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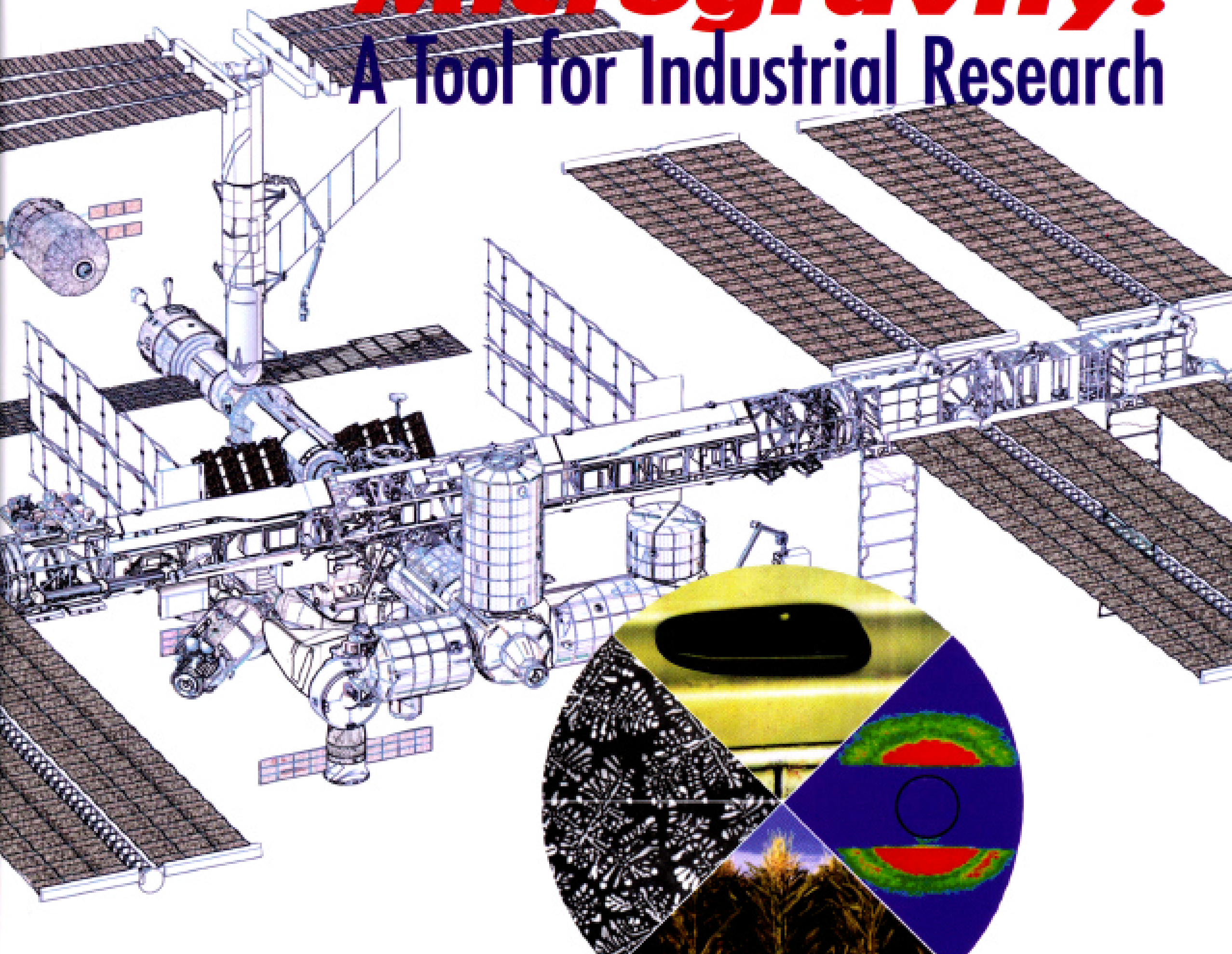
The International Space Station

Microgravity: A Tool for Industrial Research



European Space Agency
Agence spatiale européenne

Directorate of Manned Spaceflight and Microgravity
Direction des Vols Habités et de la Microgravité

Microgravity: A Tool for Industrial Research

Applied Research on the International Space Station

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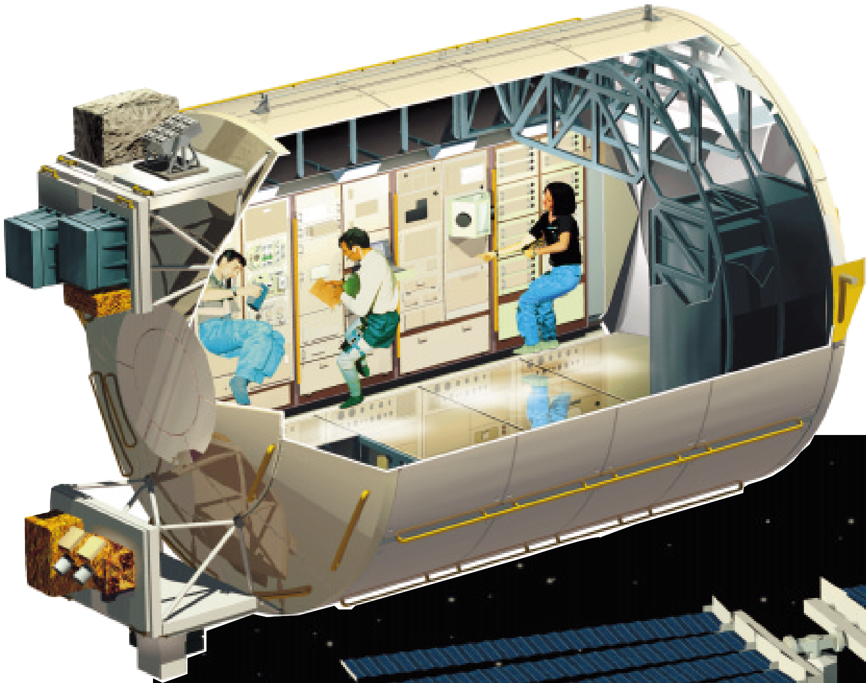
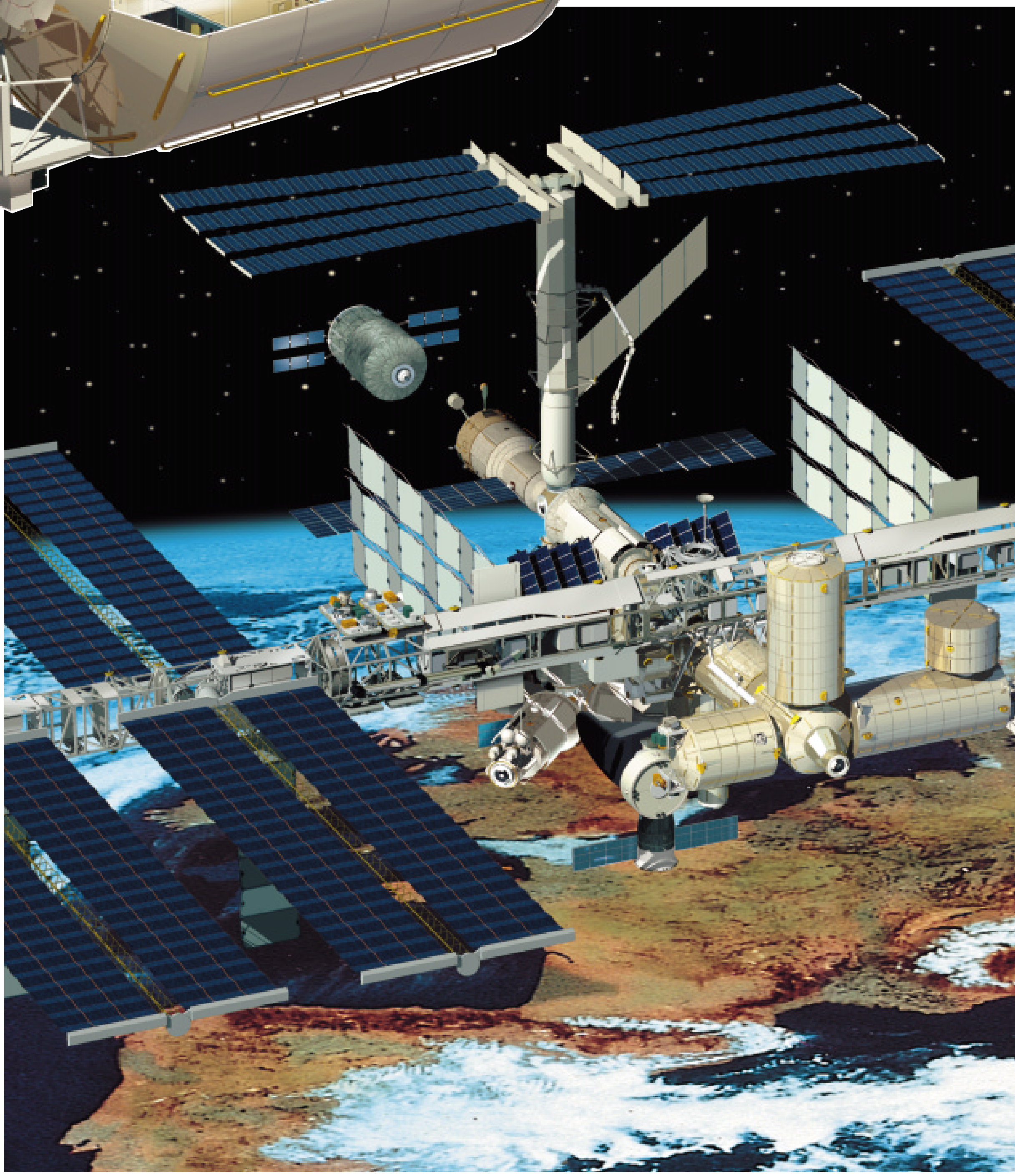
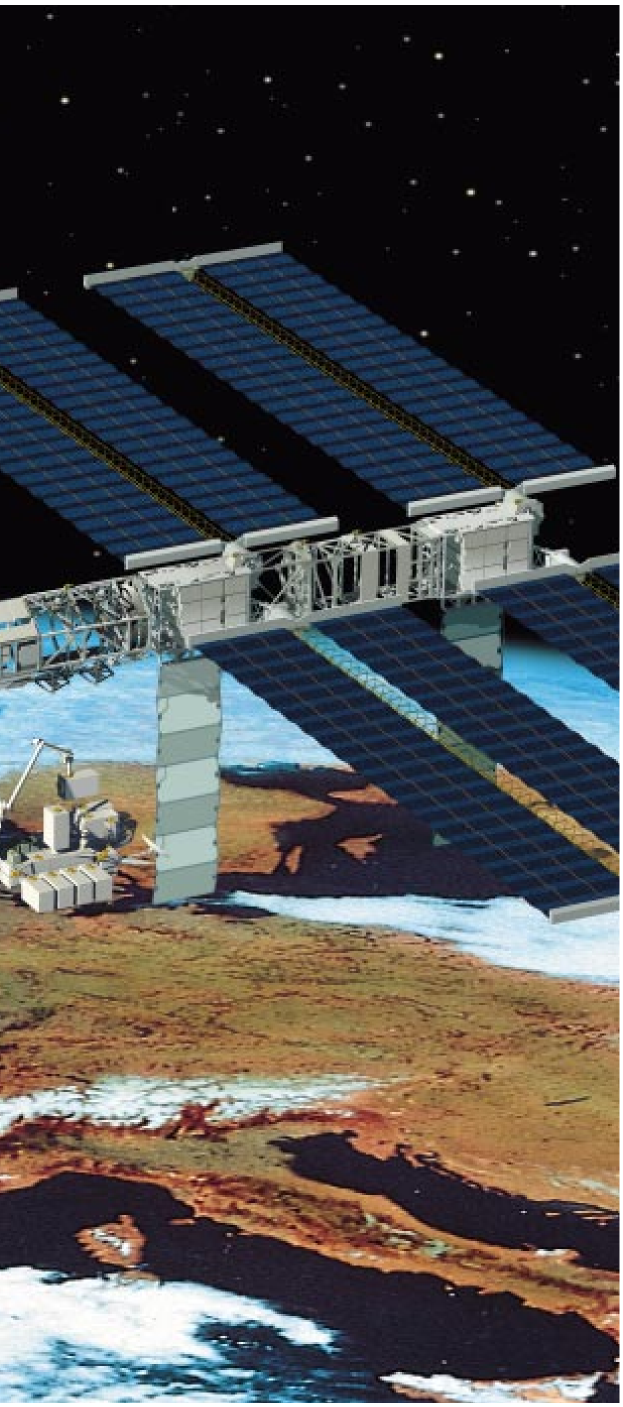




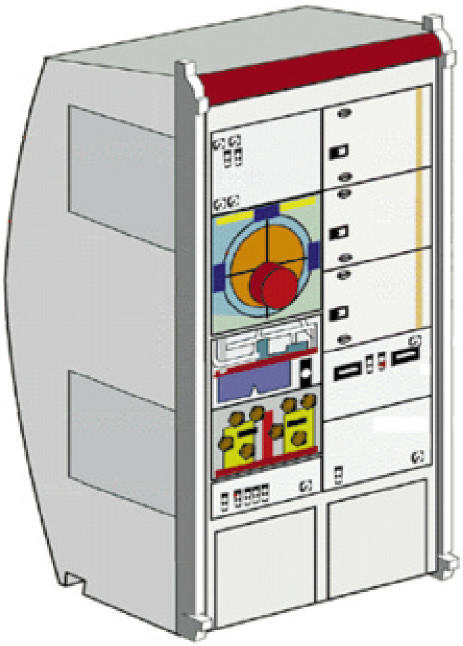
Microgravity: a Tool for Industrial Research



Microgravity research has been undertaken in Europe for the past 15 years, both through ESA programmes and initiatives at national level. With the forthcoming International Space Station (ISS), there is strong motivation to expand on these activities notably by involving European industry to achieve the move from fundamental research towards applied projects.

