two modes to photograph the sky through three different filters and to measure the wavelength distribution across the UV band. The 54-deg field of view permits studies of the large-scale structure of our galaxy and also of the remnants of large explosions that occurred eons ago in the sun's vicinity.

### **Vestibular Function Experiment Unit (VFEU)/ Neural Data Acquisition System (NDAS)**

(STS-47, 90) NASDA

The function of VFEU is to maintain long-term animal life support and support the neural experiment. The functions of NDAS are to measure, transmit, process and record the experiment data of neural activities and acceleration continuously over the mission duration as well as downlink to the ground. The power supply to transmitter is without wire. This equipment is to measure the experiment data without animal restraint. The main components of NDAS are the Data Interface Unit, the Data Interface Unit, the Data Recorder, the Receiver, the Transmitter, and the Inductive Coil.

#### **VFEU Major Specification**

(a) Water Tank: Fish Package Volume approximately 4l/unit

(b) Life Support

Life Support Duration: More than 26days

Water Control: Crushed Coral, Activated Carbon, Glass Beads with Nitrifying Bacteria

Temp. Control: 10 - 25 for the experiment)

Oxygen Supply: Gas exchange by Artificial Lung which consists of hollow fibers

(c) Equipment size: 483Wx606Dx444H (mm),

/weight: approximately 77kg

#### **NDAS Major Specification**

(a) Data Interface Unit (DIU)

Function: Data Processing

Size/Weight: 483Wx321Dx266H (mm), approximately 17kg

(b) Data Recorder (DR)

Function: Data Recording

Size/Weight: 483Wx321Dx266H (mm), approximately 19kg

(c) Receiver (Rx)

Function: Data Receiving

Size/Weight: 40x9L (mm), approximately 9g

(d) Transmitter (Tx)

Function: Data Transmission

Size/Weight: 29Wx51Dx18H (mm), approximately 47g

(e) Inductive Coil

Function: Power Supply to Tx

Size/Weight: 120x250L (mm), approximately 291g

### **Vestibular Sled (VS)**

(STS-61A) ESA

The VS is an ESA contribution consisting of a seat for a test subject that can be moved backward and forward with precisely adjusted accelerations along rails fixed on the floor of Spacelab's aisle. The seat is driven

by an electro-motor and traction rope. The sled permits tests to investigate the functional organization of man's vestibular and orientation system and the vestibular adaptation processes under microgravity. The acceleration of the astronauts will be combined with thermal stimulations of the inner ear and optokinetic stimulations of the eye.

### **Vestibular Support Kit**

(STS-90) NASA

The Vestibular Support Kit (VSK) is a 36.8 x 36.8 x 19.1 centimeter Nomex container that contains a number of small items used during the Vestibular experiment. These include: Audio Tape Player - primary and backup; Audio Tapes; AA Battery Kit - contains 28 batteries for the Audio Tape Player; Beam Splitter Screw - backup; Cotton gloves - used when cleaning beam splitter; Darkness System Headunit Cover; Dry wipes; ECS Video Monitor Data and Power Cables - backup; Emesis bags; Foam pieces - used if required for subject comfort during rotation; Front Shell Knobs - backup; Fuses - backup; Knee cushion - a foam cushion placed between the knees for all rotation sessions to increase subject comfort and provide a more secure fit of the knee/ankle strap; Knee/ankle strap - used for all rotation sessions to secure legs; Micro-switch bypass adaptors - off-nominal use; Optic wipes - used to clean beam splitter, ESS lens, and camera lenses; PC4 Recovery Cap - used with REBO; PCMCIA cards - one with backup Neurolab software load, one with Vestibular experiment off-nominal; software; Subject Headset - primary and backup; Trigger gloves - used to secure subject's hands to chair handgrips; VTR Test Cable

### **Vestibulo-Spinal Reflex Kit**

(STS-9) NASA

*Hoffman Reflex Recording Set-up:* The monosynaptic H-reflex was activated by electrical stimulation of the popliteal nerve and recorded from the soleus muscle. A needle electrode, which served as the cathode, was inserted in the popliteal fossa at a predetermined location on the right leg. The anode, a plate electrode, was placed just above the knee. Different levels of 1 millisecond (ms) constant current pulses limited to a maximum of 20 milliamps (ma) were delivered through an isolation unit under computer control. A differential amplifier and a bipolar surface electrode configuration were used to record the reflex from the soleus muscle. The reflex was a two-part response: a direct muscle response (M-wave) with a latency of 5 to 10 ms that was followed 15 to 20 ms later by the monosynaptic H-reflex. The M-wave represented the direct muscle response and was therefore used as a drop control response to assure constant stimulation. The H-reflex amplitude reflected the sensitivity of the lower spinal motor neuron pool as set by the descending postural control signals.

*Preflight and Postflight Testing:* Otolith stimulation during preflight and postflight testing was provided by dropping the subject in a special harness, designed to leave the arms and legs free, from a quick release hook. Prior to each drop, the subject grasped a T-shaped handle with both hands which allowed him to hang with his feet approximately 15 cm from the floor. For each drop the subjects were shocked three times. The shock sequence consisted of a conditioning shock and a control shock, applied before the drop, and a test shock applied during the drop. The conditioning shock, used to condition the neural tissue, was followed three seconds later by the control shock which elicited a control response. The test shock, which was applied 3 to 5 seconds later, was delivered at predetermined time delays from the onset of the drop. During the fall, tests shocks occurred coincident with the drop (0 ms delay) or at 10 ms intervals up to 80 ms following initiation of the drop. Landing times were recorded with ribbon switches placed under a rubber mat. Head acceleration was recorded with a linear Z-axis accelerometer attached to a biteboard which was held in the subject's mouth during the drop. An experimental session was composed of four drops at each of nine randomized delay times for a total of thirty-six drops. The averaged response to the test shock was normalized with respect to the averaged control shocks and presented as a percent change in H-wave (or M-wave) amplitude.

*Inflight Testing:* The inflight testing protocol utilized the “hop and drop” station to complete the drop tests. The station was composed of a special torso harness to hold the subject, a drop apparatus similar to the ground based device, and calibrated bungee cords adjusted to pull the subject to the floor of the Spacelab with a transition from free fall to -1 g. The delay times (from the onset of the drop to the test shock) ranged from 0 to 70 ms in 10 ms increments. On MET-01, four responses at each of the eight delays times were recorded. On MET-06, only two responses at each of the delay times were obtained. The inflight computer was used to control the experiment, release the drop mechanism, time the electric shock and collect the data. The inflight head accelerometer was held on the back of the head with a velcro strap. Floor contact was detected with ribbon switches attached to the bottom of the subject’s right foot. Data on body position during each drop was obtained by filming the pre-, in-, and postflight test sessions. Every 10th film frame was analyzed to determine the angle of the head, trunk, hips, knees, and ankles. Pre-drop body angles were compared to body angles during the drop to determine the percent change in a selected body angle.

