# ESA MICROGRAVITY RESEARCH ACTIVITIES IN THE FIELD OF PHYSICAL SCIENCES AND APPLICATIONS

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**Abstract.** During the eighties, microgravity research focussed predominantly on the investigation of fundamental phenomena, often with limited industrial support. Although this approach led to some rather impressive breakthroughs in terms of new theoretical insights and microgravity experimentation, the need for increased co-ordination and interest from industry became increasingly apparent. In this decade, a *user-driven* research strategy has been instigated by ESA to promote microgravity research. The objective is to coordinate ESA, national activities and industry into an overall European strategy, which will allow valuable application-oriented microgravity research to be performed aboard the International Space Station (ISS). On this basis, it is expected that scientific progress will evolve even more rapidly due to the easier planning, regular access and longer experiment-durations associated with the ISS.

This paper highlights the wealth of microgravity research being co-ordinated by ESA in the field of *physical sciences*. A number of key areas of research under microgravity conditions are currently being explored such as alloy solidification, crystal growth, measurement of thermophysical properties, combustion mechanisms, fluid flow, cold atom physics and complex plasmas, to name but a few. The following sections will provide background information relating to the various ESA research programmes, as well as emphasising their microgravity relevance.

**Keywords:** Alloy solidification, cold atom physics, combustion, complex plasmas, crystal growth, ESA, fluid dynamics, International Space Station, microgravity, multiphase systems, physical sciences

## 1. Introduction

A vast wealth of microgravity research is currently being co-ordinated by ESA in the field of physical sciences. A number of key areas representing the cutting-edge of scientific research include alloy solidification, crystal growth, measurement of thermophysical properties, combustion mechanisms, (multiphase-) fluid dynamics, cold atom physics and complex plasmas. The main purpose of this microgravity research is to gain a better understanding of the physics of matter, while actively promoting a trend towards more application-oriented research. The creation of Topical Teams and Microgravity Application Projects (MAPs) by ESA now allows European researchers, from both academia and industry, to discuss state-of-the-art results and potential applications in a team-based environment.

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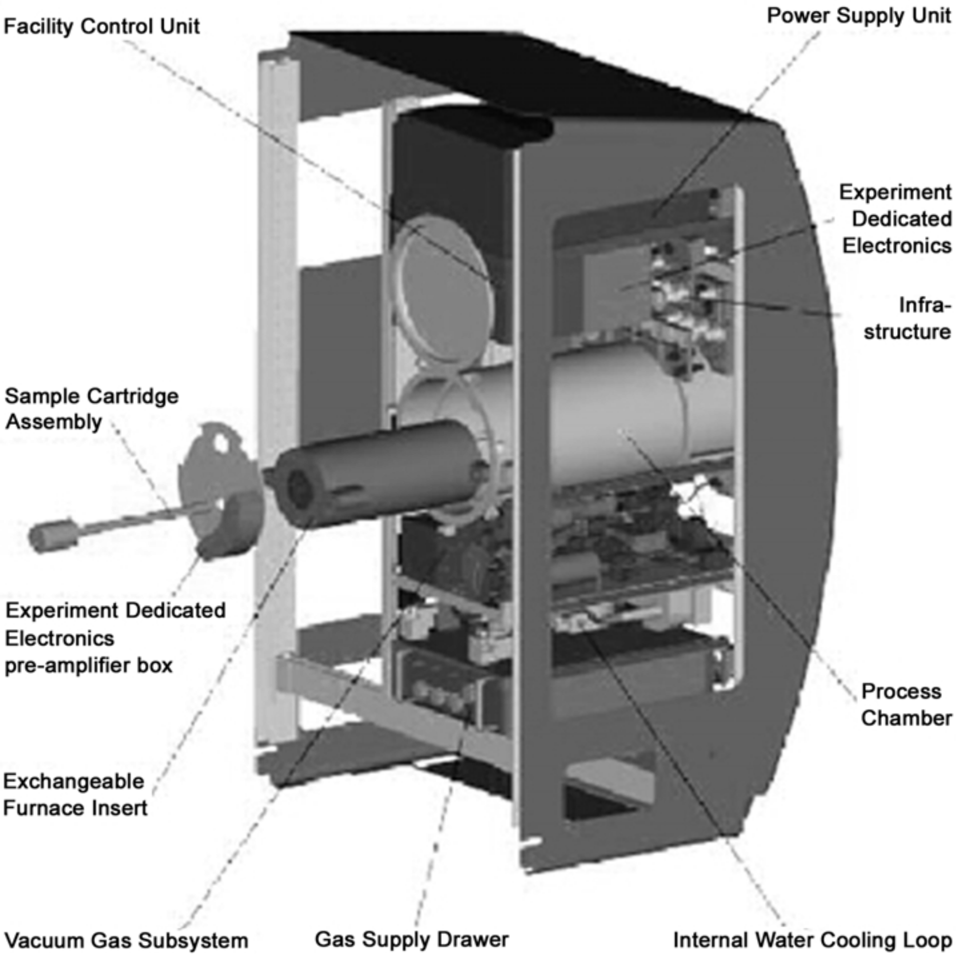


*Figure 1a.* Schematic diagrams of (a) the Materials Science Laboratory (MSL), (b) the Electromagnetic Levitator (EML) and (c) the Fluid Sciences Laboratory (FSL), which will be housed onboard the International Space Station.

ESA microgravity experiments in the physical sciences will be carried out in a number of multi-user facilities on the International Space Station, principally the Materials Science Laboratory (MSL), the Electromagnetic Levitator (EML) and the Fluid Science Laboratory (FSL). These facilities are currently under development within the Microgravity Facilities for Columbus (MFC) Programme and are shown schematically in Figure 1.

The contents of this paper will focus on topics articulated around two of the strategic objectives of the current European Research Plan for Life and Physical Sciences in Space, namely *Exploring Nature* and *Innovating Technologies and Processes*. The former focuses more on the fundamental physics of matter and its interactions, while the latter aims at understanding and improving industrial

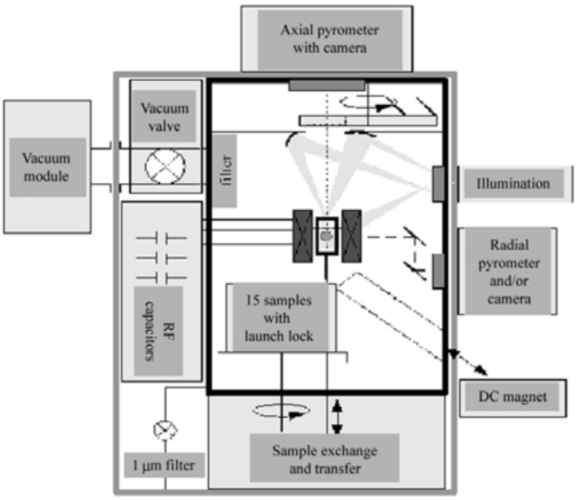


*Figure 1b.*

*Figure 1c.*

processes and at innovating technologies for Earth-bound applications. Various disciplines under these headings will be discussed, with respect to microgravity research. All projects result from a rigorous international peer-review based selection. A number of topics presented here support as well the other strategic objectives of the Research Plan: *Improving Health* and *Caring for the Environment*.

