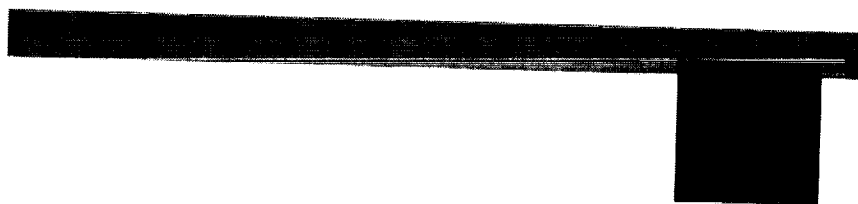NASA
Technical Memorandum 104788

Johnson Space Center

Research and Technology

Annual Report 1993

About the cover...

The illustration is composed of images that represent some of NASA's recent technical and scientific achievements—achievements that are a direct result of NASA's goal of using research and exploration involving humans to define and develop opportunities for research and technology that yield economic and intellectual benefits. The images for the cover were selected by Dr. Kumar Krishen; the illustration was created by artist Vicki Cantrell of the Management Services Division.
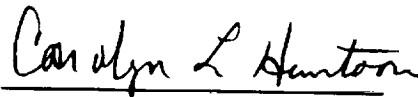
Foreword

The mission of the Johnson Space Center (JSC) is to advance the national capability for human exploration and utilization of space. Together with industry and academic institutions that support us, we overcome the challenges of distance and hostile environments to advance knowledge, inspire humanity, and broaden the human experience.

As the lead center for U. S. human space flight programs, we design, develop, and test spacecraft and associated systems for human space flights, select and train astronauts and mission specialists, and participate in medical, life sciences, technology, and engineering experiments. JSC conducts advanced research and development projects in medical and life sciences, materials technology, robotics and automation, communications and data processing, propulsion and power, avionics, guidance and control, human support, and software and computer technology.

Our strategic goals include strengthening and enhancing NASA as a recognized world-class technical and scientific organization through space research and exploration involving humans and by defining and developing opportunities for research and technology applications that yield economic and intellectual benefits. We emphasize dual development opportunities and provide interfaces to commercial entrepreneurs to facilitate beneficial development, while maintaining focus on specific technical challenges required by NASA space programs.

I believe that sharing research and technology accomplishments through this report, and initiating and continuing collaborations with other NASA centers, government agencies, academia and research communities, and industry is crucial to our strategy. Our goal is to be responsive to the needs of our partners in industry, academia, and government and to provide relevant returns to the American people. In this regard, your comments and suggestions will be highly appreciated and should be mailed to Mr. Hank Davis, Director of Technology Transfer and Commercialization, NASA Johnson Space Center, Houston, TX 77058, (713) 483-0474.

Carolyn L. Huntoon
Director

Introduction

Recently, NASA identified five strategic enterprises in its Strategic Plan. These were: Mission to Planet Earth (MTPE), Aeronautics, Human Exploration and Development of Space (HEDS), Scientific Research, and Space Technology. Each of these enterprises addresses a specific need.

Together with other global efforts, NASA's MTPE will provide information on Earth resources and the environment. These data will enable a model to be built of the way humans and other organisms affect the Earth's environment. NASA also works closely with U.S. industries, universities, and other Government agencies to promote U.S. preeminence in aeronautics. Sustained NASA advances in aeronautics and technology are needed to help assure the Nation's future competitiveness in industry. The HEDS enterprise is devoted to gaining knowledge and deriving terrestrial benefits through the exploration, use, and development of space. Specific areas of interest include transportation, the survey and characterization of space and planets, and living and working in space and on other planets. The Scientific Research enterprise looks into ways to acquire knowledge about the universe, matter, and the evolution of life. It achieves this by studying the space environment and the effect of that environment on biological and physical processes. The Space Technology enterprise deals with technological advances and their application to the space and commercial sectors. New techniques and technologies derived from space research can significantly contribute to the international competitiveness of U.S. industries. Through working with U.S. industries and with other Government agencies to develop dual-use technologies, NASA plans to help stimulate the national economy.

NASA's aims are, of course, those of the Johnson Space Center (JSC). JSC's mission is to boldly expand human presence in space and, in so doing, to provide opportunities to invest in America's future and to benefit all humankind. By overcoming the challenges of distance and hostile environments, JSC expands the frontier of space, advancing knowledge, inspiring humanity, and broadening the human experience. JSC uses the unique environment and resources of space to achieve both economic and intellectual benefits. This Center primes the engine of commerce to open the frontier of space to the full range of human activities. JSC's strategic goals include strengthening and enhancing the Center into a recognized world-class technical and scientific organization for the conduct of space research and human exploration and defining and developing opportunities for research and technology applications that will yield substantial economic and intellectual benefits. As part of its strategy to carry out these goals, JSC continues to develop in-house projects — such as flight hardware design, development, test, and evaluation projects; Space Shuttle and Space Station flight experiments; human factors research; and space science research — that support the five NASA enterprises and in turn provide more hands-on experience and reinvigorate all JSC technical and administrative organizations.

In these endeavors, JSC emphasizes dual-development opportunities. Such opportunities provide an interface to commercial entrepreneurs that facilitates the commercialization of technologies while maintaining a focus on specific technical challenges required by NASA space programs. JSC's general thrust, therefore, is to develop partnerships with industry, academia, and Government — partnerships that will support and encourage private enterprises in the utilization and commercialization of space technology.

This report summarizes JSC's Research and Technology Operating Plan (RTOP) program accomplishments for 1993. Through this report JSC communicates its accomplishments, both inside and outside the Agency, as well as informs Headquarters' program managers and their constituents of significant results that show promise for future Agency programs. Although not inclusive of all research and technology efforts, the report does present a comprehensive summary of JSC projects in which substantial progress was

made. The principal investigators' (PIs) and the technical monitors' (TMs) names appear at the beginning of each project description. These are followed by the appropriate JSC mail code or by company or university affiliations. Funding sources and technology focal points are identified in the index.

This report is organized in four sections as follows:

The **Life Sciences** section contains descriptions of projects aimed at understanding at a fundamental level the effects of space environment on humans and developing countermeasures for those that cause adverse effects. Knowledge of how microgravity affects biological systems has been significantly advanced through results obtained from the 1991 Spacelab Life Sciences (SLS-1) mission, the 1992 international Spacelab (IML-1 and SL-J) missions, and the 1993 Spacelab Life Sciences (SLS-2) mission. Results from the SLS-1 mission indicate that space flight produces an increase in heart rate, heart size, and cardiac output—presumably in response to the initial increase in central blood volume caused by fluids shifting from the lower extremities toward the torso. Ground-based activities in microbiology and water treatment this year are contributing to the technology required to monitor, service, and decontaminate the Space Shuttle's water system during flight. This is particularly important for spacecraft that will be used for long missions, during which long-term microbial contamination and biofilm formation in the water storage and distribution systems are likely. A bioreactor system was developed that incorporates a phase-contrast microscope coupled to automated image analysis. This system enables the biofouling process to be monitored and allows candidate chemical treatments to be evaluated. Ground-based cell culture systems are being expanded for use as models to study the biological effects of radiation to estimate the risk of radiation exposure during space missions and habitation. Progress continues in understanding the physiological changes associated with space travel and in developing potential countermeasures for deleterious effects. Significant progress was made during 1993 in the scoping of energy expenditure

during space flight. As a result, more accurate food patterns are being implemented for Shuttle flights.

Highlights of the **Solar System Sciences** section include: (1) fabrication of instrumentation to detect volatiles in the soil of planetary surfaces; (2) two studies related to detecting and analyzing orbital debris; (3) two separate studies to spectroscopically detect water and organic material on asteroids; (4) the use of a tether to generate electricity and remote charge from a spacecraft in Earth orbit; (5) a study of synthetic soils to enable the growth of plants in space; and (6) the fabrication and testing of a radiation dosimeter for inclusion on a Russian spacecraft to Mars.

The **Human Support Technology** section contains a variety of disciplines ranging from biomechanics to intelligent computer programs that will aid in training astronauts and mission controllers. The common goal of all these disciplines is to make crewed space flight safer and more efficient. The common theme of the work in this area is to use computerization to increase the productivity of humans in space. Two projects this past year supported repair of the Hubble Space Telescope (HST). One of these projects incorporated a virtual environment to train over 150 members of the flight team in generating task analysis reports. The second project produced a virtual reality environment of the HST to train astronauts and mission control personnel.

The objective of **Space Technology** development at JSC is to enhance the performance of human spacecraft systems and to enable efficient human exploration and development of space. JSC continued to make excellent progress in regenerative life support technology by concentrating efforts on establishing ground-based test-beds and analytical models for demonstrating the feasibility of combining physiochemical and biological components into an integrated life support system. A broad spectrum of programs is being pursued in robotics systems and advanced automation technology. Tasks under way in dexterous on-orbit grasping and manipulation will provide new capabilities for Space Shuttle Orbiter and

international Space Station robotic servicing and maintenance. Two advanced automation technology tasks have been undertaken to increase the efficiency of spacecraft ground support operations. These tasks include the development of an expert system for managing orbital rendezvous dynamics, and a new, innovative approach to real-time modeling of spacecraft systems in which the effects of operating procedures can be modeled as part of a failure modes and impacts analysis. Curtailment of space technology resources in the short term is reflected through the reduced number of projects in this area.

Several JSC organizations have provided support in developing this report. Most notably, contributions were made by the Center Operations, Information Systems, Space and Life Sciences, Mission Operations, and Engineering Directorates. Scheduling of this report provides a formidable challenge because most of the work was to be completed during December 1993. The contributors are, therefore, commended for their timely response.
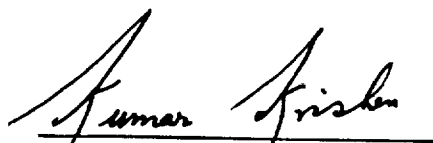
The colleagues listed below coordinated specific sections of this report and provided the summaries preceding their sections. Detailed questions should be directed to me, to the section coordinators, or to the PIs listed in the index.

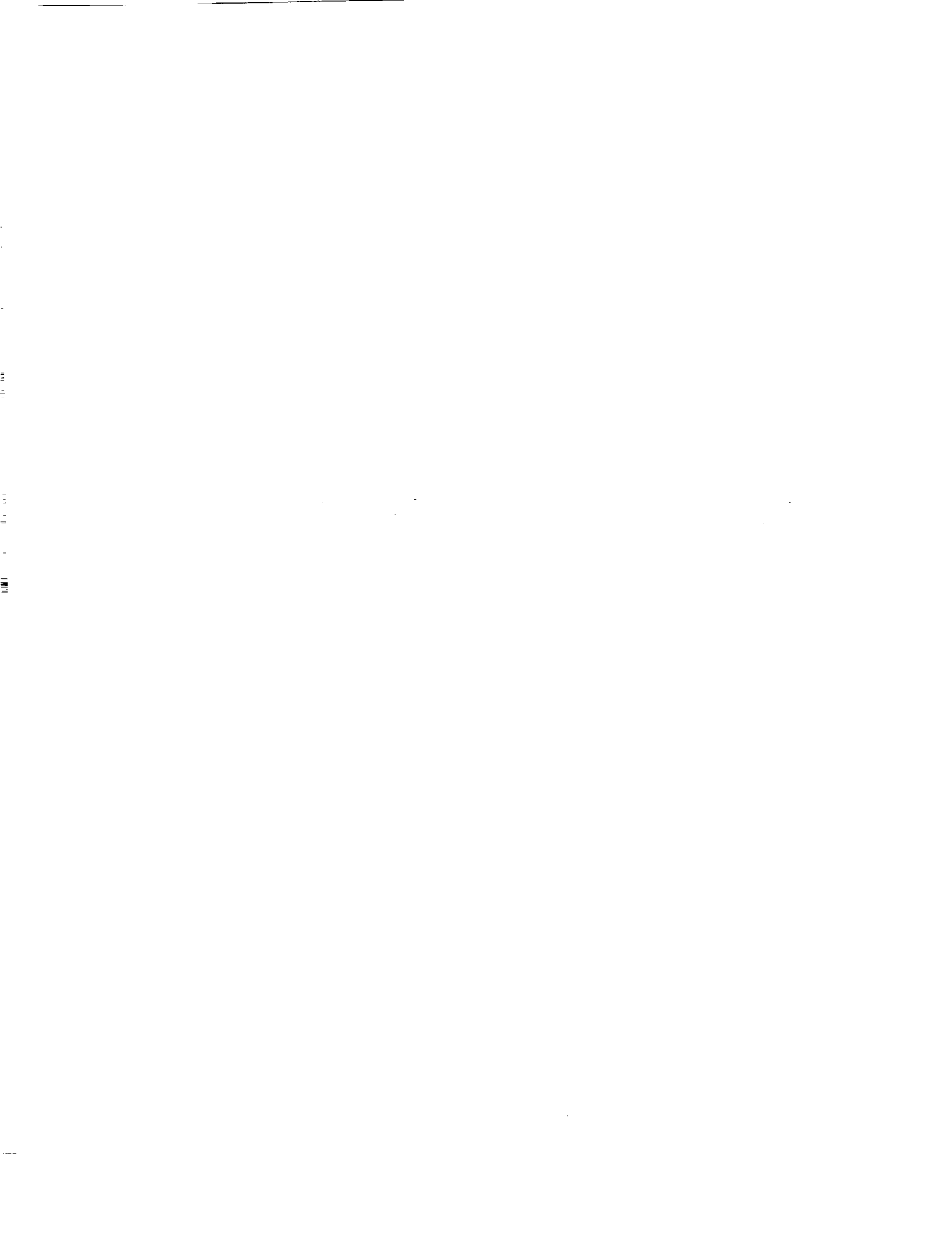Steven Gonda, Ph.D. (code SD)
Life Sciences
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JSC Chief Technologist

Contents

Section I

Life Sciences

Summary

Life Sciences Summary

NASA's Lead Center for Life Sciences, JSC, continues to develop resources and conduct scientific investigations that will serve as the underpinnings of the human space program. Knowledge of how microgravity affects biological systems has been significantly advanced through the results obtained from the 1991 Spacelab-Life Sciences (SLS-1) miss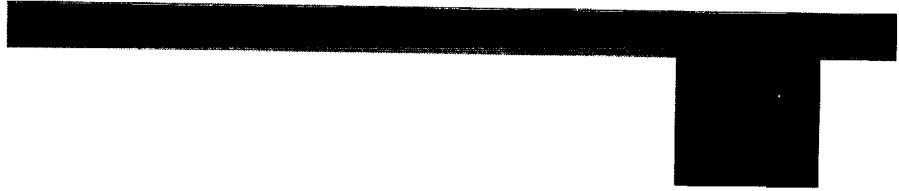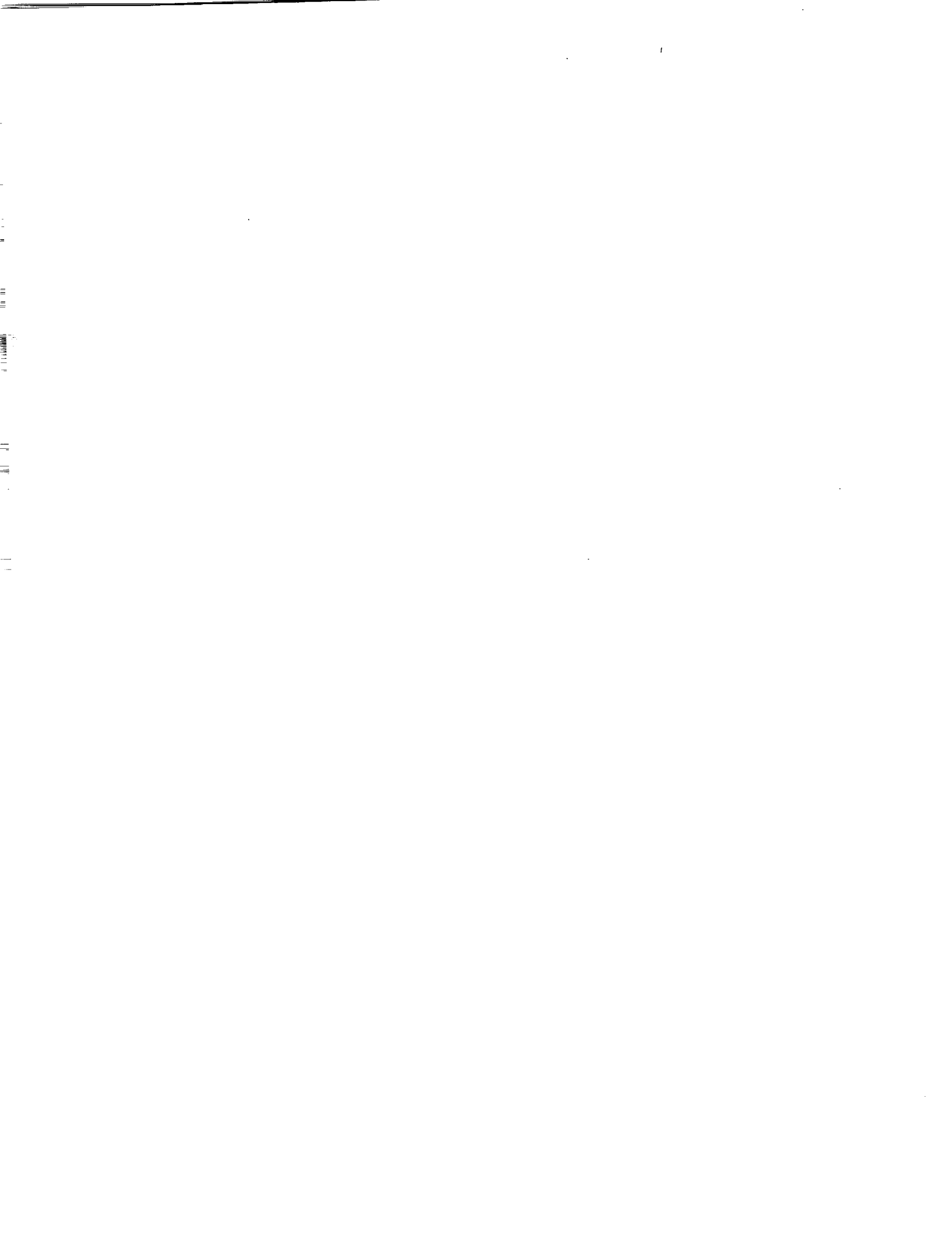ion, the 1992 international spacelab (IML-1 and SL-J) missions, and continues with the successful completion in 1993 of the Spacelab-Life Sciences (SLS-2) mission.

The SLS-2 package of experiments was assembled to provide a cohesive set of investigations on physiological function in microgravity. The 14 interrelated experiments aboard SLS-2 test scientists' current hypotheses of the way various physiological systems (cardiovascular, cardiopulmonary, fluid-electrolyte, endocrine, hematological, musculoskeletal, and vestibular) respond to weightlessness. SLS-2 will compare the physiological changes measured in humans and in rodents to discern differences and similarities in the adaptive processes of two different species.

Results from the SLS-1 mission indicated that space flight produces increases in heart rate, heart size, and cardiac output, presumably in response to the initial increase in central blood volume caused by fluids shifting from the lower extremities toward the torso. Mechanisms still not understood cause the kidneys and the endocrine system to reduce the quantity of fluids and electrolytes, leading to a reduction of blood volume and decreases in both heart volume and exercise performance.

The upcoming Shuttle-Mir Program represents a new era of international collaboration in space. Astronauts and cosmonauts will work together on the U.S. Space Shuttle, and later on the Russian Mir Space Station, to address environmental and medical sciences issues on a long-duration space platform. Environmental monitoring aboard Mir will provide important information about the environmental changes that occur during the habitation of a spacecraft, perhaps the ultimate closed system, over a period of 7 years. The first of three phases in this program, consisting of multiple Shuttle flights to Mir, will provide valuable test data that will greatly reduce technical risks associated with building and operating the international Space Station, as well as providing unique opportunities for extended investigational activities. The second phase combines U.S. and Russian hardware to create a new, advanced orbital research facility. The third phase represents completion of the construction of the international Space Station, which will then support a permanent human presence. Russian and U.S. scientists are working together to develop integrated studies in disciplines spanning metabolism, cardiopulmonary function, sensory-motor and neuromuscular function, behavior, environmental health, radiation biology, and basic biology.

Ground-based activities in microbiology and water treatment this year are contributing to the technology required to monitor, service, and decontaminate the Space Shuttle's water system during flight. This is particularly important for spacecraft that will be used for long missions, in which long-term microbial contamination and biofilm formation in the water storage and distribution systems are likely. A bioreactor system was developed that incorporates a phase-contrast microscope coupled to automated image analysis; this system enables the biofouling process to be monitored and allows candidate chemical treatments to be evaluated. Several chemical modalities were evaluated, and treatment with iodine and ozone were found to be more effective than hydrogen peroxide in removing biofilm.

Ground-based cell culture systems are being expanded for use as models to study the biological effects of radiation and to estimate the risk of radiation exposure during space missions and habitation. The Radiation Biology Laboratory at JSC is using an in vitro human epithelial-cell culture model to quantify the relationship between the relative biological effectiveness of charged particles for oncogenic transformation and the linear energy transfer of these particles. Exposing normal human epithelial cells to heavy ions was observed to induce neoplastic transformation and the formation of 3-D tumor spheroids.

Microgravity affords a unique environment in which mammalian cells, cultured under the appropriate conditions, form tissue-like structures that mimic the structure and function of tissue formed in vivo. Bioreactor systems designed at JSC can provide a similarly quiescent environment by simulating some of the physical aspects of microgravity. Human colonic carcinoma cells cultured in the JSC bioreactor on Earth have formed three-dimensional tissue-like structures and showed enhanced growth factor production.

Progress continues in understanding the physiological changes associated with space travel and in developing potential countermeasures for deleterious effects. A noninvasive method of determining energy expenditure, based on the use of stable (nonradioactive and nontoxic) isotopes of hydrogen (^{2}H) and oxygen (^{18}O), was found to be useful for measuring energy expenditure during space flight. The Space Shuttle cuisine can now be selected based upon patterns of carbohydrate, fat, and protein intake before, during, and after flight.

The following articles provide more information about these and other significant advances in life sciences research and technology.

Life Sciences

Significant Tasks

Optical Measurement of Bacterial Adhesion in Water Supply Lines

TM/PI: **D.L. Pierson, Ph.D./SD4**
PI: **D.W. Koenig, Ph.D./KRUG**
   S.K. Mishra, Ph.D./KRUG
Reference: **LS 1**

Spacecraft for use in long missions with humans must have water systems that can deliver water of acceptable quality for consumption and hygienic uses over the anticipated lifetime of the craft. Of major concern for such systems is the control of long-term microbial contamination and biofilm development in the water storage and distribution systems. Biofilms can harbor pathogens as well as microbial strains having resistance factors that could negatively influence crew health.

The means by which spacecraft water systems are disinfected may encourage the development of resistant strains. In fact, bacteria have been present in potable water from the Space Shuttle that are resistant to iodine. Thus, an alternative remediation method is needed to disinfect and remove biofilms from spacecraft water systems. Colonization events and the physiological parameters that will influence bacterial adhesion must be understood to achieve this goal. The limiting factor in developing this technology is the ability to monitor both adhesion events and the effect of biocides on sessile bacteria on a continuing basis.

The primary objective of this project is to assess the adhesion characteristics of bacteria isolated from the potable water systems aboard space shuttles using solid substrates such as glass, stainless steel, and carbon composites. The physiology of sessile bacteria also will be examined to identify any unique characteristics associated with adhesion that affect biocide resistance, production of toxic metabolites, or pathogenicity. Later studies will focus on ascertaining the effect of microgravity on biofilm characteristics.

Sessile organisms usually are monitored by direct enumeration of viable bacteria, indirect enumeration using fluid frictional resistance measurements, colorimeteric viability measurements, or electrical measurements. The method developed in this project uses automated image analysis to monitor the microbe-to-surface attachment process in real time. This method allows description of the ongoing attachment process as well as direct assessment of biocide efficacy against biofilms.

We combined a continuous flow bioreactor with an optical viewing chamber to allow direct enumeration of sessile microbes (fig. 1). The bioreactor provides a constant source of bacteria to the attachment chamber. Downstream from the fermentor and before the attachment chamber, a series of additional ports allows introduction of treatment chemicals and other test compounds. The biofouling process is monitored by phase-contrast microscopy coupled to automated image analysis (fig. 2). This approach allows the biofouling process and subsequent chemical challenges to be videotaped.

The bioreactor controls pH, temperature, and dissolved oxygen (DO), thus providing a uniform bacterial inoculation to the view chamber. Control of volume, mixing, pH, and temperature will allow the system to mimic the many types of environmental scenarios expected within the water systems of spacecraft.

The first experiments will be conducted with iodine-resistant strains of *Pseudomonas* isolated from Shuttle missions. Other organisms that may be used are *Bacillus*, *Staphylococcus*, *Klebsiella*, *Salmonella*, *Streptococcus*, and bacterial strains isolated from the operating simulated spacecraft water system test bed in the JSC Water and Food Analytical Laboratory and the Regenerative Life Support System facility at JSC.

This technology is designed to assess the adhesion characteristics of test organisms and to study the effects of various biocides, enzymes, and biopenetrants on biological deposition. Another goal is to characterize the physiological changes that occur when cells attach to substrates, how these changes correlate to biocide performance, and how attachment affects metabolite production and cell pathogenicity. The long-term goal of this project is to describe novel deposition-control measures that will be environmentally safe and compatible with closed spacecraft environmental and life support systems.
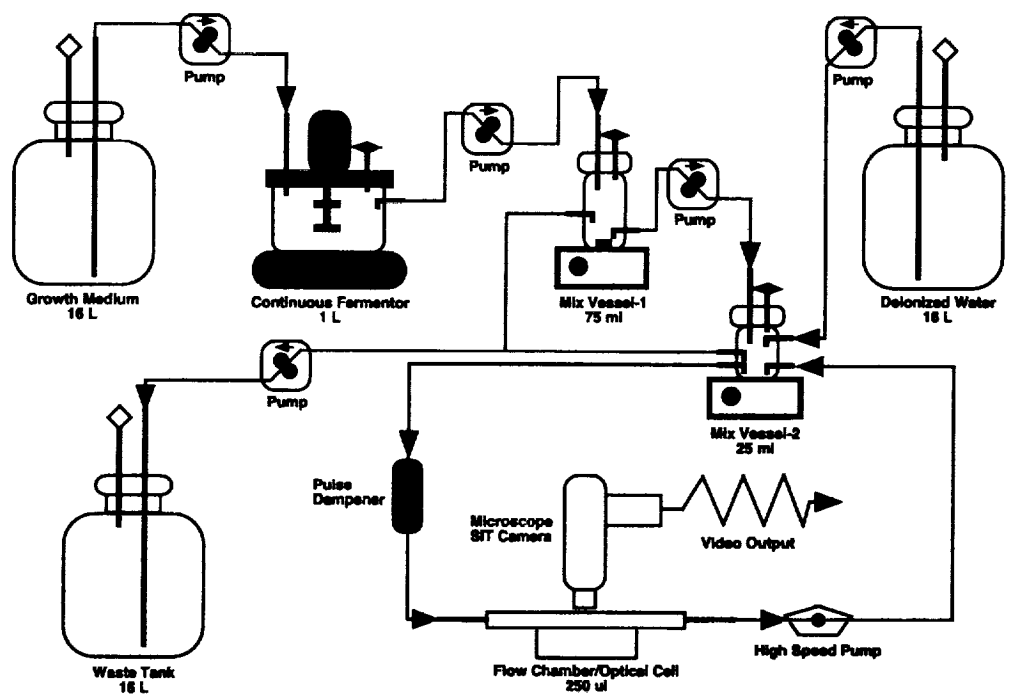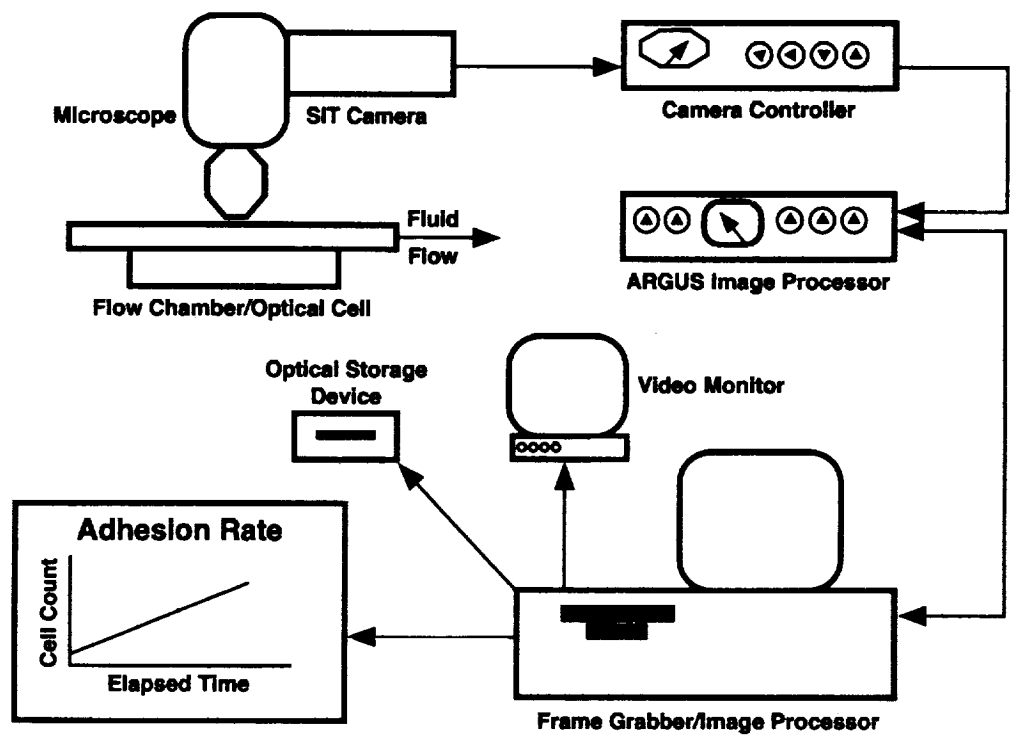
Figure 1.   Continuous bacterial attachment system.

Figure 2.   Image processing system.

Cardiovascular Response to Sympathomimetic Drugs During Head-Down Bed Rest: The Effects of Dietary Sodium and Hydration Status

TM/PI: **Peggy A. Whitson, Ph.D./SD4**
PI: **W. Jon Williams, Ph.D./SD4**
Charles A. Stuart, M.D./
University of Texas Medical
Branch, Galveston, TX
Reference: **LS 2**

Adaptation to microgravity involves several physiological changes that may compromise cardiovascular function upon return to the gravitational environment of Earth. Cardiovascular dysfunction is thought to contribute to orthostatic intolerance (the tendency to become dizzy or faint) after landing. The precise mechanisms are not well understood, but a space-related reduction in plasma volume may be a major contributing factor. In the absence of gravity, blood shifts from the lower extremities toward the chest and head. This fluid shift stimulates pressure sensors in the heart and arteries, which interpret this change as "excess" fluid volume. The "excess" volume is then excreted by the kidneys or redistributed, effectively reducing total plasma volume.

To better understand these physiological changes, we studied the effects of salt consumption on cardiovascular function during 21 days of head-down bed rest (an analog of microgravity). Subjects consumed a diet containing either normal amounts of sodium (2-4 g/day, n = 6) or high amounts of sodium (10 g/day, n = 5). The normal amount of water in the blood (plasma volume) was measured from dilution of radiolabeled serum albumin. Urine output was measured throughout the study. Cardiovascular function was tested by recording heart rate, blood pressure, and cardiac output during the infusion of one of two drugs, phenylephrine (PE) or isoproterenol (ISO). PE constricts blood vessels, resulting in increased blood pressure. ISO acts directly on the heart and blood vessels to increase heart rate and decrease blood pressure.

PE or ISO was infused in an increasing, stepwise fashion. At each infusion step, heart rate, blood pressure, and cardiac output were measured and these measurements were used to calculate total peripheral resistance (TPR), an index of blood-vessel constriction. Statistical analysis revealed that the vascular response to PE was increased throughout bed rest in the normal-salt subjects but not in the high-salt group. The TPR response to ISO was unchanged in the normal-salt group but exaggerated in the high-salt group. In the normal-salt group, urine output declined, and plasma volume was maintained; in contrast, subjects that ate the high-salt diet excreted more urine and lost more plasma volume during bed rest. From these studies, we conclude that:

- Vascular supersensitivity to PE during bed rest (present in the normal-salt but not the high-salt group) may reflect a change in function or density of alpha receptors on the peripheral blood vessels, a decrease in carotid-baroreflex function or both if subjects are well hydrated. The normal vascular response to PE in the high-salt group may be related to their low plasma volume. The exaggerated response to ISO in this group also could be related to low plasma volume, changes in beta receptors on the peripheral blood vessels, or both.

- Subjects who consumed normal amounts of salt during bed rest maintained their plasma volume, probably by decreasing their urine output. The high-salt group lost both plasma volume and larger amounts of water through urine. Thus, dietary sodium can significantly affect hydration status, which in turn can affect the cardiovascular system.

- Manipulating dietary sodium and hydration status may prove to be effective in controlling postflight orthostatic intolerance in astronauts.

These studies have provided physiological and pharmacological evidence of a change in cardiovascular function during 21 days of head-down bed rest. Dietary sodium had significant effects on hydration status and cardiovascular response to sympathomimetic drugs. Characterizing the mechanisms by which these changes appear may contribute to our ability to

minimize orthostatic intolerance after space flight.
Future studies will focus on the hormonal control
of hydration and electrolyte status and their
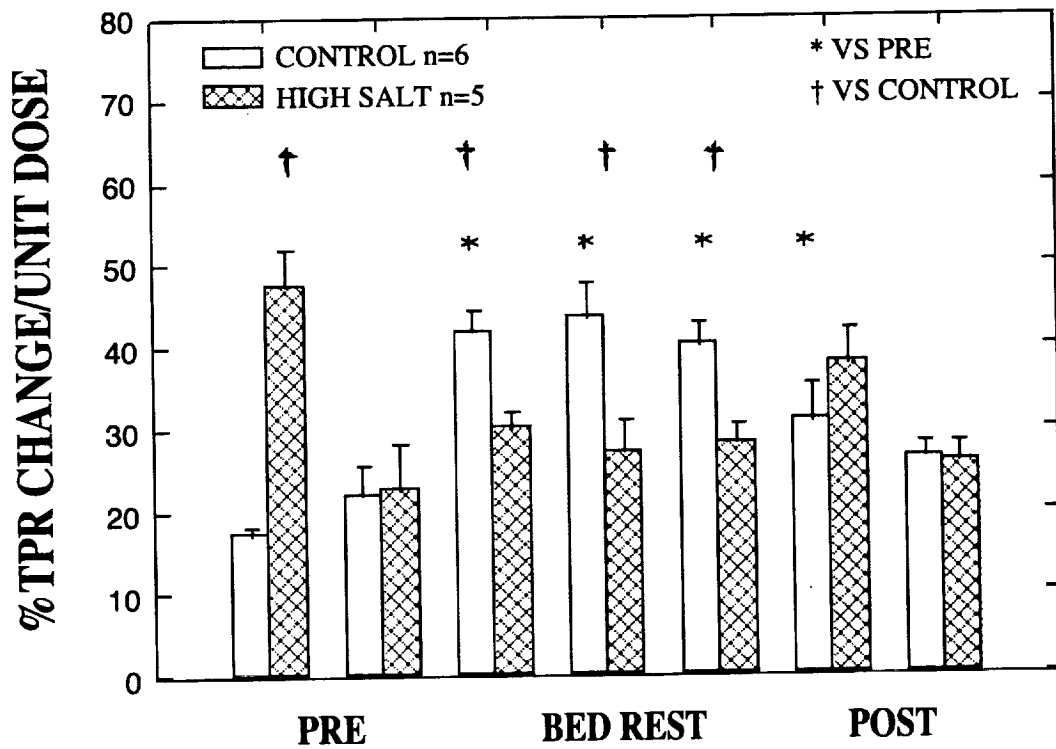contributions to cardiovascular function.

Figure 1.   The pressor response to infusion of PE was significantly (* = p ≤ 0.05) exaggerated in the
normal-salt group (open bars) but not in the high-salt group (hatched bars) during 21 days of
head-down bed rest. The pressor response to PE infusion was also significantly († = p ≤
0.05) different between the two groups.

Figure 2. The depressor response to infusion of ISO was significantly (* = p ≤ 0.05) exaggerated in the high-salt group (hatched bars) but not in the normal-salt group (open bars) during 21 days of head-down bed rest. The depressor response to ISO infusion was also significantly († = p ≤ 0.05) different between the two groups.
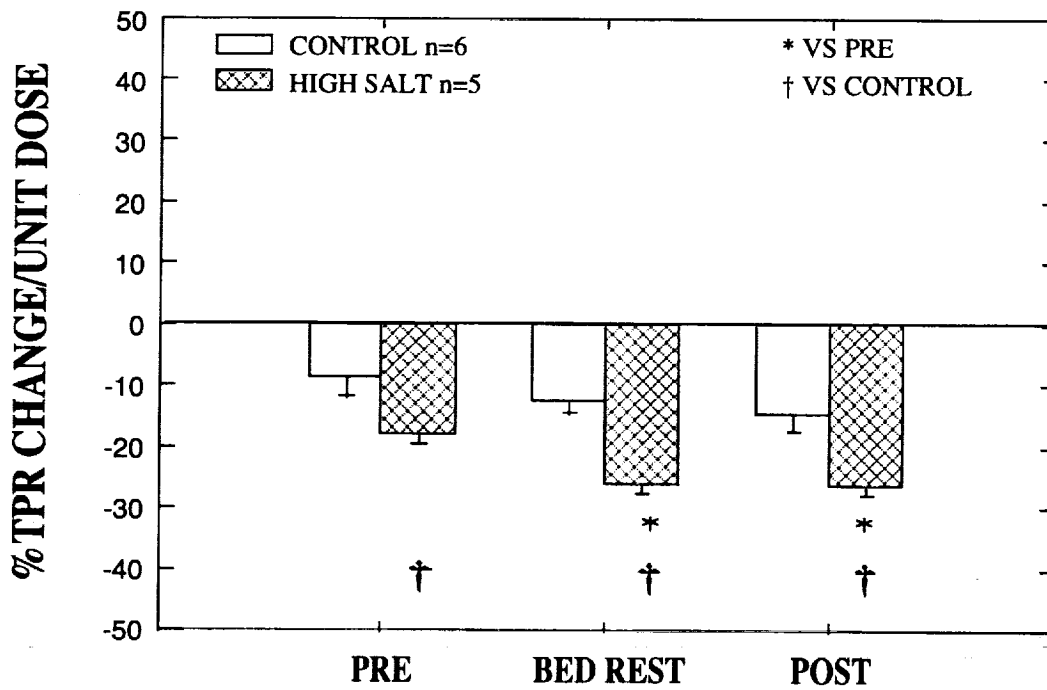

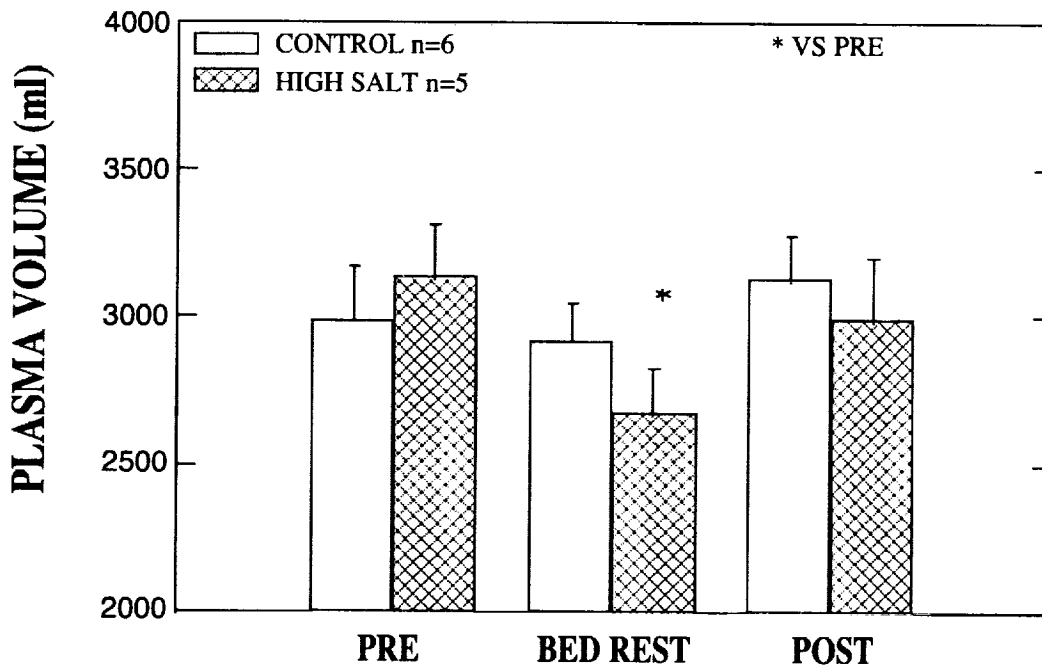
Figure 3. Plasma volume was significantly decreased (* = p ≤ 0.05) in the high-salt group (hatched bars) but not in the normal-salt group (open bars) after 21 days of head-down bed rest.

Simulated Microgravity Improves Production of Colonic Growth Factors

TM/PI: G. F. Spaulding, M.D./SD4
PI: T. J. Goodwin, M.A./SD4
        J. M. Jessup, M.D./New
        England Deaconess Hospital,
        Boston, MA
Reference: LS 3

Microgravity may allow mammalian cells to be cultured in vitro such that the tissue-like structures formed mimic the structure and function of tissue formed in vivo. We sought to determine whether growth factor production by human colonic cells cultured in simulated microgravity is enhanced relative to conventional monolayer tissue cultures. If so, then actual microgravity may be even more advantageous for producing tissues in culture.

For this study, microgravity was simulated through the use of a rotating-wall vessel (RWV) designed by the JSC Biotechnology Program. This fluid-filled, zero-head-space clinostat can suspend particles with less shear stress than is possible in conventional cultures. In earlier studies, we confirmed that human colonic carcinoma cells cultured with human fibroblasts in an RWV formed masses that were morphologically similar to the same carcinoma grown in vivo in athymic nude mice (Goodwin, T.J., et al., In Vitro Cell Devel. Biol. 28A:47-60, 1992). We also showed that freshly isolated human colorectal adenocarcinoma cells, when implanted in the wall of the large bowel of athymic nude mice, release soluble factors that selectively stimulate proliferation of goblet cells in the colonic mucosa overlying the tumor implants (Hostetter, R.B., et al., Surg. Forum 39:168-170, 1988). Goblet cells, which produce mucin, are easily distinguished from other mucosal epithelial cells.

In the present study, we encapsulated saline (0.15M phosphate buffered), tissue culture medium (alpha MEM with 10% fetal calf serum) or conditioned culture medium into liposomes (1 ml of concentrated liquid in 60 μM of CGP 19,835 A lipids [Ciba-Geigy]) (table 1). India ink, epidermal growth factor (EGF), basic fibroblast growth factor (FGF), or gastrin were incorporated in liposomes as controls. Medium was conditioned by HT29, HT-29KM, or normal human fibroblasts that had been cultured in an RWV or in roller bottles (table 1). Liposomes were used to provide sustained release of suspected growth factors.