*Gastrocnemius Electromyographic (EMG) Responses:* The relationship between the direct vestibulo-spinal reflex and the H-reflex was investigated by recording the EMG activity of the left leg. The electrodes were placed on the middle section of the gastrocnemius muscle. The EMG activity was recorded as a function of the sudden drop and then amplified and band pass filtered between 1 Hz and 1 kHz. The amplitude of the EMG activity was then determined over a 100 ms section that was between 50 and 150 ms of the total time of the sudden fall.

### **Virtual Environment Generator (VEG)**

(STS-90) NASA

The VEG Computer Drawer formed an integrated system that provided computation of the voice recording, user input, data archiving, scene generation, alphanumeric display output for console operations, and a High-Rate Multiplexor (HRM) downlink of data. The VEG Computer Drawer interfaced with the Head Mounted Display (HMD) Electronics Box through a video interface, and with VEG Joystick through the VEG Computer Drawer serial port.

The VEG Computer Drawer consisted of a modified Standard Interface Rack (SIR) drawer including a minimum of the following: Fan; Thermal cutoff switch; Passive backplane with a 6 ISA and 6 PCI full size card slots; High-Rate Multiplexor (HRM) interface card; Analog to Digital card; Personal Computer Memory Card International Association interface card (PCMCIA); Small Computer System Interface (SCSI) card (TBD); Isolation from external signals; Graphics boards, left eye view; Graphics boards, right eye view; Mass storage units for data archive; 200 MHz Pentium class Computer Processing Unit (CPU) card; Ethernet card; IDE Internal Hard Drive.

### **Visual and Vestibular Investigation System (VVIS)**

(STS-90) ESA

The VVIS consists of the Body Rotating Device (BRD), Eye Stimulation & Movement Recording System (ESMRS) and Experiment Control System (ECS). The BRD is primarily a seat driven by a motor located in the Spacelab, which is to rotate the test subject, and generates the acceleration. The ESMRS is attached to the top of the BRD and in front of the subject head. This hardware has the darkness curtain, eye stimulation system and eye recording cameras in it, for stimulation and recording of eye movement.

### **Visuo-Motor Coordination Facility (VCF)**

(STS-90) NASA

The Visuo-Motor Coordination Facility (VCF) displayed stationary or moving visual targets on a laptop computer screen that subjects viewed on a tilted reflective screen. Using real-time video analysis, it re-

coded trajectories of manual responses towards these targets. The VCF, attached to the VCF mounting structure, consisted of a Data Acquisition System and a Virtual/Real Image System (VRIS). The VCF Data Acquisition System consisted of an IBM ThinkPad computer, docking station, electronics box, image processing board, multiplexer board, input/output interface board, and a power cable. The IBM ThinkPad 755C laptop computer performed image presentation, acquisition, and processing; data Input/Output (I/O) handling and storage; and experiment control. The laptop consisted of 540-MB hard disk, 12-MB RAM, high resolution color Liquid Crystal Display, and 3.5-inch floppy drive. The docking station housed the image processing and multiplexing boards, which provided the real-time video acquisition and analysis. The docking station was the on-site expansion tray, complete with four full-length (AT) slots to accommodate 8- and 16-bit cards, an RS-232 port and a very fine graphics adapter (VGA) video display port. The electronics box housed dc-dc converters, circuit breakers, camera controllers, fans and wiring. The image processing board processed a digitized image captured by the multiplexer board. The multiplexer board simultaneously sampled, digitized and multiplexed the camera input onto the image processing board. An I/O interface board provided interfacing for status and control of the Screen Tilt/Lock Unit, power control to the glove micro-lamps and interface to the subject trigger switches. The I/O functions were performed via the laptop/docking station parallel printer port. The power cable provided power from a Space Shuttle Vdc power source to the VCF hardware. The cable did not interfere with crewmembers or experiment operations and was stowed in a compartment at the rear of the VCF. The VCF Virtual/Real Image System (VRIS) consisted of a camera assembly, two CCD cameras, reflective screen assembly, tilt/lock assembly and cover screen. The camera assembly held the cameras and reflective screen assembly in optical alignment with laptop screen. The assembly was fixed in place to reduce the risk of optical misalignment and reduce total setup time. Cameras were encased in a structure mounted to the VRIS plate and positioned with locating dowels. A Lexan cover contained the glass lens. The CCD cameras viewed glove lights on the subject's fingers inside the working volume from different angles to determine the light position in three dimensions. A Lexan reflective screen assembly with a tiltable black backing was mounted at a 45-degree angle from the laptop computer screen. The black backing could be placed in a down or up position producing reflective or semi-transparent modes, respectively. In the down position, the screen is zero percent transparent, preventing the subject from seeing his/her hand. In the up position, the screen is 50 percent transparent, allowing the subject to see the image in the computer screen, as well as hand movements. Computer control allowed the paradigms to automatically actuate the black backing without affecting the subject. The computer screen center position was 31.22 cm up and 11.5 cm back. Working volume was defined relative to the reflective screen center. The computer-controlled tilt/lock assembly moved the black backing to change the state of the reflective screen (reflective or semi-transparent). The computer control has a manual override to ensure that computer-actuated screen failure does not impede experimentation. The cover screen of the VVIS was thin Lexan attached by a hinge to the VRIS plate. Handles located on either side allowed for manual actuation of the Tilt/Lock Assembly, and a spring assembly kept the cover screen in position during manual operation. Computer control was performed by a Seromotor attached to the handle. To disengage the computer, the linkage is removed. Additional hardware used with the VCF included a hand reaction switch, a black screen, a VCF glove, the VCF mounting structure, a floppy disk kit, a back restraint and VCF stability straps. The Hand Reaction Switch (HRS) was employed on the subject's dominant hand side to allow the subject to start a paradigm. Software protected against accidentally triggering the switches, and the frame accommodated and protected the switches. The SITE Handswitch clamped to the VCF Mounting Structure. The Black Screen prevented background light from interfering with determination of the micro-lamp positions. The lightweight Black Screen assembly attached easily to the black frame of the VCF with Velcro through Black Screen spaces. A light shield prevented stray light from entering the volume subtended by the reflective screen and the computer screen. The VCF Gloves (left and right) are black Spandex gloves to be donned on the subject's dominant hand and extended to the

subject's elbow. Incandescent micro-lamps were located on the glove index finger and thumb to facilitate finger position tracking. The glove's anti-reflective surface minimized reflected light interference with light position determination. A flexible wire runs down the glove to the computer electronics box. The VCF Mounting Structure provided a rigid structure to ensure accurate and repeatable optical alignment. The Mounting Structure consisted of a VCF Mounting Bar that interfaces to the VCF and permanently attaches to a base plate secured to the Spacelab floor. Floppy disks were used to store experiment data from the VCF hard drive and run VCF software protocol. The disk kits were stored in foam in a compartment at the rear of the VCF when not in use. The back restraint supported the subject's waist and lower back during operations. The subject attached the back restraint on each side of the VCF Mounting Structure. The VCF stability straps were two tethers that attached from the VCF Mounting Bar to the VCF baseplate giving the structure stability.

### **Waves in the OH Emissive Layer**

(STS-9) CNRS

The equipment contained an image intensifier with a camera, filter, and 16-mm movie camera. The spectral part of the airglow was delimited on the short wavelength side by a Schott RG9 filter (50% cutoff at 730 nm) and on the IR side by the sensitivity of the photocathode (50% cutoff at 830 nm).