## 2. Exploring Nature

### 2.1. DIFFUSIVE MECHANISMS

Diffusion is an intrinsic property of matter that allows systems to smooth out concentration and temperature inhomogeneities in the absence of convection. Accurate measurements of mass diffusion in metallic alloys, molten salts, isotopic and organic mixtures are needed to validate various theories of diffusion based on the description of liquid structures. These theories aim to predict diffusion coefficients and their dependence on the various parameters involved. Thermodiffusion, also known as the Soret effect in liquids, leads to the segregation of components in a fluid mixture under an imposed temperature gradient, and is also the subject of much scientific interest.

However, diffusion is typically a slow process. If a concentration difference is established over a distance of 1 cm, it will take typically $10^5$ sec to become homogeneous in simple liquids. The long characteristic times of diffusive processes imply that even slow movements in the mixture (e.g., a few $\mu$m/sec) can disturb the concentration field and hamper measurements.

Several experiments have already been carried out which demonstrate that the microgravity environment offers a unique opportunity to practically eliminate natural convection inside an inhomogeneous (in temperature and/or concentration) liquid mixture. This therefore permits the accurate measurement of diffusion data which could be used in mathematical models of various industrial processes, such as solidification modelling. Such data is also reproducible and has a very low experimental scatter (0.5–2%). In addition, accurate diffusion data measured under microgravity conditions will improve current phenomenological descriptions of diffusion and thermodiffusion, as well as our understanding of the underlying structure of liquids.

### 2.2. UNDERCOOLED MELTS

A melt can be cooled significantly below its equilibrium melting point if the energy barrier for nucleation of the solid phase is high. However, the wetting of the melt on the walls of a solid crucible or on solid impurities contributes to the lowering of the energy barrier and triggers heterogeneous nucleation. Convective flows and the local energy fluctuations in the melt can also lower this energy barrier. The highest achievable energy barrier for nucleation, which corresponds to homogeneous nucleation, can therefore only be achieved in a *containerless*, quiescent, pure melt.

Upon cooling, under such conditions, the melt can either solidify extremely rapidly from a very limited number of nucleation points giving rise to unique metastable microstructures, or the melt can pass through a glass transition and an amorphous solid phase is obtained. Measuring the properties of an undercooled melt as a function of decreasing temperature is of fundamental importance to a

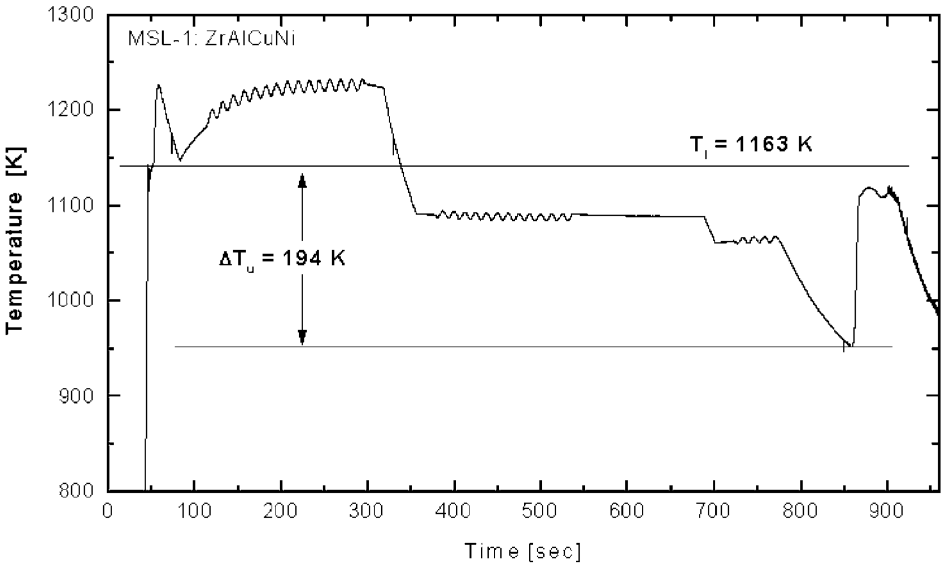


*Figure 2.* Undercooled melts – temperature/time evolution of a glass-forming $Zr_{65}Al_{7.5}Cu_{7.5}Ni_{10}$ alloy sample showing the undercooled region. (Courtesy: Fecht et al., University of Ulm, Germany.)

better understanding of microstructural evolution. This knowledge enables one to predict the formation of specific phases or glasses with very unique properties.

Figure 2 represents an impressive result from recent microgravity research, as regards controlled levitation, diagnostics and data analysis. The graph shows the temperature/time evolution of a glass-forming $Zr_{65}Al_{7.5}Cu_{7.5}Ni_{10}$ alloy sample which has been processed under containerless/vacuum conditions by means of electromagnetic levitation in space.

Attaining the proper experimental conditions required for such investigations is not possible on the ground for a wide range of materials. Recent experience, however, has demonstrated that with containerless processing in the space environment (i.e., using electromagnetic levitation), these conditions can be achieved and unique results can be harvested.

### 2.3. COMPLEX PLASMAS

The name complex plasmas refers to partially-ionised colloidal or dust plasmas. This field of research received a tremendous boost in 1994, when the condensed plasma states – crystalline and liquid – were discovered experimentally. Firstly, a classical plasma is produced. Subsequently, colloidal or dust microspheres are injected into the plasma chamber. Due to the larger electron mobility, the microspheres can charge negatively, acquiring several thousand electronic charges. The plasma is then said to be in the *strongly-coupled* regime. That is, the electrical forces experienced by the particles are substantially stronger than the thermal

