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A WORLD WITHOUT GRAVITY

– Research in Space for Health and Industrial Processes –

by
Günther Seibert et al.

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Preface

The principal task of the European Space Agency is to develop and to operate spaceflight systems for research and applications and, in doing so, to promote European and international co-operation. One of the Agency's major programmes is the European participation in the building and operation of the International Space Station (ISS). The ISS is the largest science and technology venture ever undertaken in space. Its assembly started in late-1998 and will last until early 2005, at which point the routine utilisation and exploitation phase will begin. However, access will be available to some research facilities on the ISS from 2002 onwards.

A major motivation for Europe to participate in the development and utilisation of the ISS is that this unique laboratory in space opens up a new era of research in the field of life and physical sciences and applications in space. For the first time, European scientists and industry will have routine and long-term access to a wide range of sophisticated experiment equipment and facilities in space, with laboratory-like working conditions. Experimenters who utilise the weightless conditions of space – the so-called 'microgravity environment' – will find outstanding opportunities to expand their research, to the eventual benefit of both industry and human health and welfare.

Microgravity research has been undertaken in Europe for more than 20 years, through both ESA and national programmes. Today, the life- and physical-sciences communities are mature, well-established and organised at the highest scientific level, as recently confirmed by the European Science Foundation. These user communities are of vital importance for ISS utilisation. The continuous research opportunities offered by the ISS provide excellent prospects for the futures of these research fields, which are closely related to industrial needs and health-care requirements on Earth.

Research in space life and physical sciences has benefited strongly in past years from active international co-operation. The new era that lies ahead will allow us to enhance this cooperation on a global scale, which will certainly further improve the quality of the scientific and technological undertakings.

The ESA-developed Spacelab, flown successfully many times over a 15-year period on the Space Shuttle for missions lasting typically 10 days, was until 1998 the 'workhorse' for microgravity research. Today, the advent of permanent access to the ISS's laboratories and external platforms is providing a strong incentive to expand the scientific research activities. At the same time, there is an initiative also to involve European industry much more and to encourage a move from fundamental research to application projects.

One person who has been actively involved in the definition, approval and execution of microgravity research at the European level, from the very beginning in 1982 until his recent retirement from ESA, is Günther Seibert. He therefore has unique experience in this field and a detailed knowledge of the research areas, as well as excellent contacts with the microgravity research community, European space industry, the national space agencies and our international partners.

When Günther Seibert retired as Head of the Microgravity and Space Station Utilisation Department, I thought it a good idea to ask him to take the opportunity of his retirement to work on a book that would exploit his in-depth knowledge and experience of his field to provide an overview of European microgravity research, and the various national and international programmes. It would provide a unique opportunity to document the history of European microgravity activities, and to report on past achievements and on the current status of this field both for basic research and for industrial R&D.

The publication of this book comes at a time that marks the transition between the pioneering days of experiments on Spacelab, and the Space Station era of permanent access to research laboratories in space. It comes too at a time of decision, when the future level of European activities on the ISS will be defined by the next European Space Conference at Ministerial Level. In that context, it is hoped that the wide perspective of this book and its non-specialist approach will be valuable to those who are charged with preparing for those important decisions.

J. Feustel-Büechl
Director of Manned Spaceflight and Microgravity
European Space Agency

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Foreword

When in early 2000 Mr Feustel-Büechl, ESA's Director of Manned Spaceflight and Microgravity, proposed that I should compile a book on the activities and results of past microgravity research, hardware development and programmatic aspects and provide an outlook on the future International Space Station (ISS) utilisation era, I was initially hesitant and agreed only after further reflection. My initial hesitation was caused by the fact that space research in the life and physical sciences is a multidisciplinary activity that has resulted in many incremental new findings, extensions to our knowledge and considerable technological progress, rather than in just a few spectacular breakthroughs. I therefore concluded that it would only be possible to paint a true picture of the scientific, technological and biomedical progress achieved so far by soliciting contributions and assistance from the large number of scientists involved, many of whom are distinguished experts in their respective fields. It was also obvious to me, having been involved from the humble beginnings of European life- and physical-sciences research activities on manned and unmanned space missions, that the task in prospect was huge, involving as it did the compilation of a large amount of data on experiment facilities and spacecraft, programmatic details and historical events.

In contrast to the fields of space astronomy, planetary exploration or remote observation of Earth, where the discoveries can often be shown in the form of exciting photographs, scientists working in the microgravity-research disciplines have no easy visual means of justifying the costs of their labours. The readers of this book will therefore hopefully be somewhat patient as we try to stimulate their interest in and excitement about this still rather new area of research. To facilitate this process, we have provided an extensive Introduction (Chapter 1) to try to explain in simple terms why this kind of research is of increasing interest, and how many questions with far-reaching implications for mankind can be answered in laboratories in space.

The nine life-sciences and ten physical-sciences sections of Chapter 2, entitled 'Aspects of Current Microgravity Research', have been written by more than 30 European scientists (see List of Contributors). They were asked to outline the past achievements, current status, and the future importance of space in the research field that they represent, with special emphasis on recommendations for future work in that discipline. These contributions were also reviewed for completeness by other scientists working in the field.

Chapter 3 addresses the important topic of the transition 'From Basic Research to Commercial Applications'. It includes the impact of information and technology transfer (3.1) and an extended section (3.2) on the spin-offs from microgravity research that are already on the commercial market, and on expected future developments in this field of technology transfer. Many of the technical and economic data provided on these spin-offs are based on interviews conducted during visits to some 25 companies and research institutes involved in hardware development for life- and physical-sciences research in space. The commercial sales value of these spin-offs in 2001 is estimated to be 50–60 million Euros, and for 2002 this figure climbs to 90–100 million Euros. Since industrial research in space by non-space industry has become – in view of the future utilisation and exploitation of the ISS – an issue of major political importance, I asked Dr. H. Sprenger, a long-standing expert in this subject, to contribute a section (3.3) entitled 'European Industry and Microgravity Experimentation'.

Chapter 4 describes the history of research under microgravity conditions from its origins on early American and Soviet space missions, up to the preparations for the utilisation of the ISS. It covers the early European microgravity activities performed within the framework of ESA missions and at national level, and recounts the initial difficulties encountered in setting up and funding a European programme.

Chapter 5 looks at the future of microgravity research. It addresses the differences between conducting research on the ISS and that performed during the Spacelab era (5.1). It also describes all of the major European experiment facilities presently under development for the pressurised laboratories and external platforms of the ISS (5.2). Thereafter, the strategy and basic principles underlying the planned future European life- and physical-sciences research programme are discussed (5.3).

In order to ensure the inclusion of the very latest research plans and programme proposals for future life- and physical-sciences programmes within ESA, I asked Dr. M. Heppener, Head of the ISS Utilisation and Microgravity Promotion Division, to contribute two sections (5.1 and 5.3), entitled 'Microgravity Experimentation in the Space-Station Era' and 'A Future European Life- and Physical-Sciences Research Programme'.

Chapter 6 is presented in the form of an Appendix, because it not only provides details about the programmatic structure of ESA's microgravity activities, but also gives a large amount of scientific and technical information in the form of tables on experiments and facilities flown on Spacelab, Spacehab, Bion/Foton, Mir, short-duration flight opportunities (i.e. mainly sounding rockets) and the European Retrievable Carrier (Eureca). Chapter 6 also lists the Microgravity Applications Projects (MAP) selected by ESA in the form of tables for the life- and physical-sciences and biotechnology fields.

A total of 30 people of different nationalities and with quite different professional backgrounds have contributed to this book, which has been written for the 'educated non-expert'. This means that the use of equations, specialised terminology, and formal scientific referencing has had to be minimised, which was an unusual requirement for most of the scientific contributors.

Taking into account all of these multi-faceted, multi-national inputs and the requirement not to write a scientific textbook, but rather a 'Scientific American style' volume, I soon came to the conclusion that an experienced English-mother-tongue expert with a broad scientific background would be needed to harmonise the presentation of the various contributions. Fortunately, Dr. Brian Fitton, who had already been involved in the scientific editing of several ESA-supported microgravity publications, was prepared to take on this difficult work. He also helped me to write Chapter 1 (Introduction), which addresses the important role that gravity plays for living organisms and the effects of microgravity conditions on basic physical phenomena through the quasi-suppression of buoyancy-driven convection in fluids, of sedimentation, and of hydrostatic pressure gradients, for example. Chapter 1 also summarises the role that the absence of gravity plays in the major microgravity-research disciplines of biology, physiology, fluid and materials sciences, biotechnology and fundamental physics. Furthermore, it addresses the topic of access to microgravity conditions and gives a synopsis of European Manned Spaceflight and Microgravity Research.

Günther Seibert

CHAPTER 1
INTRODUCTION

B. Fitton and G. Seibert

1.1 The Motivation for Research in Microgravity

Gravity has shaped our world, defined the way that we live, and governs the very processes of life itself. It gives rise to the basic phenomena of sedimentation, buoyancy and convection flows and it causes hydrostatic pressure. It influences such things as the movement of blood and the body-fluid distribution, how we breathe, keep cool and how we move. Acting on the body's sensors, it establishes our posture and our orientation. We are creatures of the Earth's gravitational field and the sense of weight that it gives to our body's mass.

What happens then to the human body when the influence of gravity is removed? This was the question that concerned the pioneers of manned spaceflight. Can a human actually withstand the sudden entry into the weightless conditions of orbital flight without suffering a catastrophic body-function failure?

To answer that, attempts were made to create weightless conditions on Earth. However, such attempts are necessarily of limited duration, since the test object has to be placed in a condition of free fall, essentially as if in a freely falling lift, for it to cease to perceive the effects of the Earth's gravity field and become weightless. That can be achieved for only a few seconds in an evacuated drop tower. Slightly longer exposure to weightless conditions can be obtained by flying an airplane over a parabolic trajectory. Towards the top of the parabola, the airplane and contents enter a free-fall regime, lasting about 20 seconds. Similarly, the ballistic flight of a sounding rocket can be used to provide weightless conditions lasting up to some 15 minutes.

But the only way to establish long-term weightless conditions is actually to go into space. There, a freely drifting spacecraft and its crew are in a permanent free-fall environment, since gravitational and inertial forces are counterbalanced and in equilibrium. In the particular case of a spacecraft in a stable orbit around the Earth, the inward pull on it and its contents due to gravity is countered by the outward thrust of the centrifugal force. A body's weight in that spacecraft therefore becomes zero, as that pull of gravity is effectively neutralised.

So with very little guidance gained through the use of short-duration experiments under weightless conditions, the daunting step into spaceflight was taken in those early days – first using test animals, and then finally with some very brave men.

Fortunately those early, albeit brief, manned flights showed that there was no immediate danger to life from weightlessness. However, a large number of important effects were detected which required further study. It became evident that spaceflight influenced many aspects of the functioning of the human body, including the heart and lungs, the stress-bearing bones and muscles, and the nervous system. These effects were seen as a potential risk to astronaut health on long-duration space flights. Consequently, astronaut health and long-term survival were the motivation for some of the earliest research in weightless conditions – or 'microgravity' as it is generally called. Most of that research was therefore centred on human-physiology studies and was concerned with the macroscopic effects on the body. Only later did research extend to exploring the process of change down to the microscopic level. With that extension came a broadening of the research into general biology and exobiology.

A similar evolution occurred in the study of fluid behaviour in microgravity. The first simple experiments on Skylab were largely concerned with demonstrating the changes in behaviour at a macroscopic level, as the influence of gravity was removed. It was only later, with the opportunity to fly more sophisticated experimental equipment, that it became possible to perform more structured experiments to explore in detail the changes in fluid behaviour and to undertake controlled experiments on liquid/solid interfaces, particularly in crystallisation.

In all such experimentation, gravity is regarded as a parameter and a possible variable. Its removal can illuminate the nature and extent of its direct effects, as in many human physiology experiments. Its absence may also reveal the existence of other underlying yet important processes, which are otherwise obscured and impossible to observe. Similarly, the removal of the gravity-associated effects of sedimentation, thermal convection and hydrostatic pressure provides an opportunity to establish unique conditions to probe basic processes.

- *Biology*

The early observation that gravity influences the basic processes of life is hardly surprising, since gravity has been an ever-present influence during the creation of life and in its evolution over the past 3.5 billion years. All life forms are principally composed of liquids and use surfaces to isolate their different constituents, as well as to facilitate and control the myriad reactions that support the processes of life.

Consequently, gravity would be expected to exert an influence through its effects on fluid flow, sedimentation and its modification of the behaviour of thin liquid films. By removing the effects of gravity, it is possible to investigate the changed cell activity and function. Different gravity levels can then be applied, using a centrifuge, to follow the sequence of these changes and elucidate the mechanisms at work.

Experiments of this type have shown that the cellular machinery is sensitive to subtle modifications in its mechanical and biochemical micro-environment as the level of gravity is changed. In plants, the equal partitioning of the genetic material at cell division is disturbed and chromosomal abnormalities are introduced, implying that plant cell proliferation requires positional cues from gravity. Other effects on plant and animal cells include changes to the proliferation rates, energy metabolism, cell membrane composition and function, cell and tissue differentiation, and the rate of cell ageing.

There is currently considerable debate as to the extent to which these observed changes are the result of a direct perception of gravity, through its effect on structures within a cell, or are due to an indirect effect operating through induced changes in the cell's physical and chemical environment. In view of the fundamental importance of these results and the potential insight into cell mechanisms, there is considerable motivation to develop these studies and seek further clarification of the mechanisms at work.

The direct perception of gravity undoubtedly takes place at the cellular level in those specialised cells and unicellular organisms that use gravity for orientation and movement. For example, gravity-sensitive cells in higher plants are continuously stimulated and control the direction of growth via gravity-dependent mechanisms such as the sedimentation of high-density particles within the cell. The cells at the end of root tips appear to sense the gravity vector by this means and guide the root growth downwards. The value of space experiments in this class of cell lies in exploring the detailed physical and biochemical processes at work in gravi-perception and response.

- *Human Physiology*

As yet it is uncertain whether changes that have been observed in individual human cells when cultured under microgravity conditions, could actually manifest themselves as discernible physiological changes in the whole body. On the other hand, when searching for the origins of the many reactions of the human body to weightless conditions, it is generally necessary to consider processes occurring at the tissue, cellular and molecular level. This is particularly true in the case of the bone mass-loss process, which has been well documented in astronauts and which does not appear to have an end point. It is potentially the most damaging of the physiological changes observed in response to microgravity, with an origin in a changed bone-cell environment and metabolism.

This changed bone-cell environment is initiated following the acute loss of gravitational loading of both bone and muscle in the weightless conditions. There is a rapid onset of mass loss, especially in the load-bearing bones. This is accompanied by an elevation of calcium levels in the blood, which carries a potential risk of damaging effects in terms of kidney stones and calcification of the soft tissue in the longer term. The bone mass loss continues unabated throughout the time in orbit, at a rate of about 1% per month. This currently sets a limit to the time that crews can safely remain in orbit, if they are to avoid serious risk of bone fractures on return to Earth.

The precise mechanisms driving this bone-loss process and those causing the accompanying muscle atrophy are still uncertain. Bone is in a dynamic equilibrium between bone growth and destruction - an equilibrium that can be disturbed by factors such as hormones and vitamins in the blood, as well as by the changed mechanical stressing of the bone.

Weightless conditions may modify all of these factors, but it is likely that the basic process follows from the unloading and reduced stressing of the bones and muscles, which modifies the stretch-activated chemistry at the cellular level. Exercise regimes have had little success in retarding bone mass loss and muscle atrophy. Future research in this area will therefore probably seek a solution by modifying the biochemistry at the cellular level. In so doing, it is quite possible that the knowledge gained may contribute to easing of the problems of bone mass loss in the elderly and in post-menopausal women on Earth.

There are other physiological changes observed in astronauts that also bear some similarities to those that develop as a result of the normal ageing process on Earth, such as the de-conditioning of the cardiovascular system and an apparent depression of the immune system's response to infection. The difference of course is that the changes in space begin to occur rapidly upon entering a weightless condition and they afflict a young healthy person. Consequently, investigations made under these conditions give, to some degree, an accelerated view of certain ageing symptoms in a subject free from other complicating ageing characteristics. Such investigations should assist in furthering the understanding of aspects of the normal ageing process and, in the development of countermeasures for astronauts, may also aid in relieving the symptoms in the aged.

There are other changes in the human body in weightlessness, whose study will likely lead to new insights into fundamental physiological processes and promote a better understanding of the body's functioning at a basic level. For example, the rapid upward displacement of body fluids that occurs when the downward pull of gravity disappears, automatically triggers responses in heart and kidney functions. There is an increase in fluid and electrolyte excretion by the kidneys and an increase in the blood being pumped by the heart, together with a redistribution and reduction of plasma.

Careful investigation of these and related processes in microgravity constitutes a valuable tool with which to extend the understanding of basic body-fluid regulation processes involving the kidneys, the glandular system, and the heart.

The human respiratory system and its functioning also undergo changes in space. There are changes in the chest-wall mechanics, the relative displacement of the rib cage and the abdominal compartments as gravity is reduced. The details of lung ventilation and blood perfusion patterns remain to be further investigated, taking advantage of the lack of gravity to clarify the basic processes. Similarly, the mechanics of breathing and the neuro-physiological adaptation of the respiratory system, as it encounters low gravity and radically changing biomechanical conditions, need to be studied further.

Amongst the profound changes to the human body on encountering weightless conditions, that of disorientation and the often-accompanying nausea in the first few days is particularly debilitating. The cause lies in the disturbance to the acceleration-sensing system of the inner ear, a system that registers the force of gravity and contributes to defining posture and balance on Earth. There are also visual orientation illusions and feelings of self-inversion, which originate in the loss of appropriate signals from the mechanical receptors in the muscles, tendons and joints and from the skin pressure sensors, especially on the feet.

The progressive adaptation of astronauts to this environment indicates that the nervous system can compensate for the loss of gravitation-induced stimuli. It does so by neuronal plasticity, in which the nerve cells react to new conditions by changing cellular dimensions and making new connections or adapting earlier ones. In other words, the phenomenon of neural plasticity amounts to a learning process. The question has been to what extent the peripheral neural system, involving the gravity sensing mechanisms, is included in this learning process, as distinct from the central neural system?

Space experiments have shown that in the inner ear the adaptation to microgravity conditions occurs largely by a progressive increase in the number of communication sites lying between the gravity sensor cells and the nerve fibres ending on them. This observation of rapid adaptation, starting within hours of exposure to a new environment, confirms that these peripheral sensory elements do indeed learn and respond rapidly to the changed environment. Such information has potential value in the treatment of balance disorders on Earth, a problem that afflicts millions of people, as well as having direct relevance in improving the welfare of astronauts.

Much more radical changes in the structure and connections of the nerve cells occur during the early development of the nervous system. As those changes are regulated by mechanical and biochemical factors, it is thought that gravity may play an important role in stimulating the proper development of the nervous system on Earth. For example, animals deprived of the opportunity to walk during the first weeks after birth never fully learn to walk properly. Studying how that development proceeds in animals under weightless conditions will help define the respective roles of genetic determination and environmental experience. Understanding the nature of these critical periods of neural development has important implications for paediatrics. It could also help in the treatment of those suffering from neuromuscular diseases.

- *Fluid and Materials Science*

Although, historically, studies in the life sciences have been a major activity in microgravity research as outlined above, there has also been a considerable programme in fluid- and materials-science studies. This programme is continuing to grow. In Europe, the research has been deliberately focused by the science community upon carefully selected topics that combine significant scientific interest with the potential for improving industrial processes.

The changes in fluid behaviour in space lie at the heart of these studies in materials science. By removing gravity-induced effects, the experimental conditions can be greatly simplified and the fundamental processes in fluids of many types can be more readily explored. With the consequent improvement in predicting and controlling the behaviour of fluids, particularly in regard to heat and mass flow, it becomes feasible to better understand and then to improve a whole range of industrial processes that depend upon fluids. For example, the use of electromagnetic fields for convection flow suppression, stirring and shape control, is an important and well-established method for improving the industrial processing and control of growth from conducting melts on Earth.

This has applications in metal casting and semiconductor crystal growth. The optimisation of process conditions by numerical modelling is presently constrained by the difficulty of simulating the heat and mass transport under turbulent conditions. Experiments using magnetic fields on melts in microgravity, under better defined conditions, will provide a clearer insight into the basic processes and aid in developing more realistic models of the heat and species transport.

Through similar carefully designed experiments, it has also been possible to gain new insight into the physical phenomena occurring at the growth interface in metallic materials and to improve the understanding of the processes by which the different phases in immiscible metallic alloys separate and ripen. That understanding has led to its application in a current production process and future research will extend these applications.

Other research topics include the study of the factors controlling defect generation during growth from the melt of commercially important materials such as cadmium telluride and gallium arsenide. Similarly, the influence of gravity-induced effects in the transport of material during vapour growth of semiconductor crystals and epitaxial layers, used in electronic device production, is being studied and related to the creation of defects that can limit device performance.

Despite its fundamental importance in the basic process of materials production, the understanding of how the growth of crystals and micro-crystals is initiated by nucleation is still rudimentary, especially in the case of multi-component commercial materials. The lack of accurate knowledge of the basic thermo-physical properties, such as density, viscosity, diffusivity, thermal conductivity and specific heat, which is needed to develop theories of nucleation, remains a major difficulty. Accurate thermo-physical data are also vital for numerical modelling of industrial processes in casting and crystal growth. The current figures for the viscosity of molten pure iron and aluminium, for example, are uncertain to within 50% and 100%, respectively. This lack of reliable basic data for commercial materials, as well as those for fundamental research, is largely due to the experimental problems arising from unwanted reactions of the molten materials with container walls.

Containerless methods of holding the molten materials, which use electric, electromagnetic, or acoustic pressure retaining forces, can avoid this problem and are now being used in ground-based studies. Their application in microgravity conditions means that the force needed for containment is greatly reduced, thereby reducing disturbances to the melt and greatly improving the accuracy of the data. Experiments of this type have already provided precision thermo-physical data on highly reactive alloy melts, data that could not be obtained without the use of microgravity conditions.

These containerless facilities also lend themselves to the detailed study of undercooling of molten materials and the production of metastable solids whose physical properties may differ considerably from their stable counterparts. Such materials may be crystalline structures, grain-refined and supersaturated alloys, disordered intermetallics, and quasi-crystalline phases.

All of these can provide innovative materials for engineering applications and the detailed study of the fundamentals of their formation and growth using gravity-free and containerless conditions will be invaluable.

The study of basic fluid-dynamics phenomena is greatly facilitated by the use of microgravity conditions, since without the complications of gravity-driven convection flows it becomes possible to test fundamental theories of three-dimensional laminar, oscillatory and turbulent flow generated by various other forces. The flows and instabilities induced by surface-tension or thermal-radiation forces, together with diffusive instabilities, can each be studied and all have substantial practical as well as theoretical interest.

Supercritical fluids may also be better studied under microgravity conditions. Such fluids are in a pressure and temperature regime that places them in an intermediate position between gases and liquids, where they exhibit high density, low viscosity, very high compressibility and large diffusivity. They are therefore extremely sensitive to hydrostatic pressure, which causes compression and stratification. Convection and buoyancy effects also restrict the study of their fundamental properties and behaviour on Earth. Supercritical fluids are widely used in industry, for example as 'solvents' in food and in waste-management processes, and cryogenic gases, such as oxygen and hydrogen, are often stored as supercritical fluids. Consequently, there is considerable industrial, as well as scientific, interest in the information derived from studies in microgravity of these remarkable fluids.

The absence in microgravity of hydrostatic pressure, which is the result of the collective weight of each horizontal element in a liquid column, simplifies not only the study of supercritical fluids but also of normal fluids. For example, the heat and fluid transport mechanisms involved in boiling can be more readily studied in depth and have yielded some surprising data. Continuing studies have potential value for a whole range of applications in which empiricism has so far prevailed. Interfacial phenomena, phase transitions, and the flow behaviour of liquids in multiphase systems, all of which are basic to many industrial processes, are open to investigation under conditions that simplify their observation and analysis.

Many industrial processes involve the use of foams and emulsions, of adsorbed layers of surface-active components, or manipulate powders. The behaviour of these materials is strongly influenced by gravity effects, which masks some of the underlying, but nonetheless important physical chemistry processes and these can be explored in depth under microgravity conditions.

Liquid foams are formed by gas bubbles coming together to create a liquid-gas cellular structure. They are created during many industrial processes, often as unwanted products needing control, but they are also the precursors of many solid foams, such as polyurethane and the new metal foams. Their formation and many of their properties are controlled by the surface tension that acts at the liquid/gas interface. However, gravity significantly modifies the behaviour of the foam. Under microgravity conditions, it becomes possible to create stable uniform 'wet' foams. These then allow the study of the action and dynamics of the surface-force-controlled processes in the creation and in the draining of bulk foams, providing essential basic information to help predict and understand their behaviour under industrial conditions.

Reversible adsorption plays a fundamental role in many industrial and biological processes. The familiar experience of using detergents as a so-called 'surfactant' in cleaning processes is but one of the many roles now played by this class of materials. Despite their increasing use to control surface properties, the understanding of the dynamics of the processes involved is limited and inadequate to support the technological needs. By performing studies in microgravity, where thermal convection processes and hydrostatic pressure are absent, other mechanisms operating can be studied and quantified.

Dust particles are an inevitable product of industry, and of human activity in general. Much of it is classed as a pollutant. Yet in the form of powders they are also the very basis of many industries, ranging from cement to flour. Hence a detailed understanding of such processes as aggregation is needed to improve the control and processing of these powders and to develop scavenging techniques for their removal from machinery and from air emissions. The study of the behaviour of dust and powders in microgravity will provide basic information to aid ground-based research by providing long-duration experiments with sedimentation processes, allowing studies of aggregation in the absence of convection, of scavenging techniques, and the study of single-grain behaviour in collision processes.

Combustion processes involve chemical reactions with large temperature and concentration gradients that lead to very strong convection-driven flows in gravity and to unstable burning. By contrast, controlled combustion experiments in microgravity offer the possibility to study the large steady flames that can exist in the absence of convection flows. This allows the basic properties of the burning process to be studied, together with the influence of various fuel types and fuel-injection conditions. Droplet and particle burning under high-pressure conditions, such as occurs in many propulsion systems, is another area for which microgravity experiments can provide valuable basic information to support the modelling of industrial systems. Individual droplets can be isolated in space and the temperature distribution and chemical species concentration around the burning droplet analysed in a way that is impossible on Earth.

Almost three-quarters of the emissions of gases that potentially contribute to the 'greenhouse' effect on Earth originate from combustion processes in industry, in power generation and in motor transport. The study of combustion in microgravity can provide valuable information, which complements terrestrial studies and will make a significant contribution to improving the efficiency of those processes and in reducing the pollutant emission.

- *Biotechnology*

Biotechnology is the application and the commercialisation of biology. It is an interdisciplinary field that draws upon the life sciences, the physical sciences, and engineering. It covers the practical application of biosystems at the tissue, cell, and sub-cellular component level, using controlled in-vitro or in-vivo operations in industrial processes and in the management of the environment.

The applications domain is extremely wide. It ranges from the improvement and increased control of environmental bioprocesses, through to the genetic enhancement of agricultural plants and to the understanding of the role of the cellular and tissue micro-environment conditions in artificial bio-organ engineering. In addition, biotechnology covers the development of instruments, e.g. bioreactors, that are necessary for the control of bioprocesses and for the sensing and support of the biological functions of organisms.

The use of the microgravity environment of space for biotechnology research and development is already underway and will likely accelerate in the future, with the availability of routine access to space via the International Space Station (ISS). Its application in relation to current research into tissue engineering centres upon the simplification, increased stability, and improved control of the fluid-based systems involved in the cell micro-environment during cultivation and differentiation.

An example of this is the study of the role of cell density during in-vitro cartilage reconstruction, in the absence of any exogenous supporting structure. On Earth, the maintenance of the necessary cell density without a matrix support is defeated by the sedimentation of the suspended cells in the bioreactor chamber. By studying a matrix-free growth in microgravity, it is possible to avoid the risk of undesirable chemical signalling due to the use of natural scaffolding, or the complications induced by degradation of a synthetic re-absorbable scaffold. Because of the extremely high content and organisation of exopolymeric material in cartilage, this may be the only means for in-vitro production of a functional cartilage analogue.

Of many other current activities, those relating to eventual drug development are of particular interest and involve protein crystal-growth studies. An accurate knowledge of the three-dimensional structure of proteins, of which there about a million different types, is required in order to have a full understanding of the function of each one. As yet, only a small percentage of these protein structures have been determined. A major difficulty has been the lack of large crystals of sufficient crystalline quality to allow accurate X-ray determination of the structure.

It was expected that the absence of sedimentation and convection in microgravity would alleviate some of the problems of getting these large protein molecules to crystallise, and indeed that has been the case. Several key proteins of particular interest to the pharmaceutical industry for drug development have been crystallised and are under study. In the USA, knowledge of the detailed structure of a protein that enables the spread of influenza in the body has led to the design of a drug to inhibit its action, with very promising results in cultures and in animals.

Improved European facilities and the opportunities for protein crystal growth on a continuing basis on the International Space Station will greatly expand the

opportunities for successful research in this area of biotechnology. At the same time, the current basic research by European scientists into the detailed mechanisms that control the growth of protein crystals will be speeded up, so that commercial activities can be placed on a much firmer base.

- *Fundamental Physics*

There is now a growing interest in using the microgravity environment for fundamental physics. Several experiments are being considered, but the European plan to place an atomic-clock assembly in space is of considerable importance in the context of both fundamental and applied physics.

Gravitation is a space–time property according to General Relativity, whose geometry is defined by the matter and the radiation it contains. Hence, a massive body such as the Sun modifies the local space geometry by its presence, leading to the deviation of light as it passes near to the Sun, and to retardation and frequency shifting of the light emitted. Measurement of these effects depends upon the ultra-precise measurement of frequency and time using the cooled atomic clock, currently the world's most accurate timepiece. Its operation depends upon the cooling of caesium atoms to a temperature of about 1 micro Kelvin by a laser system that slows down their thermal velocity. A microwave frequency is then locked into the resonance frequency of the cold caesium atoms. The final accuracy of this system depends upon the time for which a caesium atom can interact with this microwave field. On Earth, the caesium atoms rapidly increase their speed when the lasers are switched off for signal interrogation, due to gravity. This limits the interaction time and hence the final accuracy.

By going to the microgravity conditions in space, it is expected that the interaction time will increase by a factor 10, and that the final time-measurement accuracy will be one to two orders of magnitude better than can be achieved by the best Earth-based clocks. The ACES payload for the Space Station will combine such a clock with reference clocks and microwave and laser links to ground to provide a global time reference of unprecedented accuracy. In addition to its role in basic gravitation experiments, it will also provide the time correlation for receiving stations in very long baseline radio astronomy interferometry. The greatly improved timing accuracy will translate into improved angular resolution of remote stellar objects. It will also lay the foundation for a new level of precision in Global Positioning Systems (GPS) and in navigation, and it will allow geodesy measurements of the Earth down to millimetre precision.

- *Conclusion*

The preceding overview of current research in microgravity highlights not only the diversity and range of subjects, but also the extent to which the results of that research are finding application in many industrial and commercial activities, as well as in human health support. There is certainly no lack of motivation amongst the scientists to develop these research activities further. They look forward to taking full advantage of the major new experiment facilities that will become accessible with the completion of the International Space Station and the greatly increased time for detailed experimentation that this will offer.

1.2 Access to Microgravity Conditions

In order to access weightless conditions for long periods of time, it is necessary to go into space. Only there can the condition of 'free-fall', with the gravitational and inertial forces in balance, be sustained over an extended period. Consequently, microgravity experimentation has made use of a variety of orbiting spacecraft since its inception. Mostly these have been manned and have used the crew as an essential part of the experimentation as operators. The crew have also been used as the test subjects in human-physiology studies. Whilst this latter aspect has been very valuable, the restricted number of crew members and their closely defined physiological condition has also limited the extent of and the statistical base for such studies.

Automation of microgravity experiments is generally possible and can be successfully implemented, provided that the data-transmission capabilities to and from Earth are sufficient to permit real-time control of the experiment situation from the ground. This type of remote experiment operation, termed 'telescience', is likely to become more generally used in the future, even on manned spacecraft. This is due to the limited time that the crew has for actual experimental work and the large increase in the amount and complexity of equipment that is due to be flown. Instead the intention is to use the limited availability of the crew mostly to carry out maintenance work and to provide for flexible 'troubleshooting' activities.

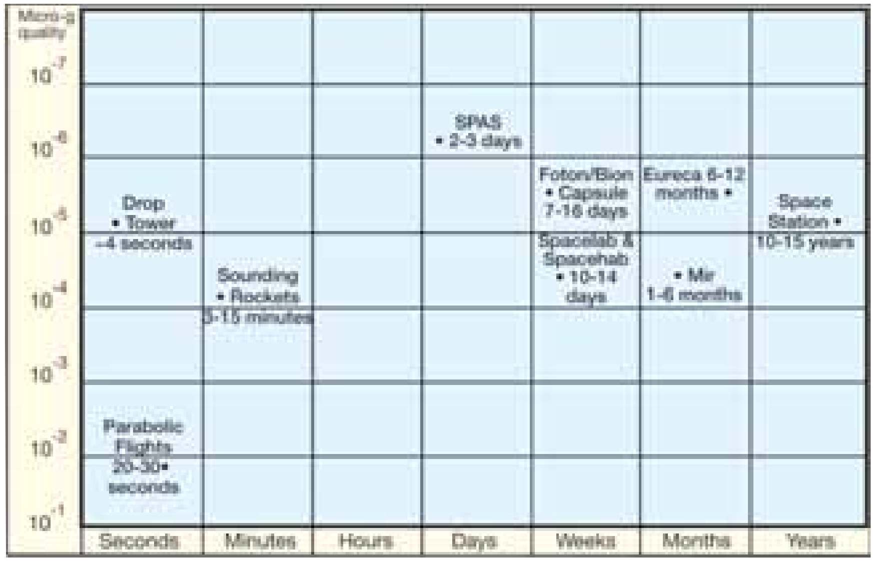


Figure 1.1. The quality of microgravity conditions and their duration for various flight opportunities

Other than for human-physiology research, the use of a manned spacecraft for microgravity research has a drawback. That is the disturbance to the microgravity environment that occurs as a result of the crew manoeuvring about the spacecraft. Their movement induces an oscillatory response of the spacecraft structure that can impair the quality of microgravity experiments if these oscillations can couple into the natural resonance frequency of the experimental equipment. There is also a greater likelihood of there being other sources on-board of this higher frequency perturbation, the so-called 'g-jitter', due to the fact that manned spacecraft necessarily have a greater amount of moving equipment, which may change the mass distribution. This is just one of several potential sources of disturbance to the microgravity environment.

In fact the term 'microgravity' itself simply reflects the reality that true weightlessness or 'zero gravity' is a condition that cannot be achieved in a practical system. There are various similar effects that induce small gravity-like accelerations in a spacecraft, and also other external forces that give rise to slowly changing or to transient accelerations. Thruster firings fall into the latter category. All of these may disturb the balance of the gravitational and inertial forces, which occurs at the centre of mass of the orbiting spacecraft.

The most important perturbation is the frictional drag on the spacecraft, due to collisions with the thin residual atmosphere at low orbits. This externally acting force creates an almost constant deceleration and can also induce a torque, since the centre of pressure and the centre of mass are not coincident. The extent of this atmospheric braking will vary with the surface area of the spacecraft presented to the incident particles of the residual atmosphere. Consequently, changing the orientation of the spacecraft or moveable sections such as solar arrays, will cause a further change to the microgravity perturbation. A similar effect will occur due to the solar photon radiation pressure.

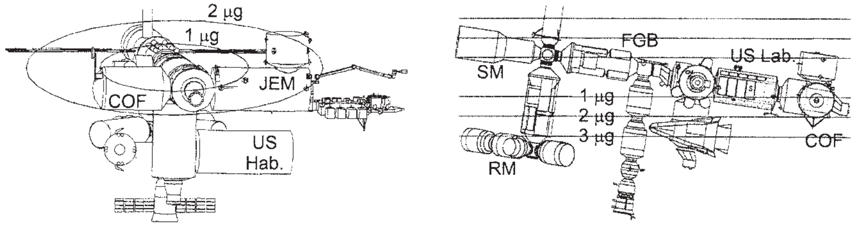


Figure 1.2. The quasi-static microgravity-level contours for the International Space Station (ISS)

Since it is obviously impossible to locate all of the microgravity experiments precisely at the spacecraft's centre of mass, where there is exact equilibrium between the gravitational and centrifugal forces, it follows that there will be an unbalanced 'tidal' force acting on equipment at other locations. The resulting perturbing acceleration will degrade the microgravity conditions, as illustrated in Figure 1.2 for the ISS. The extent of that degradation depends upon the geometrical relationship between the equipment, the centre of mass and the gravity vector. It may therefore also vary during an orbital period, in a manner that depends upon the flight orientation of the spacecraft during its movement through the orbit.

Access to the best microgravity conditions is therefore a matter of careful siting of the equipment, operating it during times of limited transient disturbances and, for the very best conditions, taking steps to isolate the experiment from transient perturbations. This may be done simply, by decoupling the experiment from the spacecraft structure using spring/damping elements. A more sophisticated arrangement would be damping actuators controlled by acceleration sensors. For a small element of an experiment, a levitation system might also be feasible.

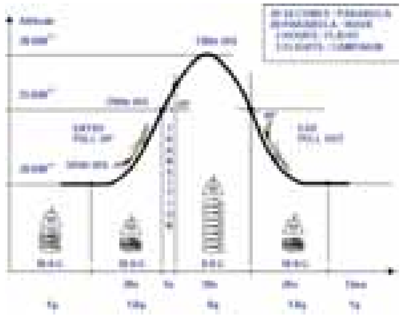
The accompanying table shows some of the types of systems and spacecraft that have been or will be used to provide access to microgravity experimentation. The indicated microgravity levels point to the superiority of unmanned vehicles for the lowest level of disturbances. The figures for the Space Station elements include provision for free-floating experiments, in order to achieve the least microgravity disturbance.

Flight Facility	**Microgravity Level**	**Microgravity Duration**	**Payload Mass (kg)**
Drop Tower	$< 10^{-5}$ g	5 seconds	125
Parabolic Aircraft Flight	10^{-2}	20 – 30 seconds	50 *
Sounding Rocket (Maxus)	10^{-4}	2 –15 minutes	450
Retrievable Capsules (Foton/Bion)	10^{-5}	16 days	500
Shuttle Pallet Satellite (SPAS)	10^{-6}	2 days	< 900
Spacelab	$< 10^{-4}$	10 – 14 days	4500
Eureca	10^{-5}	11 months	1000
ISS/Columbus Laboratory	10^{-3} to 10^{-6} *	Years	4000

**Free-floating experiments*

Drop Towers are usually evacuated tubes in which an experiment capsule is released and allowed to free-fall. Several countries have such facilities. The one in Bremen (ZARM) is typical and provides a 110 metre drop and about 5 seconds of microgravity conditions. They are of value for short-duration self-contained experiments, such as phase flow, combustion and capillarity, and for testing experiments destined for longer duration missions.

Parabolic Flights typically provide 20–30 seconds of low-gravity conditions. They use a jet aircraft with the interior specially fitted out to accommodate experiments. An accelerating entry flight is followed by a pull up and engine throttle back, to allow the aircraft to free-fly a parabolic trajectory. After leaving the free-fall parabolic trajectory, there is a short horizontal flight phase and then successive parabolic manoeuvres are again possible. These flights are particularly valuable for astronaut training and for the testing of experiment equipment and operating methodologies. Their limitation is the poor level of microgravity achieved over just a short duration.



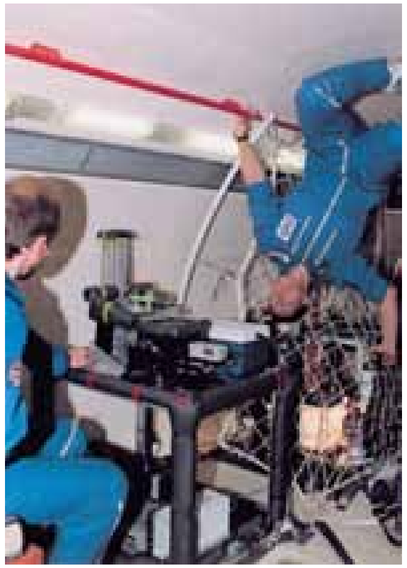


Figure 1.3. (a) Schematic of the parabolic-flight manoeuvre leading to low-gravity conditions, and (b) the result on an ESA parabolic flight in October 1994 as scientists perform fluid measurements (courtesy of S. Odenbach, Univ. Wuppertal, and J. Fabre, IMFT, Toulouse)

Sounding Rockets were one of the earliest means of achieving microgravity conditions. They too use a parabolic free-flying trajectory, but the microgravity conditions are much better than for the parabolic airplane flights. European flights (Texus) have frequently used the Skylark rocket, originally providing about 6 minutes of free-fall conditions. In addition, the Maxus sounding rocket now provides about 13 minutes of microgravity and can take a scientific payload mass of around 450 kg. Within the limited time frames and the need for largely independent operations, it is possible to carry out valuable experiments with these latest systems.

Space Platforms and Capsules potentially offer very low microgravity levels, since they are entirely free from any perturbations due to launch vehicles. They are injected into orbit and have a useful lifetime for experimentation that is limited only by the availability of any required consumables and the natural decay time from orbit due to atmospheric drag.

The Russian Bion/Foton capsule has been regularly used for microgravity experiments in Europe. This capsule can accommodate a maximum scientific payload of 500 kg and can be launched into an orbit of up to 400 km altitude. Experiments can be performed over a period of up to 16 days. On completion of the experiment phase, a retrothrust is activated to cause descent and re-entry. ESA has used the Foton system to fly and return the Biobox and Biopan biology research payloads and the Fluidpac facility.

SPAS, the German Shuttle Pallet Satellite, can be launched into orbit and later recovered by the NASA Shuttle. It carries up to 900 kg of payload and has sufficient resources to permit microgravity experimentation over a period of two days. The principal limitation on in-orbit operations is the lack of solar arrays and hence a dependence on battery power. The advantage is that with the absence of arrays the atmospheric drag is much lower and very low microgravity levels are achievable. It has been flown several times since its first launch in 1983, although with limited use for microgravity payloads.

Eureca, the European Retrievable Carrier, was designed by ESA as a long-duration automated microgravity platform. It was launched in August 1992 and recovered in July 1993, by the NASA Shuttle. It had an experiment payload capacity of 1000 kg. The high potential re-flight costs caused cancellation of the programme. Despite the good microgravity environment on this platform, the preference appeared to be to use manned vehicles for large experiment operations. This opens up the possibility of crew intervention in the case of problems, provides for operational flexibility and can simplify experiment design.

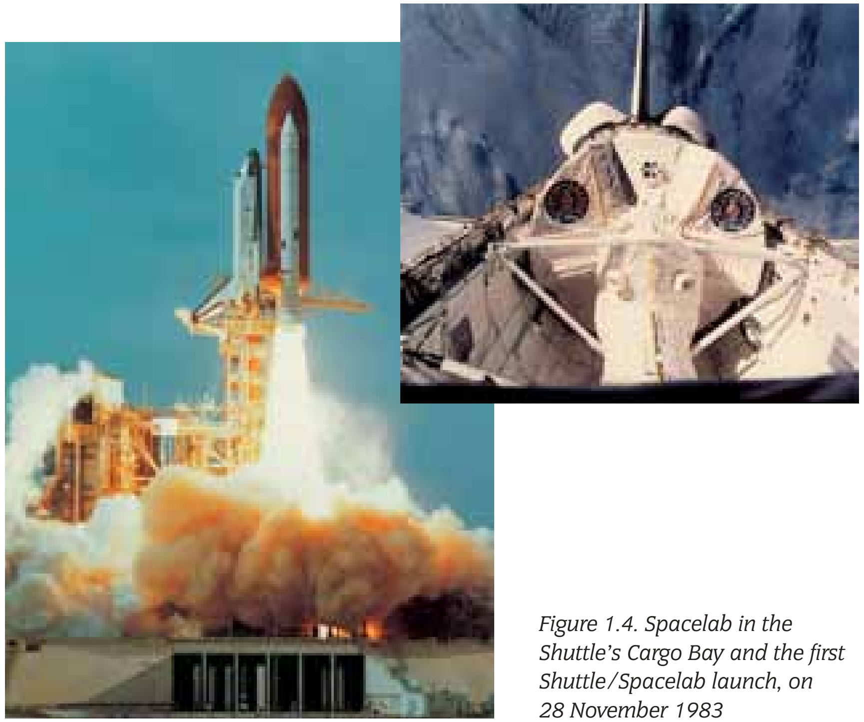


Figure 1.4. Spacelab in the Shuttle's Cargo Bay and the first Shuttle/Spacelab launch, on 28 November 1983

Spacelab was developed by ESA as a manned laboratory, to be accommodated in the cargo bay of NASA's re-usable Space Shuttle. Both Spacelab and Eureca were constructed during the same time period, as an agreed parallel undertaking.

The pressurised section of Spacelab is about 6 m long and 4 m in diameter, but the modular construction provides for flexibility in the actual flight configuration. In the Long-Module configuration, which maximises the accommodation for internal payloads, it can accommodate a mixture of 10 double racks for equipment (112 cm width) and 4 single racks, with a total payload mass of about 4500 kg. Up to seven crew members can be carried, several of whom have scientific training and competence in the experiment subject. Mission duration is nominally 10 days. Up to five external pallets, each 2.9 m long, can provide accommodation to a variety of payloads. With a Three-Pallet configuration, a total mass of 9300 kg may be carried.

Spacelab has been the workhorse of microgravity science for about 15 years. It provides substantial crew support to experiments and as subjects for human physiology studies. The overall resources are adequate and the microgravity levels are acceptable for most experiments. The problem has been the infrequent flight opportunities for many scientists, coupled with a short mission duration. The result has been a difficulty in rapidly following up on interesting observations. It has also been difficult, in some cases, to establish a sufficient body of data by the normal process of careful checks using several subjects or samples. Nonetheless, it may be judged to have been very successful at providing extensive, flexible, high-quality access to microgravity conditions for a generation of scientists.

Spacehab is a commercial development of a pressurised module that is also designed to fit into the Shuttle's cargo bay. The module has a volume of 31 m^3 and can be connected into the Shuttle. It is more limited in its capabilities than Spacelab, but it has a shorter turn-around time between flights and it is cheaper to operate. Consequently, Spacehab is being used now as a manned laboratory for microgravity experiments, having first flown in 1993.

Mir was the first true space station, following on from the limited orbital stations of Salyut-1 in 1971 and Skylab in 1973. Assembly of Mir was begun in orbit in 1986 by the Soviet Union. It survived the political changes of the following decade, continuing to operate and carry out a variety of scientific research. Assembly was finally completed in 1996. By that time, it had become international in the extent of its use, although still owned and operated by the Russian Space Agency. The main characteristics and functions of Mir are summarised in the accompanying table.

Module	Mass (tons)	Length (m)	Max. Diameter (m)	Pressurised Volume (m³)	Electrical Power (kW)	Function
Mir Core	21	13	4.15	90	10	Habit./ Support Syst.
Kvant-1	11	5.8	4.15	40	-	Astrophys.
Kvant-2	18.5	12.4	4.35	61	7	Earth Obs.
Kristall	19.6	12	4.35	61	5 – 8	Mat. Science
Spektr	19.6	12	4.35	62	7	Geophys.
Priroda	19.7	12	4.35	66	-	Earth Obs., Geophys.

Mir was initially somewhat constrained in its research capabilities, mainly by the lack of adequate data-handling and communications capabilities. That limitation was partly overcome by emphasising research that used returned samples. These were principally concerned with life sciences and improving the properties of materials such as semiconductors, alloy systems, optical and sensor materials. The research activities were expanded and the quality of the facilities for microgravity research was improved, as the partnership with the USA in the operations got underway.

Figure 1.5. The Mir space station in its final configuration

The *International Space Station* is already being assembled in orbit. It promises to herald a new era in microgravity research by virtue of the amount and diversity of experimental equipment that is accommodated for this purpose and the extended time during which it can be used.

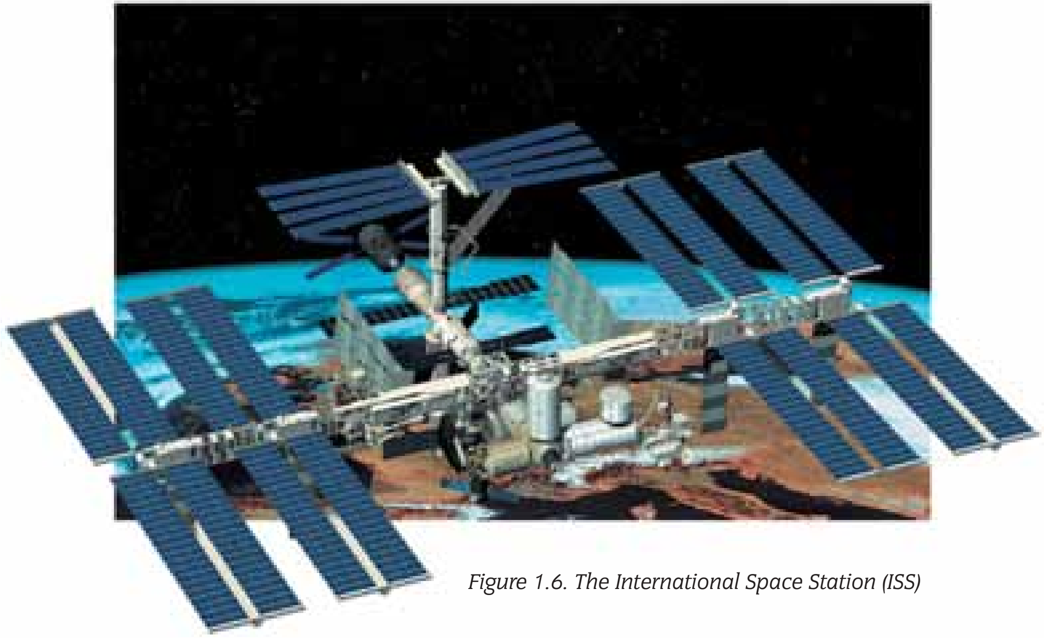


Figure 1.6. The International Space Station (ISS)

At completion, the Station will have a total mass of over 400 tons and dimensions of about 100 metres by 75 metres. Out of the total power of 110 kW, some 47 kW will be made available for research purposes. Initially, there will be three astronauts on board, increasing to around six at final assembly. Each astronaut will remain on the Station for at least three months, corresponding to the time interval between normal Shuttle re-supply flights.

There will be six pressurised laboratories attached to the Station: one from the USA, one from Japan and one from ESA, plus two from Russia and a US centrifuge module. Several unpressurised accommodation sites will also be available for scientific equipment, serviced by remote manipulator arms.

Inside each of the pressurised laboratories there will be standard experiment equipment racks, each fitted with in-situ resource provisions for the experiments. In the case of the ESA research module, the ‘Columbus Laboratory’, there will be ten exchangeable payload racks, i.e. four along each side and two in the ceiling of the 6.7 m by 4.5 m diameter module. The mass of this Laboratory and its equipment will be about 15 tons, 5 tons of which will be research equipment. Five of the ten racks will be available for ESA research, and five for NASA research. Much of the experiment equipment within the pressurised module will be dedicated to microgravity research. Payloads will also be attached on four external pallets on the exterior of the Columbus Laboratory for technology experiments, Earth observation and space-science investigations.

The resources allocated to support the operation of the five payload racks of equipment, available in the Columbus Laboratory for European scientists, and the external pallet payloads, amount to an average of 2.5 kW of power and just over 13 hours/week of crew time. Within that limited crew-time allocation is the requirement for experiment equipment maintenance as well as assistance to experiment operations.

Figure 1.7. ESA's ISS Columbus Laboratory

It is here and in the data-transmission resource allocation that scientists may encounter limitations to what they can achieve, despite the huge amount of equipment that is potentially available for their use. In that sense, the conditions that were available in the Spacelab, with a similar number of crew available for fewer racks of equipment, no maintenance, ample resources, and good data links, may seem a luxury. The major disadvantage with the Spacelab is, however, the more serious one of few flights and each of short duration.

Another limit to experiments in the ISS is set by the need to periodically boost the Station back into its original orbit, following the natural orbital decay due to atmospheric drag. At that time, the microgravity conditions are greatly disturbed. As

shown in the accompanying illustration, the re-boost process is combined into the time frame for the re-supply rendezvous, when further major disturbances occur. The result is that acceptable microgravity conditions for experimentation are available only in discrete periods of 80 days. That is still extremely long compared to what was previously available, but it will circumscribe a few experiments.

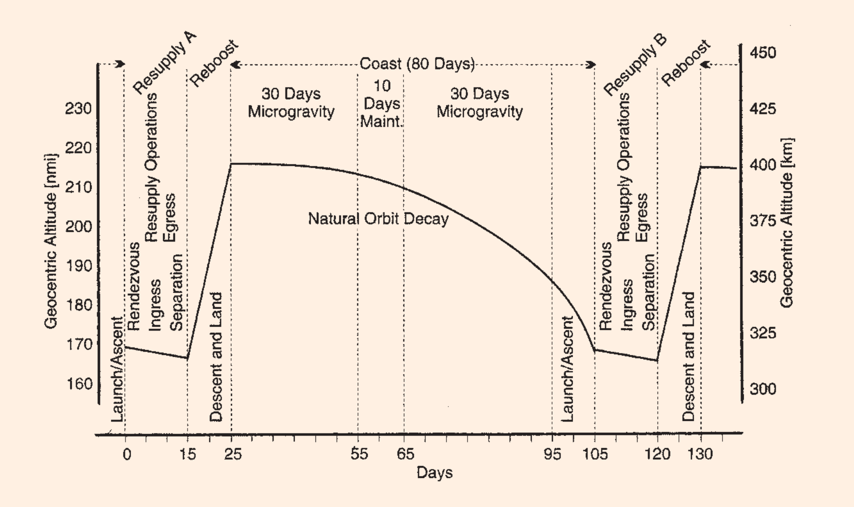


Figure 1.8. A basic plan for the ISS re-supply, orbit boost and experiment cycles

Clearly, with the advent of full operations on the ISS, scientists will have far greater access to microgravity conditions than was ever previously possible. But to use that access effectively, they will have to adapt to a new way of experimenting. They will have to bypass potential bottlenecks in research operations due to communications, crew-time and supply-logistics limitations. That means designing experiments and procedures to new levels of automation that include local intelligence and control. It means using in-situ analysis wherever possible, limiting the total mass of specimens needed and the quantity of consumable materials in experiments. Finally, they will have to ensure that experiment equipment is robust and easily maintained, since it is likely to be used in-orbit for an extended time and both crew time and spares provision are going to be restricted.

1.3 European Manned Spaceflight and Microgravity Research

July 1969 saw one of the most spectacular events in technological history, the legendary human landing on the Moon. With this extraordinary achievement the United States surpassed the Soviet Union, which had thus far led the space race with the launch of the first artificial satellite 'Sputnik' on 4 October 1957 and with the flight of the first man, Yuri Gagarin, in an Earth orbit on 12 April 1961.

The launch of the Sputnik satellite shocked the USA out of its complacency regarding its technical superiority. NASA was then created in 1958, as part of the rush to recover the initiative. In 1960, President Kennedy announced that it was an American national objective to land an American on the Moon before 1970, in the framework of NASA's Apollo Programme. With the successful accomplishment of that declared objective in 1969, the USA again demonstrated their superiority in high technology and confirmed their lead in the space race with the Soviet Union.