We injected 0.05 ml aliquots of 6 μM liposomes in PBS into the cecal submucosa of BALB/c mice. Five days later the mice were killed and their colons harvested, irrigated with saline, and each cecum fixed in formalin. Paraffin sections were then stained with hematoxylin and eosin and the cell morphology coded. Forty crypts that were sagitally sectioned over the liposomes were counted per treatment group.

Fresh medium did not stimulate any changes in crypt cell height or number compared to saline controls. In contrast, India ink caused acute inflammation and increased crypt height, number of crypt cells and goblet cells per crypt without increasing the percentage of goblet cells. Media conditioned by HT-29 or HT29KM also increased crypt height, the number of cells per crypt, and the absolute number of goblet cells per crypt compared to saline controls. However, media from RWV cultures (Experiments 1 and 3) selectively increased the percentage of goblet cells, whereas media from roller bottle cultures (Experiment 2) increased only the total number of crypt cells. These effects apparently resulted from factors released by the carcinoma cells, because media conditioned by human fibroblast cultures in an RWV had no effect on crypt height or cell number (Experiment 3). Purified growth factors (EGF, FGF, or gastrin) increased crypt height or cell number but did not increase the number of goblet cells (Experiment 4).

Cultivating established human colon carcinoma cells in the RWV produced a factor that selectively increased the number of goblet cells in normal mouse cecal epithelium. Similar cultures in roller bottles had a nonselective trophic effect. EGF, bFGF, and gastrin are known to stimulate both hypertrophy and hyperplasia in normal colon mucosa in both rodents and humans. However, purified EGF, bFGF, or gastrin did not selectively

expand the goblet cell subset at concentrations that were trophic for colonic mucosa. Since freshly isolated human colon carcinomas have the same effect on goblet cells as the RWV HT-29 colon cell line cultures did (Hostetter, R.B., et al., Surg. Forum 39:168-170, 1988), the low-shear-stress environment in the RWV may be better than conventional culture systems for isolating novel growth factors. We propose that actual micro-gravity may provide an excellent opportunity for the isolation of novel growth factors.

Table 1. Conditioned-Media Effects on Goblet-Cell Proliferation in Mouse Cecal Mucosa

	Liposome Contents	Crypt Height[a]	# Crypt Cells[b]	# Goblet Cells per Half Crypt[c]	% Goblet Cells per Half Crypt[d]
Experiment 1 (RWV)	Saline	33.6 ± 0.9	36.3 ± 1.1	3.0 ± 0.2	8.7 ± 0.5
	India Ink	76.1 ± 2.1*	66.9 ± 2.5*	5.3 ± 0.4*	8.0 ± 0.6
	Medium HT-29	32.2 ± 0.8	35.3 ± 0.9	3.8 ± 0.2	10.9 ± 0.6
	Medium	44.8 ± 0.9*	42.5 ± 1.3*	5.7 ± 0.3*	13.6 ± 0.8*
Experiment 2 (Roller Bottles)	Saline	66.2 ± 2.8	32.1 ± 1.5	5.1 ± 0.3	16.4 ± 1.1
	Medium HT-29	74.2 ± 2.1	33.1 ± 0.9	3.6 ± 0.2	11.0 ± 0.7
	Medium	93.2 ± 2.3*	47.4 ± 1.0*	7.9 ± 0.3*	16.7 ± 0.7
Experiment 3 (RWV)	Saline	58.5 ± 1.3	28.7 ± 0.7	6.0 ± 0.2	21.2 ± 0.9
	Medium Fibroblast	64.4 ± 1.4	33.4 ± 1.3	6.5 ± 0.3	19.5 ± 0.6
	Medium HT29KM/ Fibroblast	56.9 ± 1.0	30.3 ± 0.7	5.6 ± 0.3	18.5 ± 1.1
	Medium	90.9 ± 1.7*	33.0 ± 1.4	9.8 ± 0.6*	25.6 ± 1.4*
Experiment 4	Saline	54.0 ± 2.1	23.3 ± 0.9	5.2 ± 0.4	23.1 ± 1.8
	EGF 1 μg	80.1 ± 2.4*	36.4 ± 0.8*	5.2 ± 0.3	14.8 ± 1.0
	bFGF 1 μg	69.2 ± 2.4*	29.2 ± 1.1	4.3 ± 0.3	15.3 ± 1.0
	Gastrin 1 μg	71.2 ± 2.0*	34.9 ± 1.1*	5.1 ± 0.4	14.5 ± 1.0

*Indicates significant difference from saline controls at $p < 0.01$ by ANOVA and Scheffe F test.
Mice were 6 weeks old in Experiment 1 and 9 weeks old in Experiments 2-4.

[a]Mean ± SEM of the height of sagittally sectioned crypts (in 1/250 mm) formed over submucosal liposomes.
[b]Mean ± SEM of the total number of cells in one-half of a sagittally sectioned crypt.
[c]Mean ± SEM of the number of goblet cells per half crypt.
[d]Goblet cell number divided by the number of cells per half crypt for each individual crypt (Mean ± SEM).

Evaluation of Methods for Removing Biofilms in Spacecraft Potable Water Systems

TM/PI: R.L. Sauer, P.E./SD4
PI: D.L. Pierson, Ph.D./SD4
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Reference: LS 4

The need to recycle water in future spacecraft to avoid launch and resupply penalties will increase the potential for microbial contaminants to enter and proliferate in the water system. The ability of iodine, which is currently used to disinfect potable water on the Space Shuttle, and other disinfectants to control microbial growth and biofilm formation during long missions needs to be evaluated. Methods of servicing and decontaminating the water system in flight may be needed to extend the life of the water system and to protect the health of crews.

The objective of this project was to evaluate chemical methods of killing and removing biofilms developed within a simulated spacecraft water system. Treatments evaluated included 25 and 250 mg/L of iodine, 5 mg/L of ozone, and 3% hydrogen peroxide.

A schematic of the water system test-bed, which consists of two parallel stainless steel systems, is shown in figure 1. Both systems are identical except that the make-up water to one system is iodinated by passing it through an iodinated ion exchange resin called a microbial check valve (MCV). Each system has several sampling ports and biofilm coupon manifolds.

A coupon manifold containing 21 coupons was installed on the outlet of the noniodinated system (CM-5 in fig. 1). The effluent from this system contained about 10^5 colony-forming units (CFU) per 100 mL of water. After biofilm developed, the coupons were withdrawn in sets of 4 and installed in a treatment manifold (fig. 2) and exposed to the various treatments. Coupons were withdrawn periodically and subjected to microbial and scanning electron microscopy (SEM) analysis.

Bacterial enumeration involved sonicating a segment of a coupon in 5 mL of distilled water, filtering the water, and then culturing the filter on an R2A media. Since this technique determines only whether bacteria are viable, another coupon segment was examined by SEM to determine whether the biofilm had been removed. Coupons were treated for SEM by immersing the terminal segments into 0.5% glutaraldehyde in phosphate-buffered water to fix the biofilm. Coupons were then washed with phosphate buffer, dehydrated with a graded series of ethanol solutions, and then critical-point-dried. The dried coupons were then mounted and coated with gold before being examined with a JEOL JSM-T330A scanning electron microscope.

A Fischer 500M ozone generator was used to produce ozone. Ozone concentrations were measured by ultraviolet absorption spectrometry at 258 nm. Iodine concentrations were determined by absorption spectrometry at 460 nm.

Microbial analysis results from the coupons treated with 25 mg/L iodine are presented in table 1. Iodine at this concentration killed all attached bacteria after 1 hr of contact. Scanning electron micrographs of coupons after 0 and 24 hr (fig. 3 and 4), however, showed no significant decrease in the amount of matter attached after 24 hr. The results at 250 mg/L of iodine are similar, indicating that increasing the iodine concentration does not remove more of the biofilm. Similarly, treatment with 5 mg/L of ozone also killed the attached bacteria, but did not remove the biofilm.

Initial runs with a 3% hydrogen peroxide solution resulted in significant bubble formation. Further work was halted due to requirements to keep gas formation in the potable water systems at a minimum.

This work has shown that iodine and ozone can be used to kill bacteria in biofilms that have developed on water system surfaces. These chemicals, however, do not seem to remove significant amounts of the attached matter, implying that further work should be aimed at preventing biofilm development within water systems.

Table 1. Bacterial Enumeration After Treating Coupons With a 25 mg/L
Iodine Solution

| Exposure Time | Incubation Time | | | |
(hrs)	3 Days	7 Days	14 Days	21 Days
0	188*	TNTC**	TNTC	TNTC
0.5	0	1	1	1
1	0	0	0	0
2	0	0	0	0
2 (spare)	0	0	0	0
4	0	0	0	0

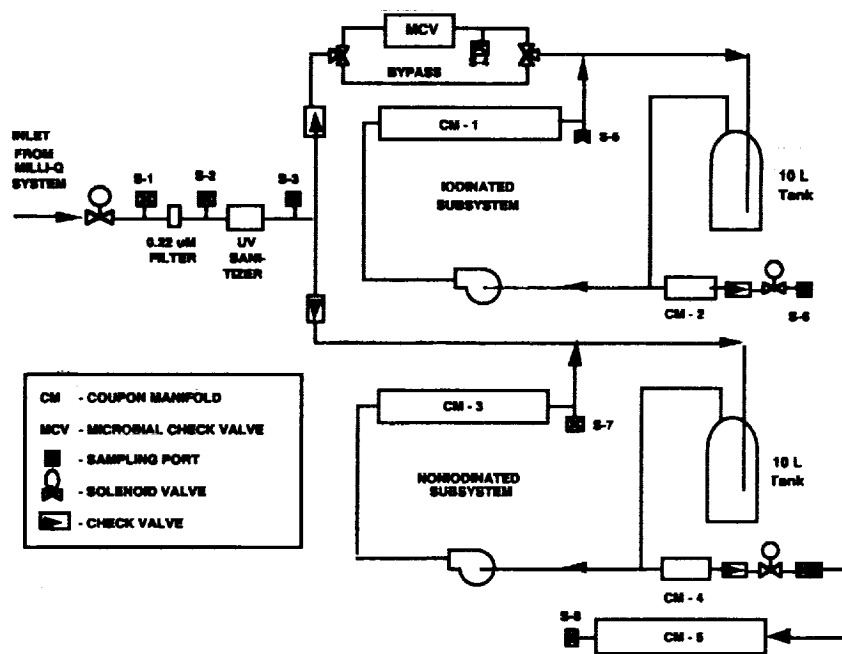*units are CFU/5 mL of water
**too numerous to count

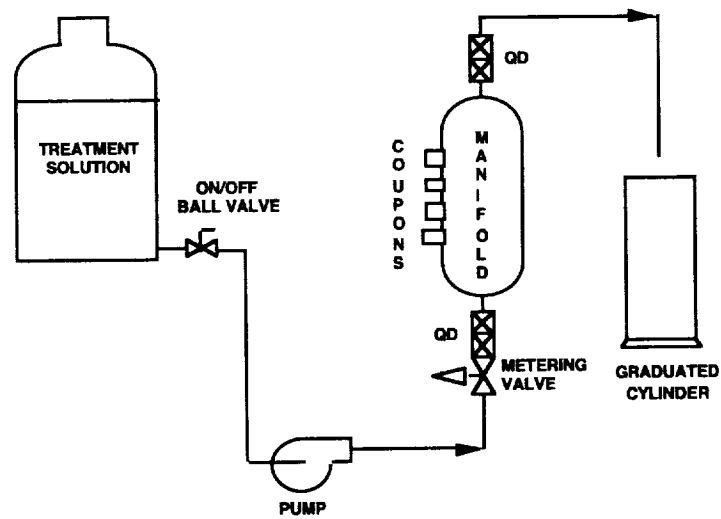Figure 1.   Biofilm test-bed apparatus.

Figure 2.   Biofilm remediation test apparatus.

Figure 3.   Scanning electron micrograph of electropolished side of coupon before treatment with a 25 mg/L iodine solution.
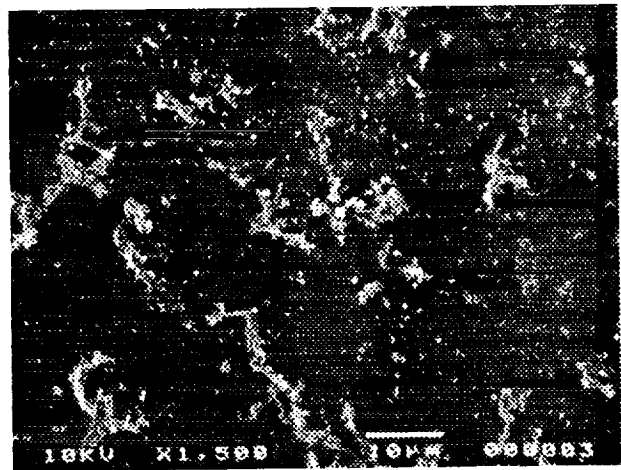
Figure 4.   Scanning electron micrograph of electropolished side of coupon after 4 hr of treatment with a 25 mg/L iodine solution.

A Simulated Space Diet: Effects on Energy Metabolism and Doubly Labeled Water (DLW) Calculations

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            Chicago
Reference: LS 5

Exposure to microgravity induces physiological and biochemical changes that may interfere with crew health and functioning in space. The near-universal weight loss associated with flight has been hypothesized to be due to inadequate consumption of food and fluid. Among the factors identified as possibly contributing to reduced food intake in space is the diet provided.

We are studying the effect of the Space Shuttle cuisine on energy metabolism (and the means by which it can be measured), aerobic capacity, and strength. Energy utilization can be measured by giving subjects water that has been labeled with two stable (nonradioactive) isotopes, ^2H (deuterium) and ^{18}O ("heavy oxygen"). Both isotopes occur naturally and are nontoxic at the levels used. The disappearance of the isotopes from urine and saliva samples are recorded over a period of days. CO_2 production is calculated from the disappearance of ^{18}O, corrected for water turnover (from the disappearance of ^2H), and converted to energy expenditure in joules. This method has been used successfully in both healthy and hospitalized humans.

The potable water available on the Space Shuttle—and thus the water used for food rehydration—is also enriched in ^2H and ^{18}O, although the amounts present are much less than those in the dose given for calculating energy expenditure. We sought to determine whether this "background" enrichment would affect the use of DLW for calculating energy expenditure. To this end, we fed 12 female subjects Space Shuttle foods and water enriched

with typical Shuttle background levels of ^2H and ^{18}O for 28 days, and measured body composition, energy intake, aerobic capacity, and strength before, during, and after this period. One group of subjects was given the DLW dose on day 1, and the other on day 14. We also calculated energy expenditure (EE) using intake balance (IB) techniques for comparison.

Figure 1 illustrates the effect of consuming the "Shuttle water" on background ^{18}O and ^2H for one subject over a 14-day period. In the first group (DLW water dose on day 1), energy expenditure calculated from DLW with no correction for background isotope changes was 43.4 percent lower than that calculated from the IB method (fig. 2). Next, we adjusted the calculations to correct for the expected isotopic background. Corrected EE from DLW was 6.4 percent higher than EE from IB. When the changing isotopic background from the second group (DLW dose on day 14) was used for correction, EE was 4.2 percent greater than IB calculations. These results show that the DLW method can be used successfully in subjects who consume isotopically enriched water, and that background isotope changes can be corrected without control subjects or time-dependent estimates of changing background.

As for the Shuttle foods, all subjects consumed the same amounts of energy before, during, and after the Shuttle food period. However, their relative intake of carbohydrate increased, and those of fat and protein decreased accordingly (fig. 3). This pattern resembles that of crews from the SLS-1, STS-45, and STS-47 missions. Moreover, neither body weight, body composition, strength, nor aerobic capacity changed during the Shuttle food period (fig. 4), suggesting that the Shuttle food itself probably does not contribute to the shifts in these measures noted during and after Space Shuttle missions.

EFFECT OF CONSUMING SIMULATED ORBITER WATER ON BODY WATER ENRICHMENT
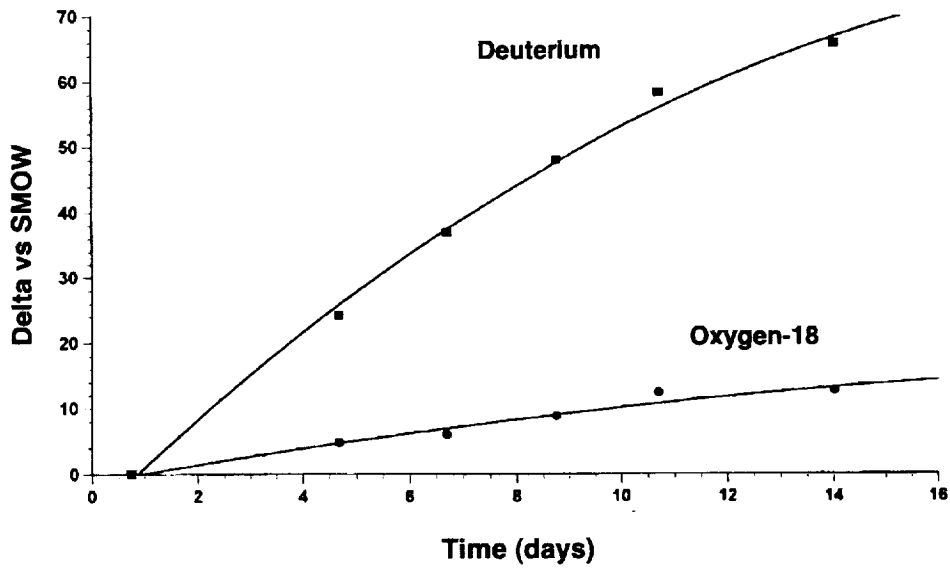
Figure 1.   Effect of consuming simulated orbiter water on body water enrichment.

ENERGY EXPENDITURE DURING A 14 DAY SHUTTLE FOOD DIET: INTAKE-BALANCE COMPARED TO THREE DLW TECHNIQUES

Figure 2.   Energy expenditure during a 14-day shuttle food diet: intake balance compared to three DLW techniques.

*Signigicant difference (p<0.05)

Figure 3.   Macronutrient intake before, during, and after consuming a shuttle
            food diet.

Figure 4.   Aerobic capacity before, immediately after, and five weeks after
            shuttle diet consumption.

Radiogenic Transformation of Human Epithelial Cells: Relative Biological Effectiveness (RBE), Growth Properties and Chromosome Studies

TM/PI: Chui-hsu Yang, Ph.D./SD4
PI: Kerry George/SD4/KRUG
           Laurie M. Craise/Lawrence
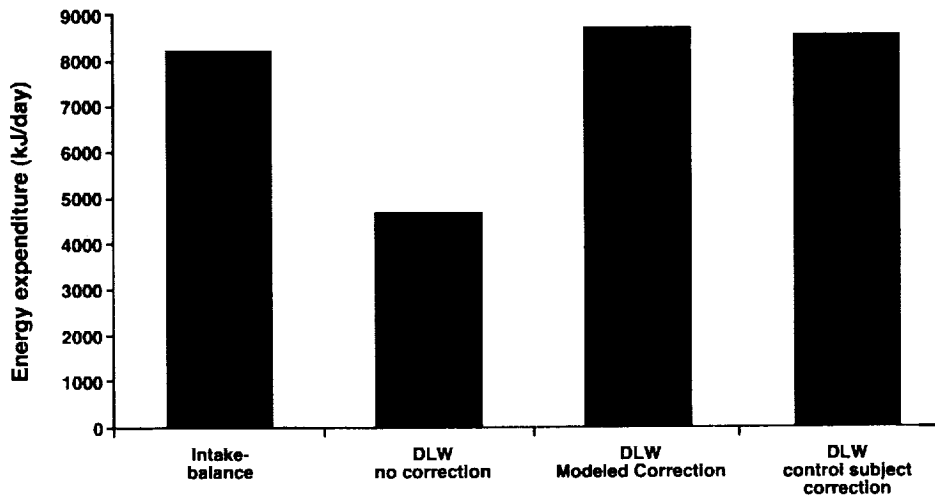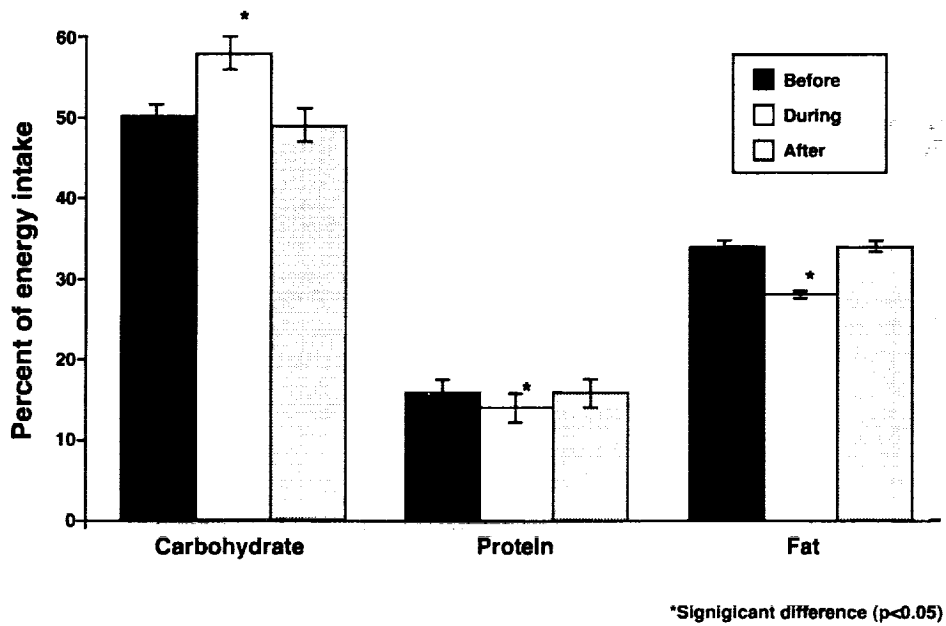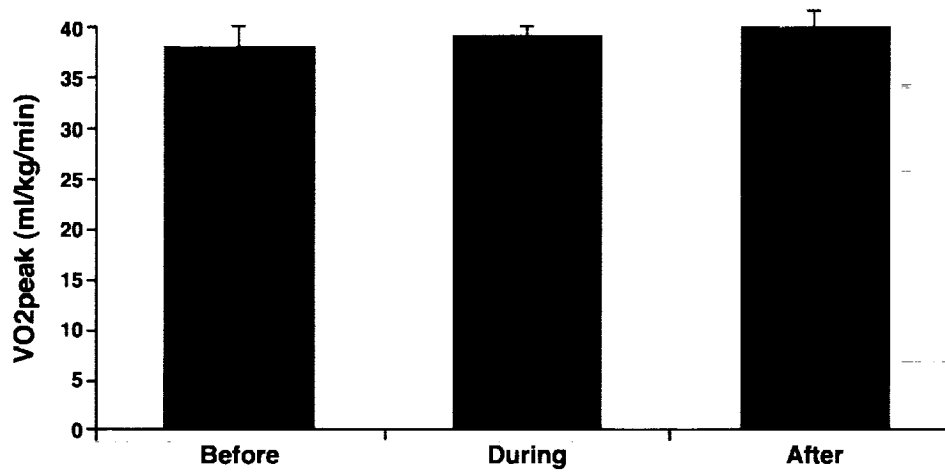   Berkeley Laboratory, UC
Reference: LS 6

During long, remote space missions, crewmembers will be exposed to health hazards associated with unique aspects of the space environment. Protecting crews from one of these hazards, ionizing space radiation, must be considered carefully to ensure the success of space exploration. Sources of radiation in space include the inner trapped proton belt, the outer electron belt, galactic cosmic rays, and charged particles from solar particle events. These forms of radiation are different from gamma rays and neutrons in terms of energy absorption and ionization pattern. Significant data have been obtained on the biological effects of gamma rays and neutrons from atomic bomb survivors; however, no radioepidemiological data exist on the biological effects of charged-particle radiation on humans. The biological risks from energetic charged particles thus must be estimated from experiments using animals and cultured cells.

The induction of cancer is an important delayed effect of radiation. The Radiation Biology Laboratory at JSC has used systematic, quantitative methods to study the relationship between the RBE of charged particles for oncogenic transformation and the linear energy transfer (LET) of these particles.

The RBE-to-LET relationship for the induction of Harderian tumors in mice (fig. 1) is similar to that for oncogenic cell transformation. The peak RBE for inducing Harderian tumors, however, is roughly four times greater than that required to transform cells. Some investigators have suggested that this difference in RBE is related to the ability of one heavy ion to traverse through many cells in the body. The maximum cross section of a heavy-ion path, calculated from initial slopes of dose-response curves, is about 100 mm^2, which is close to the geometric nuclear area of the cell. This interesting result suggests that all DNA in the nucleus could be the target for carcinogenesis. Since diploid mammalian cells contain about 1,000,000 genes, and since less than 100 genes have been identified as important for cancer formation, these results indicate that one heavy ion traversing through the body could hit targets in more than 10,000 cells. Alternatively, heavy ions could have promotional effects, killing many cells in the tissue where they hit thus allowing transformed cells to proliferate. Promotion is known to be an important step in carcinogenesis; moreover, high-LET heavy ions can be very effective in killing cells.

Because the dose rate from radiation exposure in space is low (< 1 rem per day), it is important to study similarly low dose rates of gamma rays and charged particles. We determined the RBE of charged particles with various LET relative to low-dose-rate gamma rays in mouse embryonic cells. Figure 2 shows the RBE and LET relationship for immediate plating, delayed plating, and low dose rate. The high RBE for low-dose-rate gamma rays was due in part to the inability of mammalian cells to repair oncogenic damage induced by particles with such high LET.

We also studied neoplastic transformation in human epithelial cell cultures. Exposing mammary epithelial cells to heavy ions produced several transformants, which formed colonies in soft agar and produced small nodules in athymic nude mice. When cultured on Matrigel, a synthetic substance resembling basement membrane, these transformants formed spheroids (fig. 3) rather than the multicellular 3-D structures typical of nontransformed cells. These results tend to confirm that heavy ions can transform normal human epithelial cells into tumor cells.

Because certain chromosomal aberrations are associated with the formation of particular tumors in humans, we also assessed the chromosomal integrity of these transformants using a chromosomal "painting" technique. To date, studies of chromosomes 1, 2, 3, 4, 5, 8, 13, 15, 17, and 18 have revealed no differences between nontransformed and transformed cells. Additional analyses are in progress.

RBE vs. LET Relationship for Carcinogenesis

Legend:
- ○ Cell Transformation
- ● Initial Slope (Harderian Tumor)
- ▽ 25% Tumor Prevalence

Axes: RBE (y-axis, -10 to 50); LET (keV/μm) (x-axis, 10⁻² to 10⁵)
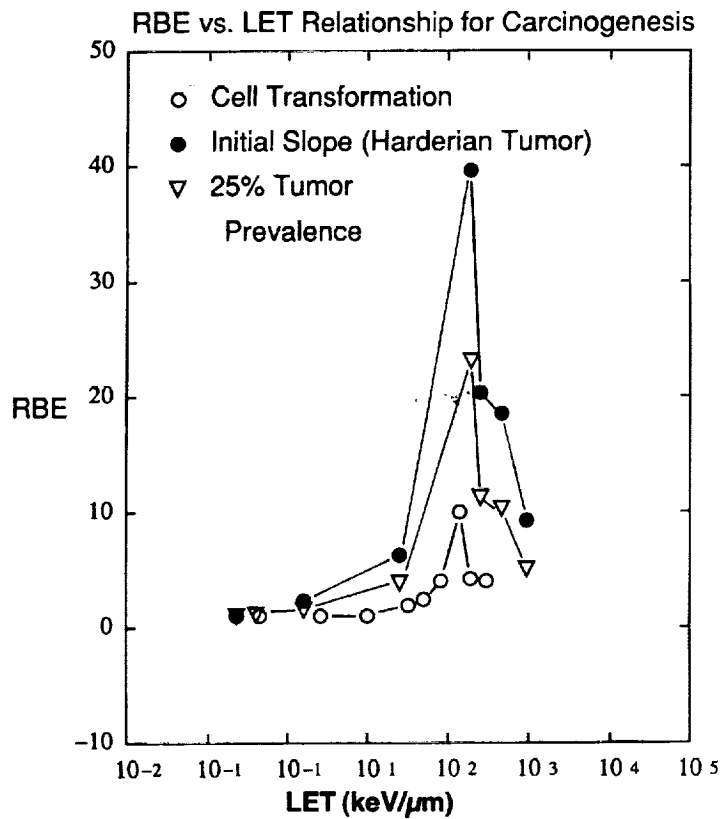
Figure 1. The relationship between RBE and LET for charged particles in the oncogenic transformation of mouse embryonic cells (C3H10T1/2) and in the induction of Harderian gland tumors in mice.

RBE vs. LET for Neoplastic Transformation

Legend:
- ○ Immed. Plating
- ● Delayed Plating
- ▽ Low Dose Rate (gamma rays)

Axes: RBE (y-axis, -5 to 30); LET (keV/μm) (x-axis, 10⁻² to 10⁵)

Figure 2. The relationship between RBE and LET for gamma rays and charged particles in the oncogenic transformation of mouse embryonic cells (C3H10T1/2). Confluent cells were exposed to gamma rays or charged particles and were plated either immediately or 1 day after irradiation.
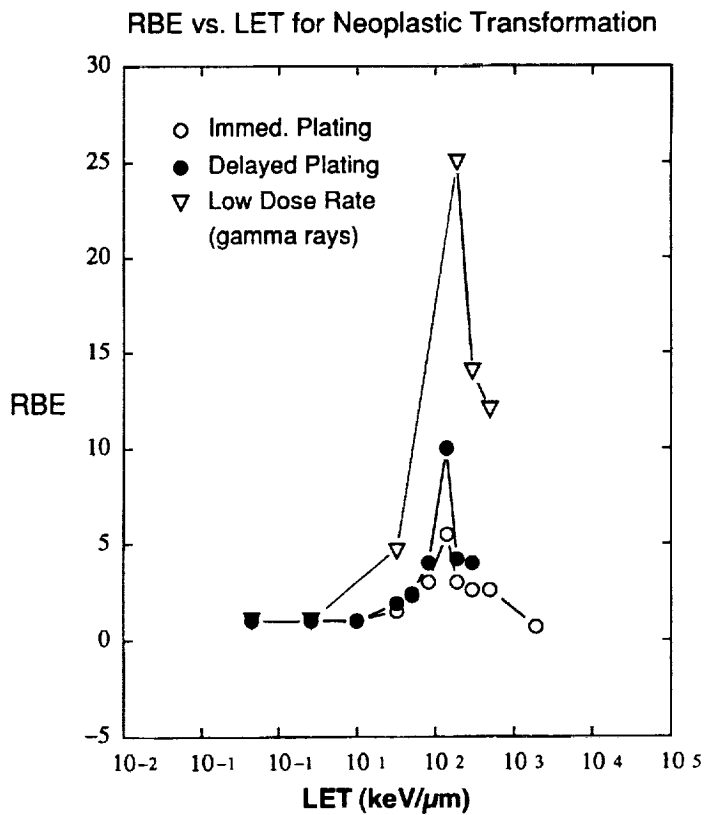
Figure 3.   Human mammary epithelial cells, transformed by charged-particle radiation, formed
spheroids after 10 days of growth on Matrigel.

Section II

Human Support Technology

Summary

Human Support Technology Summary

The Human Support Technology section includes a variety of disciplines ranging from biomechanics to intelligent computer programs to aid in training astronauts and mission controllers. The common goal of all these disciplines is to make crewed spaceflight safer and more efficient.
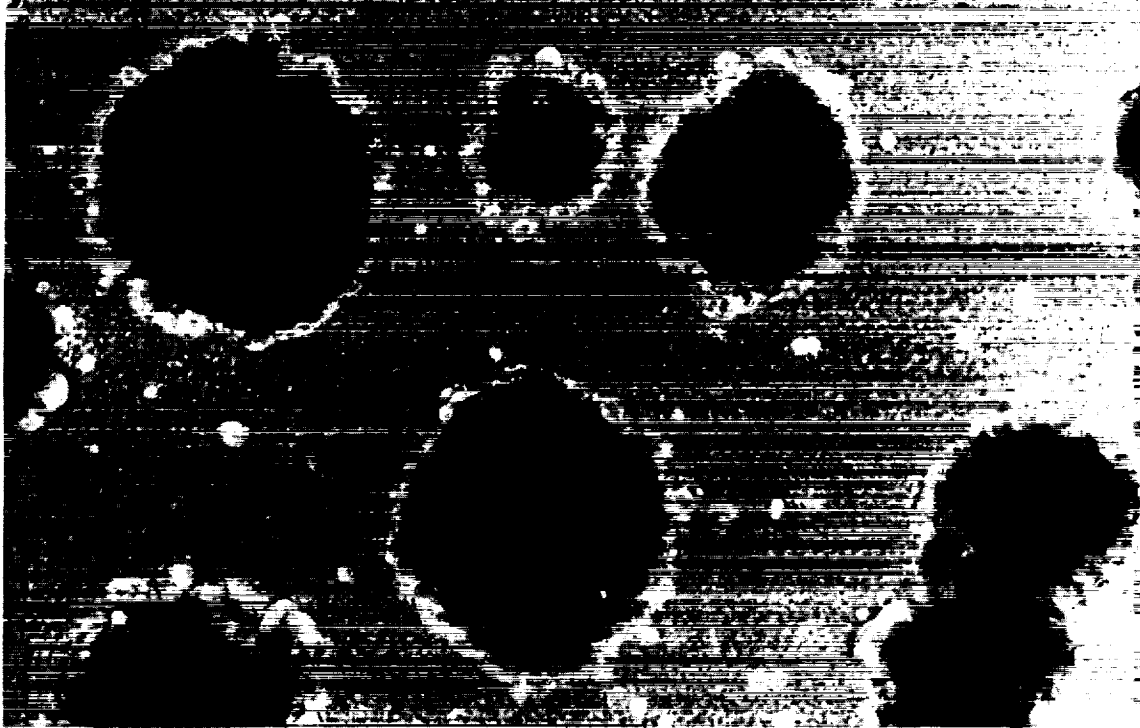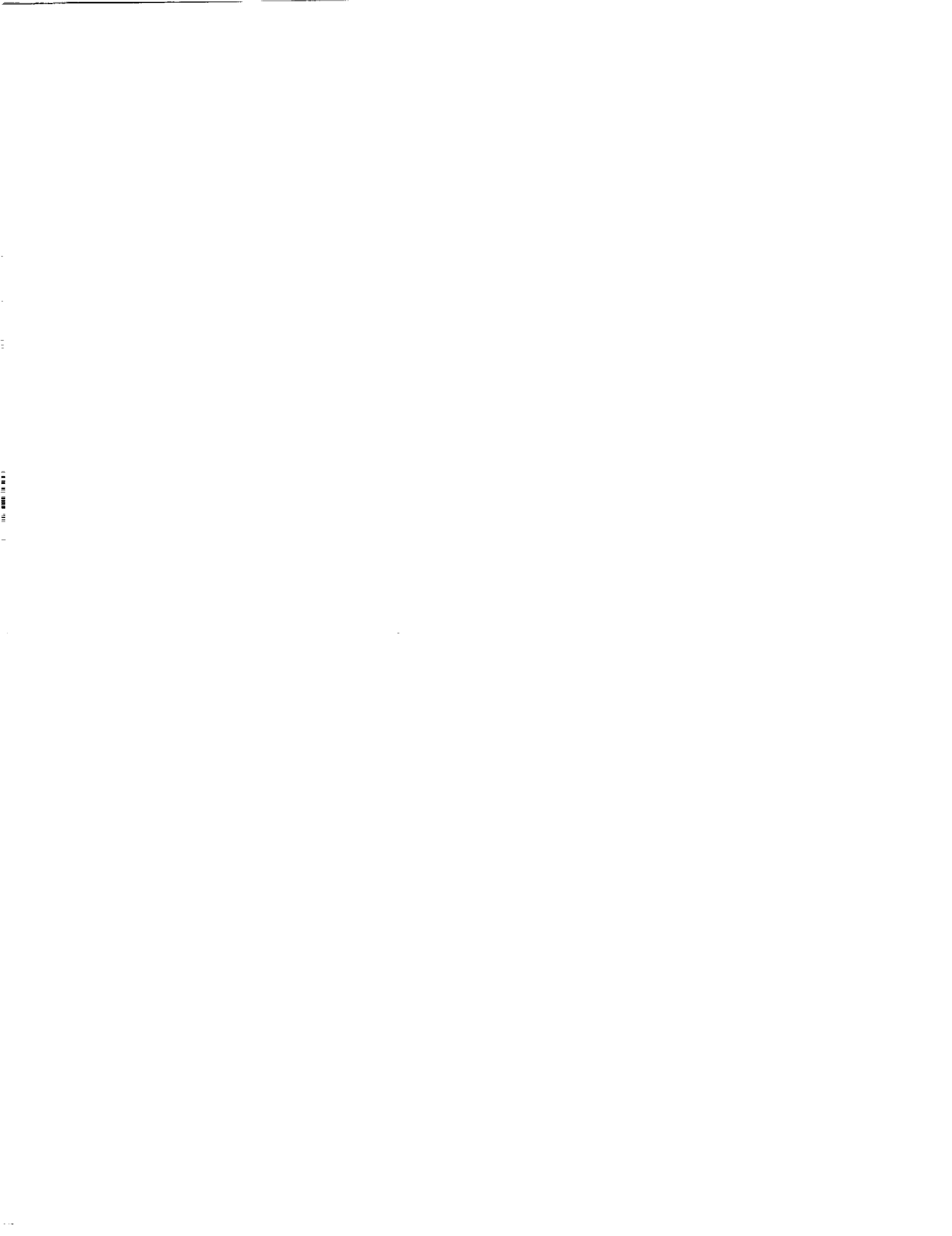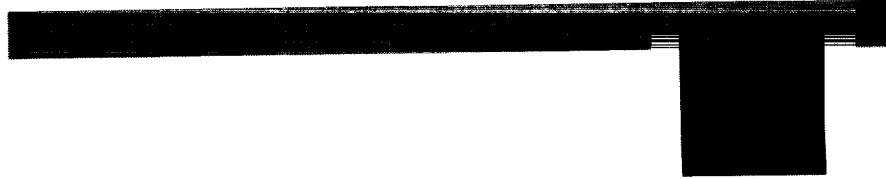
Two projects this past year supported the Hubble Space Telescope repair. These are the Task Analysis Report Generation Tool which incorporated a virtual environment to train over 150 members of the flight team and the Intelligent Computer-Aided Training project which also produced a virtual reality environment of Hubble.

With the proliferation of work stations and stand alone systems, the effective coordination of knowledge is essential. To help address the need for effective knowledge coordination, "Cooperating Expert Systems" presents "midware."

Analysis of in-flight data is also important to provide improved efficiency in future flights. Three papers addressed this: The first, "Development of PVAT - A Video Analysis Tool for Microgravity Posture Evaluations," studied neutral body posture in zero-g. The second, "Human Factors Studies Aboard STS-57/SpaceHab-01," studied posture, translation, lighting, and sound levels aboard SpaceHab. And the third, "Human Workload Analysis," used results from neutral buoyancy studies to analyze the timeline for Hubble.

Human-Computer Interface to Medical Decision Support Systems for Space addresses problems that are common to all decision support systems, including anchoring and the effect of new evidence on anchoring.

Two papers on biomechanical modeling complete the section. "Development of a Rapid Algorithm for Human Computer Model Reaching" and "Development of a Full Body Dynamic Human Strength Model," both describe graphical modeling of human biomechanics.

The common theme of all these papers is that computerization can increase the productivity of humans in space.

Section II

Human Support Technology

Significant Tasks

Task Analysis Report Generation Tool (Target)

TM: **Robert T. Savely/PA**
              Christopher J. Culbert/PT4
PI: **Christopher J. Ortiz/PT4**
Reference: **HST 1**

TARGET represents a new approach that blends graphical process flow modeling capabilities with the function of a top-down reporting facility (fig. 1). Since NASA personnel frequently perform tasks that are primarily procedural in nature, TARGET models mission or task procedures and generates hierarchical reports as part of the process capture and analysis effort. Historically, capturing knowledge has proven to be one of the greatest barriers to the development of intelligent systems. Current practice generally requires lengthy interactions between the expert whose knowledge is to be captured and the knowledge engineer who is responsible for acquiring and representing this knowledge in a useful form. Although much research has been devoted to the development of methodologies and computer software which aid in capturing and representing certain types of knowledge, procedural knowledge has received relatively little attention. TARGET also permits experts to visually describe procedural tasks in a common medium for knowledge refinement by the expert community and knowledge engineer, facilitating knowledge consensus. Systems such as TARGET have the potential to profoundly reduce the time, difficulties, and costs of developing knowledge-based systems for the performance of procedural tasks. TARGET has also found uses in such diverse areas as total quality management and documentation of operational procedures.

During FY93 the TARGET application was completely redesigned, redeveloped and delivered as TARGET, version 1.5. The primary goal for the redesign of TARGET was to rewrite and rehost the application on the Windows, Macintosh, and Sun X-Windows platforms. The application, which is graphical in nature, can now be compiled on a variety of systems with little change to the source code. This goal was achieved in TARGET version 1.5 by using a new off-the-shelf product called XVT which provides application portability. During the rehost effort several new features were added to the original version. The original version, TARGET version 1.0, which was released during FY91 on the Microsoft Windows platform, has over 177 registered users within the government. TARGET version 1.0 became available to the general public through COSMIC in August 1993.

TARGET was used initially to analyze the repair procedures for the various tasks that were part of the Hubble Space Telescope maintenance mission. These procedures were then incorporated into a virtual environment that was used to train over 150 members of the flight team. The main sources for the information which was used included the EVA Checklist STS-61 Flight Supplement and the Weightless Environment Training Facility training videos. The activities of both astronauts were decomposed and incorporated into two training modules consisting of tasks related to the solar arrays, rate sensor units, wide field/planetary camera and the corrective optics space telescope axial replacement. TARGET provided the preliminary procedural schemas that enabled further development within the virtual environment (fig. 2).

During the same time period, version 1.5 of TARGET was used to support procedural knowledge acquisition for the intelligent computer-aided training (ICAT) conduct-of-fire trainer for the National Guard. TARGET was used to capture the interaction between instructors, tank commanders and gunners. It was also used to codify the initial break down of basic surgical techniques to aid in the development of future virtual environment ICAT systems for surgical training.