### **Water Microbiology Kit**

(STS-71) NASA

The Water Experiment Kit (WEK) is used to collect water on the ground and in flight for chemical and microbiological analyses. The WEK is composed of an outer Nomex fabric container (with "Armolon", a Teflon-coated fiberglass stiffener) which contains the kit components. Six sub-packs made of the same materials are stowed within the WEK outer pouch. Each sub-pack contains the materials necessary to complete one session of water collection and processing. The following hardware are stowed within the WEK and its sub-packs: potable water samplers, water collection bags, storage bags, microbial capture devices, air filter adapter assembly, syringe pump assembly, media syringe assembly, back-up syringe, disinfectant wipes, "Sharpie" marker, temperature data logger (TDL), and nutrient growth medium (specific for each experiment). The potable water samplers are used to fill sample bags from the hot or cold Mir galley potable water ports or the ground-supplied (SVO-ZV) dispenser port. The samplers consist of a Teflon adapter that mates to the hot, cold, or SVO-ZV dispenser probe as appropriate, and a stainless steel male Luer-lok fitting that mates to the water bags. The hot/cold adapter also contains two Buna-N O-rings. Samplers are sealed in a bag and sterilized prior to flight. The water collection bags used to collect and process water samples are commercially available Teflon bags that have been modified by adding to each bag a one-way valve and a polypropylene female Luer-lok port fitted with a polyethylene cap and a polyvinyl chloride tether. Three types of bags are provided. The micro sample, in flight analysis bag is a 300-ml bag that contains 100 mg of thioneutralizer to neutralize the silver present in the Mir potable water. The small waste water bag is a 300-ml bag used to flush the dispenser port before sample collection. The large waste water bag is a 1000-ml bag used to collect waste water during sample processing. Various sizes of storage bags (polypropylene Ziploc bags) are used to contain the small waste water, micro sample, in flight analysis and large waste water bags for containment and disposal. The microbial capture devices (MCDs) are stowed in biohazard-labeled bags after processing; after use, the media syringes are also stored in biohazard labeled bags for disposal. The Microbial Capture Device (MCD) is a commercially available filter unit (field monitor, Millipore Corp., Bedford, MA) that is modified at Johnson Space Center. The MCD is used to culture microbes that are trapped on the filter as a water sample is pumped through the unit. The MCDs are constructed of two polystyrene press-fitted sections that encase a 0.22 mm cellulose acetate filter and adsorbent pad. Two female Luer-lok fittings made of K-Resin are glued to the polystyrene unit

with methylene chloride. Two male Luer-lok polyethylene caps with polyvinyl chloride tethers are used to seal the inlet and outlet ports of the MCDs. The inlet cap is blue and the outlet is red. A label is located on the side of the filter for documenting in flight results. The Air Filter Adapter (AFA) assembly interfaces the micro sample in flight analysis bag to the MCD. The AFA filters air drawn in from the cabin and across the MCD, allowing all water to be removed from the MCD; it also acts as a valve to start or stop water flow from the sample bag. The AFA includes a nickel-coated brass gate valve and a two-piece press-fitted polypropylene case containing a 0.22 mm filter. The syringe pump assembly is used to draw water through the MCD during the processing of a sample and expel the filtered water into the waste bag. The assembly consists of a stainless steel pistol grip hand pump fitted with a plastic syringe barrel and a three-way valve. The pump is calibrated to deliver a specific volume of water (10 ml) through the MCD with each stroke of the syringe plunger. The media syringe assembly is a polypropylene off-the-shelf medical syringe fitted with a polypropylene cap. The syringe contains a nutrient growth medium that is injected into the MCD after the water sample is filtered. The medium, a non-hazardous material, promotes the growth of microbes on the filter surface. The back-up syringe is an off-the-shelf polypropylene medical syringe (60 ml) with a Luer-lok fitting. This syringe is to be used if the syringe pump assembly failed. Disinfectant wipes are used to clean the Mir water ports before the water samples are collected. The wipes are cellulose fiber towlettes soaked in a 1:250 solution of benzalkonium chloride:water. Each wipe is packaged in a sealed foil, paper, and polyester pouch. A permanent "Sharpie" marker is used to record information, such as the date of collection, on the sample bag labels and MCDs. The Temperature Data Logger (TDL) remains in the WEK pouch recording the temperatures to which the WEK is exposed. Temperature logging is initiated before shipment to Kennedy Space Center for launch and ends after the hardware is returned to the ground after flight. The TDL is programmed to store data until its memory was full and then stop. The TDL is not used or handled by the crew at any time during the mission. The TDL is a commercial off-the-shelf item (HOBOTEMP data logger manufactured by Onset Systems, Inc.). The logger consists of a small electronics box (50 x 45 x 15 mm) with an attached thermistor cable. Power is provided by an internal battery (3.6V lithium wafer cell, Tadiran model TL-5186), and data are stored on an 8-KB memory chip. Temperatures between 0° C and 60° C are registered and time-tagged. Data are downloaded postflight via a RS-232 cable to a PC-compatible computer. The TDL is used for historical purposes only, so that the stowage temperature of the kit can be reviewed if necessary.

### **Werkstofflabor (WL; Materials Science Facility)**

(STS-9, 61A, 55) DARA

On STS-9, the materials science facility included 36 different experiments. Six of these experiments were individual, black-box type experiments (including the Low Temperature Heat Pipe Furnace, the Cryostat used for protein crystal growth, the Ultra High Vacuum Chamber, the Solution Growth of Crystals, and the High and Low Temperature Thermostats) which required only provision of power, data recording, and heat rejection. The 32 other experiments were performed with the help of multi-user facilities including the Isothermal Heating Facility (used for solidification studies, diffusion fundamentals, casting of metals and composites, and preparation of new and/or improved glasses and ceramics); the Gradient Heating Facility for low temperatures with vacuum and noble gas supply provisions (for different types of experiments such as crystal growth and unidirectional solidification of eutectics); the Mirror Heating Facility (an experimental facility used for investigating crystal growth using the melt zone or traveling solvent methods); and the Fluid Physics Module (a structure fitted with two disks which could be rotated separately, at the same or different speeds, and in either direction; different fluids could be injected and recovered from this structure).

The WL housed the following hardware on STS-61A: a mirror heating facility, a cryostat, a gradient heating facility (CNES), a fluid physics module, an isothermal heating facility and a high-temperature thermostat.