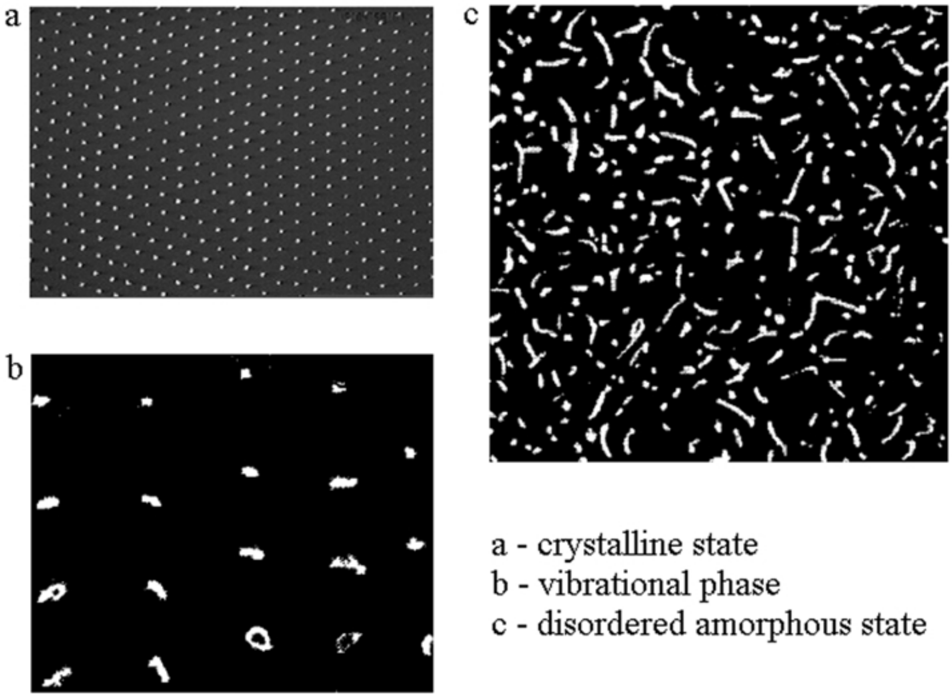


*Figure 3.* Complex plasmas – various images of a plasma crystal, using a charged coupled device (CCD) camera. (Courtesy: Morfill et al., Max-Planck-Institute für Extraterrestrische Physik, Garching, Germany.)

force. In Figure 3, under certain conditions, the microspheres can achieve ordered arrangements.

The advantages of these types of plasma are fourfold: (1) The microspheres can be visualised individually, using scattered laser light and videography; (2) the complex plasma response-time is reduced due to the larger mass of the microspheres, allowing studies to be made with normal camera time resolution; (3) the microspheres can be easily controlled and manipulated permitting the performance of active experiments; (4) a multiple combination of gases, microspheres, plasma discharge techniques, and manipulation strategies can be studied, making possible the investigation of a large number of fundamental processes over a broad parameter range.

The microgravity relevance of this research is simply stated: On Earth the microspheres precipitate out of the plasma chamber. Complex electric field arrangements are therefore necessary to suspend them. However, this gravity cancellation tool works only for a layer of particles, leading to two-dimensional systems. Under microgravity, no such restrictions apply and true three-dimensional structures can be created and studied.

The objective is therefore to acquire a sound scientific understanding of the physics of strongly-coupled plasmas. This includes investigating the temporal and spatial evolution during self-ordering under different conditions, conducting microscopic examinations of plasma phase transitions (solid-liquid-gaseous) and characterising waves in strongly coupled plasmas.

Other areas of scientific interest include the physical properties of plasma fluids, the study of various amorphous and crystalline structures, the study of lattice defects and homogenisation, as well as investigations into doped systems.

### 2.4. GRANULAR MATERIALS

This subject deals with the study of the effect of periodic accelerations on granular matter. Granular media can exhibit a wide range of behaviours, from solid-like to gas-like passing through a liquid-like state. This behaviour depends on the *dynamic coupling* of the particles with their surrounding media (typically a gas) and on the strength of the mechanical excitation.

One of the most interesting aspects of granular media is the dissipative nature of their particle-particle interactions. In order to study their steady-state properties, it is necessary to bring a steady amount of kinetic energy into the gas to balance the dissipative losses. Mechanical vibrations can be used to keep the temperature of such a macroscopic gas constant. However, on Earth these dissipative gases are perturbed by gravity.

The scientific goal is to construct a *phase diagram* for granular gases under vibration and to characterise the physics governing the dynamic coupling between the granular matter and the surrounding gas. The following are important questions: in the absence of gravity, do accelerations enhance, damp, or organise inhomogeneities? What is the influence of the size and nature of the inhomogeneities (interfaces, gradients, etc.) on the system's response to vibrations? What is the interaction between vibrations and the two competing mechanisms: surface energy for separation, and diffusion for homogenisation? It is known that in microgravity, vibrations can induce ordering in a fluid, acting like an artificial gravity. Further studies are required to understand this and other effects.

These investigations will have direct applications on the control of heterogeneous media by imposed mechanical vibrations (e.g., petroleum, two-phase rocket fuel, growth media in biotechnology, solidifying alloys), both in space and on the ground. It is anticipated that the beneficiaries of this research will be those industries dealing with the transport of granular media and segregation of binary mixtures (e.g., pharmaceuticals, cements and high-Tc superconductive composite materials). Additional applications will be more forthcoming once the mechanisms for controlling segregation are understood.

### 2.5. COSMIC AND ATMOSPHERIC DUSTS

The objective is to characterise the physics that drives the interactions between cosmic or atmospheric particles and their environment, namely dust-dust, dust-gas and dust-light interactions. This research has implications for the formation of planetary systems and regoliths in low-gravity solar system bodies (e.g., comets and asteroids), not to mention aerosol and atmospheric physics.

Current solar nebula theories predict that, during the formation of our planetary system, the velocity of collisions among growing dust aggregates increased with increasing pre-planetary dust aggregate size. Hence, the collision rates between pre-planetary dust grains grew very rapidly with time. Computer simulations suggest that somewhere within this process, a transition in grain morphology, from fractal to non-fractal, took place. Although recent experiments performed in drop-towers have started to collect data on the collision results of aggregate-aggregate interactions, many problems remain unsolved.

Furthermore, theory also predicts the existence of a fast aggregation stage, following the slow, Brownian motion induced particle growth. This fast aggregation process is usually referred to as *runaway growth*, which means that single, large dust aggregates grow much faster than their slightly smaller neighbours. Runaway growth leads to a bimodal size distribution that cannot be handled in levitation experiments on Earth, where gravity-induced compaction leads to unrealistically dense aggregates.

The surfaces of small solar system objects are referred to as regoliths. Regoliths consist of layers of loosely connected fragmentary debris of meteoritic, volcanic or sputtered origin. Regolith formation and growth depends upon gravity and the mechanical properties of its constituent particles. Gravitational effects play an important role in the shaping processes of large bodies, whereas material characteristics are more important for smaller objects.

The dominant mechanism for regolith formation in the solar system is hyper-velocity micrometeoroid bombardment. These impacts generate a spray of ejecta travelling at much lower velocities, which then deposit a fine layer of regolith. The mass and velocity of ejecta deriving from lower velocity impacts, such as those that can occur in planetary ring systems, protoplanetary discs and secondary impacts on satellite and asteroid surfaces, are unknown. Therefore, a controlled study of collision experiments in microgravity between regolith layers and solid particles becomes necessary.