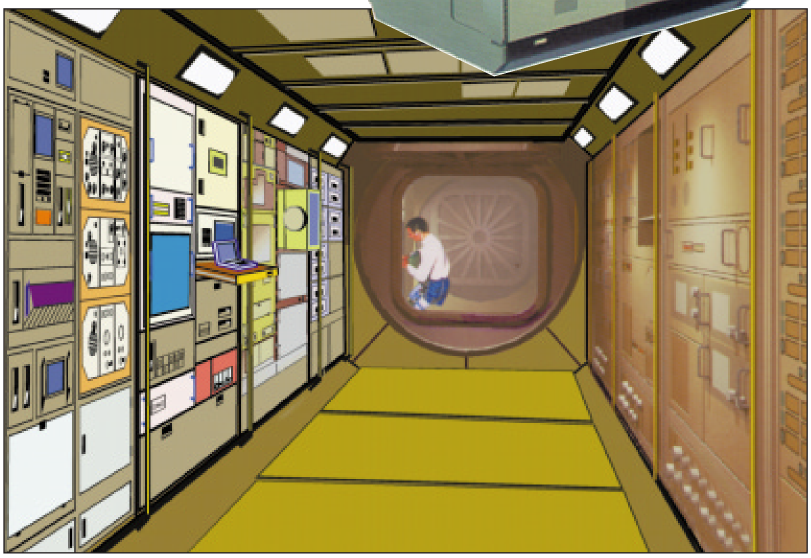
This brochure introduces selected examples of research where microgravity as a tool is relevant for application-oriented and industrial research. Each area demonstrates potential for applications and commercial spin-offs. Past results are mentioned and current and future avenues for experimentation are presented. ESA's Microgravity Applications Promotion Programme has the mission to address researchers from industry and academia and to develop relevant projects.

With the advent of the ISS, an endeavour in which Europe is fully participating, microgravity becomes a strategic research tool for innovative private ventures. This brochure provides a first step in promoting the view that integrating microgravity as an additional parameter into terrestrial research efforts can indeed be beneficial to private enterprise.



The Fluid Science Laboratory under development in ESA's MFC programme (left)

The Material Science Laboratory, an element of the MFC programme, shown in Columbus Laboratory configuration (right)



The Microgravity Facilities for Columbus (MFC): a view inside the Columbus Laboratory

Microgravity Research Possibilities

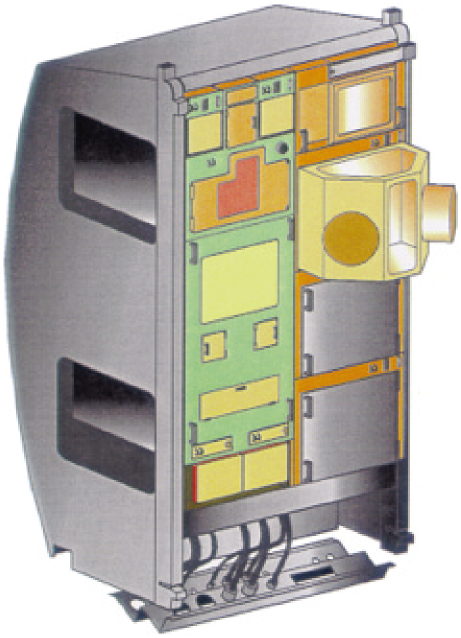
The International Space Station provides a unique opportunity for research and applications and a testbed for technological development for a period of 10 – 15 years. Disciplines of interest include research in the microgravity environment, space science (astrophysics and astronomy), Earth observation, engineering science and space technology.

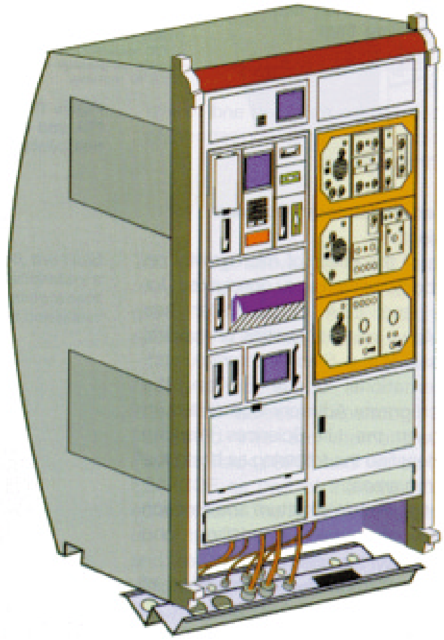
Past and present research programmes highlight how microgravity can be a useful, and in some cases unique, tool for the study of a number of physical, chemical and biological processes that are important in science, engineering and technology.

Microgravity or near-weightlessness corresponds to a free fall situation. This can be obtained through various means and for different durations: drop towers and drop shafts (up to 10 seconds), aircraft flying parabolic trajectories (about 20 seconds), sounding rockets (up to 15 minutes), unmanned satellites (weeks to months) and manned orbiting systems such as the Shuttle (a few weeks), Mir and finally the International Space Station, which will be in operation for a decade at least.

Gravity is a pervasive phenomenon, creating a force that influences virtually all aspects of life on Earth. The impact on physical and biological processes is obvious. In a number of cases it is used to advantage, for instance to shape a metallic part by pouring a melt into a mould, to separate lighter from heavier constituents through sedimentation or for the transport of fluids. However, the effects of gravity can be undesirable if we want to study the complex interaction of different forces involved, for example, in fluids (liquids and gases).

In microgravity, various phenomena are significantly altered, in particular convection, buoyancy, hydrostatic pressure and sedimentation. Scientific disciplines affected include fluid physics and transport phenomena, combustion, crystal growth and solidification, biological processes and biotechnology. Microgravity is instrumental in unmasking and unravelling processes that are interwoven or overshadowed in normal gravity. For example, crystal growth from





The Biolab; an element of the MFC (left)

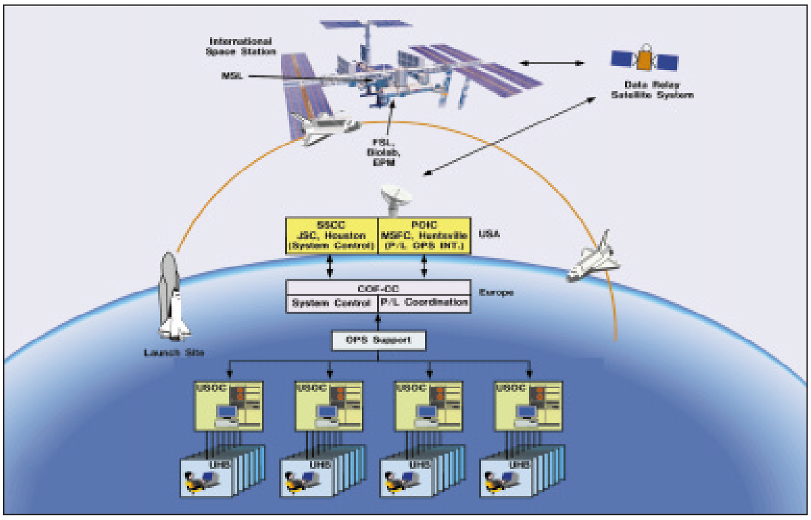
The Human Physiology Module; an element of the MFC (right)

melt and solutions, capillary effects, multiphase flow, diffusive transport processes, can under normal gravity conditions be dominated by effects such as buoyancy, thermal convection and sedimentation. Microgravity may therefore be regarded as an important tool for increasing precision in the measurement of thermophysical properties, for improving models of complex phenomena and hence manufacturing processes on Earth. In the fields of medicine and life science, the amplification in space of certain physiological changes motivates investigations of the underlying mechanisms and the development of both innovative treatments and experimental hardware.

ESA's Microgravity Applications Promotion Programme

Back in 1995, when deciding Europe's participation in the ISS project, ministers from ESA Member States stipulated an ISS Utilisation Preparation Programme including a Microgravity Applications Promotion (MAP) programme element. Its broad aim is to prepare for the 'steady-state' utilisation phase after assembly of the Station is completed in 2003.

The MAP Programme's objective is to develop pilot projects demonstrating that the ISS is a unique tool for industrial research, and to obtain data that would either be needed for numerical simulation



Science operations for the Multi User Facilities

or to give more insight into Earth-based processes so as to enable improvement or optimisation. For that purpose, specific instruments will be provided by ESA.

With the availability of the ISS, examining specific applied research questions in a microgravity environment may be, in the long term, a rewarding undertaking for industry.

A major aspect of this promotion programme is the setting up of Europe-wide teams and networks involving partners from academia and industry who will work jointly on industrially-relevant research. The aim is to initiate industrial projects in which terrestrial research with industrial objectives will be supported by ESA, including ground-based activities and flight opportunities, together with the participation of researchers from universities.

Microgravity Research Networks

Several projects are already supported by ESA's Microgravity Applications Promotion Programme. These networks, with the participation of industry and research institutes, are expecting to derive benefits from the inclusion of microgravity as an additional parameter into their applied research efforts. These projects are funded by ESA in increments of two years, leading up to flight experiments on the ISS from 2002 onwards.

Indeed, the development of advanced industrial processes and products is increasingly based on detailed understanding of the underlying phenomena.

There are presently 12 active Topical Teams:

- **The Influence of Steady and Alternating Magnetic Fields on Crystal Growth and Alloy Solidification**
- **Convection and Pattern Formation in Morphological Instability during Directional Solidification**
- **Metastable States and Phases**
- **Equilibrium and Dynamic Properties of Adsorbed Layers**
- **Particle Aggregation and Dispersion**
- **Double Diffusive Instabilities with Soret Effect**
- **Thermophysical Properties of Fluids**
- **Magnetic Fluids: Gravity Dependent Phenomena and Related Applications**
- **Foams and Capillary Flows**
- **Droplet, Particle, Spray, Cloud Combustion**
- **Flame-Vortex Interaction**
- **Combustion Synthesis**

The topics and the corresponding lead centres are:

- *Osteoporosis*, MEDES, Toulouse, France.
- *Crystal Growth of Cadmium Telluride (CdTe) and related Compounds*, Crystallographic Institute, Univ. Freiburg, Germany.
- *Precision Measurement of Diffusion Coefficients Related to Oil Recovery*, Microgravity Research Centre, Université Libre de Bruxelles, Belgium.
- *Atomic Clock Ensemble in Space (ACES)*, Ecole Normale Supérieure, Paris, France.

Furthermore, a study on a facility for commercial crystallisation of biological macromolecules in space is being initiated.

Additional topics are addressed through the activities of ESA Topical Teams. These teams seek a dialogue with European industry to expand successful basic microgravity research towards applications. Presently, 12 Topical Teams are active, listed in the table on this page. Proposals for new Topical Teams are being solicited, specifically in Biotechnology.

Ground-based research involving gravity-dependent phenomena is also supported by the European Commission.

ESA is proposing to expand relevant EU-funded projects to include microgravity flight experiments. These will be funded by the Microgravity Applications Promotion Programme.

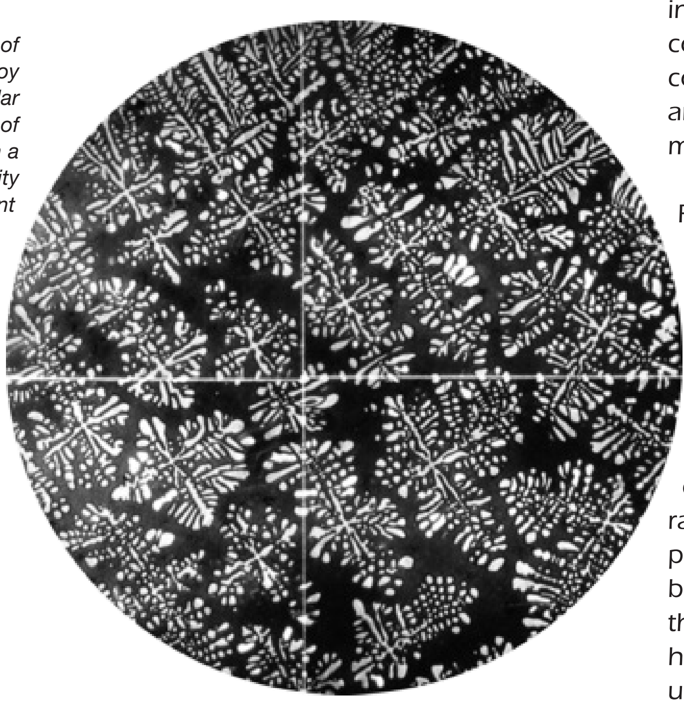
Typical research areas that are considered to be promising are described in the table on the following page.