On STS-55, the Material Sciences laboratory facility consisted of five furnaces, a fluid physics module and a crystal growth module. The facilities consisted of the Isothermal Heating Facility (IHF), a high temperature furnace to process metal samples; a Heater Facility, Turbine Blade Facility (HFT) for processing special metallic alloys; the Gradient Heating Facility (GHF) for heating and cooling of experiments; the Advanced Fluid Physics Module (AFPM), a multipurpose facility to investigate the behavior of fluids in microgravity; a High Temperature Thermostat (HTT and HTS), consisted of two identical furnaces; and the Cryostat (CRY) for growing high quality crystals of biochemical macromolecules by diffusion of protein into saline solutions. The following experiments were conducted using the WL: (1) Oxide Dispersion Strengthened Single Crystalline Alloys Improved by Re-Solidification in Space (OSIRIS) - was designed to produce a single crystalline material with finely distributed particle inclusions under microgravity; (2) Impurity Transport and Diffusion in InSb Melt Under Microgravity Environment - was an impurity diffusion experiment for InSb (a compound semiconductor), using the IHF; (3) Cellular-Dendritic Solidification at Low Rate of Aluminum-Lithium Alloys - deep cell-dendrite transition was investigated by solidifying three Al-Li alloys in the GHF; (4) Directional Solidification of the LiF-LiBaF<sub>3</sub>-Eutectic - the lamellar eutectic system LiF-LiBaF<sub>3</sub> was solidified in the GHF; (5) Separation Behavior of Monotectic Alloys - The transport mechanism of Bi droplets in Al melts was investigated; (6) Liquid Columns' Resonances - measured the resonance curves of liquid columns between coaxial circular disks and tested theoretical models; (7) Stability of Long Liquid Columns - designed to measure the outer shape deformation of long liquid bridges under microgravity; (8) Higher Modes and Their Instabilities of Oscillating Marangoni Convection in a Large Cylindrical Liquid Column - various types of liquid motion due to inhomogeneities in free liquid surfaces (Marangoni effects) was investigated; (9) Marangoni-Benard Instability - the Marangoni-Benard instability was studied in steady state to measure the critical Marangoni number and to observe inverse bifurcation behavior; (10) Onset of Oscillatory Marangoni Flows - investigated cylindrical floating zones during oscillatory conditions; (11) Marangoni Convection in a Rectangular Cavity - investigated Marangoni effects driven by temperature gradients; (12) Stationary Interdiffusion in a Non-Isothermal Molten Salt Mixture - performed diffusion experiments on molten salt; (13) Transport Kinetics and Structure of Metallic Melts - determined the temperature dependence of diffusion coefficients for different materials; (14) Nucleation and Phase Selection During Solidification of Uncooled Alloys - examined metallic melts cooled below their solidification temperature in their liquid state; (15) Heating and Re-melting of an Allotropic Fe-c-Si Alloy in a Ceramic Skin and the Effect of the Volume Change on the Mold's Stability - Tested skin technology with allotropic and non-allotropic materials; (16) Immiscible Liquid Metal Systems (NUCIM) - investigated the behavior of two liquid immiscible metals in contact with different ceramic materials; (17) Convective Effects on the Growth of Gallium Crystals - investigated the effects of convection on chemical segregation of semiconductors; (18) Vapor Growth of Indium Crystals with Halogen Transport in Closed Ampoule - investigated the relation between gravity and epitaxial layer quality; (19) Solution Growth of GaAs Crystals Under Microgravity - investigated a new technique to grow GaAs crystals; (20) Crystallization of Nucleic Acids and Nucleic Acid-Protein Complexes - studied the structure of ribosomal 5S RNAs, their protein complexes and the structure of the elongation factor EF-TU complex; (21) Crystallization of Ribosomal Particles - investigated the model of the ribosome using single crystal x-ray crystallographic studies.

### **Wisconsin Ultraviolet Photo Polarimeter Experiment (WUPPE)**

(STS-35, 67) University of Wisconsin

The Wisconsin Ultraviolet Photo Polarimeter Experiment (WUPPE) was designed to measure the polarization of light in the ultraviolet. WUPPE was a 0.5m f/10 Cassegrain telescope and spectropolarimeter. The WUPPE spectrometer was a modified Monk-Gilleson spectrometer: a plane grating is placed between a spherical relay mirror and the detector. WUPPE obtained simultaneous spectra and polarization measurements, with a spectral resolution of about 10Å, from 1400 to 3200Å. A set of halfwave plates at 6 different

angles provided spectropolarimetric modulation with 10 Å resolution on point sources through apertures from 6 to 40 arcsec. A “Lyot” analyzer was used to provide 50-100 Å spectropolarimetric resolution on faint point targets and diffuse nebulae. Because of the very high signal/noise required for polarimetry, most WUPPE targets were in the 0-8 magnitude range: readout integration times (“frames”) were less than 8 seconds, so that a typical observation was the sum of many short frames. The apertures included a 40 arcsec diameter acquisition aperture and a 4.2 arcsec diameter stellar aperture, in addition to a number of aperture shapes for diffuse source, (e.g. 6x12 and 3x50 arcsec). This telescope fed light to a low resolution spectrometer which was equipped with the aforementioned polarimetric analyzers followed by a MgF<sub>2</sub> Wollaston polarizing beam splitter. The focal plane scale was 26 arcsec/mm. The two senses of polarization were measured simultaneously by an intensified, analog-readout dual Reticon detector of exceptionally high effective dynamic range. WUPPE had the ability to offset from the other two ultraviolet instruments by as much as 15 arcminutes by use of its articulated secondary mirror. In spectral mode the field of view was 50 arcsec perpendicular to the dispersion for a spatial resolution better than 0.7x6 arcsec. The spectral range was 1300-3300 Å with a dispersion of 78 Å/mm, blaze at 2000 Å. A CsTe Microchannel Intensifier was used in combination to a dual reticon. The total system quantum efficiency was about 4 percent, polarimetric efficiency about 75 percent, polarimetric stability was better than 0.04 percent, and the instrumental polarization (from in flight observations of unpolarized standard stars) was less than 0.1 percent. In the Lyot mode the polarimeter measured Stokes Q,U,V with 50-100 Å resolution. In the 1/2 Wave Plate Mode the Stokes Q,U were supported with 5 Å resolution. Field identification, offsetting, focussing, and pointing trim were accomplished by relaying the zero-order image of the WUPPE spectrometer grating to a blue-sensitive Zero-Order Detector (ZOD) camera. The ZOD was an intensified RCA 320x512 two-dimensional CCD array. The intensifier was an ITT 18 mm proximity-focussed channel intensifier with P-20 phosphor, quartz faceplate, and S-20 photocathode for blue-sensitivity. The array was uncooled and typically read out every second. The ZOD camera had a 3.4 x 4.4 arc min field of view, 1x5 arcsec resolution, and was sensitive up to 15th magnitude for a 1-sec integration. The ZOD made it possible for the experiment team to acquire and guide upon faint targets and targets in crowded fields. There were three camera modes: field, zoom and downfield. The field mode was used for identification and acquisition of the targets. Its size was 3.3 x 4.4 arcmin, 320 x 256 pixels and used a 1-bit display. The zoom mode was used for fine pointing and focus. The size of the Zoom image was 24 x 32 arcsec, 30 x 40 pixels and used a 6-bit grey scale display. The downfield data was similar to the field data except it used the 6-bit grey scale display and was used to produce a more detailed picture of the field around the object of interest.