The West European nations had by then already begun the process of combining their economic forces in the form of the European Economic Community, which then represented the second largest economic power in the world. Despite that fact, Europe did not play any role in this demonstration of technical leadership. Consequently, a desire was created in Europe to participate in the next steps in the manned exploration of space.

The European Space Research Organisation (ESRO) had been created and built up during the mid-1960s in order to expand European capabilities in space science. With a progressive expansion of its activities and capabilities, it was in a position by 1973 to accept an invitation from NASA to participate in an international Post-Apollo Programme. This important decision marked the beginning of the manned-spaceflight programme within Europe and it led to the transformation of ESRO into a full European Space Agency.

The Post-Apollo Programme at that stage contained several options for the way forward, including a possible Space Station. However, the NASA-selected option for the Post-Apollo Programme, announced in 1972, was the Space Transportation System (STS), involving the development of the Space Shuttle. The development of a Space Station as an alternative was postponed.

The subsequent joint European–American selection of Spacelab as the European element of the STS was mainly due to US national security concerns about overlapping technology developments, and to the European desire to develop an easily identifiable element of the STS that could be built independently by European industry. Spacelab was to be the first manned multi-disciplinary research laboratory to be routinely used in space, and the concept fulfilled both the European aspirations and the American requirements.

Two Spacelab flight units and an engineering model were finally delivered by ESA to NASA, for launch and orbital operation by NASA. However, due to delays in the Shuttle and Spacelab development, the first Shuttle/Spacelab mission, SL-1, did not take place until 28 November 1983, with a 10-day mission. Ulf Merbold was aboard, as the first ESA and non-American Shuttle astronaut.

The decision to develop Spacelab was part of an overall agreement within Europe that also included a decision to develop a European launcher system (later named 'Ariane'), and a series of telecommunication satellites. These three elements, together with the continuation of the Space Science Programme of the original ESRO, were to form the core activities of the new European Space Agency (ESA).

For Europe, the introduction of the Spacelab Programme opened the way to start the novel scientific and application oriented microgravity research activities. It led to the formation of a new scientific community, consisting of life, materials, and fluid scientists, which started to explore the potential of the microgravity environment and the use of gravity as a variable.

Although in the original programme decision the multidisciplinary character of Spacelab was stressed, it soon became clear that this new infrastructure would largely be used for microgravity research. The accompanying table of Spacelab missions, which terminated in 1998 with the Neurolab mission, confirms this prediction.

The Shuttle/Spacelab system operated in the period from November 1983 to April 1998, providing 16 missions with the Spacelab Long Module (LM), 13 of which were dedicated to life sciences and/or materials/fluid sciences (MS/FS). The other three LM missions – the joint NASA/ESA SL-1 mission in 1983, and the two German Spacelab missions (D-1 in 1985 and D-2 in 1993) – were multi-disciplinary, but had more than half of their payloads dedicated to the microgravity research disciplines. In addition, on 16 further Shuttle missions Spacelab unpressurised pallets were flown. NASA flew a materials-science pallet on several of these missions.

The Shuttle/Spacelab combination, with the pressurised Long Module and a space mission of 1–2 weeks, represented a rather ideal research opportunity for the microgravity disciplines. The limitation, from a European perspective, lay in the very limited flight opportunities. This had its origins in the early gross underestimation by NASA of the Shuttle maintenance and turn-around complexity and of the associated flight and operations costs. This was presented as $18 million/flight in the 1975 plans. By 1990 it stood at $220 million and in 1999 it was $500 million. Instead of the 50 flights per year originally assumed as feasible in 1975, only 8 per year were routinely achieved.

The result of the escalating flight costs was that the ESA Member States were unwilling to fund ESA Spacelab missions, after the initial joint NASA/ESA SL-1 mission. ESA had detailed plans prepared in the late 1970s for two Shuttle/Spacelab missions, but no consensus could be found among Member States to finance them. Therefore Germany, which had already financed more than 50% of the Spacelab development costs within the framework of the ESA programme, performed two German national missions (D-1 in 1985 and D-2 in 1993). In so doing, it agreed to a minority participation of ESA scientific payloads in those missions.

Spacelab Missions using the Long-Module (Laboratory) Configuration

STS-Flight Number/	Spacelab Mission	Launch Date + Duration	Orbit Inclination/ Altitude	Research Discipline	European Astronaut	ESA Participation with Payload
STS-9 Columbia	SL-01 FSLP	28-11-83 10 days	57° 250 km	Multi-Disciplinary	U. Merbold	50%
STS-17 Challenger	SL-03	29-04-85 7 days	57° 360 km	Mat./Fluid Sciences	–	–
STS-22 Challenger	SL-D1	30-10-85 7 days	57° 330 km	Mat./Fluid Science + Life Sciences	R. Furrer E. Messerschmid W. Ockels	38%
STS-40 Columbia	SLS-01	05-06-91 9 days	39° 300 km	Life Sciences	–	–
STS-42 Discovery	IML-01	22-01-92 8 days	57° 300 km	Mat./Fluid Science + Life Sciences	U. Merbold	25 %
STS-50 Columbia	USML-01	25-06-92 14 days	28° 300 km	Mat./Fluid Sciences	–	–
STS-47 Endeavour	SL-J	12-09-92 8 days	57° 300 km	Mat./Fluid Sci. + Life Sci.	–	Japanese Payload
STS-55 Columbia	SL-D2	26-04-93 10 days	28° 300 km	Multi-Disciplinary	M. Schlegel U. Walter	25 %
STS-58 Columbia	SLS-02	18-10-93 14 days	39° 280 km	Life Sciences		–
STS-65 Columbia	IML-02	08-07-94 15 days	28° 300 km	Mat./Fluid Science + Life Sciences	–	35%
STS-71 Atlantis	SL-M	27-06-95 10 days	52° 300 km	Mission to Mir	–	–
STS-73 Columbia	USML-02	20-10-95 16 days	39° 300 km	Mat./Fluid Sciences	–	10 %
STS-78 Columbia	LMS	20-06-96 17 days	39° 280 km	Mat./Fluid Science + Life Science	J.J. Favier	35 %
STS-83 Columbia	MSL-01	04-04-97 4 days	28° 300 km	Mat./Fluid Sciences	–	ESA MG Measurement Ass.
STS-94 Columbia	MSL-01R Refl. of STS-83	01-07-97 16 days	28° 300 km	Mat./Fluid Sciences	–	ESA MG Measurement Ass.
STS-90 Columbia	Neurolab	17-04-98 16 days	28° 300 km	Life Sciences	–	25 %

In January 1982, the ESA Member States finally agreed to a small programme to which governments could contribute according to their interests and their budget. The ESA Microgravity Programme: Phase-1 for 1982-85 amounted to 48 million ECU. This allowed ESA to participate in the German 'Texus' Sounding-Rocket Programme, and to extend it by the inclusion of the Swedish Maser Sounding Rockets (with predominantly ESA payloads) to perform short-duration microgravity experiments. In addition, this Phase-1 programme covered the development of a first set of multi-user experiment facilities for Spacelab missions.

With the approval of a larger budget for Phase-2 of the ESA Microgravity Programme in early 1985 (later twice extended and named EMIR-1, European Microgravity Research Programme), ESA was in a position to establish bilateral co-operation with both the Life Sciences Office and the Materials and Fluid Sciences Office of NASA.

Unfortunately, during this period when microgravity research was beginning to accelerate, the tragic Challenger accident occurred on 28 January 1986, which led to an interruption of Shuttle/Spacelab missions for more than five years. During that period, attention was focused upon alternative means of accessing microgravity conditions and the sounding rockets provided an important element of this.

Within the framework of the co-operation between the ESA and the NASA microgravity science offices, an agreement was developed for joint (50/50) NASA/ESA use of about a dozen multi-user experimental facilities. These were to be ESA-funded and built by European industry. NASA agreed to cover the cost of the flights and the orbital operations of these facilities on Shuttle/Spacelab missions.

These ESA facilities were required to carry out novel microgravity experiments within Spacelab. They were at the forefront of high-technology equipment and had a high potential for future applications and 'spin-offs'.

With this very favourable arrangement for European scientists at a critical time, these ESA multi-user facilities flew on five NASA Shuttle/Spacelab missions:
- 1992 on the IML-1 (International Microgravity Laboratory 1) mission
- 1994 on the IML-2 mission
- 1995 on the USML-2 (US Microgravity Laboratory) mission
- 1996 on the LMS (Life and Microgravity Sciences) mission
- 1998 on the Neurolab Spacelab mission, dedicated to neurophysiology.

A similar arrangement (with a small ESA contribution for the Shuttle launch costs) was also made with the German space authorities. It led to ESA's participation with multi-user facilities in the German national Spacelab missions D-1 in 1985 and D-2 in 1993. In total, this meant that ESA participated in eight of the 16 Shuttle/Spacelab missions in which the Spacelab Long Module Laboratory was flown.

Some of the European materials and fluid scientists had requested better microgravity levels than were achievable on Spacelab missions. There were also requests from the European life scientists working in the field of radiation health/exobiology for longer mission durations. Consequently, ESA decided to develop a large (5 ton) retrievable carrier platform called Eureca (European Retrievable Carrier). This was launched by the Shuttle on 1 August 1992 and retrieved by it after 11 months of free flight in a 400 km altitude circular orbit. Eureca yielded the lowest microgravity levels yet obtained, together with some good scientific results. Nonetheless, it was not possible to find the funding for a reflight from within the ESA Member States.

Figure 1.9. Eureca in its operational orbit (courtesy of Astrium/DASA)

In order to expand the European microgravity research opportunities further, ESA provided an improvement to its Sounding Rocket Programme in 1993 by promoting an industrial initiative for a larger rocket, the Maxus. It provides good microgravity levels for about 13 minutes of flight (double that of the Texus and Maser missions) and has a payload-carrying capability of up to 450 kg, compared to the Texus/Maser capacity of 240 kg.

Figure 1.10. Mission profiles of the Mini-Texus, Texus, and Maxus sounding rockets (courtesy of Astrium/DASA)

ESA also extended the experimental opportunities for human physiology by reaching an agreement with the Russian Space Agency to perform, on a cost-reimbursable basis, two missions to Mir carrying an ESA astronaut on each one. These were:

– Euromir ’94, 30-day mission, astronaut Ulf Merbold
– Euromir ’95, 179-day mission, astronaut Thomas Reiter.

Although these missions were successfully performed, the experimentation on Mir was constrained by the very low download of only 10–15 kg for experimental equipment and specimens and by the low capability of the data downlink.

The Spacelab era was drawing to a close, as planned, in the mid-1990s, yet the assembly of the International Space Station had not begun. To fill the resulting gap, a replacement of Spacelab missions by those of a smaller commercial space laboratory, called ‘Spacehab’, was therefore offered by the American company, Spacehab Inc. Spacehab utilisation by ESA started in June 1993, with the first flight of ESA’s Advanced Protein Crystallisation Facility (APCF) on Spacehab’s maiden flight. Spacehab utilisation was continued in 1996 with several NASA/ESA co-operative (no mission costs for ESA) flights of the ESA Biorack multi-user facility. ESA has used these Spacehab flight opportunities since 1998 also on a commercial basis, flying just a few experimental facilities (multi-user and experiment dedicated ones).

During the eight Spacelab missions in which ESA microgravity scientists have participated, with a total mission duration of slightly more than 100 days, the experimentation time was about 2500 hours. This was spread over the 15-year duration of the Spacelab era. Despite the constraints on experimentation time that this implies, European scientists have achieved very substantial research results. They have made a number of unexpected discoveries, have acquired outstanding expertise in performing their experiments in space, and in several microgravity subdisciplines have taken a worldwide lead.

During the 15 years of the Spacelab era (1983–1998), astronauts from 20 different countries have performed experiments from European, American, Japanese and Canadian investigators in Spacelab.

Within the framework of the STS-84 mission in May 1997, Spacelab was even used in a Shuttle flight to the Russian Space Station Mir. This mission was part of Phase-1 of the worldwide co-operation that was established in order to gain experience for the construction and operation of the International Space Station (ISS).

- *The Space Station and Microgravity*

Europe needed more than 10 years to decide on the extent of its participation in the ISS, with the final decision being taken at the ESA Council at Ministerial Level in 1995.

The ISS assembly phase started in late 1998, with the launch of the Russian module 'Zarya' and the American 'Unity' module. This assembly process will last until 2005, at which point the routine utilisation of the ISS will start.

ISS is the largest space programme ever undertaken. With the decision by Russia to accept the USA's invitation to become a partner in ISS in January 1998, all of the world's major space powers concentrated their efforts on this ISS programme. The permanently manned ISS will demonstrate visibly to the world the advanced technical know-how of the ISS partners. In addition, the ISS has become the largest East-West cooperation. It offers the chance to create mutual confidence and at the same time illustrates how political and cultural obstacles can be overcome in a joint enterprise.

Besides these positive political aspects, the ISS programme is designed to provide a scientific and technical research platform above the Earth's atmosphere, with the aim of contributing (thanks to its particular position in low-Earth orbit) towards solving problems on Earth and in the Earth's atmosphere, and of accelerating scientific/technical progress.

The principal responsibilities, tasks and rights of each of the five ISS Partners, i.e. of the USA, Russia, Japan, Canada and Europe, were agreed already in 1988 in the Intergovernmental Agreement (IGA), in which the five Partners delegate the management of ISS to their respective space agencies. In Europe, ESA represents the 10 ESA Member States that finance the European ISS contribution.

In addition, the four ISS partner agencies of NASA concluded bi-lateral Memoranda of Understanding (MOUs) with it, which define the detailed responsibilities, management structures and mechanisms, the attribution of installations and resources and the sharing of the costs.

The European participation in the ISS consists of three major elements, representing 8.3% of the (non-Russian part of) ISS. These are the:
– contribution of the pressurised Columbus Laboratory with an attached external platform
– participation, with Ariane-5 and the Automated Transfer Vehicle (ATV), in the logistics flights to the ISS
– ISS Utilisation Preparation Programme.

In addition to these three major programme elements, ESA is making several other key contributions to the ISS, including:
– the European Robotic Arm (ERA), for the Russian segment of the ISS
– the Data Management System for the Russian Service Module 'Zvezda', launched on 12 July 2000
– in co-operation with NASA, the Crew Re-entry Vehicle (CRV).

Furthermore, ESA is participating actively in the ISS Ground Segment, providing the Control Centres for both the Columbus Laboratory and the ATV operations.

ESA's ISS Utilisation Preparation Programme was established in order to:
– develop Laboratory Support Equipment (LSE) for the ISS laboratories
– familiarise the user community with ISS
– prepare for the orbital operations, including the selection and training of astronauts.

The ISS provides the following utilisation characteristics:
– regular and permanent access for a period of 15 years
– permanent manned capability, i.e. the crew is exchanged at regular intervals (every 3 months)
– large technical resources, such as electrical energy, heat rejection and data transmission, are provided for research in the various pressurised laboratories and at the external viewing sites of the ISS.

These characteristics will radically change the microgravity utilisation of the low-Earth orbit, from a situation where Spacelab flights were too few and sporadic, to a stable and continuous utilisation mode on the ISS.

In anticipation of the utilisation of the ISS by the microgravity disciplines, ESA has started to extend its scientific user community through a complementary Microgravity Application Promotion (MAP) Programme. The latter, presently financed by the Utilisation Promotion Element of the Columbus Programme, covers two types of activities: Topical Teams (TTs), and pilot research projects called 'MAP Projects'. The TTs are European teams from academia and industry, which have the task of defining high-priority research areas with special relevance to microgravity. Based upon the recommendations of these Teams, MAP Projects are carried out by integrated teams composed of scientists from universities and also researchers from industry. They undertake relevant ground-based research and eventually space research, in order to obtain data for the optimisation of industrial processing and medical applications on Earth.

Taking into account the permanent access opportunities to the space laboratories of the ISS, these MAP teams will perform applied research programmes in a similar way to those in a normal terrestrial laboratory. The limitations due to the sporadic isolated experiments of the previous era, which have severely circumscribed microgravity research in the past, will finally be overcome. The topics addressed will have the potential to develop into concrete industrial and health-related applications on Earth (see Sections 3.3 and 5.1).

ESA provides financial support for the academic partners of the MAP Projects, whereas the industrial MAP partners contribute in cash and/or in kind. ESA takes care of the space transportation and of the development of the major experimental facilities needed by the MAPs.

By the end of 2000, some 44 MAP Projects had already been established, representing a financial envelope of about 40 MEuro. ESA contributes one third of this envelope, and the other two-thirds are covered by industry and the research institutes of the academic MAP members.

Overall, the annual financial resources that Member States have made available for the optional ESA Microgravity Programme, in the period 1982 – 2000, were in the range of 0.5% to 3% of the ESA annual budget. The research results obtained, which are discussed in detail in the following Chapter, demonstrate how well and how cost-effectively these modest resources have been used.

CHAPTER 2. ASPECTS OF CURRENT MICROGRAVITY RESEARCH

2.1 CHANGES TO HUMAN PHYSIOLOGY IN SPACE, AND SPACE MEDICINE

2.1.1. The Cardiovascular System

K. Kirsch & H-C. Gunga

2.1.1.1 Introduction

In the mid-seventies, when the Europeans started to participate actively in the American space programme aboard the Space Shuttle, they had no biomedical space-research experience of their own, relying for all practical issues on the Americans. NASA, on the other hand, could already look back on their Gemini experiments of the sixties and, particularly, the longer highly successful Skylab missions of the early seventies. The results from the latter are well-documented and in many ways shaped the thinking and planning for the early Shuttle missions.

This does not mean that Europe totally lacked experience in gravitational physiology. During the 1930s and 1940s, centrifuge experiments had been conducted and therefore there were hypergravity physiology data available. Using these data, Gauer and Haber extrapolated from hypergravity to 0g, making certain predictions about the effects of a microgravity environment on the human body. The cardiovascular system was identified as a possible problem area, since it was known from the centrifuge experiments that gravity strongly influences the distribution of blood within the human body.

Knowledge was also acquired from certain aspects of developmental and comparative physiology. When aquatic animals left their home environment, for example, they were fully exposed to the forces of gravity and the weight of their bodies impeded movement. Evolutionary processes had to ‘produce’ the structures to overcome the burden induced by gravity. Height only became an exploitable dimension when the body developed the necessary supporting muscles and bones. These maintain and support the unstable assemblage of fluid-filled bags and interconnected tubes directed along the body axis, which roughly approximate to the cardiovascular system in man and animals. Within these tubes, there are hydrostatic forces at work that have to be counteracted if the creatures are to survive.

These problems are illustrated in Figure 2.1.1.1, showing the human cardiovascular system, and Figure 2.1.1.2, which shows that of a giraffe and a dinosaur.

The human cardiovascular system is unique, in that the heart is 1.4 – 1.5 m above the ground, while the brain sits on top of the whole structure and needs to be continuously perfused by blood. The heart has to overcome a height difference to the head of 30 to 35 cm in the standing position. In the organs that lie below the heart, blood tends to accumulate and needs to be transported back to the heart, also against the forces of gravity. Bearing in mind that about 70% of the total blood volume is located below the heart, this is a major task.

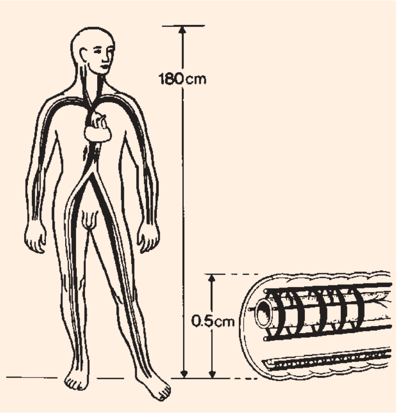


Figure 2.1.1.1. The human cardiovascular system. Note the position of the heart in relation to the feet and the brain. The system consists of long vertically organised tubes, in which high hydrostatic pressures can occur. This can be compared (right) with the horizontally organised vascular system of the worm or snail

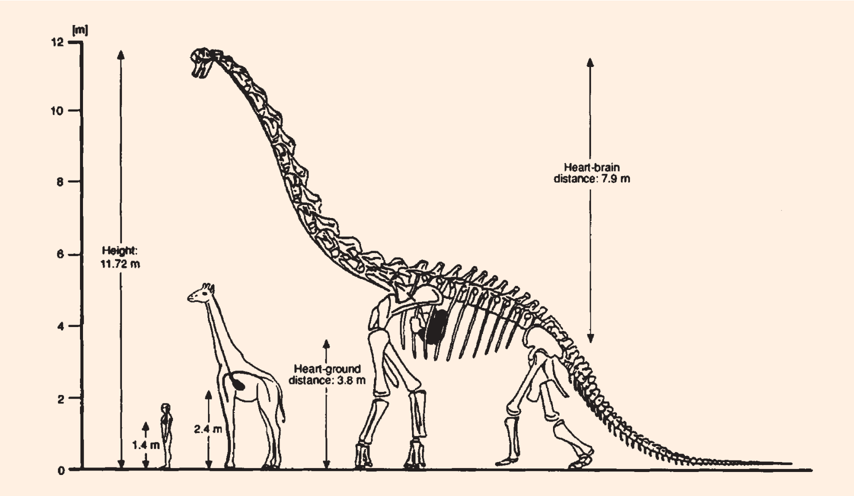


Figure 2.1.1.2. Schematic of the major hydrostatic distances acting on the heart and from circulatory systems in man, in the giraffe, and in the dinosaur Brachiosaurus branci (Gunga et al.1999, Mitt. Mus. Nat. Berl. Geowiss., p. 97)

Should fluids leak out of the blood vessels, they accumulate within the tissues of the legs, producing oedema. The body therefore has had to develop oedema-preventing mechanisms, which are just one of the many mechanisms used by the cardiovascular system to counteract gravity. In the supine position, these problems are of little importance. For worms or snails crawling on the ground, therefore, gravity plays only a minor role (Fig. 2.1.1.1, right).

In Figure 2.1.1.2, the cardiovascular system of long-necked animals like the giraffe and the dinosaur is compared with that of man. The problem is obvious: the giraffe's heart is some 2.4 m above the ground and the distance from the heart to the brain is 2.8 m. For the dinosaur, these distances are 3.8 and 7.9 m, respectively. Long hydrostatic fluid columns are therefore present. The giraffe's heart, for example, has to create a blood pressure of almost 400 mm Hg to ensure an adequate perfusion pressure for the brain (Fig. 2.1.1.3). The dinosaur's heart would have needed to generate a pressure of almost 800 mm Hg. Below heart level, the hydrostatic pressure has to be added to the heart-generated pressure. The arterial pressure in the dinosaur's limbs must therefore have been more than one atmosphere. Man's blood pressure is typically around 120 mm Hg and seldom exceeds 180 mm Hg, even during exercise. Clearly, gravity sets critical limits for these tall animals.

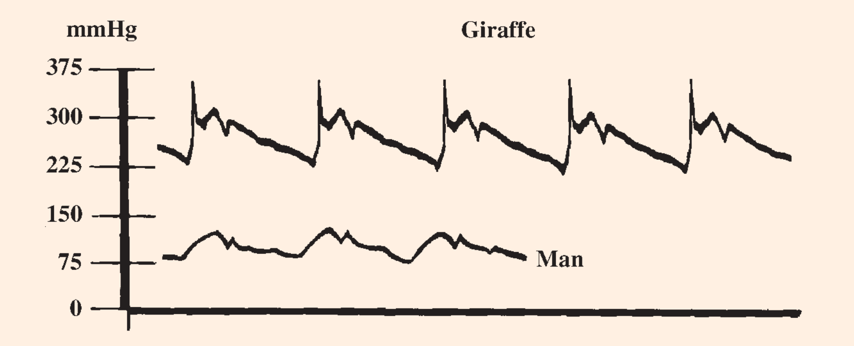


Figure 2.1.1.3. The arterial blood pressures of man and giraffe

One might argue that by man assuming a supine position, as in bed rest, many problems would be solved. This is not the case, however, because a healthy and active person spends about two-thirds of their day on their feet or haunches, and when in a supine position a de-conditioning process sets in very rapidly, reducing their ability to withstand the stress of standing upright (orthostasis). Even the 30 cm from heart to brain then becomes a problem and fainting is common upon standing after extended bed rest. Consequently, bed rest is often used to simulate the type of de-conditioning seen in astronauts after their return from space.

Ageing and upright posture may also be considered from a gravitational viewpoint. Man's upright posture is an everlasting struggle against gravity. A newborn baby, for example, is unable to stand. Neither the skeletal-muscle nor the cardiovascular system is sufficiently developed. It takes about two years for an infant to be capable of controlled movement in an upright position. The small arteries of the cardiovascular system, the arterioles in the lower limbs, have to develop constricting muscles within their walls to withstand the hydrostatic forces when standing. This is a matter of training in the Earth's gravity. This is even more the case for the venous system, in which the volume holding capacity is always challenged by gravity.

Removing the gravitational forces from these structures by entering the microgravity conditions of space leads to progressive wasting of the muscles in the blood vessels. Consequently, returning to Earth and normal gravitation leads to widening of the vessels of the lower limbs and increased blood pooling. Insufficient blood then remains in the heart and lungs, cardiac output is reduced and brain perfusion is endangered. Fainting tends to ensue, as is often observed in astronauts returning from a lengthy space flight.

In the course of maturing, man develops heavy 'antigravity muscles' around his hips and legs, which are constantly at work to prevent falling, whereby they also pump blood back towards the heart. A conservative estimate is that 50% of muscle mass can be regarded as antigravity muscles, which must be adequately perfused to support an upright gait.

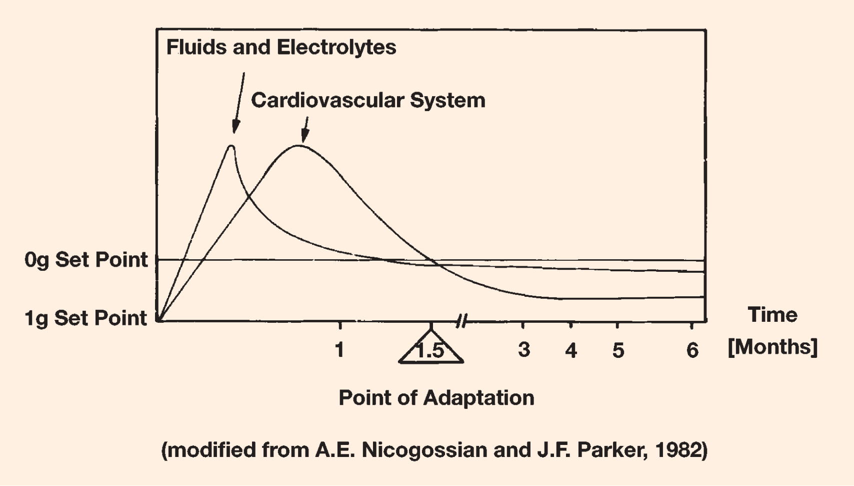
After the age of about 40, wasting of the antigravity muscles becomes apparent and the cardiovascular system also starts to deteriorate. As these processes progress, there is an increasing tendency to seek the support of a chair, for instance, to obtain relief in the fight against gravity. The walking stick, and later the wheelchair, may mark the eventual triumph of gravity over a wasting musculature and degenerating cardiovascular system. It therefore came as no surprise that gravity's removal would have a major impact on practically all of the human body's systems, and the cardiovascular system in particular.

2.1.1.2 The Cardiovascular System in Space

- Operational Demands

From what has already been said, one could expect dramatic changes in man's cardiovascular system on entering a microgravity environment. The observations that were made, and the data finally obtained, depended upon the circumstances prevailing during a particular space mission. The experimental approach in space is often dictated by the operational demands of the mission and by the methodological possibilities available. Any measuring equipment needs to be easy to handle for the astronauts and the experiments should not be too time-consuming, so that as many as possible can be performed in the time available.

The most dramatic changes can be expected in the early mission phases, particularly in the vestibular (see Section 2.1.6) and electrolyte control (see Section 2.1.3) systems. What is seen in space therefore often depends upon when during the mission the experiments are performed (Fig. 2.1.1.4).



(modified from A.E. Nicogossian and J.F. Parker, 1982)

Figure 2.1.1.4. The course of physiological acclimatisation to weightless conditions

Figure 2.1.1.4 shows that the changes in the fluid and electrolyte systems occur rather early in the mission, with astronauts losing between 4 and 8% of their body weight in the first week of a mission, due mostly to water loss from extra-cellular fluid space. The blood volume shrinks accordingly in a process that influences cardiovascular functions. After 1.5 months, a new equilibrium is reached, known as the '0g set point'. The cardiovascular system reacts more slowly, showing the widest deviations from the 1g and the 0g set point after two to three weeks in space. Later, many of the systems reach a new equilibrium, allowing them to cope with the demands of this foreign environment. What, then, do these adjustments to microgravity mean when the astronauts return to Earth?

- Hypotheses from Terrestrial Experiments

Terrestrial simulation experiments, such as bed-rest, head-down-tilt and immersion studies, attempt to remove the head-to-foot gravity vector or to shift blood from the lower parts of the body towards the cephalic areas. The latter can be accomplished best by water immersion, as demonstrated in Figure 2.1.1.5.

Standing upright induces the accumulation of blood and fluid in the lower parts of the body, as seen on the left (A). Standing in water (B,C) leads to fluid accumulation within the intra-thoracic circulation zones, because the hydrostatic pressure acts on the

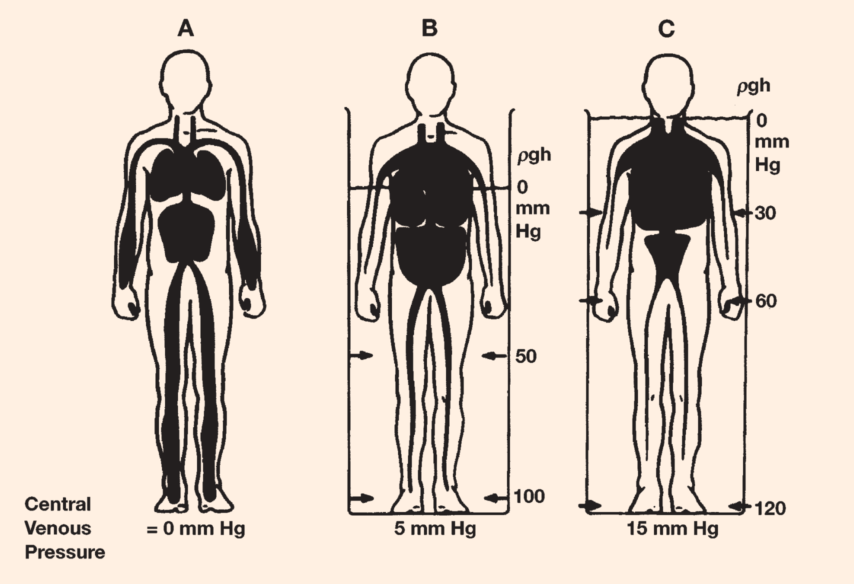


Figure 2.1.1.5. The blood-volume distribution along man's body axis when (A) standing freely, and (B,C) immersed in water. Note the fluid shift and the central engorgement of fluid whilst standing in water

tissues of the lower limbs, squeezing out the fluids contained in them. This always occurs when a person enters a swimming pool, for instance, or lies in a bath. Not only did gravitational physiologists provide a scientific explanation for the benefits of many spa therapies, they also used this model to predict the adaptation of the cardiovascular system in space. This is a good example of how space physiology and medicine has enriched our knowledge of the cardiovascular system's workings on Earth.

The head-down-tilt (HDT) model of 6° is also often used to induce a cephalic fluid shift, thereby simulating microgravity effects, particularly on the cardiovascular system. Several groups in Germany, France and Denmark have used this model to prepare for experiments in space. It could be shown, for example, that during immersion the venous pressure in the central circulation zones increased by more than 10 mm Hg. This was also expected to happen in space.

These experiments were simulated by the observations made during NASA's Skylab missions. Very early in the mission, the astronauts observed that their legs began to shrink and that there was facial swelling. The superficial veins in the head and neck area dilated, indicating they were full of blood. Measurements indicated that about 2000 ml of fluid had left the lower limbs and must have been accommodated mostly in the intra-thoracic circulation areas, in the same way as shown in Figure 2.1.1.5. ESA has therefore given priority to experiments investigating these phenomena.

- *Fluid-Shift Mechanisms*

The primary goal of these research efforts is to shed light on the fluid-shift mechanism, its progress over time and its manifestations in the human body. In an initial approach, the pressure in an arm vein was measured during the first Spacelab mission in 1983 and the German D-1 Spacelab mission in 1985. Attempts were made to obtain data as early as possible in the mission. The astronauts were therefore trained to carry out venipuncture on themselves. On the D-1 mission, the first data were recorded as early as 20 minutes after lift-off. Surprisingly, none of the values recorded exceeded those taken on the ground. Elevated values had been expected, due to the fluid engorgement within the upper part of the body. However, even in the peripheral veins, the pressures dropped by 7 – 8 cm H_20. This means that pressures in the central part must have fallen even more.

The data from the first Spacelab mission and the D-1 mission are shown in Figure 2.1.6, where the values clearly tend to decrease even more with the length of the mission.

These data were some of the first to show that the best terrestrial simulation experiments cannot replace experiments actually carried out in the microgravity conditions of space. The result obtained was exactly the opposite of what was expected. An American group, using a non-invasive technique, also showed lowered Central Venous Pressure (CVP) values, which declined progressively over the first three days of flight. This cast some doubts on the methodologies used. These discrepancies between ideas and hypotheses derived from terrestrial experiments and the early space findings prompted experiments in which astronauts were sent into orbit with a venous catheter in place. This was unthinkable in the mid-

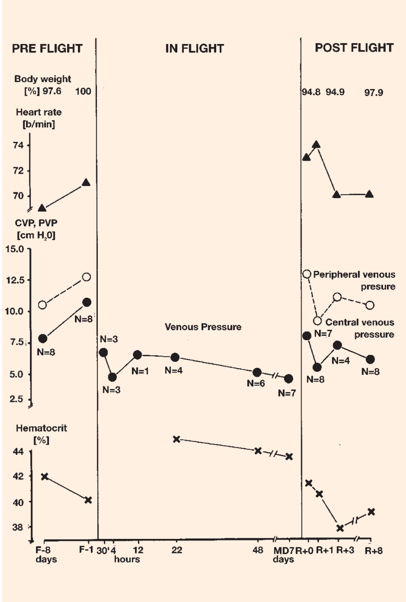


Figure 2.1.1.6. Top to bottom, body weight, heart rate, venous pressure, and Hematocrit values from eight crew members on the first Spacelab and the German D-1 Spacelab missions. Pre-flight, the crew gained weight, and their heart rate and venous pressure increased. In-flight venous pressures were rather low, with a tendency to fall even further. Post-flight, they were initially rather high, but later decreased, to remain lower than pre-flight values for about a week. Note that the body weights were also lowered at the same time

seventies when venous-pressure measurements were first planned. Eight years later, an American and a Danish group were indeed able to show, using catheter tips positioned close to the right atria, that central venous pressure fell by 5 to 8 mm Hg when entering microgravity.

As an example, the orginal recordings from one of the Danish experiments during the German D-2 Spacelab mission are presented in Figure 2.1.1.7. The upper trace gives the pressure recordings, below which are the corresponding g-levels. During the 8 minutes after lift-off, as the g-level increased, a slow but constant increase in CVP can be seen between the time markers A and D, finally reaching nearly 18 mm Hg. On entering microgravity, it then fell abruptly, below the control level seen on the left side of the pressure trace. At D, for example, the astronaut was experiencing almost 3g. Nonetheless, it could be shown that during the first days in space intra-cardiac filling and cardiac output were rather elevated, exactly as expected. These latter findings stem in part from French and German groups using different methodologies, but the discrepancy between low CVPs and high intra-thoracic filling volumes is still an unresolved problem requiring further investigation.

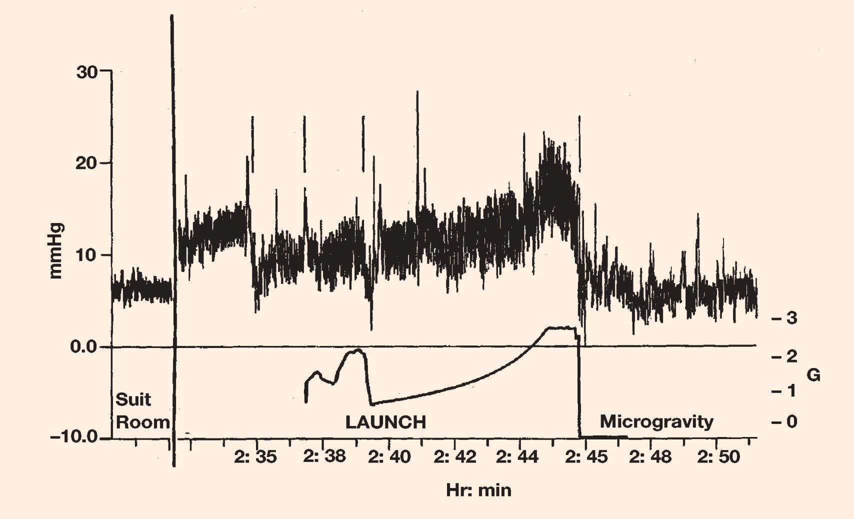


Figure 2.1.1.7. Central Venous Pressure (CVP) measurements on one subject prior to launch (A – D) and after entering weightless conditions. The gravity levels are indicated on the lower trace (from Foldager et al.1996, J. Appl. Physiol. 81, 408)

A group from the German Space Agency (DLR) quantified the fluid shift from the lower limbs towards the intra-thoracic parts of the circulation using an impedance technique in which an alternating current is passed through the body and more than 80% of it is reconducted through superficial body layers. The water content of the tissues determines the impedance. With this non-invasive technique, it was possible to make almost continuous measurements and to gain considerable insight into cardiac

performance during flight, including cardiac output. At the beginning of the mission, the impedance of the thoracic section of the body decreased, implying that its fluid content was higher compared to the controls on the ground. In contrast, total body impedance decreased, signalling an overall body-fluid loss. Later the fluid content of the thorax also decreased. The astronauts apparently dried out during the mission. Evidently, in space life is possible with a lower fluid content. Heart rate and blood pressure varied very little. Here again, the question arises as to what will happen after returning from space? Does a good adaptation to space promote a safe return to Earth?

Prompted by earlier American reports that their astronauts already got ‘bird’s legs’ and puffy faces in the early stages after lift-off, attempts were made during the D-2 mission in 1992 and a 1993 Mir mission to quantify this fluid shift, particularly that out of the superficial tissues. A simple ultrasound technique was used to measure tissue thickness at locations where a good back-wall echo from an underlying bone could be expected, e.g. from the tibia and forehead. Tissue thickness in the tibia decreased in space by 15%, whereas in the forehead it increased by 7%. From this, a fluid shift of 200 ml from the superficial tissues of the lower limbs could be calculated, only 50 ml of which accumulated in tissues in the head that on Earth are kept dry by the force of gravity. They are therefore totally unaccustomed to storing fluids. Although fluid is lost from these tissues during the mission, some still remains. Consequently, space travellers still perceive this fluid accumulation as a fullness of the head. These symptoms can be replicated on Earth by, for instance, a 6° head-down-tilt (HDT) position. Prolonged fluid accumulations of this nature can also be observed in dialysis patients, who are unable to excrete fluids via the kidneys. Between dialysis sessions, they store about 50% of their water in these superficial tissues. This example shows how these space methods can also be applied in clinical medicine on Earth.

As early as 1981, a French group applied echocardiography in space aboard the Mir station. During this short-duration flight, the left ventricular endiastolic volume was elevated on days 2 and 3 of the mission, indicating that the heart was well filled. Later, cardiac dimensions decreased below the pre-flight values. Cardiac output remained elevated during this mission. These studies were continued later and the blood flow to different organs was analysed in detail. It was found that the total vascular resistance decreased during spaceflight by 18%. The local vascular resistance was reduced in several areas, such as the brain, kidneys and the lower limbs.

In subsequent studies countermeasures were applied to prevent the fluid shift. Astronauts wore cuffs around their thighs that were inflated to prevent blood and tissue fluids returning from the lower limbs. Blood flow towards the lower limbs was indeed reduced, because the vascular resistance was increased by 12%.

This is a passive fluid-shift countermeasure compared with exercise, which is an active countermeasure. The effects seen in space depend not only upon the microgravity environment, but also upon the circumstances under which the astronaut is living in the space cabin, as was nicely demonstrated by the French experiments.

The blood volume in space is not only shifted upwards along the body axis, but it is also reduced. Shortly after entering microgravity conditions, the plasma volume decreases and later the red-cell volume also shrinks, making a close look at blood-volume control mechanisms essential. In space, erythropoietin values (EPO) are lowered; erythropoietin is a hormone excreted by the kidneys, which normally stimulates the production of red cells. EPO is excreted when the oxygen concentration in the tissues is lowered, but as normal atmospheric gas pressures prevail in the space cabin this is rather an unlikely cause. What then is the reason for the altered EPO levels in space? An answer could lie in the EPO patterns after space flight, which are drastically increased and this increase was always linked with lowered CVP values. This could also be demonstrated in other terrestrial experiments. For example, in space-simulation studies like immersion, CVP was low following the period of immersion and EPO values began to rise. As Figure 2.1.1.6 shows, CVP values are lowered after landing but how the central circulation is linked to EPO secretion is still an open question. Space physiologists believe there is a link between the filling volume of the cardiovascular system and EPO secretion. Such a link has clinical implications that need to be further explored in the future.

- Terrestrial Support Studies

Studies in space must be carefully prepared using ground-based simulation studies, as is illustrated by two fundamental aspects of space research that are often overlooked. The first is that research carried out on the same subject by a number of different teams must be integrated operationally before any data are collected, not least for the welfare of the subjects. Less obvious is the fact that integrated research requires that an integrated model drives the scientific planning, protocols and methods. Experiments in space are carried out on a small number of subjects. In these circumstances, the strength of normal statistical methods is partially replaced by a new form of validity related to the scope of measurements across traditional research boundaries in the same subject.

To satisfy these requirements, ESA and NASA, in collaboration with several national agencies in Europe, have carried out joint studies. One of these took place in Cologne in 1988, in which subjects remained in a 6° HDT position for 10 days and many parameters were studied before, during and after the session. 12 research groups participated in this study, investigating predominantly the cardiovascular system under these conditions.

The significance of the integrated model can be seen in Figure 2.1.1.8. The upper portion shows the temporal history of the study. 12 days before the HDT session started, the subjects had to undergo numerous tests, indicated on the right side of the figure. Tilt-table tests were performed to ascertain orthostatic stability before and after the HDT session. The subjects also had to undergo Lower-Body Negative Pressure (LBNP) tests, in which the lower half of the body is fitted into an airtight box. With the help of a vacuum pump, a negative pressure around the tissues is created, which induces a shift in blood volume from the upper parts of the body towards the lower limbs. This simulates an orthostasis test, although the subject is actually in a supine position. Even more importantly, the procedure can be used in space to induce a fluid distribution as if on Earth. This test helps prepare the astronauts for re-entry into the Earth's gravity, by familiarising them with the physiological changes occurring in their bodies.

The lower part of Figure 2.1.1.8 is a schematic of the equipment used, many pieces of which are mounted along the body axis. In this study, saline infusions were given to study fluid excretion under HDT conditions. These infusion experiments were later repeated in space.

Mention should also be made here of parabolic flight studies, in which periods of about 20 seconds of microgravity can be produced aboard an aircraft. A Danish group used this method extensively in the late nineties to investigate the cardiovascular

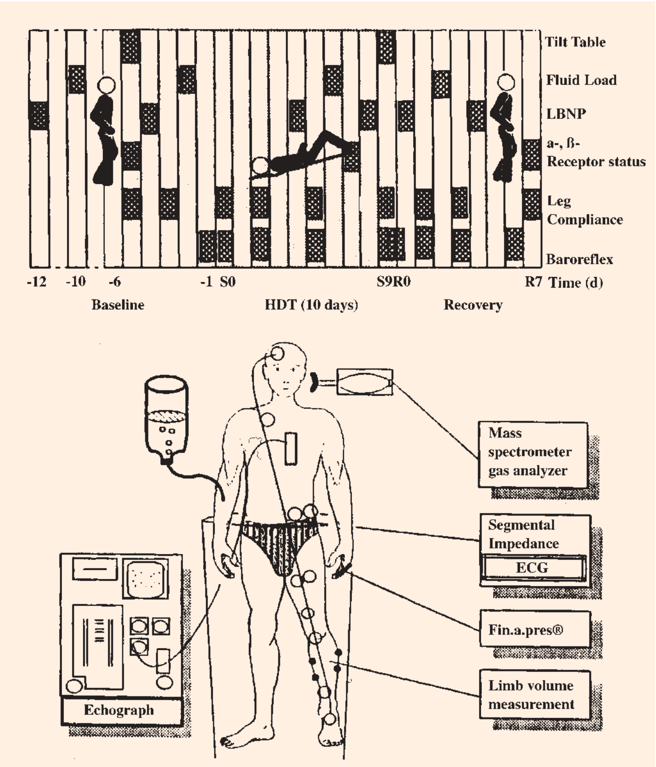


Figure 2.1.1.8. The time history of a Head-Down-Tilt (HDT) study. The different tests are listed on the right. The dotted bars indicate the times of measurements

system under microgravity conditions. Many of the short-term effects seen in space could indeed be reproduced during the parabolic flights.

In the course of such studies, European physiological researchers have learned to cooperate in large groups, like particle physicists, to do ‘big science’. In this respect, space medicine must be regarded as a trend setter for life-sciences in general.

- *Isolation Studies*

In space, a person is not only disconnected physically from the Earth, but also isolated from his/her normal social environment. An astronaut is confined together with colleagues in a rather small cabin, from which escape is impossible. Isolation, confinement, overcrowding and stress can have a major impact on the human body in general, and on the cardiovascular system in particular. To study these effects, ESA conducted three isolation studies in which several different European groups participated. Special emphasis was placed on psycho-physiology, which included cardiovascular-system investigations.

The first study, in 1990, took place in Bergen (N), with six male subjects living for four weeks in a small diving chamber. In 1992, another study was performed in Cologne in which only four subjects (1 female and 3 males) took part. Their confinement lasted six weeks. In 1994/95, a similar study was performed in Moscow with three Russian subjects, which lasted four months.

In the first study, where the subjects had a heavy workload, they felt stressed and their blood pressures and heart rates went up significantly. For the second study in Cologne, the workload was deliberately reduced and none of the subjects displayed increased blood pressure.

Another interesting point is body-weight management. Of the ten subjects investigated in the first two studies, eight ended up with lower body weights, four significantly so. In the Moscow study, the three subjects, all of whom were obliged to stop smoking before going into isolation, gained considerable weight (5 to 12%). This is an example of how previous life style can play a role in the effects observed in space, which is another interesting lesson. Which factors, in the final analysis, lead to loss of body weight in space is still unclear, with all findings in space being overshadowed by the effects of stress, confinement and isolation. Only terrestrial studies of the sort reported above will allow the true effects of the various parameters at work in microgravity on the human body to be distinguished.

2.1.1.3 Conclusions

Space physiology and medicine have led to the reconsideration of the role played by gravity in living systems in general, and in the human cardiovascular system in particular. Attention has been directed to comparative physiology where, on the basis of many examples, it could be shown that gravity has deeply shaped both the form and function of the cardiovascular system. In the course of earlier experiments, it was learned that concepts derived from Earth-based studies very often do not match the realities in space, which can be rather frustrating. It also opens up immense perspectives, however, by demanding reconsideration of the concepts developed on Earth, thereby guaranteeing progress in our knowledge. For example, the design and application of new technologies in such fields as geriatrics or psycho-physiology are the tangible outcome of our research efforts in space.

Europeans have already learned to co-operate closely with their neighbours in space physiology and medicine in order to be competitive in the race to live and work in space, both now and in the more distant future.

Further Reading

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Acknowledgements

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2.1.2 Pulmonary Function in Space

D. Linnarsson

2.1.2.1 Introduction

The lungs, the heart and the blood vessels are all links in a serially arranged transport system for the exchange of gases between the environment and the cells in the human body. Transport between the environment and the lungs is convective ('normal flow'), driven by the cyclic expansion of the lung volume. Within the air spaces of the lungs, diffusive transport (i.e. movement of gas molecules driven by concentration differences) dominates. It is also by diffusive transport that gases penetrate the thin membrane that separates the most peripheral air spaces of the lungs from their perfusing blood. Within the blood, gases are chemically bound to proteins in the red blood cells. The gas transfer between the lung gas and the blood is, to a large extent, determined by the rate of blood flow through the lungs. Thus, the functioning of the lungs cannot be seen in isolation. It must be analysed together with the cardiovascular functions, which determine the flow and volume of blood in the lungs.

Changes in the direction and/or the magnitude of the gravity vector have a profound influence on lung function and blood circulation, since both the lungs and the cardiovascular system lack rigid structural elements. They are therefore easily deformed by an external force such as gravity.

2.1.2.2 Background

The human lungs have a volume of 4 – 7 litres and a mass of 1 kg, about half of which is blood. Tissues, including blood, and air spaces are arranged in a three-dimensional elastic network and there is a 1000-fold difference between the densities of the tissues and the gas. This combination of the easily deformed structure and the large density difference between its structural elements renders the lung especially susceptible to changes in the magnitude and direction of gravity.

- *Distribution of Ventilation*

The present classical textbook concept of the influence of gravity on the distribution of ventilation in the lungs, illustrated in Figure 2.1.2.1, was developed partly from studies performed in a high-gravity environment.

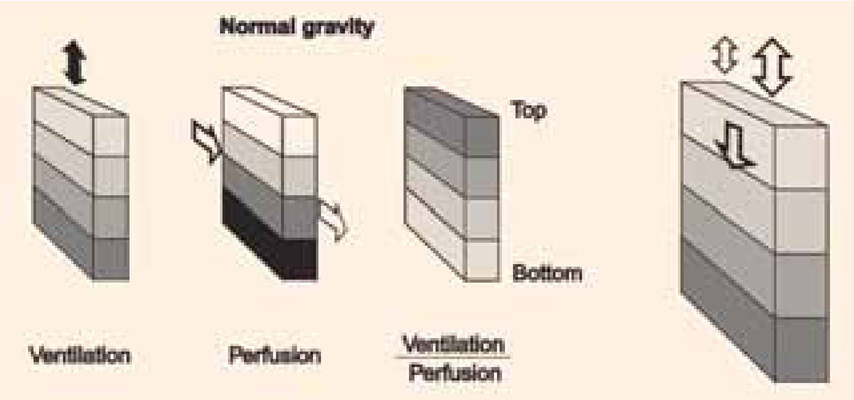

Figure 2.1.2.1. A schematic representation of the textbook concept of ventilation and perfusion distribution in the lung in normal gravity. In that concept, gravity tends to favour the bottom parts of the lung with respect to local ventilation (breathing volume/unit time and unit lung volume) and perfusion (blood flow/lung volume). The top to bottom gradient of local perfusion is larger than that for ventilation. Therefore, the ventilation/perfusion ratio is highest at the top and lowest at the bottom. The vertical gradient of this ratio is much less than that of ventilation and of perfusion

The basis for this concept is that the weight of the lung tissue pulling downwards keeps the air spaces at the top of the lung expanded, so that they cannot expand much further during inspiration. In contrast, air spaces at the bottom of the lungs are less expanded and have a greater ability to expand during inspiration. Thus, there is an inherent ventilation gradient per unit lung volume, with much higher ventilation at the bottom than at the top. Along with the greater mobility of the air spaces at the bottom, however, also comes an increased tendency for airway closure at low lung volumes.

- *Distribution of Perfusion*

Early experiments with isolated animal lungs showed that the perfusion (blood flow) differences between the upper and lower parts of the lung could be accounted for by the relationships with blood pressure in the vessels at different heights. Since the vertical pressure gradients in the pulmonary vascular system were gravity-induced hydrostatic gradients, gravity was considered to be the principal determinant of perfusion distribution in the lung (Fig. 2.1.2.1). In these experiments, perfusion per unit lung volume was assessed with a radio-isotope technique having a limited resolution. It is not surprising, therefore, that more recent studies have revealed additional, non-gravity-dependent perfusion differences between lung areas, when measuring with higher resolution and in more than one dimension. However, even these more recent techniques have inherent limitations. The existence of non-gravity-dependent differences in local lung perfusion therefore remains a matter of some controversy.

- *Ventilation/Perfusion Ratio*

A comparison of the distributions of ventilation and perfusion in Figure 2.1.2.1 reveals that, in both processes, the bottom part is favoured, so that most of the gas exchange in the lungs takes place in the lower, most gravity affected part. The distributions of the two processes, however, are not congruent. The top-to-bottom gradient for ventilation is less steep than that for perfusion. Consequently, the ventilation/perfusion ratio is highest at the top and lowest at the bottom. In other words, the top part is relatively over-ventilated, despite a modest absolute ventilation per unit lung volume, and the bottom part is relatively under-ventilated (with respect to perfusion) despite a large absolute ventilation per unit lung volume (Fig. 2.1.2.1, right).

2.1.2.3 Scientific and Clinical Problem Areas: Some Questions

Many of the basic concepts of treatment and diagnosis in pulmonary medicine and critical care rest on the above concepts of how gravity influences lung function. However, for gas exchange in the lungs to result in satisfactory oxygenation of the blood leaving the lungs, it is the ventilation/perfusion ratio, rather than ventilation or perfusion, which must be homogeneously distributed throughout the lungs. Thus, the basic scientific and clinical problems are to identify factors that influence the matching of ventilation to perfusion, or vice versa.

Question 1: 'Is it gravity that synchronises the distributions of ventilation and perfusion?'

As shown schematically in Figure 2.1.2.1, the ventilation/perfusion ratio is not perfectly homogeneous with respect to gravity, but is much closer to being so than either of the two separately involved processes. Another way to formulate the question is, will ventilation and blood perfusion in the lungs become uncoupled in the absence of gravity? Will there be a failure in the gas transport from the lung gas to the blood? Here it should be remembered that early during the era of manned spaceflight, there were serious predictions of lung failure and inner drowning resulting from fluid congestion in the lungs.

Question 2: 'Is it instead gravity that is an impediment to ventilation and perfusion in the lungs, which is partly offset by similarities in the effect of gravity on the two processes?'

In other words, would the distributions of ventilation and perfusion become homogeneous in microgravity, with a resulting ideally homogeneous distribution of ventilation/perfusion ratios and a 'perfect' gas exchange?

Question 3: 'If ventilation and perfusion do not become homogeneously distributed in the lungs in microgravity, what are the factors that determine gas and blood distributions in the lungs apart from gravity?'

Are these factors the structural properties, such as the dimensions and elastic forces of the airways and blood vessels?

Question 4: 'Are there feedback control mechanisms that synchronize ventilation and perfusion, but that cannot be discerned as long as gravity exerts a much larger influence?'

One such mechanism that has been proposed is a sensing of airway oxygen concentration and an associated control of blood-vessel diameter. This would result in reduced blood flow to a lung area with low oxygen gas content caused, for example, by an obstructed local airway (hypoxic vasoconstriction). Another mechanism proposed is the generation, or the inhalation, of nitric oxide, a potent agent that dilates the blood vessels, and which would act in well-ventilated lung areas. There are theoretical foundations for such mechanisms, but the practical importance in health and disease remains to be demonstrated.

Question 5: 'What is the reason for the dramatic improvement seen when patients with severe lung failure (acute respiratory distress syndrome, or ARDS) are treated in a prone (face-down) instead of a supine (face-up) position?'

The present understanding of the effects of gravity on lung function is not sufficient to explain this potent treatment modality.