Possible Research Topics for Gravity-related Research with Industrial Objectives

	Objectives of microgravity investigations	Industrial research objectives	Applications
Casting of High Performance Alloys			
Advanced process control	Validation of theoretical models under controlled conditions. Determination of thermophysical data with an accuracy not attainable under normal gravity	Cast products with reproducible and predictable properties	Turbine blades and cast structural parts with improved properties and reliability
Particle reinforced composites	Understand particle motion and aggregation mechanisms	Homogeneous dispersions in metal matrix composites	Cast parts of light metal with improved stiffness and high thermal conductivity
Crystal Growth			
Crystal growth of electronic and photonic materials from a melt or the vapour phase	Understand the influence of gravity on the crystal growth process and produce benchmark samples	Improve the quality and homogeneity of crystals of compounds such as GaAs, ZnSe, CdTe etc.	High sensitivity X-ray detectors for medical diagnostics
Crystal growth of biological macromolecules	Monitor and control the process in order to grow high quality crystals suitable for detailed structure determination	Identify the drug inhibiting an active molecule	Fast drug design on the basis of the detailed structure of the target molecule
Particle Technologies	Understand particle nucleation, growth, aggregation and dispersion mechanisms	Production of nanoscale particles	Advanced nanomaterials
Energy Production and Management			
Heat and mass transfer	Validation of theoretical models for multiphase flows, boiling mechanism, flows in porous media	Understanding of the basic rules of processes	Enhanced oil recovery and energy production techniques
Combustion	Basic understanding of droplet and spray vaporisation	Accurate models of energy production and propulsion processes	Low consumption, low pollutant emission engines and power plants
Biotechnology and Medicine			
Biology and physiology	Role of gravity at the molecular level, on cell physiology, and on developmental processes	Molecular and cellular control of gene expression, of cell differentiation and proliferation	Drugs modulating cell activity and proliferation for applications in agronomy and medicine
Tissue engineering	Cell-cell relations and tissue differentiation in stable, controlled fluidic systems	Controlled tissue development, intelligent bioreactors, organotypical conditions	Organotypical materials, artificial organs, and implantable intelligent curing devices
Biomedicine and health care	Better understanding of gravity effects on metabolism and physiology	Undertstanding of mechanisms leading to diseases and validation of preventative and therapeutic countermeasures	Therapies for osteoporosis and would healing, health monitoring and analytical techniques

Casting of High-Performance Alloys

Conventional materials often do not meet the demands of industry - better control is necessary of the formation of the microstructure during casting, and thereby of the final product properties.

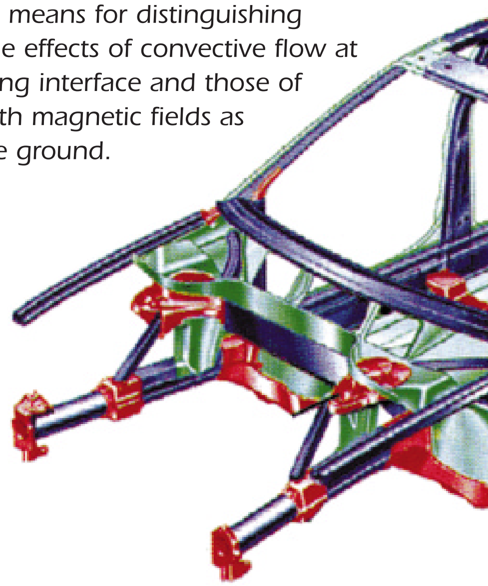


Cross section of aluminium alloy showing more regular arrangement of dendrites, grown in a microgravity environment

The microgravity environment enables us to obtain more precise data on the microstructure formation mechanisms, complementing those derived in the laboratory.

New materials for the automotive and aircraft industry are intended to provide substantial weight saving. The prospect of higher efficiency, lower fuel consumption and lower emissions is at stake. However, these new materials with higher strength and stiffness should also be produced at lower cost, e.g. by precision casting instead of machining. Advanced computational methods and melt flow control techniques using magnetic fields are used in casting processes to improve mechanical properties.

Flow in the melt dominates the transport of heat and the redistribution of elements and particles. Microgravity conditions provide for well-characterised transport conditions of pure diffusion, to help validate theories and models. Furthermore, rotating magnetic fields will be provided for achieving controlled flow in conducting melts at rates not attainable on Earth. This will provide the means for distinguishing between the effects of convective flow at the solidifying interface and those of high-strength magnetic fields as used on the ground.



Airbus A330

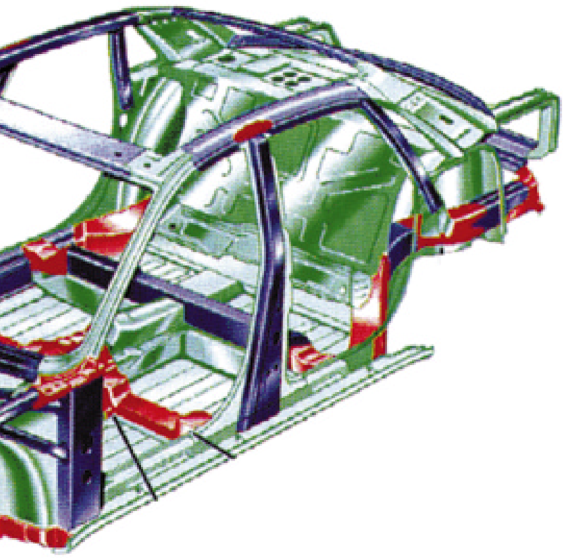
Critical knowledge gained from microgravity experiments will validate new, more complex models, accelerating the current trend towards predictable and reproducible casting, and enabling the development of new processes.

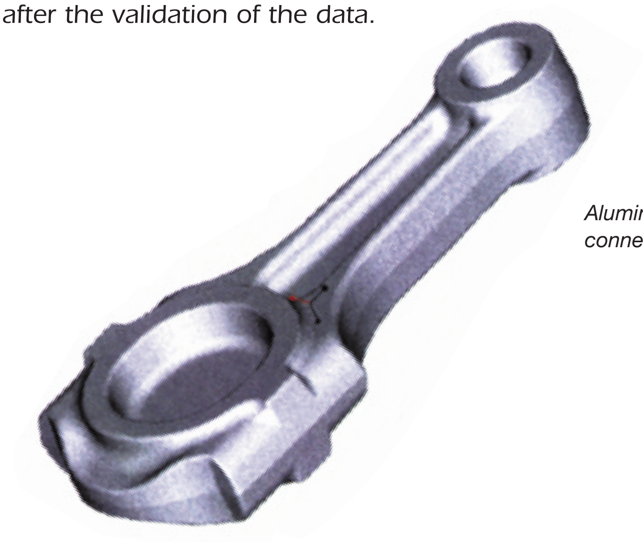
Numerical models are as accurate as the thermophysical data they use. Microgravity provides unique conditions for measuring thermophysical properties with an unprecedented accuracy.

With advances in computation techniques and numerical models, the casting industry now faces the lack of accurate data on thermophysical properties such as thermal conductivity, density, diffusivity, specific heat and viscosity. The accuracy of such measurements is frequently degraded directly or indirectly by gravity (contamination by contact with a container, surface deformation, convection etc.).

In the foreseeable future, advanced control techniques will rely heavily on numerical codes to predict deviations in processes and attempt to prevent them instead of simply reacting a posteriori. To make these tools effective and reliable, accurate data on thermophysical properties are needed.

Thermophysical properties of materials at high temperatures have already been measured in microgravity with unprecedented accuracy. This technique will be extended to industrial materials after the validation of the data.



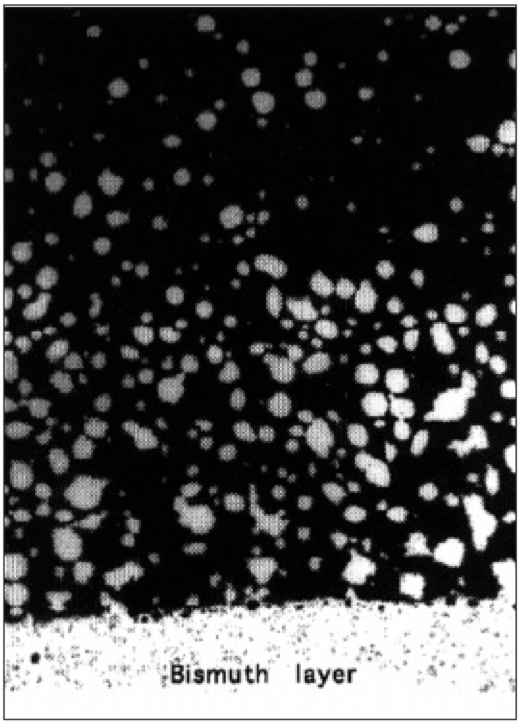


Aluminimum forged connecting rod

The advent of a permanent in-orbit capability will enable the measurement of data from experiments with industrial materials on a routine basis.

Bearing Alloys for Car Engines

The casting of immiscible alloys by conventional methods does not yield material with the expected homogeneous particle distribution.



Metallographic section of an AlSiBi-alloy rapidly cooled from about 1000°C to room temperature under normal gravity

Tests in microgravity have demonstrated the contribution of a gravity-independent mechanism in the separation process.

Some alloys exhibit two immiscible liquid phases within a certain temperature range. The different densities of these liquid phases leads, on Earth, to the formation of two layers. This prevents the homogeneous distribution of particles in a matrix using simple and inexpensive casting processes. Therefore, the industrial exploitation of such alloys has been limited so far.

A number of attempts to obtain, in microgravity, a homogeneous distribution in various alloys and model materials also unexpectedly yielded separated phases. This is attributed to a droplet migration mechanism, called Marangoni migration, which is driven by gradients of interfacial tension along the surfaces of droplets. These gradients relate directly to the local temperature gradients in the matrix during cooling and solidification and are therefore independent of gravity. This mechanism was studied on a theoretical basis and models were developed. Dedicated microgravity experiments validated these numerical models, particularly for multiple droplet migration. The possibility of controlling the direction of migration and the velocity of droplets through mastering the heat flow in molten alloys has been demonstrated. The next natural step is to transfer this new knowledge into production processes.

The ideal would be to minimise the sedimentation caused by gravity by balancing it with the Marangoni migration effect. If the droplets reach a state of dynamic equilibrium, then a

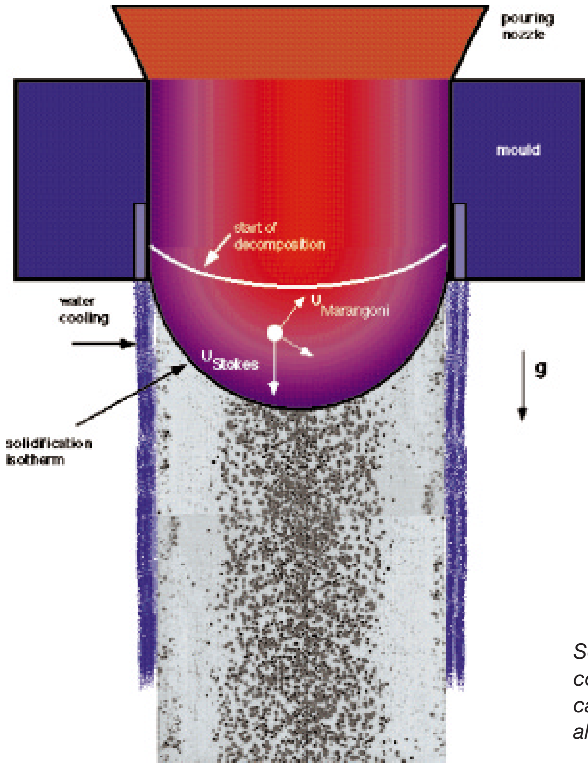
Bearing half shells

stable dispersion in a solidifying matrix becomes attainable. This concept has been tested and new materials, for example an aluminium alloy matrix with evenly-distributed inclusions of lead or bismuth, are being tested as candidates for advanced sliding bearings in car engines.

In these materials the hard matrix sustains the dynamic loads from the combustion process, while the soft inclusions provide self-lubrication. Developing this new fabrication method into an economically viable casting process would permit the development of engines consuming significantly less fuel.

Further work will address the optimisation of the process and its application to different materials. Further quantitative measurements and model validation will be needed, for which microgravity will be a tool of critical importance.

A new casting process could be devised for the fabrication of bearing alloys consisting of soft particle dispersions in a strong matrix obtained from immiscible alloys.



Schematic of a continuous process for casting of monotectic alloys

Combustion

Combustion processes provide energy sources for surface and air transportation, space heating, electrical energy production, waste incineration and material synthesis. However, combustion can also cause undesired effects, like unwanted explosions, fire hazards and toxic exhausts. The challenging goal of combustion research is to enhance the advantageous aspects and to diminish undesired effects.

Efficiency increases in automobile and gas turbine engines, power plants and industrial burners is of great interest.

Gravity fundamentally affects many combustion processes. Reducing its effects can help to highlight underlying mechanisms that are normally overshadowed by convection, buoyancy or sedimentation. Thus, microgravity offers unique possibilities for improving the physical understanding of combustion processes, precisely measuring data relevant to combustion, and developing or validating numerical models.

Droplet cloud combustion and spray combustion are examples of processes where microgravity may contribute to optimisation. These processes are employed in piston and turbine engines, and in industrial burners. A detailed understanding of the processes is necessary to maximise efficiency, and minimise fuel consumption, soot production and thus pollution.