### **X-band Synthetic Aperture Radar (X-SAR)**

(STS-59, 68) DARA/ASI

The X-SAR was operated jointly with the Shuttle Imaging Radar-C (SIR-C), built by NASA-JPL, on the same Space Radar Laboratory (SRL) platform. The X-SAR was designed and built by Dornier (Germany) and Alenia (Italy). X-SAR operated at X-band (3.1-cm wavelength or 9600 MHz) with VV polarization. The X-SAR used a passive slotted-waveguide antenna (12 meters) which was tilted mechanically to align the X-band beam with the SIR-C C-band and L-band beams. The swath width was from 10 to 45 km at 25-km resolution with illumination angle of 15 to 60 degrees off-nadir. The X-SAR antenna had a fixed beamwidth of 5.8 degrees in elevation and 0.13 degrees in azimuth as opposed to the phased array, multi-polarization antenna of SIR-C. X-SAR data was recorded on-board on the Shuttle Payload High Rate Recorder and transmitted in real-time (Ku-band via TDRSS) over selected regions. The SIR-C/X-SAR Science Team was made up of 49 members and 3 associates from 13 countries. Data was collected and focused on selected supersites in conjunction with aircraft and ground-based observations.

### **(Hard) X-Ray Imaging of Galactic Clusters and Other Extended X-Ray Sources (XRT)**

(STS-51F) University of Birmingham, United Kingdom

The instrument is a double X-ray telescope that uses a technique to produce X-ray images of small regions of the sky at higher X-ray energies than is possible using conventional methods. It uses a coded binary mask and a position-sensitive detector that produces an X-ray map of the sky. The mask uses a special case of the random pinhole mask, which produces an image by deconvolving the pattern of the mask holes that produce a shadowgram on the position-sensitive detector when illuminated by radiation from the object. The two telescopes have different resolutions. One has a coarse resolution to detect faint sources and an extended region of stronger sources, while the other has a fine resolution that resolves fine details in more intense regions. The resolution values are 12 x 12 arc-min and 3 x 3 arc-min, respectively, at full width half maximum of the response and do not necessarily imply the limits to the fineness of the detail that can be deduced. The detectors are composed of multiwire position-sensitive proportional counters. Anti-coincidence techniques are used to reject cosmic-ray events. A motorized gimbal system is used to point the telescope to within 0.5 deg of any orientation with respect to the Shuttle. A microprocessor system accepts the nominal vehicle attitude to select a preprogrammed list of targets and to drive the telescopes. A gyro package for pointing, star sensors for determination of absolute directions to within 1 arc-min, and star field cameras for long-term drift motion are also part of the instrumentation. Experiment mass: 326 kg; average experiment power: 160 W

### **X-Ray Astronomy Spectroscopy Experiment**

(STS-9) ESA

The experiment objective was the study of detailed features in cosmic X-ray sources and their associated temporal variations over a wide energy range. The equipment was a gas scintillation proportional counter having a 175-micrometer beryllium window, a xenon chamber, a photomultiplier detector, and a pulse-height analyzer.

### **YEAST (Microgravitational Effects on Chromosome Behavior)**

(STS-42) ESA

22degC grown liquid cultures of the common yeast *Saccharomyces cerevisiae* were used in this Biorack experiment because of its ability to undergo both meiosis and mitosis. The cultures were kept in separate sealed culture chambers each of which had two culture wells with a solid medium reservoir for yeast growth. Each well contained 300 microliters of solid agar medium upon which the yeast was deposited. Eight containers, each of which held four chambers, were flown. Four containers held wild-type yeast grown at 22 degrees Celsius and four held temperature-sensitive mutant yeast grown at 36 degrees Celsius. Half of the cultures were placed on 1-G centrifuges to serve as controls. At each of four times during the flight one chamber from each of the four cultures was fixed using 1.0 cc of glutaraldehyde: one at 22 deg., 1 g; one at 22 deg., 0 g; one at 36 deg., 1 g; and one at 36 deg., 0 g.

*Cell Chambers:* Cell culture chambers and assemblies were designed specifically to accommodate the yeast experiment. Each culture well consists of a Lexan chamber fitted with a movable piston, both with a molecular layer of silicone to ease piston travel up and down. The bottom plate, made of Lexan, has two grooved circular areas into which Lexan rings fit. Prior to fixation, the piston is pushed down with a syringe-type ventilation tool to vent the air inside the chamber. The fixative is injected into the chamber through the piston with a hypodermic syringe (not shown). This process takes place inside the European Space Agency (ESA) Biorack glove box.

*Culture Assemblies:* Four of the double chambers (total of eight culture wells) are placed in a specially designed tray and inserted into the Type I/O containers provided by the European Space Agency (ESA). The tray holding the chambers is fitted with a pad to ensure that the chambers are adequately held in place. These containers are opened only inside the Biorack glove box.

**Zeolite Crystal Growth (ZCG)**

(STS-73) Worcester Polytechnic Institute, Massachusetts, USA

The experiment consists of 38 autoclaves that will be activated and loaded into a furnace. The autoclaves contain two source solutions, one aluminum-based and the other silicon-based, and are designed to be loaded on Earth and mixed in orbit. Activation occurs when a nut is turned to mix the two solutions. The amount of mixing for different autoclaves and mixtures is determined by additional experiments in the Glovebox that use clear autoclaves.

## APPENDIX D - MISSION RELATED WEBSITES

## General –

International Distributed Experiment Archive (IDEA) - [http://exploration.grc.nasa.gov/fcarchive/media/htdocs/microgravity\\_experiment\\_archive.html](http://exploration.grc.nasa.gov/fcarchive/media/htdocs/microgravity_experiment_archive.html)  
European Space Agency Microgravity Database - <http://spaceflight.esa.int/eea/>  
National Space Science Data Center - <http://nssdc.gsfc.nasa.gov/>  
Japan Aerospace Exploration Agency (JAXA) - [http://iss.sfo.jaxa.jp/index\\_e.html](http://iss.sfo.jaxa.jp/index_e.html)  
International Space Environment Utilization Research Data Base (ISRDB) was developed by JAXA's Space Environment Utilization Research Center - [http://idb.exst.jaxa.jp/english/home\\_e.html](http://idb.exst.jaxa.jp/english/home_e.html)  
Spacelab Technical specs: <http://science.ksc.nasa.gov/shuttle/technology/sts-newsref/spacelab.html#spacelab>  
NASA's Space Partnership Development Office: <http://spd.nasa.gov/>  
JSC's history pages: <http://www.jsc.nasa.gov/history/shuttle.htm>

## Physical Sciences –

NASA Microgravity Research - <http://www.nasa.gov/centers/marshall/scienceandtechnology/index.html>  
SOFBALL experiment home page <http://carambola.usc.edu/research/microgravity.html>  
USMP-4 experiments - <http://liftoff.msfc.nasa.gov/shuttle/usmp4/>

## Astrophysics –

<http://archive.stsci.edu/mast.html>  
[http://adsabs.harvard.edu/abstract\\_service.html](http://adsabs.harvard.edu/abstract_service.html)

## Solar Physics –

SUSIM mission page - <http://www.solar.nrl.navy.mil/susim.html>  
Atlas Missions overview - <http://www.ghcc.msfc.nasa.gov/atlas.html>