Question 6: 'What are the characteristics of fluid exchange between lung tissue and blood?'

Excessive fluid accumulation in lung tissue and in the air spaces (lung oedema) is a very severe complication in heart failure. The unique changes in body-fluid volume and its distribution seen in humans during spaceflight offer an equally unique opportunity to learn more about the mechanisms of fluid exchange in the lungs.

2.1.2.4 The Results of Space-Related Research and Future Potential

Ever since the first astronaut Yuri Gagarin returned safely from 70 minutes of weightlessness in April 1961, it has gradually become obvious that the dire predictions of severe lung congestion were incorrect. During the early era of manned spaceflight, only limited studies of lung function in space were performed. Later, the combination of the US Space Shuttle and the European-built Spacelab provided a suitable laboratory environment for in-flight studies of human physiology. Research groups, both in the USA and in Europe, identified lung physiology as an area where much could be learned about the normal effects of gravity on lung function from experiments carried out in space. Therefore, both NASA and ESA developed facilities for pulmonary-function studies in sustained microgravity.

The first estimates of the distributions of ventilation and perfusion in the lungs in microgravity, derived from aircraft parabolic flights in 1978, suggested that both ventilation distribution and perfusion distribution became more homogeneous in the absence of gravity. But there were signs of some residual inhomogeneity, which may or may not have been ‘spill-over effects’ from the period of hypergravity that precedes the short period of microgravity during parabolic flights.

Using similar methods, but now with the advantage of a sustained microgravity environment, the same research group, from the University of California, San Diego, studied lung function in astronauts during the Shuttle Spacelab flights SLS-1 in 1991 and SLS-2 in 1993. Using more recent technology developed by ESA, a group of European and American investigators performed lung physiology experiments during the German Spacelab D-2 mission in 1993 (see Fig. 2.1.2.2). Two years later, they were able to perform experiments in long-term microgravity conditions on a 179-day Mir flight. In parallel, parabolic-flight experimentation was conducted that was instrumental in the preparation and follow-up of the space experiments.

- *Respiratory Mechanics*

Russian researchers have shown that long-term spaceflight is associated with a reduced peak expiratory flow and reduced forced vital capacity in 1 second. Significant reductions were observed after about 120 days of spaceflight. These changes were attributed to deconditioning of the respiratory muscles. This explanation seems plausible, because the postural muscles in the abdomen, thorax, shoulder, and neck are unloaded in microgravity. These muscles also serve as accessory breathing muscles during a maximum effort. Alternative or co-existing explanations that remain to be investigated are obstructive changes owing to aerosol inhalation, and changes in compliance and airway dimensions owing to local or general interstitial oedema.

Figure 2.1.2.2. Astronaut Hans Schlegel performing lung-function experiments during the German Spacelab D-1 mission

Short-term microgravity has been shown to result in well-defined changes in respiratory mechanics. Functional residual capacity decreased by about 0.3 litres compared to the upright control, to a value halfway between upright and supine. This was most likely the result of an upward shift in the position of the diaphragm, when the weight of the abdominal organs was removed in microgravity. In sustained microgravity, tidal volumes have been shown to be slightly reduced, but pulmonary ventilation of resting man was maintained owing to a slight increase in breathing rate. From a theoretical standpoint, vital capacity (VC) can be predicted to change in either direction in microgravity; a more uniform lung expansion would favour an increase in VC, whereas an increased thoracic blood volume would favour a decrease. Also, expired and inspired VC determinations may differ, since an inspired VC would start with a maximum expiratory effort, which would reduce the intra-thoracic blood volume. Expired VC, however, starts with a negative intra-thoracic pressure. It would therefore be influenced by an increased tendency for intra-thoracic blood pooling.

An increase in expired VC values has been found after two weeks in space, suggesting that, at that time, a more even alveolar expansion dominates over any tendency for increased intra-thoracic blood pooling. In contrast, during the first days of spaceflight, expired VC was not increased compared to pre-flight upright control. This supports the notion that an initially increased intra-thoracic blood volume counteracted the vital-capacity-increasing effect of a more even alveolar expansion.

- *Ventilation Distribution*

Classical methods for ground-based studies of ventilation distribution have been implemented during spaceflight. Astronauts inhaled one breath of an insoluble, non-toxic gas (with normal oxygen content), to study how it mixed with the gas remaining in the lung at the end of the preceding breath. It was found that different lung regions did not empty synchronously during expiration, and that these different lung regions had received varying amounts of the inhaled tracer gas. Such asynchronous emptying of regions and inhomogeneity of breath distribution were previously thought to be caused by gravity and, indeed, it is a regular finding in experiments in normal gravity. Subsequently, it was shown that in sustained microgravity, the wash-in time course of an insoluble gas into the lungs was far from homogeneous.

- *Distribution of Perfusion, Diffusion Capacity*

To assess the anatomical distribution of perfusion within the lungs, radiographic or isotope-imaging techniques are required. So far, such methods are not available for use during a space flight. Thus, more indirect techniques must be utilised. Figure 2.1.2.3 shows a recording obtained during a recent parabolic flight, using the Advanced Gas Respiratory Monitoring System, a facility developed by ESA for use on the International Space Station.

Essentially, inhalation of blood-soluble gases is utilised to assess the blood flow in the lungs. A breathing manoeuvre is first performed, to make the composition of soluble gas in the lungs as even as possible. Then the breath is held to permit uptake of soluble gas into the blood, and finally a slow expiration (expirogram) is made, where signs of uneven gas uptake (and perfusion) can be detected. Such signs are heart-synchronous variations of soluble gas concentration (cardiogenic oscillations) and end-expiratory (Phase-IV) gas-concentration deviations.

A similar indirect approach has been applied to humans during sustained microgravity. Alveolar PCO_2 and inter-regional PCO_2 differences in the lung were reduced by vigorous hyperventilation. Carbon-dioxide expirograms were then recorded, following a breath hold. Observed Phase-III cardiogenic oscillations of PCO_2 were considered to be the result of PCO_2 differences between lung units with different perfusion-dependent rates of CO_2 accumulation. Sustained microgravity was associated with a reduction – but not an elimination – of cardiogenic CO_2 oscillations in expired air. Phase-IV end-tidal deviations of PCO_2, however, practically disappeared in microgravity. It was concluded that inhomogeneity still existed within regions that were not gravity-dependent. Gross inter-regional perfusion differences, however, probably disappeared in the absence of gravity.

Further studies of the rate of pulmonary blood flow and of the pulmonary diffusion capacity have shown pulmonary perfusion to be increased during the initial days of microgravity and to return towards pre-flight upright values after about one week. Membrane diffusing capacity became markedly improved in microgravity, compared to both upright and supine pre-flight controls. This improvement was maintained throughout a 9 day microgravity period. The improved pulmonary diffusing capacity was attributed to a more even distribution of capillary blood in the lungs and a more efficient interface between the gas and the blood in the lungs.

The finding of an improved diffusing capacity speaks strongly against any generalised interstitial oedema in the lungs, something that was considered a risk, especially in the period before large-scale manned space operations. For long-duration microgravity, however, there is no experimental support for excluding the possibility of subclinical oedema in pulmonary tissues

Soluble gas uptake in the lungs can be used to assess the lung tissue volume. Such measurements are relevant to the question of whether there is fluid transfer into the lung tissue (lung-tissue oedema). As described in Section 2.1.3, there is a marked transfer of tissue fluid from the legs to the upper body during sustained microgravity. Contrary to expectations, the lung-tissue volume was reduced in flight, very much in proportion to the overall reduction in plasma volume.

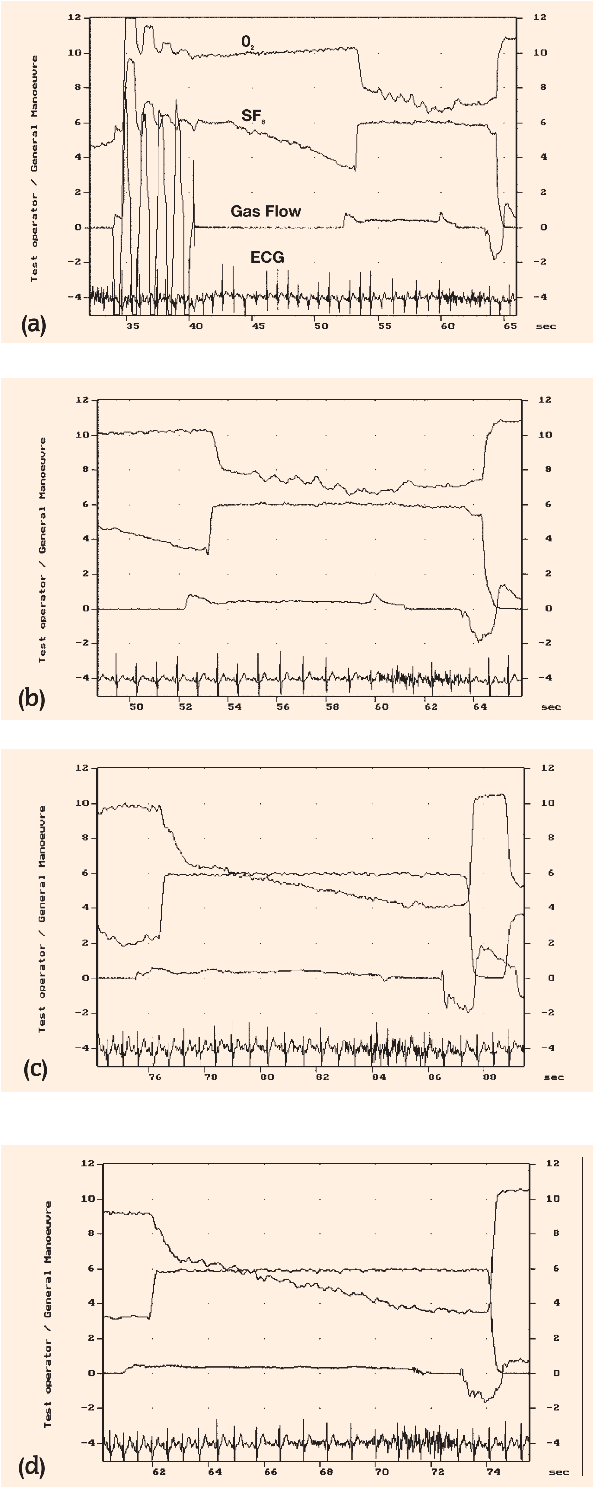

Figure 2.1.2.3. Assessment of perfusion inhomogeneity in the lungs of a sitting subject, during a parabolic flight, using uptake of a soluble gas as measured by the Advanced Gas Respiratory Monitoring System. From the top: oxygen (% x 10), SF_6 (% x 10), the respired gas flow, and an ECG measurement.
(a) Time course of typical procedure, recorded in 1g.
34 – 40 sec, rapid re-breathing of 25% O_2, 1.6% SF_6 (insoluble in blood). 40 – 52 sec, breath holding. 52 – 64 sec slow exhalation to residual volume, with fairly constant SF_6 level suggesting adequate intra-pulmonary gas mixing.
(b) Same as above, on expanded time axis during expiration. Note the marked cardiogenic oscillation of expired O_2.
(c) The same expiration in microgravity. Note the absence of cardiogenic oscillations.
(d) Following breath holding during initial high-g, the subsequent expiration recording made in low-g shows the reappearance of cardiogenic oscillations.

Together, these data show that cardiogenic oscillations of expired O_2 in 1g are due to uneven perfusion and O_2 uptake in lung units. It can be concluded that the absence of cardiogenic O_2 oscillations when both breath holding and expiration take place in microgravity must be caused by a more homogeneous O_2 content and perfusion between lung units, and not by an altered mechanical interference between the heart and lungs

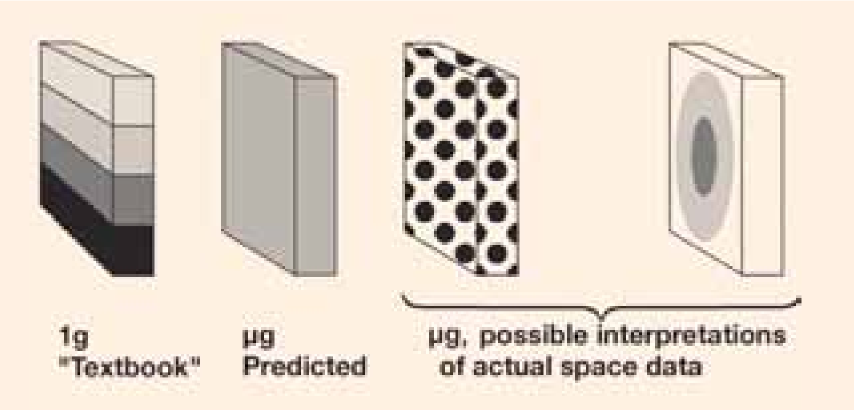

Figure 2.1.2.4. Schematic of a modified concept for perfusion distribution in the lung, based upon recent space measurements. Contrary to predictions, indirect methods suggest the presence of residual unevenness in lung perfusion in microgravity. The anatomical distribution of this uneven perfusion has not yet been established and two possible modes of non-gravity-dependent inhomogeneity are shown

- *Scientific and Clinical Problem Areas*

Some answers to the questions posed earlier have come from space-related research.

Concerning the first question that was posed: *'Is it gravity that synchronises the distributions of ventilation and perfusion?'*, the answer is no. Gravity is not such an essential coordinating link between ventilation and perfusion that these processes become uncoupled in microgravity.

'Is it, instead, that gravity is an impediment to ventilation and perfusion in the lungs, which is partly offset by similarities in the effect of gravity on the two processes?' The answer is yes, to some extent the effects of gravity on ventilation and perfusion distributions are not congruent, and so the two processes appear slightly better co-ordinated in microgravity than in normal gravity, as shown by an improved diffusion capacity.

The third question was: *'If ventilation and perfusion do not become homogeneously distributed in the lungs in microgravity, what are the factors that determine gas and blood distributions in the lungs apart from gravity?'* So far, space-related research has not revealed the nature of the factors that determine ventilation and perfusion distributions in microgravity. Imaging techniques based on ionising radiation are today the only method available for determining the topographical distribution of ventilation and perfusion in the lung. An equivalent technology needs to be made available in space.

'Are there feed-back control mechanisms that synchronise ventilation and perfusion, that cannot be discerned as long as gravity exerts a much larger influence?' This issue

of active feedback control mechanisms to synchronise ventilation and perfusion has so far not been addressed during space-related research. However, the development of hardware for in-flight analysis of nitric oxide has recently been proposed.

Question number five was: *'What is the reason for the dramatic improvement that is seen when patients with severe lung failure are treated in a head-down instead of a face-up position?'* As yet, the issue of prone/supine differences in gas exchange efficiency has only been addressed in normal and hypergravity. However, in future spaceflight experiments, both supine and prone controls will be performed on the ground for comparison with data obtained in space. Thus space experiments will be instrumental in defining gravitational effects on the lungs over the whole range of gravity directions and magnitudes.

The final question that was raised is: 'What are the characteristics of fluid exchange between the lung tissue and the blood?' The unexpected finding of a reduced pulmonary tissue volume in microgravity suggests that the understanding of the fluid exchange between the blood and the lung tissue is far from complete. This finding, however, deserves confirmation with improved instrumentation and more subjects.

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2.1.3 Fluid and Electrolyte Regulation and Blood Components

P. Norsk

2.1.3.1 Introduction

In order to sustain life, the amounts of water and salt (fluid and electrolytes) in the body are rigorously controlled within narrow limits, despite large fluctuations in intake. It is, however, surprising that despite more than a hundred years of research, the basic mechanisms of this life-sustaining system are not fully understood. One reason for this lack of understanding is that the water and salt regulation is complex and involves elements of several physiological systems such as the circulation, hormones, nerves, and kidneys. Another reason is that the methodology and experimental procedures have been insufficient.

With the advent of manned spaceflight, two possibilities emerged with regard to research into fluid and electrolyte regulation: (i) weightlessness could be used as a tool, to stimulate the body in a way that was not possible before, and (ii) the methodology for measuring the physiological variables could be improved by the space programmes.

The reason that weightlessness is unique for understanding how the body regulates the amount of salt and water is that the fluid-volume control mechanisms are sensitive to changes in gravity. During the course of daily life on Earth, there are fluctuations in blood and fluid along the body axis as the subject's posture changes with respect to the gravity vector. In the microgravity environment of space, those large fluctuations are abolished. Because those fluctuations affect the excretion rates of water and salt in the urine, more information can be gained by performing experiments in space. Microgravity thereby becomes an additional, advanced tool in studies to try to answer one of the fundamental questions of physiology: How does the body regulate the salt and water balance?

2.1.3.2 Basic Fluid and Electrolyte Regulation

The water- and salt-controlling mechanisms constitute a complex interaction between the cardiovascular reflexes, fluid- and electrolyte-regulating hormones, and the kidneys. Furthermore, physical factors such as blood pressure and dilution of the blood with tissue fluid also play significant roles. Finally, the concentration of electrolytes in the blood and tissue fluids determines the excretion rate of water in urine. If the electrolyte concentration is high, this will be perceived as thirst, so that drinking is increased and urinary water excretion diminished. It is the reverse situation when electrolyte concentrations are lowered. If, for example, one litre of pure water is abruptly consumed, the concentration of electrolytes is diminished by some 2% and the surplus water is excreted within 2 – 3 hours.

When the intake of salt is increased, not only the salt but also water is retained in the body, so that the concentration of electrolytes is maintained unchanged by the mechanism described above. Therefore, an increase in salt intake leads to fluid volume expansion. This is sensed by receptors, which through nerve signals inform the central nervous system of the increase in volume. Through another set of nerve signals, messages are sent to the kidneys to excrete more sodium. The urinary excretion rate of water will subsequently also increase to prevent the concentration of electrolytes from decreasing. Thus, the water-regulating mechanisms are activated primarily by changes in the concentrations of electrolytes in blood and tissue fluids, and the sodium-regulating mechanisms by changes in fluid volume.

The sensors for detecting changes in electrolyte concentrations reside in the brain and are connected to the main water-regulating hormone, vasopressin (antidiuretic hormone). The location of the receptors for detecting fluid volume is still debated, but they are generally thought to be located in the heart chambers, adjacent vessels and central arteries. Through nerve connections, they communicate with sodium-regulating hormones and the kidneys. In addition, peptides in the heart, brain, and kidneys can be released by nerve activity or, in regard to the heart, directly by mechanical stretching so that excretion of salt can be facilitated.

At present, it is fair to say that the qualitative significance of each of the above-mentioned systems has largely been determined, whereas the quantitative significance has not. Because the systems are sensitive to changes in gravitational stress, space research can contribute to quantifying the significance of each of these systems.

2.1.3.3 Gravity and Fluid Volume Regulation

That the water- and salt-regulating mechanisms in humans are sensitive to changes in gravitational stress has been known for decades. Humans who are upright excrete less water and salt in their urine than those who are supine. The reason is that in the upright position one retains as much salt and water as possible, in order to maintain an adequate blood pressure to the brain. On the other hand, when humans are supine, the body perceives the amount of blood and fluid in the heart as being exaggerated. Therefore, water- and salt-excreting mechanisms are activated.

The mechanisms of the posture-induced changes in urinary water and salt excretion are thought, as described above, to be primarily stimulated by fluid-volume receptors in and/or close to the heart. When humans are supine, the heart and nearby vessels are distended, because blood moves from the legs towards the head. The opposite is the case when humans are upright. During water immersion, the movement of blood and fluid towards the upper body parts is more pronounced. This leads to augmented increases in water and salt excretion by the kidneys, which exceed those of a posture change from upright to supine.

Even before manned spaceflight, it was anticipated that weightlessness would cause increased excretion of water and salt in urine. This expectation was based upon the results of water immersion experiments. Water immersion was, and is still by some, considered an analogue of weightlessness. It induces salt loss at a rate six times higher than when the subjects are seated in air. At the same time, the loss of water is more than doubled. Therefore, before humans went into space, it was expected that similar fluid and salt excreting mechanisms would be activated by weightlessness and that the astronauts would lose water and salt through the kidneys.

2.1.3.4 Distension of the Heart in Microgravity

The question of whether the heart is distended during the initial hours of spaceflight by weightlessness is important. As described previously, distension of the heart is thought to stimulate urine production. In the early studies from the Apollo and Skylab missions in the 1960s and 70s, the astronauts reported ‘puffy’ faces and feelings of fullness in the head. This was regarded as a consequence of blood and fluid transferring from the lower to the upper parts of the body. Another indication supporting this idea was the decrease in the size of the legs. Therefore, from the early days of manned spaceflight, indirect evidence supported the hypothesis that blood is moved to the heart, adjacent vessels and head during weightlessness.

More direct evidence that the blood supply to the heart is augmented at the beginning of spaceflight has been obtained in the 1980s and 90s. By imaging the heart chambers using ultrasound techniques (echocardiography), it was observed that during the initial hours of spaceflight the heart is distended. The heart is even larger than in supine humans on the ground. However, the mechanisms causing this distension are not as originally anticipated. Direct pressure measurements show that the pressure in the regions outside the heart is decreased. This decreased pressure on the outside surface of the heart augments the distension, and might be caused by a change in the configuration of the lungs and chest wall. Distension of the heart at the beginning of a spaceflight is therefore not only caused by passive movement of blood and fluid from the legs to the upper parts of the body, it is also caused by an anatomical change in the configuration of the chest walls and lungs. This is a new discovery and one that has been confirmed by experiments during parabolic flights with 20 seconds of weightlessness.

Thus, during the initial hours of a spaceflight, the heart and adjacent vessels are distended. This should, according to the results of simulation models on the ground, initiate an increased excretion rate of water and salt in the urine, with a resultant loss in body fluid.

2.1.3.5 Expected Responses in Space

During the initial decades of manned spaceflight, expectations of how physiological systems would respond to weightlessness were based on the results of simulation experiments. In this context, the head-down bed-rest model has been preferred to water immersion, because it is more easily applicable for interventions of several days or weeks, although its true applicability in this regard has never been directly tested. The model was considered adequate for simulating the effects of weightlessness on fluid and electrolyte control, because the astronauts usually lose 2 – 4 kg of body mass during the initial days of flight. This mass loss was considered to consist primarily of electrolytes and fluid. Furthermore, the volume of blood is reduced by some 10 – 17%. Head-down bed rest also reduces blood volume, by approximately 10%. Hence the head-down bed-rest model was thought to simulate the effects of weightlessness reasonably well.

The mechanisms of the augmented urinary excretion rates of salt and water during head-down bed rest are depicted in Figure 2.1.3.1. Head-down bed rest induces an increase in the blood volume in the heart and nearby vessels, which through the mechanisms described earlier promotes the higher urinary excretion rates of salt and water. A new state of adaptation is then achieved, with a diminished fluid and blood volume.

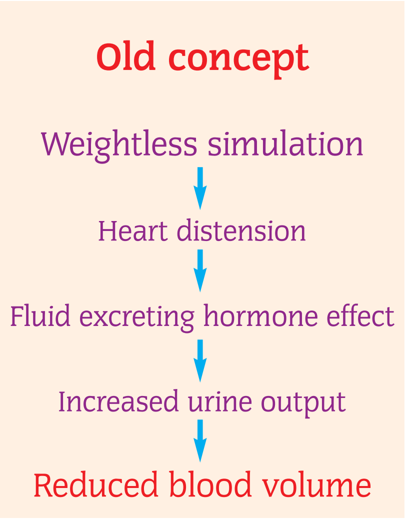

Figure 2.1.3.1. The old concept of how fluid and blood volume were reduced by weightlessness, based on the results of simulation experiments (e.g. head-down bed rest). When changing posture from upright to 6° head-down, blood and fluid from the lower parts of the body are moved towards the heart and head. The heart is distended by an increased blood supply, which through nerve connections and hormones induces an increased loss of water and salt in urine. This leads to a reduction in blood volume. When the salt- and water-excreting mechanisms in head-down bed-rest subjects are stimulated by infusion of salt solutions or drinking-water loads, urine output still remains high

When water and salt stimuli (e. g. infusion of salt solutions or drinking-water loads) are applied to head-down bed-rested humans, the urinary excretion rates stay high despite reductions in blood volume and body fluids. This observation indicates that it is the augmented urinary excretion rates of salt and water during the initial phase of bed rest that accounts for the fluid and blood volume deficit.

2.1.3.6 Surprising Responses in Space

Spaceflight results during the past 20 years indicate that the generally accepted scheme (Fig. 2.1.3.1) whereby astronauts lose water and salt in space is not correct. There are no indications that urine output is increased in space; in fact there are indications to the contrary. Already during the Apollo flights to the Moon, it was observed that the urine outputs were always lower than on the ground, even though the astronauts lost several kilogrammes of body mass. The same was observed during the Skylab flights some years later. It was suggested that the low urine outputs during the initial phase of flight were caused by less fluid intake and that the urine outputs were in fact augmented compared to the intake. This notion has not, however, been substantiated by direct observations. Recent studies on the Shuttle and on the Russian Mir station indicate that the water and salt output in the urine is not increased.

If the scheme described in Figure 2.1.3.1 were correct, one would expect urine output following a water and salt stimulus to be the same in space as during head-down bed rest, but this is not the case. During the German D-2 Spacelab mission, a salt solution with the same tonicity as body fluids was infused into the astronauts. The in-flight conditions were standardised so that, except for weightlessness, they resembled those of the ground-based control. Urine output was stimulated by the infusion, but to a much lesser degree than when the astronauts were supine on the ground. This was not anticipated. The urine output in space was therefore attenuated, which was not expected on the basis of the results from ground-based simulation studies. Results from the Euromir '95 mission confirm that urine output following the drinking of water is also attenuated and that it was not predictable from long-term simulation by head-down bed rest.

Another unexpected finding in space during the D-2 mission was that the nervous activity, which controls the degree of constriction of the blood vessels and can modulate urine production (sympathetic nervous activity), was higher than anticipated (Fig. 2.1.3.2). The increased sympathetic nervous activity was determined by estimating the concentration in the blood of a hormone, norepinephrine, which is a component of this system. Usually, the activity of this portion of the nervous system is low during head-down bed rest. There is no apparent reason why this system's activity should be high in space, because there is no obvious reason for the vessels to constrict or for the kidneys to produce less urine. These observations were confirmed later by American and European scientists during the Neurolab mission in 1998.

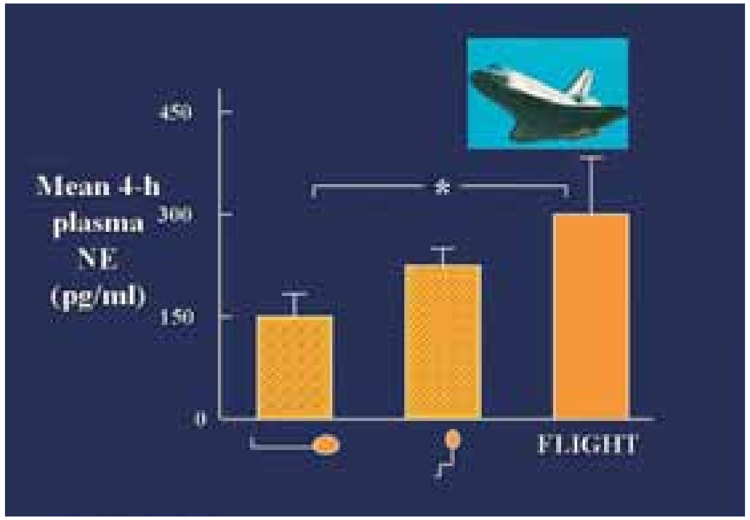

Figure 2.1.3.2. Concentration of norepinephrine (NE) in the blood of four astronauts, averaged over a 4-hour period during: (1) supine conditions on the ground, (2) upright seated conditions on the ground, and (3) after adapting to 4 – 5 days of weightlessness (flight) on the Shuttle Spacelab D-2 mission. The highest values were obtained during flight (indicates a statistically significant change). This was unexpected because head-down bed rest produces low values. The high NE levels indicate that sympathetic nervous activity is high with contraction of blood vessels and retention by the kidneys of salt and water (from Norsk et al. 1995, J. Appl. Physiol., 78, p. 2253)*

The pattern of an attenuated urine output of water and salt in space following stimulation by infusion and the high activity of the sympathetic nervous system fit together, because the latter might explain the former. However, it does not fit with the expectations from the results of the head-down bed-rest model. Therefore, the understanding of how gravity and weightlessness modulate the fluid and electrolyte regulation in humans was insufficient before the results of spaceflight experiments were available.

2.1.3.7 A New Concept

The current textbook descriptions are unable to explain why:
- urine production is not increased during the initial hours of spaceflight
- it is not stimulated to the same degree, by a water and salt load, in space as during supine ground-based conditions
- the fluid-retaining sympathetic nervous activity is high in space.

A new concept must therefore be developed.

Firstly, the diminished blood volume in space cannot be due solely to augmented urine production. Recent investigations indicate that the astronauts drink and eat less during flight. The reason for the reduced food and fluid intake is not known. It might be due to some degree of space sickness or to some as yet undetermined disturbances of the central nervous system by weightlessness. Secondly, blood volume might be reduced more by microgravity than by head-down bed rest, because there are indications that weightlessness promotes movement of fluid from blood to tissues. This might be caused by the total lack of gravity-induced tissue compression, which the body is continuously exposed to on the ground, particularly when supine. Thirdly, a minor contribution to the loss of blood stems from the fact that the heart is distended during the initial hours of weightlessness. This distension, probably acting through nerves and hormones, to some degree augments urine production.

Therefore, spaceflight might initially produce a fluid and blood volume deficit caused primarily by: (i) decreased intake of food and fluids, and (ii) movement of fluid from blood to tissues (extravasation). In space, blood volume is thereby reduced more than during head-down bed rest. This blood volume deficit could lead to activation of fluid and electrolyte retaining systems, and to low urine production and low urine responses to water and salt stimuli. This new hypothesis is depicted in Figure 2.1.3.3.

The fact that the urinary excretion rates of salt and water are attenuated in space, following stimulation by infusion or drinking water, indicates that the blood-volume deficit is not primarily caused by urinary losses at the beginning of spaceflight. It indicates rather that the urinary attenuations following infusion are secondary to those of blood-volume contraction (Fig. 2.1.3.3). This is in contrast to the effects of head-down bed rest, where the augmented urinary responses to water and salt infusions indicate that the initial urinary losses are the primary causes of the volume deficit (Fig. 2.1.3.1).

2.1.3.8 A New Simulation Model

The discrepant effects on the kidneys of head-down bed rest and of weightlessness indicate that bed rest is not a valid simulation model. Therefore, another more reliable model should be developed. The mechanisms of the discrepant effects of weightlessness and bed rest are at present unknown. As noted above, one explanation might be that during head-down bed rest the supine body is continuously compressed by its own weight. This might modulate the relationship between the heart-, fluid- and electrolyte-regulating hormones, and the kidneys. That the heart is compressed in supine humans is indicated by recent results from parabolic flights, where it has been demonstrated that the size of the heart promptly increases during weightlessness.

Whether water immersion for days, weeks or months simulates the effects of weightlessness in space better remains to be determined.

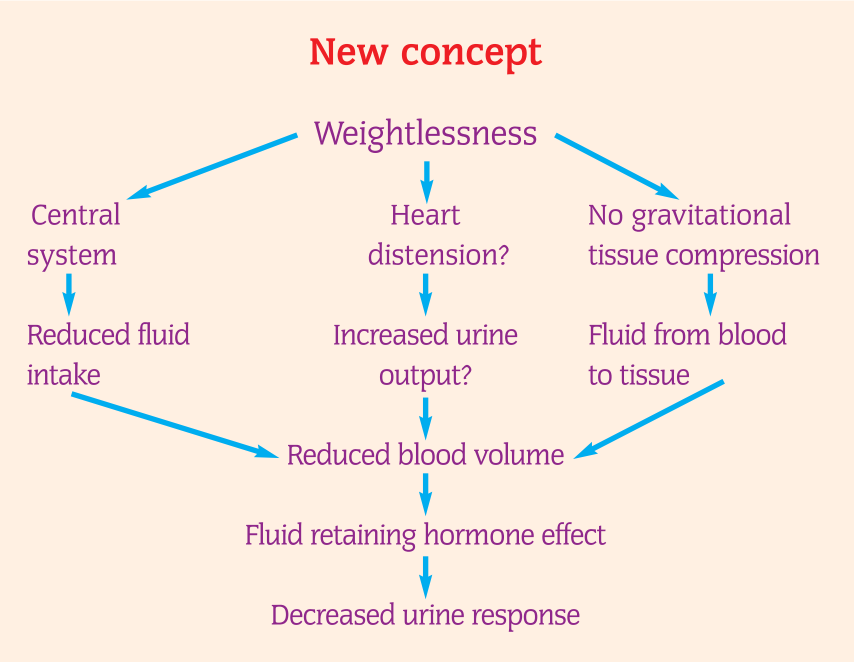

Figure 2.1.3.3. A suggested new concept for how blood volume is reduced during spaceflight. Immediately after launch, weightlessness induces: (i) a decreased fluid intake, (ii) absorption of fluid by the tissues from the blood, and (iii) distension of the heart. These effects all lead to a reduced blood volume, which activates fluid-retaining hormone systems and sympathetic nerves (Fig. 2.1.3.2), which in turn leads to secondary low urine responses to water and salt loads. According to this hypothesis, the reduction in blood volume is not caused primarily by the kidneys, contrary to the old hypothesis (Fig. 2.1.3.1) based on simulation experiments

2.1.3.9 Prolonged Spaceflight – A Testbed for Heart Disease?

The new concept (Fig. 2.1.3.3) in which the gravity-induced mechanical pressure on the body tissues in supine humans has a pronounced effect on fluid and electrolyte regulation and some of the associated blood components, is of relevance for understanding the mechanisms of disease. In patients with heart failure, fluid and electrolytes are accumulated in the body, because the heart cannot supply the organs with blood as efficiently as in healthy people. The accumulation of fluid leads to oedema and to a further deterioration in condition, thus establishing a vicious circle. Furthermore, heart-failure patients might experience difficulties when supine due to the gravity-induced pressure on the heart. Thus, the transverse gravitational stress in supine heart patients might explain some of the disease patterns. When a patient is upright, however, the weak heart has difficulty in maintaining blood pressure to the brain. Gravity is therefore a problem for heart-failure patients (Fig. 2.1.3.4).

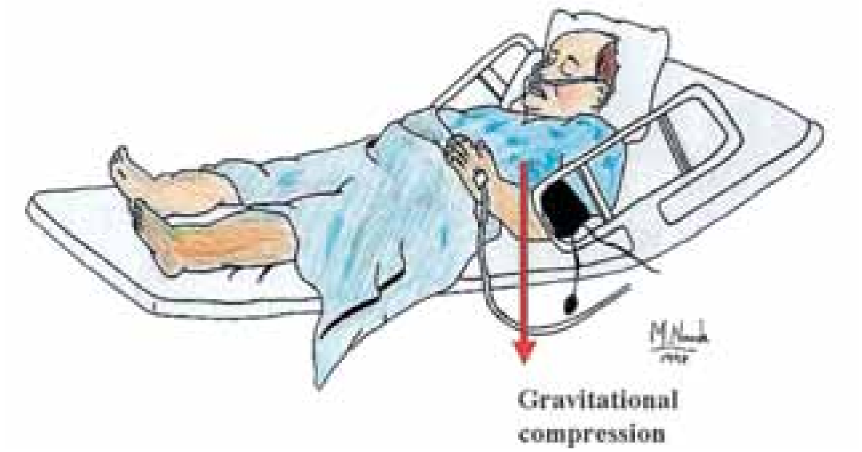

Figure 2.1.3.4. Heart-failure patients exhibit salt and water retention, with the accumulation of fluid in the tissues (oedema). The results of space and parabolic-flight investigations indicate that the heart is compressed in supine humans by gravity, which may cause further deterioration in the condition of heart patients. Investigations in space may reveal to what degree gravity affects the failing heart and how to counteract it

Heart patients also sometimes exhibit high levels of sympathetic nervous activity and of fluid- and sodium-retaining hormones. Astronauts in space exhibit the same patterns. The mechanisms of these augmented hormone releases and of sympathetic nervous activity are, however, different when comparing heart-failure patients with weightless astronauts, because the astronauts are still healthy. On the other hand, the activated hormone secretions and nervous activity might be caused by a diminished blood supply to the arteries. In the heart patients, this is because their heart is weak, while in the astronauts in space it is because their blood volume is reduced (Fig. 2.1.3.3). Therefore, prolonged spaceflight might constitute a testbed for investigating certain aspects of the mechanisms of heart disease.

By comparing the cardiovascular, hormonal and kidney variables of: (i) healthy astronauts on the ground, (ii) astronauts in space, and (iii) heart patients, the following question might be answered: *'How can astronauts, during prolonged spaceflight, exhibit the same physiological patterns as heart-failure patients without being ill?'* An answer to this question might reveal new disease mechanisms of importance for developing new treatments.

2.1.3.10 Conclusions and Future Research

In summary, fluid and electrolyte regulation and the changes in associated blood components in humans are modulated by gravitational stress. Weightlessness is therefore a unique tool for obtaining more information about integrated fluid volume control. Results from space, however, have been unexpected and not predictable from those of ground-based simulations. Consequently, the concept of how weightlessness and gravity modulate the regulation of body fluids and the associated blood components must be revised, and a new simulation model developed. In addition, the information obtained from space might be of relevance for understanding how gravity causes a deterioration in the fluid and electrolyte balance in heart-failure patients.

The surprising observations in space regarding the mechanisms of fluid-volume control in humans indicate that our knowledge of the effects of gravity on this system is insufficient. Furthermore, the conclusion that the well-known simulation model of head-down bed rest does not in fact simulate the effects of spaceflight indicates that the effect of compression of the recumbent human body by gravity is not well understood. Until the advent of manned spaceflight, only the effects of gravity on upright versus supine humans were explored. The results from space have shown that this approach is too narrow and simplistic.

Exploiting spaceflight in the future to obtain more information about how gravity affects the human body may lead to improvements in the treatment of several diseases. Gravity has a pronounced effect on fluid-volume control in heart patients. When the heart is weakened, it is more difficult for the cardiovascular system to overcome the negative effects of gravity. This leads to salt and water accumulation in the diseased body, which in turn has a deleterious effect on the heart. At present, not enough knowledge has been gained about how gravity affects heart patients, and to what degree it is responsible for the accumulation of water and salt. Research in space might well improve our knowledge on this issue.

In space, the water- and salt-regulating mechanisms adapt to a state that resembles that of being upright on the ground. Before the initiation of the manned spaceflight programmes, the expectation was that the physiological systems would adapt to a level which more resembled that of being ground-based supine. Spaceflight data have, however, shown that the body recognises the upright position as the equilibrium and the set point. This is logical because humans are mostly upright for about two thirds of the day. Acute weightlessness is therefore an unstable condition where, during the initial few days, the heart, hormones, blood volume and kidneys adapt to a state with the same values as those observed in the upright ground-based condition.

In the future, this area of space research needs to focus on the mechanisms that give rise to the surprising observations regarding water and salt balance. This will require physiological equipment for monitoring of the heart, blood pressure, hormone concentrations, and kidneys. In addition, the mineral content of the food must be accurately measured. The equipment should be more sensitive than it is today, because even small inaccuracies will, over long monitoring periods, produce large errors. Non-invasive, accurate physiological equipment is therefore an essential requirement for future space research.

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2.1.4 Muscles in Space

P.E. di Prampero, M.V. Narici & P.A. Tesch

2.1.4.1 Introduction

For man to remain in space for periods beyond a few months and for any future projects that plan to send astronauts to other planets, the negative effects of microgravity on muscle and skeletal (see Section 2.1.5) systems must be overcome. Since the beginning of the spaceflight era, it was believed that extended weightlessness alters bone and muscle integrity and function. In muscle, these changes comprise loss of mass, force and power and increased muscle fatigue and abnormal reflex patterns.

These changes are due to multiple factors, among which increased muscle protein degradation and altered neuromuscular control are probably the most important. They are brought about by the absence of the constant pull of gravity. During long-term space missions, muscle de-conditioning due to lack of weight-bearing activities could limit the crew's ability to work in space, or to operate effectively on the surface of Mars or any other planets, or to egress the spacecraft in an emergency landing. Muscle atrophy and weakness are of particular concern when the transition from 0g to 1g takes place. At that point, which occurs on returning to Earth from space, the musculoskeletal system suddenly has to bear the force of gravity again. Hence, the integrity of the motor system is essential for the accomplishment of human movement. Maintenance of posture and displacement of body weight is achieved through the action of muscles acting across joints, particularly the extensor muscles of the lower limbs. Loss of muscle (atrophy) eventually results in weakness and poor mobility. It is also a common condition resulting from bed confinement, casting, injury and trauma and reduced physical activity. The ageing process also involves loss of muscle mass, which in addition to disuse atrophy is referred to as 'sarcopenia'. Although both disuse muscle atrophy and sarcopenia are considered major causes of muscle weakness and mobility impairment, the underlying mechanisms, their development as a function of time, and functional implications are not yet fully understood.

The weightless condition of spaceflight therefore provides a unique environment for studying the effects of long-term muscle disuse on muscle function, physical performance and health. The experience gained from space research is valuable for understanding the effects of severe muscle disuse on Earth, its functional repercussions, and for its prevention by means of physical and pharmacological countermeasures. Efforts to understand and mitigate the phenomenon of muscle atrophy and weakness are therefore imperative. Learning from these studies is essential for generating technological advances and new concepts for counteracting muscle wasting in space and on Earth.

- *Muscle Form and Function*

The ability to move is so characteristic of living forms that motility and contractility have long been considered essential properties of life itself. In primitive life forms, the contractile function is served by specialised subcellular structures, called ‘cilia’ or ‘flagella’. In higher animals, differentiated muscle fibres are organised into effector organs, or ‘muscles’. Each muscle fibre transforms chemical energy into work in a co-ordinated manner, controlled by the nervous system.

In vertebrates, skeletal muscles are typically attached across articulated joints of rigid skeletons, with the muscle fibres being linked to tendons that, in turn, attach to the bones on both sides of the joint. Muscle fibres are organised into motor units, wherein a single nerve cell, called a ‘motor neuron’, innervates several muscle fibres. The collection of fibres innervated by a single motor neuron is called a ‘motor unit’. The number of fibres in a motor unit determines the finesse with which the contraction of a particular muscle can be regulated; the smaller the number of fibres, the greater the finesse. Skeletal muscle responds to an adequate stimulus, be it intrinsic (nervous) or extrinsic (electrical), giving a twitch, i.e. a brief contraction, followed by relaxation. The time course of the twitch depends on the composition of the muscle in terms of muscle fibres. Indeed, broadly speaking, muscle fibres belong to two types: ‘fast twitch’ (or Type-2) fibres and ‘slow- twitch’ (or Type-1) fibres.

Fast-twitch fibres are characterised by a large diameter. They rely mainly on anaerobic metabolism (they do not need oxygen), they are pale in colour (hence in the old literature they were referred to as ‘white’ fibres), they attain their peak tension in a relatively short time (about 10 – 20 ms), they are easily fatigued and their contraction is forceful. Slow-twitch fibres lie at the other end of the spectrum. They are of small diameter, rely on aerobic metabolism (they need oxygen), they are red, attain their peak tension (substantially less that that of the fast-twitch fibres) over a relatively long period (70 – 100 ms), and they are fatigue-resistant. For example, the breast of a chicken is a typically white muscle, whereas chicken legs contain red muscle. In contrast to the chicken, the muscles of most mammals, humans included, have a variable composition of fast- and slow-twitch fibres, and are intermingled in a mosaic pattern. Muscle-fibre-type composition is set by both genetic and environmental factors.

If a second stimulus is given to the muscle before the mechanical response to the first has completely ceased, summation occurs. If the stimuli are repeated regularly at a rapid enough frequency, the result is a fused contraction, termed ‘tetanus’, during which the tension is maintained at a constant level that is three to five times higher than that of a single twitch.

When the force applied to the muscle during stimulation is less than the maximum tension that the muscle can develop, upon contraction the muscle shortens (isotonic concentric contraction). This produces external mechanical work, given by the product of the force and the distance shortened along the direction of application of the force. If, however, the force applied to the muscle is greater than its maximum tension, then upon contraction the muscle is stretched (isotonic eccentric contraction), thus absorbing external work.

Finally, if the muscle is attached to a rigid structure, the muscle’s output upon contraction is tension only, without any shortening, and hence no external work is performed (isometric contraction). Thus contraction and shortening are not synonymous: upon contraction the length of the muscle can become shorter, longer or remain unchanged, depending upon the force applied. In all cases, however, a substantial fraction of the chemical energy utilised by the muscle to perform work or to develop tension is dissipated as heat. During everyday exercise such as bicycle pedalling, the external mechanical work performed is in the order of 25% of the total energy consumed by the muscle, the remaining 75% being dissipated as heat.

The mechanical power (work per unit of time) developed by a given muscle depends upon the duration of the effort. A young man of 70 kg body mass, for example, is capable of sustaining 0.20 – 0.25 kW for about 10 to 15 min of whole-body exercise, such as cycling or rowing. Power may exceed 1.2 – 1.5 kW in very brief (0.3 sec) explosive exercises, such as the maximal vertical jump off both feet. In athletes of similar body mass, powers may reach 0.5 and 2.0 kW for long-duration and explosive exercise, respectively.

- *Simulation of Weightless Conditions*

Although microgravity cannot be simulated on Earth, its chronic effects on the musculo-skeletal system can be simulated. Indeed, various techniques are available that can be employed in man as space analogues to prevent weight-bearing by muscles and thus simulating the unloading that occurs in space:

(i) Bed rest, in which healthy subjects are confined rigorously in bed. Typically such an intervention uses a 6 deg head-down tilt to allow for and simulate fluid shifts that occur in space.
(ii) Lower-limb suspension in humans, in which one leg is unloaded by means of appropriate straps, and/or by elevating the sole of the contra-lateral shoe. Ambulatory activities are carried out using crutches.
(iii) ‘Dry water-immersion’, in which healthy subjects are immersed in water from which they are separated by means of a layer of impermeable tissue. Their body weight is therefore supported almost completely by the buoyancy lift, but the subject’s skin remains dry, thereby permitting rather long periods of immersion.

Although these models are, at present, the best available methods for simulating the effects of microgravity on Earth, it must be remembered that the body is still subjected to the pull of gravity even if unloaded. Furthermore, the effect of microgravity on the vestibular system and its effect on motor control cannot be mimicked on Earth using the above three paradigms. Therefore, although considerable information may be obtained from research using these models, there is no real analogue to spaceflight. Thus, the effects of microgravity on the motor system can really only be studied in space.

The following discussion briefly reviews the changes in muscle structure and function that occur in microgravity, focusing on human studies. The structural alterations that follow simulated or actual microgravity are reported in the first section. The second section is devoted to the functional changes, and the final one describes potential exercise countermeasures. The concluding section addresses topics to be considered for future research.

2.1.4.2 Structural Alterations

The results of human and animal studies performed in simulated or actual microgravity consistently show that muscle undergoes substantial atrophy. This is due to a decrease in muscle fibre size, with no apparent change in fibre number. Studies also show that atrophy is considerably greater for postural muscles, i.e. for those muscles that, on Earth, support the weight of the body, as compared to the non-postural muscles, which undergo only marginal changes. In addition, substantial differences exist also amongst the postural muscles themselves. The overall picture seems to suggest that among the extensor and flexor muscles of the knee, ankle and back, there is a prevalence for atrophy of the extensor muscles, particularly those of the lower limbs.

Whereas common agreement exists regarding this general picture, the time course of atrophy is less well studied. On the whole, the picture provided by the results of bed-rest studies combined with those obtained by other unloading models, such as lower-limb suspension, suggests that atrophy is described by an exponential time function. As shown in Figure 2.1.4.1, after about 270 days of simulated microgravity, the muscle mass attains a constant value of about 70% of the initial value. These conclusions are derived from data obtained on the postural muscles of the calf in humans, during bed-rest studies lasting a maximum of 120 days without countermeasures. As such, the application of these findings to spaceflight, where countermeasures or high-intensity physical activity are undertaken, should be pursued with caution.

Muscle atrophy is the consequence of an imbalance between the rate of protein synthesis and degradation. Indeed, during the first two weeks of hind-limb suspension in rats, protein synthesis decreased and protein degradation increased. In the following two weeks, equilibrium between synthesis and degradation was again achieved, thus stabilising muscle protein content, albeit at a lower level than before hind-limb suspension. Experiments performed during long-term (more than 3 months) spaceflight onboard the Mir space station have revealed a decrease of about 15% in the rate of protein synthesis in humans. Even if the effects of a decreased dietary intake could not be ruled out, recent experiments performed on cultured avian muscle cells during spaceflight have shown that microgravity directly depresses protein synthesis.

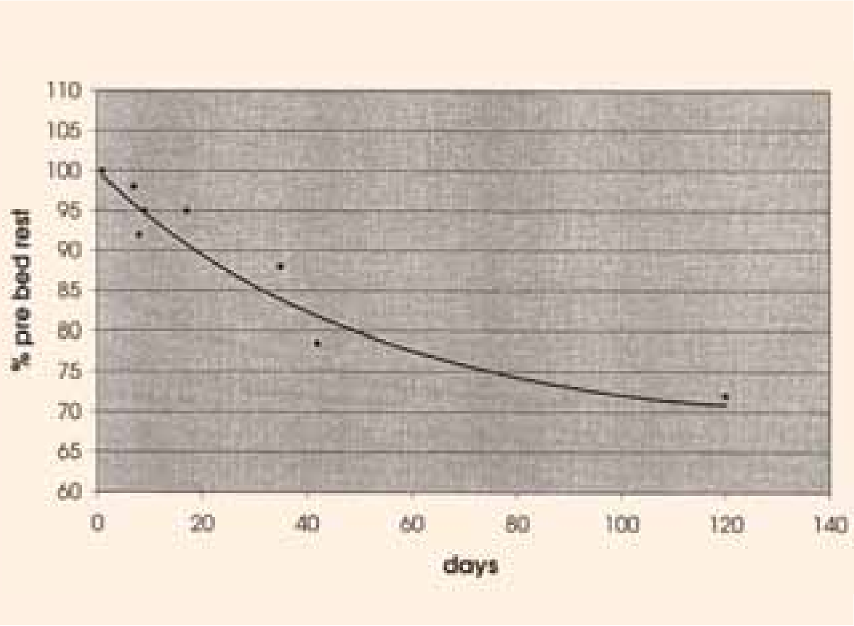

Figure 2.1.4.1. Size of the calf muscles (percent of initial value) in humans as a function of bed-rest duration (days)

Whereas most studies on mice and rats have reported preferential atrophy of the slow-twitch fibres after both simulated (hind-limb suspension) and actual microgravity exposure, albeit with some differences between the two conditions, the data obtained in humans does not show such a consistent trend. Indeed, following four to six weeks of either bed rest or lower-limb unloading, studies show a similar atrophy of slow- and fast-twitch fibres. Simulated and actual spaceflight may result in a greater susceptibility to damage upon reloading of animal and human muscles. The damage is characterised by eccentric contraction-like lesions, showing disruption of muscle structure followed by rapid repair processes. Muscle damage is accompanied by micro-circulatory changes and interstitial oedema, which are responsible for muscle swelling. At present, evidence of greater susceptibility to human muscle damage after spaceflight is sparse, since few studies have addressed this particular question, so far.

2.1.4.3 Functional Alterations

The above structural changes lead to substantial modifications of the muscle function. Indeed, the results of simulation studies on the ground, or during spaceflight on animal muscles have shown that, whereas the mechanical properties of fast muscles are generally unaffected, those of slow-reacting muscles, such as the soleus, change towards the fast-muscle type.

For example, in the soleus:

(i) the time to peak tension and the half-relaxation time become shorter
(ii) the maximal shortening velocity becomes faster
(iii) tetanic tension and specific tension (i.e. the ratio of tetanic tension to fibre cross-sectional area) are usually reduced, because of a decrease in myofibrillar protein concentration and an increase in non-contractile tissue.

In contrast, the mechanical characteristics of fast muscles, such as the tibialis anterior, are not greatly affected by simulated microgravity. In addition, the rat soleus muscle, after hind-limb suspension, showed increased fatigability, an increased rate of glycogen depletion, and a decline in the ability to oxidise long-chain fatty acids. This shows that, after hind-limb suspension, the substrate profile of the slow fibres is also shifted towards that of fast fibres.

Several studies have reported substantial decreases in muscle strength after bed rest or other simulation methods. After 42 days of bed rest, the maximum strength of the lower-limb muscles was decreased by about 30%. No changes in time to peak tension, nor half relaxation time, were found after 17 days of bed rest, whereas under the same conditions the fatigability and the ratio of tetanic force to cross-sectional area decreased significantly (8 and 13%, respectively). The observed decrease in the ratio between tetanic force and cross-sectional area may be due to:

(a) a reduction in motor drive to the muscle
(b) a reduction in fibre specific tension due to a decrease in myofibrillar density
(c) a reduction of the 'efficiency' of the electro-mechanical coupling
(d) an increase in the amount of non-contractile tissue.

After the Skylab missions, the maximal force of several muscle groups (quadriceps, trunk flexors and extensors) showed a decrease from 7 to 25% depending on the muscle group and the flight duration. In addition, since during these missions the crews performed physical exercise to prevent muscular de-conditioning, the results are difficult to interpret in terms of underlying muscle fibre function. Data from spaceflight and bed rest show the presence of a disproportionate loss of torque and power compared to that of muscle size. The decline in maximum power appears to be greater than that in maximum voluntary torque. Indeed, data obtained before and after the Euromir '94 and '95 missions on five astronauts have shown that the maximal explosive power of the lower limbs, as determined during maximal 'all-out' pushes on a force platform, was reduced to about 67% after 31 days and to about 45% after 180 days. However, the maximal power developed during 6 – 7 sec 'all-out' bouts on a cycle ergometer averaged about 75% of that produced pre-flight. Instead, the muscle mass of the lower limbs only decreased by 9 – 13%. Therefore, these data suggest that a large fraction of the decline in the maximal power, at least during the very short 'explosive' efforts, may be due to the effects of weightlessness on neural drive (involving both supraspinal and spinal reflex activity), the contractile apparatus per se, electromechanical efficiency, and/or muscle damage.

The observation of a disproportionate loss of maximal explosive power compared to that of muscle mass seems to be a specific characteristic of spaceflight that may not be easily reproduced by bed rest. Indeed, after 42 days of strict bed rest, the maximal explosive power was reduced to 77% and the quadriceps' cross-sectional area to 82% of pre-flight values, indicating that ~95% of the power loss was due to muscle atrophy. When compared to the changes occurring with spaceflight, these observations support the hypothesis that the absence of gravity, favouring smooth and delicately balanced muscle actions, brings about a rearrangement of the motor control system. That change is responsible, to a large extent, for the observed decline in the maximal explosive power during 'all-out' short-duration muscle actions. This rearrangement does not seem to manifest itself so markedly during bed rest, where the pull of gravity is not abolished, but simply shifted by 90°.

Besides changes in the functional characteristics of the lower-limb muscles, the mechanical properties of tendons are also affected by microgravity. Indeed, a decrease in the stiffness (i.e. the tendon can be stretched more easily) of the series elastic elements of the plantarflexors of the ankle was observed after 1 – 6 months of spaceflight.