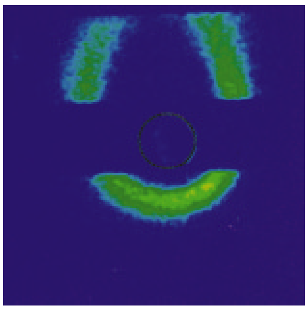
Microgravity investigations will help to unravel the complex mechanisms involved in combustion processes.

Microgravity facilitates the investigation of droplet interactions in clouds, since an environment without convection and buoyancy allows homogeneous droplet distribution, and more precise measurements of evaporation, ignition and flame propagation.

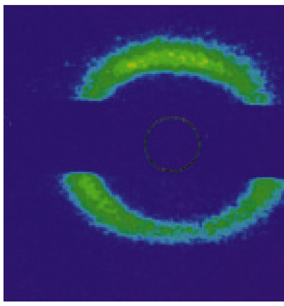
Currently in Europe, four major topics are being discussed with industrial participation:

1. High-Pressure Droplet Cloud Combustion;
2. Particle Cloud Combustion;
3. Soot Formation in Diffusion Flames;
4. Stability and Structure of Lean Premixed Flames.

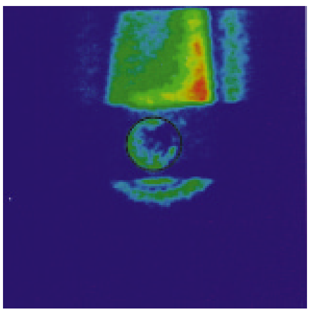
Combustion processes often occur very rapidly, so that detailed studies on droplet vaporisation and spray ignition can be



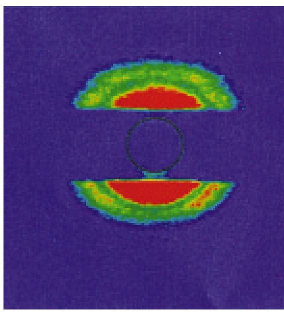
The OH concentration field around a methanol droplet flame in 1g



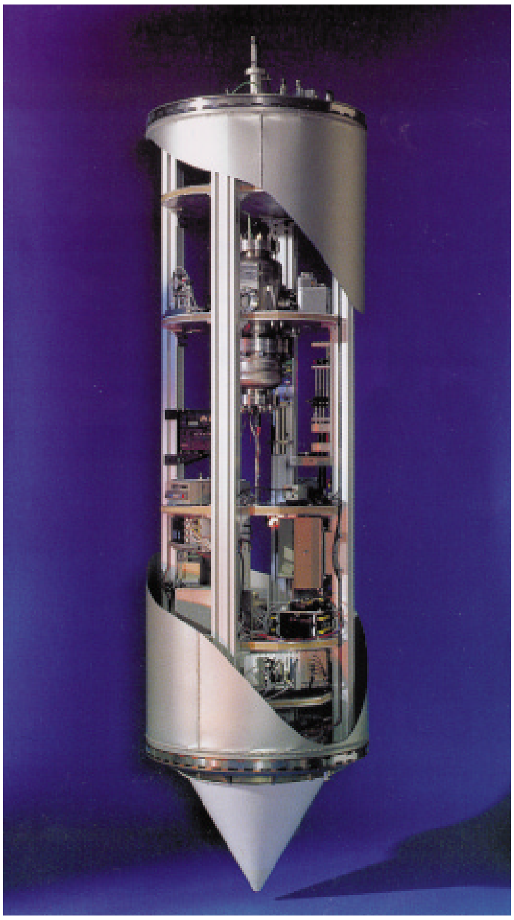
The OH concentration around a methanol flame under μg



OH plus non-resonant fluorescence of an n-heptane flame in 1g



OH plus non-resonant fluorescence of an n-heptane flame under μg performed effectively during short microgravity periods, like those provided in drop towers. However, mapping of the parameter space requires long-duration microgravity experiments, and several experiment modules are presently available for use in precursor sounding rocket experiments. These activities are expected to expand with the advent of the ISS.

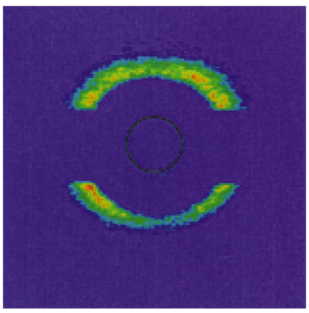


The cylindrical drop capsule of the ZARM droptower in Bremen. The cutaway picture shows an experimental setup to observe combustion processes

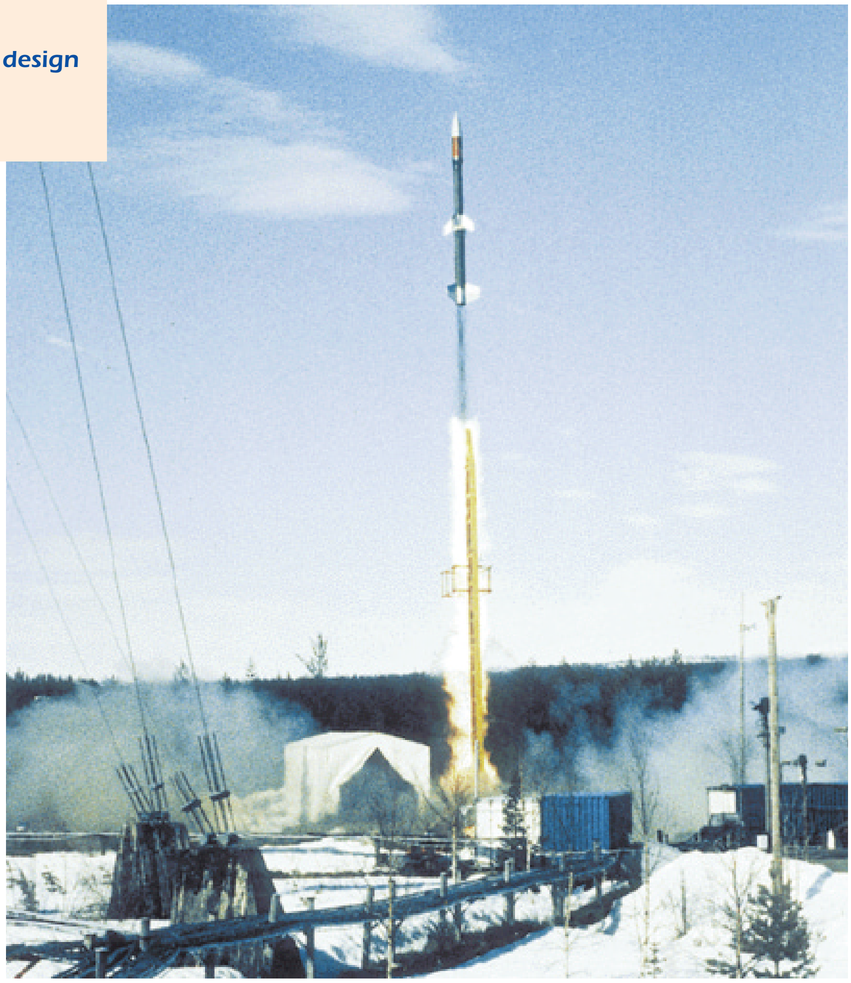
The detailed understanding of underlying phenomena will be essential in the advancement of design codes for industrial combustion processes.

OH-LIPF images of 1g and μg droplet flames

Droplets are fuel-saturated porous ceramic spheres
Diameter: 5 mm
Porosity: >80%

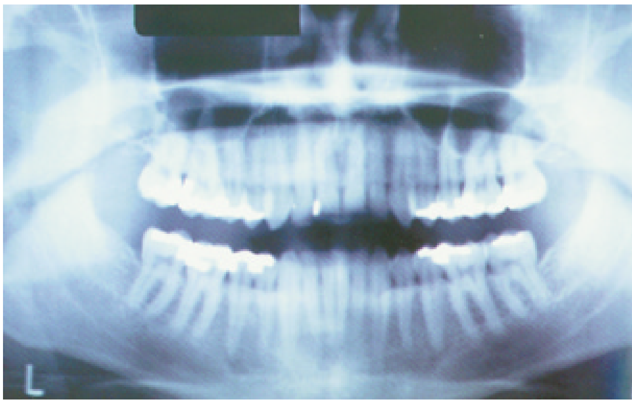


OH around an n-heptane flame in 1g after subtraction of the non-resonance image



Crystal Growth of Cadmium Telluride (CdTe)

X-ray investigation of teeth using greatly reduced radiation dose

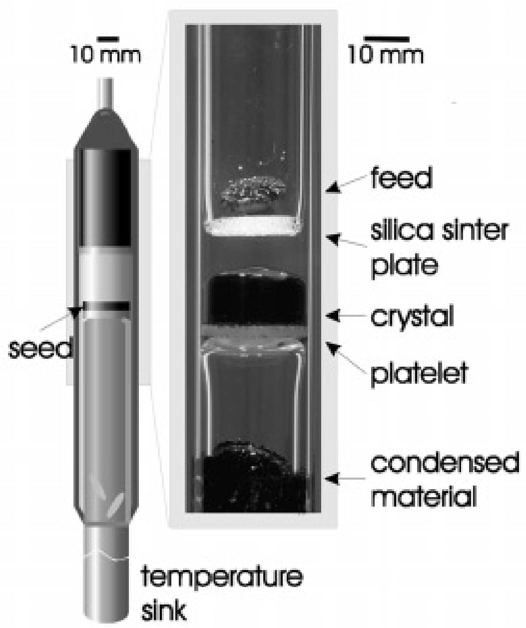


Materials for electronics such as CdTe and related compounds are used in highly sensitive detectors and photorefractive devices. To date, these applications are limited and expensive because of the difficulties in routinely growing crystals of sufficient quality.

CdTe-based X-ray and gamma-ray detectors have high potential in real time dental imaging or mammography, including 3-D tomography. This promises faster and more reliable medical diagnosis, while exposing the patient to lower radiation doses. CdTe infrared detectors enable high-resolution thermal imaging and high data rate optical telecommunication. In addition, the photorefractive properties can be exploited for high-performance devices in optical ultrasonic non-destructive testing. Today, the commercialisation of such advanced detection systems is impeded by the difficulty in growing large CdTe single crystals with the required quality. The melt growth method usually employed for the production of CdTe crystals is the vertical Bridgman technique. Crucible contact contributes to increasing the impurity content and generates extensive twinning. In addition, the stress induced by the crucible in a material with poor mechanical properties results in very high dislocation densities so that, eventually, the yield in terms of the usable fraction of the crystal does not exceed 5%.

The application potential of CdTe has not been exploited because of the difficulty in growing sufficiently large crystals with the required quality.

Recent results of microgravity experiments have demonstrated that new techniques can be employed to grow good quality crystals



Growth of Cadmium Telluride by the Markov method

Recent results of microgravity experiments have demonstrated that new techniques with substantially improved yield can be envisaged.

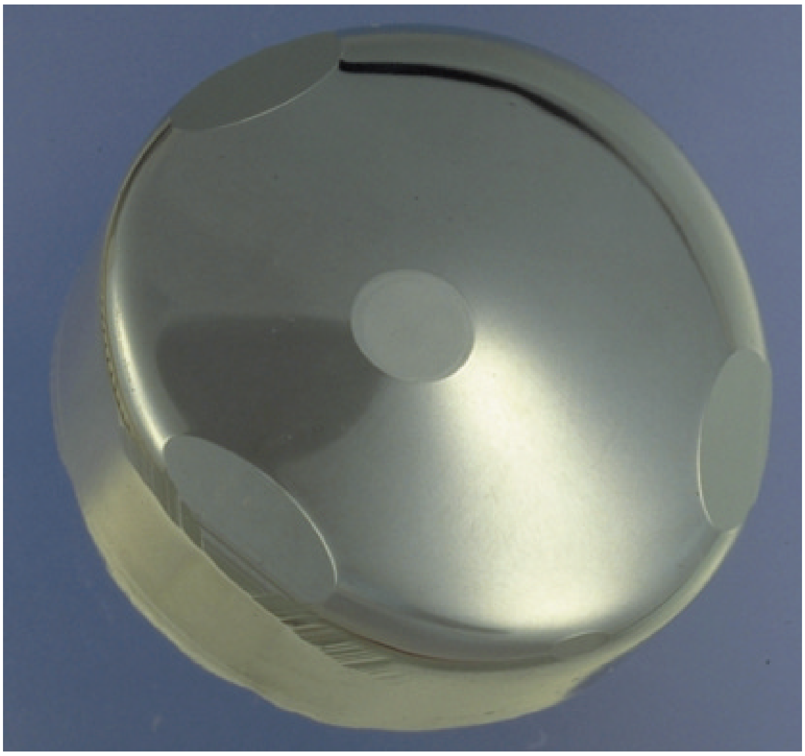
One microgravity technique is the progressive detachment of the melt from the crucible during directional solidification. When the material solidifies from a detached melt, its impurity content is lower and no mechanical stress is induced by the differential contraction of the crucible and the crystal during cooling. As a result, the density of twins and dislocations in the crystal is decreased by several orders of magnitude. Laminar convective flows can be imposed in the melt by applying a rotating magnetic field so as to minimise fluctuations at the solid-liquid interface and, thereby, enhance the homogeneity of the crystal.

Another technique is growth from vapour. It takes place at significantly lower temperatures and, in the case of semi-closed configurations, without touching the walls of the growth ampoule. Nevertheless, there is compelling evidence that gravity-driven convective flow in the vapour phase has salient effects on the compositional homogeneity of the crystals, particularly those with large dimensions. A thorough understanding of the convective flow and of its coupling with the growth process will permit major advances in optimising CdTe crystal production.