## Atmospheric Sciences –

Langley Research Center Atmospheric Sciences - <http://eosweb.larc.nasa.gov/>  
ATMOS - <http://remus.jpl.nasa.gov/atmos/atmos.html>  
CRISTA - <http://www.crista.uni-wuppertal.de/>  
MAHRSI - <http://uap-www.nrl.navy.mil/mahr/si/mahr/si.html>  
SSBUV- [http://www.gsfc.nasa.gov/gsf/service/gallery/fact\\_sheets/earthsci/ssbu.htm](http://www.gsfc.nasa.gov/gsf/service/gallery/fact_sheets/earthsci/ssbu.htm)  
SIR-C/X-SAR - <http://southport.jpl.nasa.gov/sir-c/>

## Life Sciences –

LSDA - <http://lsda.jsc.nasa.gov>  
Spaceline - <http://spaceline.usuhs.mil/>  
Protein Crystal Growth - <http://science.nasa.gov/ssl/msad/pcg/>  
Space Biology Group, Zurich - <http://www.spacebiol.ethz.ch/>  
Space Biology: An Educator's Resource: <http://spacebio.net/>  
BioServe Space Technologies - <http://www.colorado.edu/engineering/BioServe/pubbs.html>

\*All websites were verified as active and available as of 4/23/2007.

## APPENDIX E - TECHNOLOGY SPINOFFS

Technology spinoffs from particular space flight missions are often difficult to identify, since the development of new hardware or a new process might be completed over several missions, or tested on multiple experiments. Thus, while the innovations listed here are ascribable to specific experiment sets performed on Spacelab flights, they are not a complete list and should be considered as a representative sample set of the types of processes and technologies with which Spacelab flight experiments were involved.

### **Automatic Self Tonometer**

During the German Spacelab D2-mission and the German-Russian MIR-Mission a new microprocessor controlled automatic gravity independent applanation tonometer, following Goldmann's principle has been used to estimate the raised intra-ocular pressure of astronauts entering into microgravity. Following the same technical principle a new even smaller instrument has been designed for use by the glaucoma patient himself. Thus, dense diurnal profiles can be achieved, allowing precise differential diagnosis and follow up of the glaucomas. This has been stressed by Goldmann and Sampaolesi many years ago as most reliable sign for detection and evaluation of the different glaucomas. Meanwhile calibration has been certified by Physikalisch-Technisch~ Bundesanstalt. Major issue in this procedure is precise detection of the applanated surface (3,06 mm following Goldmann's hypothesis), and precision of the force necessary to achieve the applanation desired.

Summary: Automatic self tonometry is a decisive means for early detection and follow up of the glaucomas.

### **Astroculture™**

The Astroculture™ equipment flew on the USML-1, and SPACEHAB 1, 2 and 3 missions. During these flights lighting, humidity, acidity-alkalinity balance (pH), nutrient supply and composition, and carbon dioxide and atmospheric contaminant subsystems were successfully evaluated. Technology progress from previous flights has resulted in several commercial products for use on Earth. The lighting subsystem has provided technology to develop a unique lighting system for photosynthesis research and for use in some medical applications. Other commercial products from Astroculture technology include dehumidification/humidification units, water-efficient irrigation systems and energy-efficient lighting systems for large scale commercial nurseries.

### **Blood Pressure Control**

Engineering Development Laboratory developed a system for the cardiovascular study of weightless astronauts during Spacelab missions. This was designed to aid people with congestive heart failure and diabetes. While in space, astronauts' blood pressure rises, heart rate becomes unstable, and there are sometimes postflight lightheadedness or blackouts. The Baro-Cuff studies the resetting of blood pressure. When a silicone rubber chamber is strapped to the neck, the Baro-Cuff stimulates the carotid arteries by electronically controlled pressure application. Blood pressure controls in patients may be studied.

### **Electrostatic Levitation**

The pioneering work that was done using the TEMPUS electromagnetic levitator on the 1997 Material Science laboratory (MSL-1R) mission demonstrated the usefulness of being able to levitate a small sample quiescently. The desire to continue such experiments on the ground led to the development of the Electrostatic Levitator (ESL), now in operation at the NASA Marshall Space Flight Center (Fig.1). The ESL is restricted to much smaller particles than can be levitated in microgravity and the types of

data that can be extracted is somewhat limited, but the thermophysical properties measurements made on  $\text{Zr}_{57}\text{Nb}_5\text{Ni}_{12.6}\text{Al}_{10}\text{Cu}_{15.4}$  and  $\text{Ti}_{34}\text{Zr}_{11}\text{Al}_{7.5}\text{Cu}_{47}\text{Ni}_8$  in the undercooled state helped Bill Johnson at Liquidmetal Technology design metal glass-forming systems with cooling rates slow enough to form metallic glasses in bulk quantities [1]. These bulk metallic glasses (BMGs) have remarkable elastic properties (Fig. 2) and are finding commercial uses in sporting goods, electronic casings, medical devices, corrosion-resistant coatings, and various military applications.

Rick Weber, Containerless Processing, Inc., also used the MSFC Electrostatic Levitator to develop a new class of laser host glasses consisting of rare earth oxides and alumina [2].

A version of the ESL has recently been installed in the MUCAT sector of the beam line at the Advanced Photon Source for real-time studies of solidification of high temperature materials. Ken Kelton (Washington University, St. Louis) was able to show that metals tend to nucleate in the form of an icosahedral structure [3]. Since icosahedrons cannot fill a three-dimensional space, the embryonic nuclei must reform into a hexagonal or cubic structure that can fill three-dimensional space in order to form a bulk solid. These studies have helped explain the relatively high nucleation barrier in metals that has puzzled theorists for years.

1. See Liquidmetal Technologies Home Page, [www.Liquidmetal.Com/Index/](http://www.Liquidmetal.Com/Index/)

2. See Containerless Research, Inc., Glass Products Division Homepage [www.Containerless.Com/Realglass.Htm](http://www.Containerless.Com/Realglass.Htm). See Also NSF Press Release, NSF PR 03-119. October 7. 2003, "New Glass Can Replace Expensive Crystals In Some Lasers And Bring High Power To Small Packages."

3. Kelton, K. F., Lee, G. W., Gangopadhyay, A. K., Hyers, R. W., Rathz, T. J., Rogers, J. R., Robinson, M. B., And Robinson, D. S., First X-Ray Scattering Studies On Electrostatically Levitated Metallic Liquids: Demonstrated Influence Of Local Icosahedral Order On The Nucleation Barrier, Phys. Rev. Lett. 2003, 90(19), 195504:1-4

## LED-Based Lighting for Medical Applications

One of NASA's life science research goals is to better understand plant growth in microgravity. NASA found that it was difficult to use traditional plant growth light sources in space because they require considerable power and turn much of it into heat. This means that the experimental system has to have good controls to eliminate temperature variance that could affect plant growth results.

The Wisconsin Center for Space Automation & Robotics proposed using light emitting diodes (LEDs) as the photon source for plant growth experiments conducted in space. This idea generated considerable discussion, as the prevailing view among experts was that LEDs could not provide the necessary wavelengths and intensities needed for photosynthesis. The Wisconsin group teamed with Quantum Devices, Inc. to develop an LED system that was successful in supporting photosynthesis. The Wisconsin Center then produced the Astroculture3 a plant growth chamber that incorporated the LED light source and has flown on 7 shuttle missions.