Another important subject is the analysis of dust storms on Mars, where the unusual electrical environment complicates the understanding of Martian dust interaction physics. Microgravity research into atmospheric dusts would be a first step to understanding the complex situation on Mars.

## 2.6. CRITICAL AND SUPERCRITICAL FLUIDS

Fluids are said to be critical when their temperature and pressure are close to their gas-liquid critical point values. To give two examples, the critical point of carbon dioxide ($CO_2$) occurs at 31 °C and 72 bar and that of water ($H_2O$) is observed at 375 °C and 225 bar. The main reason motivating the scientific interest of critical point physics is that, in its vicinity, a large number of fundamental physical parameters (e.g., isothermal compressibility, density and surface tension) obey universal power laws (valid for all fluids) and can be easily controlled by means of small temperature variations.

Above the critical point temperature and pressure, fluids are said to be *supercritical*. In this regime, they exhibit a number of specific properties, such as large density, low viscosity and large diffusivity, which cause them to behave as intermediates between a liquid and a gas. In addition, their isothermal compressibility can become very large, much larger than that of ideal gases, especially near the critical point. These characteristics lead to very unique properties. Hence, fluids in the supercritical state are increasingly capturing interest. However, their behaviour is not fully understood and fundamental questions concerning fluid dynamics, heat transfer, interfacial phenomena and chemical processes have yet to be answered.

As mentioned before, fluids in the critical and supercritical states are highly compressible which means that on Earth their own weight affects them and prevents measurements on bulk homogeneous samples. Gravity induces transport anomalies, with disruptive turbulent phenomena taking place even under minute temperature gradients. Experiments in reduced gravity offer a unique opportunity to establish a vigorous programme to address the fundamental and application-oriented issues associated with critical fluid physics.

## 2.7. GEOPHYSICAL FLOWS

Understanding thermal convection in a fluid contained between two concentric spherical shells, rotating under the influence of a central force field is important for addressing a variety of problems in fluid dynamics, geophysics, and astrophysics.

The large-scale motions in planetary atmospheres and in the convection zones of rotating stars are strongly dependent on rotation (through the Coriolis force) and gravity (through buoyancy forces). Fluid flow experiments performed under microgravity conditions with this kind of spherical geometry would aid our understanding of a number of different astrophysical phenomena. Such phenomena include the zonal bands of Jupiter; the origin of the extremely high winds in the tropics and subtropics of Jupiter, Saturn, and Neptune; the persistent differential rotation of the Sun; the convection patterns in the Earth's mantle and the rapidly rotating flows at the Earth's core.

On a more practical level, microgravity research into flows in a spherical geometry will provide useful information for the development of gyroscopes, bearings, ion-drag and centrifugal pumps.

### 2.8. COMBUSTION MECHANISMS AND FUELS

The combustion of fuels is the main process to transfer chemical energy into heat, or to make it technically usable for mechanical motion. During this transfer process, however, part of the chemical energy is not exploited and exhausts, often toxic, are produced.

The optimisation of these processes towards maximising the energy transfer and minimising the exhaust production is a current strategic objective to which Europe has made a very strong commitment. Achieving this objective requires a thorough understanding of all details regarding fuel-composition effects. Oxidiser-fuel premixing and evaporation mechanisms, auto-ignition and flammability limits, fuel and oxidiser cloud combustion, exhaust and soot production, as well as effects of pressure and fuel pre-ignition temperature boundary conditions are topics which need careful investigation.

Dedicated experiments on fuel droplet formation in a specific gas atmosphere, determination of critical temperatures for fuel droplet evaporation, auto-ignition and combustion are carried out in ground-based laboratories to gain insight into these underlying mechanisms. However, gravity strongly affects these different processes, particularly when steep temperature and concentration gradients are involved. On the other hand, experiments under reduced gravity enable the scientists to scale up experiments and apply advanced diagnostic techniques which yield unique data, complementing those obtained in terrestrial laboratories (such as the result shown in Figure 4 for an ethane-air jet-diffusion flame at 1g).

Examples of measurements that are strongly affected by gravity-driven convection and sedimentation include flammability limit measurements, the influence of the motion of fuel droplets relative to their surrounding gas mixture, their distribution in a specific volume, their interference with neighbouring droplets and of course turbulence.

Since combustion processes occur in rather short time scales, short duration microgravity platforms will be employed to a large extent. However, the scanning of parameter maps required to provide detailed insights into complex mechanisms can only be adequately performed over long duration flights, that is to say aboard the ISS.

### 2.9. COLD ATOM PHYSICS

Research in the field of cold atoms physics and the development of systems utilising cold atoms, such as for metrology and high sensitivity sensors, has developed tremendously over the last decade. There is a general consensus within the European scientific community that space provides the most favourable environment for this field of research. This applies not only to the physical study of cold atoms (e.g., Bose–Einstein condensates), but also to the implementation of cold atom-based systems to carry out metrology, relativity and gravitational measurements.