Toward the end of the FY93, an effort was initiated to add a rule generator to the application to create C language integrated production system rules from simple decision trees. Successful demonstration was accomplished during the first quarter of FY94.
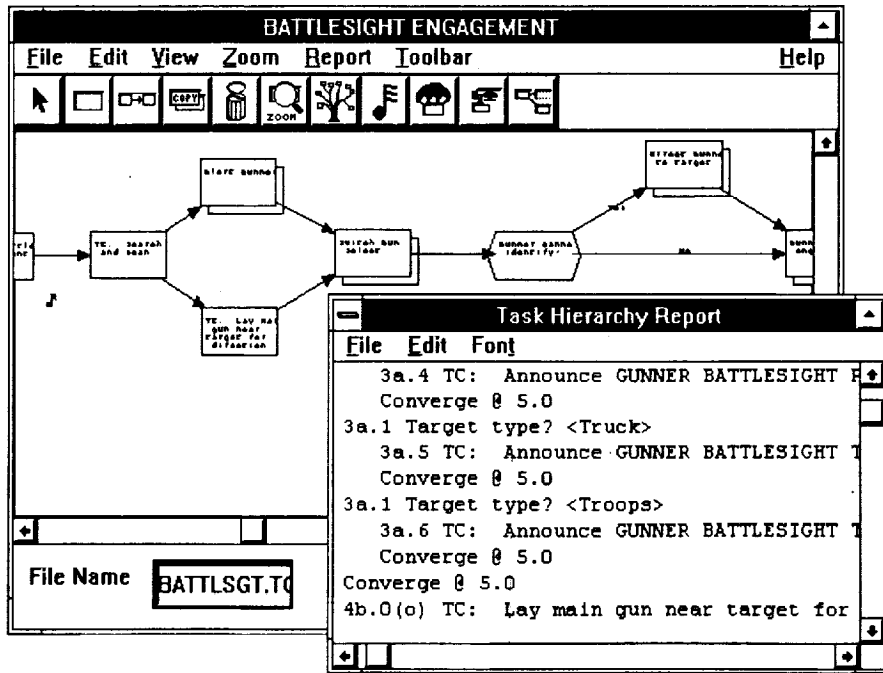
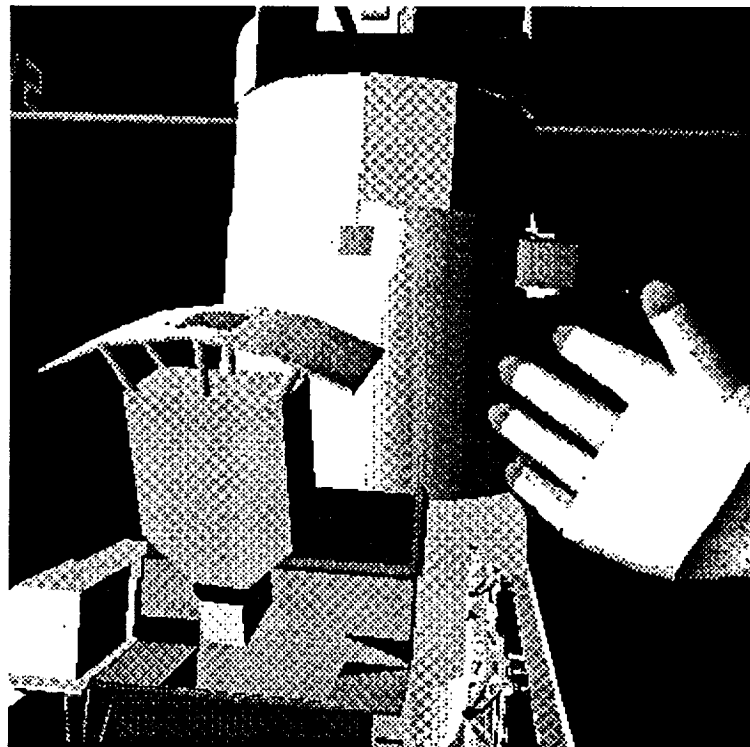Figure 1. Graphic and textual task representation in TARGET.

Figure 2.   In this virtual reality scenario, a hand acts in the right foreground as the wide field/planetary camera hovers over its protective enclosure, with the Hubble Space Telescope in the background temporarily stationed in the STS-61 cargo bay.

Intelligent Computer-Aided Training (ICAT)

PI: Robert T. Savely/PA
Dr. R. Bowen Loftin/
University of Houston-
Downtown
Reference: HST 2

Training of NASA astronauts, flight controllers, and other ground support personnel has historically required extensive on-the-job and/or simulator-based training for individuals to acquire the knowledge and skills necessary for acceptable performance and/or certification. Current flight rates and the loss of experienced personnel to retirement and transfer severely reduce the ability of traditional training approaches to produce an adequate number of trained personnel. Workstation-based, intelligent computer-aided training (ICAT) systems can deliver intensive training to large numbers of trainees, independent of integrated simulations. Such systems can significantly reduce the amount of on-the-job and/or simulator-based training necessary to achieve acceptable levels of performance.

ICAT systems bring artificial intelligence, training technology, simulation, and other software technologies to bear on the problem of training. The role of artificial intelligence in ICAT systems is to model the behavior of both experts and novices in the performance of a complex task. In addition, the expertise of a trainer is modeled and used to determine the feedback given in response to trainee errors, and to design increasingly challenging simulations to meet training goals. Thus, the efforts of both an expert in the task and an expert trainer are simultaneously applied to each trainee. Such systems offer increased efficiency and reduced cost in training and provide uniform and verifiable training, enhancing safety and the probability of mission success.

During FY93 the SpaceHab Intelligent Familiarization Trainer (SHIFT)—the first components of which were delivered in FY92—was completed and used for training in support of STS-57 (SpaceHab-01). SHIFT is intended for use in training astronauts, flight controllers, and other ground support personnel in the operation of those systems that are part of the commercial middeck augmentation module also known as SpaceHab. The SpaceHab module is an Orbiter quarter bay payload that was developed by McDonnell Douglas Space Systems Company for SpaceHab, Inc. Its purpose is to support commercial microgravity experiments during a series of at least six flights.

SHIFT addresses training in all SpaceHab and Orbiter systems used by the SpaceHab module. These include the caution and warning, communications and closed-circuit television, electrical power, and environmental systems. Based on a refinement of the general ICAT architecture (reported in the 1991 RTAR), SHIFT replaces the single system trainer normally used to prepare astronauts for similar missions. SHIFT is a unique ICAT application since it was developed concurrently with the systems for which it delivers training. This posed real challenges for the development team as they received, often daily, changes to systems design and training requirements. Design and development of SHIFT began in early November 1991, and the first modules were delivered for crew training in July 1992. Final delivery of all SHIFT elements needed for mission training occurred in January 1993. A complete description of the SHIFT capabilities can be found in the 1992 RTAR.

During FY93 the Software Technology Branch greatly expanded its efforts in applying virtual environment (also known as virtual reality) technology to training. Beginning in May 1993, members of the training technologies team constructed a complete model of the Hubble Space Telescope, as well as relevant Orbiter and payload elements, to support the training of the flight team for STS-61. Engineering drawings were used to obtain the data necessary to model all telescope and payload elements (fig. 1). ICAT technology was used in a limited way to provide additional help to those using the system. Crew procedures documents and extensive study of videotapes of the Weightless Environment Training Facility training activities were used to incorporate procedural knowledge of all major tasks into the virtual

environment. Object identification and procedural "next steps" were also available to trainees through the integration of ICAT technology with the virtual environment (fig. 2). Training with this system was initiated in September 1993. Results of this activity (completed in December 1993) will be reported in the FY94 RTAR.

In addition to the specific virtual environment training application detailed above, the training technologies team also began exploring the use of haptic displays (tactile, force, and thermal) in virtual environments. A test bed to evaluate haptic displays from industry and academia was designed and will be used in FY94 to perform detailed studies that will determine the effectiveness of the current technology and the technology gaps that must be filled for haptic displays to become useful components of virtual environments.

The continuing lack of powerful and accessible development tools for the creation and maintenance of complex virtual environments was addressed during FY93. A high-level software development tool was delivered in prototype form. This tool was based on the use of the CLIPS (C language integrated production system) and COOL (CLIPS object oriented language), products of the Software Technology Branch. The tool supports the description of virtual object attributes and relationships through COOL. User interactions with objects and the resulting behaviors are described by means of CLIPS rules. This tool promises to make a major contribution to the further maturation and wider application of virtual environment technology by greatly expanding the number of personnel who can quickly and conveniently develop and modify complex virtual environments.

In summary, FY93 saw the completion of the SHIFT ICAT project, the continued refinement of the general ICAT architecture, the first large scale application of virtual environment technology in training, and the further maturation of virtual environment technology as an adjunct to ICAT technology.
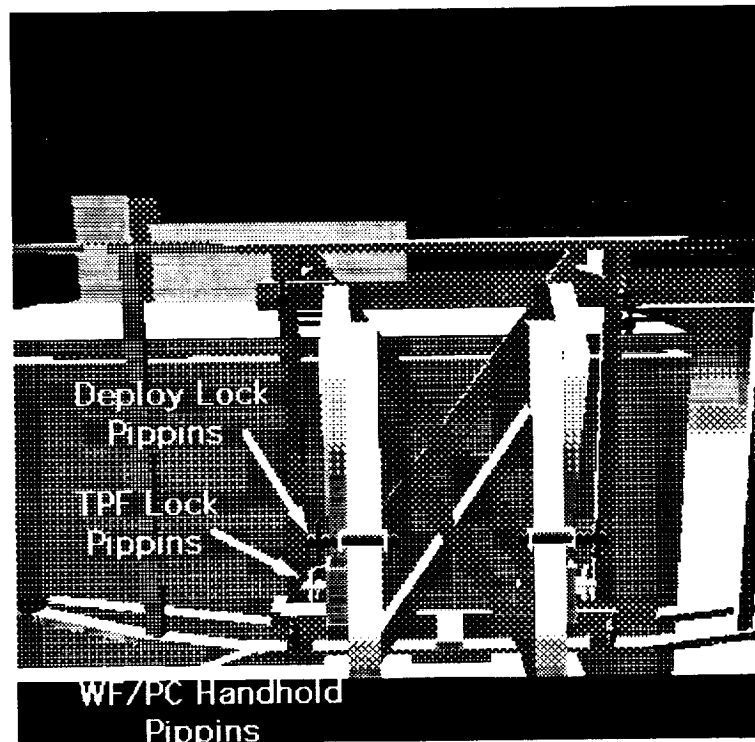

Figure 1. View of wide field/planetary camera (WF/PC) handhold parked on the temporary parking fixture (TPF) in the Shuttle cargo bay.
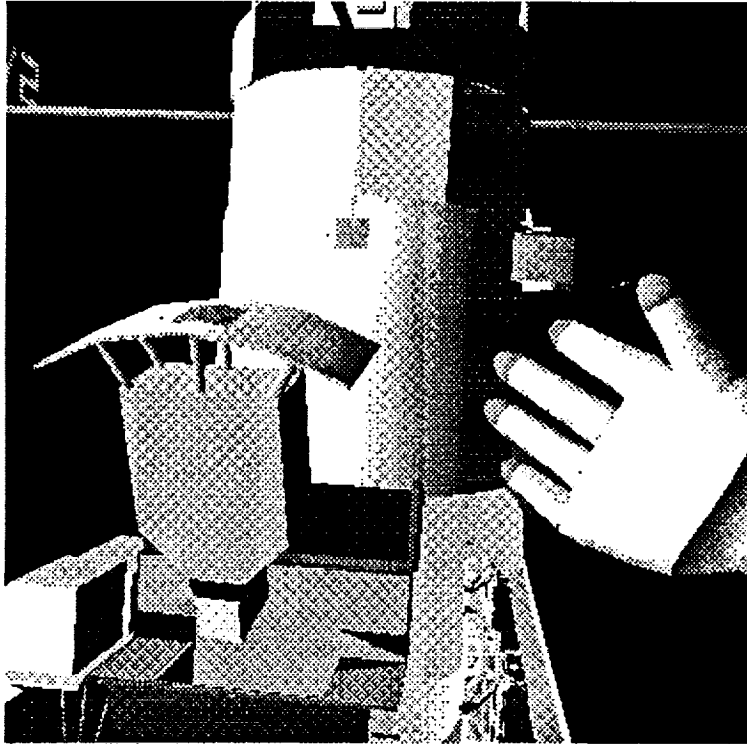
Figure 2.   In this virtual environment, a trainee's hand is shown in right foreground/
             right as WF/PC hovers over its protective enclosure, with the Hubble Space
             Telescope temporarily stationed in the Shuttle cargo bay.

Cooperating Expert Systems

PI: **Christopher J. Culbert/PT4**
Reference: **HST 3**

The purpose of the cooperating expert systems (CoopES) project is to define and develop guidelines, methodologies, and tools for distributed cooperating systems and to apply them to develop and deliver software and techniques for appropriate customers at JSC.

Previous CoopES research has focused on various models of cooperation. Two prototypes were developed based on hierarchical and peer-to-peer architectures. This work resulted in the development of significant expertise in developing cooperating expert systems, a number of reusable, distributed computing software components (several of which have been used in other projects), and functional demonstration software. The 1991 and 1992 RTAR outline some of the details of this work.

With the current trend away from centralized, mainframe-based computing to distributed, network-based software, the experience gained through the CoopES project has proven to be a valuable asset. In FY93 the project applied this expertise in developing distributed system prototypes to introduce network-based data sharing into the JSC Mission Control Center (MCC) through the real-time data system (RTDS) project. Although the project focused primarily on MCC communications, the system provides general data sharing capabilities.

RTDS technology development projects have resulted in the development of specialized, real-time tools for some disciplines (groups of flight controllers who are responsible for specific Shuttle subsystems). Software has been developed which helps controllers monitor Shuttle telemetry. It runs on networked Unix workstations, independent of the operational flight consoles, and has succeeded in introducing technologies, such as window-based user interfaces, graphical presentation of telemetry, and automated, rule-based data analysis, into the MCC without disturbing operational console software.

However, the distributed nature of the networked workstations has not yet been fully exploited. Disciplines depend on cooperation with each other to resolve many issues, and this dependence translates into (1) communication on the voice loop to pass conclusions from one discipline to another, and (2) manual data entry of the conclusions into support software. To reduce this reliance on the voice loop, some positions diagnose subsystems other than their own. The result is duplication of effort, dilution of the disciplines' exclusive responsibility for their associated subsystems, and occasionally contradictory conclusions.

To address these problems, the CoopES team developed the data sharing system (DASH). DASH provides a mechanism through which existing RTDS support applications may share data with each other via the existing network. This system can be incorporated into existing application code with minimal effort. It supports variable-length and aggregate data exchange between exporting and importing applications, and involves two simple application program interfaces (APIs) which can be called by applications wanting to export or import data. As such, DASH represents a middleware product aimed at coordinating data sharing between producer and consumer applications. DASH acts as an intermediary between the applications, the operating system and the network software. Programmers writing a producer or consumer application do not need to know anything about the DASH system, but only about the APIs calls in their code. A producer may export data to any number of interested consumers, and a consumer may import data from any number of producers using the system.

Figure 1 illustrates the relationships between various processes which make up the DASH system. In this figure, elements of the DASH system proper are represented as white rectangles. The shaded rectangles denote externally developed software. The relationships between the processes are depicted by one- and two-sided arrows. The one-sided arrows denote client/server relationships in which a client initiates contact with a server. (The arrow points to the server.) The two-sided arrows denote peer-to-peer relationships in which

both parties contact each other. For both types of relationship, information will generally flow both directions.

DASH is composed of several classes of processes which implement the APIs semantics. Publishers make data exported by producers available to so called subscribers. These subscribers locate the publisher associated with requested data and pass the data on to interested consumers. There can be many producers, consumers, publishers, and subscribers. These processes may reside at arbitrary network locations due to the presence of a network registration service which acts as a "process directory" and thereby provides network location transparency.

There are two important points which need to be made about DASH and its incorporation as a human support technology in the MCC. First, with the huge investments in flight controller training, the current workload on certified flight controllers, operational console software, and the safety requirements of Shuttle missions, flight controllers are generally reluctant to embrace a new technology if it represents an appreciable departure from the current approach to mission operations. This fact must be recognized when designing systems for this environment. Much thought has been put into the DASH API to simplify its integration with existing RTDS applications and to familiarize controllers with the benefits of electronic data sharing. Second, a middleware product such as DASH is a prerequisite to large scale inter-application cooperation. It lays the foundation for this by providing a common tool for all developers to use regardless of whether their system is a small procedural monitoring system or a complex expert system.

A significant accomplishment for DASH has been its successful demonstration in the MCC, where it is used to communicate electrical bus states from the bus loss smart system to the configurable real-time analysis system (CRANS). It has also been used to transmit Shuttle remote manipulator (RMS) data from the RMS decision support system to a version of CRANS used for failure impact and procedure analysis. DASH is also being used to share data between the task analysis/report generation tool knowledge acquisition software and the C language integrated production system expert system shell.

Future work in this area will include the development of APIs for programs written in languages other than C or G2; migration to non-UNIX platforms; the addition of communications mechanisms other than transmission communication protocol and user datagram protocol, as well as other robustness enhancements; and the possible integration of DASH concepts into the telemetry data acquisition programs in the new Consolidated Control Center.
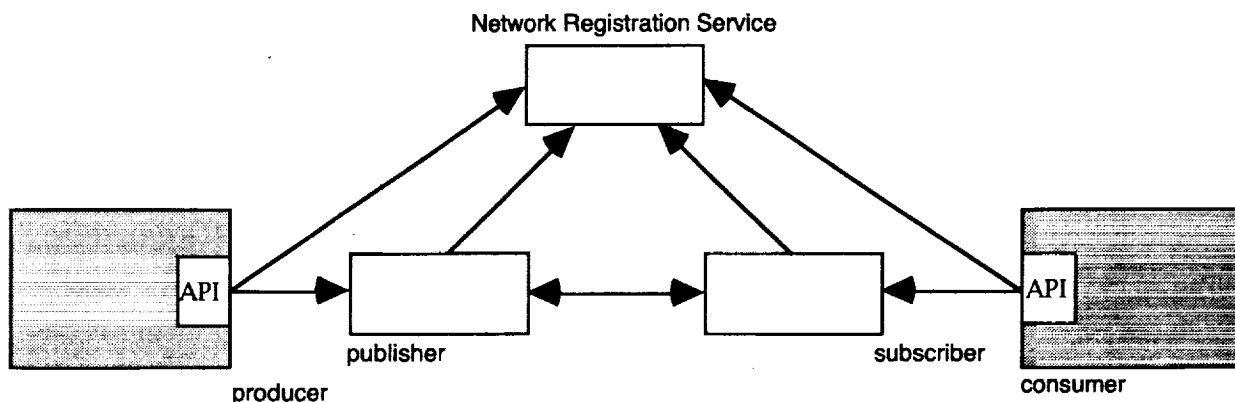

> Figure 1. The simplest DASH configuration—one consumer and one producer.

Development of PVAT—A Video Analysis Tool for Microgravity Posture Evaluations

TM: Frances E. Mount/SP34
PI: Tim McKay/LESC
            Mihriban Whitmore/LESC
Reference: HST 4

The knowledge on how humans live and work in space is necessary for planning missions. The ability of crewmembers to sustain quality performance determines mission success. Although factors affecting productivity are generally recognized, there is a need for a well defined, quantitative methodology to investigate the impact of behavioral factors on crew performance, operations and scheduling, and design parameters. It is important to understand the effects of microgravity on human performance. This information can help engineers design and modify the microgravity environment to optimize crew safety, comfort, and productivity. One factor of interest is microgravity posture, which can be impacted by the interaction of the operator with the physical environment. There is a need to identify and further quantify the relationship among the work activities, working posture, and workplace design so that postural stress can be quantified and the specific causes of awkward posture identified.

Several systems have recently been developed for measuring working posture. However, most of these systems require that specific reference points be identified prior to classifying the working posture. These types of tools are ideal when the analyst has control of the data collection procedures. Unfortunately, strict control over microgravity working posture data collection is not always possible or feasible because of hardware, flight, and schedule timeline limitations.

The primary means of obtaining microgravity working posture data has been through video downlinks and recordings, including supplementary in-flight and postflight questionnaires. Observational analysis of footage for various Shuttle missions has revealed that important, if not critical, information (e.g., general postures, duration, frequency, and design issues) can be extracted if a uniform methodology is devised. In response to this need, the posture video analysis tool (PVAT) was developed by the Human Factors and Ergonomics Laboratory (HFEL) at JSC. The purpose of PVAT is to provide a structured and controlled methodology for extracting and classifying microgravity working postures from video footage, particularly for nonexperimentally controlled footage (i.e., not recorded specifically for experimental analysis). The goal of PVAT is to identify potential design problems which may affect microgravity working posture and human performance. Such information could then be used to help focus attention on design issues requiring more rigorous ergonomics and human factors evaluation. It should be noted that PVAT does not obviate the need for the traditional techniques of data collection and assessment. On the contrary, PVAT has been developed as an intermediate system to help reduce the massive amounts of data. The data is then analyzed with off-the-shelf systems such as ARIEL system, Motion Analyzer, or Vision 3000 for further quantification of the critical working postures.

PVAT is an interactive Macintosh menu and button driven SuperCard™ software prototype consisting of several input and output screens. The objective of PVAT is to provide the analyst with a predefined set of options associated with microgravity postural assessments and human performance issues. Prior to the video analysis process, the analyst must first define the assessment parameters. These parameters are entered using keyboard and pulldown menu selections from the PVAT setup screen (fig.□1). For reference purposes, the analyst can enter the particular video footage title, video camera location (if known), task description, and the analyst's name (Rater). The Rater information may also be used to determine inter- and intra-rater reliability.

Shown in figure 1, the remaining input parameters, subject code, camera view, posture description, posture classification and rating scale, are considered to be the more critical entries. Subject code is an identifier entered by the analyst to clarify which subject is being observed from the

video footage. This is important since tasks performed in microgravity often require two or three crewmembers. Camera view is a pulldown menu selection input that helps describe the camera position at the time of recording. To access the menu, the analyst simply clicks and holds the mouse down over the entry field. Six view options are listed in the camera view menu (top, bottom, front, left side, right side, angle) as well as another option. The importance of this entry is that certain postural positions and movements may be better ascertained given different camera views. Such information could then be used to justify additional video view coverage for future missions.

Postural description and classification both refer to the target assessment behavior. As with the camera view entry, the postural description input is made via a pulldown menu. The options available are grouped into three sections. The first set of options describe the overall posture most often observed in microgravity, i.e., neutral body, horizontal, vertical, and transverse. The second group of options may be selected as an additional descriptor variable to the first category (e.g., neutral body - neck) or as the only option (e.g., neck). In either case, the analyst is given the freedom to choose between the two categories or to enter an altogether different descriptor using other.

The postural classification entry is divided into two parts (fig. 1). Inputs to these fields are made by selecting two options from any one of the A through E pulldown menu. The selections made will be the target behavior associated with the postural description, e.g., neck flexion versus neck extension. To further describe the target posture, a rating scale option is included. Once analysts have selected the postural classification, they must specify how they will rate the target behavior. The rating scale input is made via a pulldown menu. At the moment, there are two scale rating options "mild/severe" and "slow/fast," as well as "other." For this prototype version, the rating is performed using a 3-point scale where the midpoint represents neutral.

Once all these entries have been completed, the analyst presses the Set Startup button to initialize the program. A control box resembling a stop watch and a blank data screen appear as depicted in

figure 2. Other features of the PVAT prototype include the ability to use the keyboard number pad to input the rating values associated with each posture classification, a terminology and definitions library, a small animation illustrating selected posture classifications, on-line help print report capability, and basic data reduction summaries, (i.e., frequency and duration). Once the setup is complete, analysts may begin monitoring the selected video footage and making their posture classification ratings directly into PVAT. Each posture classification rating is stored and time stamped automatically. Having completed the assessment process, analysts can then summarize the data in terms of posture classification frequency and overall duration.

Posture is an important aspect of workload and a potential limitation on time and/or effectiveness of an operator's performance (Corlett, et al., Ergonomics, 1979). PVAT provides the initial step in identifying limiting microgravity postures and related workstation design concerns. Furthermore, it may provide analysts with supporting data to specify adequate microgravity posture or safe duration for certain microgravity postures perceived as potentially dangerous.

Future plans are to conduct usability testing of PVAT, to finalize the design, and to make it available for human factors engineers. Plans have been made to use PVAT for the human factors microgravity evaluations conducted on board Shuttle and KC-135 reduced gravity aircraft. It is also anticipated that PVAT will be applicable in a host of industries with little or no modification. It can contribute to various aspects of workplace design such as training, task allocations, procedural analysis, scheduling of timelines, and hardware usability evaluations. In addition, a video analysis paradigm for use in human factors microgravity evaluations will be developed and documented for future reference.

Startup

Video Title

GPWS Study (KC-135)

Camera Location

Front Cabin

Rater

Kent

Subject Code

F1

Task Description

KC-135 Flight study looking at fine motor manipulation and object handling inside Glovebox mockup.

Other

Flight Day 1 (March 1993)

Body Orientation

Neutral Body

Body Part

Neck

Camera View

Left Side

Body Movement & Rating Level

1   **Flex/Extend**

     Mild - Severe

2

Behaviors & Activities

[A - I] [K - R] [S - Z] [Other]

Twist

[Clear]   [Setup]

Figure 1. PVAT setup screen.

Output

Body Orientation	Body Part	Camera View	Subject Code
Neutral Body	Neck	Left Side	F1

Press Start

1:41:17	Flex Mild
1:41:28	Extend Severe , Twist
1:41:37	Nominal

Flex

◯ **Mild**

◯ **Severe**

Extend

◯ **Mild**

◯ **Severe**

[Nominal]

[Unsure]

[Clear Last]

Behaviors/ Activities

[Twist] [ ] [ ] [ ]

[ ] [ ] [ ] [ ]

Start [1:41:11]   End [1:42:11]   [Pause]   [Notes]   [Clear ALL]   [Start]

Figure 2. PVAT output screen.

Human Factors Studies Aboard STS-57/SpaceHab-01

TM: **Frances E. Mount/SP34**
            Susan Adam/SP34
PI: **Tim McKay/LESC**
            Mihriban Whitmore/LESC
Reference: **HST 5**

A collection of human factors studies was conducted by the Human Factors and Ergonomics Laboratory (HFEL) aboard STS-57 to investigate human capabilities and limitations in microgravity. Most of the experiments were performed within the SpaceHab module, which provides a shirt-sleeve working environment for the completion of scientific evaluations. The SpaceHab module occupies approximately one-fourth of the payload bay and contains storage space equivalent to 50 middeck lockers. A tunnel links the module to the middeck. The human factors studies performed focused on neutral body posture, translation, lighting, sound, and the use of electronic procedures.

In the neutral body posture study, 26 anthropometric body measurements were taken of the six crewmembers prior to the flight. The crew represented 5th to 90th percentile statures. The posture evaluation was performed late in the mission in the middeck of the Orbiter. Two video cameras and one still camera were placed in fixed locations to capture all body segments and limb angles. During each test session, the crew donned shorts, tank tops, and blindfolds and were instructed to assume a relaxed posture that was not oriented to any work area or task. Crew postures were recorded as they were rotated 360° in 45° increments. Posture data were compared with the postures identified in NASA-STD-3000 (Man-Systems Integration Standards).

Results showed that not a single crewmember exhibited the typical neutral body posture specified in NASA-STD-3000. Two extreme postures were exhibited by the crew (fig. 1):

- A pitched-forward posture, with an extreme bend at the knees

- An elongated, almost standing posture

The findings suggest that construction of several composite postures or a range of postures may be more constructive for design purposes than any single neutral body posture definition.

The primary focus of the translation study was the evaluation of transfer times and strategies of crewmembers moving through the 9.6 foot SpaceHab tunnel. Video cameras were placed in view of the tunnel entrances and interior. Crewmembers were videotaped moving through the SpaceHab tunnel in the course their regularly scheduled work, early and late in the mission. Crewmembers recorded translation times and strategies via an electronic questionnaire.

Overall the translation time early in the mission was greater than the translation time late in the mission, as expected. The equipment transfer time was slightly greater than the crew translation time, especially when the equipment was sensitive or large in volume. The crew found the design of the tunnel entrance and the placement of handholds to be acceptable. They did not use their feet during the tunnel translation. It was observed that both hands were used to drag the body, with arms stretched out to their sides when no equipment was transferred. However, hand push-offs were done beneath the body when carrying objects.

The lighting evaluation represented the first time that systematic light intensity measurements were taken on the Orbiter during a mission. The crew used an exposure meter to measure the in-flight light levels on the middeck, flightdeck, and SpaceHab module.

All light levels met the required brightness ratios and were rated as acceptable by the crew; however, on occasion, sun shafting through the aft and overhead windows washed out the normal illumination and caused glare on the monitors and electronic displays. Additionally, some crewmembers noted that areas along the SpaceHab outer walls were noticeably dimmer than the general or central areas when the auxiliary lights were not in use.

The objective of the sound study was to evaluate current Orbiter and SpaceHab acoustic conditions. Ten noise measurements were completed by the

crew in the flightdeck, middeck, and SpaceHab module (fig. 2).

Acoustic levels were approximately 63 dBA on the flightdeck and 62 dBA on the middeck. Sound levels in the SpaceHab module varied widely and were inconclusive due to measurement problems encountered; they are estimated to have been in the 63 - 66 dBA range. All measures were within the acoustic specification of 68 dBA. Crew comments were collected via questionnaire. Significant variability was found in the ratings, demonstrating that susceptibility to noise is highly individualistic. Overall, mission tasks were not significantly impacted by noise; however, noise levels did necessitate the use of earplugs during sleep. The ability to concentrate, relax, and communicate verbally were also reduced. Fatigue and headaches due to noise levels were cited by some crewmembers. While three crewmembers found the noise levels acceptable for the current mission length, only one believed it to be acceptable for a six month mission.

The electronic procedures study sought to define human factors requirements for electronic procedures in space environments. A computer-based task simulating a spacecraft control task was completed by one crewmember using first paper and then computer procedures (fig. 3).

The computer procedures were completed more rapidly and were preferred by the crewmember. Procedures with voice input were attempted with a soldering task, but technical problems prevented completion of that portion of the test. Results suggest that computer procedures could be used in the future in place of paper procedures to increase productivity and access to information. More work remains to be done regarding the application of voice input technology.

Data collected from these human factors evaluations will be used in the development of human factors design standards. In addition, where applicable, recommendations for improvements in Orbiter hardware design, training requirements, procedure definition, and timeline development will be provided to NASA. Issues requiring further work will be proposed for study on future missions.

Figure 1. Two extreme neutral body postures exhibited on STS-57.

Figure 2. The STS-57 commander takes a sound measurement in the SpaceHab.

Figure 3. Crewmember performing electronic procedures task.

Human Workload Analysis

TM: Barbara Woolford/SP3
PI: Manuel Diaz/LESC
Reference: HST 6

Future manned space missions will represent unprecedented expansion of civilization into the solar system. The Space Station will permit crews to live and work in Earth orbit for 90-day intervals, and perhaps longer. Lunar outposts will demand that crews work routinely in a harsh extraterrestrial environment, conducting scientific experiments and eventually supervising complex operations such as resource utilization. The proposed mission to Mars will involve outbound and return flights of a combined duration of one to three years, including time spent working on the planetary surface. As spaceflight becomes increasingly complex and of longer duration, astronauts are likely to encounter greater workloads. Human performance under various workload conditions, critical to the success of spaceflight, has only recently begun to be studied systematically.

The need to assess workload becomes even more critical in a Shuttle mission such as STS-61 which repaired and serviced the Hubble Space Telescope (HST) in December 1993. A committee review done before the mission stated that the mission was achievable but risky because of the growing workload, tight schedule, and management complexity. The independent panel noted that the timeline for EVA was "very tight, having grown 25% in the period of our review, and continues to grow." Indeed, any additional component failures would have required additional tasks to have been added. The list of repairs grew to fill an 11-day flight, with at least 5 consecutive days of EVAs by alternative pairs of astronauts, making it by far the most ambitious Shuttle EVA plan.

To date no attempts have been made to assess the workload imposed by tasks during intravehicular (IVA) or extravehicular activities (EVA), and yet of all activities performed by humans in microgravity, those performed outside the pressurized modules are the most dangerous. Clearly, there is a requirement to develop methodologies for workload measurement and a

need to identify points during a mission that may result in excessive workload.

The human workload analysis project initiated in 1992 seeks to advance current understanding of mental workload in microgravity through the use of computer simulation and performance modeling techniques. The Crew Interface Analysis section completed an initial evaluation of the usefulness of these techniques through an analysis of the remote manipulator system (RMS) deployment on STS-37. In a more comprehensive evaluation, models of the wide field/planetary camera (WF/PC) replacement during the STS-61 HST servicing mission were developed.

The work involved the development of a workload component scale of IVA/EVA tasks and translation of the scale to reflect points during HST servicing that could result in excessive workload. The scale is depicted in table 1.

Table 1. Workload Component Scales

Scale Value	Task
	Motor Processes
0.18	Discrete Activation
0.49	Translation
0.52	Ingress/Egress
0.60	Restrained Manipulation
0.65	Compensatory Tracking
0.69	Translation With Equipment
1.10	Unrestrained Manipulation
	Visual Processes
0.28	Confirmation
0.30	Discrimination/Identification
0.47	Comprehension
0.49	Status Monitoring
0.61	Alignment and Orientation
	Mediation Processes
0.24	Alternative Selection
0.49	Estimation/calculation
0.65	Plan Formulation
0.78	Problem Solving
	Auditory Processes
0.53	Comprehension
0.58	Discrimination

It was believed that the driving force for this mission was excessive workload, possibly leading to fatigue and exhaustion. Examination of the points during HST servicing that resulted in excessive workload lead to recommendations concerning the

- Expectation of degraded performance
- Need to change task allocation across crewmembers
- Need to expand the timeline
- Need to increase the number of EVAs

Figure 1 depicts accumulated motor workload estimates for each crewmember during each phase of WF/PC replacement. Figure 2 presents workload as a ratio of scale values and phase completion time. Initial results suggest that phase 2 (installation of WF/PC I into the temporary parking fixture) and phase 4 (installation of WF/PC II into the HST) were the most demanding activities. Installation of WF/PC II was anticipated to be particularly demanding due to the frequency and duration of activities requiring manipulation of WF/PC II. Also, more effort was predicted to be required of extravehicular activity crewmember 1 (EV1). This may be due to a lack of portable foot restraints.

Although the preliminary results are quite rudimentary in nature, it is believed that the methodology described provides an objective approach for evaluating the workload that astronauts are likely to encounter in EVAs. Ultimately, the methodology developed during this program of investigation will lead to a number of products that will be applied to future task network simulations of the workload likely to be experienced during future EVA activities, including

- Validated workload component scales for rating the visual, auditory, motor, and mediation components of workload
- Methods for evaluation of the workload imposed by concurrent EVA tasks
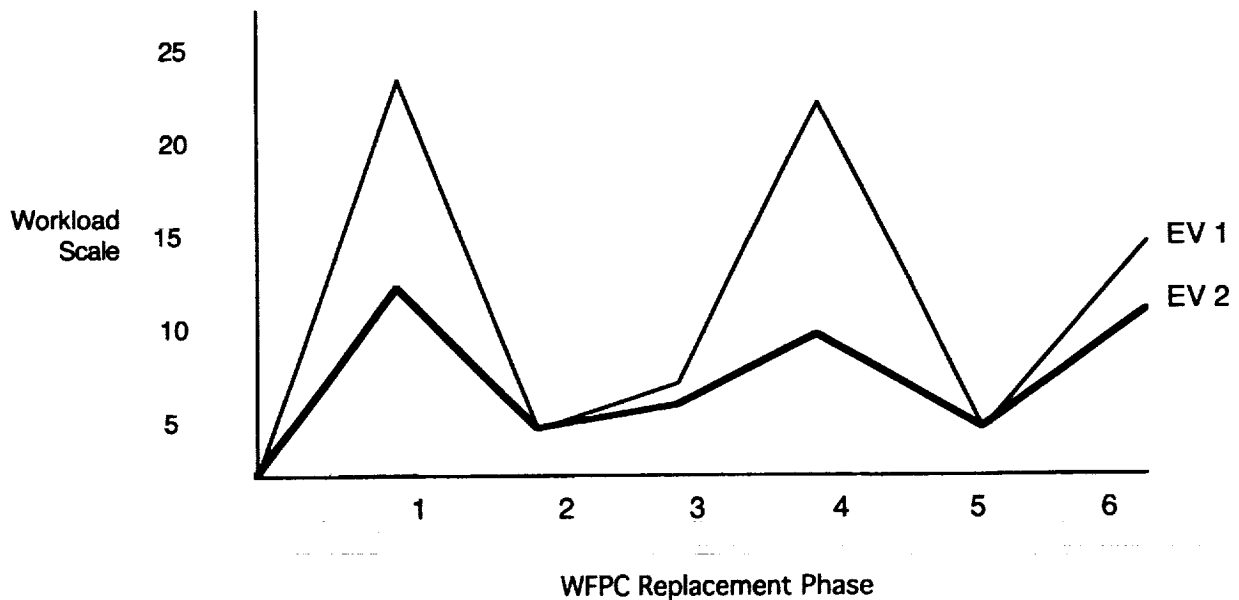- Strategies for reducing workload during EVA
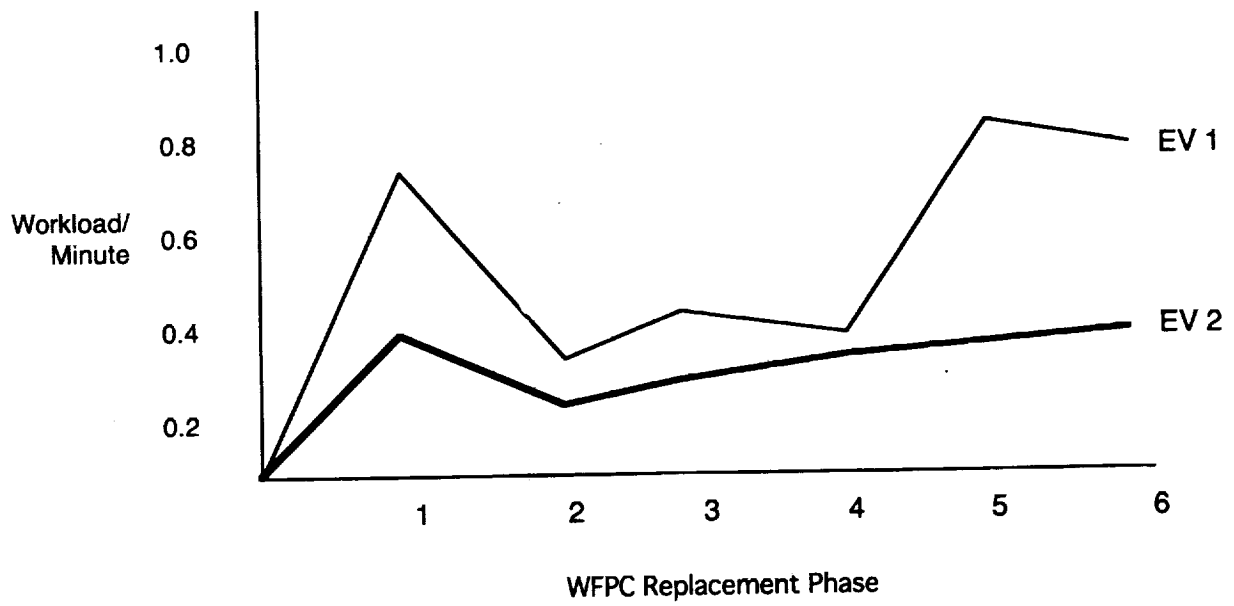

Figure 1. Accumulated motor workload.

Figure 2. Accumulated motor workload per minute.

Development of a Rapid Algorithm for Human Computer Reaching

PI: **James C. Maida/SP34**
Abhilash K. Pandya/LESC
Michael Goldsby/LESC
Ann M. Aldridge/LESC
Reference: HST 7

The Graphics Research and Analysis Facility (GRAF) at NASA JSC has developed a rapid algorithm for computing realistic human reaching. The method of determining arm joint angles from the posture of the hand is a simple look-up table approach. This approach is extremely fast and always gives a solution if one exists. The algorithm has been applied to an anthropometrically correct human model and used in a 3-D computer graphics system and a virtual reality (VR) system.

To generate our look-up table, all the arm joints of the computer figure were exercised through their range of motion. This generated vast amounts of data relating the position and orientation of the palm to the joint angles necessary to achieve these postures. This data was organized into a grid of positions, with a grid of orientations for each position. Various methods were used to prune the redundant data initially contained in this table. A strength criterion, which assumes that the human body uses maximum strength as the preferred position for the joint chain, was used initially to prune the solution set. For EVA motion, we also considered looking at joint postures closest to neutral body posture for pruning the data.

This reach look-up table application was installed in the PLAID 3-D interactive graphic system used in the GRAF lab. The user can "fly" the end effector using keyboard commands, and the look-up table fills in the joint angles to produce an accurate reach. Reaching is a complicated task, usually involving the entire body and not just the arms. The challenge is to reproduce an accurate reaching motion for the computer figure. Consider a scenario with an EVA crewmember attached to a portable foot restraint (PFR). With his feet constrained, this EVA figure must reach by moving his legs and waist as well as his arms. To move the waist as an "end effector, " a separate look-up table of leg motions was generated.

The user can then "fly" the waist as well as the arms to get motion with the PFR constraint. This application allows computer animations to be generated with greater realism and speed. Formerly, human motion for animations was guided by providing commands to control each joint individually, a tedious procedure which often produced unnatural motion (fig. 1).

GRAF has also incorporated this human reach model into a VR system. In our system the motion of the subject can be monitored using 4 magnetic trackers: one on the back to determine motions of the torso; one on each palm to determine posture of the hands; and a fourth on the head to monitor head motion for viewing purposes (figs. 2 and 3). The tracker on the back is processed first. Translation motions of the tracker are used to move the figure's waist position forward and backward. If the figure is constrained to a PFR, a look-up table determines the joint angles necessary to keep the feet attached to the PFR. Orientation of the tracker is used to rotate the waist until the computer figure has the correct back orientation. With this new body orientation, the tracker on the head is processed to determine the neck motion necessary to give the correct viewing direction. The trackers on the hand are used to get a position and orientation in space relative to the shoulder of the computer figure. Our arm look-up table algorithm is used to give solutions for the joint angles needed to obtain these postures.