The characteristics of isolated skinned human muscle fibres, obtained from soleus biopsies performed on four astronauts before and after 17 days of spaceflight, have been studied. It was found that a 4% decrease in single fibre specific tension and a 30% increase in maximal shortening velocity had occurred. This showed that microgravity tends to favour the slow to fast transition of the soleus muscle fibres, a phenomenon also observed in animals. The increase in shortening velocity was functionally important in compensating for the loss in fibre peak power (~20%), since without the compensation provided by the increased shortening velocity, the reduction in peak power would have been ~34%. For these single fibres, the reduction in peak power was entirely explained by fibre atrophy, because when normalised for changes in fibre volume the peak power was the same as pre-flight. This is not the case for the peak power generated by astronauts after prolonged spaceflights of 1 – 6 months duration (Euromir '94 and '95 missions). This supports the hypothesis that, with increased flight duration, alterations in motor unit recruitment, the contractile apparatus per se, or electromechanical efficiency, and/or the presence of muscle damage may collectively contribute to the decline in explosive power.

2.1.4.4 Countermeasures

- *Ground-Based Studies*

Aerobic Exercise

Results from a 17-day bed-rest study show that three bouts of progressive cycle ergometer exercise until exhaustion, on days 2, 8 and 13, was not sufficient to prevent muscle wasting or a decrease in isometric or dynamic strength of the quadriceps muscle. This is consistent with other observations. For example, 30 days of bed rest induced a similar effect on knee-extensor strength in individuals who performed cycle ergometer exercises for 30 min, 5 days per week, and in controls performing no exercise. Also, daily supine cycle ergometry exercise for 60 min, at 40% of maximum aerobic power, did not prevent muscle or strength loss in individuals subjected to 20 days of bed rest. Although in-flight aerobic exercise should be conducted to maintain cardio-vascular functional capacity and the integrity of the aerobic energy machinery and hence endurance, it will not prevent muscle function becoming compromised.

Resistance Exercise

Numerous studies have shown that bed rest or unilateral lower-limb suspension results in decreased muscle mass or muscle cross-sectional area. This appears to be due, at least in part, to a decrease in protein synthesis. Healthy subjects who were confined to bed for two weeks and performed knee- and ankle-extensor resistance exercises every other day using a five set, 6 – 10 repetition regimen at about 80% of maximum, were able to maintain muscle protein synthesis rate. Subjects who did not perform any training showed a decrease in muscle strength, mass and protein synthesis rate. This protocol was also sufficient to maintain dynamic strength; yet isometric strength and neural drive were reduced. While this protocol did not completely counteract the reduction in strength, this study provides evidence that unloaded skeletal muscle benefits from bouts of resistive exercise. It should be recalled, however, that the space analogue intervention lasted no more than two weeks. In a recent study it was shown that three weeks of unilateral lower-limb unloading produced marked decreases in muscle cross-sectional area and in the strength of the knee- and ankle-extensor muscle groups. These effects were abolished by a resistance training regimen consisting of two maximal isometric actions, one set of ten concentric and eccentric actions at 80%, and one set to exhaustion of the one-repetition maximum, performed every third day. Similarly, quadriceps muscle atrophy, induced by five weeks of lower-limb suspension, was prevented by four sets of seven maximal concentric and eccentric knee extensions, performed two or three times per week using flywheel technology. In fact, this regimen produced significant quadriceps hypertrophy. The magnitude of atrophy of the plantar flexor muscles was similar to that observed in individuals subjected to unloading only. Altogether, these results suggest that resistive exercise may ameliorate, or perhaps even prevent, the negative effects of unloading on skeletal muscle.

Penguin-Suit Exercise

The use of the Russian ‘penguin suit’, an all-body suit with sewn-in elastic bands for the loading of joints and their related muscles as a countermeasure, has been studied using a small group of subjects who were bedridden for about 120 days. The fibre size of the soleus muscle was maintained after a single daily 10 h bout of modest loading, i.e. about 10 kg, using the penguin suit to provide elastic resistance. Three subjects who did not load the ankle-extensor muscles showed soleus atrophy. Although these results are encouraging, further research is needed to prove that this technique should be employed in space. There are obvious constraints imposed by the penguin suit, and onboard use of the suit has not produced the desired results.

Drug Treatments

Pharmacological interventions have been considered for preventing or ameliorating muscle loss due to spaceflight. Experiments on humans, dealing with the issue of administering drugs aimed at limiting skeletal muscle protein loss during real or simulated spaceflight, are not available. However, the impact of albuterol administration in individuals subjected to 40 days of unilateral lower-limb unloading has been examined. In a small subject sample, the efficacy of a resistive exercise programme using flywheel technology to prevent the decline in muscle function was enhanced by albuterol.

Lower-Body Negative Pressure

The application of Lower-Body Negative Pressure (LBNP) alone, or while performing simultaneous exercise, has been proposed as an in-flight countermeasure. LBNP may provide forces, applied to the lower limbs, which simulate weight bearing. It is, however, unlikely that short sequences of such moderate loading would be sufficient to counteract muscle atrophy in space. Although it has been inferred that a regimen comprising LBNP treatment and isokinetic exercise may limit strength loss and muscle wasting during bed rest, it is unclear whether LBNP per se contributes to this effect. Thus, the efficacy of LBNP to prevent muscle or strength loss in response to real or simulated spaceflight remains to be established.

Electrical Stimulation

Transcutaneous Electromyostimulation (EMS) has been evaluated as an aid to control muscle wasting and dysfunction during simulated spaceflight. In a study of three healthy subjects confined to bed for 30 days, EMS (60 Hz frequency, 0.30 ms pulse width, 4 sec train duration) was given twice daily, using a 3-day on and 1-day off regimen. The results showed decreases in strength and muscle mass that were smaller than in the non-stimulated limb. However, the discomfort associated with EMS, and the fact that the normal recruitment order of motor units is reversed, make this type of countermeasure too preliminary to be implemented in space. One solution could perhaps be to administer EMS in the course of voluntary contractions. This would enable the use of physiological discharge rates, thus preventing fibre type conversion due to chronic stimulation, whilst still producing the high-level contractions necessary to prevent muscle atrophy.

- *Spaceflight Studies*

The US and Soviet/Russian space programmes have conducted strength measurements on crews before and after spaceflight. Taken together, these results show that crews suffer from loss of strength, with the effect being most prominent in the lower limb muscles. The magnitudes of the reported strength decrements show considerable variability. However, astronauts also performed in-flight exercise using different paradigms. On the Euromir '94 and '95 missions, the crew exercised for 2 h per day, following a protocol consisting of 1 h of cycle ergometry exercise at braking powers from about 100 to about 170 W plus 1 h of treadmill walking. In the latter, a force provided by bungee cords pulled them towards the ground with an effect equal to about 50% of the their own body weight on Earth.

Unfortunately, on several Shuttle and Euromir missions in the past, countermeasure activities were not always mandatory nor logged or accurately monitored with regard to frequency, duration or intensity. Therefore, no in-flight exercise programme has yet been proved to be effective in preventing loss of muscle and strength during long-term spaceflight.

In-flight Aerobic Exercise
Apollo astronauts, who experienced 1/6 g while performing Moon walks, showed no cardiac atrophy upon return to Earth. By contrast, their fellow lunar astronauts, who did not descend for walks on the lunar surface, did show a decreased heart volume after returning to Earth. This may indicate some benefit from physical activity on heart, but not necessarily skeletal, muscle mass in individuals subjected to microgravity. In-flight cycle ergometer exercise has been used mainly as an aid to maintain cardiovascular function. There is, however, no reason to believe that such exercise will maintain musculo-skeletal function in space, because aerobic exercise programmes typically do not produce muscle hypertrophy at 1g. Preliminary results from a 17-day spaceflight (STS-78), using a testing protocol identical to that employed in the bed-rest study mentioned above, suggest that it did not prevent muscle wasting or decreases in isometric or dynamic strength of the quadriceps muscle.

In-flight Resistance Exercise
Seventeen days of spaceflight (on STS-78) resulted in minute or no changes in calf strength or morphology. This seems to be explained by the fact that a testing protocol comprised of about 525 contractions (approximately 50% performed at 80 – 100% of best effort) was employed on three days during this mission. These results are further evidence that high-force muscle actions, and hence resistive exercise, may ameliorate the negative effects of spaceflight on skeletal muscle. Clearly, more research is needed to confirm this, and also to explore the efficacy of different exercise programmes.

2.1.4.5 'Explosive' and Flywheel Ergometers

To prevent muscle loss and function impairment during spaceflight, two innovative ergometers have been proposed: an 'explosive' power ergometer and a flywheel ergometer. These ergometers allow for the execution of coupled concentric and eccentric actions. Inclusion of both action types in resistive exercise programmes is an essential requirement in order to optimise increases in muscle strength and size.

While exercising on the 'explosive' power ergometer (Fig. 2.1.4.2), the subject moves along a rail on a seat. He or she (and the seat) then accelerates backwards, by exerting an 'explosive' push on an approximately equal mass moving on the same rail, but in the opposite direction. The moving component is fitted with force platforms, so that the power exerted by the subject can easily be calculated, provided that the speed of the seat and the moving mass are measured. Shock absorbers at the end of the rail provide the necessary braking power. This somewhat cumbersome system minimises the shocks and vibrations imparted to the space vehicle. Alternatively, a less bulky system, with two astronauts facing each other and accelerating in opposite directions, whilst pushing on a force platform positioned midway between them, could be used.

The flywheel ergometer is equipped with a flywheel that is set in rotary motion (concentric action) by the subject, through the unwinding of a strap anchored to the axle of the wheel and a lever or moment arm, as shown in Figure 2.1.4.3. Once the wheel has been set in motion, the same system is used to brake it (eccentric action), thus

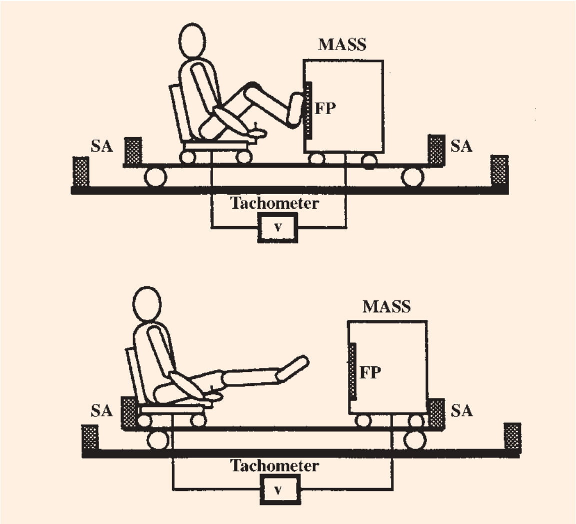

Figure 2.1.4.2. Schematic representation of the ergometer for maximal explosive power. FP = force platforms; SA = shock absorbers; v = velocity (after di Prampero & Antonutto)

absorbing the flywheel's kinetic energy, while the strap rewinds. In essence, the flywheel ergometer allows the astronaut to perform both positive and negative work. Moreover, the shocks and vibrations imparted to the space vehicle should be easier to control and minimise than those produced by the explosive ergometer. Studies comparing the efficacy of exercise using this ergometer adopted for the leg press and the barbell squat using free weights, show similar increases in muscle strength for the two methods of training over a 12-week period.

2.1.4.6 Cycling in Space

To simulate gravity on a space vehicle, the use of two mechanically coupled counter-rotating bicycles (Twin Bikes System, TBS), moving at the same speed along the inner wall of a cylindrically shaped space module, has been proposed. The concept behind this mode of exercise is that circular trajectories induce centrifugal acceleration vectors, oriented in the head-to-foot direction, thereby providing simultaneous stimuli to the muscular and cardiovascular systems.

The gravitational pull created by the tangential speed at a certain cylinder radius comes close to physiological values at radii of 6 – 10 m, thus stressing the exercising muscles as well as the circulatory system. In addition, the spatial rotation produced by the cycling action would produce a potent stimulus to the vestibular system that may prove useful for the prevention of motion sickness. The results of the head-rotation experiments performed during the Neurolab mission seem to confirm the importance of training the vestibular system. Combining high-intensity exercise and simulated gravity may prove useful for simultaneously ameliorating muscle atrophy, bone demineralisation and cardiovascular de-conditioning.

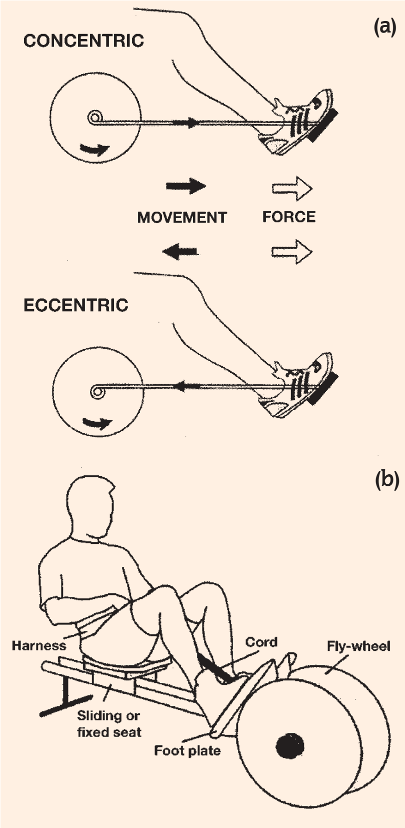

Figure 2.1.4.3 (a) The principle of the flywheel ergometer. The force generated during concentric muscle action increases the flywheel's rotation and stores kinetic energy in the spinning wheel. An eccentric muscle action is then performed to slow down the flywheel. (b) A multi-exercise configuration of the flywheel ergometer. The device is equipped with a seat that can be either fixed, allowing for e.g. upper body exercise, or sliding while performing the dead-lift, the heel raise, the leg press or the squat. The seated-leg-press exercise is shown here

2.1.4.7 Conclusions

Skeletal muscle size, structure and function show marked changes following spaceflight or disuse on Earth. The microgravity environment of space presents a unique opportunity to study true unloading of skeletal muscle. However, because of the limited access to this 'laboratory' for controlled research studies, paradigms or space analogues must be extensively used to predict the long-term consequences of spaceflight on the musculo-skeletal system.

Spaceflight results in loss of muscle and impaired muscle function. Perhaps the most intriguing issue to be solved in the future is the observation of a disproportionally greater loss in muscle force and power than muscle size as a result of spaceflight or simulated microgravity. The precise role of muscular and neural factors should be elucidated in order to fully understand the causes of this phenomenon, which may ultimately impair even the simplest motor tasks in space and locomotory activity upon re-loading in 1g. In this respect, the availability of the International Space Station (ISS) will enable an extension of present knowledge regarding the long-term effects of spaceflight, mainly acquired through the Mir missions. Using state-of-the-art instrumentation, it should now be possible to examine a significant number of crew members during long-duration missions and under identical and controlled conditions. Hence, with the establishment of the ISS as a space laboratory, the quality of research in this field should be greatly enhanced.

Recently, there has been progress in the development of techniques and devices for preventing loss of muscle and deteriorated function in space. Whereas

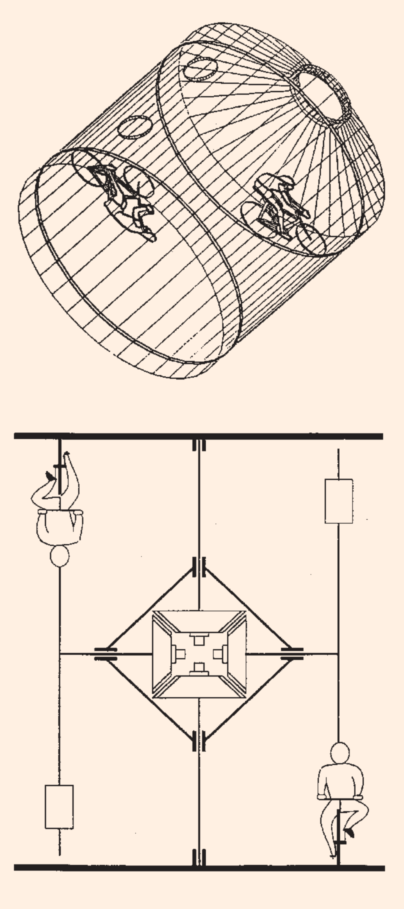

Figure 2.1.4.4. Upper panel: cyclists moving along the inner wall of a cylindrically shaped space module generate an acceleration vector mimicking gravity. Lower panel: Schematic of the Twin Bikes System, with thick lines indicating space-module walls. The differential gear coupling is drawn on a larger scale and the adjustable masses are also shown (after di Prampero & Antonutto)

medium-intensity cycling exercise may be effective in counteracting cardiovascular de-conditioning, high-intensity muscle loading by resistive and/or explosive exercise seems particularly promising for the prevention of muscle atrophy and weakness in space. Integration of the results on muscle atrophy and functional changes in space with those of disuse muscle atrophy and sarcopenia on Earth will certainly enhance our understanding of the physiological and pathological mechanisms that lead to loss of muscle and altered function. Knowledge of these mechanisms will be extremely useful for designing better strategies for counteracting muscle de-conditioning due to neuromuscular diseases, traumatic injuries and ageing.

2.1.5 The Skeletal System

R. Cancedda

2.1.5.1 Bone Remodelling, a Lifelong Process

During embryo development, bone is formed either directly, starting from an undifferentiated embryonic tissue, or via ossification of cartilaginous tissue. After birth, and until sexual maturity, bone formation via this cartilaginous model persists in the growth plate of long bones and plays a major role in their development.

Bone density undergoes physiological changes throughout life. An acquisition phase occurs during childhood and adolescence, with the peak bone mass being reached in the mid- to late-twenties. Bone density then changes very little for several years, as it goes through a ‘plateau phase’. A period of bone loss then follows, which starts around the age of 50. In the following 20 to 30 years, bone density decreases by approximately 15% in men and 30% in women. Under normal conditions, this progressive bone-mass reduction does not impair the quality of the bone’s support properties.

Throughout life, bones are continuously remodelled as a result of the coupled activities of bone resorption and formation. In this process, tiny pieces of old bone are continuously replaced by new material. By this means, spatial changes in form can also be brought about. The bone resorption is a process carried out by specialised cells called osteoclasts. In the body, osteoclasts form as the result of the transformation and fusion of specific white blood cells. Bone formation is the result of the activity of other specialised cells, called osteoblasts.

When new bone is needed, new osteoblasts are formed as consequence of an increase in the number (proliferation) and the transformation (differentiation) of a few progenitor cells, located in the bone marrow. Newly formed osteoblasts localise in the area where old bone has been removed. Here they produce and secrete several proteins outside the cell. These proteins form a mesh, filling all of the space between the osteoblasts. Calcium mineral is deposited within this protein mesh. In this way, new bone is formed and old bone replaced. The replacement of old bone may be induced due to an insufficient number of blood vessels being present and the fact that the bone is no longer responding to the changing mechanical requirements of the body.

In general, certain hormones circulating in the blood have effects on the whole skeleton, by controlling the number of active osteoclasts and osteoblasts, whereas 'local factors' have effects mainly in the skeletal area where they are released. These local factors are synthesised by skeletal and adjacent cells and include growth and morpho-genetic forming factors. Growth factors may have effects on the cells of the same class that have synthesised and released them, or on other cells within the same tissue. Circulating hormones may act on skeletal cells either directly or indirectly, by modulating synthesis, activation, receptor binding, and binding properties of local growth factors.

Among the hormones with specific effects on bone, oestrogen merits a special mention. Oestrogen depletion at the female menopause can induce bone loss by altering osteoblast bone-formation activity, which in turn leads to unregulated bone remodelling and, potentially, to osteoporosis.

Osteoporosis is the principal bone disease in Europe and in the USA. It has various potential causes in addition to the prime cause, which follows the reduction in oestrogen due to loss of ovarian function in post-menopausal women. The other potential causes include endocrinological disorders, such as corticosteroid excess (Cushing's syndrome), hyper-thyroidism, and hyper-parathyroidism. Other causes are immobilisation, bone malignancies, some genetic diseases, a low amount of calcium in the diet, eating disorders, heavy alcohol consumption, smoking, and the use of certain drugs, such as steroids.

It is also common knowledge that there is a genetic predisposition to osteoporosis, although the basis for this is still unclear. White and Asian women are at higher risk. It is estimated that almost 25% of all women over the age of 50 have osteoporosis, and about 50% have osteopenia, a low-bone-density situation that may eventually result in osteoporosis. It is expected that more than 50% of women over 50 will suffer from a fracture of the hip, wrist or vertebra. The risk of fractures for the male population of the same age is about 12 – 15%.

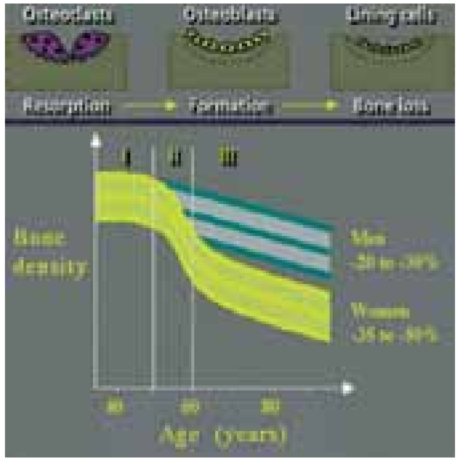

Figure 2.1.5.1. Bones are continuously remodelled as a result of the coupled processes of bone removal by osteoclasts and bone formation by osteoblasts. With ageing, bone loss prevails both in men and women, although the bone-mass decrease is much more dramatic in women. Under normal conditions, the progressive reduction in bone mass does not impair the bone's mechanical properties. Osteoporosis is characterised by an extreme reduction in skeletal mass, associated with bone micro-architectural deterioration, which results in an increased risk of fractures (modified from: www.osteovision.ch)

Osteoporosis can be defined as a reduction in skeletal mass, associated with bone micro-architectural deterioration, which results in an increased risk of fractures. It can be a debilitating disease, with devastating health and economic consequences. Osteoporosis occurs when the body fails to form enough new bone and/or when too much bone is reabsorbed. This bone loss occurs over several years and usually a fracture of vertebrae, wrists, or hips is the first sign of a pathology of which the patient was not aware. At the time of the first fracture, the disease has usually already reached an advanced stage and other serious symptoms soon occur. These include pain in the lower back, neck pain, bone pain and tenderness, loss of height over time and, eventually, a stooped posture.

2.1.5.2 The Effect of Mechanical Stress on Bone

Mechanical loading is essential for the maintenance of skeletal structure, and a reduction in mechanical loading leads to rapid bone loss. A serious loss of bone mass (and structural mechanical efficiency) is induced by complete immobilisation or by weightlessness, regardless of a normal healthy condition of the endocrine systems.

For example, in hind-limb-unloaded rats, an acute decrease in bone formation is observed at the end of the first week. This is due to a reduction in the number of bone-marrow progenitor cells, from which osteoblasts are derived, and an increase in bone resorption, leading to the net bone loss. At six weeks, significant bone loss associated with an altered bone structure was observed, and as a consequence a decrease in the skeletal structural strength also. After reloading, a rebound in bone formation was always observed, but the recovery time was longer than the duration of the limb unloading. In all cases, bone-mass recovery was never complete.

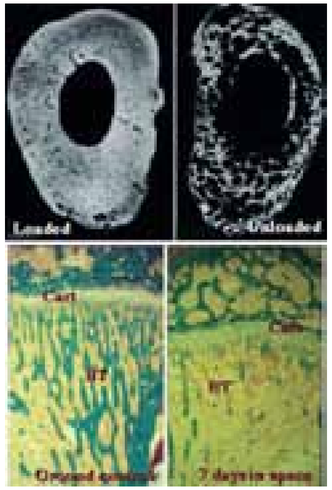

Figure 2.1.5.2. Significant bone loss occurs as a consequence of unloading or microgravity exposure. The upper panels are micro-radiographs of transversal sections of loaded and unloaded long bones. The lower panels are longitudinal sections of the shin bones (tibiae) of a rat, which remained in space for 1 week during the Cosmos-1667 mission, compared to a control rat that remained on the ground. Note the reduced amount of bone internal organisation (bone trabeculae). BT = bone trabeculae; cart = growth plate cartilage (courtesy of A. Zallone and L. Vico)

In human bed-rest experiments, volunteers are immobilised by a plaster cast from their waist to their toes. Progressive loss of mineral from bone, together with an increase in calcium excretion, was observed during the first four weeks. The calcium loss continued in the following weeks. At the end of a seven-week experiment, the average calcium loss was shown to be about 0.5% per month.

When bone loss was examined by measuring bone-mineral densities (a measure of bone quality) at specific locations, such as in the forearm (radius) and the heel bone(calcaneus), major differences were observed. In general, demineralisation was much higher in weight-bearing bones. For example, the central area of the heel bone can have lost up to 45% of its mineral mass after seven months of immobilisation.

2.1.5.3 Bone Loss in Space

The first observation of an increase in the level of urinary calcium was made in 1962, during the short flights of Vostok-III and IV. Since then, a series of reports have been published on modifications of calcium balance, alteration of bone-mineral density and bone turnover, observed in astronauts and cosmonauts who have stayed in space for various lengths of time.

The first data concerning bone loss during long-duration missions came from the Soviet/Russian missions. A significant loss at the heel bone was found after missions lasting 75 to 184 days, with the loss roughly proportional to the flight duration. Quantitative computerised tomo-densitometry (QCT) was used to determine peripheral (cortical) and central (trabecular) bone mass at different skeletal sites in two cosmonauts, who were in space for 1 month and 6 months, respectively, during the Euromir '94 and '95 missions. Weight-bearing bones were observed to be more affected by microgravity than non-weight-bearing ones. It is notable that, six months after landing, recovery was still not complete in the central area of the bones, which is characterised by a high remodelling rate, whereas the peripheral bone, characterised by a lower remodelling rate, had recovered to pre-flight levels.

So far, the published data have related to a limited number of cosmonauts and high individual variations were observed. Recently, bone-mineral density measurements at both the forearm (radius) and shin bone (tibia) have been reported for 15 cosmonauts visiting the Russian Mir space station. They had stayed in space for either one (2 cosmonauts), two (2 cosmonauts), or six (11 cosmonauts) months . After a recovery period comparable in duration to that of the relevant space mission, forearm bone density had not changed significantly. In contrast, the weight-bearing shin bone, despite the physical training of cosmonauts during space missions, still showed evidence of central bone loss after one month of recovery, and of peripheral bone loss after two months of recovery. Observed shin-bone deterioration continued to increase with flight duration.

As yet, the mechanisms underlying the observed bone loss in space are only partly understood. In this respect, it is worth noting that several endocrine systems undergo changes in space that resemble those observed during senescence. This appears to be particularly true for the systems regulating bone metabolism and turnover.

2.1.5.4 Microgravity and Osteoporosis Research

Space travel and the extension of the average human life span are two of the major advances during the last century. However, at present, the price that has to be paid for both of these advances lies in the progressive degradation of normal physiological processes.

Both old age and prolonged exposure to microgravity conditions are associated with decreased bone mass and damaged bone structure. In the latter case, however, the changes occur at a greatly accelerated rate and in healthy individuals. Consequently, it has been suggested that careful experimentation in microgravity could represent a good basis for investigating the mechanisms responsible for bone loss in old age, and the occurrence of osteoporosis. Those investigations need to consider mechanisms operating both at the cellular and at the whole organism level.

Therefore, a major long-term objective of future space research in osteobiology will be to provide new tools for both the treatment and the prevention of bone diseases such as osteoporosis. That will require an integrated understanding of their underlying causes, including genetic mechanisms. The research should take advantage of the tremendous progress made in the last decade in the cell-biology field. Animal-based research should also be used to test promising interventions, taking advantage of the accelerated bone-loss process in microgravity, which offers an excellent tool for such studies. The final goal then is to expand the transfer of the new knowledge acquired through space research directly to diagnostic, therapeutic, and preventive applications of potential benefit to an ageing world population.

- *Cell and Tissue Cultures*

The basic mechanisms that control bone cell division, activity and death may be similarly altered in both the elderly and individuals exposed to microgravity conditions. The changes observed in bone formation could be, at least partly, the result of a decreased osteoblast activity, resulting in decreased extra-cellular protein matrix deposition and mineralisation. A possible explanation may be that the osteoblasts themselves are sensitive to altered gravity levels, as suggested by several studies in which the effect of microgravity on osteoblasts cultured in space was investigated (see Section 2.2.1).

Few studies have been performed to examine the effects of microgravity exposure on explanted developing skeletal tissues. Embryonic cartilaginous mouse bones were cultured during three Space Shuttle flights, to study cartilage growth, the differentiation to form bone and the process of mineralisation in a microgravity environment. The bones cultured in microgravity grew less in length than the ground controls. In addition, the amount of calcium incorporated into the mineralised areas was significantly lower. This suggests that the composition or density of the mineralised regions was compromised in microgravity.

- *Animal Studies*

So far, the rat has been the animal most widely used for spaceflight studies. Bone measurements have been performed on growing rats returning from 4 to 21-day space flights (see Table 2.1.5.1).

Table 2.1.5.1. Studies of rat bones in space (courtesy of L. Vico)

Space flights	**Rat type**	**Weight (g) at launch (L) or death (D)**	**Time between landing and sacrifice (h)**
1973 Cosmos-605; 21.5 days	Unknown	Unknown	48, + recovery
1975 Cosmos-782; 20.5 days	Wistar	215 (L)	72, + recovery
1977 Cosmos-936; 19.5 days	Wistar	202 13.9 (L)	Unknown, + recovery
1979 Cosmos-1129; 18.5 days	Wistar	349 ± 4 (D)	7 – 11, + recovery
1983 Cosmos-1514; 5 days	Wistar, pregnant	293 ± 6.5 (D)	over 6
1985 Cosmos-1667; 7 days	Wistar	304 ± 46 (D)	over 6
1987 Cosmos-1887; 12.5 days	Wistar	303 ± 2 (D)	42 – 55
1989 Cosmos-2044; 14 days	Wistar	338 ± 2 (D)	6 – 10
1985 SL-53; 7 days	Sprague-Dawley	Large 384 ± 9 (D) Small 194 ± 10 (D)	11 – 17
1993 SLS2; 14 days	Sprague-Dawley	Around 330 (D)	5 – 6, + recovery
1993 STS-54; 6 days	Sprague-Dawley	210 – 223 (D)	6 – 13
1990 PSE-1 (STS-41); 4 days	Sprague-Dawley	120 (L)	4 – 6
1992 PSE-2 (STS-S2); 10 days	Sprague-Dawley	180 (L)	5 – 3
1993 STS-58 (SLS2); 14 days	Sprague-Dawley	251 ± 10 (L)	2–3 or 14 days of recovery
1995 STS-62; 14 days	Fisher 344, ovariectomised	about 140 (L)	4 – 6
1996 STS-78; 17 days	Sprague-Dawley	about 165	4 – 7

The results of these studies were limited by a number of poorly controlled factors, including the strains and ages of the animals and the type of restraining device. Nevertheless, some general conclusions and a catalogue of events could be derived.

An alteration in the internal organisation of bone was found to have occurred by the end of the first week. After the second week, clear evidence of bone loss was observed, mostly due to an abrupt and transient increase in bone resorption. After the third week, a net decrease in bone formation was also observed. In all of the cases investigated, recovery of bone formation occurred after return to Earth, although the decreased internal bone organisation often persisted. Investigations of the molecular mechanisms underlying the bone cellular alterations have just been started.

A few Russian experiments have involved monkeys. A two-week space flight was found to have induced a severe bone loss in the primate iliac bone, as well as a decrease in mineralisation activity and an altered mineralisation pattern.

- *Animal Models for the Study of Bone Development and Turnover*

Osteoporosis is characterised by a decrease in bone mass and a concomitant increase in the propensity for bone fractures. There are numerous risk factors for osteoporosis. Although many of them are non-genetic in nature, there is a definite genetic component as well. Genetic control of osteoporosis depends upon several genes, and the specific genes involved are just beginning to be identified.

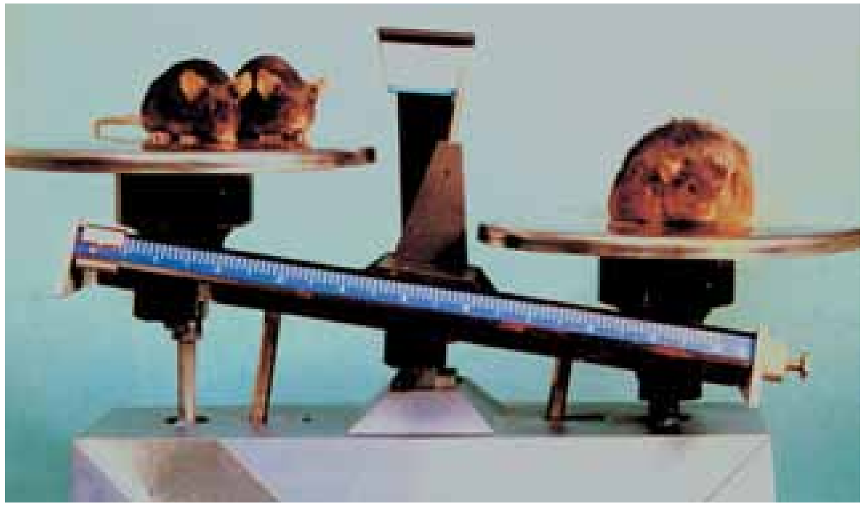

Figure 2.1.5.3. The obese mouse: an example of gene mutation affecting bone mass. Mutations in the obese (ob) gene lead to major metabolic changes in mice. In addition to obesity, diabetes and other alterations, an increased bone mass is also observed (from Nature1994, 372, pp. 425 – 432)

The possibility of manipulating the mouse genoma and of introducing mutations in specific genes is one of the most important advances in modern molecular genetics. This technology has increased the number of mutant vertebrate organisms that are available. It is becoming the main research tool directed to determining the potential activities of the new genes discovered via the human genome sequence (genomic-functional analysis).

The technologies available today permit animals to be created in whose genoma either additional copies of certain genes (transgenic genes) are introduced, or specific genes are deactivated (knock-out genes). In recent years, several 'transgenic' and 'knock-out' mice have been created that mimic human bone and cartilage pathologies, and in which a particular gene responsible for bone development and remodelling has been deactivated. Such transgenic and knock-out mice have been very useful in studying rare and lethal skeletal diseases. It was also possible to create strains of mice genetically predisposed to degenerative skeletal disorders. Studies on the transgenic and knock-out phenotype of these mice, maintained in various experimental conditions, including microgravity, will generate new information on the mechanisms that control bone formation and turnover, both in normal and in pathological situations such as osteoporosis.

- *The Development of Countermeasures*

All astronauts are required to devote several hours per day to physical exercise. The increase in muscle activity can influence bone formation positively, but so far it is only partially effective in preventing bone loss.

The mechanisms of bone loss in space are only partially understood. Consequently, the development of practical measures that are able to counteract space-induced bone loss is presently a high priority for scientists involved in bone research. High dietary calcium increases bone mass and mineral content in animal-model unloaded bones, but fails to prevent a decrease in bone mass compared to control (loaded) animals subjected to the same diet. Treatment with hormones and growth factors, known to play a role in bone formation and turnover, only partially prevents the bone loss induced by skeletal unloading. Administering drugs, such as bisphosphonates, that are potent inhibitors of bone resorption and are currently used for the treatment of human osteoporosis, does reduce the trabecular bone loss in the unloaded bones, but it also results in an alteration of the bone structure.

Therefore, none of these procedures and treatments can be considered fully satisfactory and additional studies are required. This appears all the more important because it is expected that, when the International Space Station is fully operational, many astronauts will remain in space for several months at a time.

2.1.5.5 Conclusions and Future Research

Throughout life, bones are continuously being remodelled as a result of the coupled bone-resorption and bone-formation activities, which substitute tiny pieces of old bone in both the central area and within peripheral cortical bone. When these two activities cease to be in dynamic equilibrium, excess bone may be reabsorbed and/or insufficient new bone is generated. The resulting deficit can lead to osteoporosis. This is characterised by a reduction in the skeletal mass, with an associated deterioration in the bone micro-architecture. The consequence is an increased risk of fractures and skeletal deformation. It can be a debilitating disease, with devastating health and economic consequences.

Microgravity conditions affect the skeleton and induce bone loss in both humans and animals. During spaceflight, bone is lost principally from the bones that are most loaded by gravity when on Earth. Bed-rest studies with human volunteers and hind-limb elevation studies with animals still provide useful data to help explain some of the changes occurring. Nevertheless, microgravity exposure represents the only situation whereby the absence of gravity acting on the entire body can be used as a tool.

Studies of skeletal unloading, particularly during microgravity exposure, will provide information that could improve our knowledge of the mechanisms controlling bone-mineral deposition and loss. Such understanding will lead not only to measures for preventing defective bone formation and bone loss during future long-duration space flights, but will also assist in developing cures for human osteoporosis. The mechanisms involved in these alterations need to be investigated at the cellular and molecular levels, and at the level of the whole organism.

The data available on the effects of mechanical stress and of microgravity on bone cells suggest that some of these cells may respond to stress and to unloading 'in vitro'. However, at this stage these data should be treated with caution, due to the numerous limitations related to the methods used and to the limited number of studies performed to date, especially in space.

So far, ESA has never carried out animal research in space. Some European scientists have performed experiments on animals, mainly rats, through bilateral agreements with the USA and Russia. The results obtained have shown the value and relevance of animal studies in creating the link between cell biology and human physiology. This is particularly true in the case of bone research.

The present availability of 'transgenic' and gene 'knock-out' mouse mutants, in which particular genes responsible for bone development and remodelling have been modified or deactivated, will be particularly useful for understanding the genetic component of both bone loss in space and osteoporosis. Hopefully, the information acquired will allow the development of countermeasures for astronauts on future space flights, as well as for the global prevention and treatment of osteoporosis.

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2.1.6 The Human Sensory and Balance System

G. Clément

2.1.6.1 Introduction

Andrew Thomas, an astronaut who spent 141 days on Mir in 1998 describes what it was like to return to Earth after some five months in zero gravity. *"I landed lying on my back and reached for my camera – it felt amazingly heavy, like a huge fifty-pound lead dumbbell"*, he recalled. He was overcome by vertigo, and – when he was helped to his feet and supported on both sides by the ground crew – by gravity too. *"It was incredible. Just putting one foot in front of the other required tremendous effort."* His balance was poor, and he staggered forward, listing to the side. Over the next few days, he recounts, *"I had to walk slowly with a wide-based gait. Fine balance skills took several weeks to return. When I walked with my eyes closed, I still veered to the side and walked into the wall."* Thomas underwent many weeks of rehabilitation, as is standard practice, with graduated exercises, guided movements in a warm swimming pool, and massage. Even after a month, however, he couldn't jog without becoming short of breath.

Balance disorders have also been described even after shorter space flights, such as one-week space missions aboard the Space Shuttle. Troubles reported include the sensation that the visual environment moves when the astronauts make a rapid head motion, feeling that the ground is bobbing whilst stepping, an inability to walk in a straight line with eyes closed, and loss of orientation when riding in a vehicle or walking in the dark.

Figure 2.1.6.1. French astronaut Jean-Pierre Haigneré after his return to Earth following nearly six months in the weightless conditions of space

Obviously, these changes indicate that some form of adaptation by the central nervous system to the loss of gravitational information takes place during space flight. This adaptation then carries over in a detrimental way to the post-flight period. In this Section, the way in which experiments performed during space flight can be used to enhance our understanding of the human sensory and balance system will be reviewed.

2.1.6.2 Adaptation of Human Sensory Systems to Weightlessness

Human sensory functions are classically categorised into five areas: hearing, taste, smell, vision, and touch. Neither the hearing function, nor the ability to localise sound sources, is altered in weightlessness. Slight changes in taste, smell, and vision were observed during space flight, but these changes were indirect effects of weightlessness, in which the system responds not to the gravitational force itself, but rather to changes in the local environment induced by conditions of weightlessness. For example, the changes in the taste and smell of food reported by some crew members are more likely to be related to the reduction in air convection in weightlessness. Also, the fact that 10 – 20% more stars are visible from space in low Earth orbit and that the objects outside the spacecraft appear ‘unreal in clarity’, as reported by the first astronauts, are presumably due to the absence of light scattering in vacuum. The unusual colour and shading contrasts encountered on the Moon, as well as the absence of objects with familiar sizes in the background (such as trees, people, vehicles, etc.), were presumably responsible for the impairment of the astronauts’ ability to judge distances on the Moon.

Position sensing, or limb proprioception, is derived from afferent signals of the muscle spindles and receptors situated in tendons and joints, which are interpreted in relation to ongoing patterns of muscle activity. On Earth, muscle spindle sensitivity is influenced by head orientation, which is detected by the otolith organs in the vestibular system and modulates the antigravity muscles of the body through spinal-cord connections.

The astronauts frequently report that limb position sensing is degraded in weightless conditions, and this is confirmed by experiments in which they have to point to visual targets without seeing their arm.

Figure 2.1.6.2. The Pointing Experiment on the Neurolab STS-90 mission, in which the astronaut tracked a moving target displayed on the device’s screen. The circle of light shows the track that he made with his hand

Scientists believe that this degradation is due to a change in the perceptual interpretation of proprioceptive signals, rather than a decrease in muscle spindle sensitivity. Indeed, on the ground vibration of leg muscles of a test subject restrained in the standing position leads to illusory tilting of the body. During space flight, such vibration leads to the sensation that the deck, to which the astronaut is attached with foot supports, is tilting or rising under his/her feet, depending on the muscles stimulated. Similarly, deep knee bends or raising and lowering the whole body in space with the feet anchored can evoke illusions of deck displacement. The floor seems to move upwards as the body moves towards it, and downwards as the body moves away from it. These illusions probably result from the altered relationship between the motion of the body, the muscle forces necessary to produce that motion, and the associated spindle feedback from the muscles.

Lifting and manipulating objects is also an important aspect of limb movement control. Studies of the ability to discriminate differences in the masses of objects of similar size and appearance by hefting them show a degradation of performance in weightless conditions. If the hefting frequency is increased, performance improves considerably. Rapid arm movements are known to be less dependent for their accurate execution on muscle spindle feedback and are less impaired than slow movements during space flight. Consequently, the degradation in mass discrimination associated with slow movements is likely to reflect errors in resolution of limb trajectory, at least in part. Subjects experience post-flight increases in the apparent heaviness of hefted objects and of the body and limbs. This change points to a reinterpretation by the central nervous system of the apparent effort associated with supporting the limbs or holding objects against gravity.

Our sixth sense, the sense of motion, is mediated by the vestibular system. The inner ear contains two balance-sensing organs, both of which are designed to keep the individual upright, orientated, and moving smoothly. One organ, comprised of the saccule and utricle, sends messages to the brain as to how the head is positioned relative to the force of gravity (Fig. 2.1.6.3). The saccule and utricle are tiny sacs, lined with hair cells. Small calcium-carbonate particles, the otoliths, rest on these hair cells. When the head moves relative to gravity, the weight and movement of these otoliths stimulate the hair cells and give the brain information on ‘up’, ‘down’, ‘tilt’ and ‘translation’ in a particular direction. The other balance-sensing organ is comprised of three semicircular canals. It provides the brain with information on rotation about the three axes of yaw, pitch and roll.

These two balance- and motion-sensing organs form the vestibular apparatus. The latter is connected to several other key systems involved with balance, orientation, and movement. Information travels from the vestibular system to the eyes, to keep them focused on a target

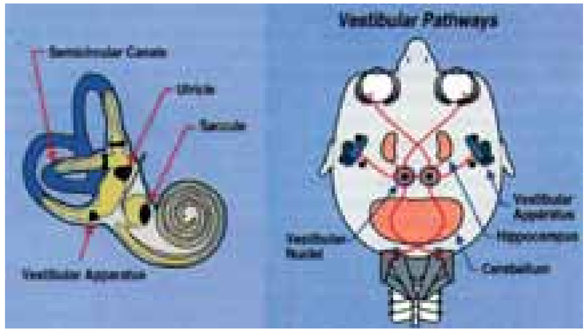


Figure 2.1.6.3. The human balance system, its location within the inner ear (left) and its connections with other key systems involved with balance, orientation, and movement (right)

whilst the body is moving. The hippocampus also uses information from the inner ear, which is important for knowing locations and navigating. Nerves travelling from the vestibular system to the cerebellum help produce precise, smooth and co-ordinated movements. Vestibular information travels down the spinal cord to the muscles, to maintain balance and posture.

The question is whether the part of the vestibular system that is sensitive to gravity continues to operate in weightlessness. Head tilt is not sensed by the otoliths in the absence of gravitational force, but they are still activated by the inertial force of translational motion. Experiments performed in space to date, including those using the ESA 4 m-long Sled moving with very low accelerations, have not shown significant changes in sensitivity to linear acceleration during and after space flight. Since the brain receives inputs from the otoliths only when there is a translational head motion in weightlessness, it has been proposed that the brain re-interprets tilt-related otolith information as translation during space flight. This has been the theoretical basis of much space research for the last 15 years. Only recently has this hypothesis actually been tested, using a centrifuge installed onboard the Space Shuttle.

However, the vestibular system rarely works alone. Vestibular inputs are generally combined with visual, proprioceptive (stretch), and tactile (touch) inputs for the perception of self-orientation and motion. These multi-modal sensory stimuli are also compared with motor feedback inputs for the appreciation and regulation of body orientation. This sensori-motor integration (often referred to as the neurosensory system) plays a key role in posture and movement control, locomotion, and object manipulation in a gravitational environment. During the last 20 years, extensive experimental research has been performed to investigate the effects of weightlessness on the mechanisms of spatial orientation, postural control, hand – eye – head coordination, and space motion sickness.

Space experiments have shown nicely that visual cues alone can provide a sense of self-motion and tilt. When presented with rotating visual patterns in the frontal plane, the astronauts experience full 360° roll self-motion, a reaction that happens rarely on Earth. This enhanced effectiveness of visual stimuli for inducing apparent self-motion is probably also responsible for the illusion of ‘feeling upside down’ when the astronauts’ feet point to the spacecraft’s ceiling. There are large differences between individuals though. For some astronauts, for example, the direction in which their feet point is always ‘down’, and changing their body orientation within the space vehicle does not shift the apparent ‘down’ direction.

Figure 2.1.6.4. The ESA Space Sled, used on the German D-1 Spacelab mission. Providing linear accelerations along all body axes, it was used to evaluate possible changes in the detection threshold for very low linear accelerations in space

On the Earth’s surface, gravity significantly affects most of our motor behaviour. It has been estimated that about 60% of our musculature is devoted to opposing gravity. For example, when making limb movements in static balance, anticipatory innervations of leg muscles compensate for the impending reaction torques and the changes in location and projection of the centre of mass associated with these movements. Similar patterns of anticipatory compensation are seen in-flight, although they are functionally unnecessary. Also, rapidly bending the trunk forwards and backwards at the waist is accompanied on Earth by backward and forward displacements of the hips and knees to maintain balance. The same compensatory movements of hips and knees are made in weightlessness. Since the effective gravity torques are absent during space flight, the innervations necessary to achieve these synergies in weightlessness are different from those needed on Earth. Consequently, these in-flight movements must reflect reorganised patterns of muscle activation.

Locomotion in the absence of effective gravity is quickly learned by the astronauts. On the other hand, post-flight posture and locomotion disturbances are commonplace. Static posture exhibits a considerable increase in sway amplitude, especially in the absence of visual and proprioceptive cues. The phases of the step cycle, during locomotion, show serious post-flight alterations, and the head is more unstable. These alterations are also presumably the consequence of adaptive changes in the central nervous system to the control of posture and movements during space flight. Full recovery can take weeks, even after short space missions. Systematic quantitative measurements of posture and locomotion after long missions are presently lacking.

During head movements, the vestibular apparatus transduces head velocity and relays this information to those centres controlling eye position to generate compensatory eye movements; this reflex behaviour ensures that vision is not blurred. When performed in darkness, this leads to a pattern of rhythmic eye movements known as nystagmus, consisting of slow phases in the direction opposite to the head and fast phases that bring the eye back when it reaches the extreme of its travel. The nystagmus response to a rapid head movement outlasts the changes in signals in the semicircular canals, through the activation of a velocity storage mechanism located in the brain stem. This so-called ‘vestibulo-ocular reflex’ has been studied systematically in orbital flight, both during active (voluntary) (Fig. 2.1.6.5) and passive head movements (Fig. 2.1.6.6). The basic finding is that gravity has no influence on

Figure 2.1.6.5. Subject participating in an experiment to measure eye reflex movements during voluntary head motion (COIS experiment, STS-78)

the peak slow phase velocity of the nystagmus, elicited by rapid yaw or pitch head movements. However, the time constant of nystagmus decay is shorter during space flight than on Earth. Interestingly, on Earth when the otolith organs are ablated, velocity storage is also diminished. The data obtained in weightlessness were the first evidence that the velocity-storage mechanism is sensitive to linear acceleration.

Humans sense gravity on Earth directly through receptors in the inner ear and indirectly by touch and stretch. In space, the central nervous system interprets the inputs from these receptors differently. In the first few days of space flight, about half of the astronauts experience a type of motion sickness. This seems to be due to the absence of the constant input from those sensors in the inner ear, the otolith organs, which sense linear acceleration and gravity. In this period, the astronauts are particularly sensitive to tilting of their head to the side, front or back, and they frequently hold their head and neck very stiffly. The basis for this space motion sickness appears to be that the brain no longer receives an input that signals that the head has moved relative to gravity. After several days in weightlessness, the neurosensory system adapts to the new situation; the symptoms relapse and head movements no longer produce nausea. It is believed that at this point the reference frame for spatial orientation has changed. Since one can no longer depend on gravity to provide a reference for 'down' or 'up', the basis for orientation shifts to an internally generated reference. Thus, the 'down/up' vector is now perceived as being aligned with the longitudinal axis of the body. However, further experiments in space involving simultaneous recording of body posture, oculomotor responses, subjective illusions and motion-sickness symptoms are required to test this hypothesis.

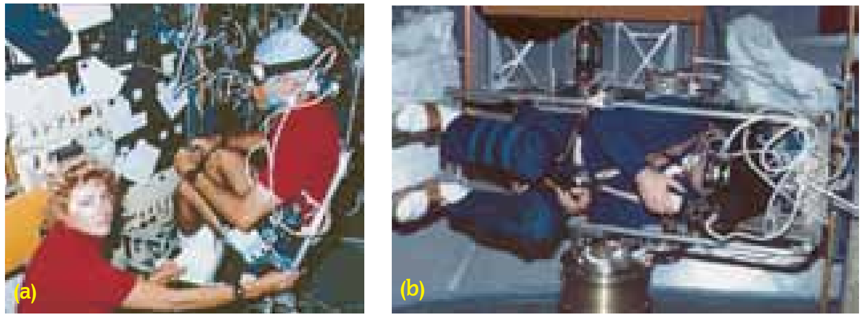


Figure 2.1.6.6. (a) The hand-spun rotating chair, used during the SLS-1 mission. (b) The servo-controlled rotating chair used during the IML-1 mission, shown here in the pitch orientation

2.1.6.3 Development of the Vestibular System

Since life first appeared on Earth, gravity has been a constant selective force. Consequently, the development and behaviour of all organisms have gravity as an indirect, if not direct, determinant. In many cases, the role of gravity in biological processes can be revealed explicitly under weightless conditions.

During gestation and early development, there is a fixed sequence in which sensory systems achieve an onset of function, i.e. when a sensory system begins to respond to stimulation, such as the visual system to light, the olfactory system to odours, the vestibular system to linear or angular acceleration, etc. In every vertebrate species that has been examined so far, the onset of function occurs in the following sequence: tactile, vestibular, auditory, visual. Interestingly, in all species the onset of vestibular function occurs prior to hatching or birth, in contrast to hearing or vision, which can be post-natal in some species. This means that the foetus is potentially susceptible to vestibular stimulation in its pre-natal environment. Mammalian offspring emerge from the birth canal in a species-typical orientation that, for rats and humans, is head-first. Foetuses typically achieve the appropriate orientation via active, in-utero behaviour. It would appear that the vestibular system is employed for this early task. Indeed, many infants born in the breach position are born with vestibular disorders. Also, the so-called 'righting response', by which newly born mammals actively adjust from a supine to a prone position, is disrupted by induced vestibular disorders during development.

In the development of the visual system, activity in the retinal pathway influences the specification of those connections that determine how visual information is processed in the cerebral cortex. In every other sensory system known, especially those that make up the neural space maps in the brain stem, sensory stimulation has been implicated in the initial specifications of the connections and physiological properties of the constituent neurons. Only in the otolithic gravitational pathway has it been impossible to study the role of sensory deprivation, because there is no way to deprive the system of gravitational stimulation on Earth.

For this reason, experiments in microgravity should be planned to test the hypothesis that gravity itself plays a role in the development and maintenance of the components of the vestibular system. These components include both the vestibular receptors of gravity – i.e. the sensory hair cells in the utricle and saccule, vestibular ganglion cells that form synapses with vestibular hair cells, and vestibular nuclei neurons – and the motor neurons. The latter receive inputs from axons of the vestibular nuclei neurons, composing the vestibular reflex pathways. The vestibular system also receives inputs from the proprioceptive system, which is involved in the control of muscle length and tension, and from the visual system, which is involved in the control of eye movements. Little is known about the exact nature of these interactions and virtually nothing concerning the development of these connections.

Morphological data, concerning potential changes in the vestibular end organs resulting from exposure to weightlessness, are scarce so far, but they indicate that significant changes may occur. In the rat, about a twofold increase in ribbon synapses of Type-II hair cells and a 50% increase in Type-I cell synapses of the otoliths have been found after two weeks of space flight, compared with ground-based controls (Fig. 2.1.6.7). The increased synaptic levels were still apparent in animals assayed 14 days post-flight. In contrast, animals exposed to increased gravity levels, through centrifugation, exhibit decreased synaptic density levels. The functional significance of these synaptic changes has not been determined. Data on whether there are alterations in the otolith crystals are less clear, with some studies suggesting that there are changes, and others not. Few data are available concerning the physiological activity of vestibular afferents in weightless conditions.

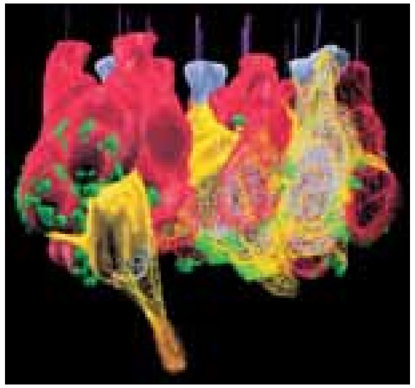


Figure 2.1.6.7. Reconstruction in 3-D from the right utricular macula of a rat, flown on the SLS-2 mission (courtesy of M.D. Ross & D.L. Tomko)

The impact on an animal's behaviour of alterations in the development of its gravity receptor systems, at the cellular level, is virtually unknown. The whole is more than the sum of the parts, and knowing only how cells perform in culture in space may reveal little about how whole organisms will respond in weightless conditions. On Earth, specific behavioural adaptations to gravity, such as the righting reflex, are seen in many species in various situations. Observations of behaviour in the absence of gravity and the analysis of adaptive responses to exotic gravitational regimes can provide valuable insight into the evolution, function, and regulation of the behaviour of organisms. For example, experiments on Earth indicate that gravity plays a significant role in learning basic motor skills like swimming and walking. Will animals, launched into space at the point where they have never walked on Earth, always be better adapted to weightlessness than to Earth, or will the changes be transient? Will they present a righting reflex in response to being tilted after they have been returned to Earth, or does a critical period exist for developing gravity-oriented reflexes?

2.1.6.4 What Exactly has been Learnt from Microgravity Experiments?

A few examples are reported here of space experiments that have provided valuable results that could not have been obtained under terrestrial conditions.