An ongoing medical objective is to find better ways to remove cancerous tumors. A promising mechanism for treating inoperable tumors is to use light-sensitive, tumor-treating drugs. This Photodynamic Therapy (PDT) approach allows physicians to activate the drug only in the tumor. The most common used light source to activate a tumor drug is a laser. The problem with a laser is that it is expensive, bulky, and somewhat unreliable in a surgical environment. What is needed is a small, highly reliable light source that could provide specific energies and intensities.

A NASA Small Business Innovative Research award was given to Quantum Devices, Inc. and Harry Whelan, MD to develop an LED light source that could be used in a surgical environment as the photon source for PDT. As a result of over 5 years of intensive research and experimentation a functioning LED probe has been developed and has received FDA approval for use in patients who exhausted all other

means of treatment. To date the LED treatment has focused on skin cancers and brain tumors. Several successful cases have been reported.

Another NASA need has led to yet another possible application for the use of LEDs. In microgravity wounds heal much more slowly. The Wisconsin team has conducted experiments that demonstrate that LEDs have helped human-cell cultures grow 5 times faster than normal. These results have led to a research program that is testing LEDs capability to increase wound healing. If the experimental results are promising, human clinical trials will follow. The outcome could be a new medical instrument that can be used on long duration space flights to treat astronaut's wounds as well as having a new technology on earth to treat burns, sport's injuries, etc.

### **Lightweight Ambulatory Physiological Monitoring System**

The Autogenic-Feedback System-2 (AFS-2) is a biomedical instrumentation package that was designed and built at Ames Research Center for use during the September 1992 Spacelab-J (STS-47) mission. The AFS-2 performed successfully during that mission and was rated by members of NASA's Astronaut Office as the best instrument of its kind because of its high data quality, ease of operation, and minimal time for setup and operation. Because of its small size, this system offers comfort and mobility greater than those of other systems developed for the same purpose.

The AFS-2 is a self-contained, battery-powered, ambulatory, physiological monitoring system. It can continuously monitor, display, and record up to nine channels of physiological data for up to twelve hours on a single change of batteries. Sensors and transducers, placed in various locations on the subject (e.g., an astronaut), monitor the physiological signals. A wrist display unit displays the subject's physiological parameters in numerical form. The AFS-2 records all acquired information on a data instrumentation tape by use of a modified nine-channel frequency-modulation data recorder. Researchers can thereafter play back the tape to extract the data and analyze the subject's performance.

By use of various sensors and transducers (see figure), the AFS-2 monitors the following parameters:

- Blood Volume Pulse (BVP) — A miniature infrared emitter-detector pair mounted in a ring that is worn on the small finger of the left hand detects changes in blood-vessel volume in the hand.
- Skin Temperature (TEMP) — A miniature sensor, mounted in the same ring used for measuring BVP, measures the temperature of the skin.
- Skin Conductance Level (SCL) — A pair of electrodes mounted on the left wrist monitors changes in the electrical conductivity of the skin.
- Respiration (RESP) — A thin piezoelectric film sandwiched between two flexible rubber housings and strapped across the diaphragm measures both the range and frequency of respiratory cycles.
- Electrocardiography (ECG) — Three standard electrodes placed at the AvR, AvL, and AvF chest nodes monitor the electrical impulses of the heart.
- Acceleration (ACCEL) — An accelerometer attached to a flexible cotton headband measures the motion of the subject's head along three axes.

The AFS-2 operates in either of two display modes: one for treatment subjects and one for control subjects. In the treatment mode, the wrist display unit displays all indications of system status, malfunctions, and monitored physiological data. In the control mode, only system-status and malfunction indications are visible to the subject.

The data recorder receives the BVP waveform, skin temperature, skin conductance, respiration waveform, ECG waveform, acceleration signals, time and date, specified events, and session timing data and records them on a standard-sized magnetic data instrumentation cassette tape. The cassette can be played through a separate playback unit for subsequent analysis at speeds up to 32 times the speed at which the data were recorded.

The AFS-2 is divided into three general subsystems: the wrist display unit, the belt assembly, and the garment and cable harness assembly. The wrist display unit, fastened to the left sleeve of the AFS-2 garment,

includes a small liquid-crystal display device that presents physiological and system-status information to the user. The belt assembly is worn around the waist and over any clothing. The belt assembly comprises belt electronic circuitry (signal-conditioning amplifiers, an analog-to-digital converter, and a microcontroller), a battery pack, the data recorder, and an interface cable. A modular design distributes the weight of the belt assembly evenly around the waist. The components of the system are interconnected through easily mated and demated connectors; this design feature minimizes the time needed for donning the AFS-2. The battery pack supplies power to all subsystems, including the data recorder. The battery pack features a clip-on design for fast and easy replacement of exhausted batteries. The AFS-2 garment assembly is worn on the upper body and covers the torso and left arm. The garment assembly comprises the garment, the cable harness, the respiration transducer, the accelerometer, and the ring transducer.

## **Nanoscale Liquid Jets Shape New Business**

Early on in his 6-year NASA career, Emanuel Barros led the development of re-flown flight hardware for an award-winning Spacelab project called “NeuroLab.” This project, the sixteenth and final Spacelab mission, focused on a series of experiments to determine the effects of microgravity on the development of the mammalian nervous system. In 1999, Barros transitioned into a project supporting the development of International Space Station research hardware, and was considered a nanotechnology expert among many of his peers in the Life Sciences Division at Ames. Fully satisfied with his accomplishments at NASA, Barros departed Ames in 2002 to succeed in nanoscale manufacturing as the chief technical officer and acting chief executive officer of NanoMatrix. NanoMatrix’s proprietary machining services and equipment are capable of performing sub- micron etching, drilling, welding, cutting, and shaping, all with nanometer precision. The company’s work represents an alternative method for developing and building small-scale electronic, mechanical, and medical devices, among other applications. To date, the company’s biggest application involves film adhesion. NanoMatrix developed a process for a client that allows its next generation of films to adhere to a glass surface, such as a window or a lens, without affecting clarity.

## **Sense of Touch**

Optical technology developed to operate the first robot in space has led to commercially available controllers for computer aided design work, visual simulation applications, and to increase the enjoyment from personal computer games.

Logitech Incorporated of Fremont, California issued versions of an advanced three-dimension (3-D) controller in 1997, a device that permits users to intuitively and precisely manipulate and navigate objects through virtual worlds.

The controller has a far-reaching history that extends, literally, into space, a result of years of work by space and robotics industries. Predecessor hardware was built under contract with the Jet Propulsion Laboratory and was tasked to remotely control a robot aboard a NASA Space Shuttle/Spacelab mission in 1993. That technology has now been adapted for a wide range of tasks from mechanical design, video animation, and virtual reality design up to robotic and medical microscope control.