The advantages of the look-up table are

- That a solution, if one exists, is always obtained

- Many criteria such as strength, posture, or task dependencies may be applied to select the correct set of solutions

- It is very fast (three orders of magnitude faster than the inverse kinematics routine used in our lab)

The one disadvantage is that the resolution of the solution is dependent on the table size, and even with moderate resolution, the table size may be enormous (e.g., a 2-inch resolution requires 1.2 million data points). We are looking at ways of interpolating between data points to improve resolution and at ways of representing the data in a

more compact form. Various other techniques
such as neural networks and fuzzy logic are also
being explored. In the hope of further increasing
the realism of the solutions, a look-up table will be
constructed using data collected by tracking the
actual movements of human subjects instead of
arbitrarily exercising joints in the computer figure.
A comparison of the results from inverse kinematic
solutions, arm motion tracking, and look-up table
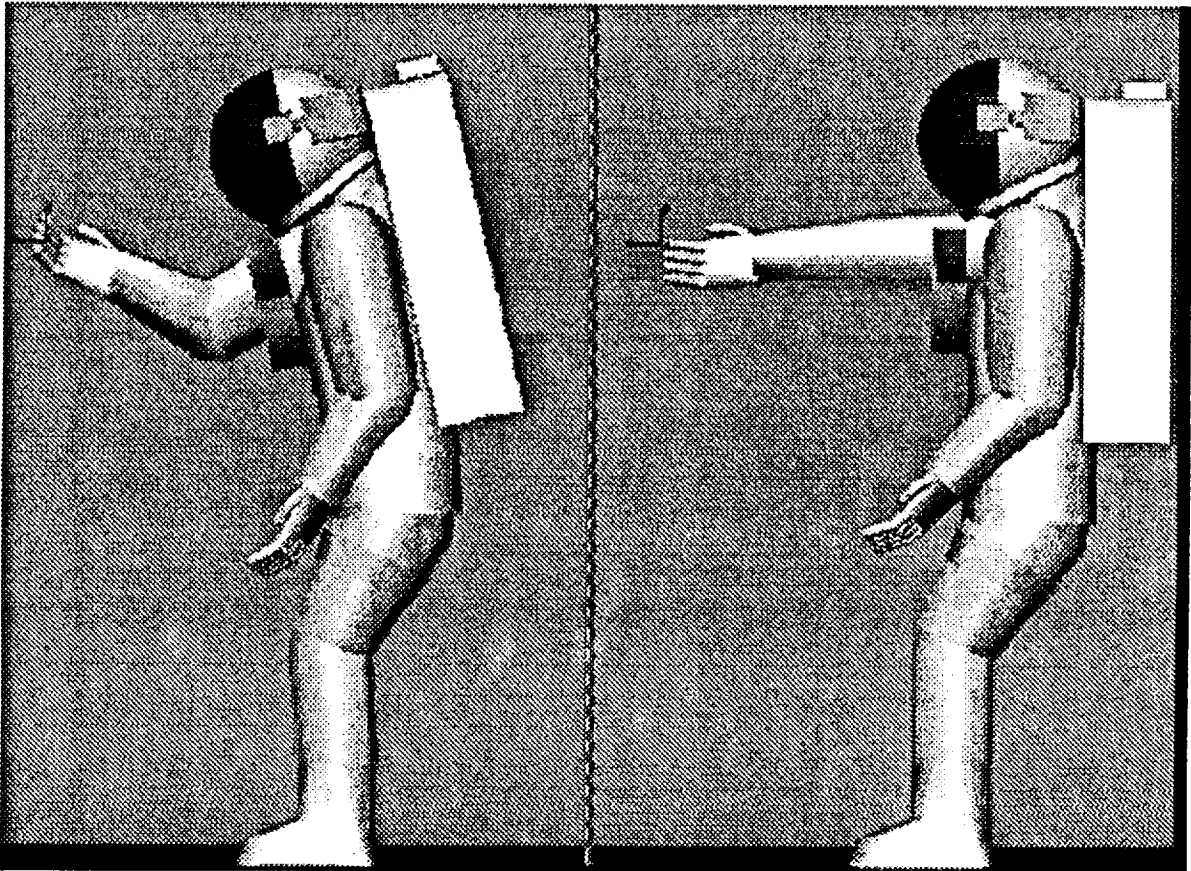solutions will be done.

Figure 1.   Old method of animating human motion in which commands were provided to control
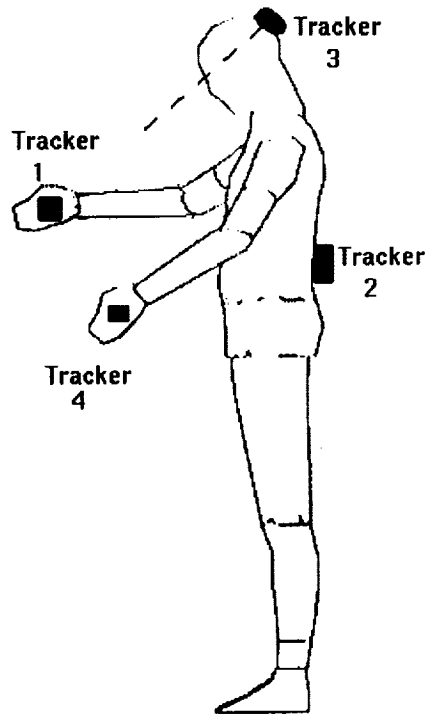each joint individually.

Figure 2. Positions of the 4 magnetic trackers used to monitor the figure's motion.
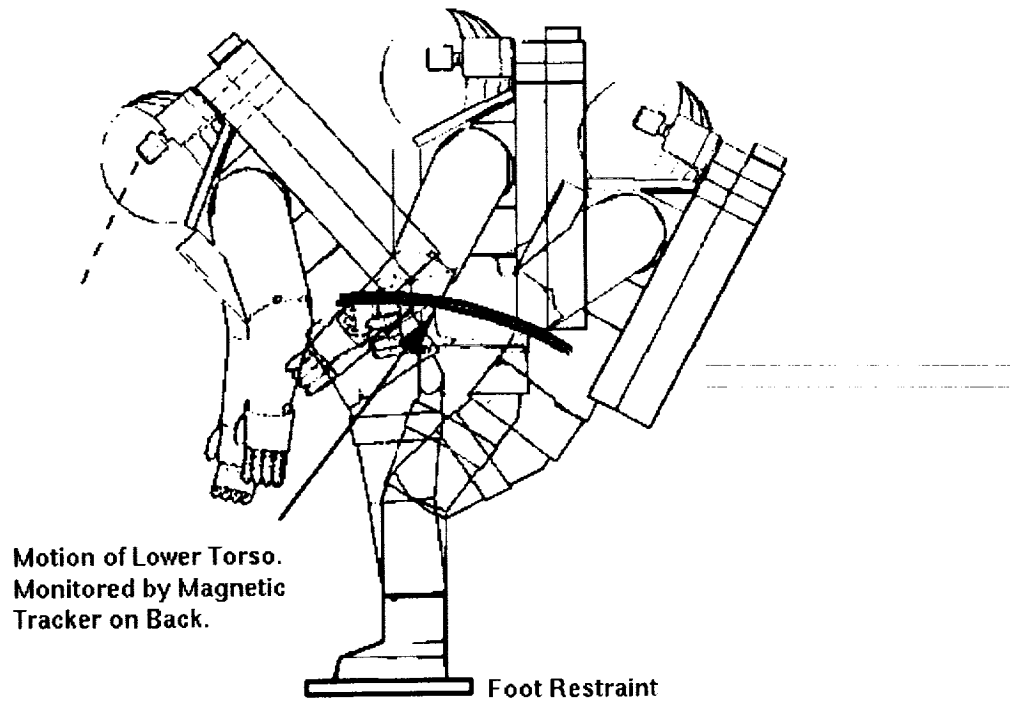

Motion of Lower Torso.
Monitored by Magnetic
Tracker on Back.

Foot Restraint

Figure 3. Translation motions of the tracker on the figure's back.

Development of Full Body Dynamic Human Strength Model

PI: James C. Maida/SP34
Abhilash K. Pandya/LESC
Ann M. Aldridge/LESC

Reference: HST 8

Planners, engineers, astronauts, and researchers who are concerned with "man-in-the-loop" activities are relying on the computer models of humans and their environments as one of the tools available to assist them in solving human fit and function problems. A full-body human strength model which allows strength predictions of a variety of tasks would be an important part of this modeling system.

A human arm strength model based on empirical data has been developed at the Graphics Analysis and Research Facility (GRAF) (Pandya, et al., NASA TP 3207, June 1992) (Pandya, et al., NASA TP 3206, June 1992). In a previous effort, the shoulder, elbow, and wrist joints were character-ized in terms of maximum isolated torque, position, and velocity in all rotational planes using a Lido, Inc., dynamometer. A ratchet wrenching task was modeled. In the modeling process when a joint motion occurred, the axis direction, angle, and speed of motion were mapped to an appropriate joint torque polynomial (derived from the collected data) and a torque value was returned. Based on the anthropometrics of the arm and the isolated joint torques generated for a ratchet wrenching motion, a force vector computation was done to derive the final torque at the ratchet center. Results indicate that forces derived from a composite motion of joints (ratcheting) can be predicted from isolated joint measures. Efforts are currently underway to systematically extend the database of strength information used by this model to encompass all major joints of the body. In addition, more complex motions are being collected to further test and validate the strength model.

Isolated joint strength measures were taken for the ankle, knee, hip, shoulder, elbow, and wrist joints for 15 subjects. The isokinetic velocity ranges were chosen so they were within the range of the multi-joint motions.

Previous validation of the strength model was based on isokinetic (constant velocity) motions. Typical motions in the real world involve isotonic motions (constant mass) with variable velocities. Kinematic and torque data were collected for each subject for three different ratchet wrenching tasks using the LIDO multi-joint II dynamometer. Task one involved ratchet wrenching in the frontal plane with the right hand initially at face level moving through a 60° range. Task two was also in the frontal plane; however, the initial position of the right hand was at chest level. Task three involved ratchet wrenching in the sagital plane with the axis of rotation at the height of the right greater trochanter. These tasks were collected using isotonic loads of 5, 15, 25, and 35 lbs and also in an ioskinetic mode at 120°/sec. A force plate was used to determine the ground reaction forces during each task. Prior to performing these tasks, each subject had 2-cm diameter retroreflective balls attached to the right foot, ankle, hip, shoulder, elbow, wrist, and hand. Each task was videotaped using two video cameras simultaneously to enable 3-D motion analysis. This video data was digitized, transformed, and smoothed using the Ariel performance analysis system (APAS). The 3-D coordinates of each joint were obtained for one repetition of each load and speed. Joint ranges, angular velocities, and angular accelerations were determined for each joint. In addition, the speed of the actuator/ratchet arm was determined for the isotonic loads, since this was not known. This data will be used to further validate the strength model.

When a multi-joint motion occurs in the model, each joint angle and instantaneous velocity will be extracted from the motion analysis data, the appropriate force function (from the isolated joint measures) will be invoked, and the torque values returned. The force will then be computed at the end effector of interest and propagated into the modeled environment.

The data collection and transfer has been initiated. The modeling programs to compute the end-effector forces are in place. Figure 1 shows one of the validation tasks to be modeled.
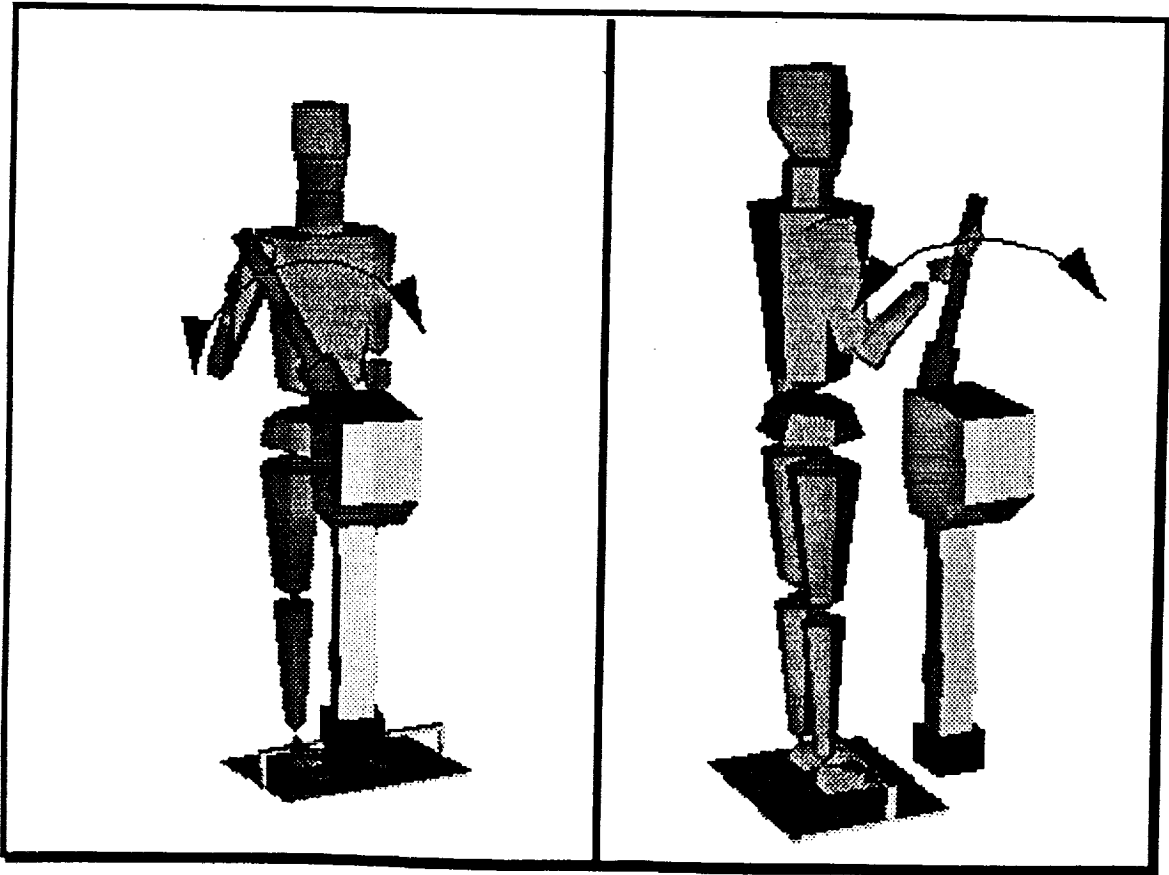
Figure 1. Human model doing a ratchet wrenching operation in the frontal plane.

Human-Computer Interface to Medical Decision Support Systems for Space

TM: Frances E. Mount/SP34
PI: Jurine A. Adolf/LESC
             Steven J. Wolf/LESC*
Reference: HST 9

Providing medical care to crewmembers in orbit is an important aspect of any space mission. As missions become longer and more complex, crewmembers will become increasingly independent of Earth-based support facilities due to uncertain communication with ground experts and improbable medical emergency rescues from a distance (e.g., lunar/Mars). Reliance on sophisticated health care delivery systems will become inevitable. In addition to a complete and accurate database of medical knowledge, crewmembers must be able to access the correct information in a timely manner. Therefore, the human-computer interface (HCI) is crucial to the overall success of medical decision support systems (DSS). Research is being conducted by the Human Factors and Ergonomics Laboratory (HFEL) personnel in the JSC Flight Crew Support Division to improve the design of HCIs to medical DSS.

After identifying several important HCI issues, HFEL personnel focused on diagnostic decision-making errors for a variety of reasons: relatively little research has been done, there were roots in psychological-based theory, and demonstrations of biases in medical environments have been reported. While a DSS could assist the health care provider at the points where decision making fails by eliminating biases, it may also contribute to systematic errors such as anchoring. Anchoring is the phenomenon in which the decision maker latches on to a starting point and does not make sufficient adjustments when new data are presented. In fact, anecdotal evidence suggests that anchoring may have been encountered when the Navy fielded a new diagnostic DSS on their submarines.

In a series of landmark papers in the field of cognitive psychology, Kahneman and Tversky demonstrated anchoring by asking subjects to estimate a proportion by starting at a random number and making adjustments. The first HFEL experiment replicated those results, shown in figure 1. The slopes of both lines in figure 1 were nearly the same, indicating comparable anchoring. Once the phenomenon had been confirmed with a basic decision task, HFEL personnel dissected the interaction between the user and DSS into several components. By analyzing each of these components, the HFEL hopes to fully understand the decision-making error.

The second experiment extended the first experiment by including an examination of the level of expertise of a subject domain. It was proposed that more knowledgeable users would anchor less because they would be able to rely on their own judgments more so than naive users. Figure 2 shows the anchoring results for subjects classified as novices, intermediates, and experts. Although all subjects anchored, preliminary results do not show any significant differences between levels of expertise. A follow-up experiment will be done to ensure an accurate operational definition of expertise. Also in this second experiment, a trustworthy starting point was provided to the subjects. It was hypothesized that more trust would result in more anchoring. Comparing the results of both experiments in figure 3, a more trustworthy starting point did dramatically increase the anchoring effect. Additional experimentation on sequential decision making, expertise level vs. trustworthy sources, and medical domain knowledge will be done. In fact, the next planned experiment will examine the effects of anchoring over many sequential decisions, just as a physician may make several differential diagnoses until the correct one is found. After all components have been examined, HCI design solutions that eliminate or reduce the effects of this anchoring bias will be developed.
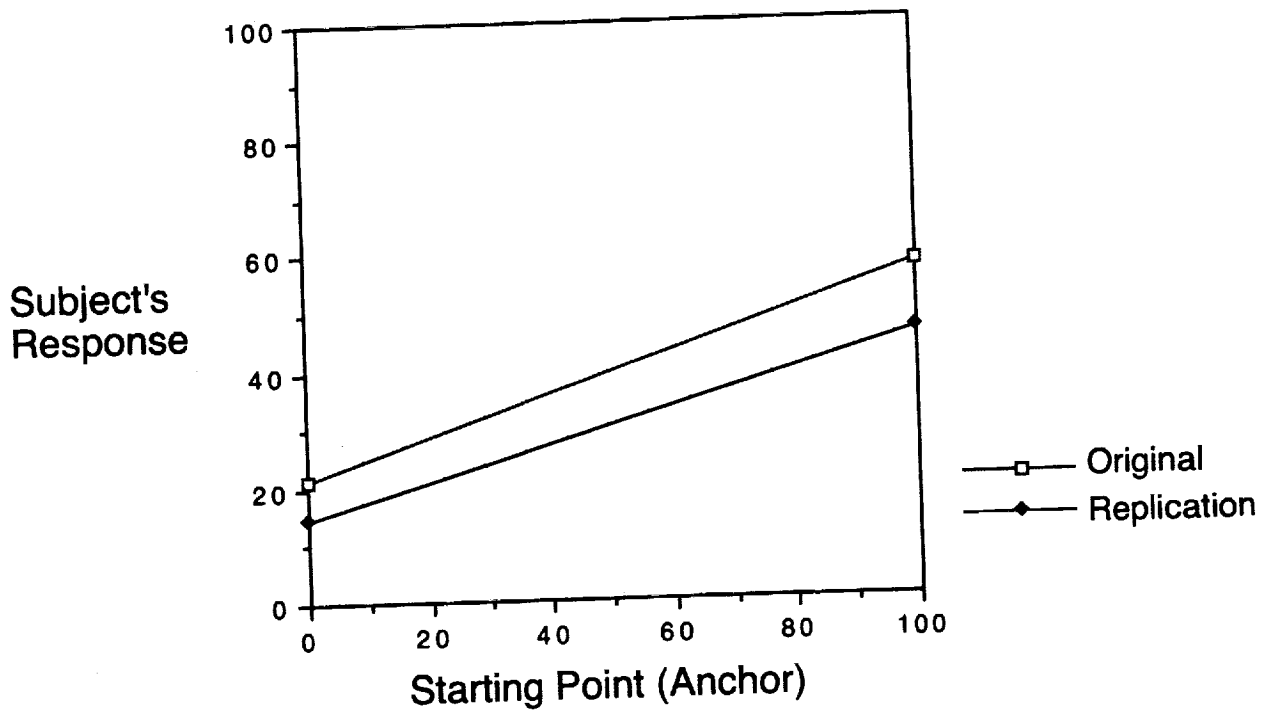
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* No longer with LESC

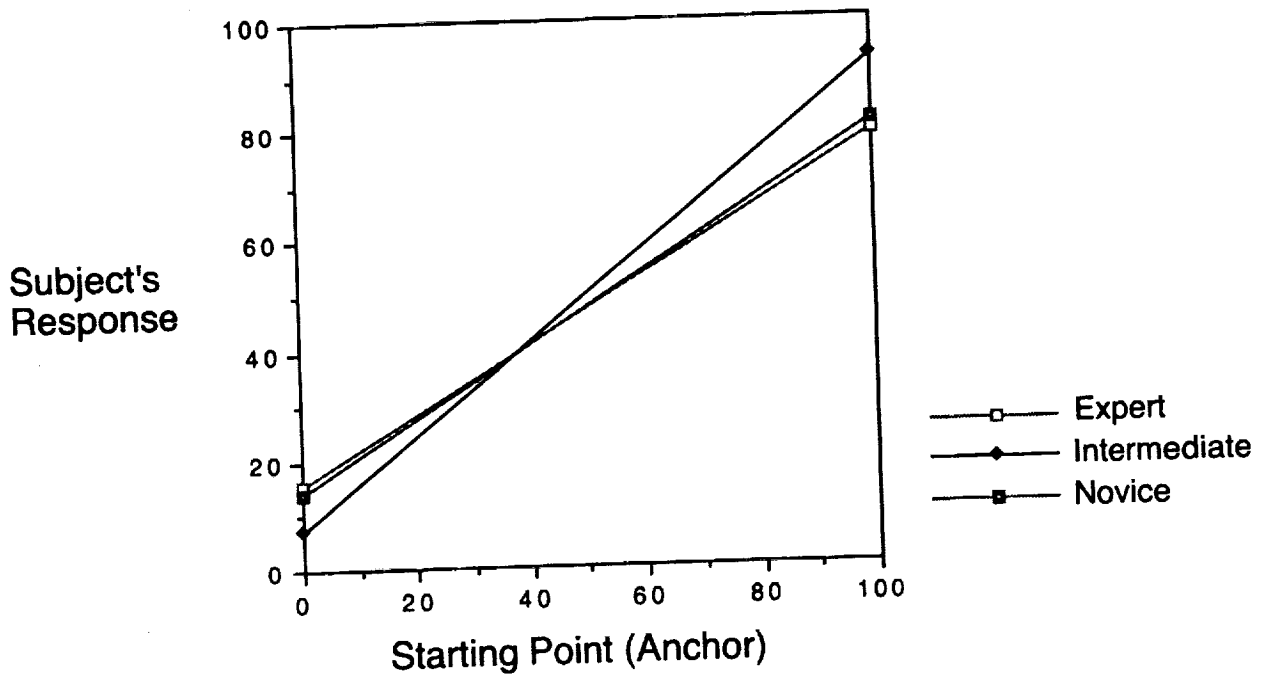Figure 1. Comparison between Kahneman and Tverksy's original and the HFEL's replicated experiment.

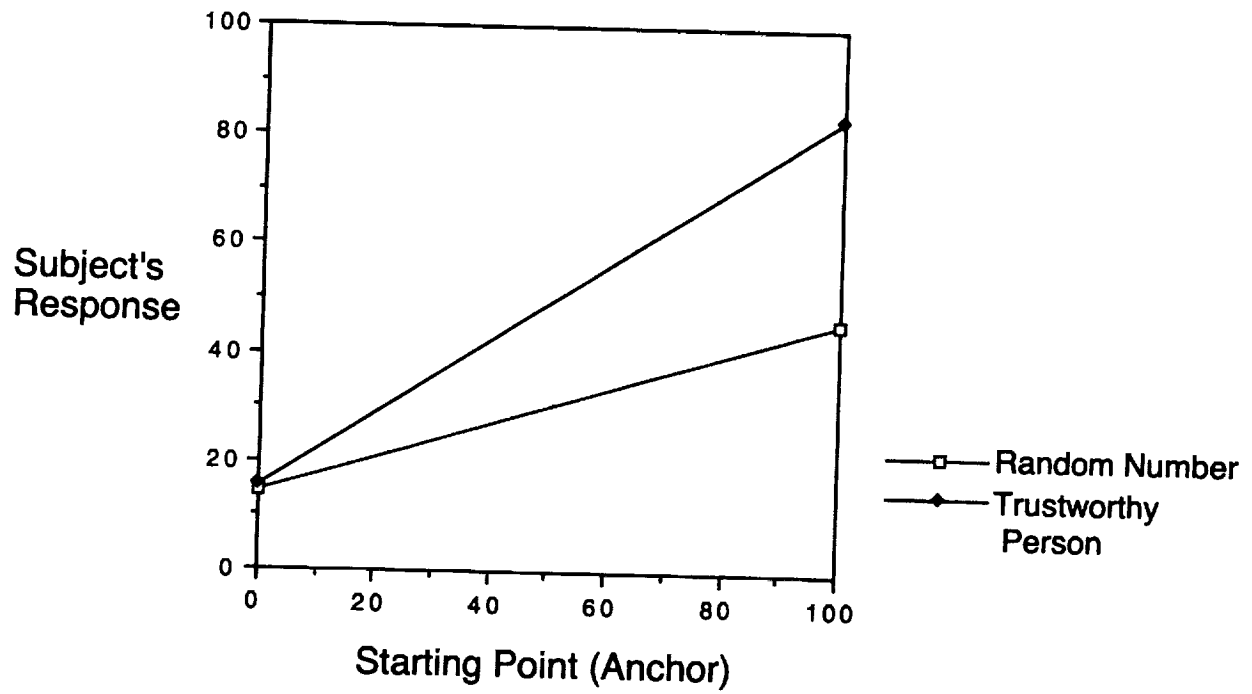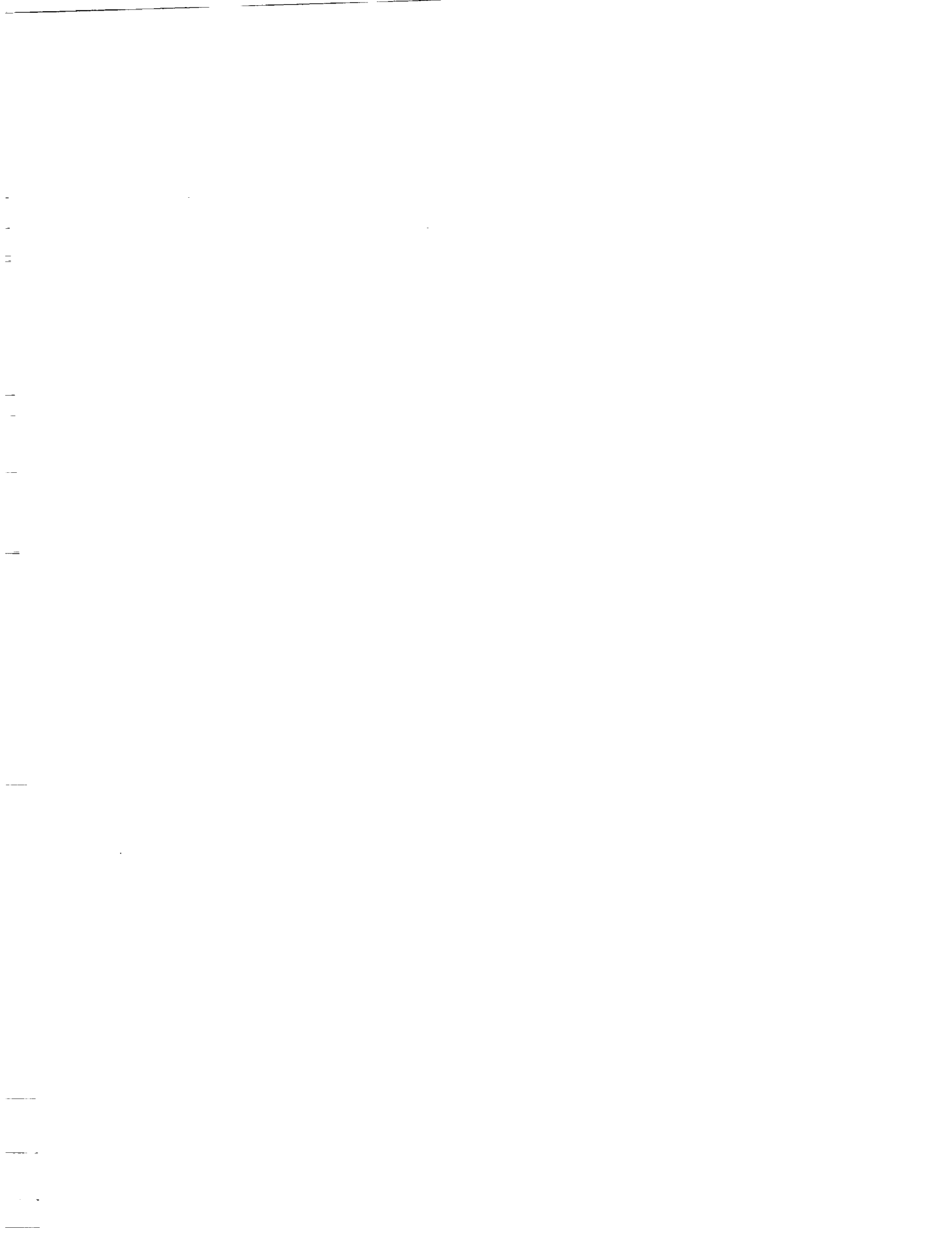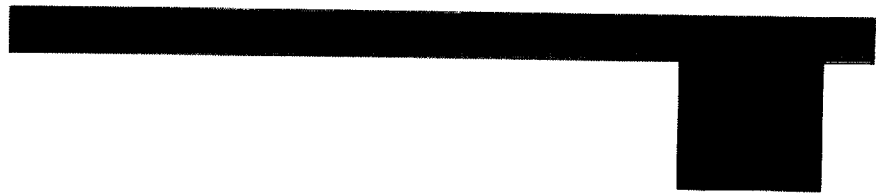Figure 2. Anchoring effects for three knowledge levels.

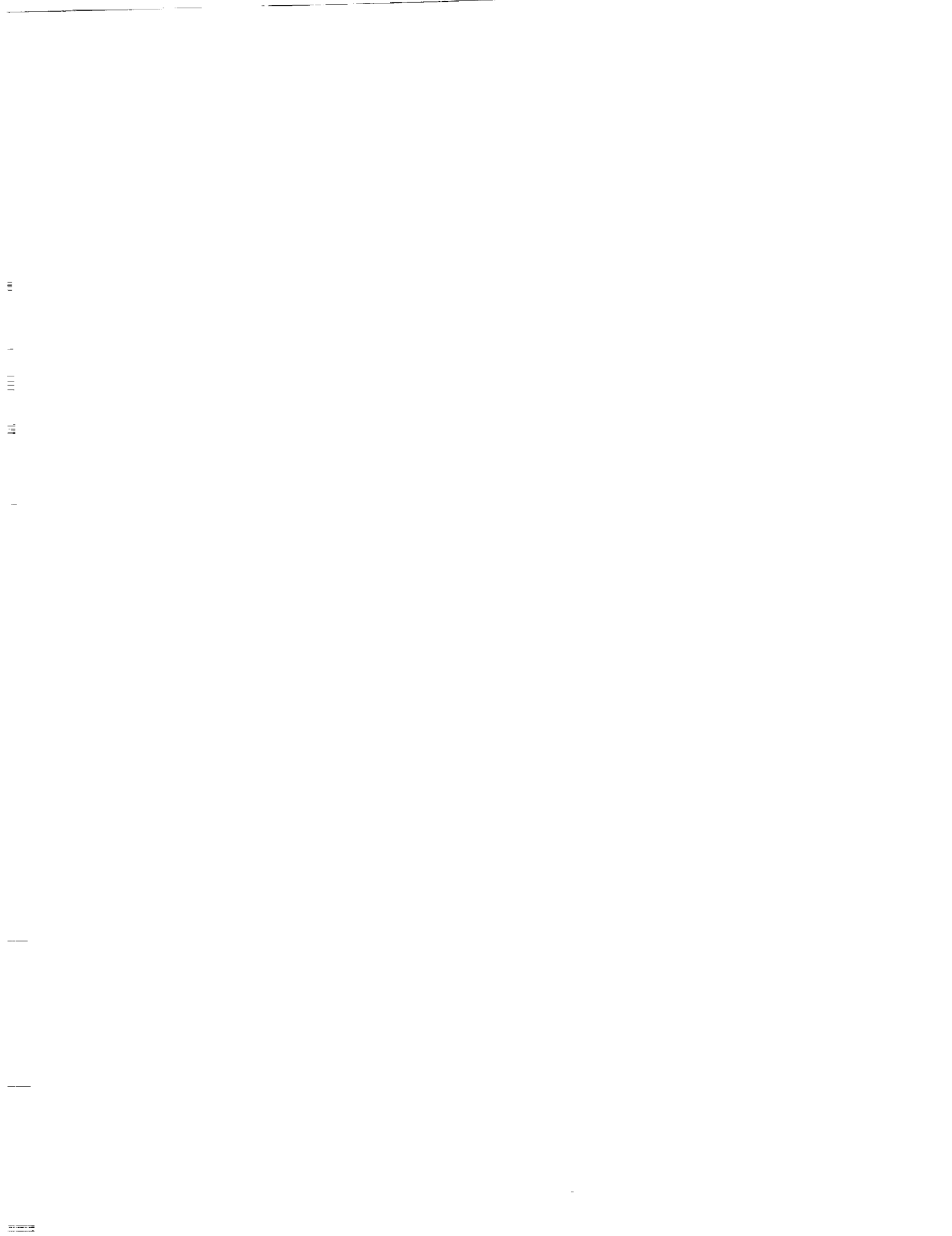Figure 3.   Comparison between HFEL experiments 1 and 2: source of anchor differs.

Section III

Solar System Sciences

Summary

Solar System Sciences Summary

Research at JSC in Solar System Sciences during FY93 covered a number of disciplines, was broad in scope, and varied in its relationship to science as a centerpiece of the missions of today and the future.

Highlights of the work this past year include 1) fabrication of instrumentation for the detection of volatiles in the soil of planetary surfaces, 2) two studies related to detecting and analyzing orbital debris, 3) two separate studies to spectroscopically detect water and organic material on asteroids, 4) the use of a tether to generate electricity and remove charge from a spacecraft in Earth orbit, 5) a study of synthetic soils to enable the growth of plants in space, and 6) the fabrication and testing of a radiation dosimeter for inclusion on a Russian spacecraft to Mars.

Exploration of planetary surfaces includes assessment of the composition of surface materials. Global characterization of Mars will require small instrument packages landed at selected sites through the Mars Environmental Survey (MESUR) program in the late 1990s. The Thermal Analyzer for Planetary Soils (TAPS) offers a specific implementation for the generic thermal analyzer/evolved-gas analyzer (TA/EGA) function included in the MESUR strawman payload. The purpose of the TA/EGA is to identify volatile-bearing minerals in Martian soils, including water-bearing clays, carbonates, nitrates, and sulfates. During FY93, the TAPS Mark-2 sensor test bed was assembled and used to validate in-house designs for sample collectors, sensors, and circuits.

Impactor residues in materials exposed on the Long Duration Exposure Facility (LDEF) are being studied to establish the nature and abundance of meteorites and debris in low Earth orbit (LEO), and also the effect hypervelocity impacts will have on spacecraft. Exposed in LEO for 69 months, LDEF continues to provide a wealth of information. New techniques were developed for the study of impactor residues in craters on LDEF surfaces.

Our understanding of the LEO particulate environment, including the composition of interplanetary dust particles and space debris, and critical information on its high-velocity interaction with spacecraft, is growing. These results will be useful to spacecraft engineers and planetary scientists.

Knowledge of orbital debris is broken into two size regimes. Knowledge of debris smaller than ~0.1 cm comes from studies such as above. The USSPACECOM maintains a catalog of objects larger than ~10 cm diameter, including debris, intact satellites, and rocket bodies. No statistically significant measurements of the debris environment in the range of 0.1 cm to 10 cm existed prior to 1990.

The Haystack radar has periodically observed debris in LEO since 1990. The measurements improve the estimate of the debris flux at Space Station altitudes. The Haystack measurements have reduced the uncertainty in the 1-cm-diameter debris environment. The project is now transitioning to monitoring trends and identifying sources of new debris. This will be greatly aided by the addition of the Haystack Auxiliary radar. This new radar will allow cm-size debris flux measurements resulting from satellite breakups.

A long-term goal of space exploration is the expansion of humans into space. The resources required to support this include water for life support. The identification of solar system objects as sources of water represents a significant step toward using in situ resources for survival.

Aqueous alteration of the near-subsurface material on asteroids and some satellites is part of the history of the Solar System. We unravel this history by observing the spectral properties of an object's surface. Aqueous alteration was discovered when an infrared feature indicating hydroxl (OH) and water in silicates was identified in the spectra of many asteroids. Additional evidence was provided by an absorption indicative of an Fe^{2+} - Fe^{3+} charge transfer transition. The quick identification of water has implications for both ground- and space-based research. Spacecraft near a planet or asteroid could survey

the surface for water. Spacecraft in low Earth orbit could survey all known asteroids for the purposes of future exploration.

Other spectral observations made this year identified porphyrins (ring-shaped, planar organic molecules) in the spectrum of the asteroid 2 Pallas. The identification of features in the reflectance spectra of solar system bodies provides clues to the conditions that formed or altered these objects. The presence of porphyrins on 2 Pallas places a maximum on the temperature experienced by that asteroid.

A new technique for dissipating electrical charge from spacecraft was tested with the Plasma Motor Generator (PMG). The Delta II rocket launched in June 1993 carried the PMG as a secondary payload. The PMG was the second in a series of three tether application payloads that are part of the Flight Demonstration Program sponsored by the Office of Space System Development. A low-cost experiment developed at JSC, the PMG assessed the effectiveness of using hollow cathode assemblies to deploy an ionized gas to "ground" electrical currents to space. The PMG also demonstrated that electricity can be generated, and that thrust and drag can be induced, by a moving tether in Earth's magnetic field.

Plants are considered an important part of regenerative life support systems for long-duration missions. In addition to supplying food, plants can regenerate air by converting CO_2 into O_2 and can convert waste water into potable water. The microgravity of space presents several problems for plant growth, however, such as providing a favorable root medium. To address this, a productive, synthetic soil, termed zeoponic plant growth substrate, has been developed for experiments on the Shuttle. The latest research on zeoponic substrates suggests that they can supply plant growth nutrients for long periods with only the addition of water. Zeoponics also has great potential for terrestrial applications.

Radiation presents a significant risk to astronauts during long-term stays in space. The only realistic method of decreasing this risk to an acceptable level is through added shielding. The shielding required is sensitive to the uncertainties in the estimated biological dose. This, in turn, is driven by our knowledge of the radiation environment and secondary particle production cross-sections. An instrument designed to directly measure the physical and biological radiation dose in space between Earth and Mars as a function of shielding depth was built and has been tested on two Shuttle flights.

Section III

Solar System Sciences

Significant Tasks
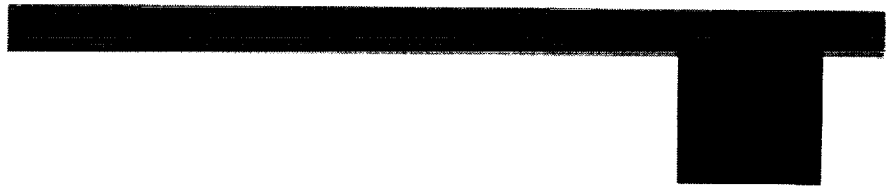
Thermal Analyzer for Planetary Soils (TAPS): An In Situ Instrument for Mineral And Volatile Element Measurements on Planetary Surfaces

PI: James L. Gooding/SN2
Reference: SSS 1

Exploration of planetary surfaces includes assessment of the chemical and mineralogical compositions of surface materials. Global characterization of Mars will include small instrument packages landed at selected sites through the Mars Environmental Survey (MESUR) program in the late 1990s.

TAPS offers a specific implementation for the generic thermal analyzer/evolved-gas analyzer (TA/EGA) function included in the MESUR straw man payload; applications to asteroids and comets are also possible. The purpose of the MESUR TA/EGA is to identify volatile-bearing minerals in Martian soils, including water-bearing clays, carbonates, nitrates, and sulfates.

The baseline TAPS is a single-sample differential-scanning calorimeter (DSC), backed by a capacitive-polymer humidity sensor, with integrated sampling mechanism. After placement on a planetary surface, TAPS acquires 10-50 mg of soil or sediment and heats the sample from ambient temperature to 1000-1300 K. During heating, DSC data are taken for the solid, and evolved gases are swept past the water sensor. Through ground-based data analysis, multi-component DSC data are deconvolved and correlated with the water-release profile to quantitatively determine the types and relative proportions of volatile-bearing minerals. The rapid-response humidity sensors also achieve quantitative analysis of total water. After conclusion of soil analysis operations, the humidity sensors become available for meteorology.

During FY93, the TAPS Mark-2 sensor test bed was assembled and used to validate in-house designs for sample collectors, DSC sensors, and circuits. Prototype hardware is shown in figure 1.

Two different sample collector mechanisms selected from among those designed in 1992 were built and tested: the "sweeping scoop" and the "ice cream scoop." Each mechanism was driven by a small DC motor that is compatible with the TAPS packaging design goals for MESUR. The sample collector tests were conducted using simulated Mars soils comprised of fine sand and silt fractions that were sieved from Cheto, Arizona bentonite. Both collectors successfully acquired samples during numerous tests, although results from the sweeping scoop were preferred over those of the ice cream scoop.

A DSC sensor was constructed by combining a small electrical resistance heater with a temperature sensor. The furnace was constructed by wrapping Pt-Rh wire around the outer circumference of a 5-mm-diameter, flat-bottomed cup made from sintered, high-purity aluminum oxide. A separate Pt resistance temperature detector was attached, with refractory cement, to the bottom of the cup to facilitate temperature measurement. The DSC heater/sensor design successfully achieved thermal cycling over the 300-1300 K temperature interval at rates of 5-10 K/min in accordance with TAPS design goals. Each of several assemblies supported more than 20 heat/cool cycles without a failure. Design goal maximum temperature was achieved using a low-voltage DC power supply of the general magnitude that is likely to be available on the MESUR lander. Although the integrated power consumption is significantly greater than our design goal, the instantaneous power draw is only about a factor of two greater than our goal. We expect that design upgrades of the heater/sensor assemblies will permit greater electrical efficiency.

The Mark-2 sensor test bed (fig. 1) was constructed to include two DSC heater/sensor assemblies and two capacitive-polymer humidity sensors. Two of the DSC heater/sensor assemblies described above were placed in active and passive locations, respectively. One assembly was installed in the sweeping scoop sample collector and the other was installed, in a permanently empty condition, within the chassis block. The two units thereby served as the "sample DSC" and "reference DSC" sensors, respectively. The two humidity sensors, which

were retained from the earlier Mark-1 test bed, were inserted into the manifold such that the "sample water" sensor would contact the gaseous effluent from the "sample DSC" sensor while the "reference water" sensor would be exposed only to dry purge gas. Electronics for the water sensors were retained from the Mark-1 test bed but new electronics were created for the new DSC sensors. Using the latter design, simultaneous DSC and EGA data were collected successfully using synthetic gypsum as the test sample (fig. 2).

In FY94, a complete TAPS Mark-3 brassboard instrument will be produced for review by NASA HQ for possible selection as the basis of the design and construction of the MESUR TA/EGA flight instrument.