- The Caloric Nystagmus is not due solely to Thermal Convection

The most widely used clinical check on the functioning of the vestibular system is the caloric test. During this test, irrigation of the external auditory ear with water or air above or below body temperature generates, by thermal conduction, a temperature gradient across the inner ear. As a result, the vestibulo-ocular reflex (see above) is triggered, producing characteristic rhythmic eye movements (nystagmus) and the subject experiences slight vertigo. For many years it was generally believed that this response was initiated by the differences in specific gravity of the inner ear fluid (known as endolymph) along the horizontal semicircular canal, generated by the induced thermal gradient, which leads in turn to a thermo-convective force. This would produce a displacement of the endolymph, thereby stimulating the canal's sensory cells, in the same way as an angular movement of the head (Fig. 2.1.6.8). At the turn of the last century, Robert Bàràny, a Viennese specialist, received the Nobel Prize for proposing this mechanism of caloric stimulation.

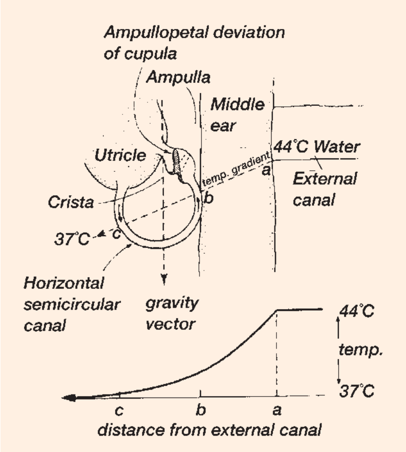


Figure 2.1.6.8 The mechanism of caloric stimulation of the horizontal semicircular canal (from 'Clinical Neurology of the Vestibular System', Baloh and Honrubia (Eds.), F.A. Davis, Philadelphia, 1990)

The microgravity of spaceflight, where normal thermal convection is absent, is ideal for verifying this mechanism. If the thermo-convective hypothesis is correct, then no nystagmus response should be observed. Caloric irrigation was first performed during the Spacelab-1 flight, and then on subsequent missions. In all test subjects, the caloric nystagmus response was elicited. A number of possible alternative source mechanisms for the latter have since been discussed. They include a direct thermal effect on the sensory hair cells or the afferent nerve connections to the CNS, or differential pressure effects due to thermal expansion of the endolymph fluid in the labyrinth.

- How does the Brain Differentiate between Linear Acceleration and Gravity?

Space research has significantly improved our understanding of the working of the otolith organs, which act as linear accelerometers. Yet Einstein's equivalence principle requires that a linear accelerometer cannot discriminate between linear acceleration and gravity. On Earth, the otoliths are continuously exposed to gravity. Is this information always coded in the otoliths' afferent nerve activity to the brain?

During the Neurolab space mission in 1998, it was shown by the author that the eye movement reflex evoked by constant linear acceleration along the inter-aural axis, so-called 'eye counter-roll', has the same amplitude in weightlessness as on Earth. On Earth, the eyes counter-roll during a head tilt to the side in order to keep the retina aligned with the vertical axis. Therefore, although on Earth the otolith organs are stimulated by both the shearing force in the plane of the horizontal otolith organs (the utricle) and by gravity, it is only the shearing force that is at the origin of the eye counter-roll. In space, linear acceleration was generated by a short-arm centrifuge (Fig. 2.1.6.9). When the centripetal linear acceleration delivered by the centrifuge was 0.5g, the ocular counter-rolling amplitude was about half of that measured at 1g. This suggests that both the direction and magnitude of the linear acceleration with regard to the head are taken into account by the brain. This result could not have been obtained on the Earth's surface in a 1g environment.

Figure 2.1.6.9. The ESA Visual-Vestibular Integration System, or off-axis rotator, used on the Neurolab STS-90 mission. In space, this short-arm centrifuge stimulated the vestibular system through a 0.5g or 1g linear acceleration directed along the subject's inter-aural axis, without the confounding effect of gravitational acceleration

Because sensory systems often provide ambiguous information, neural processes exist to resolve these ambiguities. A neural model has been proposed recently, based upon physical principles, which may be used by the brain to help estimate linear acceleration and gravity. The hypothesis that the central nervous system can develop an internal estimate of gravity and of the body's vertical has been validated by the subjective perception of astronauts during centrifuging in space. At the beginning of the flight, during a 1g inter-aural acceleration in darkness, the astronauts perceived a 45° tilt to the side, very much like on Earth. However, as the mission progressed, they felt more and more tilted, until perceiving a 90° tilt to the side on flight day 16. This simple result indicates that an internal estimate of gravity (the so-called 'body vertical vector') is used for the perception of the upright.

The internal estimate normally used on Earth (1g) carries over to the early period of exposure to weightlessness. Therefore the astronauts continue to perceive a 45° tilt during 1g inter-aural centrifugation, despite the absence of sensed gravity. After a period of adaptation, the internal estimate goes to zero and the astronauts perceive a full body tilt to the side. This finding could only come from studies in weightless conditions, where there is no confounding influence of the gravitational acceleration. Another fundamental finding of this experiment was that astronauts always felt tilted, never translated, during constant-velocity centrifuging in space flight. Therefore, despite the fact that the otoliths in weightlessness are stimulated by head translation, and not by head tilt, the brain continues to interpret low-frequency linear acceleration applied to the otoliths as being due to head tilt.

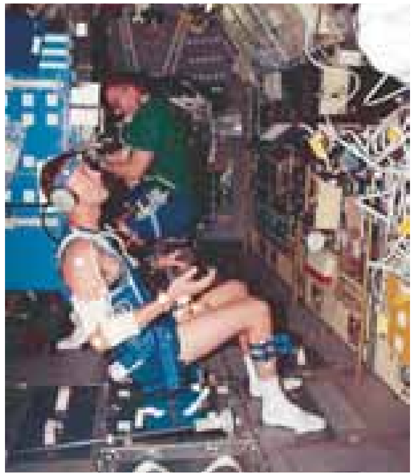


Figure 2.1.6.10. The 'Ball Catching Experiment' conducted during the Neurolab STS-90 mission. In microgravity, a thrown ball will travel at an almost constant velocity. The trajectory of the subject's arm and the activity of his forearm muscles are recorded as he tries to catch it

Using a simple ball-catching experiment in weightlessness, it has been shown that this internal estimate of gravity is also used in movement planning and execution. During the act of catching a ball on Earth, the brain estimates the trajectory of the ball, accurately taking into account its downward acceleration due to gravity. In space, a seated astronaut had to catch a ball travelling at a constant velocity, in contrast to the constant acceleration that would occur on Earth. In the first trials, the astronaut failed to catch the ball in weightlessness, but later trials were more successful. These results indicate that the compensation for gravitational acceleration is pre-programmed, based on a lifetime of experience in a 1g environment. However, this internal model of gravity adapts over time, presumably through the estimation of the object's trajectory based on visual information.

- *The Role of Neural Space Maps in Spatial Orientation*

Vertebrate brains form and maintain multiple neural maps of the spatial environment that provide distinctive, topographical representations of different sensory and motor systems. For example, visual space is mapped onto the retina in a two-dimensional coordinate plan. This plan is then remapped to several locations in the central nervous system. Likewise, there is a map relating the localisation of sounds in space and one that corresponds to oculomotor activity. An analogous multi-sensory space map has been demonstrated in the mammalian hippocampus, which has the important function of providing short-term memory for an animal's location in a specific

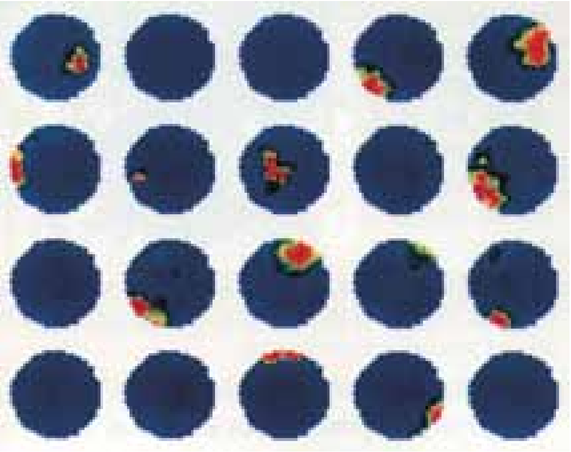


Figure 2.1.6.11. These circles show the firing patterns of twenty simultaneously recorded 'place' cells in the rat hippocampus. Each circle depicts the firing of a single neuron, as the rat traverses a round platform. The areas in red represent the 'place', or location, on the platform where that cell fired at a higher rate; the areas in blue indicate locations where the cell did not fire at all. The ensemble of the activities of all of the cells in the hippocampus encodes a 'cognitive' map of the rat's environment, which it uses to navigate through its world

environment. This neural map is particularly focused on body position and makes use of proprioceptive as well as visual cues. It is used by the animal to return to an earlier location.

This system of maps must have appropriate information regarding the location of the head in the gravitational field. So it follows that the vestibular system must play a key role in the organisation of these maps. Only recently has this been demonstrated by experiments carried out in space. During an experiment performed aboard Neurolab, rats ran along a track called the Escher staircase, which guided them such that they returned to their starting position after having made only three 90° right turns. On Earth, rats cannot run this track, but in weightlessness it provided a unique way to study the 'place cells' in the hippocampus that encode a cognitive map of the environment. The rats had multi-electrode recording arrays implanted next to their hippocampal 'place cells'. The recordings made in space indicated that the rats did not recognise that they were back where they started after only three 90° right turns.

Such studies could help to explain the visual illusions experienced by some astronauts when they arrive in space, such as the impression that the world is upside-down, and how the nervous system adapts to weightlessness as these illusions disappear later in the mission. They could also reveal how information on gravity is processed by the nervous system for more cognitive processes. In recent years, several investigations carried out in space using virtual reality have revealed that higher cortical functions, such as mental rotation of three-dimensional objects, the recognition of inverted faces, the detection of bilateral symmetry and depth, or memorised navigation, are impaired in weightlessness. The combination of virtual reality with multi-EEG recordings (for the measurement of evoked-related potentials and brain mapping) should soon provide exciting results on the adaptation mechanisms of cerebral functions in the absence of gravity.

Figure 2.1.6.12. A crew member on the Neurolab STS-90 mission wearing the Virtual Environment Generator (VEG) head-mounted display. This display generated scenes that tested how the crew member maintained orientation in space

- *Three-dimensional Orientation of Eye Movements*

On the Earth's surface, two major sources of linear acceleration are normally encountered. One is related to the Earth's gravity. The gravitational force pulls the body towards the centre of the Earth, and the body opposes this force to maintain an upright standing posture. The other source of linear acceleration arises in the side-to-side, up-down, or front-back translations of the head, which commonly occur during walking or running, and from the centrifugal force sensed when turning or going around corners. The body responds by tending to align the longitudinal body axis with the resultant linear acceleration vector. Put in simple terms, one has to exert an upward force to balance gravity when standing upright, and to tilt in the direction of the turn when in motion. Very recently, scientists have discovered that on Earth the eye movements also reflect an orientation to the resultant linear accelerations during turning. During either passive rotation, as in a centrifuge, or while walking or running around a curved path, the axis of eye rotation tends to align with the resultant axis of the summed linear accelerations.

In space flight, the gravitational force is no longer perceived. Since there is no locomotion in space, exposure to centrifugal forces is also reduced. However, the linear accelerations due to side-to-side, up-down, and front-back motion (translation) persist. Measurements have been made, by the author, of the perceptual responses of the subjects to centrifugal force and of the axis of eye rotation (Fig. 2.1.6.9). Both were in agreement, confirming that the central nervous system relies on the direction and amplitude of the summed linear accelerations for both perception and compensatory eye movements.

2.1.6.5 Terrestrial Applications of Neuroscience Space Research

Much of the neuroscience research in space is focused on understanding the mechanisms involved in the brain's interpretation of the body's orientation in three-dimensional space. With sufficient information in hand, researchers can develop procedures to protect space crew members from related disturbances, especially when they return to Earth after long space voyages. However, the results of this research are also applicable to patients with gait and postural disorders of neurological origin, including elderly people for whom falls may have especially serious consequences.

A relatively large number of individuals on Earth suffer from prolonged, frequently lifelong, clinical balance disorders. Disorders like Ménière's disease and traumatic injuries of the inner ear can severely influence the quality of life. Currently, human space flight is the only means available for studying the human response to sustained loss and recovery of inner-ear information.

Changes in the human body during space flight often resemble the effects of aging. Inflight observations of young astronauts have revealed similar degradation in balance control to that which occurs with age in Earth-bound subjects. For example, decreases in visual (near accommodation, distance perception, smooth pursuit) and vestibular (low-frequency vestibulo-ocular reflex, postural stability) performances are noted both in astronauts in space and in elderly people on Earth. Problems associated with spatial orientation (subjective vertical) and navigation (memorising a path) are also common to both groups.

In fact, the majority of people over 70 years of age report problems of dizziness and imbalance. Balance-related falls account for more than half of all accidental deaths in the elderly. There is little understanding of why older people are so prone to falling. One possible cause could be the misalignment of the body axis to the summed linear accelerations that are encountered during turning, while walking or running. Microgravity provides a powerful tool with which to discriminate between the response to the linear acceleration of translation and centrifugal force, and the linear acceleration of gravity. This cannot be done on Earth, where the body cannot separate centrifugal and gravitational forces. Astronauts can experience this in space, during rotation on a centrifuge, for example. The experiment described above, flown on Neurolab in 1998, has provided basic information about how alignment of the body axis to the summed linear acceleration occurs. Specific parts of the cerebellum (the nodulus and uvula) control this type of spatial orientation and these studies should help in understanding the nature of the processing in these parts of the cerebellum.

The stimulation and measuring devices developed for space experiments are often very sophisticated. Some of these techniques have subsequently found wide usage for patients with vestibular disorders on Earth, and have become the standard in clinical practice. For example, the first equipment for recording eye movement using video cameras was developed by ESA in the early 1980s for the Spacelab missions (Fig. 2.1.6.13). The most readily available system for recording eye movements in the clinic was to measure the magnitude of the voltage surrounding the orbit with surface electrodes. This method (known as electro-oculography) proved too inaccurate for scientific research, especially for recording vertical eye movements. More recently, a number of two-dimensional, video-based pupil trackers have become commercially available (see Section 3.2). A major limitation of these systems is that they are unable to measure ocular torsion, which is essential for the comprehensive three-dimensional measurement of eye movement. Furthermore, the use of conventional video limits the sampling rate to 50 or 60 Hz. The video-oculography technique developed for the German and European Mir missions, and later for the Neurolab mission, provides adequate measurement of all three components of eye movement (horizontal, vertical and torsional). A new generation of eye-tracking equipment currently being developed for the International Space Station is based on so-called 'smart vision sensors'. Digital processing and storage will permit online image sampling rates of up to 400 Hz, enabling the correct measurement of rapid eye movements, such as fast phases or saccades. This development is also being tested and reviewed by an international group of neurologists and engineers, for application in both the space and the clinical environments.

Figure 2.1.6.13. The first eye-movement recording system, with a video camera, developed by ESA for experiments during the first Spacelab mission

Clinically speaking, the study of vertical and torsional eye movements has also been hindered by the lack of a reliable stimulation method. Eye movements induced by voluntary pitch or roll head rotation (active or passive) have been the subject of intensive investigation during space flight. The head movements were measured with angular rate sensors (Fig. 2.1.6.5). Such tests are now commonly used in clinics. Not only do they allow testing with more natural movements on the part of the patient, but also they do not restrict the plane of testing to yaw. Dysfunction in vertical reflex eye movements in response to head pitch or roll has thus been observed in patients with lesions of the brain stem and cerebellum.

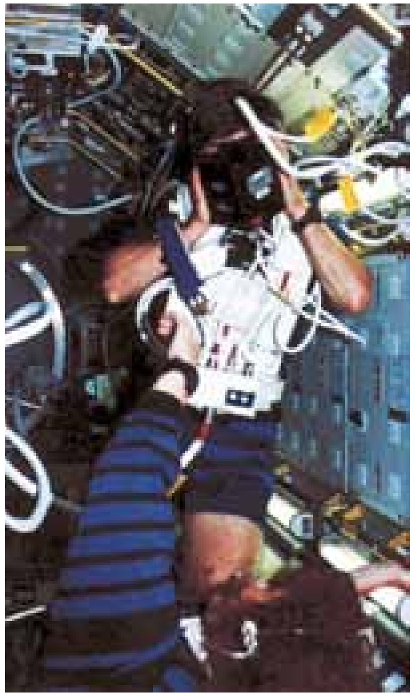
The use of off-vertical rotation, performed by seating the subject in a conventional rotational chair and then tilting the entire apparatus, has proved to be a reliable test of the otolith organs on Earth. This stimulation has been (and is still being) used on astronauts after space flight. It is also used in the clinic to detect vestibular lesions, which mainly affect the otoliths. Similarly, the short-arm centrifuge studies on astronauts in space, as described above, suggest that centrifuging might provide a useful test of otolith function on Earth. When the test subject estimates the subjective vertical during constant-velocity centrifuging, the amplitude of perceived tilt gives a good indication of how the brain measures the resultant of linear accelerations. Such estimation during centrifuging is more reliable than during a static tilt relative to gravity because, again, it allows testing under more natural conditions of motion.

Figure 2.1.6.14. The Video-Oculography (VOG) Unit, developed by DLR for use on the ISS

In many cases, the results obtained in space provide researchers with unique insights that can be applied in the search for treatments for diseases on Earth. For example space sickness, which is experienced by over half of all astronauts during the first 72 hours of space flight, is a form of motion sickness. The symptoms and the signs (stomach discomfort, nausea, pallor, cold sweating and vomiting) are similar. Reports of 'mal de débarquement', the renewed symptoms of motion sickness after returning from space flight, tend to strengthen the analogy between space and terrestrial motion sickness. The symptoms occur in about 90% of astronauts returning from missions lasting several months. Although the physiological mechanisms underlying motion sickness are poorly understood, some countermeasures used to limit the symptoms in astronauts have proved successful for terrestrial motion sickness. It has long been known that anti-motion sickness medications are less effective if given after the symptoms of motion sickness have already appeared. The transdermal patch has been tested successfully for the first time on astronauts during space flight, to deliver a small dose of an anti-motion sickness drug (0.5 mg of scopolamine) over a period of 72 hours. The same transdermal patch is now commonly used on Earth to deliver a different drug for those attempting to give up smoking. Air- and sea-sickness de-sensitisation programmes for pilots and sailors, which include repetitive exposure to rotating head and body motions, are also based on the vestibular training techniques used by astronauts prior to space flight. This training is based on the notion that the inner ear is more important than the eye in providing cues as to the orientation of the aircraft or ship.

A portable acquisition unit for the recording of eye movements and muscle activity, coupled with a visual stimulus generator, has been developed by CNES. It is designed to study the astronauts' oculomotor and postural responses during the return phase of the Space Shuttle to Earth. This period of return to the Earth's gravity is very interesting for seeking new insights into the nervous system's capacity to re-adapt, which is somewhat equivalent to healing after an injury. This portable system, known as 'Pocket', is battery-powered, because the Shuttle's main generators are shut down during re-entry (Fig. 2.1.6.15). It has been used on 21 Shuttle missions and allowed testing on 41 astronauts between 1991 and 1996, making it the most 'space-flown' life-sciences equipment to date. Nowadays, this equipment is used in clinics as bedside equipment to test the recovery of these functions in patients after inner-ear surgery.

Figure 2.1.6.15. A free-floating crew member on the STS-78 mission, wearing a head-mounted visual stimulator and a vest carrying the 'Pocket' multi-channel portable recording system for measuring eye movement and muscle activity



Similar clinical applications are already foreseen for the virtual-reality systems currently being developed by space agencies for the Space Station (Fig. 2.1.6.12). Also, in preparing for a manned mission to Mars, for example, it will be vital to have appropriate spatial-motor training before performing extra-vehicular activities (EVAs) or tele-operational tasks. Virtual-reality training may be a way to train astronauts (as well as patients on Earth) to compensate for their altered neurosensory responses. However, the use of virtual environments in space could potentially exacerbate motion sickness, and therefore further studies in this area are needed.

As mentioned above, neural coding of spatial navigation may be affected by the change from a 1g to another force background, and this may be related to some of the orientation illusions experienced by astronauts. The influence of altered gravity conditions (whether 0g as in space, or 0.38g as on Mars) on orientation and geographical localisation should therefore be further explored, in both human and animal experiments. There is also a critical need to evaluate the influence of long-term exposure to weightless conditions on the coordination of body activities and locomotion, involving coordination of eye, head, torso, arm, and leg activities, and on cortical maps. Ground- and space-based centrifuges, body-loading conditions, and virtual-reality conditions should be utilised for testing. Ultimately, limited exposure to artificial gravity during the course of an interplanetary mission might prove to be a sufficient countermeasure for most of the detrimental effects of being weightless for long periods. The image of returning cosmonauts being lifted out of their Soyuz capsules in the steppes of Central Asia, placed in litters, and then whisked by helicopter to the nearest hospital, as anxious medical personnel watch over them, will then no longer deter the enthusiasts from wanting to fly to Mars.

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2.2 SPACE BIOLOGY

2.2.1 Cell and Molecular Biology

R. Bouillon, J. Hatton & G. Carmeliet

2.2.1.1 Introduction

Several physiological systems are altered by spaceflight as a result of the exposure to psychological and physical stress, to cosmic radiation or to microgravity. An understanding of the mechanisms by which these factors alter human physiology is obviously important for the prevention and treatment of spaceflight-related symptoms.

One of the most intriguing questions related to the influence of exposure to microgravity conditions is: '*What is the nature of the 'sensor' for microgravity: Is it the whole body, or is it at the tissue or cellular level, or even a sub-cellular structure?*' Connected to this is the fundamental question of whether individual cells can sense changes in gravity.

There are some specialist gravity-sensing (gravimetric) cells, but they are involved in normal plant growth and development, as discussed in Section 2.2.2. The discussion here, however, concerns normal mammalian cells. Studies of different mammalian cell types, cultured under simulated microgravity conditions or during spaceflight, show that gravity may have an effect on isolated cells and that some of these effects are cell-specific and even function-specific.

The observed alterations, common to diverse cell types, include changes in cell proliferation and differentiation. The recent observation that the expression (transcription) of over 1600 genes in a human renal cell culture was altered in microgravity provides further evidence for a differential gravity effect on cell function. Although the mechanisms involved remain a mystery, the data suggest a role for the filamentary network of the cell (cytoskeleton) and for the signal transduction pathways in these processes.

Spaceflight has been shown to produce consistent changes in the immune system and also in the bones (see Section 2.1.5) of both humans and animals. For that reason, the following discussion will focus mainly on the effect of microgravity on the cells involved in the immune system and on the cells that are responsible for bone formation (osteoblasts).

2.2.1.2 Changes to the Immune System

The body's defence against pathogens relies upon the coordinated action of different types of leukocytes or white blood cells. Immunological studies performed post-flight on astronauts have consistently shown alterations in the numbers and activity of circulating white blood cells (leukocytes). In these studies, the circulating leukocytes were found to be redistributed in a similar way to the redistribution produced by stress hormones. This alteration in monocyte abundance and leukopoiesis may contribute to the retarded wound healing that has been observed in rats during spaceflight. In addition, a reduction in the activity of natural killer cells and T-lymphocytes has been observed.

The activation of T-lymphocytes plays an important role in various immunological responses. Because of their critical role in the immune response, circulating T-cells are maintained in a resting state of the cell cycle, their growth and differentiation being strictly regulated. Given the importance of this pathway in the immune system and the decrease observed in astronauts, several groups have investigated this process, using cells cultured under microgravity conditions (Fig. 2.2.1.1). Comparable results to the in-vivo data were obtained, but at present the underlying mechanism for the observed changes remains only partially understood.

- *Proliferation and Cell Death (Apoptosis)*

Experiments in microgravity and in ground-based model systems have clearly indicated that, in a reduced-gravity environment, human T-lymphocytes fail to proliferate in response to mitogenic lectins, which would normally stimulate such proliferation. In addition, the death rate of these cells (apoptosis) is found to increase in microgravity. These data suggest that the reduced response of certain cell types to growth stimulation during spaceflight is partially a result of increased apoptosis.

- *Gene Expression*

The entry of T-cells into the cell cycle (mitogenic stimulation) is accompanied by the activation of numerous cellular events. These include gene transcription and the expression of activation markers on the plasma membrane.

In a normal simple growth response, an external inducer is docked at the surface of the cell and the command is transduced into the cell via an internal communication, or signalling, network (Fig. 2.2.1.1). Through this process, the cells are told to deliver the proteins, such as CD69, interleukin-1 and -2, and the interleukin-2 receptor, that are necessary for an adequate immune response. In fact, the cells sense multiple simultaneous inputs, resulting in the activation and integration of several signalling pathways. Microgravity is one of the stimuli that alters a normal growth response.

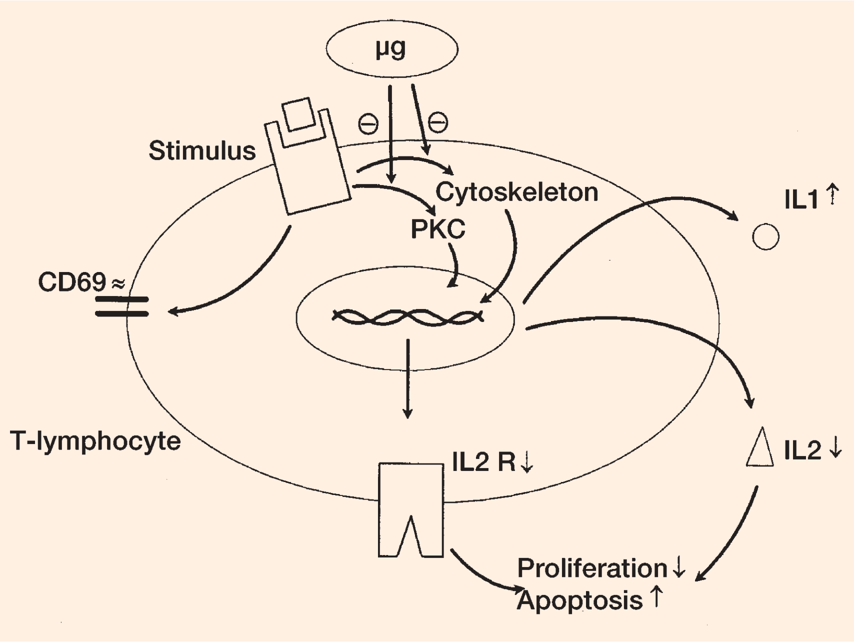

Figure 2.2.1.1. A model of microgravity-induced effects on T-lymphocytes. Microgravity has no effect on ligand binding or cell – cell interaction, but interferes with signal transduction via the protein kinase C (PKC) pathway and cytoskeleton. This results in altered gene expressions of interleukin-1 (Il-1), interleukin-2 (Il-2) and interleukin-2 receptor (Il-2R). Other intracellular processes function normally, as evidenced by the normal expression of CD69. These changes lead to decreased proliferation and an increased cell death rate (apoptosis)

The observed inhibition of proliferation in microgravity cultures is most likely a result of alterations in the cellular events that lead to the surface expression of the important regulatory molecules, such as the interleukin-2 receptor. This process requires induction of gene transcription and of new protein synthesis within hours of activation.

In microgravity cultures, the surface expression of the interleukin-2 receptor is found to decrease. However, the surface expression of those receptors that are pre-synthesized and stored in lymphocytes, such as CD69, can occur to a great extent in microgravity cultures and the expression level of interleukin-1 is actually enhanced under microgravity conditions. This differential regulation indicates that microgravity modifies cellular function in a complex manner. The changes seen in this cytokine production process in microgravity do not involve a general shutdown. Rather, microgravity appears to modify only certain signalling pathways.

- *Mechanisms*

One of the most intriguing challenges of microgravity research in this area is to understand how an identical chemical input produces, under altered gravity conditions, a different functional output in T-lymphocytes or other cell types. In trying to elucidate this issue, investigators have concentrated their research on cell–cell contact and cell morphology on the one hand, and on the different steps in the signalling cascade on the other.

Cell morphology and motility
Microgravity-induced alterations in the cytoskeleton are thought to underlie some of the effects seen in these changes to proliferation and gene expression. Human lymphoblastoied cells, cultured under microgravity conditions, have shown a time-related change in microtubule appearance, with diffuse, shortened microtubules extending from poorly defined microtubule organizing centres.

Cell–cell interactions and aggregate formation are important means of cell communication and signal delivery in T-lymphocyte activation. Electron-microscopy observations of lymphocyte activation have indicated that surface contact between monocytes and lymphocytes does occur in microgravity culturing. As already mentioned, synthesis of interleukin-1 is normal under (simulated) microgravity conditions. This synthesis occurs in response to intercellular signalling between T- cells and monocytes and it requires cell–cell contact. This suggests that intercellular signalling can occur effectively under altered gravity.

Correlated with this process is the ability of lymphocytes to traverse the interstitium. Culturing human lymphocytes under microgravity conditions, however, impaired their capacity to locomote. These data suggest that specific types of cell–cell and cell–matrix interactions, in which adhesive and cytoskeletal proteins are involved, are altered by gravitational changes.

Signal transduction
Several experiments have demonstrated that the binding of an extra-cellular stimulus to its receptor was normal under microgravity conditions. This suggests that it is the intra-cellular signalling network that is modified by a change in gravity. Surprisingly, microgravity does not disturb all of the different signalling pathways at once, but alters rather specific subsets of a certain signalling cascade (protein kinase C).

In summary, under altered gravity conditions certain types of white blood cells show a decreased response to growth stimuli. Due to alterations in specific subsets of signalling pathways inside the cell, certain functions of these cells are modified under microgravity conditions.

2.2.1.3 Changes to the Skeletal System

Bone is a multifunctional organ that has to fulfil two main roles. One is the provision of mechanical integrity, for both locomotion and protection. The other is an involvement in the metabolic pathways (homeostasis) associated with mineral regulation and control (see Section 2.1.5).

Bone is a dynamic tissue and in healthy individuals the amount of bone produced by the bone-forming cells (osteoblasts) is of the same magnitude as the amount of bone resorbed by the bone-resorbing cells (osteoclasts). The amount and the architecture of bone are regulated by hormones and local growth factors, as well as by the mechanical factors.

Mechanical factors are essential for the maintenance of skeletal integrity, the architecture of bone being correlated with the mechanical stresses exerted upon it, resulting in a material with an optimal functional design. The target cells that respond to the mechanical signal produced by skeletal loading have not been identified with certainty. They probably include osteocytes, osteoblasts, bone lining cells, and possibly marrow stromal osteoblast progenitors.

In the weightless conditions of spaceflight, the consequent skeletal unloading has been observed, in both humans and rats, to induce a series of events in bone which results in bone loss and compromised bone mechanical properties. It has been estimated that, in a microgravity environment, on average about 1 – 2% of the skeleton is lost each month. Bone mass changes are, however, site-specific, rather than evenly distributed throughout the skeleton. The tendency is for weight-bearing bones to be more affected by microgravity than non-weight-bearing bones. In addition, the flight's duration and the level of bone remodelling before unloading also appear to be factors able to modulate bone response to microgravity. Although no pathological fractures have yet occurred, spaceflight-related bone loss may have potentially serious consequences in long-term spaceflight, especially as recovery is a lengthy process.

Recent biochemical data from astronauts has confirmed the previous findings in rats, namely that microgravity induces an uncoupling of bone remodelling between formation and resorption that could account for bone loss. All bone-formation parameters were decreased, whereas bone resorption markers were increased when measured during flight. Analysis of bones from rats flown on space missions shows decreased bone formation and defects in bone maturation, suggesting inappropriate functioning of the bone-forming cells (osteoblasts) themselves when in microgravity. Interestingly, these histological findings are preceded by a detectable reduction in gene expression of bone-related proteins. In addition, spaceflight alters the message level for local growth factors.

Bone formation occurs by the bone forming cells or osteoblasts, which first proliferate and thereafter start to secrete bone-matrix proteins. In this way, a typical bone matrix is produced that becomes mineralized. These processes can be studied in-vitro using osteoblastic cell cultures. A decreased osteoblast function is claimed to play a role in the process of spaceflight-induced bone loss. The underlying mechanism may involve an altered cellular behaviour when osteoblasts are exposed to microgravity. Recent experiments, using several osteoblastic cell types (Table 2.2.1.1) show that cell morphology, as well as the gene expression of growth factors and matrix proteins, is altered under microgravity conditions.

Most of the studies listed in Table 2.2.1.1 used ground-based samples as a comparison control to the space experiments. Ideally, of course, an in-flight 1g centrifuge should be used to provide for controls, in order to ensure an equivalent environment.

Table 2.2.1.1. The effect of microgravity on osteoblast cells in-vitro

Cell Type	Origin of Cells	Micro-g Period	Treatment	Major Parameter Tested
ROS17/2.8	Rat osteosarcoma cell line	6 days		Cell morphology, cytoskeleton
MC3T3-E1	Mouse osteoblastic cells	4 days		Cell and nuclear morphology
Rat osteoblastic cells	Femur marrow cultures	5 days		Gene expression: cytokines
Rat osteoblastic cells	Femur marrow cultures	4-5 days	Vitamin D	Gene expression: growthfactor receptors
MG 63 cells	Human osteosarcoma cell line	9 days	Vitamin D TGFβ	Gene expression: matrix proteins
hFOB 1.19	Human foetal osteosarcoma cell line	17 days	Cytodex beads	Gene expression: growth factors, matrix proteins

- *Proliferation*

Several different osteoblastic cells, derived from different species, have been studied during spaceflight. In both rat and human osteoblastic cells, normal cell proliferation was observed in flight cultures. In contrast, a decreased number of cells were detected in a mouse osteoblastic cell line after spaceflight.

- *Gene Expression*

Gene expression for matrix proteins, growth factors and receptors are altered when osteoblastic cells are cultured in microgravity. The production of matrix proteins is an essential feature in the differentiation of the osteoblast and is required for mineralisation. Human osteosarcoma cells, MG63, showed a reduced gene expression for several osteoblast-related matrix proteins (collagen-I, alkaline phospatase and osteocalcin) when cultured in microgravity. These data are consistent with the in-vivo findings. However, in a human foetal steoblastic cell line, no changes were detected in the expression of several of these proteins. The differences in cell type and in the culture settings are possible explanations for the (apparent) contradiction.

In bone, a clear interaction exists between the different cell types, and osteoblasts play an important role therein by secreting and responding to several growth factors. Under microgravity conditions, the message level of interleukin-6 and insulin-like growth factor binding protein-3 is increased, whereas insulin-like growth factor binding protein-5 and -4 mRNA levels are decreased. In addition, the mRNA level for platelet-derived growth factor-ß receptor was reduced in microgravity cultures compared to ground controls, whereas the epidermal growth factor receptor was unaltered.

- *Possible Mechanisms*

The mechanisms by which osteoblastic cells respond to gravitational stress are still largely unknown. Among several possibilities, nitric oxide and protein kinase-C might act as early mediators of non-gravitational mechanical stimulations, but only a few studies have investigated signalling pathways in altered gravity conditions.

Cell Morphology

Changes in cell morphology have been observed after 4 days of microgravity exposure in rat osteosarcoma cells, resulting in a morphologically mixed cell population. Changes were also observed in mouse osteoblastic cells, which became rounded. No major changes in cell focal adhesion parameters were detected in the former cells after a short period of simulated microgravity (clinostat), whereas gravity variations (parabolic flight) induced a significant decrease in cell area that was associated with reorganization of the focal contact plaques. However, after longer exposures to microgravity, the focal adhesions of those cells were modified. The cytoskeleton of the mouse osteoblastic cells that were flown had a reduced number of stress fibres and the nuclei of these cells were smaller, oblong in shape, and with fewer punctate areas. In contrast to these findings, no qualitative differences were observed in the morphology or extracellular matrix of human foetal osteoblastic cells between the flight and ground-control cultures.

Signal Transduction

Only limited investigations of the different signal transduction pathways in osteoblastic cells under altered gravity conditions have been carried out so far. These suggest that certain signalling pathways may be disturbed in microgravity.

In summary, in microgravity the proliferation of osteoblastic cells seems to proceed normally, but the production of bone matrix proteins is evidently hampered. A co-ordinated action between osteoblasts and osteoclasts is required. Growth factors, synthesized by osteoblasts, play an important role in this communication between bone cells. The production of several of these growth factors is altered when osteoblastic cells are cultured in microgravity.

Studies investigating the underlying mechanism of this altered cell behaviour suggest that the morphology of osteoblastic cells is changed and that the contact between the osteoblastic cell and the matrix is reduced. These two cellular aspects will influence the level of gene expression.

2.2.1.4 Ground-Based Research

Because of the complexities of spaceflight, scientists have searched for ground models of simulated gravity. Recently it was demonstrated, using identical cell types and comparable culture conditions, that a clear distinction exists between clinorotation and microgravity culture, depending on the cell type used and the process investigated. These data indicate that whereas clinostats are a very good modelling system for mimicking some of the effects of microgravity culture, they are only an approximation. Experimental results must therefore be interpreted accordingly. However, in view of the complexity of spaceflight experiments and the fact that clinorotation is the best available terrestrial model system for studying the effects of reduced gravity on cells, clinostat studies continue to play an important role.

In addition, other aspects of spaceflight, such as the vibrational force and the increased acceleration during launch, can alter gene expression in osteoblastic cells and have to be taken into account when analyzing spaceflight data.

2.2.1.5 The Nature of the Gravisensor

The mechanism by which normal cells can sense changes in gravity remains a mystery. Theoretically, gravity can potentially be sensed either indirectly, through gravity-dependent changes in the extra-cellular environment, or directly, by sensing gravity-dependent changes within the cell.

Many researchers have considered direct cellular gravi-sensing to be impossible, since at the mechanical level the force exerted by gravity on intracellular structures and biochemical processes is significantly lower than the system's thermal noise. Nevertheless, changes in cell function clearly do occur. So, if the indirect effects of gravity can be excluded, this then provides an interesting and exciting problem. However, many potential artefacts have been identified in studying gravitational biology. The characterizing and quantifying of these potential artefacts needs to be incorporated into the planning and design of future experiments in this area, if gravi-sensing mechanisms are to be clearly identified.

Potential extra-cellular/indirect gravi-sensing mechanisms are:

(i) effects related to the absence of buoyant convection flows in microgravity

(ii) sedimentation (or lack of sedimentation) of non-adherent cells, resulting in altered cell–substrate contact and cell–cell contact.

The first process could result in modified mixing of the culture medium, leading to alterations in gas exchange, to changes in autocrine or paracrine stimulation by soluble growth factors, or to altered disposal of nutrients and waste products. The second effect could be particularly important for leukocytes which, although not anchorage-dependent for growth, are certainly modulated by contact with cell surfaces. Potential intracellular (direct) sensing mechanisms include gravi-sensing by sedimentation of intracellular structures.

2.2.1.6 Conclusion

The absence of gravity has major effects on the immune defence system (immune cells) and on the skeleton. Apart from possible indirect influences, via systemic stress hormones, isolated cells grown in culture during spaceflight also show abnormalities that resemble the in-vivo effects observed in astronauts and animals.

Cell and molecular biology studies have tried to identify the precise mechanism by which isolated immune cells and bone cells sense microgravity, and what the subsequent consequences are. The pathways involved have been partially identified. No generalized shutdown of cellular activity is observed. Rather, there is a decrease in specific proteins (interleukin-2 and interleukin-2 receptor), most likely due to interference in the protein kinase-C pathway. Whether this pathway-specific alteration is related to the changes seen in cell morphology has not yet been elucidated.

Also, the altered behaviour of osteoblastic cells under microgravity conditions correlates with the reduction in bone formation observed in humans and animals. Most of the osteoblastic cells that have been tested proliferate normally in microgravity, but their differentiation and response to stimuli are altered, as seen in the changed expression pattern of matrix proteins and growth factors. Elucidation of the signalling pathways involved has only recently been started.

These reported data suggest that gravity has an effect on certain cell types and it affects a limited number of cellular functions and pathways. Exactly how isolated cells that are not specialist gravi-sensing types can sense a change to microgravity conditions is yet to be determined. The answers to such questions are not only relevant to understanding the effects of microgravity on living organisms during future spaceflights and to preventing specific problems in astronauts, they will also increase our understanding of the fundamental processes in normal cell physiology, and may well provide links to the patho-physiology of certain diseases, such as age-related bone loss or immune disorders.

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2.2.2 The Role of Gravity in Plant Development

G. Perbal

2.2.2.1 Introduction

Land plants are a prime constituent of the animal and human food chain. They provide not only the carbohydrates, but also the proteins and lipids, the vitamins and antioxidants, which are a vital part of the human diet. They also sustain the oxygen of the atmosphere and assist in controlling the level of carbon dioxide, the dominant 'greenhouse' gas. A detailed understanding of all aspects of their growth is therefore of obvious importance to mankind.

When plants left their aquatic environment some 400 million years ago, to evolve and spread across the land masses, they encountered a gravitational force about a thousand times larger than that to which they had been subjected in the buoyant conditions of their original underwater environment. Consequently, they have evolved on land with gravity as a major determinant for their form and growth.

Gravity has been shown to play a major role in the orientation of plant organs (gravitropism) and in plant morphogenesis (gravimorphism). Gravitropism is a bending response, due to a change in orientation or to an inadequate orientation of an organ with respect to gravity. For example, when a root germinates, its tip can be initially orientated at random in the gravitational field, but it must penetrate quickly into the soil to assure the survival of the seedling. If the root is placed horizontally, its apex bends downwards (Fig. 2.2.2.1) and the curvature is almost completed after 2 h. This curvature is due to differential growth of the upper and lower sides of this organ.

Figure 2.2.2.1. Gravitropic curvature of a lentil root as a function of time. The seedling was held in place by a metal bar and grown in a vertical position for 27 hours. It was then placed horizontally (0 h) for 3 hours. The counter reaction, which occurred after 3 hours, is indicated by the arrow and led to a reduction in the angle of curvature. C = cotyledon, cr = counteraction, s = sponge, r = root

The optimal direction of growth for the primary root is along the gravity vector and this organ therefore shows positive gravitropism (Fig. 2.2.2.2). By contrast, the shoot has a negative gravitropism, since its apex is oriented in the opposite direction. Secondary roots and lateral branches grow obliquely with respect to gravity and their gravitropism is positive or negative, respectively. Only a few organs do not show any preferential direction of growth and are for this reason classed as agravitropic. Thus the whole morphology of plants depends upon gravity.

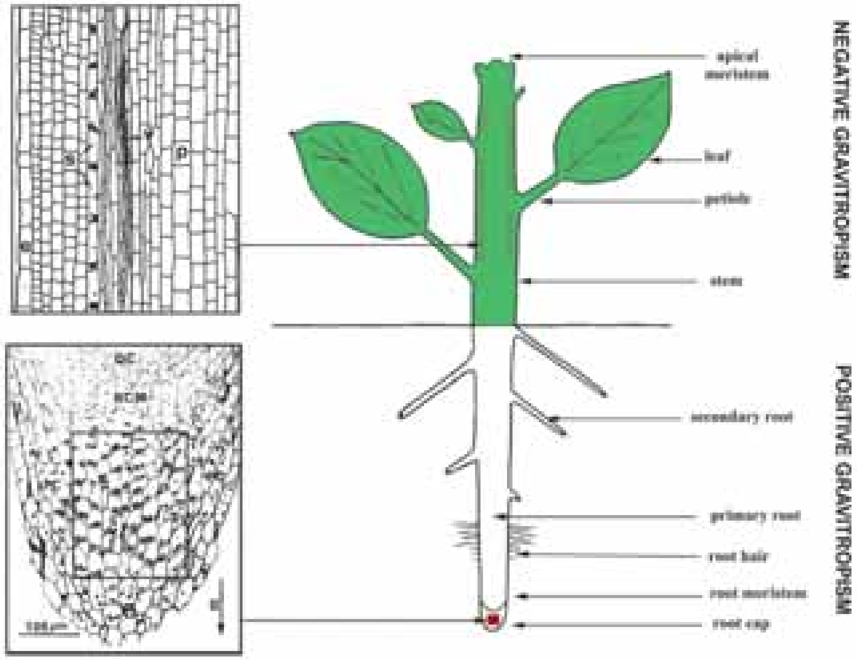

Figure 2.2.2.2. Orientation of plant organs with respect to gravity and localisation of the gravi-sensing cells in the stem and roots. The gravitropic behaviour is indicated in parentheses. Inserts: localisation of the statenchyma in the shoot and in the root. S = statocytes; e = epidermis; p = parenchyma; QC = quiescent centre; RCM = root-cap meristem; PC = peripheral cells; g = gravity

Despite over a century of research into the mechanisms by which plants respond to gravity, the details of several important aspects have remained uncertain. Only with the opportunity to remove the gravitational force almost entirely, by experimentation in microgravity, has it finally been possible to begin to unravel the details of gravitational response. In space, with the aid of a centrifuge, gravity can be a variable parameter ranging upwards in value from almost zero. Details of gravitational sensitivity and the time scales for the various responses can now be explored in a way that was hitherto impossible.

2.2.2.2 How Plants Orientate With Respect To Gravity

- Perception Site of Gravity

Since plants are static, the survival of young seedlings depends upon, among other things, their correct orientation. This is established by using the direction of the local gravity vector as a guide to their growth. That growth is based on a highly complicated stimulus response chain, in which the gravity stimulus is first transformed into a biochemical signal. This signal is then transmitted via several cells, probably by cell–cell communication, to the relevant growing tissue. The scientific objectives of space experiments in this area tend to be focused on the details of the structure of gravity-sensing cells, upon the way cell structures could act as gravity sensors and the sensitivity of those sensors.

At the beginning of the 20th century, it was discovered that a special tissue (called ‘statenchyma’) in roots and in shoots contains movable organelles (statoliths) in their cells (statocytes), which sediment under the influence of gravity (Fig. 2.2.2.2). These organelles possess large starch grains, which are denser than the surrounding cytoplasm. In animal cells, the statoliths lie outside the cell, whereas in plants they are inside.

Experiments involving the removal of the root cap, or ablation of the statocytes with a laser beam, have demonstrated that these cells are necessary for gravitropism in roots. In shoots, the role of the statocytes was confirmed recently by the analysis of an agravitropic mutant of Arabidopsis thaliana, which lacks statenchyma. It has also been shown that sensitivity to gravitropic stimulus is much greater in the root cap than in any other region of this organ. For this reason, it is generally accepted that the statenchyma cells in roots and shoots are the site of gravity perception.

However, despite many observed correlations, the actual role of statoliths in the perception of gravity still remains to be conclusively demonstrated. Statoliths sediment because of the density of starch. However, studies on starch-depleted mutants, as well as experiments leading to a lowering of the starch content, have indicated that the movement of the statoliths is not an essential requirement. Consequently, these organelles cannot be the only structures that can perceive gravity. Some researchers have argued that the whole protoplast (i.e. the cell itself) could also play this role.

This continuing controversy is due to the fact that the perception phase of the gravity stimulus, which takes place in the statocytes, is not easy to investigate on the ground, where it is impossible to remove gravity. Space therefore offers a unique opportunity to study the sensitivity to and perception of gravity.

Data on sensitivity are required in order to understand the mechanisms of sensing in general, and this data can be obtained in space with the aid of a centrifuge. The gravitational force imposed can thereby be varied upwards from essentially zero. The results from space experiments have demonstrated an astonishingly high level of sensitivity of plant organs to gravitational stimulus. The minimum force that is sensed by plant organs is about 1/1000th of the Earth's gravitational field. The minimum 'dose' is about 25 g sec. In other words, a 25 second exposure of plant roots (in a horizontal position) to 1 g triggers the stimulus response chain for gravity-oriented growth.

These results indicate that the root is able to perceive its orientation with respect to the gravity vector and to generate a signal of curvature in less than half a minute.

- *The Structural Polarity of Gravity-Sensing Cells*

The structural polarity of the statocytes has been studied intensively on the ground and can be considered to be relatively constant from one species to another. The nucleus of gravity-sensing cells is always situated close to the proximal wall, whereas the statoliths are sedimented on large aggregates of endoplasmic reticulum tubules located along the distal wall (Fig. 2.2.2.3A).

One of the most intriguing observations made in microgravity concerns the position of the nucleus within the statocyte. In microgravity, this organelle is closer to the longitudinal axis of the statocyte, in a more central position than in the statocytes differentiated on the ground (Fig. 2.2.2.3B). Some observations have indicated that there is a denser region between the plasma membrane and the nucleus' envelope. This suggests that the nucleus could be attached to the cell periphery by some elements of the cytoskeleton (actin filaments). This hypothesis was confirmed by a treatment that perturbed the polymerisation of the actin filaments and provoked sedimentation of the nucleus under the influence of gravity, providing a more central distribution of this organelle in microgravity.

Another unexpected result was obtained by studying the distribution of the amyloplasts in microgravity. These organelles should have been distributed randomly in the absence of a gravitational field. However, in the lentil statocyte they were preferentially located in the proximal part of the cell, around the nucleus. A three-dimensional reconstruction has shown that the amyloplasts were also not distributed at random in the statocyte of white clover grown in microgravity.

- *Movement of the Nucleus and Statoliths in Microgravity*

In microgravity, the location of the nucleus in the lentil root statocyte was different from that observed in 1g on the ground. Yet in the 1g control in space it was very close to the microgravity sample. It has been suggested that this apparent discrepancy is due to the fact that the 1g control in space was subjected to microgravity for 15 minutes, prior chemical fixation. Thus, within 15 minutes, the nucleus was able to move (about 0.8 µm) from the proximal plasma membrane towards the cell centre. It was therefore proposed that the nucleus is attached to the cell periphery by actin filaments, and that these filaments are sensitive to tensions created by the weight of this organelle. It has been suggested that the nucleus' displacement was due to a relaxation of the cytoskeleton. However, this organelle remained attached to the actin filaments, since a 1g centrifugation of the lentil seedlings grown in microgravity caused a movement of the nucleus towards the proximal wall.

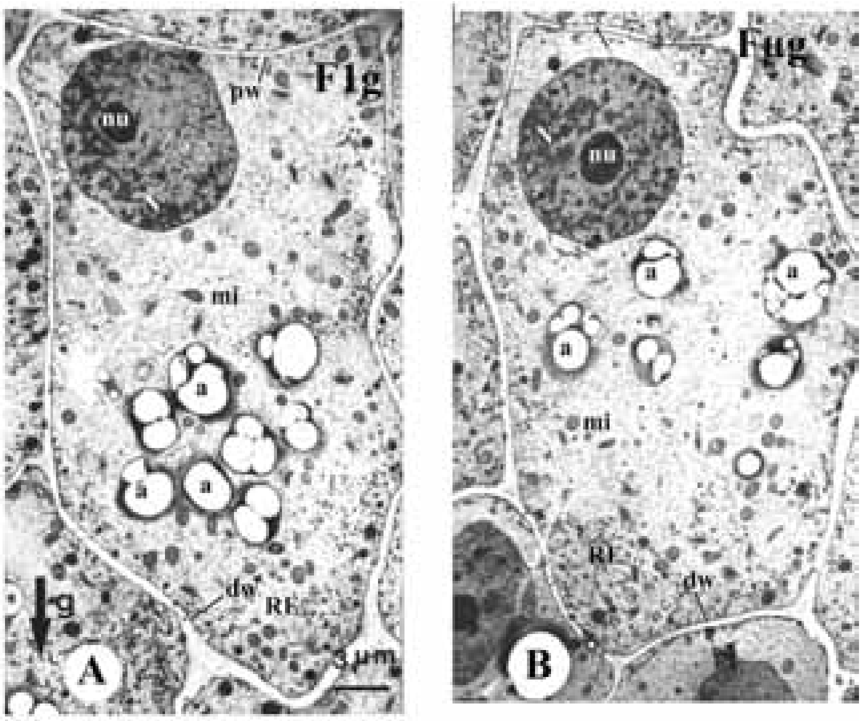

Figure 2.2.2.3. Root statocytes of lentil seedlings grown for 28 hours.
A. Flight control (F1g), in which the seedling was centrifuged at 1g in space.
B. The seedling was grown in microgravity (Fµg).
a = amyloplast; g = gravity; mi = mitochondria; N = nucleus; nu = nucleolus; dw = distal wall; pw = proximal wall; RE = endoplasmic reticulum

As noted above, the statoliths in microgravity are located in the proximal part of the statocytes. The 1g control in space shows a different distribution of these organelles compared with the 1g control on Earth. The reason for this difference between the two controls has been elucidated. It was demonstrated using a sounding-rocket flight that the transition from 1g to microgravity for about 6 minutes was sufficient to provoke movement of the amyloplasts toward the nucleus. The researchers pointed out that the gravitational force on the ground is greater than the basipetal force exerted by the cytoskeleton. However, in microgravity this basipetal force becomes prominent and the amyloplasts are pulled towards the nucleus. Unfortunately, because of the short duration of the flight, it was not possible to see if this movement would continue during a longer period of microgravity. Recently, the kinetics of the movement of the amyloplasts have been studied: (i) in the gravitational field, by putting roots in the upward position, and (ii) by transferring lentil seedlings grown in a 1g centrifuge to microgravity.

The velocity of the displacement was seven times greater in the inverted roots on the ground than in roots grown in 1g and transferred to microgravity. In roots treated by cytochalasin D, the movement observed in microgravity was much slower than that observed in non-treated roots. These results show that on the ground some forces exerted by the cytoskeleton cannot be detected simply because their intensity is below that of the gravity force. The fact that the transfer from 1g to microgravity induces some displacement of the cell organelles demonstrates that the cytoskeleton is able to react to tension existing within its filament networks.

- *Transduction of the Stimulus*

The nature of the gravity sensors is not yet known and it is difficult to determine which cellular structure contains the receptors. These receptors are able to transform the mechanical effect (the potential energy dissipated) into a biochemical factor (e.g. calcium efflux). It has been suggested that the endoplasmic reticulum, which is mainly situated at the basal pole of the statocyte (Fig. 2.2.2.4a), could be involved in the transduction step of gravistimulation. Due to the geometry of the statocyte, an asymmetrical message could be created in the root cap. This hypothesis is consistent with the fact that it is well established that the concentration of cytosolic calcium is very low, whereas its concentration in the endoplasmic reticulum is much greater. It was therefore proposed later that the result of the amyloplast exerting a mechanical action on the endoplasmic reticulum could be to provoke an efflux of calcium and to locally increase the calcium concentration. This could activate some Ca_{2+} -dependent proteins as calmodulin. This protein could in turn activate (eventually after a cascade of events) an auxin pump and a Ca_{2+} channel.

In fact, the results obtained from microgravity experiments are not in agreement with this hypothesis. In microgravity, the amyloplasts of the root-cap cells are located close to the proximal wall, i.e. far from the distal endoplasmic reticulum (ER) membranes. In contrast, in the 1g centrifuge these organelles are sedimented onto these membranes. If the original hypothesis was correct, roots grown in microgravity should be much less responsive than those grown in 1g, since only a few contacts between ER and statoliths were possible. However, the opposite result was obtained, for both lentil roots and cress roots. The fact that the amyloplasts are attached to actin filaments and are moved along these filaments by motor proteins led to the proposal of a completely different mechanism for the transduction of the gravitropic stimulus. According to this, the amyloplasts could create tensions within the actin network on the ground. A stimulation could provoke a change in the tensions on the actin filaments (Fig. 2.2.2.4 b) and activate mechano-sensitive ion channels.