As an example, worldwide customers of the 3-D input device, called MAGELLAN/Spacemouse, include BMW, Chrysler, Toyota, Audi, Daimler-Benz, Porsche, and Zeiss, among many others. Engineers have found the controller particularly helpful in designing complex products, be they automobiles or airplanes. Surgeons have adopted the device to position microscopes without disturbing a surgical procedure.

A patented optical absolute measurement system imbues the 3-D controller with its impressive abilities. This opto-electronic sensor technology provides six degrees of freedom in high precision and impressive reliability.

Leading manufacturers of robots have equipped their control panels with the 3-D input tool in order to provide a powerful and reliable human/machine interface for teaching and guiding robots in the six degrees of freedom.

The controller works by providing a spring-mounted puck which the user maneuvers in order to provide motion and rotation information to the computer. In 3-D applications, the controller is used in conjunction with a 2-D mouse. The user positions an object with the 3-D controller, while working on the object using a mouse. An analogy would be a workman holding an object in his left hand and working on it with a tool held in his right hand. By eliminating the necessity of going back and forth to a computer menu, the 3-D controller increases productivity substantially in most three-dimensional applications.

Thanks to fingertip operation, the controller translates a user's sense of touch into dynamic movement of objects in those six degrees of freedom (X, Y, and Z axes, pitch, yaw, and roll). Features of the compact controller unit include freely programmable buttons to customize a user's preference for motion control and sensitivity.

Logitech has also devised a digital game controller, an input device that lets its user move realistically in all directions. Unlike a joystick that emphasizes the physical action of a controller's hand to play a game, the digital game hardware, in a sense, connects your mind to the action. With one hand, a player controls a rubber puck that can be raised, lowered, turned, and twisted to achieve 360-degrees of movement in all directions. The other hand manages the programmable buttons.

Sophisticated combination maneuvers, such as flips and spins, can be performed using the controller without touching a computer keyboard. The speed of movements can be easily controlled, with high accuracy. Four levels of customization are offered, permitting each player the ability to create and save different configurations for each game.

Compatible with a variety of personal computer systems and entertainment software packages, the digital controller offers players the experience of being "inside" the game. With its six-degrees-of-freedom capabilities, the product is virtual reality-ready, as this new game category emerges, while offering players added realism in a broad variety of games currently on the market, notes Logitech.

By matching space program technology with a computer controller, a new dimension to game playing is attained--a winning combination where a fast mind, instead of a fast hand, is a hands-down favorite.

## **Space Age Training**

Teledyne Brown developed a computer-based interactive multimedia training system for use with the Crystal Growth Furnace in the U.S. Microgravity Laboratory-2 mission on the Space Shuttle. Teledyne Brown commercialized the system and customized it for PPG Industries Aircraft Products. The system challenges learners with role-playing scenarios and software-driven simulations engaging all the senses using text, video, animation, voice, sounds and music. The transfer of this technology to commercial industrial process training has resulted in significant improvements in effectiveness, standardization, and quality control, as well as cost reductions over the usual classroom and on-the- job training approaches.

## **Vehicle Tracking System**

Tracking information originally used on board Space Shuttle Spacelab missions now helps track vehicles on Earth. The commercial spinoff of the tracking software allows vehicles to transmit a signal back to a home base. Municipalities today use the software to track and reassign emergency and public works vehicles. It also is used by vehicle fleet operations, such as taxis, armored cars and vehicles carrying hazardous cargo.

## APPENDIX F - MISSION LIST AND DESCRIPTIONS

### Spacelab Missions in chronological order.

Year	Mission	Payload	Discipline	Hardware
1981	STS-2	Office of Space and Terrestrial Application (OSTA)-1	Earth Observations, Life Science	Pallet
1982	STS-3	Office of Space Science (OSS)-1	Multidisciplinary	Pallet
1983	STS-7	Office of Space and Terrestrial Application (OSTA)-2	Physical Science	MPRESS
1983	STS-9	Spacelab-1	Multidisciplinary	Pallet & Module
1984	STS-41D	Office of Applications and Space Technology (OAST)-1	Technology	MPRESS
1984	STS-41G	Office of Space and Terrestrial Application (OSTA)-3	Atmospheric Science, Earth Observations	Pallet & MPRESS
1985	STS-51B	Spacelab-3	Multidisciplinary	Module & MPRESS
1985	STS-51F	Spacelab-2	Multidisciplinary	Pallet
1985	STS-61A	Spacelab-D1	Physical and Life Science	Module
1985	STS-61B	EASE/ACCESS	Technology	MPRESS
1986	STS-61C	Microgravity Science Laboratory (MSL)-2	Physical Science	MPRESS
1990	STS-35	ASTRO-1	Astronomy	Pallet & IPS
1991	STS-40	Spacelab Life Sciences 1 (SLS-1)	Life Science	Module
1992	STS-42	International Microgravity Laboratory-1 (IML-1)	Physical and Life Science	Module
1992	STS-45	Atmospheric Laboratory for Applications and Science 1 (ATLAS-1)	Multidisciplinary	Pallet
1992	STS-47	Spacelab-J (SL-J)	Physical and Life Science	Module
1992	STS-50	United States Microgravity Laboratory (USML)-1	Physical and Life Science	Module
1992	STS-52	United States Microgravity Payload (USMP)-1	Physical Science	MPRESS
1993	STS-56	Atmospheric Laboratory for Applications and Science 2 (ATLAS-2)	Atmospheric Science, Solar Physics	Pallet
1993	STS-55	Spacelab-D2	Multidisciplinary	Module
1993	STS-58	Spacelab Life Sciences 2 (SLS-2)	Life Science	Module
1994	STS-59	Space Radar Laboratory (SRL-1)	Earth Observations	Pallet & MPRESS
1994	STS-62	United States Microgravity Payload (USMP)-2	Physical Science, Technology	MPRESS
1994	STS-65	International Microgravity Laboratory-2 (IML-2)	Physical and Life Science	Module
1994	STS-64	LIDAR In-space Technology Experiment (LITE)	Atmospheric Science	Pallet
1994	STS-66	Atmospheric Laboratory for Applications and Science 3 (ATLAS-3)	Atmospheric Science, Solar Physics	Pallet
1994	STS-68	Space Radar Laboratory (SRL)-2	Earth Observations	Pallet & MPRESS
1995	STS-67	ASTRO-2	Astronomy	Pallet & IPS
1995	STS-71	Spacelab-Mir	Physical and Life Science	Module
1995	STS-73	United States Microgravity Laboratory (USML)-2	Physical and Life Science, Technology	Module

Year	Mission	Payload	Discipline	Hardware
1996	STS-75	United States Microgravity Payload (USMP-3)	Physical Science	MPSS
1996	STS-78	Life and Microgravity Spacelab (LMS)	Physical Science, Life Science, Technology	Module
1997	STS-83	Microgravity Science Laboratory (MSL-1)	Physical Science, Life Science, Technology	Module
1997	STS-87	United States Microgravity Payload (USMP-4)	Physical Science, Technology	MPSS
1997	STS-94	Microgravity Science Laboratory (MSL-1R) (reflight)	Physical Science, Life Science, Technology	Module
1998	STS-90	Neurolab	Life Science	Module

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