The dehydration doublet peak is not resolved under these operating conditions but the DSC and EGA data are well correlated. The DSC signal comprises raw voltage only; with calibration as differential power, the integrated peak corresponds to an absolute quantity of gypsum. The EGA signal is expressed as uncalibrated percent relative humidity; with calibration, the integrated peak corresponds to an absolute quantity of water.
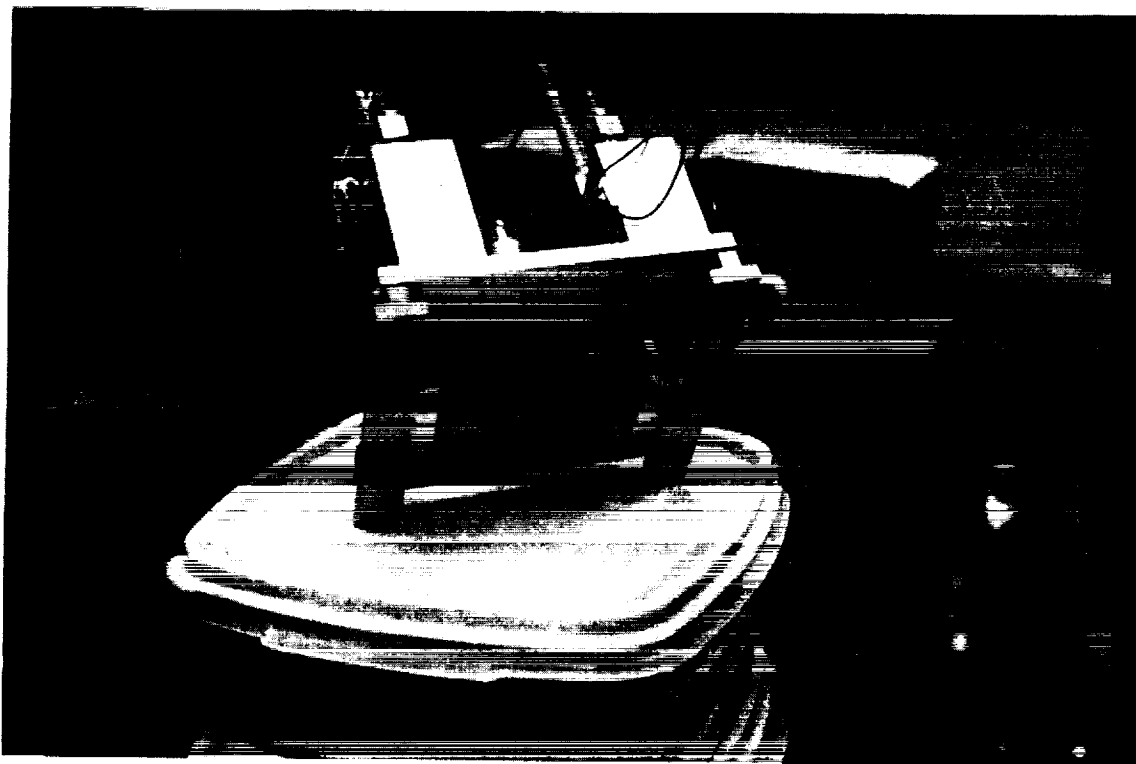
Figure 1. TAPS Mark-2 sensor test bed. The edge length of the metallic chassis block is 10 cm. The sweeping scoop sample collector appears in the open position; the light-colored inner lining is the DSC furnace/sensor assembly. Pipes and cables represent purge-gas, electrical, and data utilities that will be self-contained in the Mark-3 brassboard. NASA JSC file photograph S93-046085.
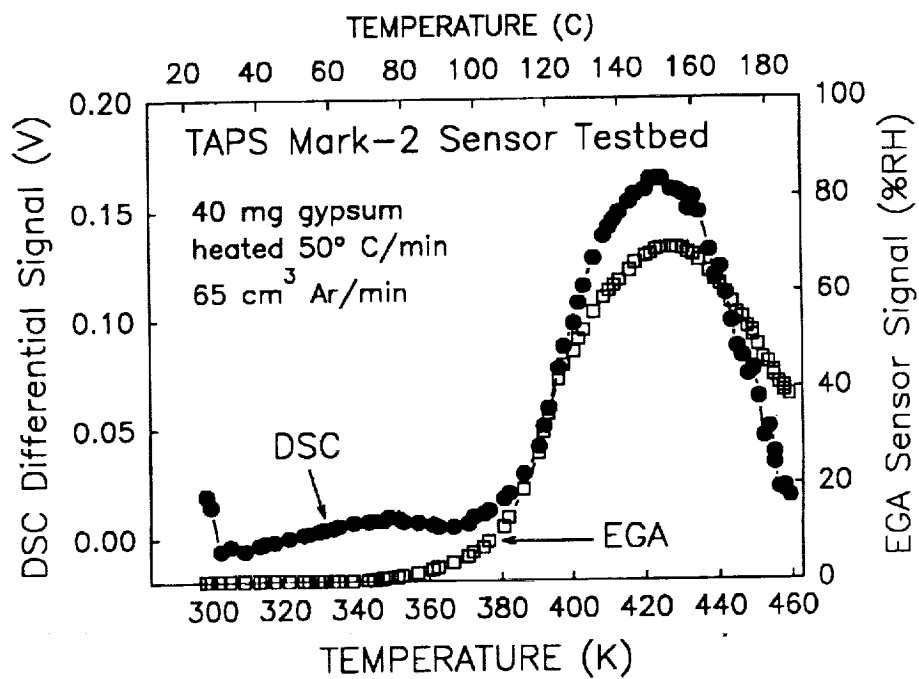
Figure 2.   Simultaneous DSC/EGA data, acquired by the TAPS Mark-2 sensor test bed, during the thermally induced dehydration of synthetic gypsum:

$$CaSO_4 \cdot 2H_2O_{(s)} \rightarrow CaSO_{4(s)} + 2\,H_2O_{(g)}$$
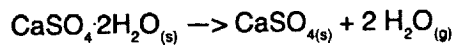
Backscatter Mössbauer Spectrometer (BaMS) for Extraterrestrial Surfaces

PI: **Richard V. Morris, Ph.D./SN4**
              Tad D. Shelfer, Ph.D./NRC
Reference: **SSS 2**

Instrumentation to provide in-situ mineralogical and elemental analyses is a primary concern for future spacecraft missions which land on solid planetary objects, such as the Moon, Mars, and asteroids. These analyses will provide the fundamental data required to characterize and identify surface components and provide insights into their creation and subsequent modification over time. In terms of its abundance, mineralogical importance, and multi-valent nature, the element iron provides a wealth of diagnostic information about naturally occurring materials.

It is for these reasons that we are developing a miniature prototype BaMS. A flight instrument based on our design would be capable of in-situ measurement of the distribution of iron among its oxidation states, its distribution among iron-bearing mineralogies, and its concentration in solid materials. The backscatter geometry we have chosen, shown schematically in figure 1, also allows X-ray fluorescence analysis (XRF) to be performed simultaneously without additional hardware. A combined BaMS/XRF instrument would provide iron mineralogy and elemental composition without the need for sample preparation in a single compact, relatively simple, rugged package.

Our focus in this instrumentation project has been directed toward three main objectives: 1) minimize the physical parameters of mass, volume, and power requirements; 2) maximize the quality of the data while minimizing the time needed for data acquisition; and 3) build a library of data from standard mineralogical samples, laboratory analogues, and extraterrestrial samples (Martian meteorite and lunar specimens).

We have achieved the first objective of this project by designing and constructing a working laboratory quality BaMS instrument which surpasses our target goals of mass < 500 g, volume < 300 cm^3, and power < 2 watts. These goals were established with a flight-qualified space instrument in mind. Highlights of this design include the world's smallest loudspeaker-type Mössbauer drive, four PIN (positive-intrinsic-negative) photo-diodes for radiation collection, and a transputer-based multichannel analyzer system.

We are currently finishing our efforts toward maximizing signal-to-noise ratios while minimizing data collection time. This is a complex issue involving many parameters. Our goal for this portion of the project is to provide laboratory quality spectra with our miniaturized instrument and to provide quick (< 1 hour) mineralogical identification of iron-bearing phases.

In summary, the high sensitivity to mineralogical variations of the iron-bearing phases and the requirement for no sample preparation make BaMS ideally suited for in-situ analysis of planetary surface materials. It is suitable for prospecting for oxygen-rich iron-bearing minerals on the Moon or for use in sample return missions where it is necessary to perform sample discrimination.
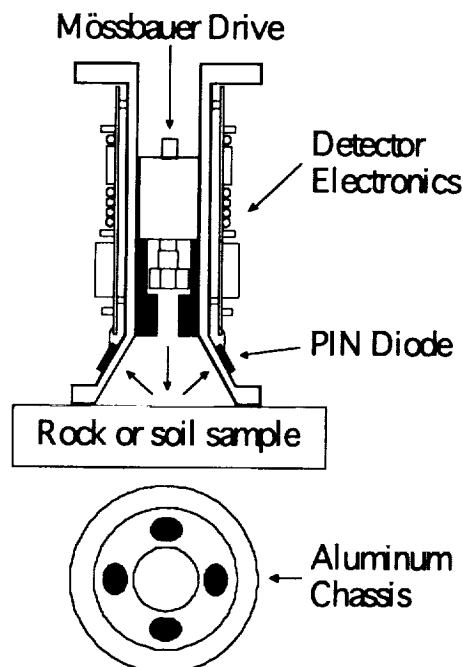

Figure 1. Cross sectional and end views of the BaMS instrument.

Radar Measurements of the Orbital Debris Environment

P.I.   **Gene Stansbery/SN3**
Reference: **SSS 3**

Orbital debris is increasingly important for the design of spacecraft operating in low Earth orbit (LEO). The Haystack radar has been periodically observing debris in LEO since October 1990. Knowledge of the orbital debris environment before 1990 was broken into two size regimes. For objects larger than about 10 cm diameter, the USSPACECOM maintains a catalog which includes debris as well as intact satellites and rocket bodies. The catalog is maintained by the use of ground-based radars. The 10-cm limit is somewhat arbitrary, but is mainly the result of the radars having relatively long wavelengths (70 cm or longer).

Knowledge of debris smaller than ~0.1 cm comes from analysis of surfaces exposed to space and returned to Earth. The size limit of these data result from limitations of the area exposed and the length of time in orbit. No significant measurements of the debris environment in the range of 0.1 to 10 cm existed before the Haystack measurements.

The measurements from Haystack have addressed a requirement to improve the estimate of the debris flux at Space Station altitudes, nominally 350-450 km. Requirements for protection of the Space Station are based on NASA's orbital debris model (Kessler, D.J., SSP 30425, Rev. A, 1991) which has a large uncertainty. The Haystack measurements have reduced the uncertainty of the 1-cm debris to ±50%. The project is now transitioning to its long-term goals of monitoring trends in the debris environment and identifying sources of new debris. The latter goal will be greatly aided by the addition of the Haystack Auxiliary (HAX) radar, now undergoing testing. The Haystack radar was only available during fixed times of the year, but the HAX radar will be available year-round. This will allow examination of new satellite breakups, the amount of debris associated with each breakup, and its dispersion over time.

The Haystack and HAX radars are located in Tyngsboro, Massachusetts and are operated by M.I.T. Lincoln Laboratory for the U.S. Air Force and other elements of the Department of Defense. Operation for NASA is provided through a Memorandum of Agreement between NASA and USSPACECOM.

The Haystack radar is a high-power, X-band, monopulse tracking radar with very high sensitivity (Armstron, G.R., et al., DARPA report ESD-TR-77-124, November 1977). A pulsed, single frequency waveform has been selected for use. Single pulse signal-to-noise ratio (SNR) on a $1 \, m^2$ target at 1000 km is 56.8 dB. Objects as small as 1 cm in diameter can be observed at over 1000 km.

For debris observations, the radar is operated in a staring, or beam park mode in which the antenna is pointed at a specified elevation and azimuth while objects randomly pass through its field of view. This provides a fixed detection volume critical to the measurement of the debris flux. By not tracking individual objects, a precise measure of its orbit is sacrificed. However, position in the radar beam and rough orbital elements can be determined. A Processing and Control System records data in a rotating buffer which is saved only when the signal exceeds a threshold above system noise. In this way, many hours of observation can be performed with a practical amount of recording.

Orbital debris data has been collected with the radar directed vertically and at low elevation angles. With the radar directed vertically, it can only detect orbits with inclinations between 42° and 138°. To sample orbits of lower inclination, the antenna was directed due south at low elevation angles. At an elevation of 10°, the radar can sample orbits as low as 28° inclination at 500 km altitude. This increases the slant range to an altitude and reduces the sensitivity of the radar.

Calibration of the radar is a major concern for data collection. Two types of calibrations are performed using calibration spheres of known size. The first is an absolute calibration performed by tracking a sphere at the center of the radar beam.

Second, the relative sensitivity of the antenna pattern is measured by scanning around the sphere as it moves across the sky. However, spheres only return radar in the primary polarization. Thus, no true calibration exists for the orthogonal polarization channel. NASA is planning to deploy orbiting dipoles from an upcoming Space Shuttle flight for calibration of the orthogonal polarization channel.

Orbital debris data are transmitted to JSC via 9-track, 6250-bpi tapes. The data are processed on a Silicon Graphics, Inc. computer by a team of NASA and contractor personnel.

In the beam park mode, consider an orbiting object passing through the radar field of view. The key step in data processing is determining the location of an object for each radar pulse. From these locations, its motion can be used to estimate orbital elements. Also, signal strength can be augmented by the relative antenna gain, determined by the antenna pattern calibration discussed above. Thus, the returned signal strength can be estimated as if the object were at the center of the radar beam. The radar cross section (RCS) is determined by applying the absolute radar calibration.

A study was done to develop a size estimation model to relate RCS to physical size. Thirty-nine "representative" debris objects were selected from two hypervelocity impacts of simulated satellites conducted by the Department of Defense. The RCSs of the objects were measured at an RCS radar range for all orientations. At each orientation, the frequency of the radar was stepped from 2.0 to 18.0 GHz. For debris sizes much smaller or larger than the wavelength, the scaling curve approaches the Rayleigh or optics region curves, as expected. In the resonance region, the curve deviates from the optical curve such that, for a given RCS, the object is smaller than predicted by the optical approximation.

A radar performance model (RPM) was developed to relate the flux of objects passing through the radar beam to the number of objects detected by the radar. The RPM uses a straightforward, brute force approach. It initially calculates the trajectory of an object through the center of the radar beam. The model considers 12 points along the trajectory

spaced appropriately to be the individual radar return pulses. The model calculates the SNR of each of the 12 points corrected for the antenna gain at that point. It then integrates the SNR and calculates the probability of detection (P_d) for the trajectory. The P_d is calculated assuming Swerling 2 scintillation statistics for sizes in the optical scattering regime, Swerling 1 statistics in the resonance regime, and Swerling 0 statistics for the Rayleigh scattering regime. The model repeats the P_d calculations for many parallel trajectories stepping away from beam center toward the edge of the beam. The RPM then calculates the average P_d and the beam edge-to-edge distance. The RPM repeats this calculation for object sizes from 1 mm to 10 m diameter in 1 dBm steps. For 90° elevation data, there is no variation in average P_d as a function of orbital inclination. However, at other elevations, an altitude slice of the beam gives an ellipse. Therefore, objects with different inclinations will have different corrections and edge-to-edge distances. The program then calculates the debris flux that would pass through the beam as a function of size, altitude, and inclination from the NASA debris model. It uses the appropriate P_d and edge-to-edge distance and calculates the expected detection rate.

Figure 1 compares the measured debris size and altitude distributions with the results of the RPM using the NASA debris model. Looking at the altitude distribution, Haystack detects about 40 times the catalog flux. The USSPACECOM catalog contains about 7000 objects. Therefore, a simple ratio of the Haystack flux to the catalog flux would indicate that there are about 280,000 objects visible to the radar.

The main difference between the measured and modeled size distributions occurs between 3 cm and 2 m in diameter. The debris model in this size range is based, in part, on data collected by telescopes. The sizes of debris detected by telescopes was determined by comparing optical brightness with RCSs reported for those objects correlated to cataloged satellites and debris. Most catalog RCSs are derived from measurements made by the FPS-85 radar located at Eglin AFB. It is known that, between 1983 and 1990, all Eglin RCSs were biased by nearly 3 dB toward larger

sizes (Henize, K.G. et al., M.I.T. Lincoln Laboratory report STK-206, Vol. 1, March 1993). Consequently, all cataloged objects were modeled too large by a factor of 1.4. Since the results of the optical observations used in the model were ratioed to the Eglin RCS, these objects were also too large in the model. Consequently, there is a need to reduce the modeled size of debris in this range.

In addition to the direct measurements of debris in the 0.6- to 10-cm-diameter size range, the Haystack results have provided the high fidelity measurements which allow examination and improvement of the debris model. The new HAX radar will provide even more capability by allowing immediate centimeter-size debris flux measurements resulting from new satellite breakups.
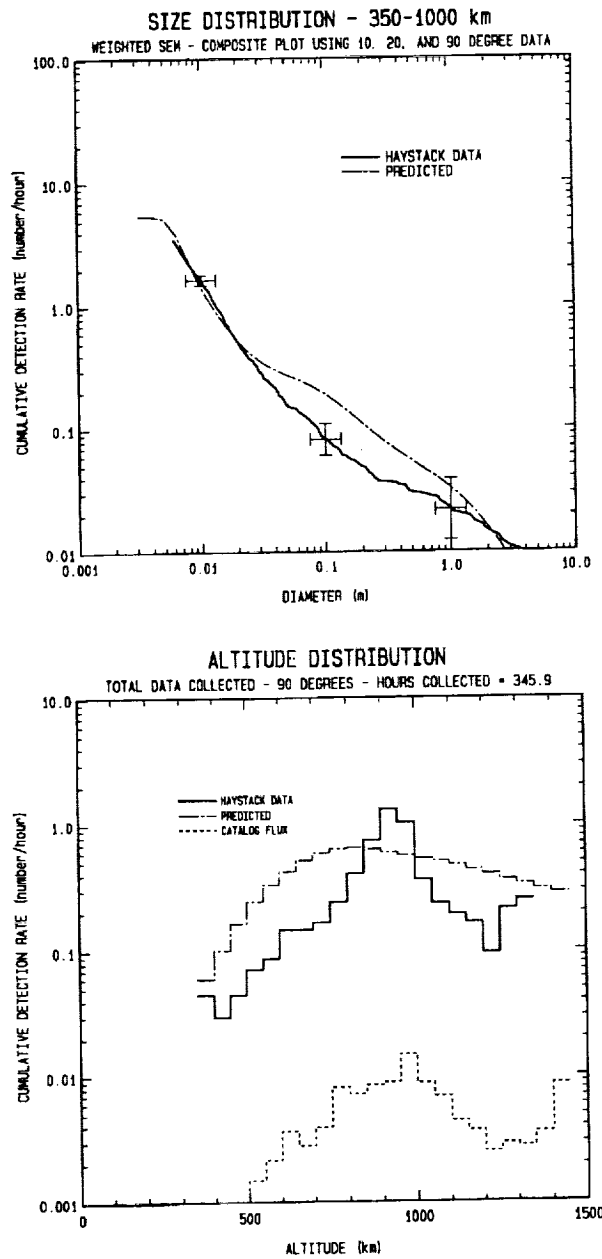

Figure 1. Distribution of orbital debris as measured by Haystack by size and altitude.

Composition and Structural State of Space Debris and Interplanetary Dust Particle Impact Residues Recovered From Long Duration Exposure Facility (LDEF) Impact Craters

PI: M.E. Zolensky, Ph.D./SN2
            F. Hörz, Ph.D./SN4
            R. Bernhard/LESC
            R.A. Barrett/LESC

Reference: SSS 4

Impactor residues in materials exposed on the LDEF satellite are being characterized to establish the nature and abundance of meteoritic and orbital debris materials in the low Earth orbit (LEO) environment, and also the effect hypervelocity impacts will have on spacecraft. The LDEF satellite, exposed in LEO for 69 months before recovery by the Space Shuttle in January 1990, continues to provide a wealth of information on space exposure effects. In this study, new techniques were developed for the study of selected impactor residues in shallow craters in gold plates and aluminum surfaces from LDEF experiments. A detailed structural and compositional analysis of several of these impactor residues was performed utilizing transmission electron microscopy, energy dispersive spectroscopy, and electron diffraction. The immediate goal of this continuing work has been to (1) broaden our understanding of the LEO particulate environment, (2) provide critical information on high-velocity particulate interactions with spacecraft (data not obtainable in the laboratory), (3) determine the effects of the impact process on impactor mineralogy, (4) determine mineral composition of chondritic interplanetary dust particles (IDPs) and space debris, (5) determine the provenance of debris particulates in LEO, and (6) compare impactor residues to chondritic IDPs collected from the stratosphere and Earth's polar caps. These results will be immediately useful to spacecraft engineers and planetary scientists. Additionally, the techniques developed here will find immediate use in diverse fields of materials science.

Optical scanning of LDEF experiment and frame surfaces is being conducted at JSC to locate and document impacts as small as 30 μm in diameter. Following optical identification, these impacts are inspected by scanning electron microscopy/energy dispersive X-ray analysis to identify those features which contain appreciable impactor residues. Based upon the bulk composition of these residues, and using criteria developed at JSC, we have made a preliminary discrimination between space debris- and micrometeoroid-containing impact features. In addition, this data is being input into the Meteoroid and Debris Special Investigation Group Database, which documents all LDEF meteoroid and debris results, and is accessible to interested investigators (Bernhard, R. P., et al., NASA TM 104759).

Residues from the interior of several craters in LEO-exposed gold experimental plates were removed with a tungsten needle, mounted in EMBED-812 epoxy, and ultramicrotomed into 90-nm-thick sections using a diamond knife. The sections were placed on carbon-coated copper grids and observed by transmission electron microscopic techniques using JEOL 100CX and 2000FX analytical electron microscopes. Chemical analyses of crystalline areas were performed with a PGT System 4 energy-dispersive X ray (EDX) spectrometer and reduced with the PGT dedicated software and LINK EDX system and software. The structural states of all analyzed materials were assessed by electron diffraction, which proved to be a critical step, considering the noncrystalline nature of many materials observed.

We examined the mineralogy of residues from three impact features: numbers 102, 121, and 295. Impact residue 102 has very finely divided clinopyroxene and orthopyroxene [(Ca, Mg, Fe)(Mg, Fe)Si$_2$O$_6$] with an unequilibrated composition, showing abundant evidence of intense shock, these being planar deformation features, mosaicism, and, in some instances, evidence of recrystallization (120° grain intersections) (fig. 1). The residue matrix consists of vesicular, ferromagnesian, silicate glass. Spherical bodies of Fe-Ni (±Cr) metallic glass and pyrrhotite abound locally, particularly at grain boundaries. All of the glasses probably formed during the impact event.

Impact residue 121 contains fragmental grains of equilibrated olivine [(Mg,Fe)$_2$SiO$_4$] ortho-pyroxene, Fe-Ni metallic glass, and abundant silicate glass. The olivine and pyroxene grains show evidence of shock (see above for criteria). Impact residue 295 contains shocked, fragmental, equilibrated olivine and orthopyroxene, Fe-Ni metallic glass, and silicate glass.

Despite previous expectations, these residues retain sufficient mineralogical, structural, and chemical information to permit determinations of impactor origins to be made. For example, impactor 102 was probably a grain from an outer belt asteroid, based on the compositional range of the pyroxene grains. The metallic glasses encountered among the residues deserve additional attention (Bradley, J., et al., MVA Report 02N0180542), since these materials, not known from nature, have potentially significant economic potential. Metallic glasses have hitherto been fabricated only by spin-cooling techniques; their occurrence among highly-shocked impactor residues suggests other possible fabrication techniques.

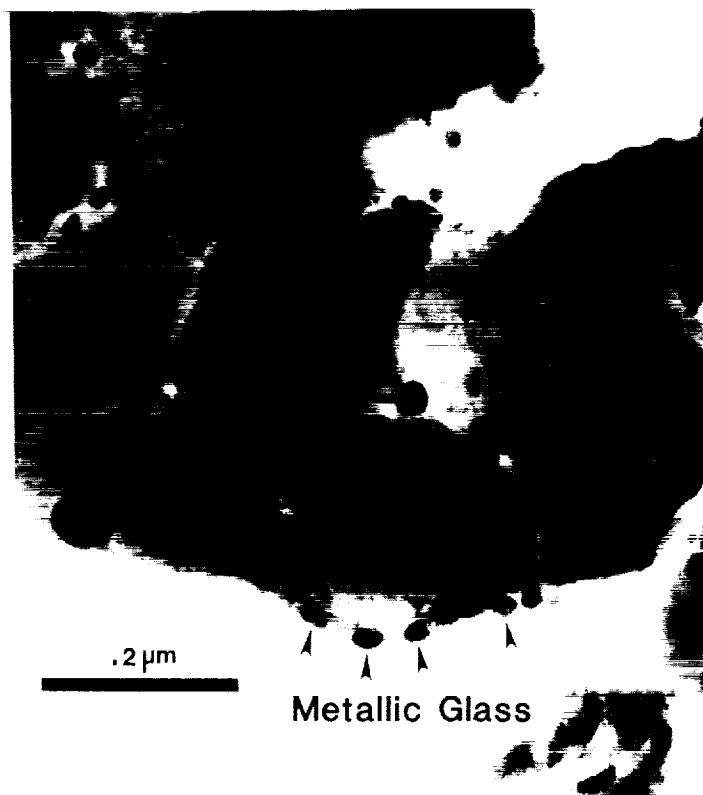Figure 1. A transmission electron microscope image of a portion of the interplanetary dust particle impactor residue from LDEF impact 102. Evidence of shock recrystallization are the 120° grain intersections between individual pyroxene domains. Spherical bodies of Fe-Ni (±Cr) metallic glass and pyrrhotite abound locally, particularly at grain boundaries (some metallic glass bodies are arrowed).

A Cheaper, Faster, Better Way to Detect Water of Hydration in Solar System Bodies

PI: **Faith Vilas/SN3**
Reference: **SSS 5**

One long-term goal of space exploration is the expansion of humans into space. The resources required to support humans in space include meeting the two basic needs of survival—air to breathe and water to drink. The identification of specific solar system objects as sources of water represents a significant step toward using in situ resources for survival. Many objects in the outer solar system have icy material on their surfaces (e.g., Callisto, Iapetus, comets). These objects would obviously be a good source of water when human explorers reach the outer regions of the solar system. First, however, humans must traverse the inner part of the solar system and cross the asteroid belt. While some ice has been suggested in the surface material of 1 Ceres, as a rule one does not expect ice in large quantities in the main belt asteroid population.

The action of aqueous alteration (the alteration of material by its interaction with liquid water, probably formed by melting of ice) of the near-subsurface material on the asteroids and probably some satellites in the solar system is part of the formation history of the solar system. We unravel this history through observing the spectral properties of an object's surface material. Some asteroids are believed to have undergone aqueous alteration based upon their low amount of reflected light and neutral broadband colors. A definitive indication of aqueous alteration came when the broad infrared (IR) absorption feature having a minimum near 3.0 μm, indicating structural hydroxl (OH) and interlayer and adsorbed water (H_2O) in clay silicates, was identified in the spectra of many dark asteroids. Additional compositional evidence was provided by an absorption feature centered near 0.7 μm, indicative of an Fe^{2+} - Fe^{3+} charge transfer transition in oxidized iron in clay silicates in the spectra of some dark asteroids and primitive carbonaceous meteorites (fig. 1). Among the 13 asteroids that have been observed in both

visible and IR spectral regions showing the 0.7-μm ferrous/ferric iron absorption, 11 objects also have the 3.0-μm water of hydration absorption.

Problems arise when trying to compile data to study the aqueous alteration history of the solar system, or the availability of water in minerals as a possible space resource. IR observations directly address the question of the availability of water of hydration in clay silicate materials, but the limitations of available IR astronomical instrumentation and the strong background signal limit the asteroids that can be observed to only the brightest asteroids.

Is there a quick method of finding water of hydration in the surface material of asteroids that does not rely upon IR observations? If one assumes that (1) the presence of clay silicates indicates the presence of water of hydration in the surface material of the asteroid, and (2) the feature centered at 0.7 μm is due to the Fe^{2+} - Fe^{3+} charge transfer transition in oxidized iron in clay silicates, then the presence of the 0.7-μm absorption feature in the high resolution spectrum could serve the purpose of identifying hydrated water in minerals. The long integration times necessary to produce high-quality, high-resolution spectra sufficient to identify the absorption feature preclude this from being a quick look method of determining its presence.

The solar system can, however, be sampled extensively by applying a simple technique using filters in the visible/near IR spectral region developed for asteroid studies in the early 1980s. The 0.7-μm absorption feature has a lower wavelength edge near 0.57 μm, a minimum reflectance near 0.70 μm, and an upper reflectance edge near 0.83 μm; this varies slightly among asteroid spectra. The passband for the 0.550-μm filter is concentrated primarily in a spectral region that does not contain the absorption feature. The 0.701-μm filter is centered at the minimum of the absorption feature. In order to delineate this feature in a high resolution charge coupled device (CCD) spectrum, a simple linear continuum defined by a linear least squares fit to the points in the spectrum is removed from the spectrum. Any weak absorption features present remain. This

removes the effects of slope on the spectrum. This same technique can be applied to the broadband photometry. The photometric values are expressed as relative reflectance with $R_{0.55} = 1.000$. The background slope is first removed from the photometry. If the 0.7-μm feature is present, then $R_{0.701}/R_{0.550} < 0.990$. If the feature is absent, for whatever known asteroid type, then the calculated value above is ≥ 0.990. Multicolor photometry of 589 asteroids acquired in this earlier program can now be used to search for water of hydration.

The quick identification of a feature indicating hydrated water has some strong implications for both ground-based telescopic research and space-based missions. The emergence of CCD spectroscopy as a method of observing faint asteroids incorporates the advantage of the improved responsivity of a CCD in the same

spectral range, plus the advantage of obtaining a spectrum across the same range simultaneously. A CCD could be used with a much lower dispersion element to sample very faint asteroids quickly with a strong signal-to-noise ratio.

It is easy to incorporate a filter centered near 0.7 μm in the suite of filters chosen for spacecraft missions such as the Clementine missions to the Moon and near-Earth asteroids (the 0.55-μm filter is a standard in astronomy and likely to be present). The identification of water remains one of the significant problems in space resource utilization. Spacecraft in orbit around or flying past another planet or asteroid would be able to survey the surface material for water of hydration. Spacecraft that would remain, for example, in low Earth orbit could survey all known asteroids for the purposes of future exploration.
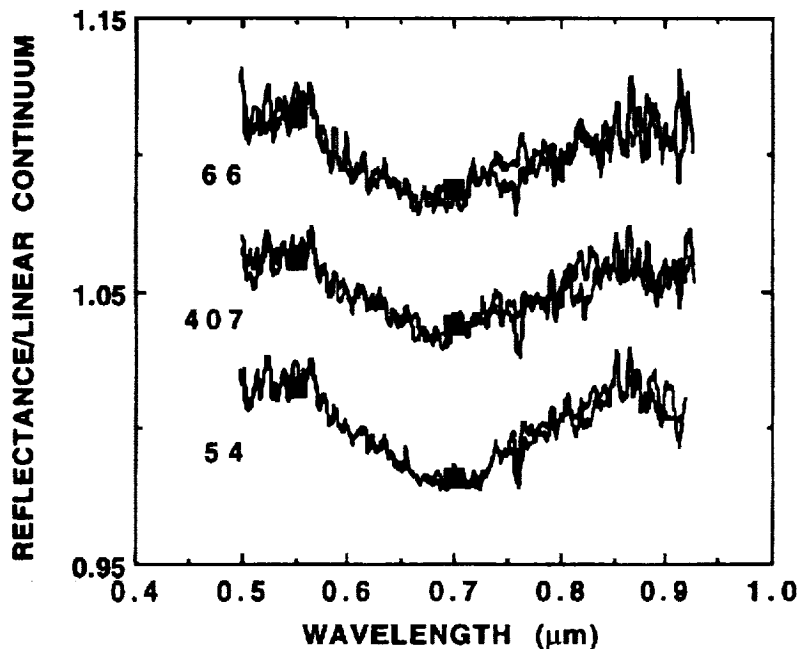
Figure 1.   Spectra of three dark asteroids taken on two separate nights showing the 0.7-μm Fe^{2+} - Fe^{3+} absorption feature due to oxidized iron in clay silicates. A linear continuum has been removed. Broadband photometric values at 0.550 and 0.701 μm (created using a program that simulates the filters in the earlier asteroid photometry program) show the placement of the 0.550- and 0.701-μm filters with respect to the absorption feature.

Porphyrins in the Surface Material of Asteroid 2 Pallas

P.I.: **Faith Vilas/SN3**
Reference: **SSS 6**

Spectral observations of the diffuse sunlight reflecting from the top ~1 mm of the surface material of a typical planetary regolith can provide a remote sensing probe of the surface mineralogical composition. In the blue and ultraviolet spectral regions, high resolution reflectance spectra have not been obtained until recently. These spectra allow scientists to resolve features seen in laboratory spectra of extraterrestrial materials such as meteorites and of terrestrial rock samples. The identification of different features in the reflectance spectra of solar system bodies provides clues to the conditions that formed or altered these objects.

Porphyrins are planar, ring-shaped organic molecules consisting of four pyrrole sub-rings linked by methine bridges (fig. 1). The wide radius of the porphyrin ring interior, and the availability of free electrons from two of the pyrrolic nitrogens, frequently leads to the chelation of bivalent metal ions. The relative ease with which the arrangement of peripheral alkyl and other substituents may be modified results in a variety of naturally occurring porphyrin structures.

A wide variety of nickel (II) and vanadyl (II) complex porphyrin structures have been isolated from oil shales and other organic-rich sedimentary deposits in abundances generally less than 100 μg/g. The majority of these are derived from chlorophyll precursors with additional contributions from heme-related compounds. An analytical search of meteorites in the late 1960s revealed nickel porphyrins at very low concentrations in the four carbonaceous chondrites Orgueil (CI1) (0.0100 μg/g), Cold Bokkeveld (CM2) (0.0010 μg/g), Murray (CM2) (0.0030 μg/g), and Mokoia (CV3) (0.0005 μg/g).

Spectra of porphyrins are dominated by an intense absorption band (millimolar extinction coefficient ~100-500 mL/M·cm) located near 0.40 μm commonly referred to as the Soret band. Considerably less intense absorption bands are located in the 0.50- to 0.65-μm range. The Soret band is sensitive to the conjugation pathway of the porphyrin ring, while the weaker bands are most strongly affected by structure type in the case of metalloporphyrin complexes.

We have identified a Soret-like band at 0.405 μm with a full spectral width of 0.02 μm in the reflectance spectrum of asteroid 2 Pallas at an ~3 sigma level of confidence. The spectrum of 2 Pallas is compared with laboratory spectra of samples of the Green River Shale and the meteorite Orgueil in figure 2. The Green River Shale sample contains nickel porphyrins at a concentration of at least 5 μg/g. This is the first time a plausible porphyrin feature has been seen in the spectrum of an extraterrestrial body.

A lower limit for the average porphyrin concentration of the surface material of Pallas was calculated using a semiempirical model developed for interpretation of geologic reflectance spectra. The calculation assumes that surface conditions are very favorable for the detection of porphyrin absorption bands (e.g., fine particle sizes [< 44 μm] and low specular reflectance [< 2.6%]) and that the shape of the continuum does not reduce the apparent intensity of the band. Using the albedo value of Pallas, the feature is calculated to be consistent with a concentration of ~15 μg/g nickel porphyrins in the surface material of Pallas.

The significant question of how porphyrins could have formed on the surface of Pallas remains. Abiotic synthesis of porphyrins in the solar system is within the realm of possibility as porphyrins have been produced in the laboratory from methane, ammonia, and water by the action of electric discharges. The presence of lightning would not be completely unexpected in the history of carbonaceous chondrites since the flash heating of dust by lightning in a cool nebular region is proposed as one method by which many chondrules are formed.

The presence of the porphyrins on 2 Pallas places a constraint on the maximum temperature experienced by that asteroid. We conservatively estimate this temperature to be 573K. This is based on the temperature at which vanadium and nickel bonds cleave in crude oils, assuming that most or all vanadium and nickel in crude oils is bound in some

type of porphyrin complex. Sedimentary porphyrins are destroyed at temperatures considerably lower than 573K over geologic time scales.

Figure1. The skeletal structure of a porphyrin showing the pyrrole sub-rings joined by methine bridges.
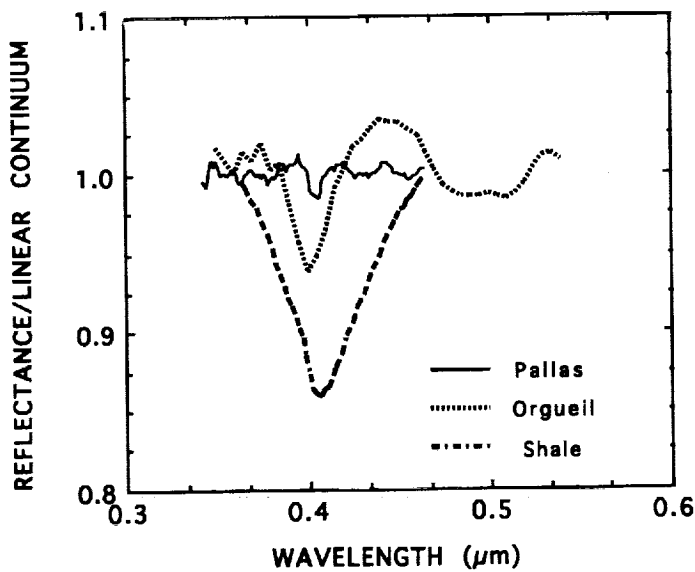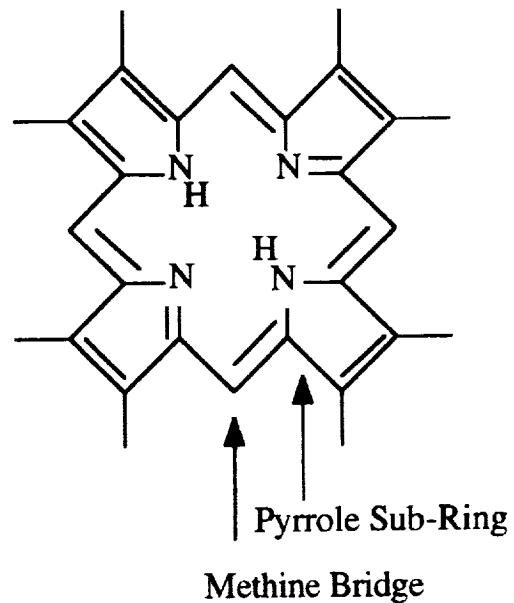
Pyrrole Sub-Ring

Methine Bridge

Figure 2. Reflectance spectra of asteroid 2 Pallas, the carbonaceous chondrite Orgueil, and the Green River Shale containing nickel porphyrins. The asteroid spectrum has been smoothed once with a 5-pt running box average. A background continuum has been removed from each spectrum.

Plasma Motor Generator (PMG)

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Reference: SSS 7

A new technique for dissipating electrical charge from spacecraft was put to the test this past year with NASA's PMG. The Air Force Delta II rocket launched in June 1993 carried a Navstar Global Position Satellite (GPS) as its primary payload and the PMG as the secondary payload (fig. 1).

The PMG was the second in a series of three Delta-launched tether application payloads that are part of the Flight Demonstration Program sponsored by the Office of Space System Development. The PMG, a low-cost experiment developed at JSC, assessed the effectiveness of using Hollow Cathode Assemblies to deploy an ionized gas to "ground" electrical currents by discharging the energy to space. The PMG also demonstrated the theoretical prediction that electricity can be generated, and that thrust and drag can be induced.

In order to understand the operation of an electrodynamic tether system, the Earth can be thought of as a giant magnet, a principle used for direction-finding with a magnetic compass. If a copper wire is placed in orbit around the Earth, it will move through the Earth's magnetic field and a voltage will be induced in the wire. The wire will function like the armature in an electrical generator or motor, and the Earth itself will act as the magnetic pole-piece and frame against which the resulting forces on the "armature" wire react. If an electric current is allowed to flow through the tether wire by grounding it to space at both ends, the wire conductor will experience a mechanical force. This force can be either thrust or drag, depending on the direction of the current flow.

A spacecraft can build up an electrical charge while moving in orbit either due to natural phenomena or due to operation of high power electrical devices on the spacecraft. Typically, this type of electrical buildup is not seen with the Shuttle in low Earth orbit. It is, however, seen among satellites in geosynchronous orbit that are exposed to magnetic storms from solar events. It can also occur with large spacecraft using high electrical power loads—like a space station. In all such cases, the electrical charge buildup is due to an imbalance between electron or ion currents reaching the spacecraft from its surrounding space environment and the total current leaving the spacecraft due to operation of electrical devices. To eliminate this charge buildup, the spacecraft needs to complete an additional circuit path between itself and the surrounding environment (the ionosphere), thereby "grounding" itself to the ionosphere.

One experimental system capable of producing spacecraft charging is the electrodynamic tether. Its basic principle of operation involves collection of current by a spacecraft at one end to be driven by substantial voltages to another spacecraft at the opposite end of the tether wire. This requires the use of techniques for spacecraft grounding at each end and provides a good method for testing the performance of such grounding devices. The PMG experiment used a 500-m wire as an electro-dynamic tether to test the hollow cathode "plasma contactors" as grounding devices and to study electrodynamic tether behavior.

Once the Delta's third stage separated to take the GPS to its semisynchronous orbit, leaving the second stage behind, a spring ejected the 27-kg Far End Package (FEP) on an electrodynamic tether wire. The FEP spooled out, trailing the little "spacecraft" to a distance of about 500 m from the second stage. The Near End Package (NEP) stayed fixed to the rocket body and used the stage's remaining power for the experiment (fig. 2). The deployment device was developed by JSC and Tether Applications, Inc. The deployer, which weighed only 11 kg, used a passive "spinning reel" concept with no moving parts.

Prior to release of the FEP, plasma contactors were energized, releasing ionized xenon gas from $\frac{1}{4}$-inch-diameter cathode tubes on each of the

packages. This gas created a plasma ball, or pocket of ionized gas, that served as the "ground" for electrical charges carried through the tether. The FEP collected an electrical charge as it moved through space. The charge moved through the tether to the NEP which allowed it to dissipate into space. A series of tests were conducted to better understand the performance of the Hollow Cathode Tubes. During "motor" operations, the direction of current flow was reversed to collect a charge at the NEP and release it at the FEP. Voltage and current generated by movement of the conducting tether through the Earth's magnetic field were also measured.

A combination of onboard instrumentation and ground-based sensors were used to evaluate the performance of the flight demonstration. Observations from about 10 ground-based radars, magnetometers, and optical sensors provided independent evaluations of the overall PMG performance from both the dynamics and plasma interaction standpoints.
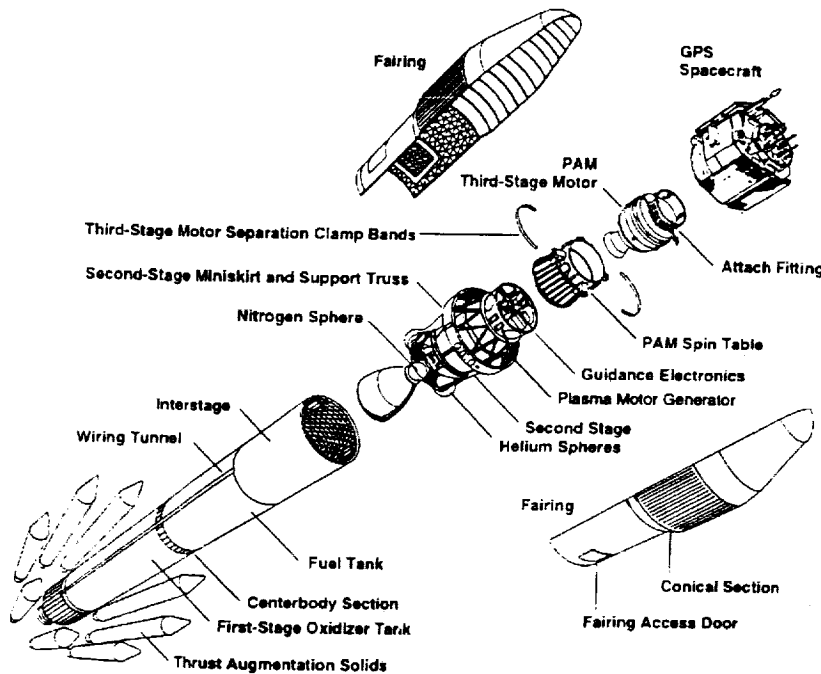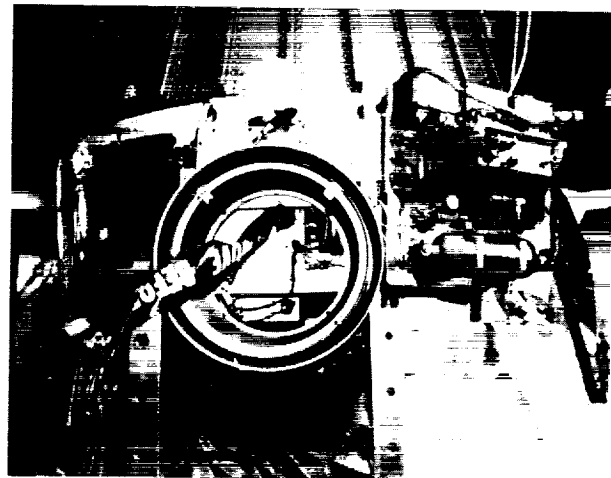

Figure 1. PMG location on Delta II second stage.