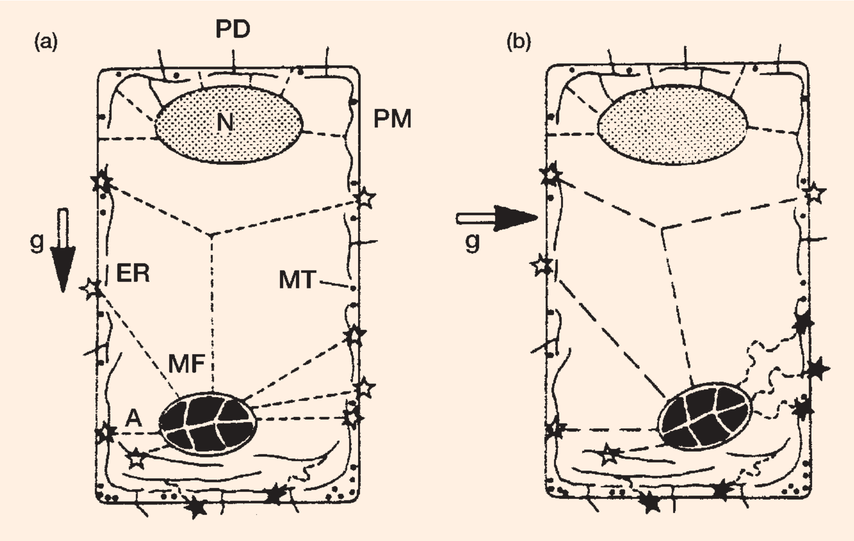

Figure 2.2.2.4. Cytoskeleton and statocyte polarity. (a) statocyte of a root placed vertically; (b) statocyte of a root stimulated in the horizontal position. The amyloplasts (A) and the nucleus (N) are in contact with actin filaments (MF), which are attached to stretch-activated ion channels (asterisks). These channels are open or closed, depending upon the tension exerted by the actin filaments. In stimulated statocytes (b), the tension in the actin network increases in the upper half of the cells and decreases in the lower half. This leads to an asymmetrical efflux or influx of ions in the cell. ER = endoplasmic reticulum; black dots = microtubules (from A. Sievers and M. Braun, in 'Plant Roots', Dekker, New York, 1996)

Thus, research in microgravity has led to a new concept for the transduction of the gravitropic stimulus, which implies a role for the actin network in the transformation of the mechanical effect of gravity (statolith movement) into a biochemical factor (calcium efflux). Recently the role of actin has been questioned, since it has been shown that treatment with cytochalasin D, which perturbs actin polymerisation, does not prevent gravitropic reaction. However, it has been proved that, after the transfer from 1g to microgravity of lentil seedlings treated with cytochalasin D, there was still a movement of the amyloplasts. This result indicates that a cytochalasin D treatment actually perturbs the formation of the actin network, but does not prevent it completely.

- *Gravitropic Curvature in Space*

The involvement of the hormone auxin in gravitropism is well-established. The Cholodny-Went theory states that the lateral (downward) transport of auxin is the cause of the gravitropic bending. It operates by inducing a greater elongation of the lower side of the shoot (or coleoptile) and an inhibition of growth of the lower side in the root. However, this hypothesis does not completely account for the patterns of gravitropic bending.

For instance, the gravitropic response of lentil seedling roots was analysed during the fifth Shuttle to Mir mission. The lentil seedlings were grown in microgravity for 25 h and then placed on a 1g centrifuge for 22 min. The gravitropic response was followed by time-lapse photography for 3 h after centrifuging. In microgravity, the tip of the stimulated roots overshot the direction of the acceleration that was responsible for the gravitropic stimulus (i.e. the roots could bend by more than 90°), whereas the roots continuously stimulated on the ground did not reach the direction of the acceleration or gravity. Thus, in the Earth's gravitational field, there must be gravity-dependent regulation (inhibition of root curvature). This regulation is observed when in some roots there is a kind of counter-reaction, which reduces the bending (cf. Figs. 2.2.2.1 and 2.2.2.5).

Thus, space experiments were very useful for the analysis of gravitropism, since they have provided new data on the perception and transduction of the gravitropic stimulus by the statocytes. These have shown that these phases could take place very quickly, within less than half a minute. These experiments have also shown that the cytoskeleton is involved in the transduction of the gravitropic stimulus; in particular the actin network should sense tensions exerted by the weight of the amyloplasts. It has been shown that the extent of the induced curvature is regulated by gravity on the ground, in order to prevent overshooting of the vertical direction by the root tip.

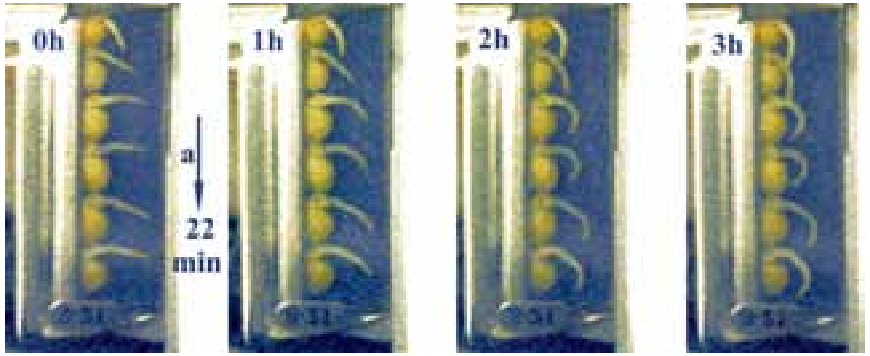

Figure 2.2.2.5. Curvature of lentil roots grown in microgravity, stimulated for 22 min and placed back in microgravity for 3h. The roots overshoot the direction of the acceleration (a, arrow) that was responsible for the gravitropic response (from Perbal et al. 1999, ESA SP-1222, p. 251)

2.2.2.3 The Role of Gravity in Plant Development

The scientific interest in the influence of gravity on plant development embraces germination, cell division and elongation, the development of storage and supporting tissues, formation of flowers and propagating cells, pollination and the production of fruit and seeds. The gravimorphism is the result of the developmental responses of the plant to gravity, i.e. the effects of this physical factor when the organs are oriented correctly with respect to the gravity vector. In principle, the action of gravity on plant development could easily be analysed by comparing plants grown in microgravity and plants grown on the ground. Unfortunately, the culture conditions in a spacecraft are completely different from those on the ground, because for example of the presence of cosmic rays and the cabin atmosphere. For this reason, a 1g control experiment must be carried out in space in parallel, thereby subjecting the sample to the same space factors as the microgravity sample. However, very few experiments have so far been performed with such a space control.

On the ground, it is possible to simulate the action of microgravity (with a device called a 'clinostat') by rotating the plant about a horizontal axis. The unilateral effect of gravity is thereby compensated, but it is obviously still present. Analysis of plant development in microgravity and in the clinostat has shown that the latter cannot provide a true simulation of microgravity.

- *Germination and Root Orientation*

Many species have been grown in microgravity and it appears that the absence of gravity has no real effect on germination. However, the growth orientation of the root of the embryo seed plant (radicle), which is strongly dependent upon gravity on Earth, is related to the position of the embryo in microgravity and the root tip can oscillate strongly during germination. Such movements have been observed in lentil roots. After a growth period of 25 h in microgravity, the emerging root was bent and its tip was in most cases pointing away from the cotyledons. Although the mean angle of curvature was about the same after 25 and 29 h, some roots were subject to a strong change in orientation during these 4 h.

Root growth in cress was studied to determine whether the root tip was subject to a random direction of growth (random walk) in microgravity. The seedlings were grown between two agar slices and the deviation angle of the root tip was measured with respect to its initial orientation. The mean angle of deviation was about 0°, and the square of this angle of deviation increased proportionally with time, which represented two characteristics of random walk. However, this random walk was limited in duration.

- Growth of the Primary Root

It has often been assumed that the effect of gravity on the primary root should be constant, but it has been pointed out that it depends upon the stage of development. This was concluded after a careful analysis of the literature, which showed that root length was generally the same in microgravity and on the ground for a growth period of less than 1 or 2 days, whereas it was greater in microgravity than in 1g for a growth period of 3 to 5 days. For longer periods of growth, the root length was smaller in microgravity than in 1g.

Plant hormones play a key role in the developmental processes of the root system, including control of the cell cycle in the apical meristem, elongation and lateral root initiation. As auxin and abscisic acid are considered to be involved in root gravitropism, it was obvious that the role of these two hormones had to be analysed first, since their distribution in the plants grown in microgravity had more chance to be perturbed. In a space experiment, the auxin and abscisic contents of maize seedlings grown in microgravity were analysed. A significant difference was only observed for auxin in roots.

- Cell Cycle and Mitotic Disturbances in the Primary Root Meristem

A study of mitotic activity and chromosome disturbances in the roots of three species (oats, mung beans and sunflowers) showed that cell division was substantially reduced in space. In oats and sunflowers, there were chromosomal aberrations ranging from an abnormal number of chromosomes, to breakage and bridge formation. In mung beans, however, no chromosome aberration was detected. Evaluation of the available data indicates that indirect effects play a major role in these modifications and that plants grown in space are subject to various stresses.

As noted earlier, the culture conditions in space are not always satisfactory, since the cabin atmosphere can contain gases (e.g. ethylene) that may affect plant growth. This problem can be solved to some extent by using a 1g centrifuge in space. This can allow discrimination between the effects of microgravity and those due to other space factors (cosmic rays, cabin atmosphere).

For the majority of species investigated, a decrease in the mitotic index (MI = % of cell division) was observed. It must be stressed, however, that MI is a very poor indicator for studying the cell cycle, because it can vary as a function of many different factors. For that reason, researchers have chosen rather to study the cell cycle and its various phases (G1, S, G2, M) in a homogenous tissue (i.e. the cortical cells of the root). The periods of growth were 28 h and 29 h (see Table 2.2.2.1) for the Spacelab IML-1 (1992) and IML-2 (1994) missions, respectively. For the space-grown lentil seedlings of IML-1 and IML-2, cortical cells have at most completed just one cell cycle. In principle, the majority of these cells should be at the beginning of the second cell cycle. From the data in Table 2.2.2.1 it can be concluded that, in 1g on the ground, more cells were further along in the process of the second cell cycle (more cells in the S-phase). This means that the first cell cycle was faster on the ground, and also on the 1g centrifuge in space, than in microgravity.

*Table 2.2.2.1. Percentages of the various phases (G1, S, G2, M) of the cell cycle in the primary root meristem of lentil seedlings, grown in space during the IML-1 and IML-2 Spacelab missions**

Cycle		**First**		**Second**	
Phase		G2	M	G1	S
IML-1	G1g	11.2	7.2	55.4	26.2
28 h	F1g	11.9	8.9	58.7	20.5
G. Perbal &	Fμg	27.9	6.8	55.5	9.8
D. Driss-Ecole,					
Physiol. Plant,					
90, 313, (1994)					
IML-2	G1g	10.6	4.0	52.8	32.6
29 h	F1g	19.7	6.0	48.2	26.1
F. Yu et al.,	Fμg	17.8	3.9	61.1	17.1
Physiol. Plant,					
105,171, (1999)					

* The percentages of the various phases were determined by image analysis, following Feulgen treatment. G1g = ground control; F1g = flight control; Fμg = microgravity sample. IML-1 and IML-2 = International Microgravity Laboratory 1 (1992) and 2 (1994) missions.

- Development of the Plant Body in Microgravity

Figure 2.2.2.6 summarises the changes occurring in microgravity in the development of plant organs. The orientation of the primary axis, which is vertical on the ground, is variable in microgravity and to some extent the primary roots could be subjected to random walk. The apical dominance of the primary root over the secondary roots is reduced in microgravity such that the latter elongate faster and are initiated very close to the primary root tip.

A careful analysis of the results obtained on shoot development in microgravity has indicated that, in general, growth was often reduced when the plants were subjected to acceleration or gravity during the Shuttle's launch and re-entry into the Earth's atmosphere. When the plants were grown in microgravity, growth was greater than in 1g.

The results obtained for lettuce on Salyut-7 were the most impressive and reliable, because there was a 1g control both in space and on the ground. Taking the length of

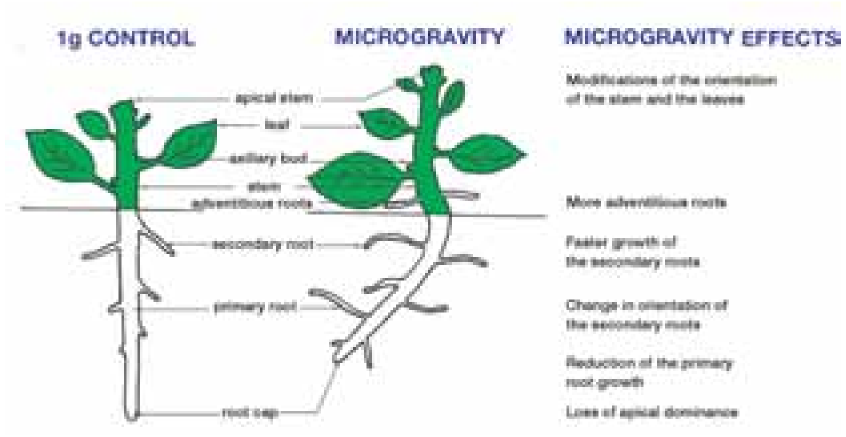

Figure 2.2.2.6. Summary of the effects of microgravity on the differentiation, development and direction of growth of plant organs

the stem growing on the 1g centrifuge in space as 100%, a decrease in g-level led to an 8–16% increase in stem length.

It must be stressed that the growth of the shoot, as well as that of the root, in space was much slower than on the ground for this particular experiment. Doubtless other space factors were responsible for the slowing down of growth. In this respect, recent studies have demonstrated the role of ethylene in the development of Arabidopsis thaliana grown in space. It was observed that flight seedlings (microgravity and 1g control) were smaller (60% in total length) compared to the ground controls. Seedlings grown in space had two structural features that distinguished them from the control, namely greater root-hair density and an anomalous hypocotyl hook structure. It has been shown that the slower growth and morphological changes observed in the flight seedlings may be due to ethylene present in the spacecraft, since plants treated with 10 ppm of ethylene on the ground showed the same features as those in space.

Comparing the results for primary roots and shoots, it can be concluded that both types of organs should have the same growth on the ground and in microgravity during the first few days. Then there is an increased shoot and primary-root growth for less than one week. For longer periods, the growth of the primary root decreases, with a loss of apical dominance. Thus, microgravity could increase the biomass production, but only during the starting phase of the plant's development.

It should be noted that in the space experiments the environment was mostly not controlled and that the atmosphere was not monitored in the growth chambers. Since microgravity alone may have a slight but continuous effect on plant growth, it may be

that space factors other than microgravity could become prominent. That is why the results of experiments without a 1g control are questionable.

Another problem is the fact that data must be numerous enough to be analysed effectively statistically, which is in obvious contradiction with the need to use very small volumes or masses in space.

- *Reproductive Development in Space*

Several attempts to grow plants through a complete life cycle (from seed to seed) in space have proved unsuccessful because of the delayed development and death of the plants. Arabidopsis thaliana has been the most successfully studied species in this respect, because of its small size and short life cycle. However, partial or total sterility of the reproductive material that eventually did develop has also been observed in this species.

Detailed study of the different types of hardware used in space has shown that before 1997 about eight different types of hardware were used for plant-reproduction studies. Of these, those having some kind of ventilation permitted seed formation. Three different experiments were performed on Arabidopsis with the Plant Growth Unit (PGU). The different degrees of success in subsequent reproductive development in microgravity were related to variations in the gas phase of the plant-growth chambers. In the first experiment, no viable pollen was observed and young megaspores were deformed and empty. It was considered that during the experiment there was a carbohydrate-synthesis limitation due perhaps to a lack of carbon dioxide in the atmosphere. In a second experiment, the atmosphere was supplemented with CO_2 and the plant had mature pollen and normal embryo sacs. However, no fertilisation occurred, because pollen was not released from the anthers. In a further experiment, air flow through the plant-growth chambers was provided and it was found that development then proceeded normally in orbit, through to the stage of immature seeds. The space-grown plants were similar to the ground control.

In these three experiments, the plants were launched after a period of 13 days of complete vegetative growth on the ground. It is thus not possible to determine if microgravity had an effect on their development before the reproductive stage.

Whether or not a seedling growing from the outset in microgravity can flower and produce normal seeds remains a matter of debate. As the modifications observed during the vegetative phase were quantitative rather than qualitative, one can argue that it should be the same for the reproductive phase.

A series of recent space experiments should have provided an answer to this problem. Super-dwarf wheat was grown on board Mir. The height of the shoots was reduced by half in microgravity and there were 2.7 times fewer headed shoots. No seeds were found in the heads formed in space. The analysis showed that the most profound changes observed in the reproduction stage of this plant were caused by the toxic effect of ethylene, rather than spaceflight factors. Its concentration in the Mir station's atmosphere was high enough to account for the modifications observed in space-grown wheat plants. These results show that the effect of microgravity should be studied with facilities in which the atmosphere is perfectly controlled.

A recent analysis of the life cycle of Brassica rapa onboard Mir in the Svet greenhouse confirms this hypothesis. It has been shown that gravity is not absolutely required for any step in the plant life cycle. However, seed quality is compromised by development in microgravity. In particular, seed size is reduced, and the reserves are stored in the form of starch rather than protein and lipid. It therefore appears that the reserves storage too is perturbed in microgravity. It seems also that the utilisation of these reserves is modified in the absence of gravity. The causes of these effects of microgravity on metabolism remain to be determined.

2.2.2.4 Conclusion

Microgravity has proved to be a very useful tool for analysing the influence of gravity on plant orientation (gravitropism), since it is the only opportunity to remove gravity and hence to clearly measure such parameters as the sensitivity threshold.

The level of acceleration that can be perceived by the organs is about $5x10^{-4}$g for roots and 10^{-3}g for shoots. A more accurate experiment on the threshold acceleration will be performed on the International Space Station (ISS) in the context of the European Modular Cultivation System (EMCS) project.

So far, the main result obtained in space relates to gravity sensing and the mode of action of statoliths. It has been shown that the cytoskeleton is intimately involved in the perception of gravity. The analysis of statocyte polarity in space showed that the statoliths were principally located in the centre of the cell (statocyte), close to the nucleus. The transfer from gravity to microgravity induces a movement of the amyloplasts towards the cell centre. This finding has led to a new hypothesis concerning the signal transduction of the gravity stimulus. According to this, the statoliths could exert a tension on the biopolymer actin network of the cell, which becomes asymmetrical when the organ is placed horizontally.

Although the nature of the gravity sensors is still disputed, it must be recognised that space experiments have provided new data about gravity sensing, causing plant physiologists to change their views on how plants sense gravity. It must also be noted that space experiments on gravitropism were always performed in parallel with active ground-based research and that space was also a driver in this field. Space experiments will continue to be necessary in order to develop the study of gravity sensing further. The ground experiments will be useful in determining the mechanisms for stimulus transmission and differential growth. In particular, the nature of the gravity sensors must be confirmed (statoliths versus protoplast) and the receptors must be identified (cytoskeleton). The role of Ca_{2+} and stretched ion channels must also be defined.

The analysis of plant development in space has shown that germination is normal in microgravity. However, even during the first phases of root growth, some differences can be observed between plants grown in microgravity and in 1g. Although the morphology of the primary root is not strongly modified, there is a change in the root cell cycle. The first cell cycle (after hydration) appears to be longer in microgravity than in 1g, and after several cycles the delay seems to increase because the mitotic index in roots grown in microgravity for several days is lower than in 1g. In microgravity, the apical dominance of the primary root over the secondary roots seems to be reduced. Thus, gravity is at least partly responsible for the apical dominance of the primary root and seems also to be involved in the dominance of the apical meristem.

The reproductive phase is completed in microgravity when the culture conditions are adequate. A lot of problems encountered in growing plants in space are related to the fact that the physical environment is different in microgravity. There is the absence of convection, for example, and it is clear that the limitation of gas exchanges influences plant growth.

A new generation of space experiments is certainly needed in order to confirm some of the most important results on the basis of improved statistics, by using more samples and better plant environment controls than has been possible previously. Such experiments are expected to include the following objectives:

- identification of possible gravity-related genes in general
- determination of possible gravity-related genes in different organs
- identification of possible 'cross-talk' between genes with different stimulus response chains, e.g. gravity versus light
- identification of proteins related to the gravi-stimulus response chain
- determination of interactions of related proteins.

Future experiments will be performed using instruments such as EMCS, which will be better able to monitor and control the physical environment of plants in space. In particular, it will be possible to carry out experiments with a 1g control in space and with a monitored gas composition of the atmosphere.

Growing plants and producing crops in space is a challenge that needs to be overcome for the long-term future of space travel. The optimization of plant growth for the benefit of agriculture on Earth, based upon a deeper understanding of plant growth, represents the major future ground-based return from these programmes.

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2.2.3 Exobiology: The Origin, Evolution and Distribution of Life

A. Brack

2.2.3.1 Introduction

Exobiology, in its broader definition, includes the study of the origin, evolution and distribution of life in the Universe. Although it is difficult to define what is meant by the term 'primitive life', one generally considers as living any chemical system able, as a minimum, to transfer its molecular information via self-reproduction and to evolve. The concept of evolution implies that the chemical system normally transfers its information fairly faithfully, but makes a few random errors. These may lead to potentially higher complexity and possibly to better adaptation to the existing environmental constraints.

Due to this process of evolution acting over several billion years, existing life must differ considerably from the original primitive life forms. Consequently, only hypothetical descriptions of primitive life can be proposed. Also, because of the limitations of time, the prebiotic chemistry that may have led to those primitive life forms can never be fully repeated in the laboratory. Therefore, laboratory simulations may only represent possible support for plausible hypotheses. The only way around this difficulty is to collect clues from different disciplines.

Today, many data related to the history of terrestrial life, as well as to possible niches for extraterrestrial life, have been collected by scientists in astronomy, planetology, geology, paleontology, biology and chemistry. These data are like the pieces of a jigsaw puzzle that can now be put together to give a clearer picture of the possible distribution of life in the Universe (see next page).

2.2.3.2 The Origins of Terrestrial Life

By analogy with contemporary life, it is generally believed that primitive life originated from the processing of reduced organic molecules by liquid water.

- The Primitive Earth

Liquid water is considered to be one of the prerequisites for life to appear and evolve on a planet. Water molecules are widespread in the Universe, as grains of solid ice or as very dilute water vapour. By contrast, liquid water is a fleeting substance, which

LIFE IN THE UNIVERSE

Terrestrial Life as the Reference

Origins of life
- the primitive Earth
- prebiotic formation of small molecules
- life in a test tube

Relics of primitive life
- fossil bacteria
- oldest sediments
- one-handedness

Limits of life
- temperature
- salt
- pH
- pressure
- deep subsurface

Extraterrestrial Life

Extrasolar life
- extrasolar planets
- spectral signature of extrasolar life

Panspermia
- bacterial life in space
- interplanetary transfer of life

Life in the Solar System
- life on Mars and SNC meteorites
- life on Europa
- organic chemistry on Titan

can persist only above 0°C and under an atmospheric pressure higher than 6 mbar. Therefore, the mass of a planet and its distance from the star are two basic characteristics that will determine the presence of liquid water.

If a planet is too small, like Mercury or the Moon, its small gravitational field will not be able to retain any atmosphere and, therefore, any liquid water. If the planet is too close to the star, the mean surface temperature rises, due to starlight intensity. Any seawater present would evaporate, delivering large amounts of water vapour into the atmosphere and thus contributing to the 'greenhouse effect'. This, in turn, causes a further temperature rise. Such a positive feedback loop could lead to a runaway greenhouse, where all of the surface water would be transferred to the upper atmosphere. There, photo-dissociation by ultraviolet light would break the molecules down into hydrogen and oxygen. Loss of the atmosphere would eventually result, due to the escape of hydrogen to space and the combination of oxygen with the crust. If a planet is far from the star, it may permit the existence of liquid water, provided that it can maintain a constant greenhouse atmosphere. However, water could provoke its own disappearance. The atmospheric greenhouse gas CO_2, for instance, would be dissolved in the oceans and finally trapped as insoluble carbonates by rock-weathering. This negative feedback could lower the surface pressure and consequently the temperature to such an extent that any water would be largely

frozen. The size of the Earth and its distance from the Sun are such that our planet never experienced either a runaway greenhouse or divergent glaciation.

- Prebiotic Formation of Small Molecules

Present-day life is based upon organic molecules made of carbon, hydrogen, oxygen, nitrogen, sulphur and phosphorus atoms. Originally, the carbon needed to construct the molecules of life was available as simple volatile compounds, either reduced as methane or oxidised as carbon monoxide or carbon dioxide.

Synthesis in the Atmosphere

In 1924, the Russian biochemist Aleksander Oparin suggested that the small, reduced organic molecules needed for primitive life were formed in a primitive atmosphere dominated by methane. This idea was tested in the laboratory by Stanley Miller in 1953. He exposed a mixture of methane, ammonia, hydrogen and water to electric discharges, to mimic the effects of lightning. Among the compounds formed, he identified four of the twenty naturally occurring amino acids, the building blocks of proteins. Since this historic experiment, seventeen natural amino acids have been obtained via the intermediate formation of simple precursors such as hydrogen cyanide and formaldehyde. It has been shown that spark-discharge synthesis of amino acids occurs efficiently when a reducing gas mixture containing significant amounts of hydrogen is used. However, the true composition of the primitive Earth's atmosphere remains unknown. Today, geochemists favour a non-reducing atmosphere dominated by carbon dioxide. Under such conditions, the production of amino acids appears to be very limited.

Synthesis in Oceanic Hydrothermal Vents

Deep-sea hydrothermal systems may also be likely environments for the synthesis of prebiotic organic molecules and perhaps even for primitive life. Amino acids have been obtained, although in low yields, under conditions simulating these hydrothermal vents. Hydrothermal vents are often disqualified as efficient reactors for the synthesis of bio-organic molecules, because of the high temperatures. However, the products that are synthesized in hot vents are rapidly quenched in the surrounding cold water, which may preserve those organics formed.

Extraterrestrial Delivery of Organic Molecules to the Earth

Besides abundant H and He, 114 interstellar and circumstellar gaseous molecules are currently identified in the interstellar medium. Ultraviolet irradiation of cosmic dust grains may result in the formation of complex organic molecules or even total carbonization of the sample, forming, according to the local environmental conditions, carbonaceous matter such as amorphous carbon, hydrogenated amorphous carbon or coal- and kerogen-like materials. The incorporation of such interstellar matter into meteorites and comets in the earliest stages of the evolution of the Solar System provides the basis for the cosmic dust connection.

The ESA Infrared Space Observatory (ISO) has provided extraordinary results concerning the nature of these cosmic dust particles. ISO's spectroscopy has allowed a new definition of the composition of interstellar ices, thermal processing in the protostellar vicinity and gas-grain chemistry. A comparison of interstellar and cometary ices, using ISO data, has revealed important similarities between interstellar ices and volatiles measured in the comas of some comets. The link between the processes occurring in these dense clouds of interstellar dust and molecules and the comets seems now to be clearer. Studies of the connection between interstellar, cometary and meteoritic dust provide important constraints on the formation of the Solar System and early evolution on Earth.

Comets show substantial amounts of organic material, as was nicely demonstrated by ESA's Giotto mission in 1986. On average, dust particles ejected from Comet Halley's nucleus contain 14% organic carbon by mass. About 30% of cometary grains are dominated by the light elements C, H, O, and N, and 35% are close in composition to the carbon-rich meteorites. Among the molecules identified in comets are hydrogen cyanide and formaldehyde. The presence of purines, pyrimidines, and formaldehyde polymers has also been inferred from the fragments analyzed by Giotto's Picca and Vega's Puma mass-spectrometers. However, there is no direct identification of the complex organic molecules present in the cosmic dust grains and in the cometary nucleus.

Many chemical species of interest for exobiology were detected in Comet Hyakutake in 1996, including ammonia, methane, acetylene, acetonitrile and hydrogen isocyanide. In addition, Comet Hale-Bopp was also shown to contain methane, acetylene, formic acid, acetonitrile, hydrogen isocyanide, isocyanic acid, cyanoacetylene, and thioformaldehyde. It is possible, therefore, that cometary grains might have been an important source of organic molecules delivered to the primitive Earth.

The study of meteorites, particularly the carbon-rich ones known as 'carbonaceous chondrites' that contain up to 5% by weight of organic matter, has allowed close examination of the extraterrestrial organic material that has been delivered to the Earth. Eight proteinaceous amino acids have been identified in one such meteorite, among more than 70 amino acids found therein. These amino acids are asymmetric.

The two enantiomers, L and D (mirror-image geometrical configurations of the same amino acid), are generally found in equal proportions. However, a 9% excess of L-amino acids has recently been measured in that particular meteorite. The presence of this excess points towards an extraterrestrial process of asymmetric synthesis of amino acids, an asymmetry that is then preserved inside the meteorite, and in this case delivered to the Earth.

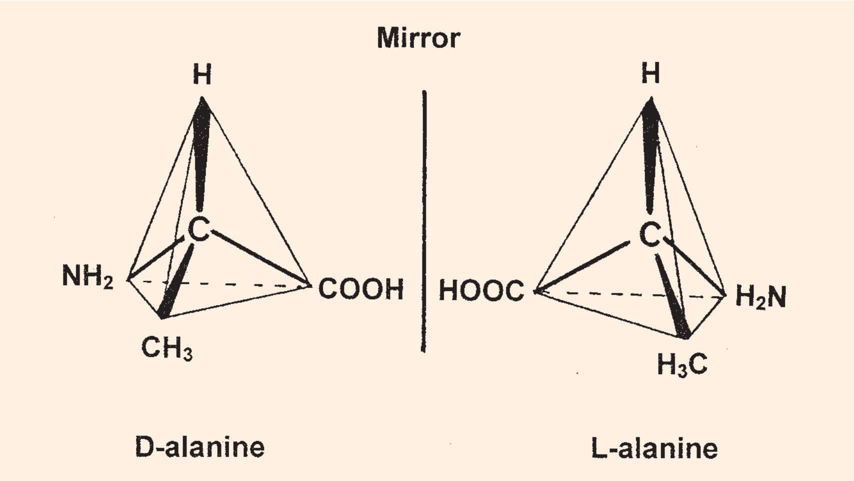

Figure 2.2.3.1. Each amino acid – with the exception of glycine – is asymmetrical and could exist as either of two non-superimposable mirror images, called 'enantiomers L and D'. Only the L-amino acid enantiomers are found in proteins on Earth

These excesses may help us to understand the emergence of a 'one-handed life'. For example, proteins are built up with twenty different amino acids. Each amino acid, with the exception of glycine, exists in two mirror-image forms, L and D. But the proteins of life actually use only the L-form amino acids. Proteins adopt asymmetrical rigid geometries, right-handed alpha-helices and beta-sheets, which play a key role in the catalytic activity. The excess of the one-handed amino acids, as found in this particular meteorite, may be the result of stellar radiation acting on the organic mantles of the cosmic dust grains from which the meteorite was originally formed.

Analysis of dust collected in the Greenland and Antarctic ice sheets shows that the Earth captures interplanetary dust as micro-meteorites at a rate of about 50 – 100 tons per day.

About 99% of this mass is carried by micro-meteorites in the 50 – 500 µm size range. This value is much higher than the most reliable estimate of the normal meteorite flux, which is about 0.03 tons per day. A high percentage of micro-meteorites, from 50 to 100 µm in size, have been observed to be unmelted, indicating that a large fraction entered the terrestrial atmosphere without drastic thermal alteration. In this size range, the carbonaceous micro-meteorites represent 80% of the samples and contain 2% of carbon, on average.

This flux of incoming micro-meteorites might have brought to the Earth about 10^{20} grammes of carbon over a period of 300 million years, corresponding to the late terrestrial bombardment phase. This delivery represents more carbon than that engaged in the present surficial biomass, i.e. about 10^{18} grammes. Amino acids, such

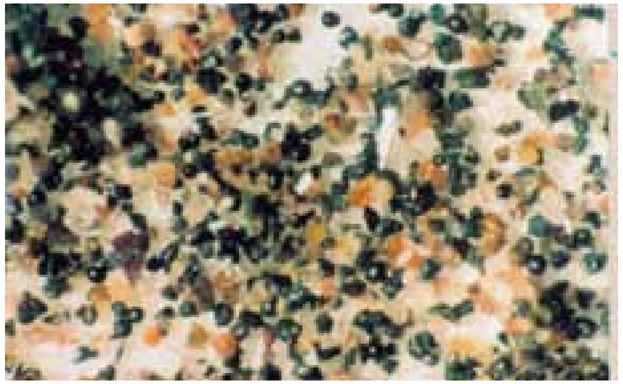

Figure 2.2.3.2. Grains collected from Antarctic old blue ice. All dark grains are micro-meteorites. Only a few of them (bright spheres) have melted during high-speed atmospheric entry (courtesy of M. Maurette)

as α-amino isobutyric acid, have recently been identified in these Antarctic micro-meteorites. These grains also contain a high proportion of metallic sulphides, oxides, and clay minerals that belong to various classes of catalysts. In addition to the carbonaceous matter, micro-meteorites might also have delivered a rich variety of catalysts, having perhaps acquired specific crystallographic properties during their synthesis in the microgravity environment of the early solar nebula. They may have functioned as tiny chemical reactors when reaching oceanic water.

Amino acids like those detected in the carbonaceous meteorites have been exposed for 10 days to the space conditions of Earth orbit, using the unmanned Russian satellites Foton-8 and Foton-11, and for three months with the Mir station (Perseus experiment). The amino acids were both free and associated with a mineral powder. Analyses run after the flights by the Exobiology Group in Orléans (F) showed that exposed aspartic acid and glutamic acid were partially photo-processed during exposure to solar UV. However, decomposition was prevented when the amino acids were embedded in clays. The main limitations of these experiments were the relatively weak irradiation of the samples due to the short flight duration, the non-synchronous orbits, and the absence of an automatic Sun-pointing device. The ESA Expose Facility, to be located on the International Space Station, will offer an important opportunity for long-duration exposure of amino acids and other biogenic molecules.

- *Life in a Test Tube*

Primitive Cellular Life

By analogy with contemporary living systems, it is tempting to consider that primitive life emerged as a cellular object, requiring boundary molecules able to isolate the system from the aqueous environment (membrane). Also needed would be catalytic molecules to provide the basic chemical work of the cell (enzymes) and information-retaining molecules to allow the storage and the transfer of the information needed for replication (RNA).

Fatty acids are known to form vesicles when the hydrocarbon chains contain more than ten carbon atoms. Such vesicle-forming fatty acids have been identified in the carbonaceous meteorites discussed above. However, the membranes obtained with these simple amphiphiles are not stable over a broad range of conditions. Stable neutral lipids can be obtained by condensing fatty acids with glycerol or with glycerol phosphate, thus mimicking the stable contemporary phospholipid.

Most of the chemical reactions in a living cell are achieved by proteinaceous enzymes, made of 20 different L-amino acids. Amino acids were most likely available on the primitive Earth as complex mixtures. Chemical reactions able to selectively condense the protein amino acids, at the expense of the non-protein ones in water, have been identified by the author. Helical and sheet-structures can be modelled with the aid of only two different amino acids, one hydrophobic, the second hydrophilic. Polypeptides with alternating hydrophobic and hydrophilic residues adopt a water-soluble beta-sheet geometry, because of hydrophobic side-chain clustering. Due to the formation of a beta-sheet, alternating sequences gain a good resistance to chemical degradation. Aggregation of alternating sequences into beta-sheets is possible only with all-L or all-D polypeptides. Short peptides have also been shown to exhibit catalytic properties.

In contemporary living systems, the hereditary memory is stored in nucleic acids, long chains built from nucleotides. Each nucleotide is composed of a base (purine or pyrimidine), a sugar (ribose for RNA, deoxyribose for DNA), and a phosphate group. However, the accumulation of significant quantities of natural RNA nucleotides does not appear to be a plausible chemical event on the primitive Earth.

The RNA World

Some ribozymes (RNA) are able to act as catalytic molecules. Since RNA was shown to be able to act simultaneously as an information and as a catalytic molecule, it has been considered to be the first living system on the primitive Earth. A ribozyme-based 'RNA world' has been studied in some detail. One should, however, remember that the synthesis of RNA itself, under prebiotic conditions, remains an unsolved challenge. It seems unlikely that life started with RNA molecules, because these molecules are not simple enough. The RNA world probably appears as an episode in the evolution of life, before the appearance of cellular microbes, rather than as the birth of life itself.

Autocatalytic Life

Chemists are now tempted to consider that primitive replicating systems must have used simpler information-retaining molecules than biological nucleic acids or their analogues. They are looking for simple self-sustaining chemical systems capable of self-replication, mutation, and selection. It has been shown that simple molecules, unrelated to the nucleotides, can actually provide exponentially replicating autocatalytic models. Beautiful examples of autocatalytic micelle growth have been demonstrated. However, these autocatalytic systems do not really store hereditary memory and cannot therefore evolve by natural selection.

2.2.3.3 Relics of Early Terrestrial Life in Geological Records

- Bacteria Microfossils

The earliest morphological fossils occur in rocks from South Africa, dating back 3.3 to 3.4 billion years.

Eleven species of cellularly preserved filamentous fossil microbes, comprising the oldest diverse microbial assemblage now known in the geologic record, were discovered in Northwestern Australia. This assemblage has established that filamentous cyanobacterium-like micro-organisms were extant and both morphologically and taxonomically diverse at least as early as ~3.465 billion years ago. It suggests that oxygen-producing organisms that relied upon solar energy and manufactured their organic constituents from inorganic material, may have already evolved by this early stage in biotic history.

- Oldest Sediments

The isotopic signatures of the organic carbon found in Greenland meta-sediments provide indirect evidence that life may be 3.85 billion years old. Taking the age of the Earth as 4.5 billion years, this means that life began as a quite early event in the Earth's history. This isotopic evidence stems from the fact that the carbon atom has two stable isotopes, carbon 12 and carbon 13. The $^{12}C/^{13}C$ ratio in abiotic mineral compounds is 89. In biological material, the process of photosynthesis gives a preference to the lighter carbon isotope and raises the ratio to about 92. Consequently, the carbon residues of previously living matter may be identified by this enrichment in ^{12}C.

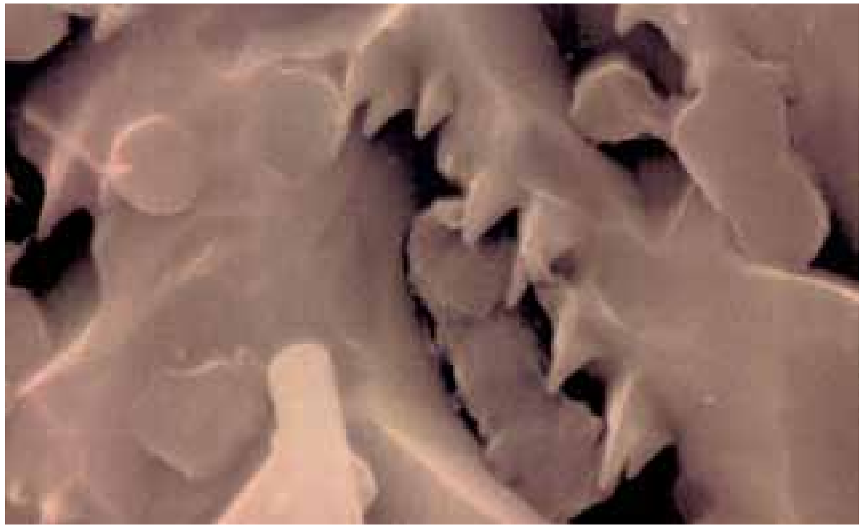

Figure 2.2.3.3. Fossilised terrestrial prokaryote (Early Archean 3.3 – 3.4 Ga), South Africa (Courtesy of F. Westall)

A compilation has been made of the carbon isotopic composition of over 1600 samples of fossil kerogen (a complex organic macromolecule produced from the debris of biological matter) and compared with that from carbonates in the same sedimentary rocks. This showed that the biosynthesis by photosynthetic organisms was involved in all of the sediments studied. In fact, this offset is now taken to be one of the most powerful indications that life on Earth was active nearly 3.9 billion years ago, because the sample suite encompasses specimens right across the geological time scale. Some organic matter in ancient sediments has been measured as being even more enriched in the light isotope of carbon, which would suggest the involvement of methane-utilizing organisms.

Unfortunately, the direct clues that could help chemists to identify the molecules that participated in the actual emergence of life on Earth about 4 billion years ago have been erased by geological plate tectonics, by the permanent presence of running water, by solar ultraviolet radiation and by oxygen produced by life.

- Homochirality: A Geometrical Indicator of Life

Pasteur was probably the first person to realize that the biological asymmetry (one-handedness) discussed earlier could best distinguish between inanimate matter and

Figure 2.2.3.4. A loosely packed conglomerate from the Greenland Isua Suite attesting to the presence of running water on the terrestrial surface 3.8 Ga ago (courtesy of M. Schidlowski)

life. Life that would simultaneously use both the right- and left-handed forms of the same biological molecules appears, in the first place, very unlikely for geometrical reasons. Enzyme beta-pleated sheets cannot form when both L- and D-amino acids are present in the same chain. Since the catalytic activity of an enzyme is intimately dependent upon the geometry of the chain, the absence of beta-pleated sheets would impede, or at least considerably reduce, the activity spectrum of the enzymes.

The use of one-handed biomonomers also sharpens the sequence information of the biopolymers. For a polymer made of n units, the number of sequence combinations will be divided by 2^n when the system uses only homochiral (one-handed) monomers. Taking into account the fact that enzyme chains are generally made up of hundreds of monomers, and that nucleic acids contain several million nucleotides, the tremendous gain in simplicity offered by the use of monomers restricted to one-handedness is self-evident. Life on Earth uses homochiral left-handed amino acids and right-handed sugars. A mirror-image life, using right-handed amino acids and left-handed sugars, is perfectly conceivable and might develop on another planet. Thus, homochirality can be a crucial signature for life.

2.2.3.4 The Limits of Life on Earth

Life on Earth is based upon the chemistry of carbon in water. The temperature limits compatible with the existence of life are thus imposed by the intrinsic properties of the chemical bonds involved in this type of chemistry at different temperatures. Presently, the maximum temperature limit known for terrestrial organisms is around 113°C for the deep-sea microbe Pyrolobus fumarii.

Important factors preventing life at temperatures well above 110°C are the thermal instability of some chemical bonds involved in biological molecules and the membrane permeability. Life is extremely diverse in the ocean at temperatures of 2°C. Living organisms, especially micro-organisms, are also present in the frozen soils of arctic and alpine environments. Antarctica has a wide range of extreme habitats and microbial ecosystems developing in dry valley rocks. The lower limit for bacterial growth published in the literature is –12°C, the temperature at which intracellular ice is formed.

In some theoretical scenarios, life appeared at very high temperatures. That means today's hyperthermophiles might be viewed as relics of the last common universal ancestor of all living beings. However, this hot-origin-of-life hypothesis has been seriously disputed, based on the fact that RNA is very unstable at high temperatures. The most attractive hypothesis might be that life appeared in a moderately thermophilic environment, hot enough to boost catalytic reactions, but cold enough to avoid the problem of macromolecule thermal degradation.

Salt-loving organisms, known as ‘extreme halophiles’, have been well-studied. They tolerate a wide range of salt concentrations (1 – 20% NaCl) and some procaryotes, the extreme halophiles, have managed to thrive in hypersaline biotopes (salines, salted lakes). They are, in fact, so dependent on such high salt concentrations that they cannot grow (and may even die) at concentrations below 10% NaCl.

The chemistry of life on Earth is optimised for neutral pH. Again, some micro-organisms have been able to adapt to extreme pH conditions, from pH 0 (extremely acidic) to pH 12.5 (extremely alkaline), albeit maintaining their intracellular pH between pH 4 and 9. As with temperature, the intracellular machinery cannot escape the influence of pressure. However, there are organisms in the deepest parts of the ocean where pressures reach 1100 bar. The extreme pressure limit for life on Earth is unknown – environments above 1100 bar have not been explored.

For a long time, it was believed that deep subterranean environments were sterile. An important recent development has been the recognition that bacteria actually thrive in the terrestrial crust. Subterranean micro-organisms are usually detected in subterranean oil fields or in the course of drilling experiments. For example, recent research has demonstrated that microbes are present much deeper in marine sediments than was previously thought possible, extending to at least 750 m below the sea floor, and probably much deeper. To depths of at least 432 m, microbes have been identified as altering volcanic glass. These data provide a preliminary, and probably conservative, estimate of the biomass in this important new ecosystem. It amounts to about 10% of the surface biosphere.

These discoveries have radically changed the perception of marine sediments and indicate the presence of a largely unexplored deep bacterial biosphere that may even rival the Earth's surface biosphere in size and diversity. Clearly, this discovery also has important implications for the probability of life existing on other planets in the Solar System and elsewhere.

2.2.3.5 The Search for Life in the Solar System

- *Life on Mars and the SNC Meteorites*

Mars mapping by Mariner-9, Viking-1 and -2 and Mars Global Surveyor revealed channels resembling dry river beds.

The inventory of the total amount of water that may have existed at the surface of Mars is difficult to estimate and varies from some metres to several hundred metres. Liquid water is generally considered to have been restricted to the very early stages of Martian history.

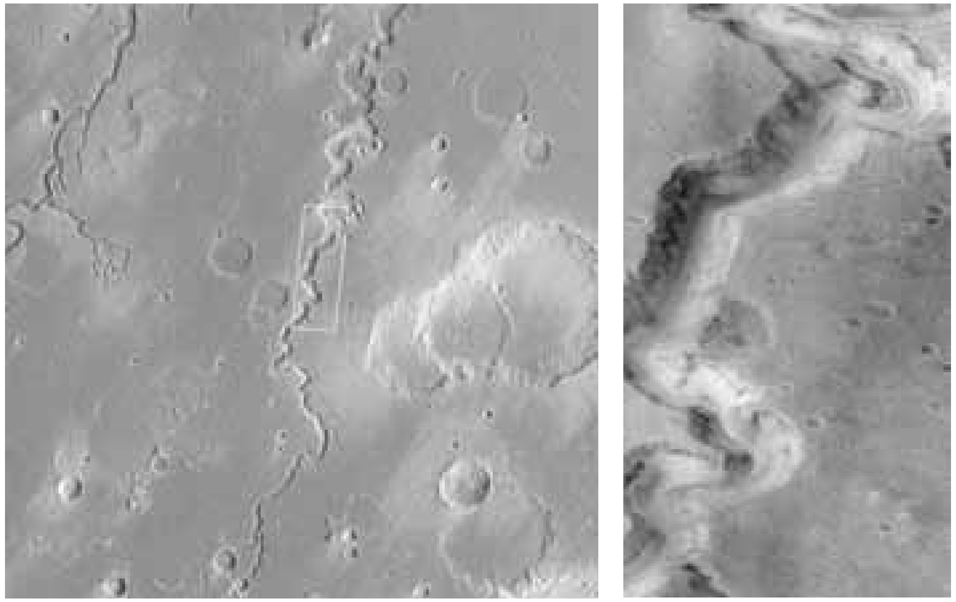

Figure 2.2.3.5. A portion of the meandering canyons of the Martian Nanedi Valles system viewed by Mars Global Surveyor (courtesy of Malin Space Science Systems/NASA)

Mars therefore possessed an atmosphere capable of decelerating carbonaceous micrometeorites, and chemical evolution may have been possible. The Viking-1 and -2 lander missions were designed to address the question of extant (rather than extinct) life on Mars. Three experiments were selected to detect metabolic activity such as photosynthesis, nutrition and respiration of potential microbial soil communities. Unfortunately, the results were ambiguous because although 'positive' results were obtained, no organic carbon was found in the Martian soil by gas-chromatography/mass-spectrometry. It was concluded that the most plausible explanation for these results was the presence at the Martian surface of highly reactive oxidants, like hydrogen peroxide, which would have been produced photochemically in the atmosphere. The Viking lander could not sample soils below 6 cm, and therefore the depth of this apparently organic-free and oxidising layer is unknown. Direct photolytic processes can also be responsible for the dearth of organics at the Martian surface.

Although the Viking missions were disappointing for exobiology, in the long run the programme has proved to be extremely beneficial for investigating the possibility of life on Mars. Prior to Viking, it had been apparent that there was a small group of meteorites, all of igneous (volcanic) origin, known as the 'SNC' (after their type specimens Shergotty, Nakhla and Chassigny) that had comparatively young crystallisation ages, equal to or less than 1.3 billion years. One of these meteorites, designated EETA 79001, was found in Antarctica in 1979. It had gas trapped within

glass pockets. Both compositionally and isotopically, this gas matched in all respects the makeup of the Martian atmosphere, as measured by the Viking mass-spectrometer. The data provide a very strong argument that at least that particular SNC meteorite came for Mars, the product of a high-energy impact that ejected material into space.

There are now fourteen SNC meteorites known in total, with EETA79001 and ALH84001 supplying new and highly interesting information. A subsample of EETA79001, excavated from deep within the meteorite, has been subjected to stepped-combustion. The CO^2 release from 200 to 400˚C suggested the presence of organic molecules. The carbon is enriched in ^{12}C, and the carbon-isotope difference between the organic matter and the carbonates in Martian meteorites is greater than that seen on Earth. This could be indicative of biosynthesis, although some other as yet unknown reason for this enrichment cannot be ruled out. McKay and co-workers have reported the presence of other features that may represent a signature of relic biogenic activity on Mars, but today this biological interpretation has been almost abandoned.

Because Mars had a warm and wet past climate, its surface must be covered by both an impact-generated layer and by sedimentary rocks deposited by running and/or still water. Such consolidated sedimentary hard rocks ought therefore to be found among the Martian meteorites. However, no such sedimentary material has been found in any SNC meteorite. It is possible that they did survive the effects of the escape acceleration from the Martian surface, but did not survive terrestrial atmospheric entry, because of deterioration of the cementing mineral.

The STONE experiment flown by ESA is designed to study just such physical and chemical modifications of sedimentary rocks during atmospheric entry from space. A basalt (in-flight control), a dolomite (sedimentary rock) and an artificial Martian regolith (80% crushed basalt and 20% gypsum) were embedded in the ablative heat shield of Foton-12, which was launched on 9 September and landed on 24 September 1999.

The samples collected after this world-first have had their chemistry, mineralogy and isotopic compositions analysed by a European consortium. Atmospheric infall modifications are made visible by reference to the untreated samples. The results suggest that some Martian sediments could partially survive terrestrial atmospheric entry from space.

Even if the evidence for ancient life in ALH84001 is not established, the two SNC meteorites do show the presence of organic molecules. This suggests that the ingredients required for the emergence of a primitive life form may have been present on the surface of Mars. Therefore, it is tempting to consider that micro-organisms may

Figure 2.2.3.6. The STONE experiment mounted on the re-entry heat shield of the Foton capsule. The samples were of different compositions: one represented a possible Martian regolith material, another was a normal sedimentary rock. A basalt was used as a control. The goal was to see if sedimentary rock materials can withstand high-velocity entry into the Earth's atmosphere

have developed on Mars until liquid water disappeared. Since Mars probably had no plate tectonics, and since liquid water seems to have disappeared from Mars' surface very early on, the Martian subsurface perhaps contains a frozen record of very early forms of life.

NASA has planned a very intensive exploration of Mars, and European and Japanese missions are also taking place. Exobiology interests are included, especially in the analysis of samples from sites where the environmental conditions may have been favourable for the preservation of evidence of possible prebiotic or biotic processes. ESA has convened an Exobiology Science Team to design a multi-user integrated suite of instruments for the search for evidence of life on Mars. Priority has been given to the in-situ organic and isotopic analysis of samples obtained by subsurface drilling. A first exobiology lander, called 'Beagle-2', is expected to be launched in June 2003, as part of the ESA Science Directorate's Mars Express mission.

- *Life within Europa's Ocean?*

Europa appears one of the most enigmatic of the Galilean satellites. With a mean density of about 3.0 gcm^{-3}, the Jovian satellite should be dominated by rocks. Ground-based spectroscopy, combined with gravity data, suggests that the satellite has an icy crust kilometres thick and a rocky interior. The Voyager images showed very few impact craters on Europa's surface, indicating recent, and probably continuing, resurfacing by cryo-volcanic and tectonic processes.

The Voyager spacecraft also revealed that Europa's surface is crossed by numerous intersecting ridges and dark bands. It has been suggested that Europa's outer ice shell might be separated from the silicate interior by a liquid water layer, which is prevented from freezing by tidal heating as a result of the variation in gravitational field across the body of the satellite. Heat transfer from the core to the bottom of the ocean, similar to thermal vents in terrestrial oceans, is another possible source of thermal energy. Although the existence of such an ocean is still uncertain, the last images from Galileo showing evidence for mobile icebergs support the presence of liquid water at shallow depths below the surface, either today or at some time in the past.

Figure 2.2.3.7. A Galileo image of an 80 km x 95 km area of Europa, where the youngest features are domes that are probably viscous cryo-volcanic flows or sites of shallow intrusion – good targets for the search for traces of life (courtesy of NASA)

If liquid water is present within Europa, it is quite possible that it includes organic matter derived from thermal vents. Terrestrial-like prebiotic organic chemistry and primitive life may therefore have developed in Europa's ocean. If Europa maintained tidal and/or hydrothermal activity in its subsurface until now, it is possible that bacterial activity is still present. Thus, the possibility of extraterrestrial life being present in a subsurface ocean on Europa must be taken seriously. The most likely sites for extant life would be at hydrothermal vents below the most recently resurfaced area. To study this directly would require making a borehole through the ice in order to deploy a robotic submersible. On the other hand, biological processes in and around hydrothermal vents could produce biomarkers that would appear as traces in cryo-volcanic eruptions and thereby be available at the surface for in-situ analysis or sample return. Mineral nutrients delivered through cryo-volcanic eruption would make the same locations the best candidates for photosynthetic life.

- *Organic Chemistry of Titan*

Titan's atmosphere was revealed mainly by the Voyager-1 mission in 1980, which yielded its bulk composition: 90% molecular nitrogen and about 1 – 8% methane. Also, a great number of trace constituents were observed in the form of hydrocarbons, nitriles and oxygen compounds, mostly CO and CO_2. Titan is the only other object in our Solar System to bear a resemblance to our own planet in terms of atmospheric pressure (1.5 bar) and carbon/nitrogen chemistry. It therefore represents a natural laboratory for studying the formation of complex organic molecules on a planetary scale and over geological times.

The ISO satellite has detected tiny amounts of water vapour in the higher atmosphere, but Titan's surface temperature (94 K) is much too low for the presence of liquid water. Although the latter is totally absent, the satellite provides a unique milieu to study, in- situ, the products of the fundamental physical and chemical interactions driving a planetary organic chemistry. Titan also serves as a reference laboratory for studying, by default, the role of liquid water in exobiology.

The NASA/ESA Cassini-Huygens spacecraft launched in October 1997 will arrive in the vicinity of Saturn in 2004 and perform several flybys of Titan, making spectroscopic, imaging, radar and other measurements. The Huygens descent probe, managed by European scientists, will penetrate Titan's atmosphere and systematically study the organic chemistry in Titan's geofluid. For 150 minutes, in-situ measurements will provide detailed analysis of the organics present in the air, in the aerosols and at the surface.

2.2.3.6 Panspermia: The Distribution of Life

- *The Survival of Microbes in Space*

In order to study the survival of resistant microbial forms in the upper atmosphere and free space, microbial samples have been exposed in-situ aboard balloons, rockets and spacecraft. The ESA Microgravity Programme has continued to support experiments of that type. A priori, the space environment seems to be very hostile to life. This is due to the high vacuum, intense radiation of galactic and solar origin, and extreme temperatures. In the endeavour to disentangle the network of potential interactions of the parameters of space, methods have been applied to isolate each parameter and to investigate its impact on biological integrity, applied singly or in controlled combinations.