Three typical ampoules shown before integration into the Automatic Mirror Furnace (AMF) flown during the long-duration EURECA mission.
Left: flight ampoule for the growth of $AgGaS_2$ using the Travelling Heater Method (THM)
Centre: flight ampoule for the growth of InP using THM. The three parts of the sample between the two graphite plugs (dark) can be seen. From top to bottom; the source material, the solvent zone and the seed.
Right: the gold-plated flight ampoule provided the thermal gradient suitable for crystal growth in the Bridgman configuration

Microgravity will help to validate and optimise the 'detached growth' process. To that end, experiments are already in preparation.

Space experiments will be instrumental in validating models and demonstrating the full potential of the vapour growth technique for detector materials.



Cd (Te, Ga) crystal grown from vapour without wall contact (5 cm diameter)

Enhancement of Oil Recovery

Oil is one of the Earth's greatest resources. Oil companies are working continuously to enhance oil recovery methods and to discover new reservoirs. Modern geophysical and geological exploration methods allow detection of hydrocarbon reservoirs at depths of up to 7000 m.

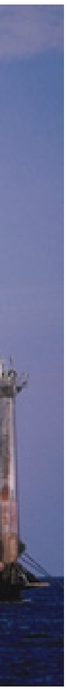
The reliable prediction of oil reservoir capacity and oil composition enables oil companies to economically optimise their exploitation techniques.

Two projects have been initiated dealing with the precise determination of mass transport in hydrocarbon mixtures: 'Diffusion Coefficient for Crude Oil' and 'Soret Coefficient for Crude Oil'.

Understanding fluid physics in crude oil reservoirs is a major challenge for optimising exploitation. Present modelling methods are based on pressure-temperature equilibrium diagrams and on gravity differentiation. However, rising exploitation costs are forcing oil companies to develop improved models that more accurately predict reservoir production capabilities. Advanced models account for constituent concentrations, and thus allow the determination, from the chemical analysis of a probe taken from a reservoir, the reservoir's volume, its vertical extension and the quality of its oil. However, the development of such models requires precise diffusion coefficients, which so far are not available because convective motions and buoyancy affect their measurement on Earth. This results in inaccurate forecasts.

The availability of accurate diffusion coefficients allows the reliable prediction of oil prospect specifications by numerical codes. Such codes simulate laws that describe the kinetics of pressure and temperature-dependent physicochemical processes that generate hydrocarbon mixtures from organic matter. The concentration distribution of constituents in these hydrocarbon mixtures is driven mainly by phase separation and diffusion caused by concentration differences and temperature gradients.

The role of thermodiffusion (the Soret effect) in petroleum reservoirs is not yet fully understood. Numerical modelling neglecting thermodiffusion results in the predicted vertical extension of a reservoir



being inaccurate to an order of 100 m, indicating the need to account for thermodiffusion.

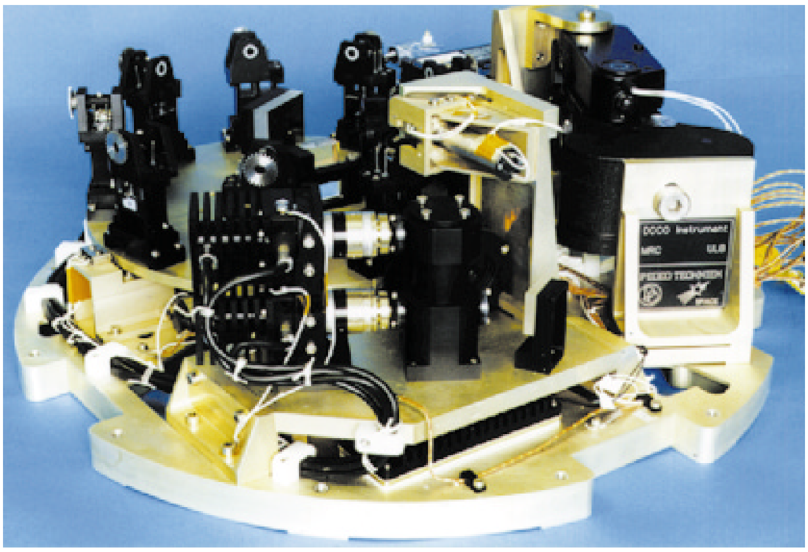
As buoyancy and convection affect the distribution of constituents in fluids under normal gravity conditions, accurate coefficients of pure diffusion can be measured only in microgravity. Several days or even weeks are required for such measurements. Consequently, ESA is sponsoring two projects on the precise measurement of diffusion coefficients in crude oil mixtures. The relevance of the projects is underlined by the active participation of the European petroleum industry.

In the first project an experiment aboard the US Space Shuttle flew during June 1998 (STS-91), during which – among others – the diffusion coefficients of various crude oil and hydrocarbon mixtures were measured accurately with a specific experimental setup. This experiment was housed in a 'Getaway Special' canister, a low-cost standardised payload container.

The second project aims to measure precisely Soret diffusion coefficients of crude oil mixtures, and considers temperature gradients and pressure conditions as found in oil reservoirs. Again a Getaway Special canister will be used, scheduled to fly in spring 2000.

Getaway Special (GAS) carrying the experiments

Diffusion coefficients, measured precisely in microgravity, will be used in numerical codes to predict oil reservoir capacities reliably.



Experimental arrangement of DCCO

Crystal Growth of Biological Macromolecules

Biological macromolecules such as proteins, enzymes and viruses play a key role in the complex machinery of life. They possess active sites which make them bind or interact with other molecules in a very specific manner that determines their biological function. They intervene in the regulation, reproduction and maintenance mechanisms of living organisms, and they can be the cause of diseases and disorders. Pharmaceutical drugs are molecules that inhibit the active sites of macromolecules and, in principle, are intended to affect only the targeted macromolecule.

The vast majority of current drugs are the result of systematic testing, first at molecular level, then at a clinical level. This extensive process significantly increases the cost of the product.

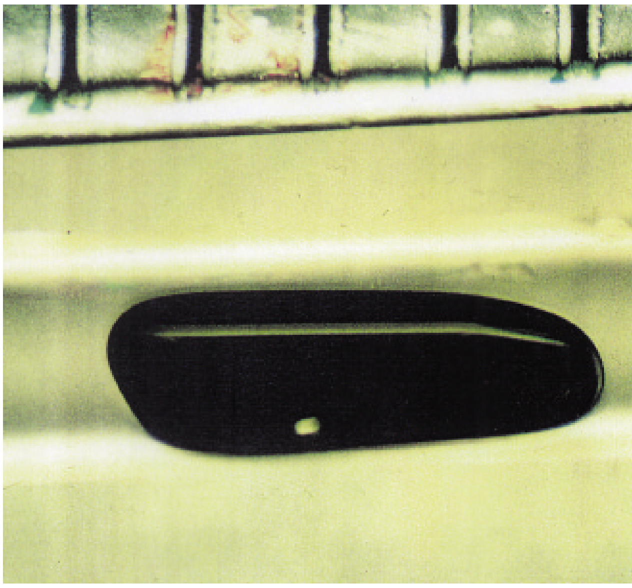
With a detailed knowledge of the 3-D structure of a macromolecule, biochemists can restrict the range of drugs to be tested. Furthermore, with a rational drug design approach, one may attempt to synthesise a drug targeted exclusively on a specific macromolecule. That means a drug will perfectly bind to the macromolecule and inhibit its biological function while remaining inert vis-a-vis other macromolecules.

The 3-D structure of the macromolecule can be discovered through the analysis of crystals by X-ray diffraction: the diffraction pattern maps the structure of the molecules in the crystal. The better the quality of the crystal, the faster and the more accurate the determination of the structure and the faster the identification of a drug.

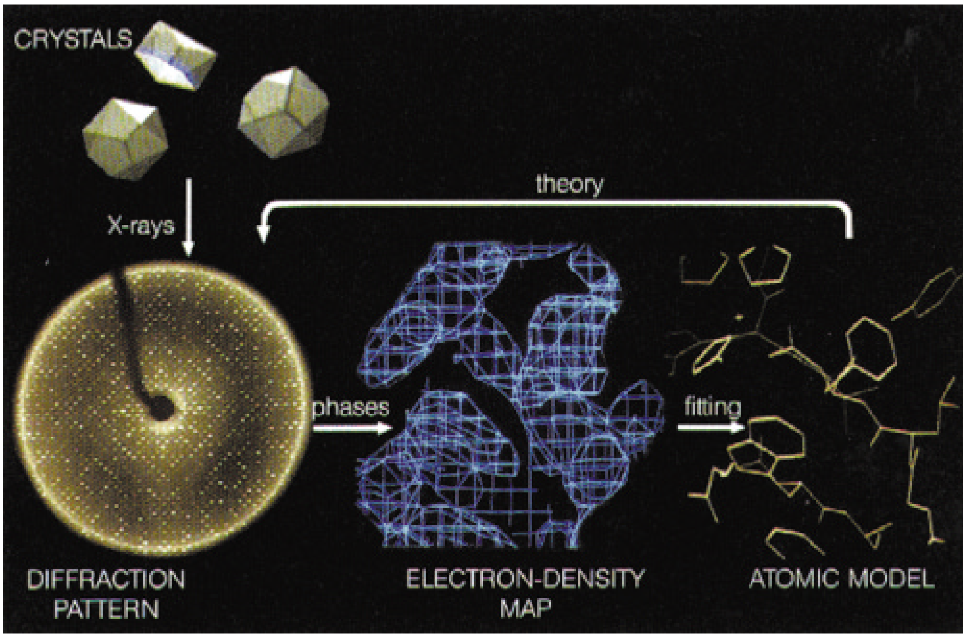
Crystals of a biological macromolecule enable researchers to determine the structure of the macromolecule itself and understand its function.

Knowing the structure of a macromolecule permits a faster selection of the appropriate drug, or the design of a new drug.

The lack of good quality crystals precludes the precise determination of molecular structures with adequate precision.



This crystal of the membrane protein complex Photosystem I was grown in space in ESA's Advanced Protein Crystallisation Facility (APCF). 4 mm in length, 1.5 mm in diameter, it yielded the best data set ever obtained



The principal of protein structure analysis

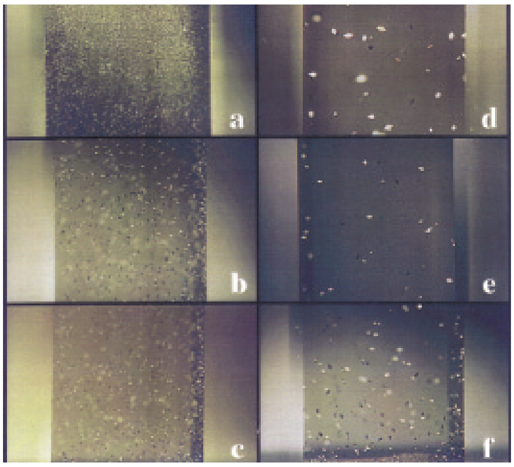
Freed from the effects of gravity, crystallisation in space has generated some highly promising results.

Controlled crystallisation requires a multi-parameter approach. Gravity-dependent parameters that may affect crystallisation include sedimentation, convection and consequently nutrient transport rate and wall contacts.

Research efforts in laboratories aim to control the conditions in order to favour the nucleation of a small number of crystals and, subsequently, steady growth to large sizes and crystallographic perfection.

Crystals of *Photosystem I* grown in space had a 10 to 20 times larger volume than those grown on the ground and allowed the refinement of the structure from 4 Å to 3.4 Å. Space crystals of Collagenase diffracted with a higher intensity compared with their ground counterparts, and allowed a further refinement of the structure. Under otherwise identical conditions in space, fewer but larger *thaumatin* crystals were obtained with a measurably higher internal order.

Comparable improvements in crystallisation under microgravity have been reported in the scientific literature for about 20% of the macromolecules



Under otherwise identical conditions, significant fewer, though larger, crystals of thaumatin were obtained in APCF reactors activated in microgravity (d,e and f) than in their counterparts activated on the ground (a, b and c, respectively). In addition, the space-grown crystals exhibited a marked increase of structural quality over the ground-grown crystals (higher resolution and lower mosiacity)

tested. It is likely that the growth of many crystals could be conducted more successfully in space.

Current efforts toward understanding and controlling the various mechanisms involved in the overall process will continue. Well defined and documented experiments in microgravity will help us learn to control and optimise conditions, leading to better crystals. It will also permit the prediction of which molecules of interest to the pharmaceutical industry will benefit from crystallisation in space conditions.

Atomic Clock Ensemble in Space (ACES)

ACES is a programme to test the performance of a new type of atomic clock that exploits and depends upon microgravity conditions. The project has been approved to fly on the International Space Station as an external payload, starting in 2002 for a period of one and a half years.