Figure 2. PMG hardware: NEP, with spool, and FEP mounted on the Delta second stage.

Zeoponic Plant Growth Substrates

PI: Doug Ming/SN4
Don Henninger/EC3
Reference: SSS 8

Plants are being considered as an important component of regenerative life support systems for long-duration missions (e.g., Space Station, planetary outposts). In addition to supplying food, plants have the capability to regenerate air by converting CO_2 back into O_2 and, through evapotranspiration, to convert waste water into potable water. However, the microgravity environment of space presents several problems for plant growth. One problem is providing a favorable root medium. Nutrient delivery systems (i.e., hydroponic systems) are complex and require pumps and sophisticated control and monitoring systems. It would be desirable to develop a substrate that provides the plant essential elements in a static watering system which eliminates the circulating pumps and monitoring systems required for hydroponic systems.

To address this need, a highly productive, synthetic soil (or substrate) has been developed for plant growth experiments on the Shuttle. The synthetic soils have been termed zeoponic plant growth substrates. Zeoponics is defined as the cultivation of plants in zeolite mineral substrates that contain essential plant-growth nutrients. Zeolites are crystalline, hydrated minerals that contain loosely bound ions (e.g., Ca^{2+}, K^+, Mg^{2+}) within their crystal structures. Zeolites have the capability to freely exchange some of their constituent ions with ions in solution without change to their structural framework. In addition to zeolites, the zeoponic plant growth substrates developed at JSC also consist of a synthetic calcium phosphate mineral (i.e., apatite). This synthetic apatite has several essential plant growth nutrients incorporated into its structure (e.g., Ca, Mg, S, P, Fe, Mn, Zn, Cu, B, Mo, Cl). The substrate (consisting of the zeolite and synthetic apatite) has been designed to slowly release these plant growth nutrients into "soil" solution, where they become available for plant uptake. A zeoponics system is illustrated in figure 1.

The objective of this research was to develop zeoponic substrates wherein all plant growth nutrients are supplied by the plant growth medium for many growth seasons with only the addition of water. The substrate has been designed to be incorporated into a Shuttle flight experiment (ASTROCULTURE™) in collaboration with the Wisconsin Center for Space Automation and Robotics. The ASTROCULTURE™ experiment is scheduled to fly on several Shuttle flights in FY94-95.

Wheat plants have been successfully grown in zeoponic substrates. Dry weight production of wheat was highest in the zeoponic substrates, as compared to control substrates which were watered with nutrient solutions (fig. 2). These substrates have adequately supplied all of the plant growth nutrients for extended growing seasons. For example, the zeoponic substrates provided either adequate or slightly higher amounts of the primary nutrients required for plant growth (fig. 3). The latest research on zeoponic substrates suggests that the substrate has the capability to slowly supply plant growth nutrients for long periods of time with only the addition of water.

Zeoponic plant growth substrates have numerous possibilities for terrestrial applications. The technology has captured the attention of commercial greenhouse and nursery companies. JSC is currently working on transferring the technology to the private sector.
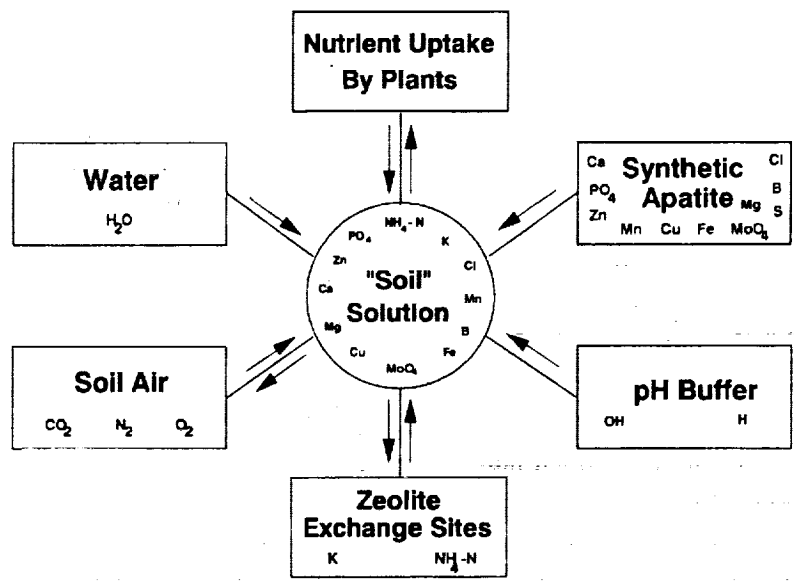
Figure 1. Dynamic equilibria for a zeoponic system. Plant growth nutrients are slowly released from zeolite minerals and synthetic apatite. The reactions in soil solution (i.e., nutrient release) are driven toward the root-soil interface by the uptake of nutrients by the plant.

DRY MATTER PRODUCTION

Sand/Hg = Sand Substrate watered with Hoagland's solution
Cp/Hg = Clinoptilolite Substrate watered with Hoagland's solution
Cp/SA = Clinoptilolite/Synthetic Apatite Substrate watered with deionized H_2O
Cp/NA = Clinoptilolite/Natural Apatite Substrate watered with deionized H_2O
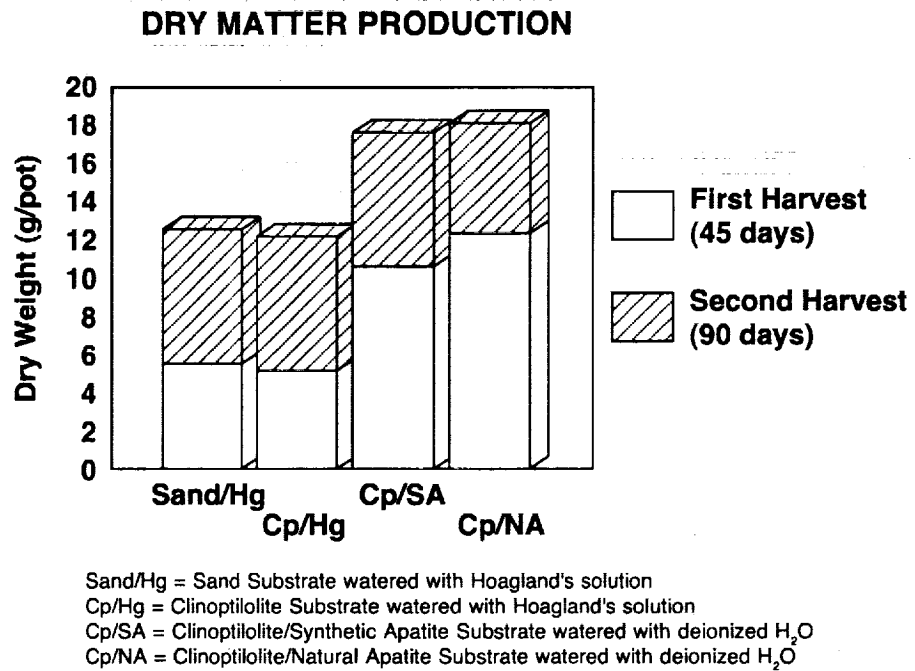
Figure 2. Wheat plants have been successfully grown in zeoponic substrates in controlled environment plant growth chambers. Hoagland's solution (Hg) is a nutrient solution most commonly used in hydroponic systems. The dry matter production (i.e., biomass production) was highest in the zeoponic substrates (Cp/SA and Cp/NA) as compared to the control substrates (i.e., Sand/Hg and Cp/Hg) after 90 days of continuously cropping wheat.

PLANT ANALYSIS: PRIMARY NUTRIENTS

Nitrogen

Phosphorous

Potassium

First Harvest
(45 days)

Second Harvest
(90 days)

Sand/Hg = Sand Substrate watered with
Hoagland's solution
Cp/Hg = Clinoptilolite Substrate watered with
Hoagland's solution
Cp/SA = Clinoptilolite/Synthetic Apatite
Substrate watered with deionized
H_2O
Cp/NA = Clinoptilolite/Natural Apatite Substrate
watered with deionized H_2O

Figure 3.   Zeoponic substrates adequately supplied the primary nutrients (nitrogen, phosphorous, and potassium) required for plant growth after continuously cropping wheat for 90 days. Similar trends were observed for the other essential plant growth nutrients. These data suggest that zeoponic substrates will slowly release plant growth nutrients for many growing seasons with only the addition of water.

InterMars Tissue Equivalent Proportional Counter

PI: **Gautam Badhwar/SN**
Reference: **SSS 9**

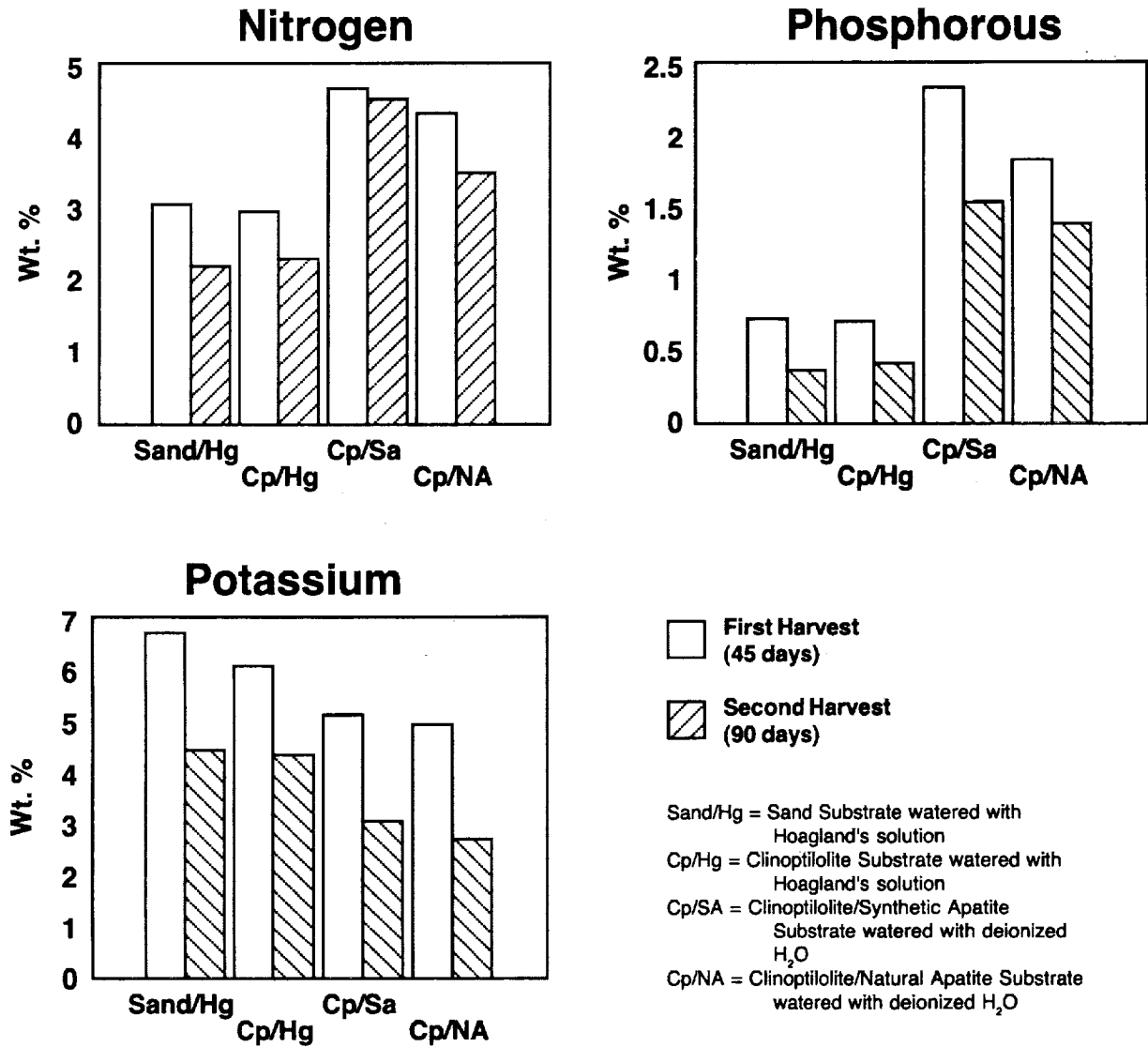Radiation presents a very significant risk to astronauts during a long-term stay in space. The only realistic method of decreasing this risk to an acceptable level is by added shielding. The amount of shielding required to stay below a fixed percentage of excess cancer risk is, however, very sensitive to the uncertainties in the estimated biological dose. These uncertainties are largely driven by uncertainties in the knowledge of the radiation environment and secondary particle production cross sections. It is simply not practical to measure all of the needed cross sections and their energy dependence. An alternative is to directly measure the physical and biological dose as a function of shielding depth in space. An instrument designed to do this on the Russian Mars 94 mission was built and has been tested on two Shuttle flights.

The new instrument is shown in figure 1. It consists of a cylindrical detector 1.8 cm in length and 1.8 cm in diameter that is enclosed in tissue equivalent plastic. The detector uses low pressure propane gas and is typically operated around -640 volts. The signal is run into two very low-noise amplifiers that differ in gain by a factor of about 50. The voltage output from each amplifier is pulse-height analyzed in a 256 channel ADC (analog-to-digital converter). The root mean square noise of the entire system is ~130 electrons at room temperature. The lower level discriminator was set at 0.4 keV/mm. The instrument covered a y range of 0.4 to 1250 keV/mm. The energy resolution is 0.1 keV/mm below 20 keV/mm and 5 keV/mm above 20 keV/mm. The full lineal energy spectrum is recorded every minute on a 8.192 MByte flash memory. In addition, absorbed dose is computed onboard the instrument and recorded either every 2 or 20 seconds, depending upon the dose rate. Engineering data, such as the detector bias voltage, various other operating voltages, currents, and temperature, are recorded every 10 minutes to provide a measure of the overall health of the instrument. Also, a measure of the gain stability of the electronics and any shift in the lower level discriminator is obtained every 8 hours using a calibrated voltage from an internal stable pulse generator. The instrument is housed in an aluminum box that is thermally and vibrationally isolated from the detector box by specially compressed Nomex felt pads. Extensive thermal-vacuum tests have established that the detector system will function properly from -50° to +70° C with a gain shift of less than 2.5%. Vibrational tests have established that, at the location of the detector, the vibrational loads were less than 2 g's even when the input g-load was 9.8 g's. The whole shroud, with detector inside, is covered with a thermal blanket and mounted on an attached payload carrier to the top inside starboard wall of Shuttle bay two, which is located toward the forward part of the Shuttle.

Figure 2 is a plot of the measured dose rate with mission elapsed time for the STS-51 mission. The spikes are passes through the South Atlantic Anomaly and the generally quiet period is the time when the detector measures the galactic cosmic radiation. Figure 3 shows the comparison of the measured and calculated integral GCR lineal energy spectrum. Table I gives a comparison of the measured dose and the calculated dose equivalent using the International Council on Radiation Protection (ICRP-60 or ICRP-26) definition of the quality factor.

We have developed a high resolution tissue equivalent proportional counter for the Russian Mars 94 mission. The instrument was tested in two Shuttle flights. Results show that, given an accurate input GCR spectrum, the radiation transport model can yield fairly accurate (±15%) dose and dose equivalent for moderate shielding thickness. These results also show that there are significant differences in the model and observed LET spectra, however.

Table I

Comparison of Measured and Calculated Doses
STS-56 (57° x 160 nm)

Location	Dose mGy/day	Dose Equivalent mSv/day	Quality Factor	Remarks
Payload (TEPC)	113.1	481.7	4.26	ICRP-60
GCR Model	94.6	400.4	4.27	ICRP-60
Albedo	14.0	34.0	2.43	ICRP-60
Total (Model)	108.6	434.4	4.00	ICRP-60
(TEPC/Model)	1.04	1.11	1.07	ICRP-60
Dloc2 (TEPC)	138.3	414.0	2.99	ICRP-26
GCR Model	102.0	358.0	3.51	ICRP-26
Albedo	8.0	12.0	1.50	ICRP-26
Total (Model)	110.0	370.0	3.36	ICRP-26
(TEPC/Model)	1.26	1.12	0.89	ICRP-26
STS-51 (28.5° x 160 nm)				
Payload (TEPC)	46.0	177.9	3.87	ICRP-60
GCR Model	34.5	120.0	3.48	ICRP-60
Albedo	14.0	34.0	2.43	ICRP-60
Total (Model)	48.5	154.0	3.18	ICRP-60
(TEPC/Model)	0.95	1.16	1.22	ICRP-60

0.075 PLASTIC — 0.035 STAINLESS STEEL
0.001∅ ANODE WIRE
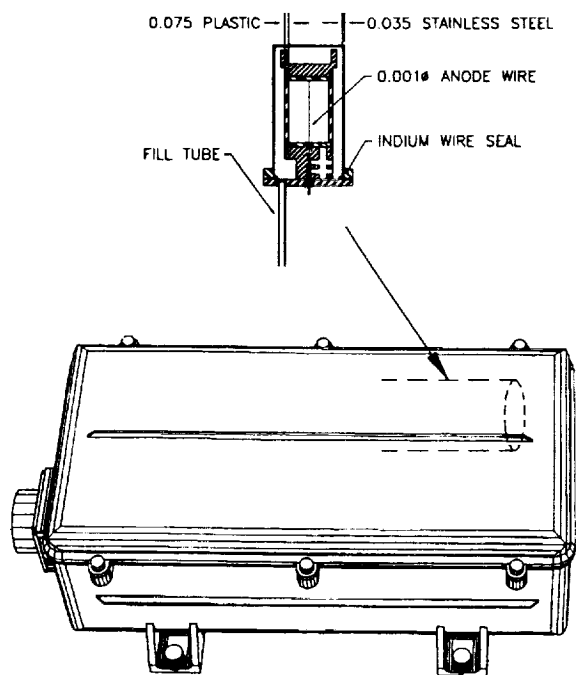INDIUM WIRE SEAL
FILL TUBE

Figure 1. A schematic of the payload bay tissue equivalent proportional counter.
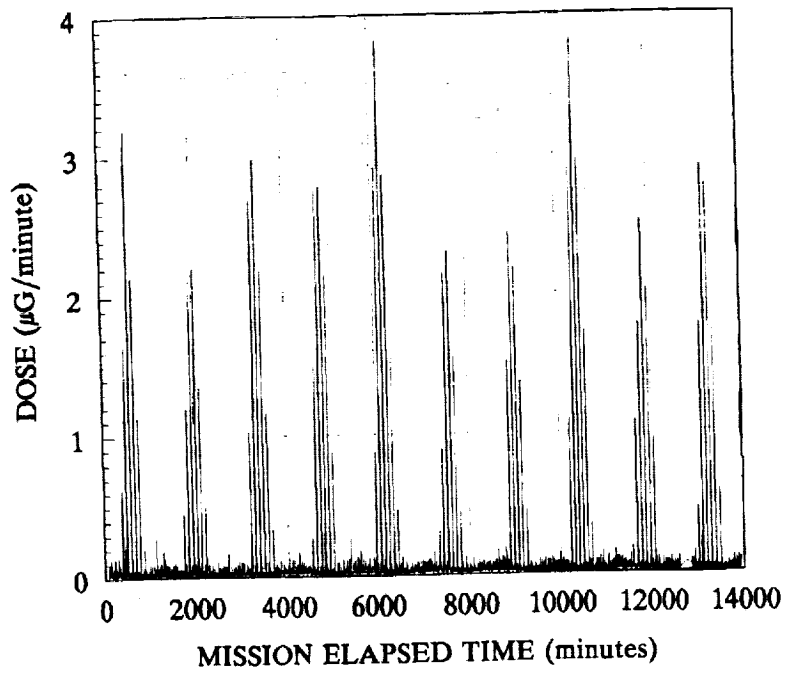
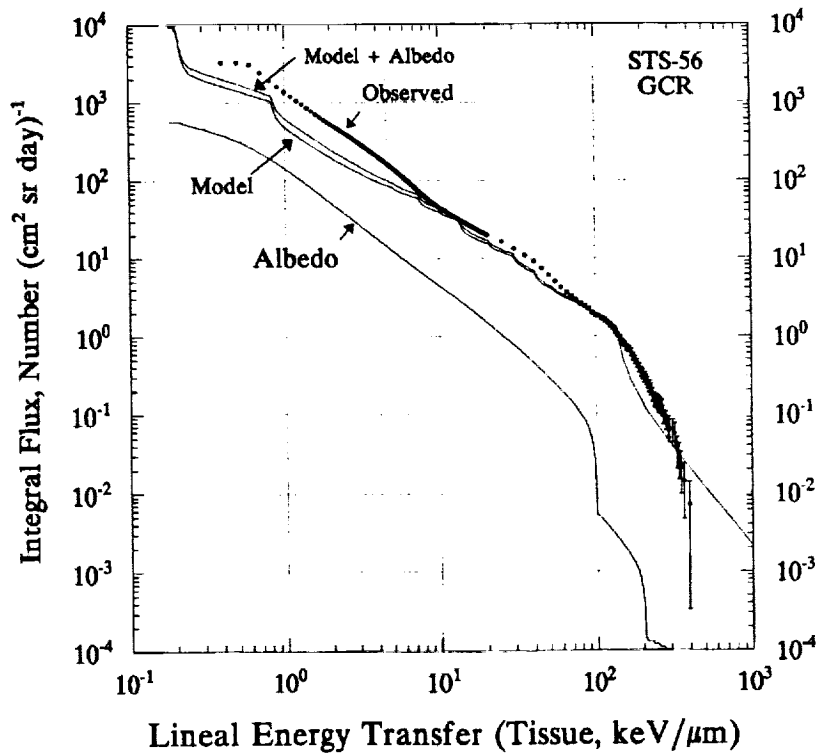Figure 2.   Dose rate versus mission elapsed time.

Figure 3.   Integral lineal energy spectrum for a 57° inclination flight. Solid
lines are HZETRN model calculations.

Section IV

Space Technology

Summary

Space Technology Summary

The overall objective of these research and technology efforts is to enhance the performance of human spacecraft systems and to enable more efficient human exploration and development of space. The FY93 space technology resources for human spaceflight were invested in (1) direct crew support projects such as life support, active thermal control, and extravehicular activity and (2) indirect crew and operations support projects associated with automation and robotics.

JSC continued to make excellent progress in regenerative life support technology, concentrating efforts on establishing ground-based test-beds and analytical models for demonstrating the feasibility of combining physiochemical and biological components into an integrated life support system. The results of these efforts include modeling of plant growth chamber investigations, large-scale plant growth investigations, and regenerative systems. Additionally, JSC received approval to initiate a phase C/D program for a water electrolysis flight experiment and began development of an engineering model for the experiment. In active thermal control technology, development of an Ultralite fabric reflux tube (UFRT) radiator concept for enhanced thermal management continued. The FY93 effort emphasized optimization of the UFRT geometry, materials, and fabrication techniques. In the EVA area, an electronic cuff checklist for subsequent inflight evaluation on the Space Shuttle flight STS-64 in FY94 was developed.

A broad spectrum of programs is being pursued in robotics systems and advanced automation technology. Tasks underway in dexterous on-orbit grasping and manipulation will provide new capabilities for Space Shuttle Orbiter and international Space Station robotic servicing and maintenance. Included in this set of tasks are (1) the flight demonstration of a dexterous magnetic end-effector for the Shuttle remote manipulator system, establishing an alternative to the present cable-snare design; (2) the development of a set of flight experiment dexterous manipulator hardware, based on the flight telerobotic servicer program hardware, to be demonstrated in the Orbiter payload bay; (3) the development and demonstration of design concepts for fault tolerance within robotic manipulators through multiple levels of mechanical redundancy; and (4) the evaluation of advanced technology for manipulation and grasping targets and proximity detection systems.

Two advanced automation technology tasks have been undertaken to increase the efficiency of spacecraft ground support operations. These tasks include the development of an expert system for managing Orbital rendezvous dynamics, and a new, innovative approach to real-time modeling of spacecraft systems in which the effects of operating procedures can be modeled as part of a failure modes and impacts analysis.

Three decades of investment in space for the security and welfare of the United States has achieved significant successes: economic stimulation of the country through technological advancements, and major direct and indirect contributions to winning the cold war. The direct factors include opening up the flow of information (and the information age) through communication satellites, while the indirect factors include demonstrating the unparalleled capability of our advanced democratic society and a positive vision for our youth. These accomplishments have been made possible by the high-leverage investment in people, facilities, and a foundation of space technology. Curtailment of space technology resources will be obvious in the short term only in reports. Longer term accomplishments will reflect the level of today's investment.
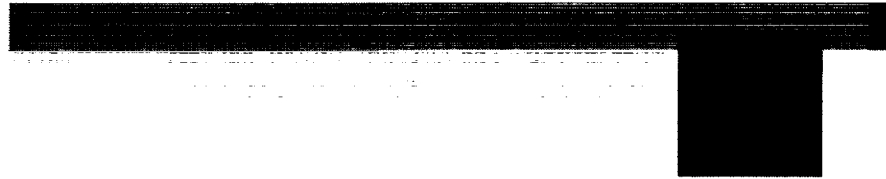
Section IV

Space Technology

Significant Tasks

Regenerative Life Support Systems (RLSS) Test Bed Modeling and Analysis

PI: Marybeth Edeen/EC7
Reference: ST 1

The RLSS test bed modeling and analysis work has been a multiyear effort by McDonnell Douglas Aerospace (MDA) to accurately model plant growth and the chamber support systems of the RLSS test bed: the Variable Pressure Growth Chamber (VPGC) and the Ambient Pressure Growth Chamber (APGC). At the beginning of FY93, models for all of the support systems of the individual chambers had been developed (thermal, lighting, nutrient delivery, atmospheric conditioning, etc.) as well as a model of lettuce growth based on data from the VPGC. These models were developed in CASE/A (Computer Aided Systems Engineering and Analysis tool.) In FY93, three specific tasks were undertaken.

The first task was to upgrade the condensing heat exchanger model of the VPGC so that the model more accurately predicted the performance seen in the chamber. To accomplish this task, it was necessary to model the heat and mass transfer across the condensing heat exchanger separately, instead of using a combined heat and mass transfer coefficient, as was done previously. The separate heat and mass transfer coefficients were calculated from test data provided to MDA from previous chamber testing. The resulting model can very accurately predict the performance seen in the chamber and has been used as a predictive tool to determine the feasibility of increasing the light levels (and thus the heat load to be removed) in the chamber.

The second task was to develop a model of wheat growth in the APGC. In previous years, a model of lettuce growth in the VPGC was developed by running a designed experiment during a lettuce crop cycle. In that experiment, air velocity, carbon dioxide (CO_2) concentration, light level, and temperature were varied according to a Box-Behnkin experimental design. The plants' response to the changing environmental conditions was measured by their change in CO_2 assimilation rate and evapotranspiration rate. The effect of the plant aging was taken into account by running a baseline set of conditions every day and measuring the change in rates as a function of age. For the wheat growth model, a Box and Wilson, or central composite experimental design, was used. This type of design was chosen because it contains three portions: factorial, centerpoint, and optional axial. The axial portion allows the user to get two-way interactions if the factorial portion indicates that interdependence of the factors exists. Also, the axial portion is tested with one factor at its limiting value so that the resulting model can be validated over a much wider range of data. This is especially useful in systems like ours where the maximum temperature and dew point cannot be achieved simultaneously due to thermal limitations but can be achieved one at a time. For the wheat growth model, CO_2 concentration, temperature, vapor pressure deficit, and air velocity were varied according to the Box and Wilson design throughout the course of a wheat crop. The measured variables were the evapotranspiration rate and the CO_2 assimilation rate, which were also used to predict biomass accumulation and oxygen production. The experimental matrix was repeated once a week for the last 7 weeks of the test to incorporate the effects of plant aging into the model as well as the plant's response to the changing environmental parameters. The data that were collected were provided to MDA and the wheat growth model was developed. The wheat growth model was then incorporated into the existing APGC model and checked out.

The third task in FY93 was to develop a model of the solid amine water desorbed CO_2 removal subsystem (SAWD II) and determine the best way to integrate this physicochemical subsystem with the chamber control systems and a human input while maintaining the desired conditions for plant growth. The existing CASE/A model of the SAWD II was modified to better predict performance data for the subsystem. Once this was done, the SAWD II model was incorporated into the VPGC model to evaluate integration issues. Since the SAWD II works best if it runs continuously instead of being repeatedly turned on and off, the most important issue was how the SAWD II should be integrated with the chamber.

One possibility was to integrate it in such a way that the subsystem could switch between processing ambient air and chamber air, depending on the concentration of CO_2 within the chamber, as shown in figure 1. The concern was that the chamber CO_2 concentration would deviate markedly from the desired set point of 1000 ppm CO_2. As shown in figure 2, when the SAWD II switches to ambient air because the chamber air concentration has dropped below the desired set point, the chamber CO_2 concentration rises significantly because the plants can not remove enough CO_2 to handle the person loading being placed on the system. Alternately, if the SAWD II

always draws air from the chamber and the chamber control systems make up CO_2 when the SAWD II removes too much, the concentration of CO_2 in the chamber remains much closer to the desired set point, as shown in figure 3. Thus, the results of the modeling that suggest that the best way to integrate the control systems for the SAWD II and the VPGC would be to have the SAWD II always drawing air from the chamber atmosphere.
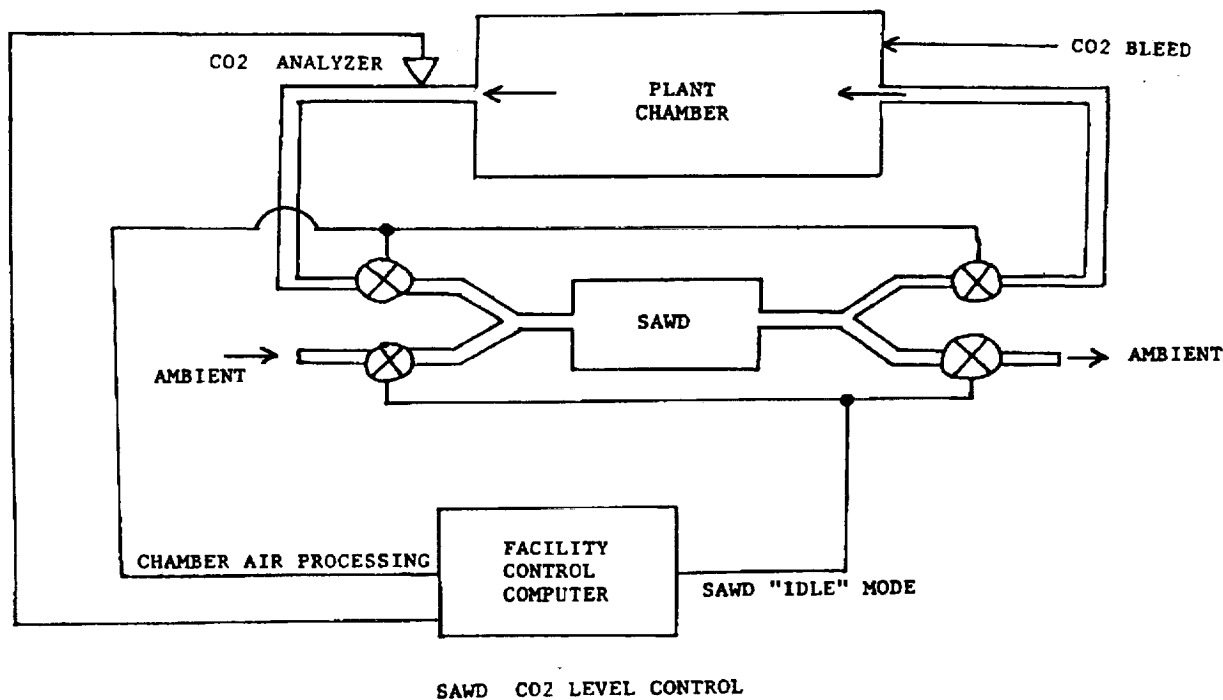

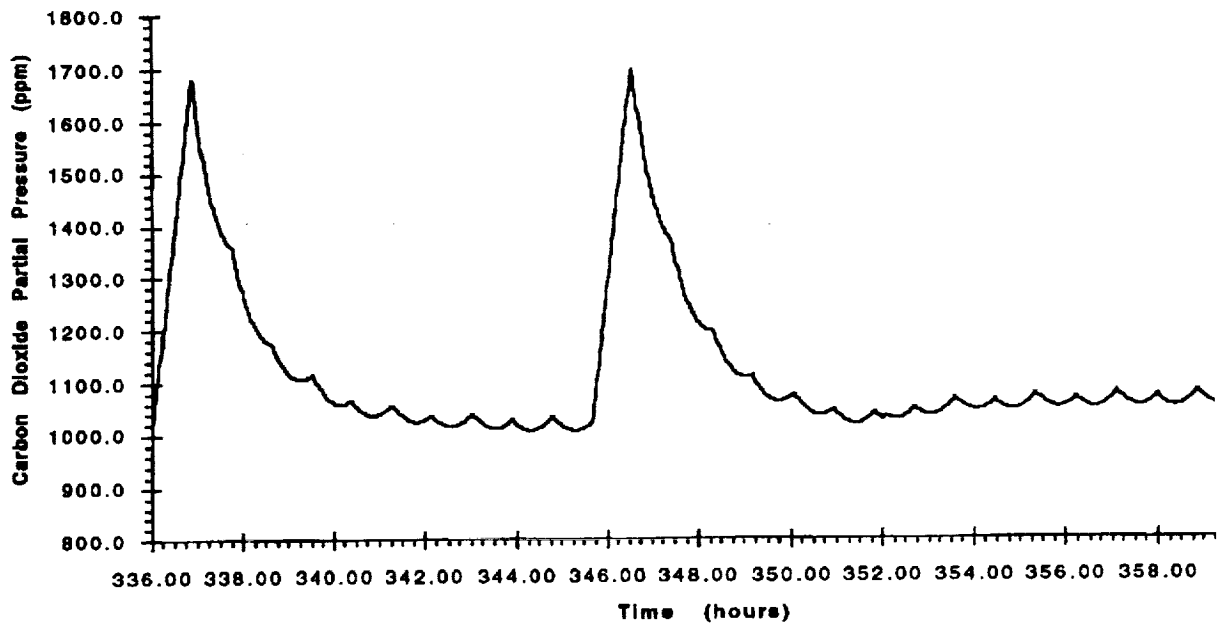Figure 1.   SAWD II/VPGC integration schematic.

Figure 2.   Chamber CO_2 concentration during crop day 15 with SAWD II configured as in figure 1.
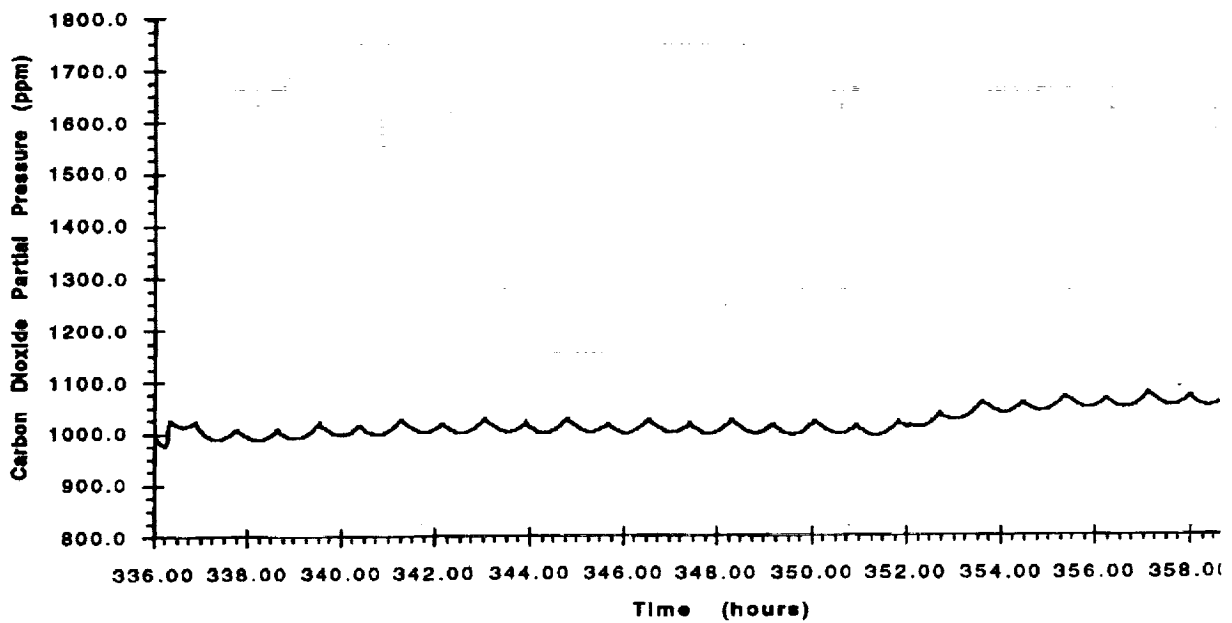

Figure 3.   Chamber CO_2 concentration with SAWD II continually drawing from chamber atmosphere.

Advanced Life Support Systems Integration

PI: Terry O. Tri/EC3
Reference: ST 2

The advanced life support Systems Integration Research Facility (SIRF) Project is a key part of the Office of Advanced Concepts and Technology (OACT) Regenerative Life Support Program, whose goal is to develop life support technologies and perform extended testing of these technologies in response to future human exploration mission requirements. The SIRF Project is using the Crew and Thermal Systems Division's (CTSD's) 6-meter chamber to integrate and test these life support technologies. The project will provide the system-level integration, operational experience, and performance data necessary to confidently proceed with the design, development, fabrication, and testing of a regenerative physicochemical life support system, including thermal control, required for future human space exploration mission scenarios. Trade studies, analyses, integration, and long-duration testing both with and without human test subjects will be performed in the 6-meter chamber to evaluate technology readiness and bridge the gap between existing subsystems, sensors, and control and monitoring methods and the actual development of an integrated physicochemical regenerative life support and thermal control system for human space exploration.

The life support and thermal control functions of SIRF have been allocated to three major systems: the air revitalization system (ARS), the water recovery system (WRS), and the thermal control system (TCS). These systems and the subsystems which comprise them have an integrated control system, which can provide process as well as supervisory control functions. The operations of the ARS, WRS, and TCS are supported by facility systems designed to perform necessary interfacing functions, such as external gas supply and venting. A major facility support system is the human interface to the WRS, which provides for the collection of multiple waste water streams for distribution to the appropriate subsystems of the WRS.

As shown in figure 1, the upper level of the three-level 6-meter chamber is a sealed control volume from which the ARS draws an air stream for CO_2 removal and reduction, O_2 generation, and trace contaminant removal. Simulated metabolic inputs of CO_2, water vapor, and heat are provided to the control volume by means of the facility's unique human atmospheric simulator (HAS). The middle level of the SIRF chamber is reserved for the ARS subsystems and the internal TCS components, which interface with air circulation ducting originating from the upper level control volume. On the lower level of the chamber reside the WRS subsystems and the human interfaces for collection of waste water streams.

During FY93, the primary project activities involved buildup of test support equipment for the ARS subsystems, performance testing of individual ARS and TCS subsystems, design of the WRS and waste water collection provisions, and development of the SIRF integrated controller. During the first quarter, a test series totaling 28 days of around-the-clock performance testing of the AlliedSignal Four-Bed Molecular Sieve (4BMS) CO_2 removal subsystem was initiated after it was succeSpace Stationully installed in the second level of the 6-meter chamber. Controlled inlet conditions to the 4BMS were provided by the facility HAS during performance testing. During the first quarter, upon delivery of the required hardware and software, development of the SIRF integrated controller was initiated. A succeSpace Stationul integrated test with the controller and the 4BMS was completed during the fourth quarter of FY93, paving the way for subsequent subsystem integration activities. Also during the first quarter, the Sabatier CO_2 reduction subsystem (CRS) and the water electrolysis oxygen generator subsystem (OGS) were received from Hamilton Standard. Facility support equipment buildup for performance testing of these two subsystems neared completion at the end of FY93, in support of testing the CRS and OGS during the first quarter of FY94. Individual

performance testing and integrated testing of both the CRS and OGS will be completed in CTSD's room 2007 lab, after which both subsystems will be moved to the second level of the 6-meter chamber and integrated with the 4BMS. Subsystem performance testing of the TCS condensing heat exchanger (CHX) was also completed during FY93. A 3-day series of CHX performance tests was carried out during the third quarter, followed by data reduction and analysis activities. During the fourth quarter of FY93, the first phase of construction of the new 6-meter chamber control room, which will be used in support of the SIRF project, was completed. Subsequent outfitting of the control room will take place in FY94.
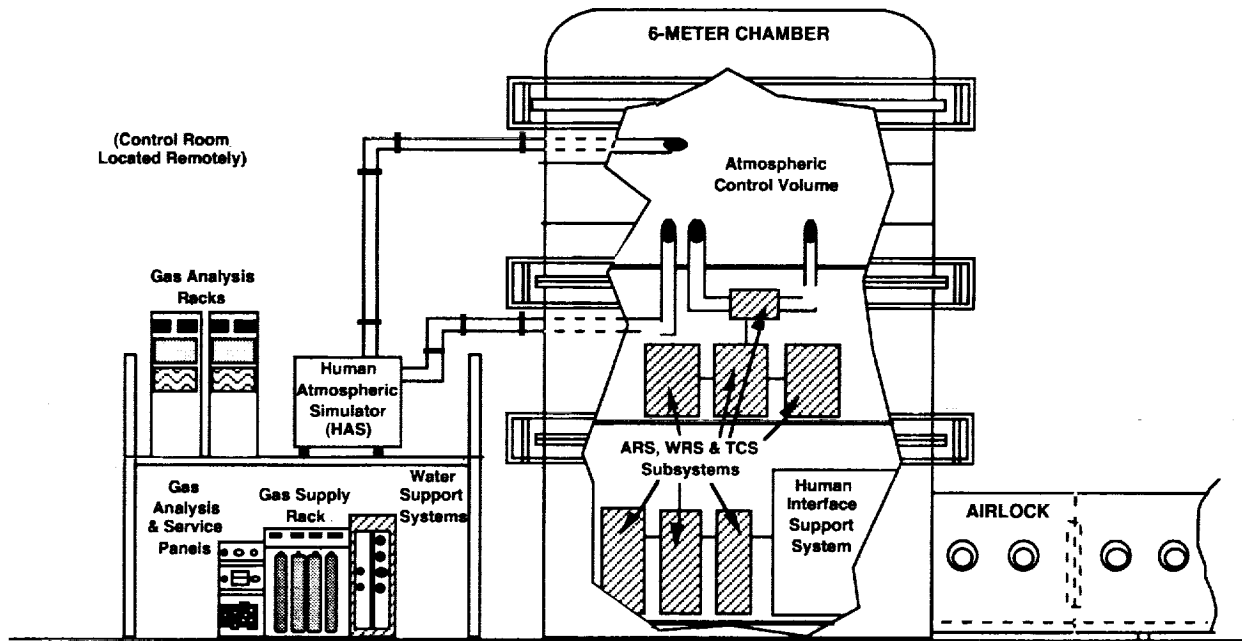

Figure 1. Schematic of the SIRF 6-meter chamber configuration.