Space vacuum has been considered to be one of the factors that may prevent interplanetary transfer of life because of its extreme dehydrating effect. However, experiments in space have demonstrated that certain micro-organisms can survive exposure to space vacuum for extended periods, provided they are shielded against the intense solar UV radiation. Most results are available from spores of the bacterium Bacillus subtilis. If shielded against UV, spores survive for at least six years in space, the maximum period of exposure tested so far. Space experiments have also shown that up to 70% of bacterial and fungal spores (a dormant form) can survive short-term (e.g. 10 days) exposure to space vacuum, even without any protection. The chances of survival in space are increased if the spores are embedded in chemical protectants such as sugars or salt crystals, or if they are exposed in thick layers. For instance, about 5% of a species of the extreme halophile Haloarcula survived a two weeks of space exposure on a Foton flight.

Solar UV radiation has been found to be the most deleterious factor in space, as tested with dried preparations of viruses, bacterial and fungal spores, with DNA being the most lethal target.

The radiation field in the Solar System is governed by components of galactic and solar origin. It is composed of electrons, alpha-particles and cosmic heavy ions, the latter being the most ionising and therefore the most damaging components. The heavy particles of cosmic radiation are conjectured to set the ultimate limit on the survival of spores in space because they penetrate even heavy shielding. The maximum time for which a spore can escape a hit by a heavy particle has been estimated to be 10^5 – 10^6 years.

During the major part of a hypothetical journey through deep space, micro-organisms are confronted with the 4 K cold emptiness. Laboratory experiments under simulated interstellar-medium conditions point to a remarkably less damaging effect of UV radiation at these low temperatures. Treating B. subtilis spores with three simulated factors simultaneously (UV, vacuum and 10 K temperature) produces an unexpectedly high survival rate, even at very high UV fluxes. From these data, it has been estimated that, in the most general environment in space, spores may survive for hundreds of years.

- *Interplanetary Transfer of Life*

Although it will be difficult to prove that life can be transported through the Solar System, the chances of the different steps in the process occurring can be estimated. These include: (1) the escape process, i.e. the removal to space of biological material that has survived being lifted from the surface to high altitudes; (2) the interim state in space, i.e. the survival of the biological material over time scales comparable with interplanetary passage; (3) the entry process, i.e. the non-destructive deposition of the biological material on another planet.

The identification of some meteorites as being of lunar origin and some others as most probably being of Martian origin, shows that the escape from a planet of material ranging from small particles to boulders, after it has suffered a high-energy impact, is clearly a feasible process. In that context, it is also interesting to note that bacterial spores can survive shock waves produced by a simulated meteorite impacts and huge accelerations.

Concerning the subsequent survival of life forms during the interim voyage through space, it has so far only been possible to observe directly the influence of exposure of bacterial spores to space for a maximum period of six years. The high survival rate of these spores and the high UV-resistance of micro-organisms at the low temperatures of deep space are interesting results. However, travelling from one planet to another, e.g. from Mars to Earth, by chance requires an estimated mean time of several 10^5 – 10^6 years for boulder-sized rocks. Periods of only a few months have been calculated for the case of microscopic particles. Evidently, more data on the long-term effects in space are required to allow meaningful extrapolation to the time spans required for the interplanetary transport of life.

ESA has initiated the development of an exposure facility ‘Expose’, to be attached to an Express Pallet on the truss structure of the International Space Station (ISS). This will allow extensive study of bacterial survival in space.

2.2.3.7 Life Beyond the Solar System

- *Exoplanets*

New planets have been discovered beyond the Solar System. On 6 October 1995, the discovery was announced of an extrasolar planet orbiting an 8 billion year old star called 51 Pegasus, forty-two light years away within the Milky Way. The suspected planet takes just four days to orbit the star. It has a surface temperature of about 1000°C and a mass about half that of Jupiter. One year later, seven other extrasolar planets were identified. One of them, 47 Ursa Major, has a surface temperature estimated to be around that of Mars (–90 to –20°C), and another, 70 Virginis, has a surface temperature estimated at 70 – 160°C. The latter is the first known extrasolar planet whose temperature might allow the presence of liquid water. So far, about 30 exoplanets have been identified.

- *Spectral Signatures of Life*

Extra-solar life will not be accessible by space missions in the forseeable future. The formidable challenge to detect distant life must therefore be tackled by astronomers and radio-astronomers. The detection of water and ozone (an easily detectable tell-tale signature of oxygen) in the atmosphere will be a strong indication, but not an absolute proof. Other anomalies in the atmospheres of telluric exoplanets, such as the presence of methane, could be the signature of extra-solar life. European astrophysicists are proposing the construction of a five-telescope infrared interferometer to study the atmospheres of exoplanets. The mission, known as ‘IRSI-Darwin’, is presently under study by ESA. The detection of an unambiguous electromagnetic signal (via the SETI programme) would obviously be the most exciting event, but remains problematic.

2.2.3.8 Conclusion

Is there life elsewhere? Recent discoveries have allowed a better estimate of the chances of discovering an extraterrestrial life form. Biologists have shown that bacterial life can survive under extreme conditions. Life has continued to develop very well in water that is very acidic, alkaline, or is a strong brine solution. It has also survived and flourished in water at high pressure and at temperatures above 100°C. A flourishing biosphere has been discovered a kilometre below the Earth’s surface.

Primitive terrestrial life probably relied on extraterrestrial organic molecules, made in the interstellar medium and delivered to the Earth by cometary grains. Such an import process only required an atmosphere to decelerate the particles. Such an atmosphere existed 4 billion years ago, as attested to by the presence of liquid water at the Earth’s surface. As a consequence, any planet harbouring liquid water at its surface can be considered a potential site for the emergence of life.

There is clear evidence that water existed in substantial amounts on the surface of Mars at some earlier epoch. Therefore, primitive life might also have developed there. How long water was present at the Martian surface is not known. Nor is it yet certain if water still exists in subsurface aquifers, although there are clear indications of the existence of large permafrost regions and of old water flows out of associated areas. Given the discovery of a flourishing biosphere even a kilometre below the Earth’s surface, it would seem possible that a similar microbial community might still be present below the surface of Mars, having long ago retreated into that ecological niche following the disappearance of a surface-water environment. The possibility that life may have evolved on Mars during an early period when there was water on its surface and that life may still exist deep below the surface, makes it a prime candidate in the search for life beyond the Earth.

Some of the organic molecules that participated in the emergence of life might also have been made in hydrothermal oceanic vents. Europa may have an ocean of liquid water beneath its icy crust, as suggested by both data and theory. If submarine volcanism exists on Europa, the question arises as to whether such activity could support life, as do volcano-hydrothermal sites on the Earth’s sea floor.

Organic chemistry has been shown to be universal, since over eighty different organic molecules have been identified in the interstellar medium by radio astronomers. Extra-solar planets have also been discovered, which begins to raise the future possibility of detecting water-harbouring planets beyond the Solar System.

The distribution of life in the Universe may even be favoured by the migration of life through space, a notion known as ‘panspermia’. Recent discoveries that have given new support to this idea include:

(i) The identification of meteorites of lunar and probably also of Martian origin.
(ii) The probability of small particles reaching escape velocities through the impact of large bodies on a planet.
(iii) The ability of bacterial spores to survive the shock waves of a simulated high-energy impact.
(iv) The high UV-resistance of micro-organisms at the low temperature of deep space.
(v) The high survival rates of bacterial spores over extended periods in space, provided they are shielded against the intense solar ultraviolet radiation or are coated with a mantle of absorbing material that attenuates it.

The probability that primitive life developed without reliance upon the large complex molecules of its later evolution, such as RNA, would likely increase the chances of survival of such organisms if ejected into space.

On Earth, life probably appeared about 4 billion years ago, when some organic molecules processed by liquid water began to transfer their chemical information and to evolve by making a few accidental transfer errors. Schematically, the prebiotic conditions can be compared to the parts of a robot. By chance, some parts were assembled to form a robot able to assemble other parts to form a second identical robot, etc. Sometimes, a minor error in the process generated more efficient robots.

The number of parts required for that first robot is still unknown. The problem is that, on Earth, those earliest parts have been erased by plate tectonics, by the permanent presence of liquid water, by solar ultraviolet radiation, and by life itself. If the number was small, life has a real chance of establishing itself on any body presenting environmental conditions similar to those that prevailed on the primitive Earth, because simple chemistry is reproducible.

If the number of parts was very large, then life is probably a very rare event, perhaps even restricted to the Earth. Primitive life is expected to have been simple because it appeared when the Earth was constantly being heavily bombarded. A simple self-reproducing system would have been more robust and offered a better chance of resisting the cataclysmic impacts that probably periodically sterilised the Earth during the heavy bombardment. Taken together, all these data strongly support the hypothesis that life is probably not restricted to the Earth.

Looking to the future, the search for the origins of life and its existence elsewhere will benefit from new and extended space observations using the International Space Station. It is important to understand better the limits to the survival of simple organisms in space, in order to decide if life on Earth originated from elsewhere.

The search for life elsewhere in the Solar System remains one of the great scientific endeavours of our age. The Beagle-2 mission destined to land on Mars represents a milestone for Europe on the road towards that objective, and one that must surely be followed by other, more ambitious European attempts to probe deep below the surface of Mars, to find the relics of an earlier life form or, just possibly, a novel living world.

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2.3 PHYSICAL SCIENCES AND APPLICATIONS

2.3.1 Macromolecular Crystallisation

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2.3.1.1 Introduction

Biological macromolecules such as proteins, lipids, nucleic acids, carbohydrates and viruses (and their assemblies) are central to living systems. Understanding the mechanisms of life is not only a matter of knowing the function that each of these macromolecules performs, but also of knowing how they perform it, i.e. of finding out the relationships between the intimate structure of these molecules and the different types of function that they perform. The success of molecular biology in deciphering the mechanisms by which certain important macromolecules perform their biological roles has awakened the interest of pharmaceutical, medical and food companies and research institutions, and has triggered the establishment of some of today's largest scientific research programmes, like genomics and proteomics.

Crystallisation enters onto the scene because the structure of macromolecules larger than about 20 kDalton can be only determined from the X-ray diffraction of their crystals. Therefore, most advanced molecular-biology projects face not only the tedious and complex isolation and purification of the macromolecules, but also their crystallisation, for which there is not yet a rationale. Many macromolecules are reluctant to crystallise, or when they do so the internal order of the crystalline arrangement is not good enough to provide X-ray diffraction data at the resolution required to establish structure–function correlations. This, linked with the usual small amount of purified protein available for crystallisation trials, makes crystallisation a critical step.

It is now well-established that macromolecular crystals grow from solutions by the same mechanisms employed by small inorganic and organic molecules. Experimental evidence for screw dislocations, two-dimensional nucleation, direct accretion and three-dimensional nucleation, has been obtained by Michelson interferometry, atomic-force microscopy, electron microscopy, and X-ray topography. The driving force for macromolecular crystallisation is also achieved in the same way as for solutions of small molecules, i.e. by (a) thermal changes, (b) solubility reduction, (c) chemical reaction, and (d) evaporation.

The techniques employed for protein crystallisation are basically the same, with small variations, as those developed in the past for the crystallisation of soluble and slightly soluble compounds of small molecules. However, macromolecules show some peculiarities, which need to be considered in what follows because they render crystallisation a difficult challenge:

1. Macromolecules display a rather asymmetric and weak bonding configuration at their surfaces. This, together with their large size, makes attachment at the correct contact points less probable for growth units landing on the crystal surface.

2. They tend to aggregate in *n*-mers, which diversifies the possible shapes and sizes of growth units, making the ordered accretion of growth units more complex.

3. Typically, macromolecular solutions contain considerable amounts of contaminants, even after thorough purification. The incorporation of impurities during the crystal growth process is an additional source of problems in the crystallisation of proteins.

4. Because of the large molecular size, and also the small number of molecules comprising the critical nuclei, the nucleation process typically takes place outside the expected window for classical nucleation theories. Thus, under some circumstances, biological macromolecules have properties resembling colloids, rather than small molecules, e.g. when liquid/liquid phase separation precedes crystallisation.

All of these peculiarities make macromolecular crystals very sensitive to the processes transporting growth units from the bulk of the solution towards the crystal face. The belief that the convection-free environment provided by microgravity would enhance the perfection and size of macromolecular crystals triggered the interest of molecular biologists and structural crystallographers in the use of space facilities. Most of these space experiments were performed by direct extrapolation of the on-ground crystallisation techniques, using blind facilities. Therefore, in most cases the study was approached as a 'black box' problem, where only the initial conditions and the results were known, whilst the actual course of the experiment was unknown.

After fifteen years of conducting experiments in microgravity, improvements in crystal quality and crystal size have been reported in a number of cases. In general, however, the space-grown crystals, evaluated by Wilson-type plots or by mosaicity measurements, do not show a dramatic increase of order in the three-dimensional arrangement of the molecules. More specifically, although it seems clear that the degree of order is generally higher at low-to-medium resolution, in only a few cases has a significant enhancement of the maximum resolution level been experimentally measured and reported.

The very limited flight opportunities for European experiments made it advisable to discard this strategy, which was mostly based upon crystallisation screening with blind experiments (only 426 ESA protein crystallisation experiments have so far been performed, compared with over 7600 by NASA). ESA's Expert Group on Protein Crystallisation correctly recommended that more careful attention should be paid to the fundamental reasons for the plausible benefits of the gravity-less scenario, using monitored experiments wherever possible. Thanks to this new strategy, in the last five years a number of new results have been produced, either through on-ground or space based research, that allow a better understanding of the problem of macromolecular crystallisation and the inconsistency of the effects observed for space experiments. The results of these investigations will be summarised here.

2.3.1.2 The Concentration Depletion Zone

Certainly, microgravity sensu-strictum, i.e. 10^{-6} times the value of gravity on Earth, inhibits buoyancy-driven convection and sedimentation of the growing crystals. In principle, that has important consequences for the critical processes taking place at the crystal/solution interface.

Crystals grow from solutions by accretion of growth units of the solute. Naturally, a Concentration Depletion Zone (CDZ) is immediately formed around the growing crystal. Within this region, the solute concentration changes from the concentration in the bulk solution C_{INFIN} to the concentration of solute at the crystal face C_i. On the ground, the very existence of the concentration depletion zone unavoidably creates density gradients that trigger the mechanisms of convective flow.

Under microgravity conditions, where the mass transport is controlled by diffusion, the concentration profile in the CDZ varies with time as the crystal grows. That variation is controlled by the balance between the flow of growth units towards the crystal face and the rate of incorporation of these growth units into the crystal lattice. The kinetics of incorporation at the crystal surface are linked to the bond distribution of the crystallographic structure and are measured by the coefficient β_{face}, while the flow towards the crystal face is highly dependent upon the mass-transport properties in the bulk solution. The competition between surface kinetics and diffusion transport is measured by the relation $\beta\ \delta/D$, where δ is the width of the CDZ and D is the diffusion coefficient of the macromolecule. When $\beta\ \delta/D << 1$, the crystal growth is controlled by the processes taking place at its surface. The growth rate is independent of crystal size, which increases linearly with time. However, when $\beta\ \delta/D >> 1$, mass transport is the rate-controlling parameter and crystal size increases with the square root of time.

From this simple analysis it is clear that the existence of a diffusion-controlled mass-transport scenario does not necessarily imply diffusion control of the overall crystal growth process. In fact, the experimental β_{step} data, which are available for several protein molecules, together with values found for their diffusion coefficient in water, lead to the conclusion that those protein crystals grow in the so-called 'mixed transport-kinetics' regime under microgravity conditions.

There are two implications arising from this conclusion. Firstly, during the growth of the crystal there can be a transition from surface control to mass-transport control, as the diffusion length increases with the size of the crystal. In that case, the periphery of the crystal may have a better quality than its core, and therefore X-ray diffraction data sets from the outer regions of large crystals may provide better structural information.

The second important implication of these results is that the control of the overall crystal-growth process is very sensitive to the diffusion coefficient of the macromolecule. This is because any increment due, for example, to a convective contribution will displace the system towards surface-kinetics control. It is also relevant to the recent finding that, due to the coupling between the transport and surface-kinetic processes, the growth rate of protein crystals fluctuates, even under steady external conditions. It has been proposed that these fluctuations affect the quality of crystals grown in the mixed transport-kinetics regime, as they can be damped by pushing the system into either transport or surface-kinetics control.

The problem of impurity incorporation into the protein crystal is another important subject that is linked to the above discussion. It is known that impurities affect the crystallisability of nucleic acids. Incorporation of impurities is the source of macroscopic disorder observed in protein crystals, as they may increase the lattice strain. The strain can be released by continuous bending of the lattice, by misalignment of growth-sector boundaries, by formation of mosaic blocks, and by dislocations. It has recently been found that protein crystals grown in space contain several times less impurities than their terrestrial counterparts. It was also shown that the effect of impurities on nucleation and crystal growth is less important in crystals grown from gelled solutions than from pure protein solutions. The observed beneficial effect of such stagnant solutions can be explained by the existence of an impurity depletion zone, which forms when the crystal preferentially incorporates the impurities, i.e. when the partition coefficient is larger than unity. The efficiency of this self-purification process by diffusive 'filtering' increases with the volume of the protein solution. Certainly, the above discussion only applies if the spherical symmetry of the concentration depletion zone (either that of the impurity or that of the macromolecule itself) is ensured. Thus the quality of the microgravity scenario, which will be reviewed in the next section, becomes a critical issue for macromolecular crystallisation.

2.3.1.3 Required Quality of the Microgravity Environment

In the preceding discussion, two simplifying assumptions have been made. Firstly, that the disturbances to the microgravity environment in an orbiting spacecraft, from remnant or perturbing accelerations, are of negligible effect. Secondly, that all convective motions are absent.

In practice, fluid/gas interfaces exist in some protein crystal-growth techniques, namely in all variations of vapour-transport methods, which are the most commonly used protein-crystallisation techniques for on-ground experiments. In that situation, surface-tension-driven Marangoni convection is known to occur (see Section 2.3.4). Obviously, therefore, crystallisation techniques without free liquid surfaces, such as free-interface diffusion or dialysis, are the appropriate candidates for growing crystals in space. Hence, the discussion about the required quality of the microgravity environment should be restricted to this type of crystallisation technique in which Marangoni convection cannot occur. However, it is still necessary to consider the possibility that some buoyancy-driven convection could occur in response to remnant or induced accelerations, since concentration (density) gradients obviously do exist in the crystallising solutions as an intrinsic consequence of the crystal-growth process itself.

As discussed in Section 1.2, all microgravity experimentation facilities suffer some degree of residual acceleration and impulse-like 'g-jitter', mostly stemming from Orbiter manoeuvres. It is also known that these g-jitters, particularly those of very low frequency, are able to trigger particle motion in solutions. In fact, monitored experiments performed by ESA have demonstrated the existence of protein-crystal motion during Shuttle flights. It is important to emphasise that, in all of these cases, the effect was observed inside interface-free diffusion devices. The relevance of these motions in perturbing CDZ symmetry was theoretically analysed and the problem faced experimentally in two recent ad-hoc experiments performed on the STS-95 mission. These experiments were performed in ESA's Advanced Protein Crystallisation Facility (APCF).

The top row of Figure 2.3.1.1 shows three consecutive interferograms, corresponding to the growth of ferritin crystals. The small crystal in the lower part of the image is attached to the wall of the reactor, while the largest crystal in the centre is floating in the solution and moves across the field of view (5 mm x 4 mm). The average rate of motion of the crystal between the first and second images was R12 = 104 μm/h and between the second and third images R23 = 256 μm/h. These relatively fast crystal movements were induced by large g-jitters during the flight. The bottom row of the figure shows the concentration fields, reconstructed from the interferogram. Note that the depletion zone around the large crystal changes from being slightly deformed in the left interferogram to being severely distorted in the middle. In the right one, it is almost non-existent. As expected, whenever the velocity of flow of macromolecules

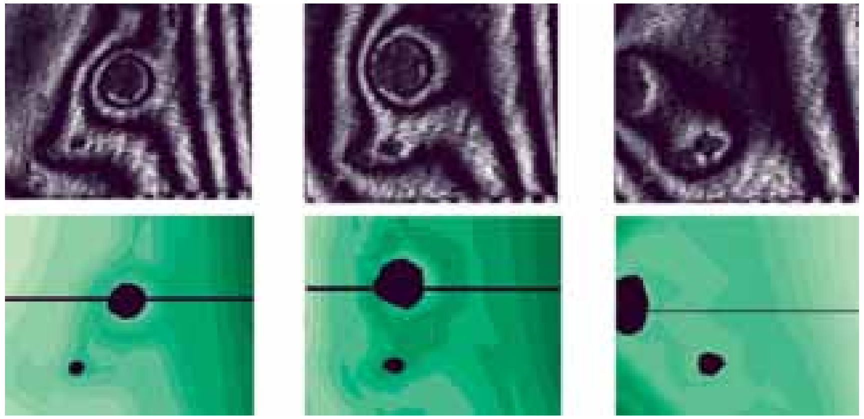

Figure 2.3.1.1. Three interferometric images of a ferritin crystal growing in space (STS-95 mission). The large crystal floating in the solution is growing within its concentration depletion zone (left). Motion of the crystal at a velocity greater than 200 μm/h provokes breakage of the symmetry of the depletion layer (centre and right pictures obtained about 7 h and 14 h later, resp.) The observational window is 5 mm x 4 mm

towards the crystal face is slower than the rate of motion of the crystals, the spherical symmetry of the CDZ is broken.

The second experiment was technically very demanding. The objective was to observe the depletion zone around only one fixed single crystal. This was made possible by gluing a reinforced tetragonal lysozyme crystal to the wall of the reactor and then selecting the initial conditions to permit the growth of the crystal whilst avoiding nucleation, i.e. to maintain the system inside the metastable zone.

Figure 2.3.1.2 shows the concentration field reconstructed from the interferogram, demonstrating for the first time the existence of the depletion zone around a growing protein crystal in space. The picture also shows that the depletion zone, ideally having spherical symmetry, is distorted. This is a consequence of the buoyancy-driven convection that is triggered by the residual accelerations and g-jitters.

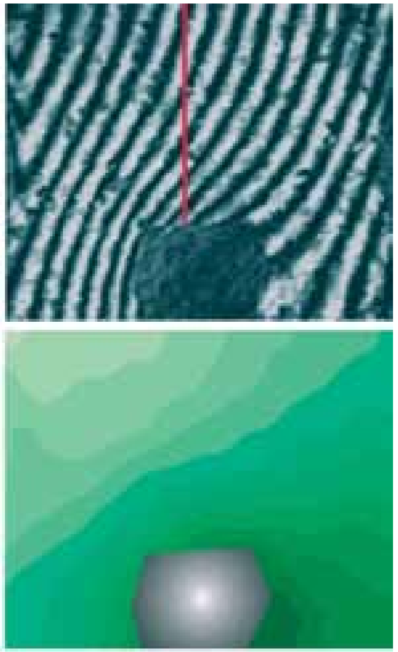

Figure 2.3.1.2. Interferogram (top) and corresponding protein concentration map showing the concentration depletion zone around a protein single crystal growing in space (STS-95 mission), glued to the wall of the reactor. Spherical symmetry of the depletion zone is lost due to fluid motion provoked by g-jitter

These experiments clearly show, for the first time, that the 'gravitationally' noisy environment on board the Shuttle may provoke not only crystal motion, but also buoyancy-driven fluid motion inside interface-free diffusion reactors. They also demonstrate that, in some cases, the symmetry of the depletion zone from which microgravity experiments should benefit can actually be broken.

These results have important implications. For example, suppose that the ferritin crystals shown in Figure 2.3.1.1 were grown in a 'blind' space experiment and then their X-ray quality compared with that of crystals grown on the ground. Should one conclude that there is any reasonable correlation between 'microgravity' and crystal quality? The answer is obviously no, and it implies that better knowledge of the correct space environment for crystal growth is presently needed. Monitoring space crystallisation experiments with appropriate tools is the only way to obtain useful information for rationalising protein crystallisation. It is also important to obtain insight into the growth processes occurring close to the crystal face which, because of the effect of gravity in terrestrial experiments, are one of the less understood problems in crystal growth.

2.3.1.4 New Crystallisation Techniques Exploiting Diffusion-Controlled Mass Transport

All of the crystallisation techniques currently used on the ground can be implemented under microgravity conditions. A diverse range of facilities are currently offered by several space agencies for growing protein single crystals under microgravity conditions. The so-called 'hanging (or sitting) drop method' is an elegant evaporation technique developed for protein crystallisation and the most appreciated by molecular biologists. For that reason, it has been the method most commonly used so far in space experiments. Unfortunately, for the reasons explained above (the existence of a free fluid interface and the low mechanical stability), an evaporation method is not an appropriate choice for space crystallisation. Interface-free diffusion and dialysis methods have also been tried several times in space. The problem is that the very existence of mass transport controlled by diffusion converted most of these experiments into a slow mixing batch method, since the time required for equilibration is shorter that the waiting time for nucleation. Finally, space facilities for performing crystallisation by changing the temperature of the solution have recently been implemented.

Very little has been done to design and explore crystallisation methods that actually exploit the potentially convection-less scenario provided by microgravity conditions. One such attempt is the use of a non-equilibrium counter-diffusion technique, which consists of the counter-diffusion of the macromolecules and the molecules of their precipitating agent, in a two- (or three-) chamber linear device. Thus, both interacting solutions are placed in line, separated either by a membrane or an intermediate chamber containing either a free fluid or a chemically inert gel. The very nature of the technique requires a diffusive environment, because convection will destroy the symmetry of the precipitation pattern.

The initial conditions are selected to provoke the precipitation of the protein far from equilibrium – at very high supersaturation – as soon as the precipitating agent meets the protein solution. Because the molecules of the precipitating agent (usually either a salt or polyethylene glycol) diffuse faster than the biological macromolecules (typically one to two orders of magnitude faster), the precipitation phenomena occur in the protein chamber. Due to the coupling between mass transport and precipitation, a wave of supersaturation is triggered which moves across the protein chamber with decreasing amplitude. This provokes successive precipitation phenomena, occurring under different crystallisation conditions, namely at decreasing supersaturation values.

The advantages of the technique over classical crystallisation techniques are that while vapour diffusion or batch methods scan only one crystallisation condition per experiment, this counter-diffusion technique explores a large range of crystallisation conditions in one single experiment. The technique was tested under microgravity using an ad-hoc designed APCF reactor with a long protein chamber, a sine qua non condition for permitting spatial development of the precipitation pattern. The experiment confirmed the existence of such a supersaturation wave, which was observed for the first time.

As shown in Figure 2.3.1.3, the maximum of supersaturation advances as a wave, its amplitude decreasing and its width increasing as the wave moves across the protein chamber with decreasing velocity. As the supersaturation wave moves towards equilibrium, it automatically screens for the best growth conditions. In fact, the crystals obtained by this automatic screening produced the highest-quality X-ray-diffraction data ever collected (completeness of 98.4% in the 0.94–25 Å resolution shell) from crystals of the model protein in the experiment (tetragonal hen-egg-white lysozyme). Because of the g-jitters triggered by the release and retrieval of a satellite during this Shuttle mission and by the thruster firing system, the dynamics of the supersaturation wave were affected on three different occasions. This demonstrates once again that 'gravitational' noise due to stray accelerations may affect the crystallisation process, this time at the scale of the whole reactor.

An early criticism of space crystallisation was that the limited number of opportunities for flying experiments makes it impossible to employ the trial and error methodology used so far on Earth in the search for optimum crystallisation conditions. It is evident that this type of counter-diffusion experiment provides an interesting opportunity for those who wish to use that methodology, particularly as the use of capillaries as growth chambers reduces the volume of protein needed to values comparable to

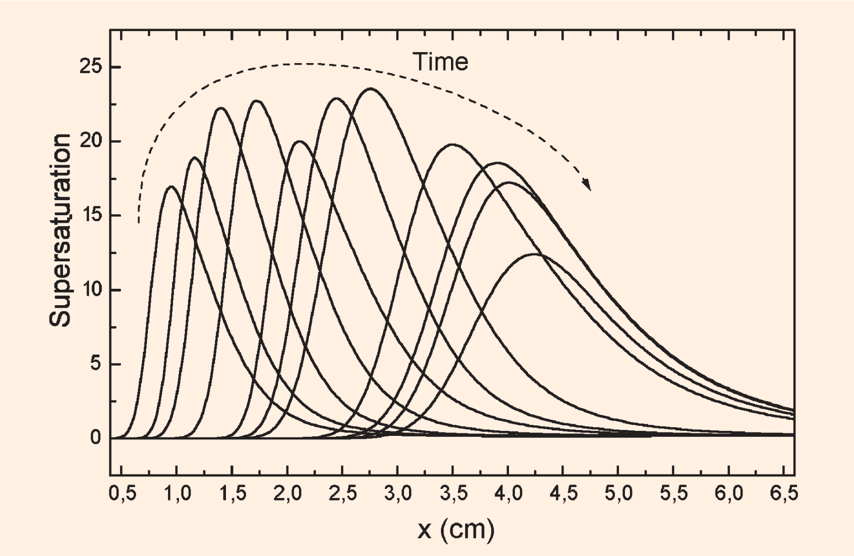

Figure 2.3.1.3. Development of supersaturation across a 70 mm-long protein chamber in a non-equilibrium counter-diffusion experiment performed in space (on the STS-95 Shuttle mission). The data correspond to the actual development in time and space of the supersaturation values obtained by interferometric analysis. The precipitating agent diffuses from left to right, creating a wave of supersaturation that moves across the protein chamber. It provokes successive protein-crystallisation events under increasingly favourable conditions for optimal crystal quality. Despite three perturbations of the trend provoked by g-jitters, the best crystals (0.94 Å resolution) of the model protein tetragonal HEW lysozyme ever grown were obtained in this experiment

those used in classical 'drop' techniques. In fact, an apparatus that exploits the counter-diffusion technique by using X-ray capillaries as the protein chamber, the Granada Crystallisation Box, will soon be commercially available. In addition to the advantage of reducing the number of trials in the screening for optimal crystallisation conditions, this apparatus also avoids post-crystallisation manipulation of crystals for X-ray diffraction.

2.3.1.5 Simulating Microgravity

As already mentioned, all the expected benefits of space crystallisation come from the ability of the microgravity scenario to reduce density-driven convection. It includes the possibility to grow the crystals under diffusion control, to homogenise and reduce impurity concentrations at the crystal face, and to avoid sedimentation of crystals as well as the secondary nucleation of 3D protein clusters. To identify the environments able to reduce convective fluid motion, it is convenient to use the dimensionless Grashof number (Gr_N), which accounts for the relative importance of buoyancy and viscous forces in a fluid system.

$$Gr_N = L^3.\alpha.\Delta c.g.\nu^{-2}$$

where L is the thickness of the reactor (cm), Δc is the concentration difference, ALPHA is the solutal expansivity in cm^3/mg (the ratio of change in density to change in concentration), and ν is the kinematic viscosity (cm^2/s^{-1}). Note that to reduce Gr, either the value of g can be reduced, or the characteristic length of the reactor reduced, or the viscosity of the fluid increased. It is also possible to tune the density gradient, but the effect is not dramatic and moreover this is difficult to implement in crystallisation techniques. Figure 2.3.1.4 shows the variation in Gr_N as a function of L, for three values of g, using data relevant to protein crystallisation.

Reducing the dimensions of the reactor by using capillaries is very effective, because L appears to the third power in the Grashof number. Batch crystallisation inside capillary volumes has been used to illustrate diffusive transport in protein crystallisation. As pointed out above, the non-equilibrium counter-diffusion technique was implemented using X-ray capillaries as a protein chamber. Using an innovative implementation that basically consists of punching the capillary into a gel of agarose or silica, the counter-diffusion technique can be used on the ground. However, it is now known that X-ray capillaries are not able to completely remove buoyancy-driven convection when used under terrestrial conditions. A negligible contribution from buoyancy-driven forces can be expected only for diameters of less than 1 µm, i.e. much smaller than the minimum size of crystals useful for X-ray diffraction experiments. As can be seen from Figure 2.3.1.4, a combination of X-ray capillaries and microgravity (even milligravity) seems very promising.

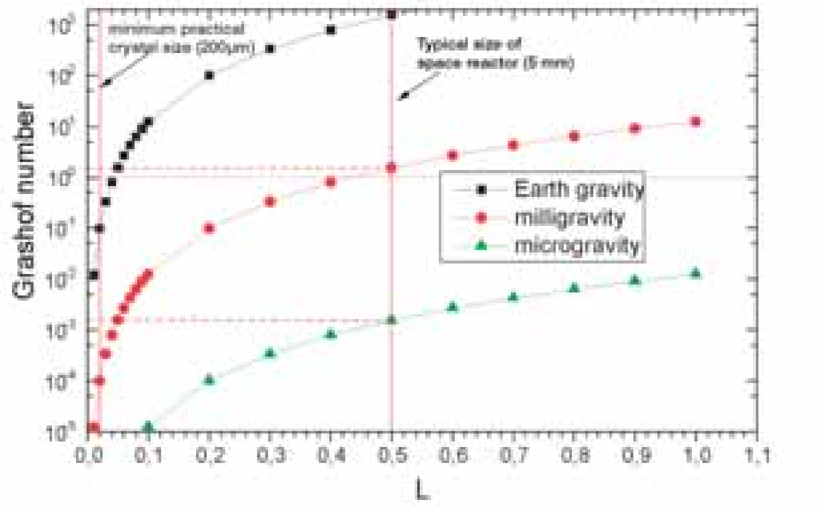

Figure 2.3.1.4. Variation in dimensionless (mass) Grashof number with the characteristic length of the reactor, for three different values of gravity. The minimum practical crystal size for X-ray studies refers to most conventional X-ray sources

Another way to reduce L is to gel the macromolecular solution. The pore size of the gel (which now defines the characteristic length of the system L) is usually a function of the polymer concentration used for gelling purposes. A typical pore-size distribution is on the scale of nanometres, thus making gels an excellent crystallisation scenario able to remove buoyancy and sedimentation. The gelling of the 'mother solution' is a technique that has been used in crystallisation experiments for many years. Obviously, it involves the addition of a foreign chemical (agarose, silica, acrylamide, etc.) to the mother solution, to provoke the polymerisation reaction. These chemicals are known to either retard or enhance the nucleation of some globular proteins. This creates some difficulties in the use of gelled solutions when fundamental aspects of the crystallisation process are being investigated.

It is known that, unlike most inorganic crystals, protein crystals incorporate the polymer fibres when they grow in gels, although the crystallisation pressure exerted is higher than the gel strength. There are not yet enough data available to assess the full effect of gel incorporation on crystal quality. However, in the few cases where mosaicity and resolution limit were measured, an unexpectedly high quality of the diffraction data set and rocking curves was observed. Finally, increasing the viscosity of the system can also reduce Gr_N. This can be done with the same polymerisation compounds used for gelling purposes. For instance, agarose at a concentration lower than the critical concentration to form a gel produces a non-Newtonian viscous fluid able to avoid sedimentation and buoyancy, thus reducing the risk of chemical interaction with macromolecules.

2.3.1.6 Conclusions

It seems advisable to maintain the current ESA strategy for understanding macromolecular crystallisation, combining terrestrial research with monitored space experiments. In the past, this was possible due to the design of the APCF, considered one of the outstanding space-crystallisation facilities with almost zero risk of malfunction. During the past five years, this strategy has yielded the valuable fundamental knowledge reviewed above. In addition, it has provided the basis for the design of a new diagnostic machine, the Protein Crystallisation Diagnostic Facility (PCDF), which is the best machine available today for simultaneous characterisation by different techniques of protein nucleation and growth, either for space or for ground experimentation. The PCDF, which can be considered a spin-off of the ESA Microgravity Research Programme, includes several characterisation techniques. These include phase-shifting Mach-Zehnder interferometry, dynamic light scattering, low- and high-resolution microscopy, and thermal control, and it allows different crystallisation techniques to be used. It will permit the study of some critical but not yet fully understood crystallisation problems, such as the nature of crystallising solutions and the nucleation process.

Concerning applications, the main target for macromolecular crystallisation is the growth of crystals of superior quality for X-ray structural determination. Most molecular biologists like to use the trial-and-error methodology to meet that target. In space experimentation, such a methodology is not compatible with monitored experiments. It is therefore advisable to design inexpensive devices optimising the number of experiments by volume and weight. The Granada Crystallisation Box (GCB) is one example. This very inexpensive passive crystallisation box combines gels and X-ray capillaries and allows more than 600 counter-diffusion experiments to be conducted within one cubic decimetre. These applied experiments should be performed with macromolecules already crystallised on the ground, but it is difficult to do so at high resolution (less than 2 Å). In any case, the selection process for reactors and crystallisation techniques for blind experiments must take into account the features of the space scenario discussed above.

The prospects for future commercial applications of macromolecular crystallisation in space certainly depend upon having the skill to develop imaginative tools for obtaining high-quality crystals. In addition, however, they also depend on external factors such as the availability of universal gels or high-viscosity fluids that do not interfere with the crystal quality, and on improvements in synchrotron X-ray sources.

Finally, it can be expected that the crystallisation of biological macromolecules will, in the future, face the challenge of growing the larger crystals for purposes such as neutron diffraction measurements. In fact, the interest in large macromolecular crystals will lie also in characterisation studies of their physical properties, because their technological application is still an unexplored and exciting field. Microgravity offers an appropriate environment to grow these large macromolecular single crystals. It can avoid the limitations inherent in the use of capillary volumes. First, however, it is necessary to control impurity distribution and its effects on the cessation of growth.

Acknowledgements

We acknowledge the useful suggestions of our colleagues in the ESA Topical Team on ‘Fundamental Aspects of Macromolecular Crystallisation under Microgravity’.

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2.3.2 Crystal Growth of Inorganic Materials

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2.3.2.1 Introduction

Single crystals consist of three-dimensional, regular arrangements of atoms, ions, or molecules. Their industrial use has grown rapidly in recent decades and continues to increase. Single crystals of silicon, for example, are the very basis of the ‘electronic age’. Modern computers would not be possible without the ready availability of integrated circuits made on wafers of single-crystal silicon.

Semiconductors such as silicon cannot be found as minerals in nature. They first have to be produced as an extremely pure chemical, and then grown as a single crystal, under conditions that ensure a very high level of chemical purity, homogeneity and crystalline perfection. Single crystals may be grown either from the melt, from a solution, or from a vapour phase via a solidification process. In the so-called ‘Czochralski process’, which is widely used in the semiconductor industry, a small single crystal (seed) is first dipped into the molten material. It is then very slowly withdrawn. In so doing, the original small seed crystal begins to grow, increasing in both diameter and length simultaneously. Some 10 000 tons of silicon single crystals are produced each year by such methods.

Unfortunately, crystals do not grow readily in the ideal geometrical arrangement of their atoms. A crystal will normally contain growth defects such as vacancies or interstitials, where atoms have wrongly been omitted or added. There will be dislocations in the regular layers of atoms, extraneous grain boundaries, or inclusions of impurities. For technical applications such as computer chips with an increasing device density, the quality of these semiconductor crystals, expressed in terms of low defect density and crystallographic perfection, must be continuously improved.

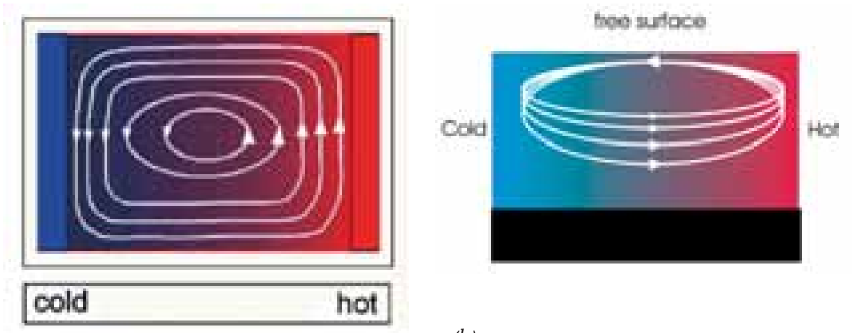
The scientific objective of research into crystal growth for such applications is to explain the connection between the resulting crystal quality, its physical properties and the parameters of the growth process. Gravity is found to play a very important role in all of the various growth processes, as already discussed in Section 2.3.1.

In general, heat and mass transport in the melt, in the solution or in the vapour phase, are all influenced by convective flows. These are normally created as a result of buoyancy effects. In the gravitational field, hot and less dense melt rises and the colder, denser melt sinks down (Fig. 2.3.2.1a). In turn, heat and mass transport influence the growth process and govern the crystallographic perfection of the grown crystal, as well as the concentration and distribution of defects and of doping elements. Crystal growth under reduced gravity in space reduces buoyancy convection drastically. Heat and mass transport may then be dominated by diffusion and it has been demonstrated theoretically that this happens when the magnitude of the buoyancy convective flow is reduced below the microscopic growth velocity.

However, in the presence of fluctuations in the residual gravity field, which always exist on space-transportation vehicles, this condition cannot be guaranteed and it requires specific attention. More generally, the application of external forces on the melt, such as static or transient magnetic or electric fields, provides the opportunity to study the growth under a number of flow configurations that are difficult to achieve on the Earth, because of the masking effect of the buoyancy convection.

There is another type of convection that is independent of gravity, which can occur in liquids (melts) that present a free surface to a gas or another liquid. The surface tension at the free surface decreases with increasing temperature. Hence if there is any temperature gradient parallel to the surface, a stress gradient may develop from hot to cold, resulting in a gravity-independent convection. This is the Marangoni convection, discussed in Section 2.3.4, and illustrated in Figure 2.3.2.1b. The influence of this additional convection process on the crystal growth can be studied only under microgravity conditions. Otherwise, its effects are masked by normal convection.

Gravity also causes hydrostatic pressure in melts and this in turn influences the shape of a liquid surface. Under microgravity conditions, the liquid shape is only determined by the surface tension. The shape of floating liquid zones is therefore likely to be modified in the absence of gravity. Also, the wetting behaviour of the melt on solid surfaces, such as seeds, crucibles or technical parts is modified by the absence of gravity, and liquid meniscii are formed that markedly influence the crystal-growth process.



(a) (b)

Figure 2.3.2.1. (a) Buoyancy convection. (b) Marangoni convection

Consequently, the motivation for carrying out crystal-growth experiments in space and the related scientific topics to be explored can be summarised as:

- Study of crystal growth under purely diffusive conditions.
- Study of the effect of buoyancy convective flows on crystal growth and quality, mainly chemical heterogeneity, by comparing space- and ground-based experiments.
- Investigations of the influence of residual microgravity on homogeneity at the macro- and micro-scale.
- Study of the solute segregations caused by stationary and time-dependent Marangoni flows.
- Effect of such flows on solid/liquid interface shape and velocity.
- Reduction of defect concentration and heterogeneity.
- Study of the effect of gravity on the size and shape of floating zones.
- Establishment of wall-free configurations for the growth, and study of the effect on crystal quality.
- Investigations into the control of transport conditions in melts and solutions by the application of external fields, such as rotating or stationary magnetic fields.

An overview is presented below of the crystal-growth experiments performed in microgravity over the past 25 years.

- *Selection of Materials*

So far, about one hundred experiments focusing on inorganic crystal growth have been performed in space. Scientists from the former Soviet Union have grown a large amount of crystals onboard the Salyut and Mir space stations. Unfortunately, data on these experiments and their results are very scarce and only those that are well documented are included in this discussion. Ninety percent of those experiments were dedicated to semiconductor materials for the following reasons:

- Their potential application in industry has prompted worldwide experimental and theoretical studies of their physical and chemical properties and of their growth process, so that they are particularly well-known materials.
- Potentially, growth under microgravity conditions can give perfectly homogeneous crystals, which are of considerable interest for applications.
- Many characterisation techniques have been developed in the past and are available to study the crystals on a broad, reliable and sensitive basis.
- The expensive Space Shuttle programme needed an economic justification and that included research on applications-oriented materials.

The selection of materials has therefore focused on semiconductors. It has included silicon and germanium (Si and Ge), the III-V compounds, gallium arsenide (GaAs), gallium antimonide (GaSb), and indium phosphide (InP), and also cadmium telluride (CdTe), and mercury cadmium telluride. Crystal growth of these materials belongs to a core technology underpinning the whole electronics and opto-electronics industry. Single crystals of silicon are the basis of more than 90% of the electronics market. The III-V compound semiconductors are basic materials for opto-electronic devices and integrated circuits with ultra-short switching times (e.g. GaAs).

Unfortunately, some people have attempted to justify space experiments on these materials in terms of a potential for commercial crystal growth in space, despite the fact that specialists have argued for over 15 years that this idea is totally unrealistic on both technical and economic grounds. Nonetheless, some still persist with such arguments.

2.3.2.2 Crystal-growth Experiments over the Past 25 Years

- *Studies of Chemical Segregation in Bridgman Crystal Growth*

A principal objective of the past space experiments has been to study the origin of chemical heterogeneities, at the macroscopic (axial and radial segregation) and microscopic (striation) level, in connection with fluid dynamics in the melt. Growth experiments in space with confined melts will have no Marangoni convection and no, or highly reduced, laminar buoyancy convection (depending on the size of the residual gravity vector during the experiments in space). They should therefore exhibit a purely diffusive nutrient transport process and thus produce homogeneous crystals.

The first space experiments tested this concept of diffusion-limited solidification and the avoidance of dopant striations. It was shown that, in contrast to Earth-processed samples, there were no striations visible in doped indium antimonide. That was true also for doped germanium crystals. The overall distribution of doping elements was also found to fit perfectly with what was theoretically expected for the case of pure diffusion transport in the melt. These results have been confirmed during a number of subsequent space experiments.

Simultaneously, the physical understanding of the coupling between solidification and fluid flow has been improved, and it became possible to take into account the effect of the residual gravity in spacecraft on the chemical perfection of the grown crystals. Figure 2.3.2.2 shows two zones, separated by theoretical lines, representing, respectively, growth perturbed by fluid flow and unperturbed growth. All of the results of space experiments focusing on this subject are in agreement with this theoretical prediction (see Garandet & Dufar (1999) for a review on this research topic).

- *Results of Floating-Zone Experiments in Mirror Furnaces*

Another point of interest was related to the effect of free-surface (Marangoni) convection on crystal growth and the effect of the absence of gravity on the shape of

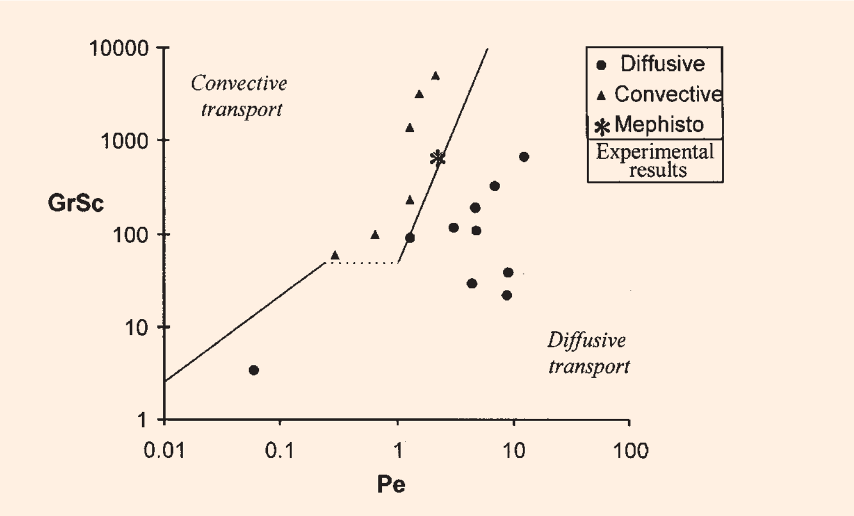


Figure 2.3.2.2. This GrSc/Pe diagram can be interpreted as a convection/growth rate diagram. The two straight lines are the theoretical prediction for the transition between diffusion-dominated transport in the melt (lower right side, unperturbed crystal growth) and convection-dominated transport (upper left side, chemical homogeneity perturbed by fluid flow). The points correspond to all the experiments performed in space for which diffusive (dots) or convective (triangles) transport has been experimentally and unambiguously identified. The MEPHISTO point (see Chapter 4.1.3) corresponds to the experimental transition obtained by varying the growth rate at constant convective level

these surfaces. The restricted space and power availability on board spacecraft led to the development of well-defined growth facilities such as the mono-ellipsoidal and double-ellipsoidal mirror furnaces for the floating-zone growth technique.

Crystal growth by the floating-zone technique involves a single crystalline rod that is partially melted. The zone to be melted remains fixed between the upper and lower crystalline parts and is positioned at the lower focus of the mirror furnace (Fig. 2.3.2.3). It is melted by a halogen lamp located at the upper focus. By moving the furnace with respect to the sample, crystallisation at the advancing melt/seed interface is achieved. Simultaneously, feed material is dissolved at the feed/melt interface. The weight and diameter of the liquid zone are limited on Earth (diam. less than 10 mm), due to the weight of the molten zone itself which cannot be sustained by surface forces for the larger diameters. In similar space experiments, there is no such limitation and crystals with a dramatically increased diameters can be grown. Figure 2.3.2.4 shows free silicon melt zones on Earth and in space (Texus-29 sounding-rocket experiment). The zone on Earth is bottle-shaped, due to its weight.

In practice, only silicon is grown on Earth by the floating-zone process, thanks to its low density. It has been used to study the details of Marangoni-flow during growth.

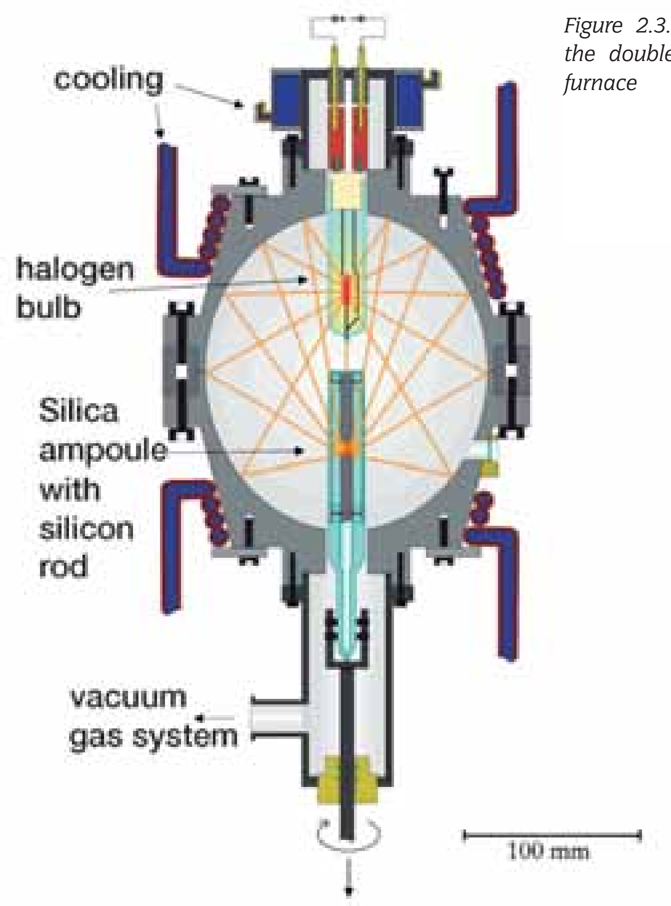


Figure 2.3.2.3. Principle of the double-ellipsoid mirror furnace

The striation formation in the grown crystal was used as evidence of such flow and allowed the tracking of fluid dynamics within the molten silicon.

The most important results of the floating-zone experiments under reduced gravity, in comparison with 1g reference experiments, are the following:

- Dopant striations in floating-zone silicon are caused by time–dependent Marangoni convection. If the free surface of the molten silicon is covered, e.g. with a silicon-oxide layer, the Marangoni convection is suppressed and with it the striations. This important effect of Marangoni convection was impossible to demonstrate on Earth because of the masking effect of the buoyancy convection, and it was taken as highly hypothetical until the publication of these space results.

- The transition regime from laminar flow to time-dependent surface convection could be evaluated by microgravity and 1g reference experiments. For example, during the Texus-10 campaign, a striation-free crystal was obtained by working with

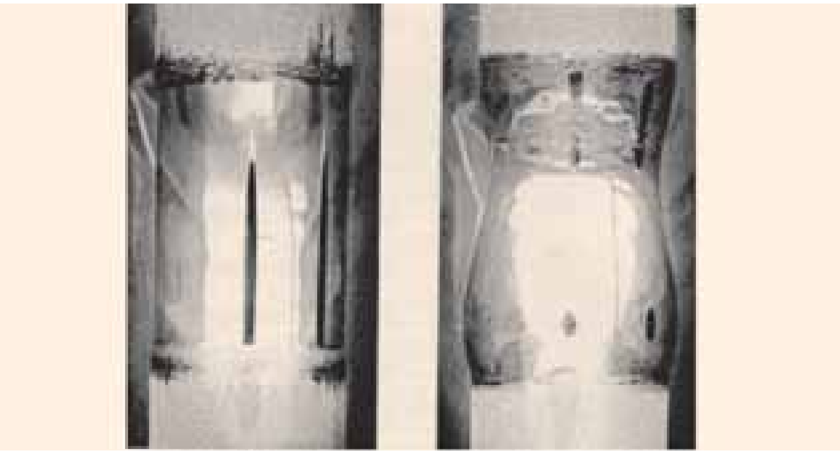


Figure 2.3.2.4. A floating-zone experiment with silicon: microgravity and 1g reference experiment (Texus-29)

a small sample of gallium-doped germanium in a low temperature gradient (without coating the melt surface).

– The additional laminar convection on Earth affects both the axial and the radial macro-segregation in doped silicon crystals, which could be demonstrated by resistivity measurements.

Figure 2.3.2.5. Gallium-antimonide (GaSb) crystals grown during the Spacehab-4 (STS-77) mission in May/June 1996

Other growth experiments using the floating-zone technique in space were dedicated to compound semiconductors such as gallium arsenide and gallium antimonide. The objective in this case was to produce commercially important materials in sizes not attainable on Earth with the same technique. GaAs crystals of 20 mm diameter were grown during the Spacelab-D2 mission (the maximum diameter achieved with this method on Earth is 6 mm). The crystals contained dopant striations, as expected, due to the presence of Marangoni convection in the uncoated GaAs melt. Floating-zone growth of gallium-antimonide crystals was performed during the Spacehab-4 mission. Figure 2.3.2.5 shows the samples prepared for the space experiments, as well as two 16 mm-diameter space-grown crystals compared with the size of the Earth-grown crystal.

- Contact-free Crystal Growth in Crucibles by the Bridgman Method

Directional solidification is the growth technique used most in the industrial semiconductor business. Conventional semiconductors, like germanium or gallium arsenide, are grown from the melt by the Bridgman or Czochralski method. Some others, like cadmium telluride, are only grown by the Bridgman process. A common problem with the Bridgman method stems from the use of crucibles. The contact with the crucible produces distortions of the thermal field in the sample and hence stress patterns in the growing crystal. These stress patterns induce defects, such as dislocations or twin and grain boundaries. The crystallinity is also reduced due to spurious nucleation in the case of crucible contact.

In most of the Bridgman space experiments, it has been observed that the crystal was detached from the crucible and that the structure of the crystals grown was improved compared to the Earth-grown material. In many cases, large diameter differences were found. The first observations were made for indium gallium antimonide, InGaSb, on board Skylab in 1974.

The list of materials in the field of detached experiments ranged from metals like silver or aluminium to many kinds of semiconductors. In all of these experiments, the crystals were grown partially detached. The observed gaps between crystals and crucibles were not constant, either in the growth direction or in the radial direction. The growth conditions are unstable and not reproducible. In space there are a number of configurations that lead to detachment of the crystal from the crucible, including bubbles, geometrical free-surface generation, and shrinkage.