In its European baseline configuration, ACES consists of the following key elements:

- A laser-cooled atomic clock 'PHARAO' – contributed by France,
- A Hydrogen Maser – contributed by Switzerland,
- A laser link for optical transfer of time and frequency – contributed by France
- A microwave link for transfer of time and frequency – contributed by ESA

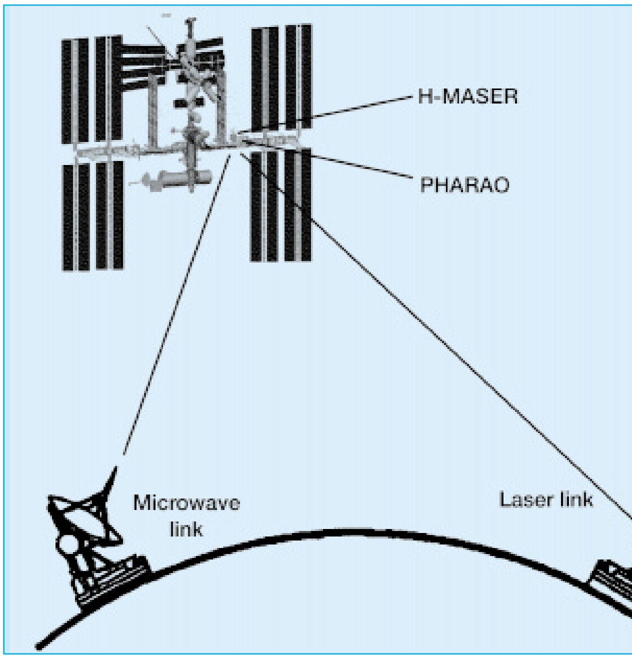
Fundamental Physics Experiments with ACES

New experiments testing General Relativity within the solar system.

- ***Measure the Shapiro effect (the retardation of photons, in the Sun's gravitational field).***
- ***Measure the Einstein redshift to an accuracy of 10^{-6} i.e., an improvement by a factor of 100 compared to existing measurements.***
- ***Check the stability of some of the fundamental constants of physics: assessing possible time-dependent drifts and/or spatial effect.***

Radio astronomy

- ***Improving the angular resolution when observing remote stellar objects by Very Long Base Interferometry(VLBI).***

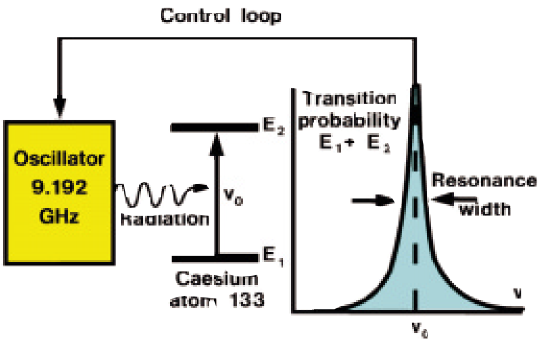


The caesium atom clock 'PHARAO' uses laser cooling to reduce the velocity of atoms to a few centimetres per second, which corresponds to a temperature of about 1 μK. Under microgravity conditions the atoms remain at these low velocities, while on Earth they would increase their speed rapidly due to gravitational acceleration when the lasers were switched off for signal interrogation.

The principle of the atomic clock

The principle of an atomic clock is to lock an oscillator to the atomic resonance frequency ν_0. Heisenberg's uncertainty principle shows that the greater the interaction time of the atoms with the radiation emitted by the oscillator, the narrower the resonance.

Two key points determine the ultimate performance of an atomic clock: a narrow resonance and a high signal-to-noise ratio.



Laser cooling allows an interaction time 100 to 1000 times greater than for a conventional aesium clock.

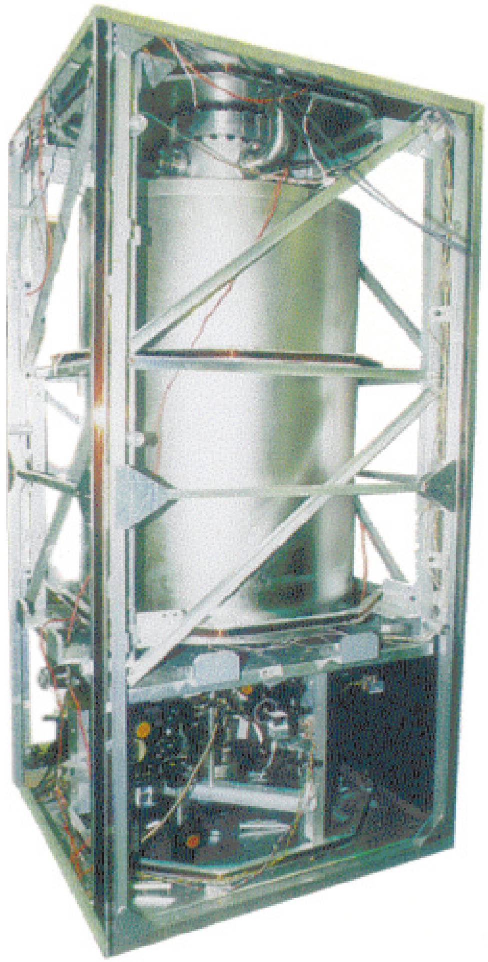
It is expected that the new atomic clock will reach a frequency stability between 10^{-16} to 10^{-17} per day with an accuracy of 10^{-16}. This is one to two orders of magnitude better than can be achieved with the most advanced clocks on the ground.

The Hydrogen Maser will serve as a reference clock to verify the performance of the atomic clock. The microwave and the optical links will allow laboratories on the ground to receive the data and to interact with the space-based systems.

The aims of ACES

- Validate in space the performance of this new generation of clocks.
- Provide an ultra-high performance global time-scale.
- Perform fundamental physics tests.

The ultra-precise measurement of frequency and time will enable advanced investigations in fundamental physics and will also have practical applications. It will allow experimental investigation of the properties of space and time, which are fundamental in all modern, classical, quantum and gravitational physics. For time and frequency metrology, the accuracy and stability of PHARAO, together with high-performance techniques for comparing Earth-based and orbiting clocks, will improve the accuracy of International Atomic Time and allow new navigation and positioning applications.



This atomic fountain clock has been in operation at the Observatoire de Paris since 1995, and has a relative stability of $1.3 \times 10^{-13}\ \tau^{1/2}$ (where τ is the measurement time in seconds). With an accuracy of 2×10^{-15}, this is currently the world's most accurate clock.

'ACES'
- **An exemplary model of the synergy between Science and Technology**
- **A tool for improving knowledge of the interplay between radiation and matter.**
- **A tool for high-performance synchronisation of ground-based clocks.**
- **A testbed for a new generation of spaceborne atomic clocks.**
- **A scientific cooperation project involving European and international laboratories.**
- **A project demonstrating the value of the International Space Station as a testbed for advanced Research and Technology**

Navigation and positioning

- **New concepts for higher performance GPS systems.**
- **Geodesy with millimetric precision.**
- **Precise tracking of remote space probes.**

Time and frequency metrology

- **Comparing and synchronising clocks over intercontinental distances to an accuracy of 10^{-16}.**

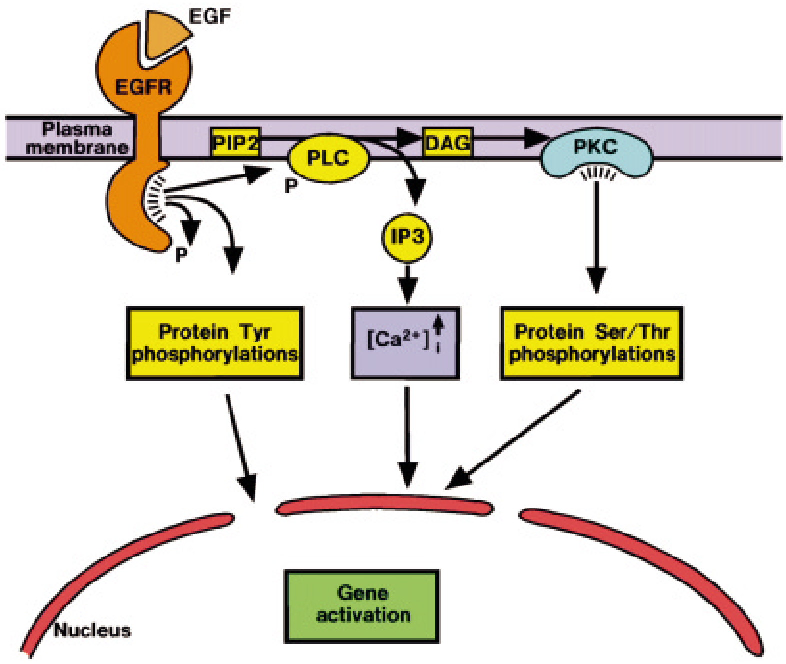
- **Distributing the International Atomic Time with an accuracy of the order of 30 picoseconds, i.e. an improvement by a factor of 100 compared to current GPS and GLONASS systems.**

Life Sciences and Biotechnology

Influence of gravity on living organisms

Gravity is a fundamental force that has a marked influence on all life on Earth. Life scientists and biomedical researchers exploit the space environment and in particular the near-weightlessness in order to answer fundamental questions in basic biology relating to humans, plants and animals. Various investigations on the response of microgravity on lungs, brain, nervous system, bones and muscles have already been performed. This research is not only of interest for the health and survival of astronauts but is also relevant in the understanding of balance disorders, osteoporosis, and cardiovascular disease.

Microgravity is a new non-invasive tool to investigate cellular functions. It will provide new insight into how cells perceive signals and react to them. This is essential for the better understanding of biological and physiological processes with potential applications in molecular medicine, such as wound and tissue repair.

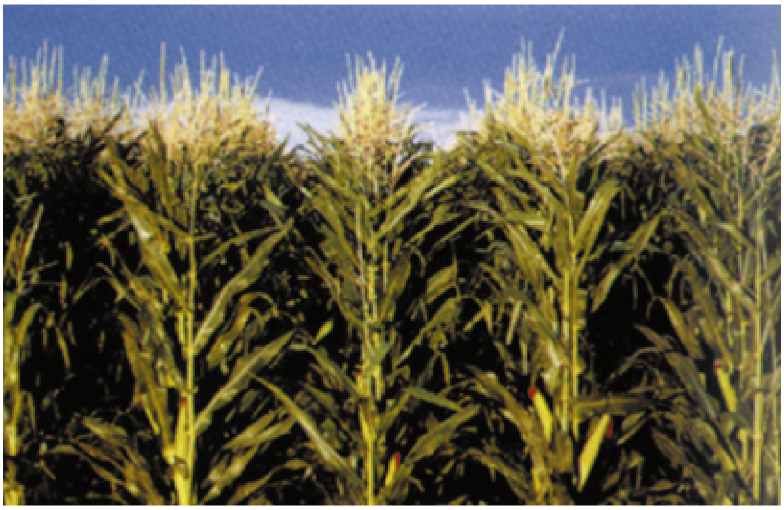


"Regulation of Cell Growth and Differentiation" - Cascade of early cellular responses to growth factor binding to a membrane receptor; a process that may amplify microgravity sensitivity

This research is only at the very beginning of clarifying the role of gravity at the molecular level. Present basic studies address the reaction-diffusion feedback pattern-forming processes that occur in self-organising systems.

For cell-cell relations or for the respective cell functions within a differentiating tissue, the origin of a change is likely to involve subtle modifications of their mechanical and biochemical micro-environment. Experimental investigation of such minute changes and their eventual application would benefit from the increased stability of fluid systems in microgravity and from reduced mechanical loads.

Fluid dynamic models describing macroscopic systems are not valid in the sub-micron range. Experiments in microgravity are needed to observe and to determine the influence of gravity on the processing and amplification of signals involved in the gravity sensing and response of cells, cell aggregates and tissue or whole organisms. Any advance in the understanding of these fundamental aspects is important for the future of medical science.

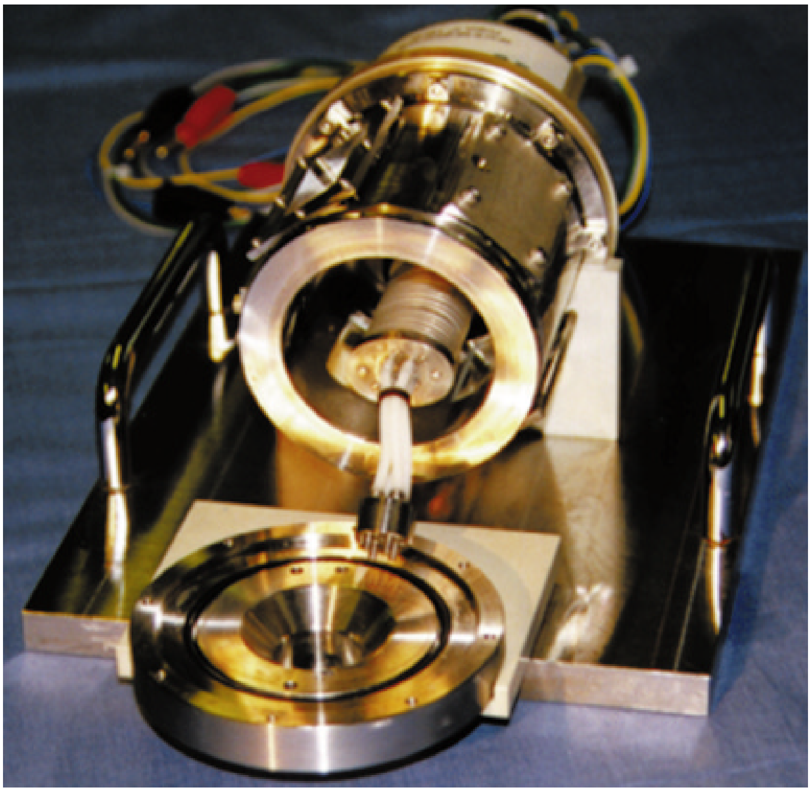


Biotechnology - tissue engineering

Millions of people suffer organ or tissue loss from diseases and accidents every year. Yet transplantation of tissues and organs is severely limited by the availability of donors. Growing tissue samples outside the body is one of the major goals of current medical research, and the microgravity environment has great potential for advancing this research.