Extravehicular Mobility Unit Electronic Cuff Checklist Development

PI: **Jose A. Marmolejo/EC5**
Reference: **ST 3**

Because extravehicular activity (EVA) missions have grown in complexity, the amount of information required by the EVA astronaut has also grown. At JSC a project is underway to demonstrate that an electronic cuff checklist could replace the current paper procedural checklist. This paper cuff checklist is limited to 25 3.5-inch by 4.5-inch sheets (50 pages including front and back) of text and simple graphics, cumbersome to use, and time-consuming to assemble. Proper configuration management control of it is difficult.

The electronic checklist currently under development is expected to improve astronaut EVA productivity by providing a portable, self-contained information display system which will allow the crewmember to have ready access to a much larger database. This database is even capable of being modified on-orbit.

The electronic checklist consists of an off-the-shelf liquid crystal display, touch screen (for screen selection), driver electronics (including microcontroller, memory, and serial data programming port), and battery pack enclosed in an aluminum frame protected thermally by softgoods.

Access to the memory contents is accomplished via the touch screen through a unique sextant screen protocol. Worn over the space suit arm assembly (as is the current paper cuff checklist), the electronic cuff checklist provides easy access to text and graphics databases of greater than 500 pages. To accommodate the data requirements of various Shuttle EVA mission tasks, this database is both reprogrammable and expandable through a serial data port. Software training tools have been developed to allow efficient creation of pages and loading of the checklist database. The additional benefit of better configuration management control can be achieved by an access-controllable electronic database.

The current year's activities include the development and crew test of a functional prototype (fig. 1), which is scheduled to be tested in manned vacuum environment in late 1993. Also planned are flight unit tests during an intravehicular flight experiment and during an actual EVA in fiscal year 1994 (currently planned for STS-64, September 1994).

Accomplishments to date include breadboard/ prototype models and various engineering design trades with valuable inputs provided from the crew, Flight Crew Support Division, Mission Operations (Flight Data File and EVA Crew Systems), and Crew and Thermal Systems division (EVA Equipment Branch) personnel.
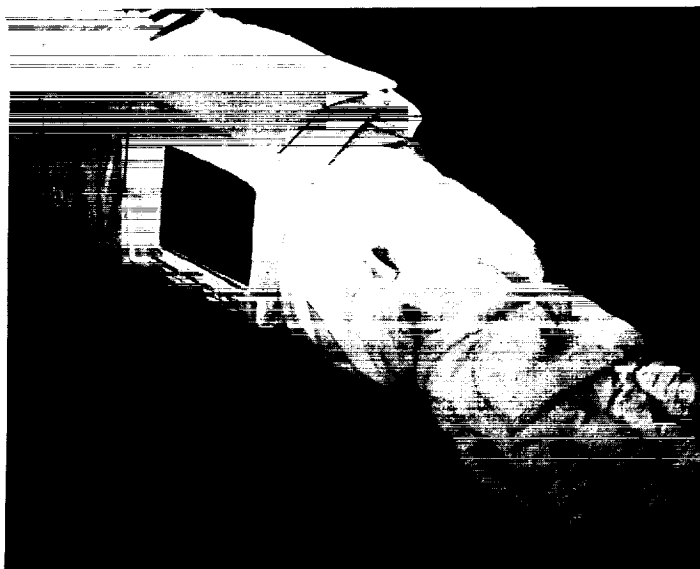

Figure 1. Electronic cuff checklist Phase I ground test article with sextant screen.

Electrolysis Performance Improvement Concept Study (EPICS)

PI: Sandra Foerg/EC3
Reference: ST 4

Work began in 1991 to develop a flight experiment with the objectives of demonstrating and validating the static feed electrolyzer (SFE) concept in microgravity and investigating ways a microgravity environment may improve SFE performance. If this Shuttle middeck experiment is succeSpace Stationul, the results can be used to improve SFE process efficiency for such activities as life support, propulsion, energy storage, and space manufacturing. The space environment is needed for this experiment because the SFE process has not been operated in microgravity, data on gas and liquid transport in microgravity are very limited, and one-g test results are compromised by buoyancy and by gravity-affected fluid configuration within the electrolysis cells. A lower cell voltage operation may result from microgravity effects on the distribution of liquid electrolyte, the gas/liquid interfaces with the cell, and the capillary forces on fluids within the pores of the electrodes and the electrolyte matrix.

Table 1 provides the vehicle conditions and the EPICS operating conditions as they are now planned. The experimental hardware consists of a mechanical/electrochemical assembly (M/EA) and control/monitor instrumentation (C/MI). The M/EA is composed of three separate, self-contained integrated electrolysis units (IEUs), ancillary components, and the supporting structure. Each IEU is made up of an integrated electrolysis cell, a thermal control plate, and O_2 and H_2 accumulators. The integrated electrolysis cell consists of an electrolyzer cell core and a recombiner cell core (fuel cell concept) to enable the experiment to be self-contained. The C/MI controls the operation of the experiment via the M/EA components and provides for monitoring and control of critical parameters and storage of experimental data. The experiment is designed for independent operation, requiring only electrical energy, and cabin air for cooling. The water supply for the electrolysis will be self-contained in the experiment. A single on-actuator of the experiment is all that is needed by the operator. The experiment is designed to be compatible with the weight, power, and heat rejection capability of two standard middeck locker spaces (fig. 1).

The major milestones completed in FY93 include initiation of Phase C/D of the program after approval by the Non-Advocate Review Board, completion of the Preliminary Design Review, and initiation of the engineering model development.

The planned milestones for FY94 include the Phase 0/1 Flight Safety Review and the Payload Integration Plan Review, the completion of the engineering model development and testing, the Critical Design Review, and the flight hardware fabrication and assembly. The EPICS flight experiment is expected to be ready for flight in early 1995.

Table 1. Vehicle Conditions and EPICS Operating Conditions

Vehicle Conditions

Middeck Total Pressure, kPa (psia)	101.3 ± 1.4 (14.7 ± 0.2)
Middeck Temperature, K (F)	292 to 300 (65 to 80)

Nominal Operating Conditions

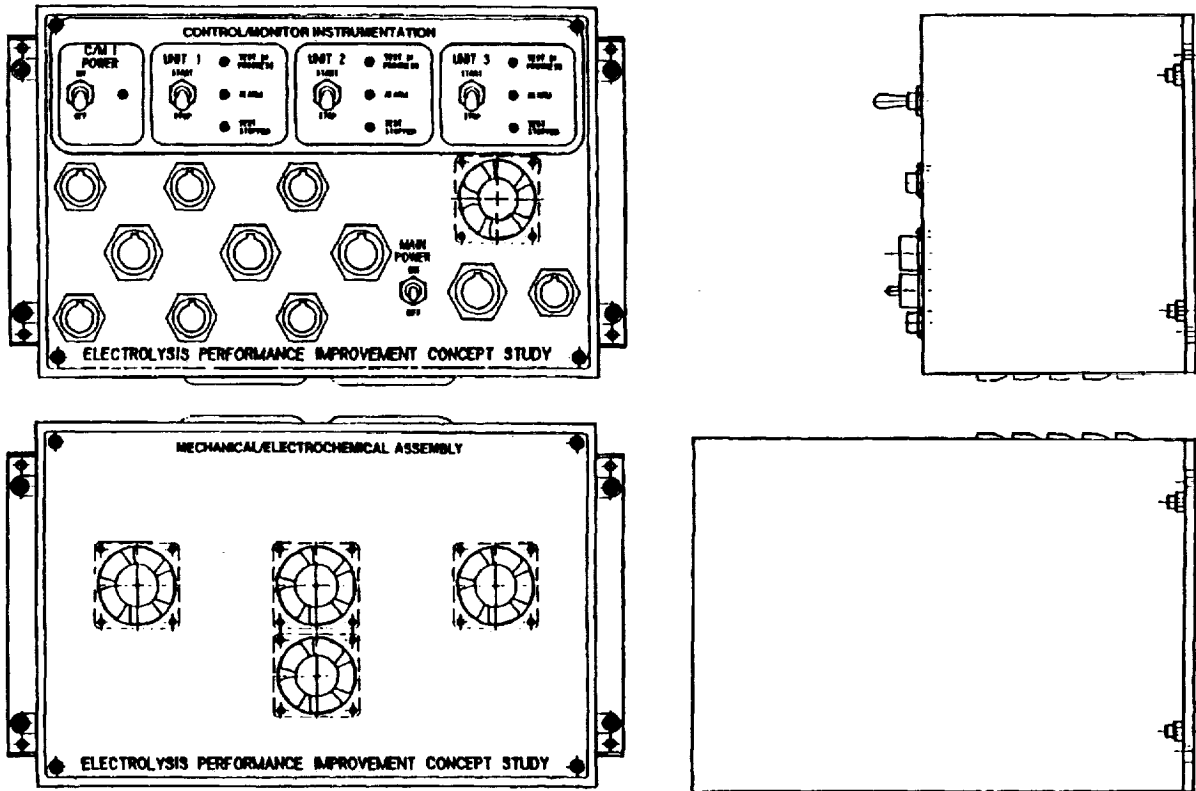|	
Number of IEUs	3
Current Density, mA/cm2 (ASF)	34 to 137 (32 to 129)
Operating Pressure, kPa (psia)	114 ± 13 (16.6 ± 1.9)
Nominal Operating Temperature, K (F)	331 (135)

Figure 1.   EPICS flight experiment hardware packaging.

Ultralite Fabric Reflux Tube Radiator

PI: **Patricia A. Petete/EC2**
Reference: ST 5

The Bubble Membrane Radiator Project was initiated in March 1988 to continue development of promising thermal management concepts for space applications. The initial concept studied, the bubble membrane radiator, is designed for space thermal management on missions such as a long-duration planetary probe during which low-temperature heat rejection would be required for cooling the habitat and scientific equipment. Work on the second phase of development for the bubble membrane radiator was finished during FY92 with the completion of the Steady-state Condensation with Rotational Acceleration Boundary Layer Examiner (SCRABLE) code and materials compatibility testing that was conducted with Oregon State University.

Work was refocused during FY92 from the bubble membrane radiator concept to fabrication and testing of Ultralite fabric reflux tubes (UFRTs) because of a need for heat rejection concepts that take advantage of low gravity environments. Development, optimization, and testing of UFRTs continued in FY93 under two tasks: measurement of radiative properties and development of UFRT tough metal technology. Both were completed in FY93. Three additional tasks were initiated in FY93: (1) fabrication of the tough metal tubes, (2) heat transfer optimization, and (3) analyses follow-on.

The radiative properties mesurement involved life testing of a UFRT and wicking tests at Oregon State University. Vacuum chamber testing of a UFRT at moderately low vacuum and temperature included an accelerated life test at a steady-state power input of 78 W and two subsequent start-up and shutdown tests. The life testing succeSpace Stationully demonstrated continuous operation over a period of 800 hours. Tests to determine the wicking capability of five different materials were also completed. The data will be reviewed in FY94, after which time the wicking material will be selected.

A new cluster mill for fabricating liners was developed under the tough metal technology task. The new cluster mill was designed in FY92 and fabricated during FY93. It will allow the fabrication of liners with diameters as small as 1.27 cm out of materials tougher than copper. The testing of this new cluster mill is scheduled for FY94.

The primary goal of Task 1, the first added in FY94, was to fabricate new UFRTs with an improved design. A search was conducted for a better liner material than copper, which was used in the first UFRTs. Titanium was selected due to its greater strength and lower weight. Battelle has had previous experience with fabricating titanium parts and has confidence in its selection for the new UFRTs. One UFRT (fig. 1) was succeSpace Stationully fabricated of titanium during FY93, and additional ones will be fabricated in FY94.

Task 2 for FY94 involved evaluations of UFRT tests conducted in FY92 to validate and/or recommend improved performance. Several improvements to the test procedure were recommended, along with some design changes to the UFRTs. One example of a design change is to improve the heat transfer by decreasing the evaporator wall thickness. These changes will be incorporated in the next series of tests as funding permits.

Additional analyses were started under FY94 Task 3 on data collected during the thermal vacuum test conducted at JSC in FY92. The analysis centered on frozen start-up characteristics and on temperature variations between the evaporator and condenser outer surfaces. These analyses will continue into FY94.

Plans for FY94 include (1) selection of wicking material, (2) testing of the new cluster mill, (3) fabrication of titanium liners, (4) implementation of design changes identified under Task 2, and (5) analyses follow-on. Testing of the tough UFRT will be done if additional funding becomes available.
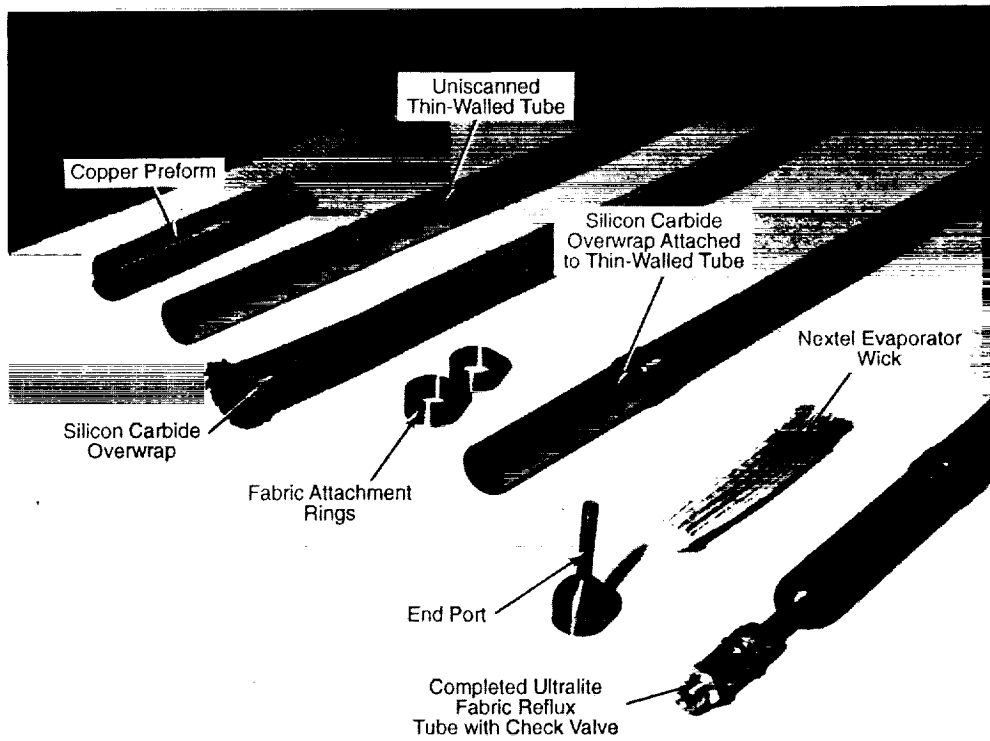
Figure 1.   Ultralite fabric reflux tube radiator.

Regenerative Life Support Systems

PI: **Donald L. Henninger/EC3**
Reference: **ST 6**

The Regenerative Life Support Systems (RLSS) Project is concerned with the development of systems which will recycle the air, water, and wastes and produce food-use plants for long-duration missions. The envisioned system will combine physicochemical and biological components to form an integrated life support system.

Two major test bed facilities were built: the Variable Pressure Growth Chamber (VPGC), completed in FY91, and the Ambient Pressure Growth Chamber (APGC), completed at the end of FY92. The APGC was designed to serve as an ambient pressure control for tests performed in the VPGC at reduced atmospheric pressures. In addition, the APGC includes several design improvements, based on crop tests in the VPGC. This new facility provided the capability to perform large-scale testing with higher plants at ambient atmospheric pressure using a fluid delivery system configurable for hydroponics or solid support substrate operation. In the first quarter of the fiscal year, functional testing of the facility systems was completed and the first facility verification crop test was initiated. During the balance of FY93, three crop tests were conducted in the APGC. These tests demonstrated the growth of higher plants in a closed, controlled environment for use as a component of an integrated RLSS. The tests were performed to obtain scientific and engineering data characterizing crop growth and test bed performance over the full cycle of each crop, from seed to maturity, using the Crew and Thermal Systems Division's newly developed hydroponics system. Biological test data included CO_2 uptake, O_2 production, evapotranspiration, biomass production, and trace contaminant generation. Unique characteristics of each crop test follow.

- APGC Facility Verification Lettuce Crop I (fig. 1)

  Test Duration: 30 days. Planted December 14, 1992; harvested January 13, 1993.

  Cultivar: "Waldmann's Green" leaf lettuce. Seeding density: 84 seeds m-2.

  Performance of the chamber's engineering systems was verified with the physiological loading from a lettuce crop.

- APGC Facility Verification Lettuce Crop II

  Test duration: 30 days. Planted February 8, 1993; harvested March 10, 1993.

  Cultivar: "Waldmann's Green" leaf lettuce. Seeding density: 84 seeds m-2.

  The crop was grown as a replicate to the Facility Verification Crop I to provide a measure of the variability of crop performance over test cycles, except the level of photosynthetic lighting was reduced by 60% during the first 4 days of the test to improve seedling emergence through the hydroponics lid assembly.

- APGC Wheat Growth Model Development Test (fig. 2)

  Test Duration: 79 days. Planted April 19, 1993; harvested July 7, 1993.

  Cultivar: "Yecora Rojo" hard red spring wheat. Density: 2000 seeds m-2.

  Plant physiological and facility performance data were obtained to develop a wheat growth model. The model is based on a Box-Wilson (central composite) experimental design and was incorporated as a component in the CASE/A APGC and VPGC facility models. Air temperature, vapor pressure deficit (dew point temperature), CO_2 concentration, and air velocity were systematically adjusted to determine the effects on CO_2 utilization and transpiration (as measured by condensate collection). Data from a total of 272 test points collected over the course of the test were used in development of the model.

Preliminary results for the three crop tests are shown in Table 1.

Table 1. Crop Test Results

Parameter	Hydroponics Lettuce Crop I	Hydroponics Lettuce Crop II	Wheat Model Development
Yield Component	Fresh Leaves	Fresh Leaves	Dry Grain
Production (Kg)	64	62	5.7
Yield (Kg m-2)	5.6	5.5	0.5
Harvest Index*	86%	87%	38%

* Percent of total biomass that is edible

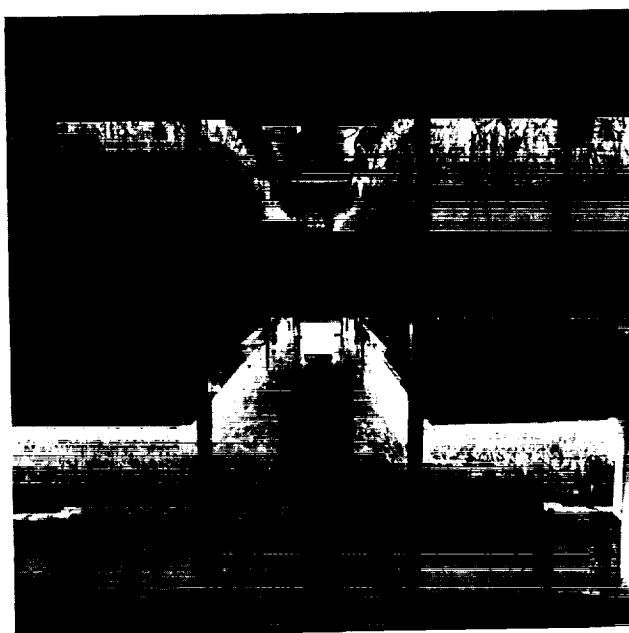Figure 1.   View of APGC with mature 30-day-old lettuce crop.

Figure 2.   Internal view of wheat crop within the APGC one week before harvest.

Dexterous End Effector Flight Demonstration

PI: **Leo G. Monford/ER4**
Reference: **ST 7**

The dexterous end effector (DEE) is a flight demonstration of the ability of five new elements of technology to assist the Shuttle robotic manipulator system (RMS) in dexterous and/or automatic tasks. The main technology development is the force torque sensor (FTS). Three of the other developments support the FTS demonstration: the targeting and reflective alignment concept (TRAC), the magnetic end effector (MEE), and the carrier latch assembly (CLA). The fifth development, added during FY93, is AUTO TRAC, which utilizes some of the elements of the other DEE equipment.

The FTS provides visual feedback to the RMS operator of the forces exerted by the RMS. This feedback is in the form of digital and analog displays on the aft flight deck TV monitor or, alternately, on the screen of the payload general support computer (PGSC). Thus the operator may be able to perform dexterous tasks such as pin-in-hole insertion, electrical connector mating, module changeout, or structure erection.

TRAC allows precise alignment of the RMS to the payload or alignment between movable payload elements. Because TRAC is essentially a flat mirror, target space/weight requirements for accurate payload alignment are less than those of other six-axis targets. In addition, TRAC separates the cues for pitch and yaw alignment from those for X, Y, Z, and rotation, thus improving the operator's ability to interpret and control.

AUTO TRAC is a system for automatic targeting. It uses a mirror target with several retro-reflectors and a TV camera with flashing LEDs near the camera lens. The target can be recognized in the camera scene, and an algorithm operating on the scene calculates the position and attitude of the target. The AUTO TRAC hardware is compatible with TRAC.

The MEE is a system of electromagnets, which allows magnetic, fault-tolerant grappling of payloads. The fault tolerance is achieved by redundancy in power, controls, and magnet coils. In addition, the MEE is inherently highly reliable, low cost, and low maintenance because it contains few moving parts.

The CLA extends the fault tolerance capability of magnetics to the berthing or docking of payloads and spacecraft. Mechanical latches are provided for long-term holding, but holding during the berthing or docking is done by magnetics alone.

The overall objective of the DEE task is to demonstrate these five technology developments in the Space Shuttle environment. The detailed objectives are as follows:

- Demonstrate that the RMS has increased dexterity through the use of a force and torque sensing device. This includes safely performing tasks requiring constrained motion.

- Demonstrate the feasibility of magnetic grappling on orbit through the use of a magnatic attachment tool (MAT) that can be picked up by the RMS.

- Demonstrate TRAC as a precise method of determining the position of the RMS for close-tolerance operations and as an effective camera target for assembling structures on orbit.

- Simulate Space Station erection activities using the RMS and DEE hardware for insertion, removal, and rotation tasks.

- Simulate an MST insertion activity using the RMS and DEE hardware and a module servicing tool (MST) receptacle.

- Demonstrate the use of a magnetic holding device to temporarily stow hardware on orbit.

- Obtain data to determine the control resolution of the RMS in several modes of operation on orbit.

- Use the payload bay targeting camera to demonstrate automatic recognition of the target and determination of the target attitude and position vectors by computer analysis of the target scene.

The approach for the project is to develop space-compatible hardware which can be flown as a Shuttle flight experiment, meeting all of the applicable Space Shuttle Program requirements for payloads.

The following work was accomplished during FY93:

- All of the experiment operations were demonstrated in the Manipulator Development Facility or in the DEE Lab with prototype hardware.
- The flight equipment was 99% assembled.
- All environmental testing was completed.
- The structural analysis and test correlation was 99% completed.
- All required thermal analysis and test correlation was completed.
- Detailed planning was developed and the flight rules, mission timeline, malfunction procedures, and cargo system manual were baselined.

- All Payload Integration Plan (PIP) Annex data were developed and delivered to the book managers.
- The Phase III payload safety review was completed.
- A PIP change to add a payload bay targeting camera was processed, and the equipment was designed and fabricated in the last 5 months of FY93.

Future work will be the completion of assembly, completion of the analysis, verification analysis review, final testing, shipment to KSC, integration onto the Orbiter, STS-62 flight support, and de-integration. All work on this task will be completed in FY94.

C-2

Flight Telerobotic Servicer Manipulator Technology Capture

PI: John Chladek/ER4
Reference: ST 8

NASA's Office for Advanced Concepts and Technology (OACT) was tasked with capturing the technologies that went into the design, analysis, and development of the flight telerobotic servicer (FTS) after it was canceled from the Space Station Freedom Program. The FTS flight manipulator mechanism was almost ready for assembly at Martin Marietta Astronautics (MMA), the majority of flight components having been delivered by the subcontractors. To complete the manipulator assembly would allow testing of the high risk item, the flight manipulator. The characterization of its performance in space environments would also serve as part of the technology capture. This task has several team players: MMA to complete assembly of the flight manipulator, JSC's Automation and Robotics Division to receive the manipulator and perform environmental characterization tests, and Langley Research Center's (LARC's) Information Systems Division to continue to develop and refine the robotic control system. JSC added the objective of retaining the flight heritage of the manipulator for possible flight use in an Orbiter flight experiment or operational use.

The FTS manipulator system developed for the Space Station required a high-performance, safe, fault-tolerant dexterous mechanism that could operate reliably and survive 30 years in space. The original FTS was designed to provide telerobotic assistance to enhance crew activity and safety and reduce crew extravehicular activity. Tasks foreseen included orbital replacement unit changeout, Hubble Space Telescope servicing, Gamma Ray Observatory refueling, and several in situ Space Station servicing and maintenance tasks. Operation of the FTS was planned to evolve from teleoperation to fully autonomous execution of many tasks. The manipulator properties were to allow positioning control to one thousandths of an inch, with zero actuator backlash over a temperature range of -50 to +95 °C, and were to include impedance control and inertial decoupling. Safety and reliability requirements were developed to allow a 30-year life in space with minimum maintenance.

The first spaceflight of the FTS manipulator system was to be in the Orbiter payload bay to demonstrate several candidate tasks and verify manipulator performance parameters. The system had to meet the safety requirements for hazardous payloads for operation in the Orbiter payload bay during the demonstration test flights prior to Space Station use. These initial tasks included unlocking a Space Station truss joint, mating/demating a fluid coupling, contact following of a contour board, demonstrating peg-in-hole assembly, and grasping and moving a mass.

The flight manipulator system assembly, integration, and tests were completed at MMA, with a NASA acceptance test in July 1993. Integration of the flight end-of-arm tooling, a parallel jaw gripper, and the wrist camera and lights was completed in October of 1993. This system integration effort was continued to better prepare for a possible flight experiment dexterous Orbiter servicer system (DOSS) proposed by JSC to NASA Headquarters.

Lessons learned from the FTS program were many. The wide range of Space Station FTS mission tasks, combined with the goal of evolution toward full autonomy, forced several extremely demanding requirements that influenced the development cost and schedule of the manipulator system. Some of these requirements seemed excessive to the telerobotics community, but they were created to accommodate an open-ended evolution that was not to be impeded by functional limitations. A recommendation to remedy the possible impacts from such ambitious requirements is to better analyze candidate robotic tasks and to thoroughly define system operational requirements for mission safety.

JSC and LaRC provided the technical and managerial monitoring of the flight manipulator integration and development at MMA. JSC developed environmental characterization test plans for the flight manipulator and subsystems at JSC after MMA's completion of the manipulator

arm. JSC also involved Orbiter safety, reliability, and quality engineering (SR&QE) staff in the ongoing development decisions at MMA in order to retain the flight heritage of the manipulator. LaRC monitored the manipulator internal control system software development at MMA, and received the hydraulic manipulator test bed (HMTB) in November of 1992. This system provides a kinematic duplicate of the flight arm with control responses that closely mimic the flight system. LaRC will use this system for control system refinement and to provide task assessments for the proposed flight experiment.

Development and integration of the flight actuators and controllers in FY93 resulted in the completion of the flight FTS manipulator at MMA. An acceptance test was performed on July 28, 1993, that demonstrated to JSC and LaRC the assembled manipulator operating on an air bearing table at MMA (fig.1). Some unique tuning of the joint servos had not been accomplished, so performance of the manipulator was not tested to specifications. In lieu of the joint servo tuning, further component testing and integration of the end-of-arm-tooling (gripper) and wrist camera onto the manipulator was accomplished (fig. 2). This additional integration work on the flight manipulator system was pursued to provide an earlier awareness of any integration problems, as a means of risk mitigation prior to costing a possible flight experiment.

Proposals were submitted to NASA Headquarters research and flight program calls for flight experiments. These proposals included multicenter participation by JSC, LaRC, and Jet Propulsion Laboratory (JPL) in demonstrating robotic technologies developed by the OACT program, including those applicable to ground control and operational capabilities.

A planning session was held by the JSC Orbiter community and the DOSS team, composed of JSC, LaRC, JPL, and MMA. They reviewed the technical and operational aspects of the DOSS concept for application to a flight experiment and for use as an Orbiter resource in payload servicing and payload bay contingencies. To support the DOSS concept, significant systems engineering was accomplished to determine a method for the DOSS to operate on the end of the Shuttle remote manipulator system from ground control and the aft flight deck. Remote teleoperation of the HMTB at LaRC was accomplished from the JSC SPACE STATION control station mockup via the Tele-Robotic Interconnect Protocol (TelRIP) connection with LaRC. TelRIP, a data distribution mechanism used to control telerobot systems with networked computers, is used extensively at JSC and also at other NASA centers.
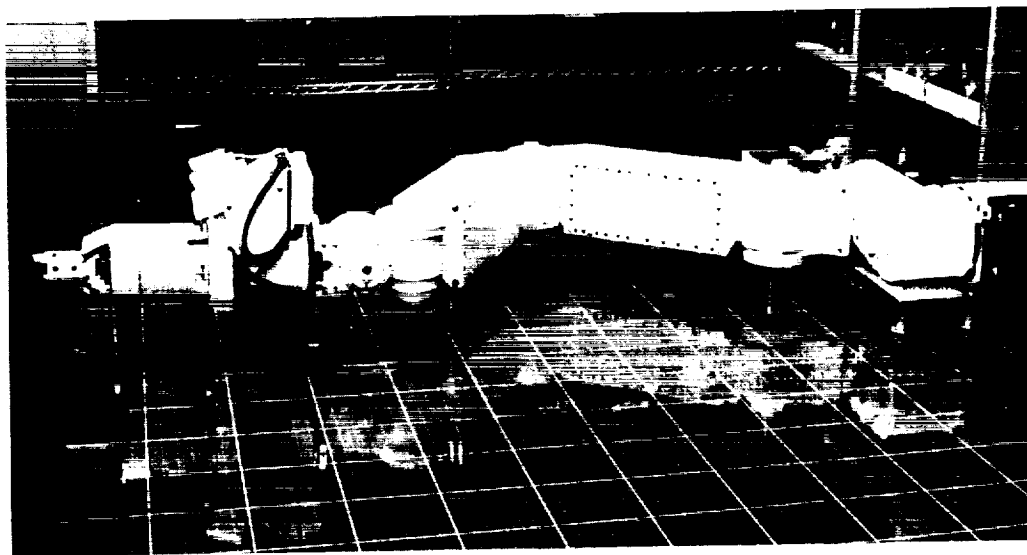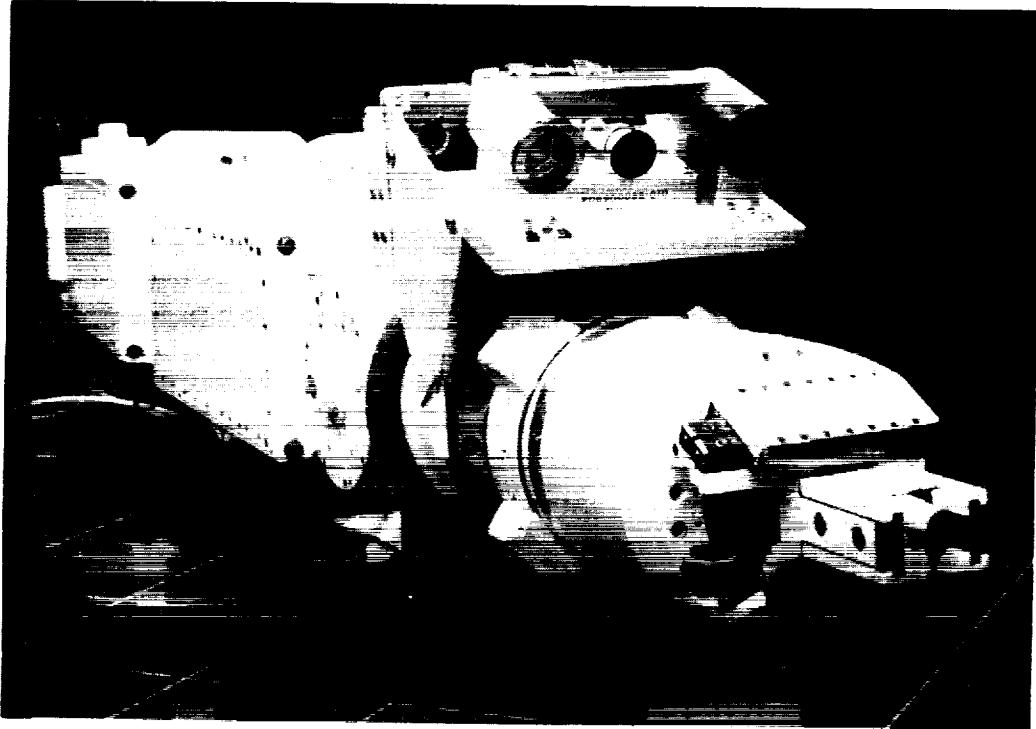

Figure 1.   FTS manipulator on air bearing table.

Figure 2.   End-of-arm tooling (gripper) and wrist camera & lights.

Fault Tolerant Robotics

PI: John Chladek/ER4
Reference: ST 9

NASA's development effort in fault tolerance for robotic systems includes a research grant to the University of Texas at Austin. A program was created for developing fault-tolerant reconfigurable manipulator architectures and adaptive control concepts. This research effort is to enhance three new areas in robotics: the development of a fault-tolerant manipulator joint module which is compact and scalable in size, the design of various sizes of these scalable modules that can be readily tailored into a reconfigurable manipulator architecture to fit the application, and the development of sophisticated decision-making system controls to drastically improve the failure tolerance capability at the individual joint level and to intelligently utilize any excess redundancy available in the manipulator system. Control of such configurations will require continuing research into using adaptive control techniques for rejecting disturbances caused by component failure.

Space-based robotic systems, operating in an environment where the costs can be high and consenquences serious, must employ failure tolerance to ensure safety and mission success. To meet the requirements for acceptance by mission managers concerned about success and safety risks, the operational limitations and constraints currently imposed on robotic systems must be minimized. Research continues in safe and reliable control and operations of robotic systems which could transparently absorb drastic control or electromechanical failures. This ability would effectively eliminate the current operational restrictions imposed on space robotic systems due to their risk of producing uncommanded motion by component or control failures. Full incorporation of such advanced concepts would also allow task continuation with full coordinated control while accommodating a failure in the system.

The purpose of this project is to demonstrate that multiple levels of fault tolerance for space or other high risk robotic applications can be provided by standard, scalable, modular manipulator joint configurations with adaptive controls that readily allow intelligent use of the redundant degrees of freedom (DOF) available in such manipulator systems. The extra DOF in space-based manipulators provide enhanced dexterity, operational usefulness, and multiple level tolerance to failures for assured long duration use. Extensive future work will be required on controls for these extra-DOF manipulator systems. A sophisticated decision-making package utilizing hybrid and adaptive controller synthesis for reacting to internal disturbances (failures) continues in development, and will be incorporated to dramatically improve the active fault tolerance capability of robotic systems.

The approach is to provide structural redundancies or alternative capabilities that allow up to four levels of fault tolerance in a modular manipulator architecture. The first level is in the dual actuator module (prime mover) with independent servo controllers. This becomes a common building element. The second level is redundant mechanism structures, either parallel or serial. The third level of fault tolerance uses active criteria-based decision-making software in a fault tree structure for controlling the first two levels of fault tolerance capabilities during disturbances (failures). The fourth level is accomplished by duality of the entire mechanism system, including its control.

The manipulator architecture under concentrated study contains excess redundancy in a series of mechanism joints, with duality in each servo control module. The reason for this arrangement is that in space the otherwise detrimental effects of gravity are not present. There are a few remaining single points of failure in the dual-servo-joint modules that could disable the joint, even though the number is significantly reduced due to the duality. The excess serial redundancy architecture would allow a failed joint to be rigidized, while the remaining operational joints provide the dexterity, end point control, and arm pose control to complete the task objectives.

These developments are demonstrated in test-bed configurations to evaluate the fault tolerance and control responses in actual mechanism structures. One such test-bed is composed of a four-legged,

sixteen-motor, four-gimbal mechanism prototype. The mechanism will be capable of fault recovery at several levels, both mechanical or electrical, and will be able to demonstrate three levels of fault tolerance. Accomplishments in the first year (FY90) included the development of a compact, scalable dual-actuator fault-tolerant servo module, which forms the first level for modular fault tolerant manipulator systems. Second year (FY91) efforts provided characterization tests of the dual-actuator servo module, the overall design of the multilevel test-bed, and the development and evaluation of a prototype 2-DOF gimbal module as a common element in the mechanism test-bed. Third year (FY92) accomplishments included redesign optimization of the dual-actuator servo module design based on performance tests and space environmental considerations, analysis and experimental tests of actuator controllers capable of responding to internal actuator failure transients, development of a dynamic simulation of the actuator module to test control strategies that minimize internal fault transients, and studies to determine comparative benefits of various adaptive control methods to the field of fault-tolerant robotics.

Accomplishments in FY93 included evaluation testing of the dual-actuator servo mechanism and completion of the yoke assembly for the 2-DOF knuckle, one of the common elements for the multilevel test-bed. On adaptive controls development, time regulation and torque distribution algorithms were successfully applied to serial and parallel fault-tolerant manipulators, and hybrid algorithms that employ sliding mode control have been succeSpace Stationully simulated.

Special Purpose Dexterous Manipulator Emulation and Technology Integration Evaluation

PI: **LeBarian Stokes/ER6**
Reginald B. Berka/ER4
Reference: **ST 10**

The special purpose dexterous manipulator (SPDM) emulator has been designed as a test-bed for evaluating advanced robotic technologies in a simulated Space Station (SS) environment. Robotic technologies developed at the NASA research centers are being transferred to this facility, where their performance relative to the SS baseline performance will be assessed. SS maintenance tasks will be executed with and without these advanced technologies to assess SS performance enhancement.

The SPDM emulator, also known as the facility for automated robotic maintenance of Space Station (ARMSS), is designed as a high fidelity SS maintenance simulator. Two Robotics Research 1607 manipulators emulate the SPDM arms. Like the SPDM arms, these commercial manipulators have 7 degrees of freedom and approximately a 2-meter reach. The SPDM's three dimensional motion capability is modeled using two X/Y towers and a mobile pre-integrated truss (PIT) segment. The towers move along a rail and the manipulators are mounted on plates that travel up and down each tower. The PIT segment rotates about its long axis and can be moved in a plane with the tower/rail system. Combined, these degrees of freedom permit the manipulators full access to all six faces on the PIT.

The PIT segment contains faces from two separate SS mission build (MB) segments, MB4 and MB2, and provides a comprehensive robotic testing environment. On each face, Orbiter replacement units (ORUs) are attached to the inside of triangular and rectangular doors. Both the doors and ORUs are robot-compatible. The manipulators acquire and install the ORUs using parallel grippers, force/torque sensors, and torque drives modeled after the SPDM end effector design. An on-orbit lighting simulator is also used in the ARMSS facility and consists of a set of high-powered lamps, curtains, and supporting structure that provide controlled lighting for the portion of the PIT where the manipulators are working.

The baseline facility (fig. 1) was completed in FY93 and the process of technology transfer is underway. Robotic technologies from both Jet Propulsion Laboratory (JPL) and Goddard Space Flight Center (GSFC) are being evaluated using this facility. JPL's surface inspection software has been transferred to JSC and demonstrated, and plans have been made to fully integrate the surface inspection hardware into the ARMSS facility. The operator control station (OCS) software from JPL has been integrated with the ARMSS facility and has been used to perform ORU changeout tasks in the ARMSS facility with robot commands originating at JPL. Testing of OCS will soon be completed and transferred to JSC. A high-resolution version of the JPL flat target is scheduled to be tested in the ARMSS facility in the first quarter of FY94. A version of GSFC's capacitance sensor was fabricated at JSC and is now being evaluated in the ARMSS facility. Special antennas have been developed for using the sensor in a subcarrier installation task which will be evaluated in the first quarter of FY94.

Figure 1. SPDM emulator.

Rendezvous Expert System

PI: H. K. Hiers/ER2
Reference: ST 11

The objective of the Rendezvous Expert System Project was to develop workstation application software to assist the Rendezvous Guidance and Procedures Officer (RGPO) and backroom support personnel in their flight control duties at the Mission Control Center (MCC). This year the 3-year project, funded by the Office of Space Systems Development, Advanced Programs, was completed. Implementation of this software, called the Rendezvous Operations Software System (ROSS), was closely coordinated with the Mission Operations Directorate Trajectory Operations Branch (DM4). Periodic laboratory demonstrations gave the user the opportunity to critique the design and assess development progress.

The RGPO is the flight controller responsible to the Mission Flight Director for onboard rendezvous operations and procedures in the flight control room of MCC. The RGPO monitors ROSS and the standard MCC displays and makes recommendations to the Flight Director concerning Shuttle guidance, navigation, and procedures during Shuttle missions when a rendezvous or proximity operation with another spacecraft is planned. The standard MCC displays present data in a textual format which requires careful attention to ensure correct interpretations of the data. ROSS has added a significant level of automation to the previous labor-intensive MCC mode of operation. The use of ROSS would save an estimated 2.5 work year equivalents in training, simulation, and mission support for six rendezvous missions.

ROSS, implemented in the generic X Windows programming environment, runs on a concurrent (Masscomp) 6600 workstation in MCC. The initial version of ROSS was used for mission support during the STS-49 Intelsat rescue in May 1992. One benefit to that mission was that the ROSS time-to-node processor was used to optimize Orbiter plane control, resulting in reaction control system fuel savings. Since STS-49, ROSS has been used routinely in support of rendezvous missions.

In the MCC operational configuration, the ROSS workstation receives real-time telemetry data via the real-time local area network (LAN) and certain mission operations computer (MOC) data on demand via the general purpose LAN. The ROSS then presents these data in specialized X Window displays (fig. 1) for monitoring the progress of the rendezvous.