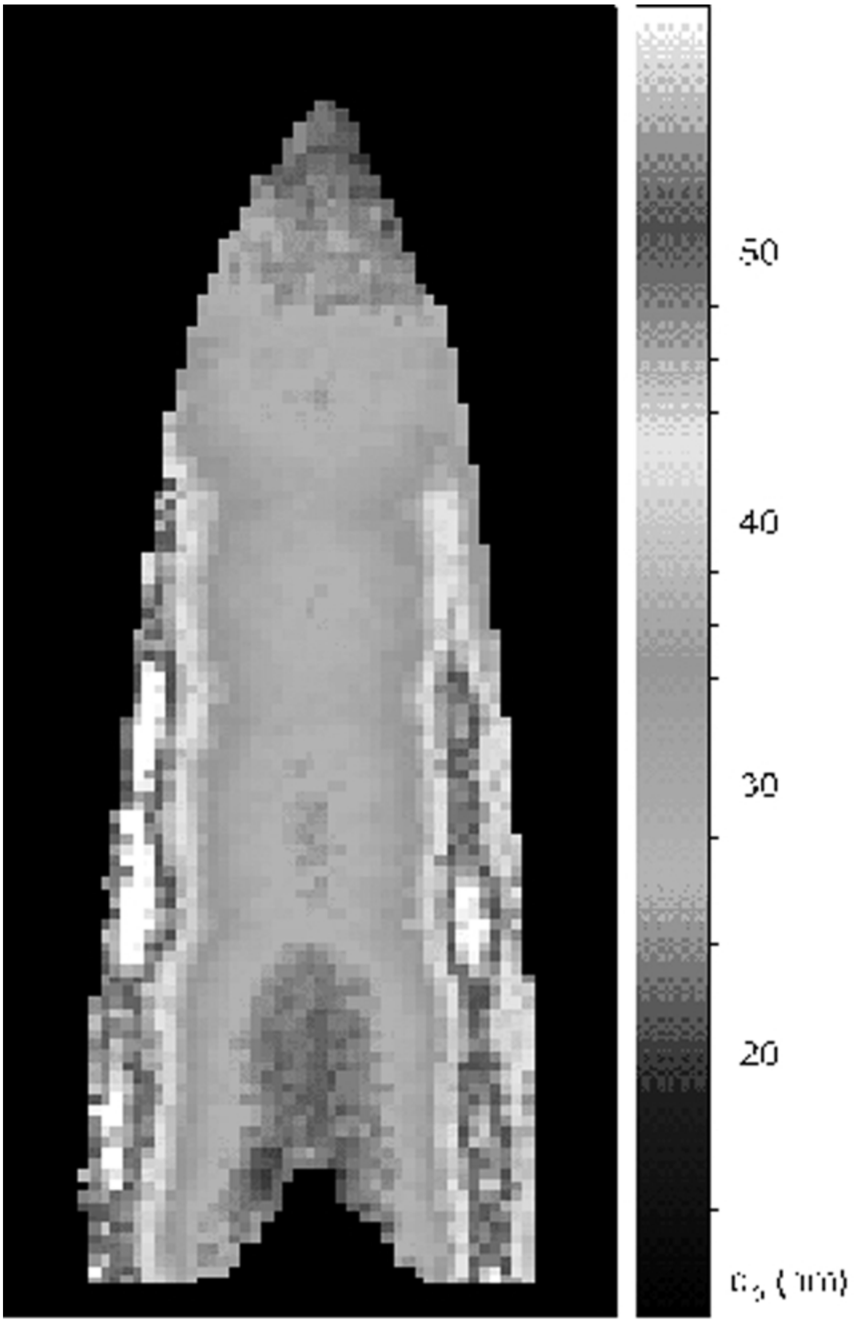


*Figure 4.* Combustion mechanisms and fuels – size distribution and location of primary soot particles formed in an ethane-air jet-diffusion flame at 1g. (Courtesy: Will et al., University of Erlangen, Germany.)

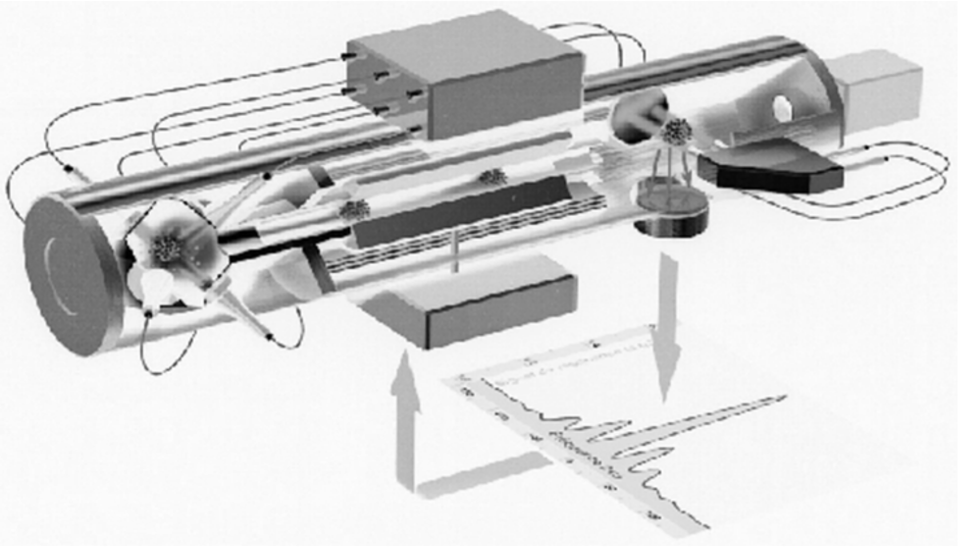


*Figure 5.* Cold atom physics – schematic diagram of the PHARAO cold atom clock in microgravity showing the resonance signal of the cold caesium atoms.

Gravity is one of the main limitations to the operation of cold atom clocks on Earth, in that it perturbs atom trajectories and limits interaction time – the time available to carry out a useful frequency measurement. The maximal interaction time reached in a ground-based cold atom fountain is currently less than one second. Operating a cold atom clock in a microgravity environment, on the other hand, enables interaction times much longer than one second (quoted values being of the order of 10 seconds). Figure 5 shows a schematic diagram of the PHARAO cold atom clock that will be located onboard the International Space Station. Both the stability and the accuracy of such a clock are expected to be greatly enhanced. Investigating the influence of collisions between cold atoms also enables one to predict the ultimate accuracy of these clocks.

The transfer of the clock signal to the ground by means of highly stable and accurate links is a prerequisite for global time synchronisation which is the basis of advanced global positioning and navigation systems. Moreover, the combination of two high performance links enables high-resolution measurements of wave propagation through the high atmosphere in support of theoretical and analytical models.

The availability of an ultra-stable time and frequency reference in orbit also enables the verification of relativity theories at an unequalled level of accuracy. There are fundamental reasons to search for new interactions, new particles and violations of the equivalence principle. Our present understanding of physics is based on two separate theories, Quantum Field Theory and the theory of General Relativity. While the standard model is able to unify three of the four fundamental interactions (electromagnetic, weak interactions and strong interactions), no theory so far has managed to reconcile quantum mechanics, general relativity, and gravity. Cold-atom clocks in orbit, with their accurate measurements of the red shift and the detection of the drift of the fine structure constant, could bring the two theories closer together.

An improved measurement of the red shift can be performed by comparing ultra-stable clocks onboard the space station and on the ground by means of ultra-precise links. A number of auxiliary measurements such as a high-precision test of the Sagnac effect and the search for a possible anisotropy of the one-way speed of light (the theory of special relativity) can be performed with significantly improved precision.

At present, there is a search for a possible drift of the fine structure constant $\alpha$. The fine structure constant characterises the strength of the electromagnetic interaction. The principle of the experiment is to compare the rate of atomic clocks (using different elements) as a function of time. Cold-atom clocks will enable frequency comparisons between a large number of different clocks world-wide at the $10^{-16}$ level per year. An improvement of two orders of magnitude over present laboratory capability is expected.

The possibility of establishing a communication link between ultra-stable clocks of different types developed by ISS partners additionally offers the opportunity of cross-referencing between clocks and performing other relativity tests at unprecedented levels of accuracy. These include tests of the Local Position Invariance, Kennedy–Thorndyke experiments to test the isotropy of the Lorentz transformation and Michelson–Morley experiments. The accuracy of these measurements will be improved by factors of $10^2$ to $10^5$.