Experiments in bioreactors are performed to study how cells multiply and interact to form skin, bone and organs, and these cell and tissue culturing techniques also aid the study of cancer cells and tumour formation.

Knowledge gained in microgravity on the regulation of cell growth and differentiation will also help improve the cultivation of sensitive and highly differentiated cell strains like those needed to obtain artificial organs. Studies of cells' ability to migrate in reduced gravity may produce new insights into the factors that allow cancer to spread. When combined with biomedical research on Earth, these investigations could contribute to the development of new ways to prevent and treat related diseases.



ESA's Space Bioreactor for Suspension Culture of Sensitive Cell and Multicellular Systems

Experimental data obtained in microgravity and hypergravity studies indicate a change in cell functions related to the gravity level. The underlying fundamental mechanisms responsible for the sensitivity of living systems to gravity remain, however, to be fully understood.

The benefits of low gravity for growing cell cultures derive from the absence of convection and sedimentation, which for 3-D cell aggregates favour the creation of tissue-like environment.

Biomedicine - Osteoporosis

Osteoporosis is often called a 'women's disease', although 15 % of the osteoporotic-related problems reported concern men.

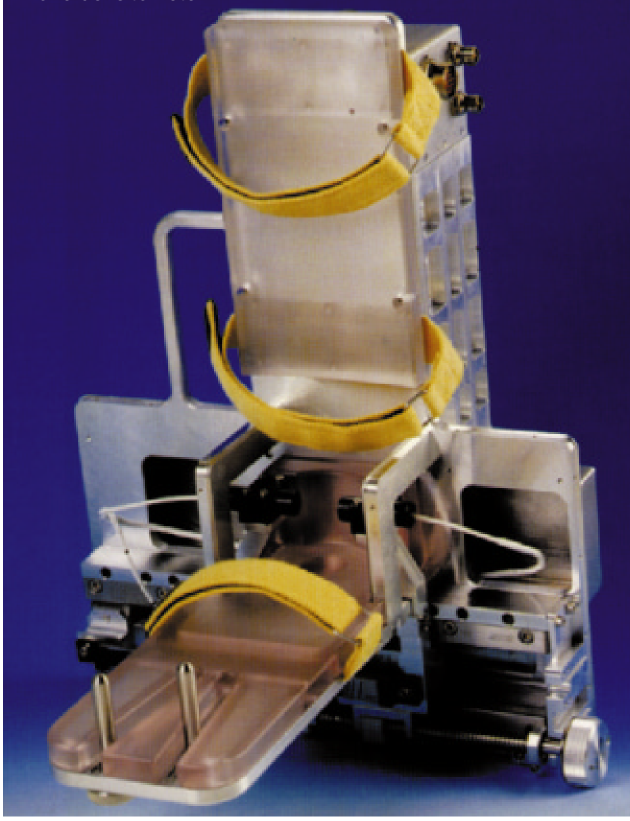
In Europe, osteoporotic-related fractures total more than one million a year. The frequency of osteoporotic fractures is expected to increase dramatically, partly due to the increasing percentage of elderly in the population.

Astronauts and other biological systems experience accelerated bone loss. Microgravity therefore provides for an accelerated testbed for osteoporosis studies.

With related health care expenses in Europe amounting to 25 million ECU daily, osteoporosis attracts considerable attention from the biomedical industry. Microgravity is particularly relevant since studies performed on astronauts and on animals showed an accelerated bone loss and a bone structure impairment especially in the weight-bearing bones.

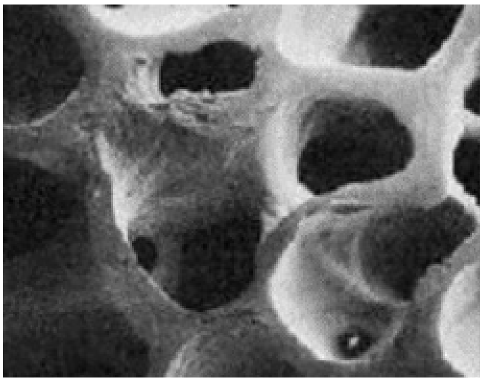
ESA is sponsoring a project on osteoporosis. It aims at developing an accelerated experimental model to evaluate trabecular bone architecture and bone quality evolution during space flight exposure. The activity includes bone sample and in vivo observations, as well as in vitro samples (2-D and 3-D biomaterials). These will serve as standard biosamples. They could also be used for drug screening. The second major element of the Osteoporosis project is the development of a 3-D high resolution

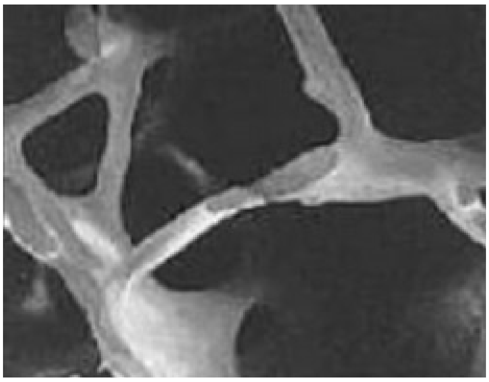
Bone densitometer



analytical instrument for the quantitative characterisation of bone density and bone architecture.

This instrument will first be applicable for in vitro investigations, and ultimately for investigations on humans. The in vivo observation of the microstructure of bones is today clinically not feasible. This instrument will therefore be a major contribution towards the better understanding of bone evolution and for a more accurate prediction of risks. Since the risk of bone fracture seems to be





Normal trabecular bone (left) and osteoporotic bone (right)

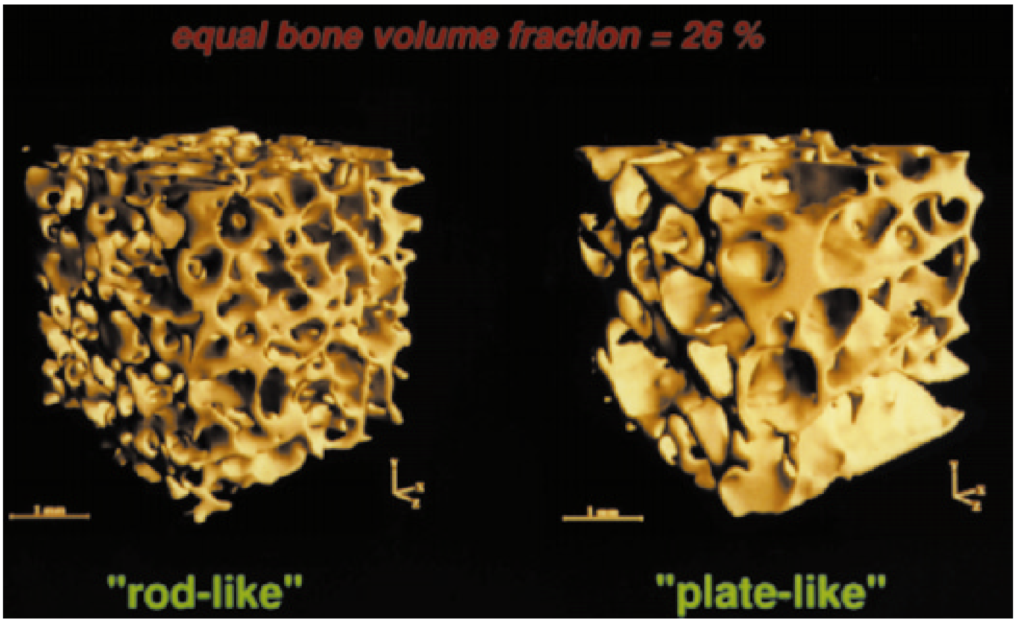
strongly related to bone microstructure, it can be assessed quantitatively with the new instrument.

On the basis of the data obtained with this instrument an accelerated physiological model will be developed and validated. It can be employed for:
- the testing of bone reconstruction matrices, i.e. biomaterials,
- the study of osteopenia prevention based on exercise, mechanical constraints, and diet,
- the testing and screening of drugs.

The project has two major objectives:
- to develop a 3-D bone artefact supporting the co-culture of bone cells together with the experimental setup for the simulation and control of organotypical conditions.
- to develop a bone microarchitecture analyser for the quantitative, high resolution, rapid, non-invasive characterisation of the kinetic evolution of the model. This will also be applicable to humans in the longer term. The analytical tool is a 3-D Peripheral Computer Tomograph with an in vivo target resolution of 20 μm.

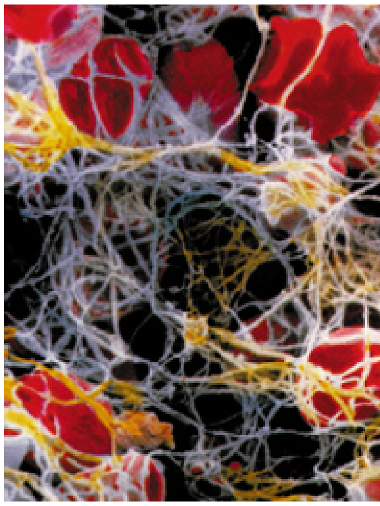
This project began in spring 1997 and involves academic and industry partners.

In April 1997 ESA started to support an application-oriented project with the objective of exploiting the enhanced bone-loss phenomenon observed in space.



3D-μCT image of bone samples exhibiting a considerable bone strength difference

Biomedicine



Blood cell preservation

Simulating microgravity conditions on Earth could increase the preservation time of blood cells both for therapeutic and research applications. To achieve this goal one must first understand how microgravity acts on the cell metabolism and then create these conditions in blood banks.

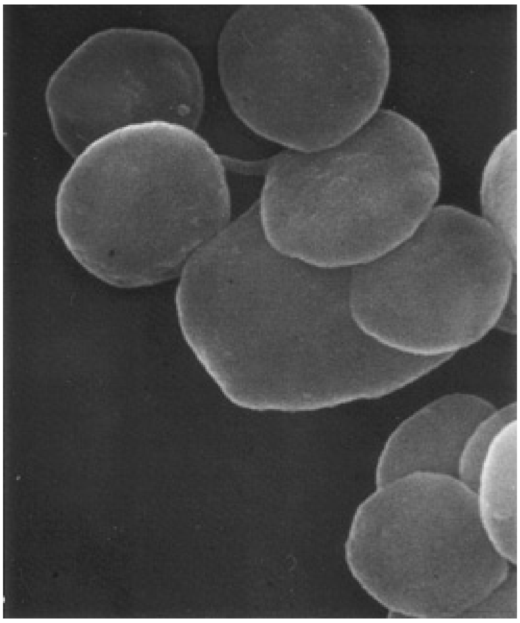
The use of stored blood cells is of importance in the treatment of bleeding or the pathological deficiency of certain cell types. Platelets and red blood cells must be stored ready to use in blood banks. Improving the preservation conditions would preserve the functional state of the cells and therefore guarantee the efficiency of the treatment while at the same time reducing the treatment costs.

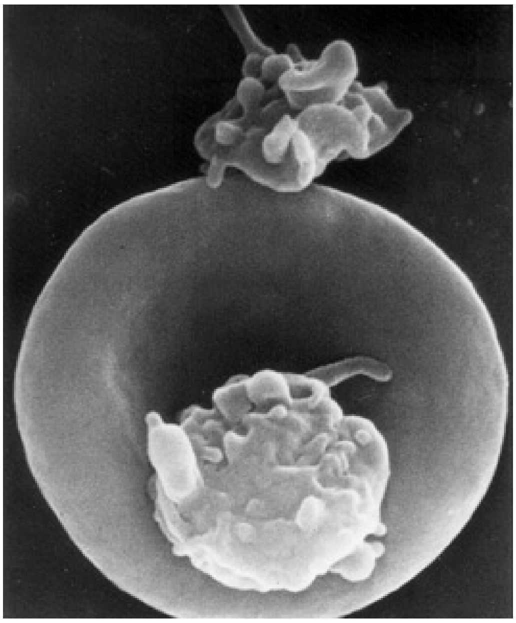
The preservation state of platelets in microgravity has been observed to be significantly higher than in ground-stored samples due to reduced platelet aggregation.

Other topics of interest

Monitoring the health and body function of astronauts and related investigations have led to a variety of new insights into the influence of space environment on human beings. Dedicated instruments were developed for medical diagnostics and validated in space, and are now used on Earth.