The FY93 ROSS development consisted of window management improvements, enhancement of existing applications, and addition of five new applications. Examples of these updates include user-selectable screens configured for mission phases; a three-dimensional representation of Orbiter attitude; the addition of atmospheric drag effects to the Orbiter/target relative motion plots; an alarms display panel containing up to 24 user-programmable alarm conditions; and a new application, NAVCON, to monitor convergence of the onboard navigation with planned rendezvous profile. The final version of ROSS was delivered to MCC in September 1993.
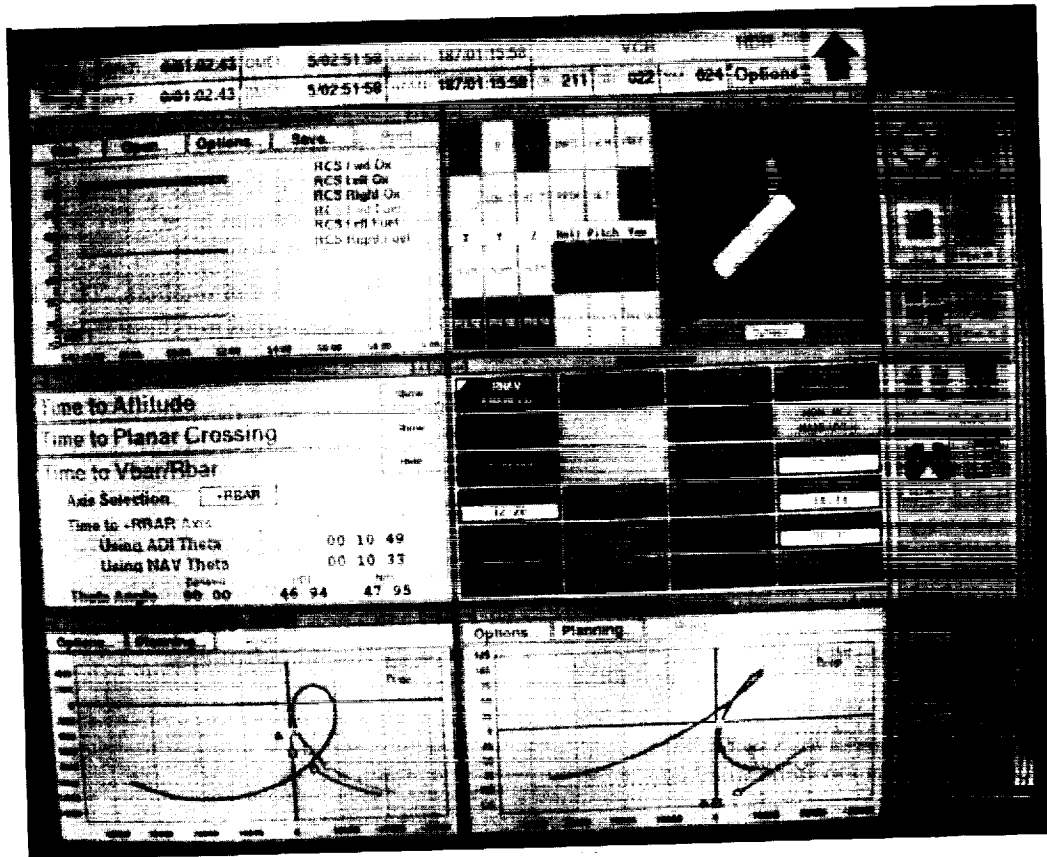
Figure 1.   Rendezvous operations software system (ROSS) display.

Integrated Support for Failure Impact and Procedure Analysis

PI: Jane T. Malin, ER2
Reference: ST 12

Diverse fault management tasks are performed in ground operations, both during missions and in mission preparation. Support is needed beyond expert systems for real-time monitoring and fault detection. The goal of the Failure Impact and Procedure Analysis (FIPA) Project has been to develop approaches and concepts for integration of distributed computer systems to support a more complete set of these tasks. The project has focused on malfunction procedure analysis and failure impact assessment by Space Shuttle payload deployment and retrieval system (PDRS) flight controllers and how these tasks can be supported by integration with monitoring and fault detection systems.

The project was funded only in FY93. A study was done of the FIPA tasks of PDRS flight controllers and candidate systems for supporting these tasks, including systems currently in use and advanced technology systems. The objective was to identify types of systems that would need to be integrated. Data-flow diagrams of the FIPA tasks were developed, and intelligent system automation technology requirements were developed and prioritized. Figure 1 shows the major FIPA tasks and intelligent system technology support candidates. Concepts developed in this study are being used in the FY94 NASA Headquarters Code C Space Propulsion Robust Analysis Technology (SPRAT) Project.

The next objective was to learn about integration issues by building the first link in the FIPA structure of support systems shown in figure 1. A prototype was developed that linked two preexisting PDRS support applications: (1) a real-time monitoring and fault detection support application, DEcision Support SYstem (DESSY), built in a commercial expert system development environment (G2); and (2) an off-line application for identifying relevant malfunction procedures and failure modes and effects analysis (FMEA) data,

built in a government-furnished system (CRANS). An electronic representation of a ground malfunction procedure was also developed in CRANS to identify electronic procedures issues.

Integration of the systems required several layers of functionality. The base layer is data communication software for distributed systems, ported from the JSC Cooperating Expert Systems Project. Above that layer, software was developed to synchronize and manage information transfer, to translate from DESSY to CRANS representations, and to manage conflicts between DESSY information and manual inputs to CRANS. There are critical context assumptions in the procedures and FMEAs that are not explicit. The electronic procedures support making these implicit assumptions explicit.

New approaches were developed to integrate the on-line and off-line tools. For CRANS to identify relevant FMEAs and procedures, real-time alarm information from telemetry must be supplemented with persistent situational context information. By analyzing real-time data, DESSY builds a snapshot of Fault Situation Data to support further off-line analysis by flight controllers.
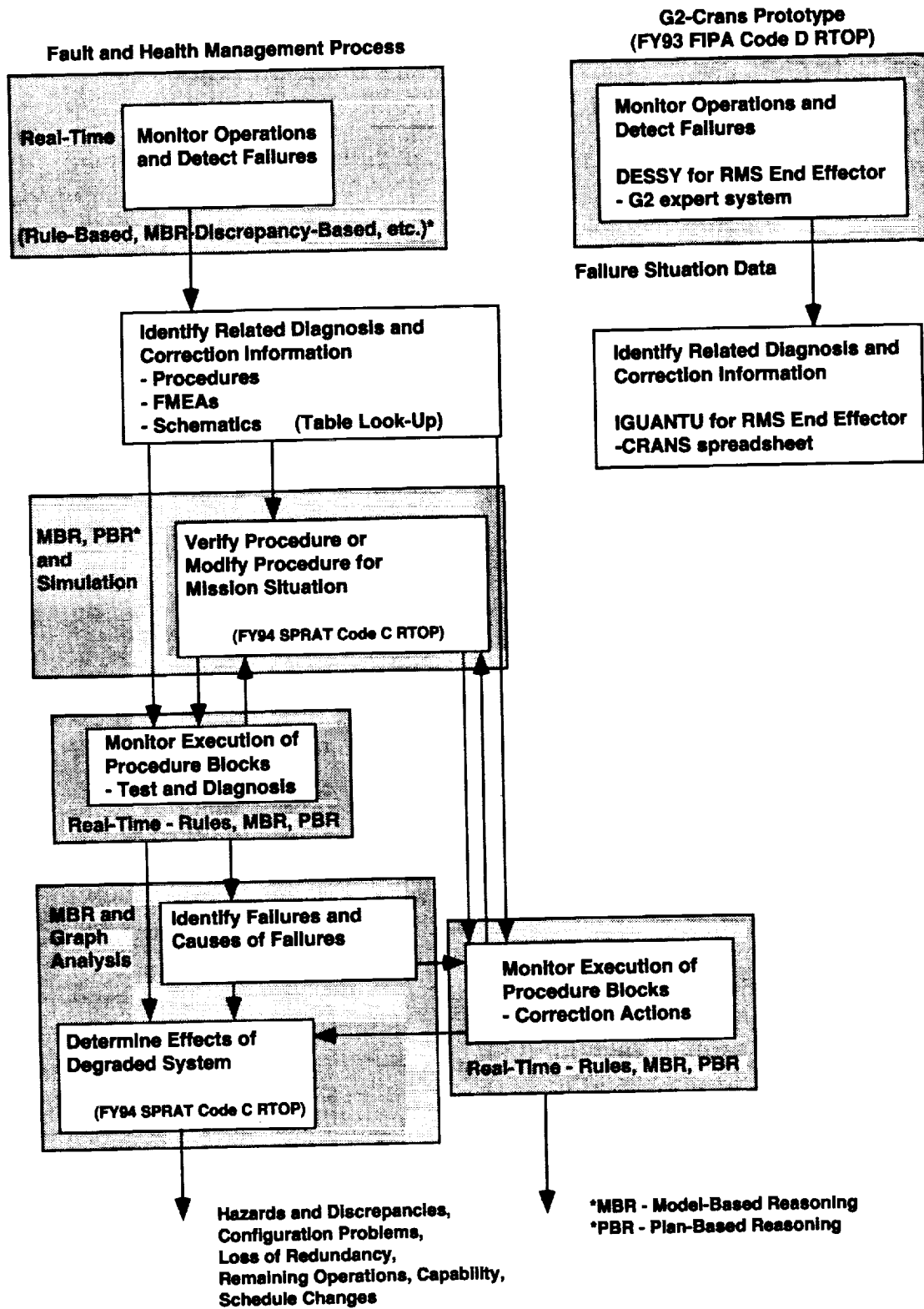
Fault and Health Management Process

G2-Crans Prototype
(FY93 FIPA Code D RTOP)

Real-Time | Monitor Operations
and Detect Failures

(Rule-Based, MBR-Discrepancy-Based, etc.)*

Monitor Operations and
Detect Failures

DESSY for RMS End Effector
- G2 expert system

Failure Situation Data

Identify Related Diagnosis and
Correction Information
- Procedures
- FMEAs
- Schematics   (Table Look-Up)

Identify Related Diagnosis and
Correction Information

IGUANTU for RMS End Effector
-CRANS spreadsheet

MBR, PBR*
and
Simulation | Verify Procedure or
Modify Procedure for
Mission Situation

(FY94 SPRAT Code C RTOP)

Monitor Execution of
Procedure Blocks
- Test and Diagnosis

Real-Time - Rules, MBR, PBR

MBR and
Graph
Analysis | Identify Failures and
Causes of Failures

Monitor Execution of
Procedure Blocks
- Correction Actions

Real-Time - Rules, MBR, PBR

Determine Effects of
Degraded System

(FY94 SPRAT Code C RTOP)

Hazards and Discrepancies,
Configuration Problems,
Loss of Redundancy,
Remaining Operations, Capability,
Schedule Changes

*MBR - Model-Based Reasoning
*PBR - Plan-Based Reasoning

Figure 1.   Intelligent fault management automation.

Section V

Technology Transfer

The following is a summary of the Johnson Space Center (JSC) Technology Utilization (TU) FY93 activities and accomplishments. These activities center on two of the TU Office's major on-going responsibilities: (1) New Technology Reporting and (2) Applications Engineering Projects.

New Technology Reporting

The New Technology Reporting process starts when NASA and/or contractor employees report their innovations to the TU Office. These innovations, called New Technology Reports (NTR), are recorded and used as a basis for articles in *NASA Tech Briefs*. Each NTR is evaluated by the JSC Legal Office for patentability and by the TU Office for possible publication in *NASA Tech Briefs*. Innovations chosen for publication in *Tech Briefs* are issued a monetary award. The TU Office also monitors each NTR to assure that the innovation is not published until intellectual property rights have been protected. Software innovations are also evaluated and indexed in the Computer Software Management and Information Center's (COSMIC) catalog where they are offered for sale to the public. Yearly, all JSC technologies that have been used by the commercial sector to develop and market a product or service are published in *Spinoff*.

New Technology Reports Reviewed and Selected for Publication

During FY93 the TU Office received 169 NTRs. Also in 1993, the office selected 68 articles for publication; those 68 articles represent 159 innovators. The following 62 articles were published in the 1993 *NASA Tech Briefs*.

January 93, Volume 17, No. 1
Disk Valve for Cryogenics
Lightweight Right-Angle Valve for Cryogenics
  Fail-Safe Pressure Plug
Dummy Cell Would Improve Performance of
  Fuel-Cell Stack

February 93, Volume 17, No. 2
Pressurized Shell Molds for Metal-Matrix
  Composites

Energetic Atoms Would Etch Photoresists
  Anisotropically
Program Computes Flows of Fluids and Heat
Deployable Debris Shields for Space Station

March 93, Volume 17, No. 3
Flexible Weighting-and-Matching Scheme for
  Incomplete Data
Phase Detector for Rectangular Waveforms
Improved Statistical Model of 10.7-cm Solar
  Radiation
In Vitro, Matrix-Free Formation of Solid Tumor
  Spheroids
Making Porous Zirconia for Heat Pipes
Mechanism Guides Hatch Through Hatchway
Simulation of Fluctuating Geomagnetic Index
Shape-Memory-Alloy Release Mechanism
Easy-to-Use Connector

April 93, Volume 17, No. 4
Bag for Formulating and Dispensing Intravenous
  Solution
Unit-Dose Bags for Formulating Intravenous
  Solutions
Solute-Filled Syringe for Formulating
  Intravenous Solution

May 93, Volume 17, No. 5
Monatomic Oxygen Makes Materials
  Biocompatible
Fiber-Coupled Acoustic-Optical-Filter
  Spectrometer
Augmented Computer Mouse Would Measure
  Applied Force
Device for Perception of Polarization

June 93, Volume 17, No. 6
Indium Foil Serves as Thermally Conductive
  Gasket
Digital Electronic Still Camera
Protecting Spacecraft-Insulating Tiles Against
  Meteoroids

Synthesizing Friction in a Force-Reflecting Hand
  Controller
Inflatable Habitat Structure
Program Helps in Analysis of Failures
Neural-Network-Development Program

July 93, Volume 17, No. 7
Test Would Quantify Combustion Oxygen From
  Different Sources
High-Performance Water-Iodinating Cartridge
Kinetic Tetrazolium Microtiter Assay
Flexible Sandwich Diaphragms Are Less
  Permeable
Microwave Pretreatment for Hydrolysis of
  Cellulose

August 93, Volume 17, No. 8
Software or Graphical Representation of a
  Network
Balloonlike Shields Against Fast Projectiles
General-Purpose Graphics-Library Program
Optimization of a Computational Grid

September 93, Volume 17, No. 9
Droplet Evaporator for High-Capacity Heat
  Transfer
Low-Fatigue Hand Controller for Remote
  Manipulator
Instrumented Pneumatic-Impact Tester
High-Emittance, Low-Absorbance Thermal-
  Control Coating
Compact Circuit Preprocesses Accelerometer
  Output
Instrumented Glove Measures Positions of
  Fingers
Microstrip-Transmission-Line Shock-Front
  Sensor

October 93, Volume 17, No. 10
Low Gravity Improves Welds
Stitched Conductive Threads for Monitoring
  Composite Parts
Generating AC with Rotating Solar Cells

November 93, Volume 17, No. 11
Simulating Orbital Operations of Spacecraft
Pump Propels Liquid and Gas Separately
Improved Nystrom Integrators
Multishock Shields Containing Aluminum Mesh
Quantitative Tester and Reconditioner for Hand
  and Arm
Chemical Strips Anodic Film From Aluminum

December 93, Volume 17, No. 12
Program Helps Simulate Neural Networks
Fluorescent-Antibody Measurement of Cancer-
  Cell Urokinase
Suppressing Oscillations in a Poppet Valve
Thermal-Radiation Program
Automated Estimation of Software-Development
  Costs
Synchronizing a Television Camera With an
  External Reference

Tech Brief Conference

In 1993 NASA, together with *NASA Tech Briefs*
magazine and the Technology Utilization
Foundation, sponsored the Tech 2002 conference
and exposition. The JSC TU Office booth featured
two major technologies: Ice Detection and
Thickness Measurement and Failure Environment
Analysis Tool. This conference was held during
National Technology Transfer Week at the
Baltimore Convention Center in Baltimore,
Maryland. JSC sponsored 11 of the conference
papers. These 11 papers were subsequently
published by the TU Office and made available to
industry.

Spinoffs

The following 10 commercial applications of JSC
technologies were featured in NASA's annual
magazine *Spinoff*.

1. Special "Cool Suit" designed to alleviate some
   of the symptoms of Multiple Sclerosis patients
   based upon Apollo space suit cooling
   undergarment technology.

2. Rotating bioreactor cell culture apparatus for growing tissue that otherwise will not grow outside the human body, developed by the Shuttle Bioreactor Program.

3. Heart imaging system based upon MultiWire Gamma Camera technology originally planned as a Skylab flight experiment for monitoring the health of astronauts.

4. Water filter for home use based upon technology developed to sterilize the drinking water on Apollo spacecraft.

5. Airline operations software based upon CLIPS (C Language Integrated Production System), developed in support of astronaut and flight controller training.

6. Human Factors model for general use by designers of human operated systems based upon technology funded by NASA at the University of Pennsylvania.

7. Security system using CLIPS (C Language integrated Production System), developed in support of astronaut and flight controller training.

8. Risk assessment system based upon FEAT (Failure Environment Analysis Tool) technology, developed for use in spacecraft design and development.

9. Computer seminar artificial intelligence training using NETS (Neural Network Development Tool), developed in support of astronaut and flight controller training.

10. Software for management of dairy heads based upon CLIPS (C Language Integrated Production System), developed in support of astronaut and flight controller training.

Application Engineering Projects

Application Engineering Projects (AEP) are projects designed to develop a specific commercial application from a JSC technology. AEPs can result from technologies identified in the NTR process, from the needs of industry as outlined in Problem Statements, or from concepts of technology innovators. These projects may involve some combination of other government agencies, universities, hospitals, and companies. The AEP process consists of five phases: project identification, evaluation and selection, project preparation, prototype development, and product commercialization.

During the project preparation phase, the TU Office works between the commercial partner and the NASA technologist to help identify the rights and responsibilities of each party and document them in a Space Act Agreement. Most often this is one of the more difficult portions of the AEP process. To reduce misunderstandings and speed-up this activity, in FY93 the TU Office worked with the JSC Legal Office and generated a generic example of a Space Act Agreement. This example was successfully used in the initiation and negotiation of Space Act Agreements for several subsequent projects. It has also been submitted to NASA Headquarters and several other NASA centers for their common use.

The TU Office presents its AEPs at several expositions during the year, such as the Technology 2002/2003 conferences and the Space Technology Hall of Fame. JSC received a number of 1993 Hall of Fame awards for its participation in two past, multi-center projects: Liquid-Cooled Garments and Physiological Monitoring Instrumentation.

NASA JSC, in cooperation with many other organizations, planned and executed the Dual-Use Space Technology Transfer Conference and Exhibition at JSC during February 1-3, 1994. More than 150 papers, representing current NASA technology development projects, were presented during the 3-day symposium. There were more than 35 exhibits and over 300 registered participants. It is estimated that attendants at the exhibit hall exceeded 600. The proceedings of this conference will be published as a NASA conference publication.

During FY93, the AEP Office worked with 10 specific technology projects. Eight different technologies were selected from four separate JSC directorates. A description of these projects follows.

Rotating Wall Cell Culture (RWCC) Technology

This technology can be used to grow cells of all types, including delicate normal human cells. The devices are horizontally rotating cylinders filled with a cell culture medium. The horizontal rotation creates simulated weightlessness for cell particles that are free to associate with each other and form complex structures. Oxygen is delivered by diffusion through a central oxygenator membrane. This membrane allows the vessel to operate without creating air bubbles that would cause destructive turbulence.
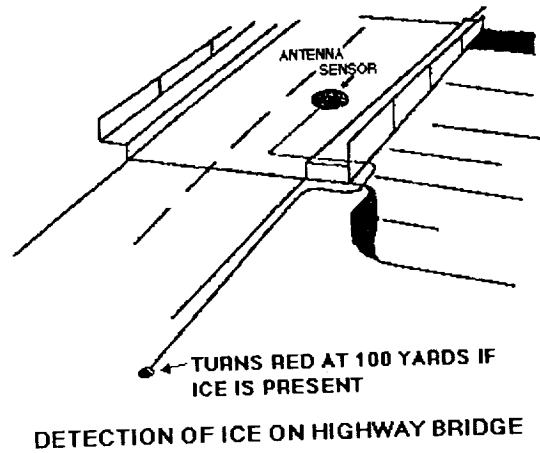
The TU Office negotiated and awarded a contract with SYNTHECON, a small Texas company, for the design of a culture vessel that improves usage, size, and manufacturability of this technology's product. The company has sold several of these vessels to hospitals and research institutes.
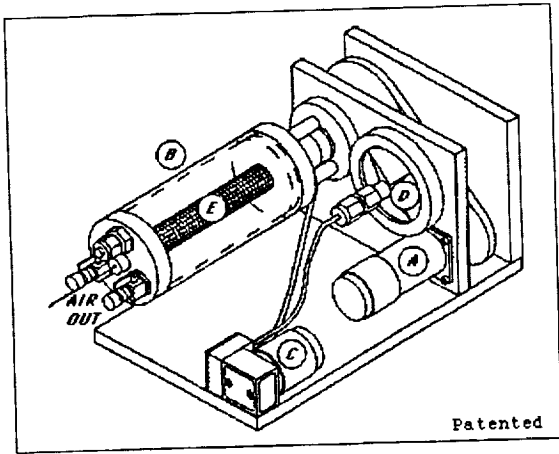
Ice Detection and Thickness Measurement

This project applies JSC's antenna technology to public safety via ice detection on commercial aircraft wings and highway bridges. It uses a small, lightweight microstrip patch antenna as a sensor element of a Maxwell bridge to measure water/ice thicknesses. The antennas are electromagnetically strobed and their output parameters processed and interpreted by software algorithms prior to being sent to a monitor. The antenna can be attached to most surfaces and its measurements transmitted to a central location.

During FY93, the TU Office negotiated and awarded a contract with Raton Technology Research for a prototype of this system. To date, Raton has designed the system and will soon submit the prototype to JSC for test and evaluation. Subsequently, the instrument will be transferred to the FAA for final evaluation and certification.

ANTENNA SENSOR

TURNS RED AT 100 YARDS IF ICE IS PRESENT

DETECTION OF ICE ON HIGHWAY BRIDGE

AIR OUT

Patented

Early Language Intervention System (ELIS)

This project uses Think C, C++, Intelligent Computer-Aided Training (ICAT), and CLIPS (JSC-developed but not patented) software to provide children and youths with disabilities an equal opportunity (as specified by U.S. Mandate) to improve their language skills. The software will also include fuzzy logic attributes that aid teachers in state-of-the-art instructional strategies.

Education research has indicated that using computers with speech output capabilities to teach emerging language skills can significantly increase the language skills of young children with disabilities. A number of computer programs for teaching isolated language concepts and vocabulary are available for use with children learning initial language skills. Although these programs provide a stimulating content for learning and a thorough and consistent plan for training, they do not adjust the content of the lesson based on the responses of the child, nor are they sensitive to the unique needs and learning styles of individual children. The effectiveness of these programs is, therefore, dependent upon the ability of the educator to make the needed software available at the appropriate moment. The clinical judgments that this process demands are critical to successful outcomes. The ELIS resolves these issues.

Early in FY93, the TU Office identified, defined and initiated this partnership between JSC and Laureate Learning Systems (a leading software developer in the area of improving handicapped children's language skills). By mid-year, the TU Office had gotten a Space Act Agreement negotiated and signed. The project plan indicates that Laureate will purchase a license for use of ICAT and CLIPS and that the resulting tutoring devices will be evaluated and validated in the Oregon State Educational System and marketed to all elementary school and educational systems throughout the U.S. Currently, the first prototype has been developed and is being evaluated along with the other Laureate products.

Contextual ALarm Management System (CALMS)

One of the challenges to integrating medically fragile children into the classroom environment successfully is developing effective monitoring technology. Monitors must function reliably and provide appropriate alarms that notify the teachers of impending problems without disrupting the classroom or providing confusing information. Since teachers are not health professionals with a detailed knowledge of the support technology used by these children, the alarms must specify the problem so that attempts to remedy it are well directed and panic is avoided.

The CALMS project applies JSC's CLIPS and fuzzy knowledge technology to the development of a single-alarm management system that integrates the alarms of several individual devices for alerting a teacher or care-provider to a problem. This system will also provide basic guidance and instructions on a visual display.

In FY92, the TU Office identified and defined this partnership but initiation was not started until FY93. This was due to multiple negotiations over the terms of the Space Act Agreement. Finally in mid-FY93, the TU Office got final signatures on the agreement.

This project combines the technologies of three JSC directorates and the commercial expertise of a U. S. medical manufacturer. During the life of the project a prototype will be developed, tested in the operating room of a major medical center, clinically evaluated in a hospital environment, evaluated in the Oregon State Department of Education classrooms, and finally made available to schools and hospitals throughout the U.S. Currently, the prototype management alarm system software has been developed and the clinical testing protocols defined.
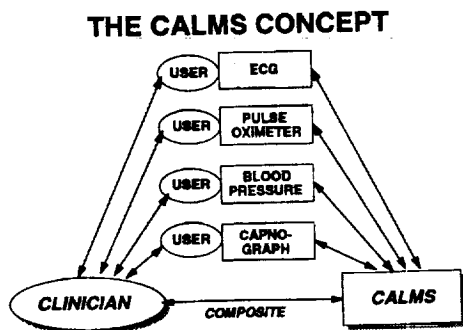
Laser Eye Surgery Pointing Control

This technology eliminates eye motion aberrations that are present during laser eye surgery and does it at a reasonable cost. The system uses a JSC developed (U.S. Patent 5,029,220) joint Fourier transform correlation invention to correlate actual images with reference images and effectively remove the involuntary eye jitters so that a laser surgeon can photocoagulate the eye structure exactly and avoid collateral damage.

JSC has teamed with Pinnacle Imaging, Inc., and the U. S. Army Missile Command to develop this technology for NASA, military, and commercial use. During FY93, a Space Act Agreement was signed with Pinnacle and a license agreement was negotiated. Pinnacle is currently soliciting funding from its sponsors to cover the large costs of this complex prototype system.

THE CALMS CONCEPT

Microwave Measurement for Two-Phase Flow

This project also uses JSC's antenna technology. In this case, two sets of antenna are mounted in a pipe, one set is downstream from the other and senses the mixture of fluids flowing. A computer performs statistical analysis on each of these antenna parameter sets and makes comparisons and analysis.

Currently, this technology has no commercial partner; however, it is finding numerous industrial applications. For example, it would be of great economic benefit to the oil and gas industry to have an instrument that can identify and meter the raw production components as they are being drawn from the well-head in frontier areas, such as the deep waters of the Gulf of Mexico, where conventional systems are unsuitable.

Another example is in the food processing industry. The National Food Processors Association has to measure the time individual food particles remain in the sterilization processor as they flow to the canning operations. This technology, with modification, is being considered for use by the food processing industry.

A third example is in the pulp/paper industry where a need exists for a sensor that can continuously measure the amount of dispersed air/gas in pulp/paper process waters and/or a sensor to continuously measure the height of air/water foams present above the pulp/paper process waters.

And last, the medical industry has application for a sensor that can measure the time volume of urine excreted from a patient.

Artificial Intelligence for Adult Literacy Training (ALT)

The ALT uses artificial intelligence (AI), Intelligent Computer-Aided Training (ICAT), and fuzzy logic in designing, developing, and producing a computer-based, multimedia instructional package. This application of expert systems in the diagnosis and evaluation of reading problems is a significant advancement over current computer-assisted instructional systems.

The ALT team is developing a simulation program called "finding a friend a job" that will be distributed to literacy centers on CD-ROM. Adult literacy students begin the program by selecting a friend they will help find a job from photographs displayed on the computer screen. They listen to four people describe their job interests and needs. Then the literacy students work through each phase of the simulation—from reading job ads to find one that "fits" their friend to completing a job application and getting ready for an interview. At each stage of the job hunting process, the literacy students must read text (such as job ads) and make decisions. When they need help, students can call on an electronic support system that helps them select a reading strategy and work through the material they do not understand. The support is provided by sound (in English or Spanish), and is supported by visuals on the screen.

The ALT project team consists of JSC, the National Institute of Corrections, and the University of Houston. Several commercial partners are being considered to market the final product(s).

Multi-Fluid Flow Measurement

Litera City
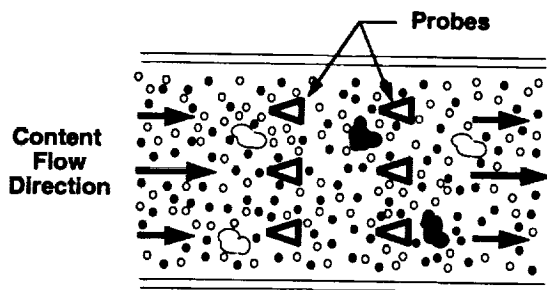
Virtual Visual Environment Display for Medical Education (VIVED)

This technology was initiated by JSC developing a prototype of a helmet-mounted stereo visual system for application to real-time part-task simulation and astronaut training in docking and extravehicular activity maneuvers. In full development, this technology will create a high-fidelity learning environment that, in effect, places the student inside the body with the ability to move while observing his or her surroundings. The graphics for these virtual displays are based on digitized anatomical images from computerized axial tomography (CAT) scans, magnetic resonance imaging (MRI), and anatomical specimens. JSC has developed software that combines with these graphics to provide the ability to observe and interact in difficult areas of clinical anatomy. The first prototype of the VIVED will be a computerized visual module. This module will provide students at all levels of medical and allied health education with a simulation of a wrist, arm or human skull cavity. The release of new chip architectures by industry will make the technology affordable to medical educators.

The University of Texas Medical Branch, the Galveston Independent School District, and the Harris and Eliza Kempner Foundation have joined NASA to develop this project. Even though there is much interest in this technology and its applications, no company has yet stepped forward and offered to co-fund further development.

Monoclonal Antibodies for Cancer Diagnosis

JSC has developed new monoclonal antibodies for different cellular products. Selected monoclonal antibodies can now be developed to identify and quantitatively measure secretions associated with cells which are metastatic and actively invading healthy tissue. The monoclonal antibodies can also be used to establish diagnostic tests for small numbers of human cells, tissue specimens, and tumor biopsies from patients.

As part of the follow-on research, new molecular-specific antibodies have been developed with Baylor College of Medicine. There are more than 15 major cancer centers and at least 10 commercial laboratories in the United States that provide cytometry testing of tumor biopsies as a fee-for-service business. Once the JSC quantitative test for urokinase is established, it has been estimated that at least one-half of all tumor tests would also include an assay for uPA.
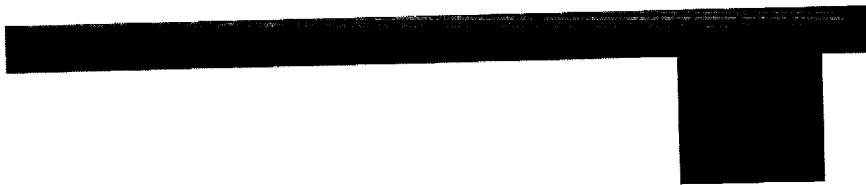
Neither the TU Office nor any of their support services have been able to find a commercial partner for this technology; however, many companies have sent letters of inquiry and the American Cancer Society has shown great interest in the technology.
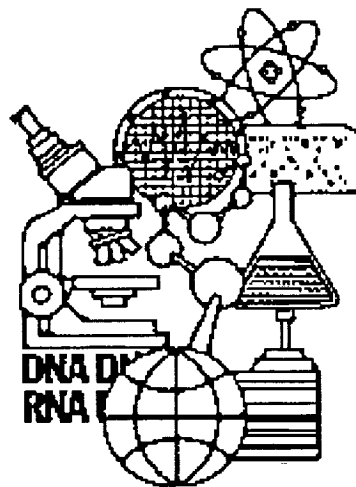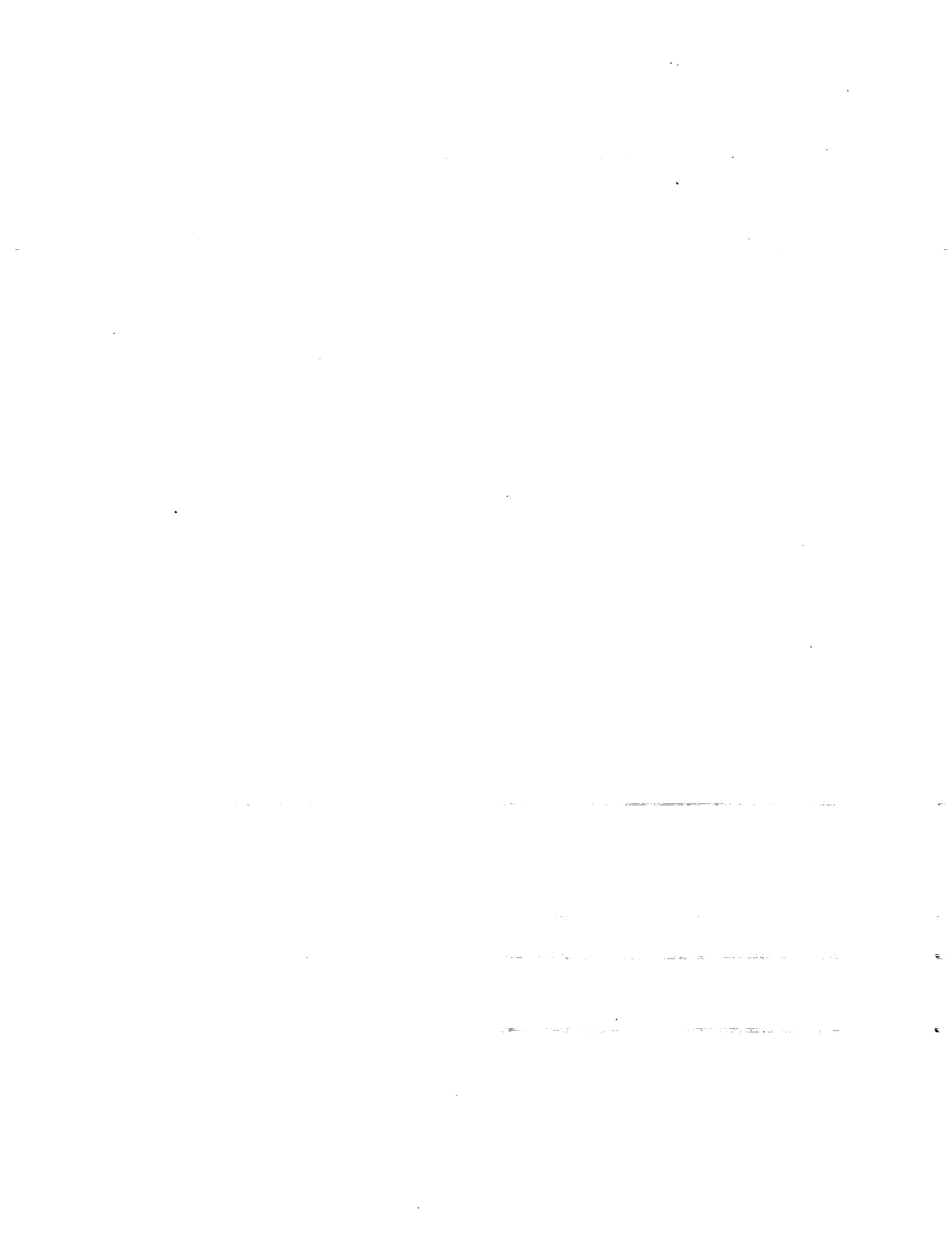
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Life Sciences (LS)

LS 1   **Optical Measurement of Bacterial Adhesion in Water Supply Lines**

Funded by:	199-04-11-35
TM/PI:	D.L. Pierson, Ph.D./SD4
PI:	D.W. Koenig, Ph.D./KRUG
	S.K. Mishra, Ph.D./KRUG
Task Performed by:	Johnson Space Center
	KRUG Life Sciences

LS 2   **Cardiovascular Response to Sympathomimetic Drugs During Head-Down Bed Rest: The Effects of Dietary Sodium and Hydration Status**

Funded by:	199-18-11-01
TM/PI:	Peggy A. Whitson, Ph.D./SD4
PI:	W. Jon Williams, Ph.D./SD4
	Charles A. Stuart, M.D./University of Texas Medical Branch, Galveston, TX
Task Performed by:	Johnson Space Center
	University of Texas Medical Branch at Galveston

LS 3   **Simulated Microgravity Improves Production of Colonic Growth Factors**

Funded by:	674-23-01-05
TM/PI:	G.F. Spaulding, M.D./SD4
PI:	T.J. Goodwin, M.A./SD4
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	New England Deaconess Hospital

LS 4   **Evaluation of Methods for Removing Biofilms in Spacecraft Potable Water Systems**

Funded by:	199-04-11-18
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PI:	D.L. Pierson, Ph.D./SD4
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	M.H. Huls/KRUG
Task Performed by:	Johnson Space Center
	KRUG Life Sciences

Note: Technical Monitor (TM)
         Principal Investigator (PI)

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LS 5   A Simulated Space Diet: Effects on Energy Metabolism and Doubly Labeled Water (DLW) Calculations

Funded by:	106-30-02-45
TM/PI:	H.W. Lane, Ph.D./SD4
PI:	E.K. Gibson, Jr./SN2
	R.J. Gretebeck, Ph.D./SD4
	R.A. Socki/LESC C-23
	D.A. Schoeller, Ph.D./University of Chicago
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	University of Chicago

LS 6   Radiogenic Transformation of Human Epithelial Cells: RBE, Growth Properties and Chromosome Studies

Funded by:	199-04-11-92
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PI:	Kerry George/SD4/KRUG
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	Lawrence Berkeley Laboratory, UC

Human Support Technology (HST)

HST 1   Task Analysis Report Generation Tool (Target)

Funded by:	967-20-20-06
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	Tim Saito/LinCom Corp.
	Dr. Bowen Loftin/University of Houston-Downtown
	Sean McRae/University of Houston
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	University of Houston
	LinCom Corporation

HST 2   Intelligent Computer-Aided Training (ICAT)

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	Dr. R. Bowen Loftin/University of Houston-Downtown
Task Performed by:	Johnson Space Center
	University of Houston-Downtown
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HST 3   Cooperating Expert Systems

Funded by: 967-20-20-08
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Task Performed by: Johnson Space Center
                        LinCom Corporation

HST 4   Development of PVAT - A Video Analysis Tool for Microgravity Posture Evaluations

Funded by: 199-06-11-33
TM: Frances E. Mount/SP34
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Task Performed by: Johnson Space Center
                        Lockheed Engineering and Sciences Company

HST 5   Human Factors Studies Aboard STS-57/SpaceHab-01

Funded by: 199-06-11-39
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                        Lockheed Engineering and Sciences Company

HST 6   Human Workload Analysis

Funded by: 199-06-11-34
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Task Performed by: Johnson Space Center
                        Lockheed Engineering and Sciences Company

HST 7   Development of Rapid Algorithm for Human Computer Model Reaching

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                        Michael Goldsby/LESC
                        Ann M. Aldridge/LESC
Task Performed by: Johnson Space Center
                        Lockheed Engineering and Sciences Company

HST 8   Development of Full Body Dynamic Human Strength Model

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                        Ann M. Aldridge/LESC
Task Performed by: Johnson Space Center
                        Lockheed Engineering and Sciences Company

**HST 9   Human-Computer Interface to Medical Decision Support
Systems for Space**

Funded by: 199-06-11-35
TM: Frances E. Mount/SP34
PI: Jurine A. Adolf/LESC
Task Performed by: Johnson Space Center
                      Lockheed Engineering and Sciences Company

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**SSS 1   Thermal Analyzer for Planetary Soils (TAPS): An In Situ
Instrument for Mineral And Volatile Element Measurements
on Planetary Surfaces**

Funded by: 186-30-21-11
PI: James L. Gooding/SN2
Task Performed by: Johnson Space Center
                      Lockheed Engineering and Sciences Company

**SSS 2   Backscatter Mössbauer Spectrometer (BaMS) for
Extraterrestrial Surfaces**

Funded by: 157-30-10-02
PI: Richard V. Morris, Ph.D./SN4
                      Tad D. Shelfer, Ph.D./NRC
Task Performed by: Johnson Space Center

SSS 3   Radar Measurements of the Orbital Debris Environment

Funded by: 967-30
P.I.   Gene Stansbery/SN3
Task Performed by: Johnson Space Center

**SSS 4   Composition and Structural State of Space Debris and
Interplanetary Dust Particle Impact Residues Recovered
From Long Duration Exposure Facility (LDEF) Impact
Craters**

Funded by: 506-43-61-01
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                      F. Hörz, Ph.D./SN4
                      R. Bernhard/LESC
                      R.A. Barrett/LESC
Task Performed by: Johnson Space Center
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Space Technology (ST)

ST 1 **Regenerative Life Support Systems Test Bed Modeling and Analysis**

Funded by:	199-61-61-21
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Task Performed by:	Johnson Space Center
	McDonnell Douglas Aerospace

ST 2 **Advanced Life Support Systems Integration**

Funded by:	593-41
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Task Performed by:	Johnson Space Center
	Lockheed Engineering and Sciences Company
	AlliedSignal
	Hamilton Standard
	Life Systems Inc.

ST 3 **Extravehicular Mobility Unit (EMU) Electronic Cuff Checklist Development**

Funded by:	506-71/906-21
PI:	Jose A. Marmolejo/EC5
Task Performed By:	Johnson Space Center

ST 4 **Electrolysis Performance Improvement Concept Study (EPICS)**

Funded by:	506-74-62 (FY93)
	236-99-02-13 (FY94)
PI:	Sandra Foerg/EC3
Task Performed By:	Johnson Space Center
	Life Systems, Inc.

ST 5 **Ultralite Fabric Reflux Tube Radiator**

Funded by:	593-41-51
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Task Performed by:	Johnson Space Center
	Battelle
	Pacific Northwest Laboratory

ST 6 **Regenerative Life Support Systems**

Funded by:	199-61
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Task Performed by:	Johnson Space Center
	Lockheed Engineering and Sciences Company

ST 7   **Dexterous End Effector Flight Demonstration**

Funded By: 967-30-30-01
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Task Performed By: Johnson Space Center
                   Lockheed Engineering and Sciences Company

ST 8   **Flight Telerobotics Servicer (FTS) Manipulator Technology Capture**

Funded By: 470-01-11-02
PI: John Chladek/ER4
Task Performed by: Johnson Space Center

ST 9   **Fault Tolerant Robotics**

Funded By: 506-59-62-01
PI: John Chladek/ER4
Task Performed by: Johnson Space Center
                   University of Texas at Austin

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Funded By: 586-02-11-01
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                   Reginald B. Berka/ER4
Task Performed By: Johnson Space Center
                   Lockheed Engineering and Sciences Company

ST 11   **Rendezvous Expert System**

Funded By: 967-20-20-04
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                   Lockheed Engineering and Sciences Company

ST 12   **Integrated Support for Failure Impact and Procedure Analysis**

Funded By: 967-20-20-05
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                   The MITRE Corporation

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13. ABSTRACT *(Maximum 200 words)*

Johnson Space Center research and technology accomplishments during fiscal year 1993 are described and principal researchers and technologists are identified as contacts for further information. Each of the four sections gives a summary of overall progress in a major discipline, followed by detailed, illustrated descriptions of significant tasks. The four disciplines are Life Sciences, Human Support Technology, Solar System Sciences, and Space Systems Technology. The report is intended for technical and management audiences throughout NASA and the worldwide aerospace community. An index lists project titles, funding codes, and principal investigators.

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