In addition, investigations carried out on the International Space Station will be precursors to experiments using sensors, based on atomic wave interferometry. These missions are primarily aimed at determining the fine-structure constant, in order to test quantum electrodynamics theories and map the spatial structure of the general relativistic gravito-magnetic effect of the Earth. In conclusion, it can be seen that the unparalleled precision derived from microgravity experiments on cold atoms has some very profound implications for the measurement of time and other physical effects.

## 3. Innovating Technologies and Processes

### 3.1. MICROSTRUCTURE FORMATION IN METALS AND ALLOYS

The properties of metallic materials such as tensile strength, creep strength, fatigue life, ductility, wear resistance and corrosion resistance are determined by the structure, chemical composition and defects, at all length scales, resulting from the liquid-solid phase transformation. For high precision castings, the control of the material structure during the whole process is crucial for quality control, and for the design of advanced materials for specific technological applications.

Fluid flow driven by gravity (i.e., thermal and solutal convection) occurs in melts, at the macroscopic scale of a cast product as well as at the microscopic scale of grains, and can significantly affect the homogeneity across the casting. These inhomogeneities are of primary concern to producers dealing with multiphase, multicomponent alloys.

Therefore, the demand for advanced numerical models of casting processes, incorporating both solidification and fluid flow, has greatly increased in recent years. The aim for the foreseeable future is to couple the macroscopic and microscopic length scales in an attempt to predict grain structure evolution at the mesoscopic scale. Figure 6 shows the considerable advances being made in solidification modelling over a number of different length scales. This capability will enable further optimisation of casting, welding and advanced solidification processes, while also spurring the progress of new processes.

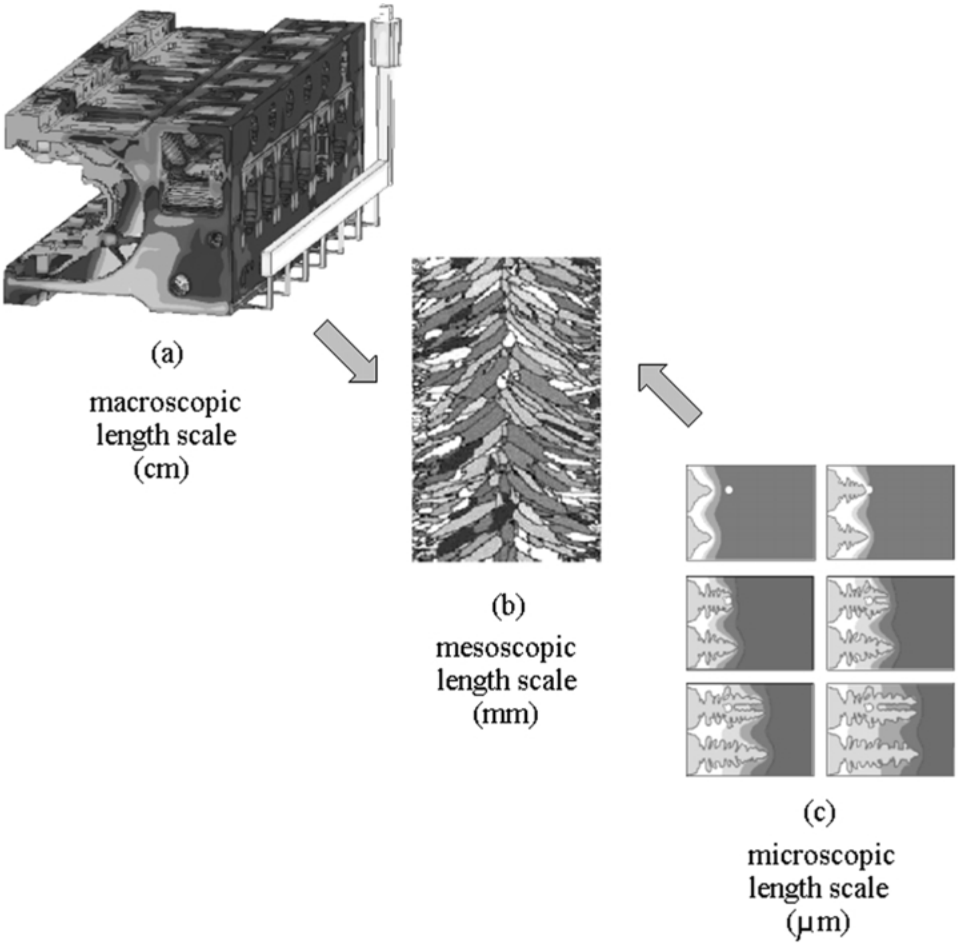
Benchmark solidification experiments performed onboard the ISS will answer many open questions relating to microstructural evolution under purely diffusive and controlled convective transport conditions. This information will be used to improve fundamental understanding of solidification; for example, the columnar-to-equiaxed transition, the influence of fluid flow on dendritic growth, micro- and macrosegregation, as well as to validate existing mathematical models of solidification, such as the phase-field and cellular automaton models.

### 3.2. DEFECT FORMATION IN CRYSTAL GROWTH

Research in the area of crystal growth is concerned with the understanding of defect formation, often driven by gravity-induced effects, that limits the perfection of crystals on the ground.

Past experiments have provided a reasonable understanding of the influence of convection, especially Marangoni convection, in crystal growth processes. This has already contributed to the development of means to improve commercial crystal growth processes, in terms of quantity (i.e., higher percentage of usable material) and quality (i.e., better intrinsic properties of the material).

The remaining problems, which experimentation in space can greatly help to tackle, are to understand the mechanisms leading to detached growth of semiconductor crystals and the influence of convection on defect formation. The crucible de-wetting phenomenon and, specifically, its impact on crystal perfection and twin formation has been previously observed in microgravity experiments. Gaining a detailed understanding of this phenomenon and its effect on the crystal quality through carefully targeted experiments in space can enable one to conceive means of improving ground processes.



(a)
macroscopic
length scale
(cm)

(b)
mesoscopic
length scale
(mm)

(c)
microscopic
length scale
(μm)

*Figure 6.* Simulation results from macroscopic, mesoscopic and microscopic models of solidification, covering a range of length scales from centimetres to microns. (Courtesy: (a) Magmasoft® software, Aachen, Germany – (b) Gandin et al., Ecole des Mines de Nancy, France – (c) Jarvis et al., University of Swansea, Wales, UK.)

Recent microgravity experiments, based on the floating-zone technique to grow gallium-antimonide (GaSb) crystals (shown in Figure 7), have demonstrated the validity of this approach with commercially important crystals.