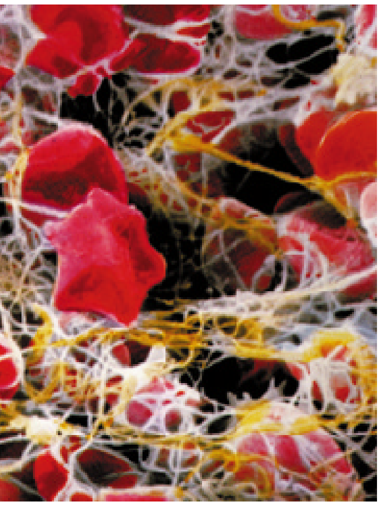
An example is the **fluid shift in the human body** caused by the absence of hydrostatic pressure observed under microgravity conditions. A dedicated instrument using ultrasound has been developed to measure fluid accumulation in human tissues resulting from such fluid shift. Analogous forms of oedema occur preferentially in the facial tissue for kidney disease for example, whereas cardiac patients show oedema in the lower part





Unactivated platelets, in a resting state, with characteristic disc shapes (~3µm in diameter) (left)

Two activated platelets with characteristic pseudopodia enabling them to aggregate and to adhere to vascular surfaces. A red blood cell is present behind one platelet (~7µm in diameter) (right)



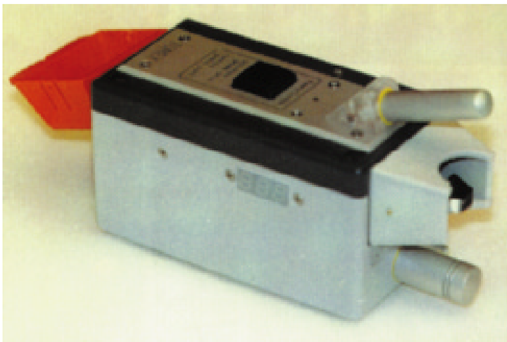
Formation of blood clots of fibrin networks and blood platelets (thrombocytes)

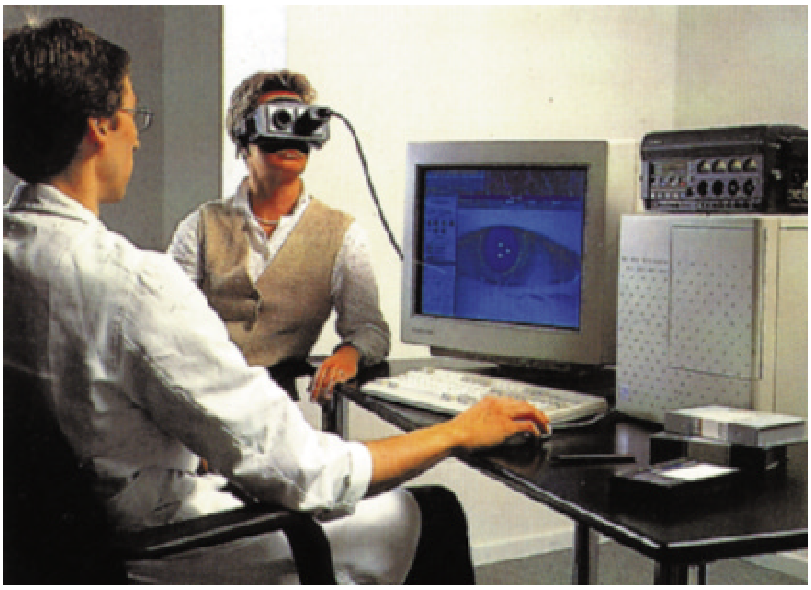
Monitoring the health of astronauts has led to additional knowledge of the influence of space flight on human beings. Dedicated instruments were developed, validated in space and are now used for medical diagnostics on Earth.

of the body. In this way swellings in the forehead or the tibia can serve as diagnostic or prognostic hints and be controlled by the new ultrasound instrument.

For the **measurement of inner eye pressure** in space a device, which the user can operate without help, has been developed that determines the increase due to microgravity. This 'self-tonometer' can also be used to control the increase of the intra-ocular pressure on Earth. The instrument registers the pressure by total reflection of an infrared beam and is now on the market for regular self-control and diagnostic of patients with risk of glaucoma, one of the most frequent reasons for early blindness.

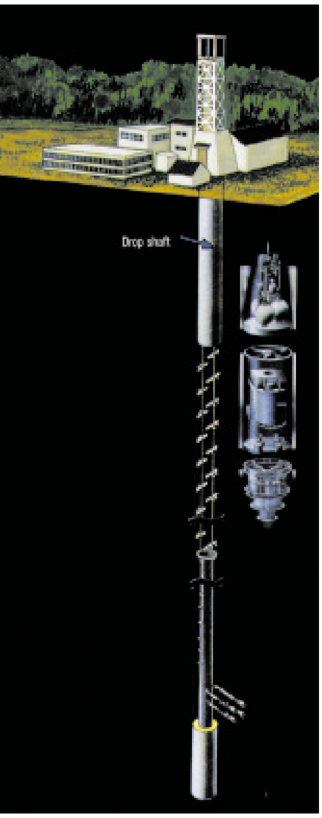
The development of a non-invasive detection instrument to observe eye movements in all three dimensions by **video-oculography** is another example. The reaction of the eye to light stimulation can be registered continuously and has been used to investigate the coordination of information on orientation obtained by the eye and by the gravity-sensing organ in the inner ear. This method has been successfully tested on Mir and Shuttle missions, and can be used in the detection of disturbances in the vestibular, neurological or oculomotor domains. This diagnostic instrument is now commercially available for terrestrial use.





Activities in the US and Japan

NASA began a programme in 1985 to promote the involvement of industry in space-related activities through the formation of Centers for Space Commercialization (CSC). The objective is to motivate industry to invest in space-based R&D. The following centres are jointly supported by industry and NASA:



Drop Shaft, Hokkaido (Japan)

– University of Alabama-Birmingham: macromolecular crystallography, growth of structurally improved protein crystals under microgravity.
– Auburn University: solidification design by measurement of critical thermophysical property data of molten alloys for improved alloy and process development on Earth.
– Colorado School of Mines: commercial applications of combustion in space: combustors (power plants, aircraft engines), fire safety, ceramic powders, combustion synthesis.
– BioServe Space Technologies: bioprocessing/bioproduct development, using space as a laboratory to address terrestrial health concerns, 'biocybernetic' materials.
– University of Alabama in Huntsville: Consortium for Materials Development in Space: liquid metal sintering, vapour grown single crystals, electrodeposition of hydroxyapatite.
– University of Houston, Texas: Space Vacuum Epitaxy Center: use of the ultra-vacuum of space for processing ultra-pure, thin-film materials by epitaxy.
– University of Wisconsin-Madison: Center for Space Automation and Robotics, use of microgravity to enhance production of plant materials for pharmaceutical and agricultural purposes.

– Northeastern University Boston, MA, industrial research on zeolite crystal growth.

In Japan, microgravity applications are promoted by the Japan Space Utilisation Promotion Office, with participation from NASDA and MITI. The activities are concentrating on the utilisation of a 750 m drop shaft - JAMIC. By providing an inexpensive and easily accessed microgravity environment for experiment durations of up to about 10 seconds, the interest of industry in later using the Space Station is being developed. A high-priority project is focusing on the determination of thermophysical properties of molten semiconductors with the goal of developing high-quality silicon single crystals for the next generation of miniaturised electronic devices. This will be achieved through numerically controlled processing using material data (thermal conductivity, diffusivity, etc.) of high precision, measured without the disturbing influence of convection. Other topics are the investigation of technical combustion processes for which the better understanding of basic phenomena, such as droplet evaporation and ignition, is expected to result in the reduction of fuel consumption and exhaust emissions, thus leading to improved process efficiency of gas turbines, burners and diesel engines.

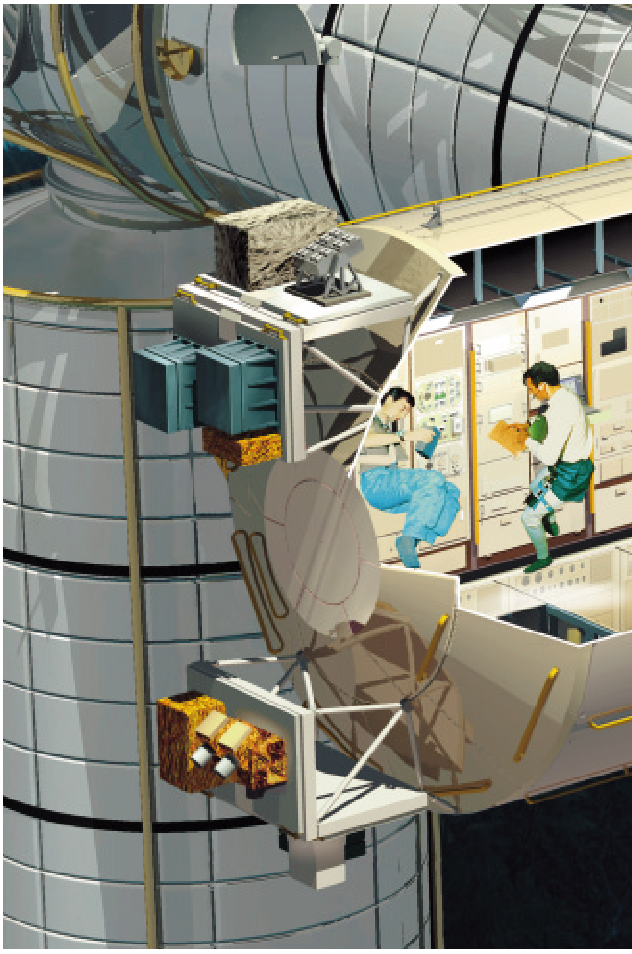
National Initiatives in Europe

Combustion research experiments can easily be carried out at the Drop Tower in Bremen (Germany)

One of the Japanese projects on combustion is being carried out in cooperation with Germany, using the 110 m drop tower of ZARM Bremen. The German Aerospace Research Centre (DLR) has strongly supported application oriented and applied research in the past. A typical example is the research and development of monotectic alloys, which resulted in a patented casting process for the production of self-lubricating bearing materials. This process uses the knowledge gained through microgravity experiments on interface tension-driven convection to compensate for separation by sedimentation on the ground. A specific programme for the promotion of applied research has been initiated, and the programme of 'Research under Space Conditions' emphasises industrial applications. Space industry is starting its own promotional activities by contributing to existing research networks and by stimulating new applied research fields, including applications in space. Examples are materials for sensors and detectors operating in harsh environments.

Other national agencies are now shifting their microgravity programme priorities from fundamental to applied research. An example is the French space agency CNES, which has been supporting the investigation of phenomena near the critical point. Experimental results showed the existence of a new, so far unknown, mechanism of heat transport, the so-called 'piston effect'. Efforts are now under way to use this effect in industrial applications, e.g. in supercritical fluids, chemical and nuclear decontamination processes, as well as for the control of fluids in fuel cells in space. CNES is also involved in the development of a new atomic clock, relying on the quiescent state of ultra-cold atoms that can be achieved in a microgravity environment. This will eventually lead to at least one order of magnitude improvement of frequency stability of space-based clocks.

Outlook



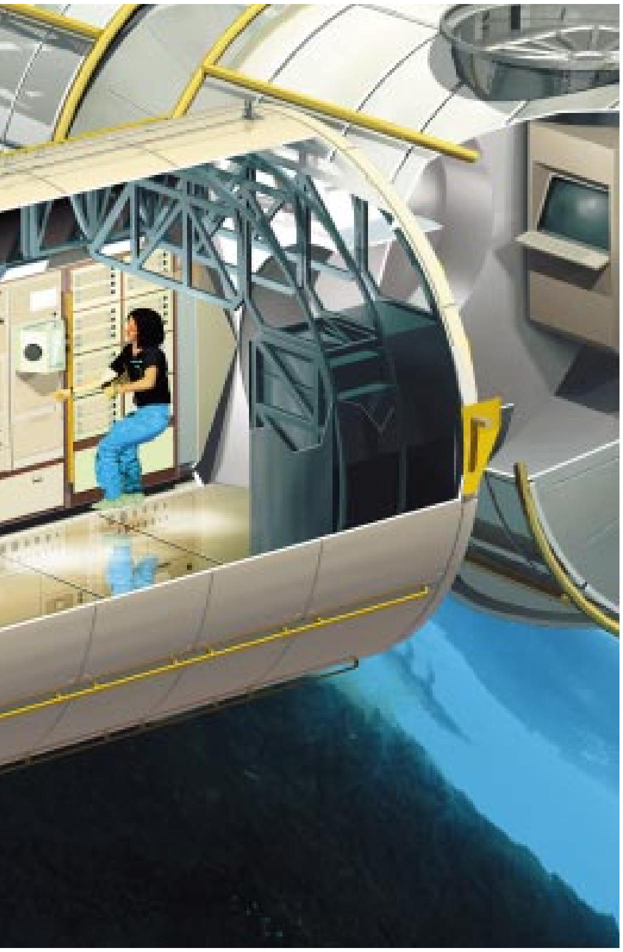
Towards commercial utilisation ...

This brochure has presented some examples on how microgravity as a research tool increases the understanding of gravity-related phenomena in processes and products of industrial significance. Microgravity can also help to obtain more accurate data needed for the improvement of certain ground-based processes and products. An important task is to include microgravity as a tool in industrial research and to use the results for increasing the reliability of numerical simulation and modelling. Recent workshops have helped to identify topics of interest to industry and of a high microgravity relevance. Another important aspect is the development of instruments for experimentation in space that are also of interest for new commercial terrestrial applications. This is particularly true in the medical field.

The era of the International Space Station will open new opportunities for application-oriented research. The unique feature of the ISS is the availability of microgravity for long periods and the presence of astronauts for experimentation. This large-scale research facility will allow flexible access for the accommodation of sophisticated instruments.

The possibilities range from basic to applied research to the utilisation of the ISS as a platform for industrial R&D by the private sector on a commercial basis. For such customers, adequate guarantees of confidentiality, including intellectual property rights, will be secured.

For the early utilisation phase of the ISS, a call for proposals was issued in 1998. New projects will be selected and approved early in 1999.



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