As stated before, convection in the fluid phase can have a marked influence on the formation of defects and inhomogeneities in crystals grown from the melt, from solution or from the vapour phase. However, the subtle mechanisms, which lead to the formation of these defects, are not yet fully understood. Well-defined and carefully controlled microgravity experiments, supported by advanced numerical models, can provide answers to current questions, relevant to industrial crystal growth.

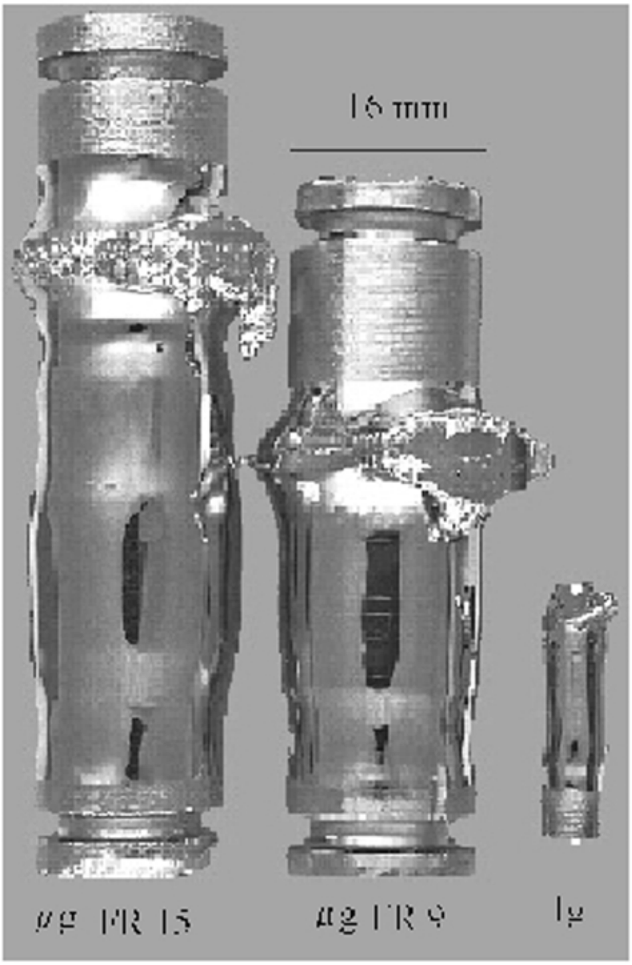


*Figure 7.* Crystal growth – two gallium-antinomide (GaSb) crystals grown during the SpaceHab-4 mission in 1996, compared with a 1g sample.

### 3.3. METALLIC FOAMS

The utilisation of lighter structures is a permanent challenge to the car and aircraft industry. Lighter vehicles require less engine power and thus consume less fuel. Nevertheless, the structures must have predictable properties in terms of stiffness, elasticity and durability. One promising avenue lies with metallic foams.

Experiments on metallic foams on the ground are complicated by the fact that liquid drainage above the metal's melting point is very fast. Gravity acts on the liquid films, separating the individual bubbles, and this can limit the investigation of bubble formation mechanisms and bubble distribution.

Under microgravity conditions, however, drainage occurs by capillary effects only and the influence of magnetic or electric fields on the porosity of the sample can be studied with greater success. Benchmark samples will provide reference data for the validation of numerical models of metallic foam formation. These data will also support the development of foaming methods applicable to industrial processes, not only in the realm of metal processing, but also in the field of liquid emulsions and oil recovery.

### 3.4. THERMOPHYSICAL PROPERTIES MEASUREMENTS

With the rapid development of computer power and the increased sophistication of numerical models, the availability of precise thermophysical data to improve the reliability of the modelling of industrially relevant solidification processes is becoming a crucial issue. The standard ground-based techniques cannot be confidently applied to reactive melts at high temperatures, due to contamination from and reactions with the crucibles. At present, accurate thermophysical data for commercial alloys, in particular nickel-, iron-, titanium-, copper- and aluminium-based alloys, is either non-existent or subject to intolerable experimental scatter. For instance, the reported viscosity measurements for pure iron (the basis of all steel production), shown in Figure 8, differ by as much as 50%.

New methods, such as electromagnetic levitation, are now available which permit containerless measurements to be made. However, it has been demonstrated that the intended accuracy can only be achieved by performing measurements in the microgravity environment of space, under ultra-high vacuum conditions. The following properties can then be measured: Melting range, fraction solid evolution, heat capacity and enthalpy, density, surface tension, thermal conductivity and diffusivity, viscosity, total hemispherical emissivity, electrical (and thermal) conductivity as a function of temperature in the stable and metastable (undercooled) liquid state. This wealth of thermophysical data can subsequently be used to improve numerical simulations of casting and solidification processes, for industrially relevant alloys.

### 3.5. MAGNETIC FLUIDS

Ferrofluids, also called magnetic fluids, are liquids that contain nano-sized magnetic particles. In addition to the classical behaviour of liquids, ferrofluids exhibit density gradients and motions under the effect of magnetic fields. This opens the possibility of manipulating them without direct contact with the fluid. The design of ferrofluids with properties adapted to specific customer demand will greatly benefit from measurements in microgravity under the sole effect of magnetic forces. This new class of fluids has many potential applications in the automotive and aerospace industries as well as in medicine.

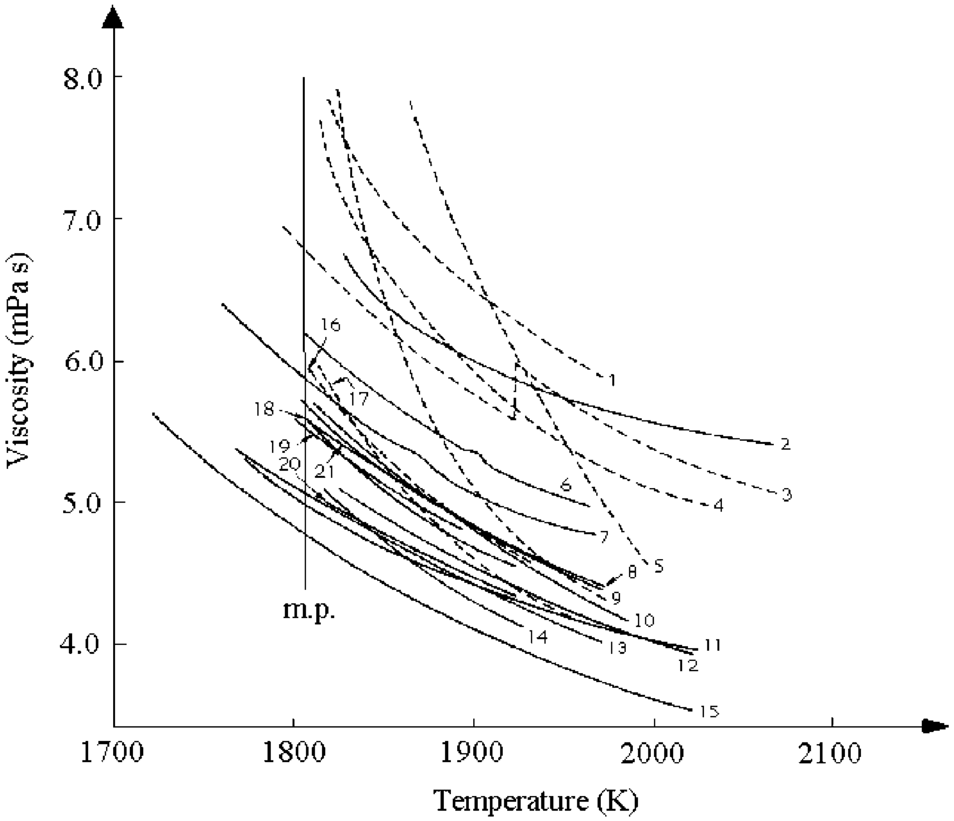


*Figure 8.* Thermophysical properties – measured viscosity data for pure iron as a function of temperature. (Courtesy: Tanaka et al.; Z. Metallkunde, 1996, Vol. 87, p. 380.)

### 3.6. INTERFACES, NON-METALLIC FOAMS, AND EMULSIONS

The transport of matter across a fluid interface is a complicated process that can involve diffusion due to concentration gradients, diffusion due to temperature gradients, surface motions due to surface tension gradients, and sedimentation and buoyancy due to gravitational forces. Furthermore, the fluid's continuous attempt to reach a state of thermodynamic equilibrium often results in a moving interface. All these effects usually take place at the same time. Therefore, such complex systems can seldom be investigated in great detail on the ground. Space experiments, on the other hand, allow to eliminate all gravity-dependent phenomena, facilitating the understanding of the remaining mechanisms. This knowledge is needed for the construction of accurate models to predict and optimise the behaviour of a variety of important industrial processes on Earth.

Gravitational forces also affect the stability of foams. In a foam column, the liquid in the films separating the bubbles is constantly drained by the gravitational force. The drying out of the column, starting at its upper part, leads to the progressive disruption of these films. Gravity acts on each individual film, causing its extension, accompanied with thinning on the upper side, and thickening and compression of the lower side. This drives also variations in the concentration of surfactant and thereby, changes of the surface properties of the films. The modelling of liquid drainage in foams, and of foam film rupture, requires accurate measurements of surfactant effects, coarsening, and the respective influence of capillary forces and gravity on the liquid distribution between the bubbles.

On Earth, some of these influences, particularly that of capillary forces, is swamped by gravity-driven processes. Space experiments will lead to an improvement in our understanding of foams and their properties. This knowledge will be fundamental for enhancing the efficiency of various foam applications, such as waste water refurbishment, oil recovery and crude oil post processing.

### 3.7. HEAT TRANSFER IN FLUIDS

Fluids are at the core of thermal control and life support systems in spacecraft. Capillary pumped fluid loops are used to transport the thermal energy generated by spacecraft sub-systems, such as electronic equipment, to radiators where this energy is dissipated by radiation to space. Thermal energy is absorbed by evaporating a liquid collected in grooves. Capillary forces act as a pump, sucking liquid from the condenser area, to feed the grooves with fresh liquid so that the system functions as a closed loop, without the need of any mechanical action. The liquid's wetting property drives the formation, at the groove walls, of a meniscus - where the evaporation is most effective. Steep temperature gradients at the meniscus yield gradients of surface tension, which in turn drive microconvection in the bulk of the meniscus, greatly contributing to the process. If the evaporation is too intense, it will lead to the occurrence of hot spots that will damage the evaporator. Therefore, the design of the groove is an important factor in the maximisation of the heat transfer capability of the system. The knowledge-based optimisation of this sensitive process, and the design of high-performance and reliable heat pipe systems, requires a detailed understanding of these intricate mechanisms, which can be individually investigated in the absence of gravity.

Also important for these systems, it is known that the presence of an electric field can greatly enhance heat transfer in single-phase convection processes, and during boiling. This effect is due to additional body forces arising in the fluid(s) due to the electric field's presence. However, the mechanisms leading to this enhancement are still not well understood, to a large extent due to the masking influence of gravity on ground experiments. Elucidating what basic physical mechanisms are responsible for the action of electric fields during boiling will result in direct technological applications for thermal control systems in spacecraft.

Furthermore, the handling of fluids in space, where the gas and liquid phases do not separate as they would under the effect of buoyancy on the ground, poses additional technological problems. The ability to predict and manage flows of two-phase fluids in pipes calls for detailed experimental investigations, which are coupled to studies on heat exchange systems.

## 4. Conclusion

Many of the physical phenomena observed in nature are heavily dependent on gravitational forces. Therefore, performing experimental investigations under strongly reduced gravity conditions, that is to say the microgravity conditions expected on the International Space Station, will enable scientists to quantify, understand and eventually predict, through the use of knowledge-based numerical models, the individual contributions of different physical mechanisms.

In recent years, the European scientific community, with the support of leading industrial companies within Europe, has recognised the enormous potential of microgravity research as a means of gaining a better understanding of the physical world, while at the same time improving industrial processes. The vast wealth and diversity of ESA microgravity research projects in the field of physical sciences, described in this paper, is testimony to this fact. They involve close to 600 European researchers who have joined expertise to identify key problems and adequately tackle them with the help of space experiments. Numerous industries have supported the first phases of many of these projects, and these industrial partners will clearly become more active and more demanding as the first experimental results become available. Many of the aforementioned projects are already underway, and will continue to accelerate with the availability of the International Space Station.

## References

Interested readers are invited to consult: “A World Without Gravity – Research in Space for Health and Industrial Processes” by G. Seibert et al., ESA SP-1251, June 2001.

## Discussion

**A member of the audience:** Has anyone done a cost-benefit analysis as to whether these experiments are actually worth the cost of doing them in space?

**Dr. Minster:** We haven’t done that, but I know that in Germany there has been a very thorough review of the space station utilisation programme organised by the Ministry of Research, and that the organisers of this review were not horrified by the figures they came up with. Actually, I don’t think it is a very relevant issue insofar as there is not only the cost/benefit per scientific article to consider, but also all the technology development behind it which will have an enormous impact.

Studies have shown that there is a significant return on investment from space activities (there is a chapter on this in the book referenced above). I think the question here is not to justify the space station, which already exists, but how we can utilise that investment in the best possible manner.