In contrast, ‘dewetting’ refers to the particular case in which a very thin and regular gap is established between the crystal and the crucible. Consequently, at the solid/melt interface the crystal is not touching or wetting the crucible wall. For example, a gap of 20 ± 2 μm was observed all along the 4 cm of a GaInSb sample grown during the LMS mission in a boron-nitride crucible. On Earth, the melt wets the crucible due to the hydrostatic pressure. In microgravity, the hydrostatic pressure vanishes and the melt shape and position depend only upon capillary forces.

This behaviour is dependent on the crucible material and the so-called ‘wetting angle’ of the semiconductor melt on it. The important parameters for dewetting are the crucible material and preparation, the vapour pressure in the closed crucible, and the wetting parameters of the crystal melt. In some cases, as shown on Figure 2.3.2.6, a simple geometric consideration between the wetting and growing angles leads to dewetting. In some other cases, it is necessary to take into account the gas pressure that is acting on the melt surfaces and some pollution of those surfaces. This is the reason why dewetting is not yet a fully understood and reproducible phenomenon.

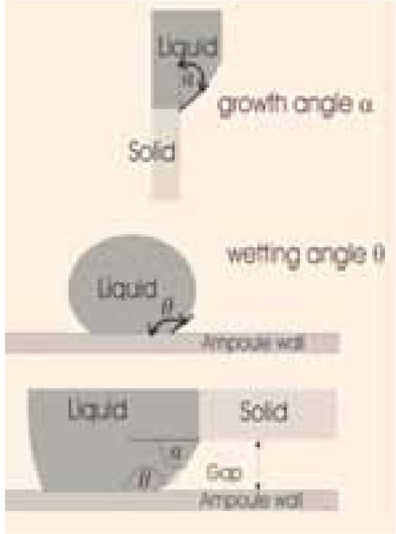


Figure 2.3.2.6. Parameters of the dewetting phenomenon are the growing angle, α, that always exists between a free melt and its solid phase and the wetting angle, θ, of the melt on the crucible

Dewetting is generally associated with a decrease in structural defect density in the crystals. For example, investigations of the quenching and back melting of pre-processed crystals have been studied for the HgTe–ZnTe system. The density of defects (e.g. subgrain boundaries) was found to be reduced after this space treatment. To improve their structural quality, CdTe and (Cd,Zn)Te crystals were grown under microgravity to study the mechanism and effect of dewetting growth. Encouraging results were obtained from the USML-1 and -2 missions. It was shown that the etch pitch (i.e. dislocation) density was reduced by a factor of 400 compared to the Earth-grown sample. This improvement was correlated with the dewetting-grown part of the crystal. A scientific review on this topic can be found in Regel & Wilcox (1998).

The discovery of the dewetting phenomenon in space and the understanding of its physical basis has led to the development of a ground-based process. In this, the dewetting is obtained by counterbalancing the hydrostatic pressure with an inert gas acting on the fluid. This has permitted a considerable enhancement of crystallinity in the case of GaSb. The process is under development for more useful crystals such as cadmium telluride, which could not previously be obtained on Earth as a single crystal because of the crystal-crucible sticking phenomenon.

- *Solution Growth: The Travelling-Heater Method and Rotating Magnetic Field*

Growth from a solution can be used to grow semiconductors as well as organic or inorganic materials. It offers the possibility of growing nearly perfect single crystals, due to a lower growth temperature compared with growth from the melt. Defect and heterogeneity formation is significantly reduced.

Using, as solvent, alkaline water at high pressure (hydrothermal growth) or molten salts or oxides (flux growth), this process is very important in the industrial production of oxide crystals such as piezo-electric quartz or magnetic garnets.

Several experiments have been performed in microgravity to grow single crystals from metallic solutions for various semiconductors, including germanium, gallium arsenide

and ternary compounds. During the Spacelab-D1 mission, GaSb and InP were grown by the Travelling-Heater Method (THM). This is a very powerful method for growing single crystals with the same level of perfection as the epitaxial layers grown by Liquid-Phase Epitaxy (LPE). Both techniques are very similar, but THM uses a temperature gradient perpendicular to the growing interface and the growth temperature is significantly higher than for LPE. This offers the advantage of a higher growth rate and it permits the growth of bulk single crystals when feed material is used.

The objective of the THM experiments that were carried out in microgravity was to grow bulk single crystals in order to study the origins of dopant or compositional heterogeneities (striations) and defects. Under normal gravity, two kinds of striations are present: Type-I striations are induced by time-dependent buoyancy flows in the solution, while Type-II, or kinetic, striations are closely related to morphological instabilities in the growth face and are therefore gravity-independent. Without disturbances from the time-dependent flows, which are absent in microgravity, it has been possible to measure and calculate the critical growth velocity that is responsible for the formation of Type-II striations. Below this growth velocity, they disappeared. A technique was established and patented that avoids the formation of Type-II striations. It can be used for the growth of semiconductors by THM or LPE, as well as for the growth of oxide crystals from solutions.

The use of external fields, e.g. magnetic fields, is of important interest for both scientific and industrial crystal-growth processes. It provides the possibility to control the flow in the solution and to improve material homogeneity in terms of structural defects and dopants. A constant magnetic field produces an induced Lorentz force, which acts as a damping force on the moving fluid. The mixing of the material and thus the homogeneity are both reduced. If, however, a rotating magnetic field is used, it induces a current and the resulting force generates a forced convection. The mixing is then increased and a homogenous distribution is obtained.

Experiments were carried out for different materials, under transport regimes driven by diffusion (under microgravity), 1g convection or forced convection. THM experiments for CdTe, Cd(Se,Te) and (Cd,Zn)Te were performed on three Russian missions (Foton-7 to -9) in the Zona-4 facility. In all three configurations, a rotating magnetic field was applied to the tellurium solution zone. The results demonstrated the improved homogeneity that it provided.

Figure 2.3.2.7 shows a CdTe crystal. It is an infrared image of a 2 mm axial crystal slice divided into five parts: (a) seed crystal (b) grown crystal within magnetic field (c) grown crystal without magnetic field, (d) Te zone and (e) feed material. Between (b) and (c), the number of Te inclusions (black spots) is significantly increased. This is correlated with the effect of the rotating magnetic field and the improved mixing in the (b) part. The positive effect for the homogeneity of transport properties could also be determined.

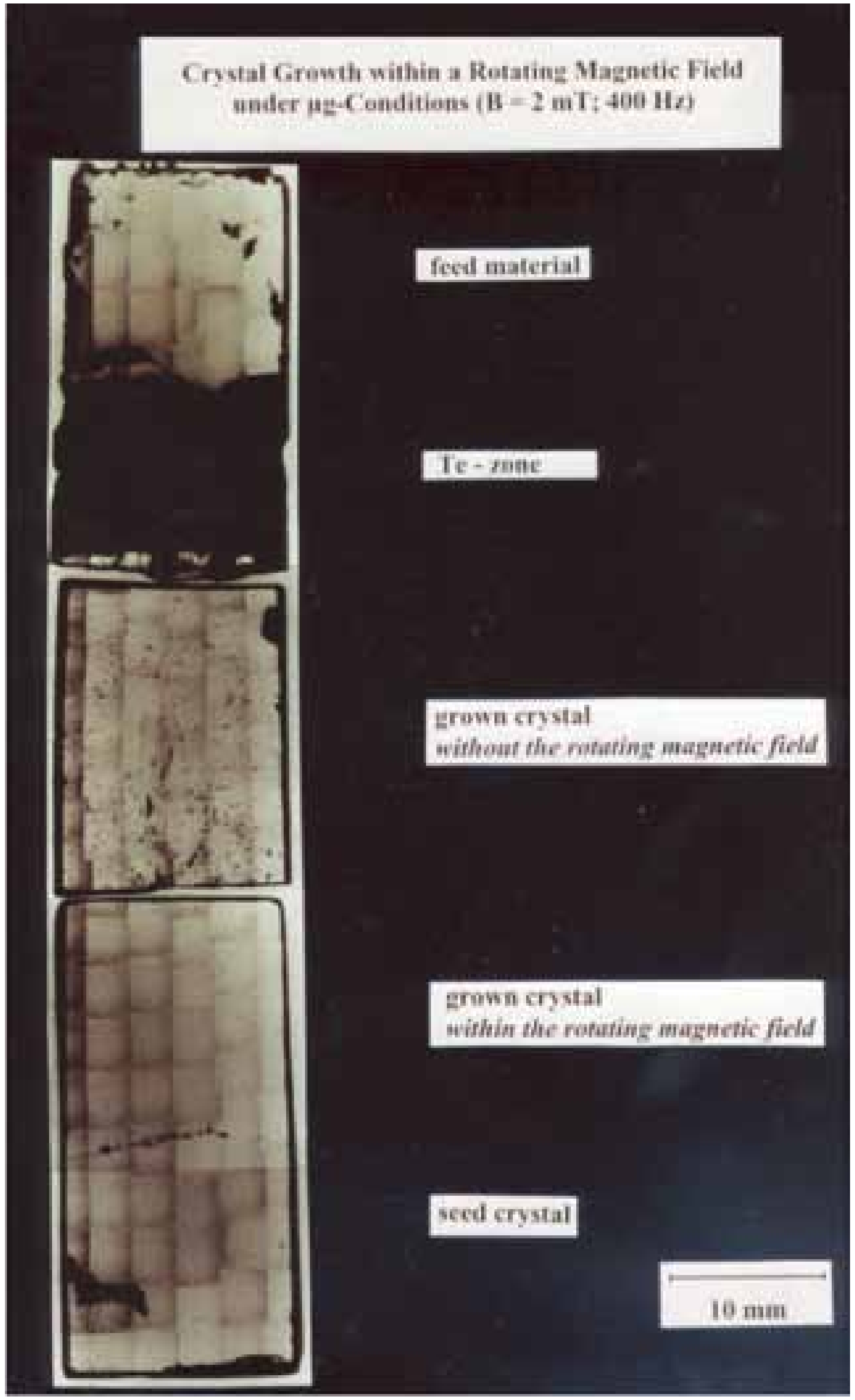


Figure 2.3.2.7. An infrared image of a 2 mm axial slice of cadmium-telluride crystal

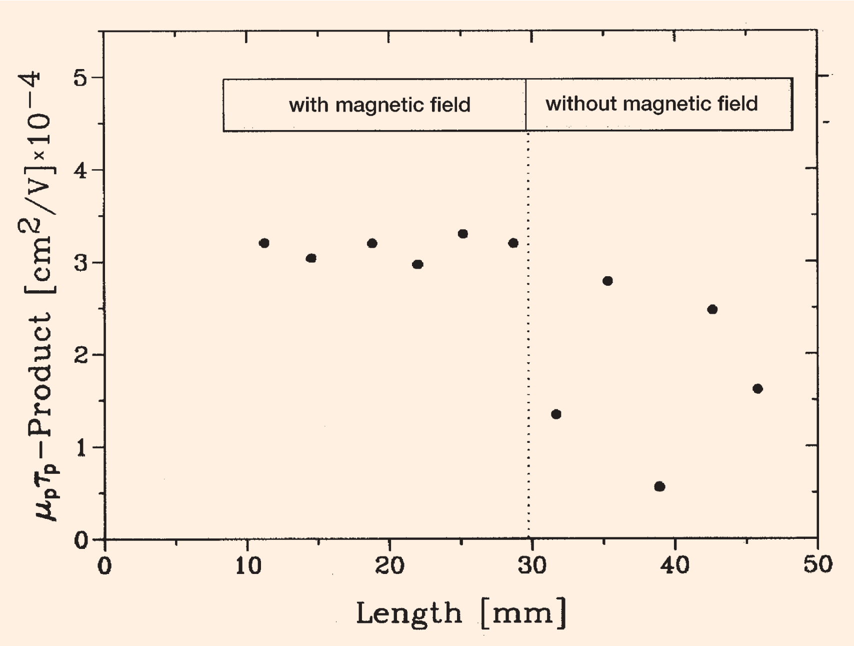


Figure 2.3.2.8. The mobility-lifetime product as a function of crystal length (with and without an applied rotating magnetic field) for a cadmium-telluride crystal, grown by the Travelling-Heater Method in a rotating magnetic field on the Foton-7 mission

In Figure 2.3.2.8, the product of lifetime and mobility is presented as a function of crystal position. In the part grown within the magnetic field, the values are nearly constant.

- *Growth from the Vapour Phase*

From the point of view of lowest growth temperature and best equilibrium conditions, growth from the vapour phase is the most attractive of all of the methods. For industrial processing, the limitations are set by the low growth rate and the small diameter of the crystals. Gaseous impurities affect the mass flow disadvantageously – especially in closed systems. Furthermore, the crystal's compositional perfection is disturbed by gravity-induced convection instabilities in the vapour. Growth experiments have to be performed under well-defined conditions in order to optimise growth rates and crystal quality.

Mercuric iodide (HgI_2) was the typical model substance for growth experiments from the vapour phase under microgravity, using the Physical Vapour Transport method. This essentially involves evaporation from the hot side of a cell and deposition at the

cold side. Important results included the following findings:
- Growth rates depended upon growth direction and surface-kinetics effects.
- Gravity affected the mass-density-gradient layer that is present all around the growing crystal, much more than the overall vapour flow.
- Surface roughness and rocking curves showed better crystalline quality of all space-grown samples.

In the other vapour-growth method, known as 'Chemical Vapour Transport', a chemical reactant is used to transport the material from a feed zone, at high temperature, to the growth zone, at a rather lower temperature. The quality and size of the crystals obtained by this technique in space were generally better than for Earth-grown crystals, and measured growth rates were within the error limits of theoretical predictions for diffusive mass transfer. For example, iodine was also used for the transport of Ge and diffusive mass transfer was clearly in evidence, allowing computation of the kinetic factors of the heterogeneous reaction governing the vapour-phase transport.

2.3.2.3 Conclusion and Future Activities

The main reason for performing crystal-growth experiments in space is to understand the role of the basic transport mechanisms in determining the final properties of the crystals grown. This in turn may help to improve the crystal quality of technically interesting and valuable materials back on Earth. Detailed studies are planned of the coupling between the many parameters controlling the growth process. This fine control of process-related parameters, including (micro)gravity, has the potential to bring major economic benefits. For example, the semiconductor laser was invented in 1962. An economic industrial breakthrough was only finally reached some 20 years later, after improvements to the crystal-growth process for laser-device fabrication.

An improved understanding of crystal-growth processes, gained from previous experiments performed in microgravity, has permitted the development of new technologies on the ground. This includes the use of magnetic fields or baffles, in order to decrease the convective flow level in Bridgman, Czochralski and floating-zone techniques. The use of molten encapsulants or of gas pressure differences, in order to counterbalance the hydrostatic pressure and so avoid crystal/crucible contact, has allowed the achievement of dewetting conditions also on Earth, and consequently has provided improved crystals. Better knowledge of the effects of Marangoni convection has permitted improvements in the silicon-crystal production process.

From the first encouraging results, it was thought that a truly industrial crystal-growth production process in space would be very valuable. However, further results have shown that, due to size, energy, time and above all unavoidable residual gravity fluctuations, this cannot be expected in the near-term.

In the future, space crystal-growth experiment activities will inevitably be concentrated on the International Space Station (ISS). As the residual gravity level in the ISS will be rather high, there will be an additional need for some experiments on Shuttle missions or satellites and sounding rockets. But the possibility of more and longer-term growth experiments, newly defined conditions and reproducible results will only be realisable on the International Space Station. The key topics in the field of crystal growth are likely to be:
- Wall-free growth of semiconductors from the melt: dewetting growth of CdTe and related compounds of Si and Ge.
- Growth from the vapour phase: identification of growth limits (growth rate and size of crystals), and the scaling-up of scientific configurations for industrial needs.
- Further studies on chemical segregation in crystal growth, in the field of radial segregation and striations, and in the case of highly concentrated alloys.

Taking advantage of the previous results, the new generation of space facilities are designed with in-situ diagnostic capabilities to measure real-time experimental data and to process materials at higher temperatures. This will provide us with even deeper knowledge of the gravity-related physical phenomena that affect crystal-growth processes.

Further Reading

Garandet J.P. & Duffar T. (in press), Physics of Fluids in Microgravity (Ed. R. Monti), Chapter 13, Gordon and Breach (Review article with 201 References).

Regel L.L. & Wilcox W.R. 1998, Microgravity Science and Technology, Vol. XI/4, p. 152 (Review article with 157 References).

Walter H.U. (Ed.) 1987, Fluid Sciences and Materials Science in Space, Springer Verlag (Chapters X, XI, XII and XIII deal, respectively, with crystal growth from the melt, from the vapour phase, and from solutions of biological materials).

2.3.3. Microstructure and Control in Advanced Casting Processes

B. Billia & H.-J. Fecht

2.3.3.1 Introduction

Cast materials are common objects in everyday life, primarily because of their good mechanical properties, resulting from their ability to sustain and/or transmit forces with negligible damage. The production and fabrication of such materials by the casting and foundry industry generates a considerable amount of wealth within Europe. Some 10 million tons of castings were produced within the European Union in 1993, worth around 18 billion Euros. The continuation of this business in Europe relies upon maintaining and improving the industry's competitiveness with the United States, Japan and others, in the design and processing of structural materials. Competition is severe and therefore there has to be a continuing effort in Europe to produce materials of higher performance, to optimise their characteristics for specific applications, and to improve processing controls.

Casting is a non-equilibrium process in which a molten alloy is solidified. The liquid–solid transition is driven by the departure from thermodynamic equilibrium, in the same way that cooling pure water below 0°C results in the formation of ice. From the standpoint of physics, casting thus belongs to the vast realm of out-of-equilibrium processes in which unwanted patterns may form. Rather than growing evenly in space and smoothly in time, the solid phase prefers to form a diversity of microstructures. Figure 2.3.3.1 shows this effect in a foundry casting of a several-ton ingot with, on the left, the distribution of the two basic microstructures: (i) columnar dendrites, grown in an array from the mould wall inwards (see also Fig. 2.3.3.6), and (ii) equiaxed grains, packed together in the centre. Depending on their local proximity to thermodynamic equilibrium, these change from globular at the bottom to dendritic (tree-like, with branches in cascade) at the top.

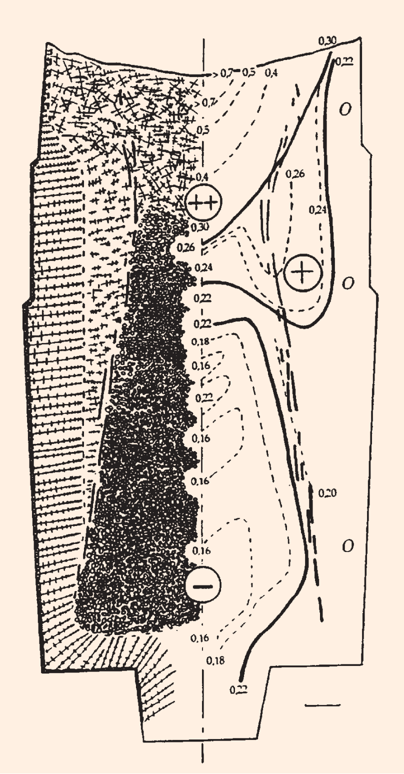


Figure 2.3.3.1. Schematic of a longitudinal cut in a heavy steel ingot. The distribution of the different microstructures is shown on the left, and that of the carbon concentration on the right (negative carbon segregation, due to sedimentation of equiaxed crystals, can be seen at the bottom, and positive segregation on top) (from T. Mazet, PhD Thesis, Institut National Polytechnique de Lorraine, 1995)

The mechanical properties of these materials such as strength, creep and wear resistance and ductility, as well as their chemical, magnetic and electronic characteristics, are determined by the structure, chemical composition and number and kind of defects produced, at all length scales, during the material synthesis process. Besides the atomic scale, inherent to condensed matter, and the intermediate scales associated with the solidification microstructures, fluid flow driven by gravity generally occurs in the melt at the macroscopic scale of the cast product. Consequently, the relevant length scales in casting are spread over 10 orders of magnitude. They range from the atomic size (capillary length, crystalline defects such as dislocations, attachment of atoms, etc.) to the metre size of the ingot (fluid flow), going through the micron (spacing of dendrite side branches) and the millimetre levels (columnar microstructure, solute diffusion). It follows, therefore, that for high-precision castings, the control of material structure during the liquid-to-solid phase transition is absolutely crucial in terms of quality control and for the design of advanced materials for specific technological applications.

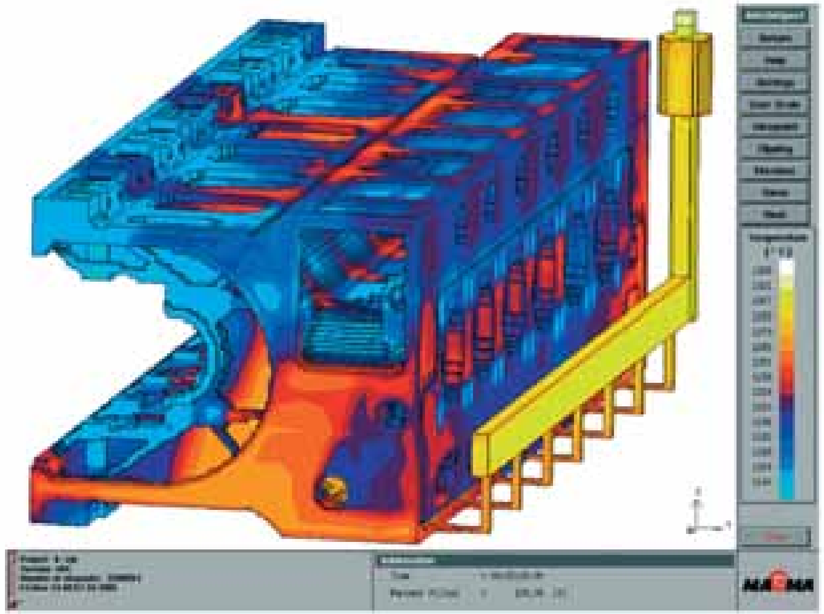


Figure 2.3.3.2. Filling simulation and temperature distribution for a car engine-block produced using Magmasoft® software

For this reason, the quantitative numerical simulation of casting and solidification processes is increasingly demanded by manufacturers. Compared to the well-established but time-consuming and costly trial-and-error procedure, the simulation process provides a rapid and cheap tool for optimising the microstructure of high-quality castings. In particular, where process reliability and high geometric-shape accuracy of the cast structural component are important, simulation can be very advantageous. Figure 2.3.3.2, for example, shows the filling simulation for a complex engine block and the associated temperature distribution. Any improvement in the numerical simulation results in improved control of the fluid flow and cooling conditions. That enables further optimisation of the defect and grain structure, as well as the stress distribution in critical regions of components. Moreover, through the control of unwanted crystallisation events, it becomes possible to produce completely new materials with a controlled amorphous (glassy) or nano-composite structure.

The demands on engineering materials are continuously increasing: higher mechanical strengths at higher temperatures (superalloys), weight reductions (light alloys, metallic foams), augmented lifetimes, better resistance to corrosion, reduced development times and costs, lower energy consumptions, environmental compatibility and materials recycling, etc. It follows that a continuing R&D effort is needed to improve materials in these ways, as well as advanced production technologies. That often implies breaking through technology barriers. In order for global numerical simulation to successfully contribute to that process, two aspects are crucial:

– *Reliable determination of the fundamental physical mechanisms and relationships that govern microstructure formation and selection*. Indeed, complete numerical simulation over all the length scales and complex shapes of real castings is presently, and probably still for some time, beyond the reach of the most powerful computers. These computer limitations can be overcome by using micro-macro approaches, in which the phenomenological microstructure relationships are incorporated into macroscopic numerical simulations to bridge the small length scales and get rid of the fine meshing effect, which can overwhelm the computation.

– *Reliable determination of the thermophysical and related properties*. These are required as input parameters in describing balances in the volume phases (heat, chemical species, momentum ...) and at the boundaries (solid/liquid, liquid/gas ...). Together, they form a set of coupled equations whose solution, for prescribed process parameters and initial conditions, should realistically reproduce the microstructure of an alloy cast under the same conditions. At present, further quality optimisation is limited by the lack of precision in the thermophysical data on industrial materials. This is because of the difficulties inherent in determining these data, due to the high temperatures that are involved and the chemically aggressive nature of the melts that are in contact with container materials.

It is in these contexts that experimentation in the microgravity environment has repeatedly proved of value. Indeed, beyond the inherent technological process difficulties that need to be overcome in a gravity environment, particularly when high temperatures are involved, there are at least two major limiting factors on Earth. The first is the contribution to transport in the melt by gravity-induced fluid flow, which carries away heat and chemical species and adds to the step-by-step diffusive transport by means of atomic or molecular displacements. This effect is responsible, for example, for the very large uncertainties in the measurement of diffusion coefficients, as well as for the drastic changes in the size and/or type of solidification microstructure and strong macro-segregation of components that may render cast materials unusable. The second effect is due directly to gravity, resulting in the problem of holding and positioning during containerless processing, and also leading to sedimentation effects and lack of homogeneity in mixtures and dispersions.

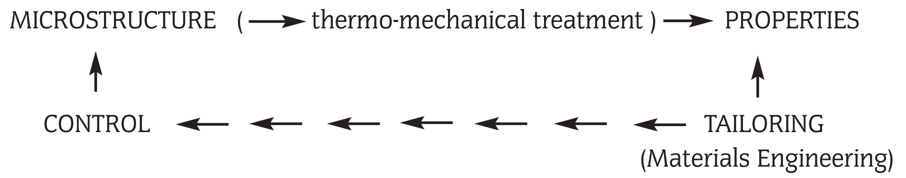
Microgravity has provided experimenters with a unique way to remedy these problems: firstly by the suppression of fluid flow driven by buoyancy in the liquid and gas phases, and secondly by allowing more effective holding and controlling of reactive melts without containers in the weightless conditions and the homogeneous dispersion of refining particles in the absence of sedimentation.

In both the formation of a solidification microstructure and in the measurement of melt properties, the time needed to reach the asymptotic state in an experiment is generally long (several hours to a day or more). Extended periods of microgravity are therefore required. That can be achieved onboard the Space Shuttle, on a Retrievable Carrier like Eureca, on Mir, or on the International Space Station (ISS). By these means it has been possible, for example, to obtain the unambiguous benchmark data that are needed to distinguish between the diverse alternative 3D models that are proposed for solidification and casting processes, in order to select the most accurate. Moreover, the reliable and precise thermophysical coefficients needed for materials engineering or model assessment have been measured in space experiments.

A few examples that demonstrate the soundness and value of using microgravity, together with some perspectives for potential developments over the next decade, are given below, successively addressing the two critical points introduced above.

2.3.3.2 Microstructure Formation in Solidification Processing

Materials-engineering research and development (R&D) is concerned with the control of the solidification microstructure. This will include its formation during processing and, potentially, its further evolution in thermo-mechanical treatment, as indicated in the following schematic:



The ultimate challenge is the tailoring of the dendritic grain structure and the segregation of chemical species, formed on the scale of the whole casting during the solidification process (Fig. 2.3.3.1), together with the fine microstructure and micro-segregation of the grains. In order to arrive at reliable microstructure relationships, pattern formation in solidification processing is being investigated under diffusive conditions, and with fluid flow in the melt, by means of comparative experiments.

The various areas of research in this field, in which critical questions have been addressed, are discussed below. Some striking experimental results obtained in recent years in space, and in preparatory ground-based work, are presented.

- *Crystal Nucleation and Growth Transients*

Transient stages, during which new phases may form and new patterns begin to develop, play a central role in processing from the melt, which includes casting, welding, single-crystal growth and directional solidification. Crystal nucleation and growth is usually the first step, achieved by cooling the liquid below its thermodynamic equilibrium (liquidus) temperature. Crystalline nuclei of nanometer dimensions are formed, which subsequently grow. Alternatively, if the formation of nuclei fails to occur, then a metallic glass is formed at the glass transition temperature.

Presently, our basic understanding of the fundamentals of the nucleation of crystals from the melt is generally limited to pure substances under well-controlled conditions. The main limitations for the description of the more generally used alloys stem from the lack of precise values for their thermophysical properties. Indeed, the basic thermophysical properties used in classical nucleation theory, such as viscosity, interfacial crystal/liquid tension and the driving force for crystallisation as a function of temperature, are generally not known with the precision required. The analysis of nucleation therefore currently relies mostly on circular arguments. This is even more important for complex multi-component alloys, which are used for engineering components, and for highly undercooled melts, where theory generally fails.

Consequently, it is essential to measure the relevant data, as a function of temperature, with the required precision. That data is also required for improving the control of crystal growth. Indeed, for most advanced materials, the relevant thermophysical properties needed for the simulation of heat flow and fluid flow during solidification processes are not known, due to inherent experimental limitations. For instance, the viscosity measurements reported for pure iron, the basis for any steel production, differ by about 50%, as shown in Figure 2.3.3.3.

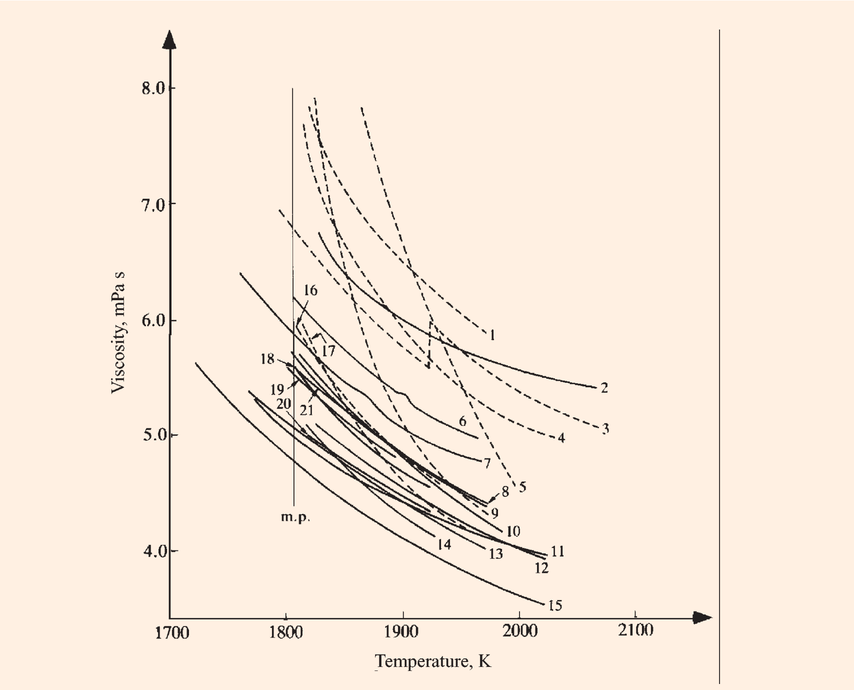


Figure 2.3.3.3. Measured viscosity data for iron as a function of temperature (from T. Tanaka et al., Z. Metallkunde, 87, 380, 1996)

Growth transients and microstructure formation and evolution are then the central issues, especially as many castings are the result of microstructure competition and selection (e.g. columnar versus equiaxed grains). Cast billets cool down slowly and thus are always in a time-dependent state. In industrial technologies, process control becomes particularly important for the growth of single crystals and complex shapes.

Even in the case of directional solidification, an established model technique that allows microstructure formation in alloys and composites to be examined under well-defined conditions, the mere application of the pulling velocity induces front recoil, due to the building of a solute boundary layer in the melt adjacent to the solid/liquid interface (Fig. 2.3.3.4a). It is precisely during this period that the planar front becomes morphologically unstable. For a massive specimen, the thermal exchange between the furnace and the sample varies significantly. Also, gravity-driven convection adds its own contribution to the transport, so that the front withdrawal (Fig. 2.3.3.4b) is quite different from what is observed in thin samples under diffusive transport and a frozen temperature field. It is therefore very complicated to analyse. The value of a real-time and precise investigation of transients under microgravity, which is a particularly promising area of research for the ISS era, has already been amply demonstrated (Fig. 2.3.3.4c) by means of the measurement of the Seebeck voltage. The Seebeck method is a non-destructive thermoelectric diagnostic technique, based upon the solid/liquid junction acting as a thermocouple. It was used during a series of runs at different pulling rates on a single Sn–Bi alloy that is repeatedly recycled. This is a critical advantage in space, where the opportunities for sample exchange are generally restricted, if only because of basic security rules.

- *Columnar Growth*

The columnar growth (cellular and dendritic) process has repeatedly been addressed since the earliest microgravity investigations, often with striking results, such as the millimetre-sized dendrites obtained in Al–Cu. Nonetheless, only a series of a few data points are available on various alloys, processed in diverse solidification facilities. The limited data is mostly due to timeline and/or energy constraints. Consequently, it has not been possible so far to carry out any comprehensive and systematic study, nor to check the reproducibility of the results.

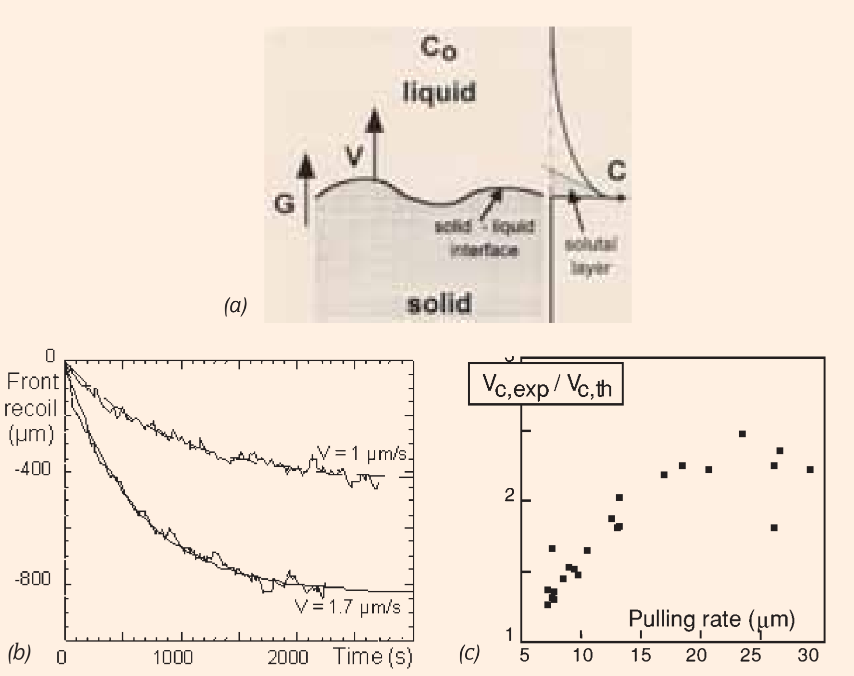


Figure 2.3.3.4. (a) Directional solidification: the pulling velocity V determines solute flow, the thermal gradient G drives heat flow and, in the presence of gravity, they both control buoyancy convection in the melt. (b) Front recoil in a succinonitrile-acetone bulk sample; the asymptotic solutal recoil under diffusive transport would be at −1680 µm (from H. Jamgotchian et al., in Proc. Symp "Utilisation of the International Space Station", ESA, Noordwijk, 1999, p. 329). (c) The increase in the ratio of the experimental ($V_{c,exp}$) and theoretical ($V_{c,th}$) values of the interface velocity at the breakdown of the planar solidification front indicates that the recoil delays morphological instability (from J.J. Favier et al., in Materials and Fluids under Low Gravity, Springer, Berlin, 1996, p. 77)

Figure 2.3.3.5. Columnar dendritic growth in a directionally solidified Co–Sm–Cu peritectic alloy. The view of the dendrite array is obtained by etching away the $Co_{17}Sm_2$ matrix from the primary Co dendrites (courtesy of R. Glardon & W. Kurz, EPFL)

It is anticipated that future research into columnar dendritic growth is likely to focus on the solid/liquid region extending from the dendrite tips to the fully formed solid, the so-called 'mushy zone'. This is where the dendrites form, in active interaction with neighbours, and with fluid flow in the porous 'mush' during ground processing. This topic is especially critical for super-alloy turbine blades that must be single crystals made of a fine and regular array of columnar dendrites. Single-crystal turbine blades, with enhanced thermal-fatigue strength and creep resistance are required, for example, by the aerospace and electrical power industries. However, the reproducibility of single-crystal growth of sufficiently large blades, particularly for stationary turbines, is rather limited and needs to be improved. Indeed, the mechanical performance of these commercial cast-to-shape products can rapidly deteriorate if dendrite misalignment, parasitic nucleation of new grains, or freckling induced by severe solute-driven convection, occur during casting.

In addition, the current development of facilities dedicated to studies in space of transparent media (e.g. ESA Fluid Science Laboratory and DECLIC project at CNES) will enable the real-time and in-situ three-dimensional observation of the growth of organic compounds by optical methods, with negligible convection. Some of these compounds solidify in the same manner as metals, and the data can therefore be of relevance for understanding the 3D behaviour of metallic melts. Numerous liquid–solid–liquid cycles can be performed on one sample, using a large range of control parameters. In the succinonitrile–acetone system, for example, convection is largely dominant at 1g, which creates a solute gradient at the solid/liquid interface. Hence, morphological instability propagates against fluid flow and a gradient in microstructure is ultimately observed, extending from a smooth interface to dendrites (upper-left corner) in Figure 2.3.3.6a. Recent experiments in the MOMO facility onboard the Space Shuttle have demonstrated that detrimental effects are actually suppressed in microgravity, where homogenous cellular patterns do form (Fig. 2.3.3.6b).

- Equiaxed Growth and Columnar-Equiaxed Transition (CET)

When, in production, a non-uniform material with dispersed properties must be avoided, such as in the investment casting of engine blocks for the automobile industry, a thin equiaxed grain structure that is homogeneous in all directions would appear to offer a convenient way of fulfilling the requirements. In practice, grain sedimentation is commonly observed on the ground (Fig. 2.3.3.7b). This undesirable effect is suppressed in a low-gravity environment, where samples with fully regular equiaxed microstructures are obtained (Fig. 2.3.3.7a).

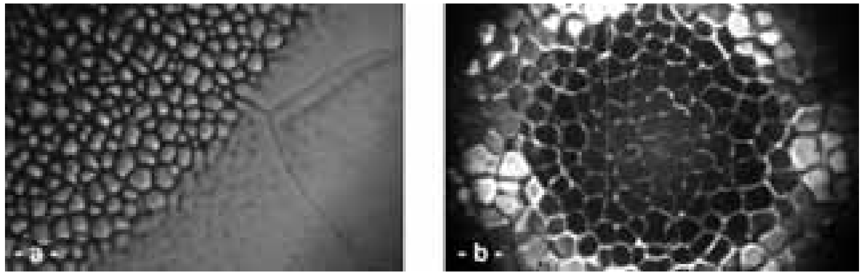


Figure 2.3.3.6. Direct observation of the morphology of the solid/liquid interface in the succinonitrile–acetone system. (a) 1g: gradient of microstructure due to convection in the liquid phase (from N. Noël et al., J. Crystal Growth, 187, 1998, 516). (b) microgravity: extended cellular pattern obtained under diffusive transport (from B. Kauerauf et al., J. Crystal Growth 193, 1998, 701)

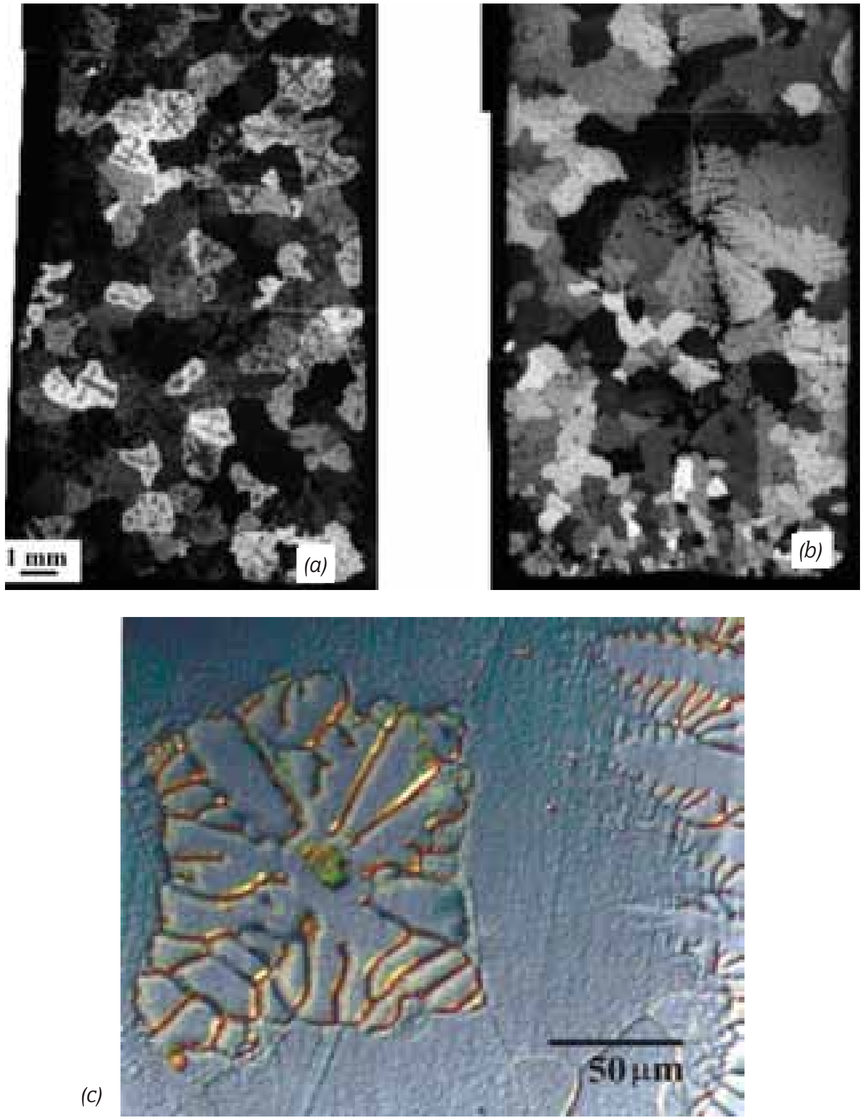


Figure 2.3.3.7. Equiaxed growth of refined Al–4wt% Cu alloys in microgravity, with regular equiaxed grains (a), at 1g, with a strong settling effect (b) (from M.D. Dupouy et al., in Proc. 'Modelling Welding and Advanced Solidification Processes', TMS, Warrendale, 1998, p.415). (c) Nucleation of an equiaxed grain on a TiN particle ahead of columnar dendrites in a GTA weld of ferritic stainless steel (courtesy of H.W. Kerr)

This example shows that better knowledge of equiaxed growth is imperative for the further understanding of the casting process. For many years, studies have therefore been carried out at different scale levels, ranging from the minute level of the free growth of a single dendrite, at the intermediate level of the envelope of a single grain embedded in its neighbourhood, through to the collective level of a set of interacting grains. Any fluid-flow interference makes such studies much more convoluted, so that the ISS will be the appropriate place to continue with these experiments, and to extend them to competitive grain growth.

It will also be valuable to thoroughly investigate and precisely determine the conditions for the transition from columnar dendritic growth to equiaxed crystal formation. This transition strongly depends on seeding of the melt with solid nuclei. That is achieved either by conveying detached solid fragments of columnar dendrites into the bulk of the liquid, or by crystal nucleation on inoculated refining particles, as shown in Figure 2.3.3.7c. For both methods, nucleus sedimentation is a limitation, against which electromagnetic/vibrational stirring is employed to promote homogeneous dispersion of nuclei. In space, it will be possible to assess the effectiveness of stirring processes by deliberately creating low to high fluid flow levels in a perfectly clean and controlled way. Such experiments may require the use of isolation mounts to reduce interference from g-jitter effects.

- *Multiphase Growth and Multicomponent Alloys*

The most common case of multiphase growth is certainly the solidification of binary alloys around the eutectic composition, where coupled growth of lamellae or rods of different solid phases is observed. These eutectics are the simplest natural composites. Some such systems may have interesting mechanical properties, for example by introducing fragile but high-strength rods into a ductile matrix. Monotectic patterns, in which rods of a second liquid phase form together with a solid matrix, are eutectics' cousins. The major difference is the presence of a number of fluid/fluid interfaces that are known to be prone to strong surface-tension-driven convection. This phenomenon is generally of secondary importance on Earth, where buoyancy effects most often dominate fluid flow. In space it becomes important and there it can be studied acting alone. Furthermore, monotectic systems with concentrations in the liquid miscibility gap, where droplets of the second liquid phase form in the melt, have potential application in car bearings where, once solidified, the droplets provide lubricating soft inclusions (e.g. Pb, Bi, in a hard matrix).

Peritectic systems are those in which a second solid phase forms by reaction between the melt and a first solid phase. They are of both practical and fundamental interest. The former follows from studies of the peritectic reaction, which are making a step forward towards real commercial multi-component alloys (e.g. steels) that form more than one solid phase, often in a sequence along the solidification path. The fundamental interest lies in the richness of nonlinear dynamic phenomena, whose investigation benefits advancement of our understanding of the basic physics of out-of-equilibrium systems.

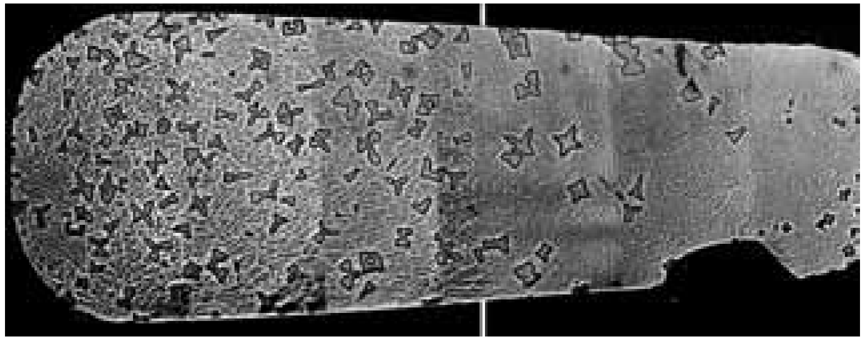


Figure 2.3.3.8. Cross-section of an Sn–13 at%Sb sample solidified in microgravity during the Texus-34 mission. The peritectic phase is directionally solidified from the left until the marker (white lines). The properitectic Sn_3Sb_2 phase is dispersed in the whole sample because there is no sedimentation in microgravity (from Th. Kammler, VDI-Fortschrittsberichte 487, VDI Verlag, Düsseldorf, 1997)

Trapped pores are another class of multiphase growth and a source of extremely detrimental defects. They are due either to residual gas(es), causing the nucleation and growth of bubbles, or to the shrinkage of the solid. The solidification of metal-matrix composites, engineering materials in which the solid is reinforced during growth by the incorporation of particles or fibres (e.g. alumina-zirconia fibres in an aluminium matrix), bears similarities in the sense that the engulfing of the reinforcement is again a critical issue. Particle trapping is still a subject of active microgravity research. It is a process that is influenced and even prevented by fluid flow. Peritectic reactions can also produce particles in-situ, such as the Sn_3Sb_2 ones (Fig. 2.3.3.8), whose formation in Sn–Sb alloy has been studied on Texus sounding rockets.

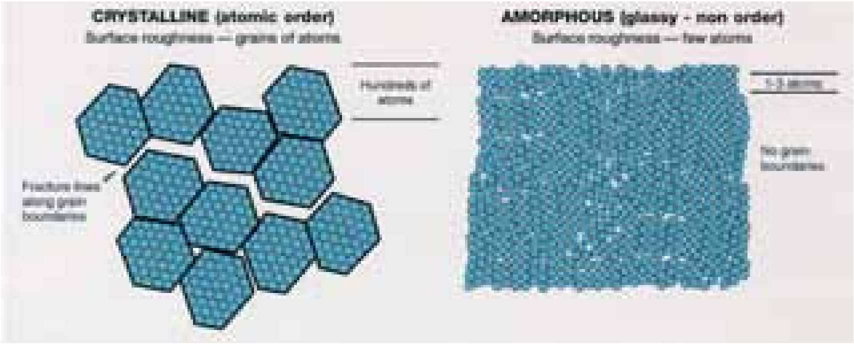


Figure 2.3.3.9. Schematics of a polycrystalline structure, with long-range crystalline order, and an amorphous atomic structure, with short-range liquid-like order

- *Glass Formation*

If crystal nucleation in the under-cooled liquid can be avoided completely below the liquidus temperature, the liquid eventually freezes into a non-crystalline solid – a glass (Fig. 2.3.3.9). Glasses have of course been manufactured from silica and related oxides for thousands of years. More recently, by developing new alloys and processing techniques, it has become possible to produce more and more materials in an amorphous form. These have superior properties compared with their (poly)crystalline counterparts, including materials with covalent (Si-based), van der Waals (polymers) and metallic bonding.

In particular, the new metallic glasses that can now be produced in large dimensions and quantities, the so-called ‘bulk metallic glasses’ or ‘supermetals’, are becoming an important industrial and commercial material. They are superior to conventional Ti-, Al- or Fe- based alloys. They have about twice the mechanical strength (about 1.8 GPa) of conventional materials, excellent wear properties and excellent corrosion resistance due to the lack of grain boundaries. These advanced materials can now be produced with dimensions of several cubic centimetres by casting or by zone melting techniques under high-vacuum conditions. In order to develop and optimise the casting process for the production of these new advanced materials, a number of measurements have been performed in microgravity during the recent IML-2 and MSL-1 space missions.

Due to their strong resistance to crystal nucleation and growth, the control of microstructural development is unique for metallic systems. By varying cooling rates and using different heat treatments, the range of microstructural length scales can now be varied by several orders of magnitude, extending from regular eutectic microstructures to the nano-crystalline and glassy state. For instance, cooling rates as low as 1 K/sec are sufficient to obtain high levels of under-cooling and produce a bulk glass for a number of pseudo-eutectic Zr-based alloys. This is illustrated in Figure 2.3.3.10.

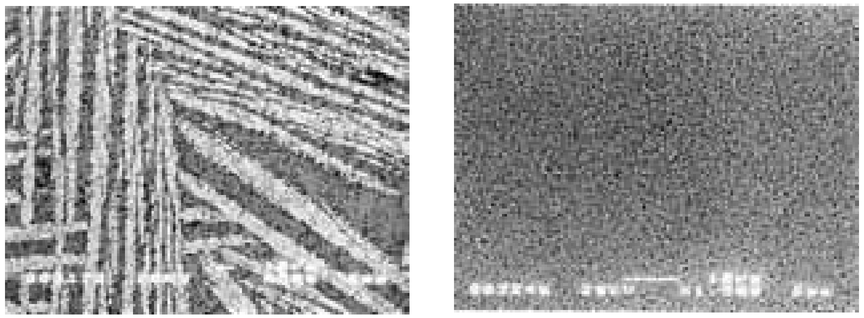


Figure 2.3.3.10. Variation of microstructural length scales in multi-phase samples with the identical chemical composition $Zr_{41}Ti_{13}Cu_{13}Ni_{10}Be_{23}$. Sample (a) is crystallised at small under-cooling (length scale 100 µm), while sample (b) corresponds to an initially glassy sample annealed and crystallised at 600°C for 5 hours (length scale 1 µm)

Analysis of the different microstructures that can be achieved in the pseudo-ternary $(Zr_{41}Ti_{13})(Cu_{13}Ni_{10})Be_{23}$, under different cooling and annealing conditions, reveals that a broad range of length scales are available. They are controlled by nucleation and growth kinetics under the appropriate processing conditions. Figure 2.3.3.10 exhibits two different microstructures as typical examples. For the same material, with identical chemical composition, a multi-component phase mixture with several (five stable and metastable) intermetallic compounds is obtained by crystallisation just below the eutectic temperature (length scale of 0.1 mm, Fig. 2.3.3.10a). A nano-crystalline microstructure is obtained by thermal annealing of the glass (length scale of about 50 nm, Fig. 2.3.3.10b). The cast material (a) is extremely brittle, whereas the nano-structured material (b) has excellent mechanical properties. The maximum mechanical strength of the glass is 1.5 to 2 GPa under both tension and compression, which is more than double that of conventional crystalline metallic materials. It is rather typical for refractory ceramics, but they do not have good mechanical properties under tension due to their brittle nature.

2.3.3.3 Thermophysical Properties and Containerless Processing

The paucity of thermo-physical property data for both commercial materials and those of fundamental interest is a result of the experimental difficulties that arise at high temperatures. As discussed earlier, knowledge of these properties is essential for the understanding and subsequent modelling of metallurgical processes, for thermodynamic phase equilibria and phase-diagram evaluation. Thus, accurate input data are needed for the stable liquid and at different levels of liquid under-cooling.

Some of these data can be obtained more or less accurately by conventional methods. High-precision measurements, however, on chemically highly reactive melts at the temperatures of interest, require the application of containerless processing using non-contact diagnostic tools.

- *Containerless Processing*

By eliminating the contact between the melt and a crucible, accurate surface nucleation control and the synthesis of materials free of surface contamination become possible. For highly reactive metallic melts, electromagnetic levitation (EML, Fig. 2.3.3.11) is a well-developed containerless technique. It offers several advantages over alternative levitation methods due to the direct coupling of the electromagnetic field with the sample. In microgravity, the considerably reduced electromagnetic power-input requirement for levitation allows processing under ultra-high-vacuum

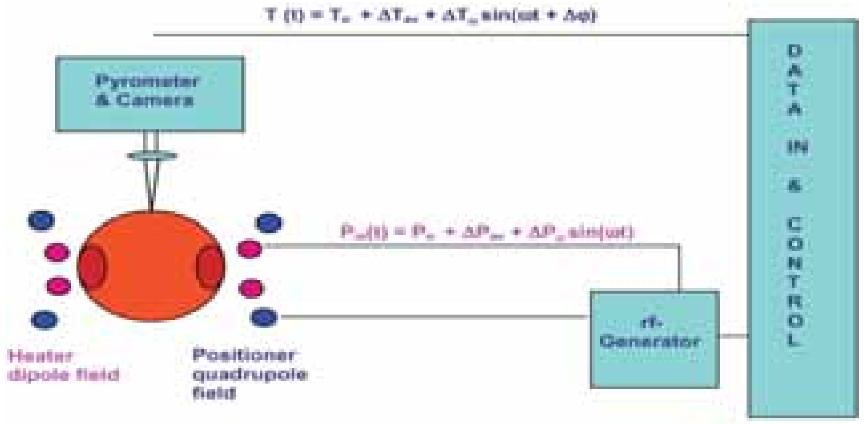


Figure 2.3.3.11. Schematic of the electromagnetic containerless processing facility, with power modulation inducing a controlled temperature modulation on the hot sample

conditions, with a much extended temperature range (700 – 2700 K) and better temperature control (T-measurements better than 0.1 K) of a quiescent liquid sample.

Based upon the successful development of containerless processing and diagnostic methods in space, high-precision measurements of critical and reactive melts at high temperatures are now becoming possible. These avoid any chemical reaction of the specimen with a containing environment. However, the required high accuracy can only been achieved when the following conditions are fulfilled:

- Extended processing periods (> 10 000 sec).
- Ultra-high-vacuum conditions (better than 10^{-8} torr).
- Minimised levitation forces and thus controlled heating and reduced liquid convection compared with 1g gravity conditions on Earth.
- Sophisticated analytical tools.

These conditions can be only fully satisfied in a long-duration microgravity environment. Based on the positive experience with recent long-term spacecraft missions and several hundred hours of processing time, new scientific methods as well as equipment modifications are being developed. These will allow the precise determination of the much-needed temperature-dependent data for highly reactive melts. This, in the future, will allow considerable improvement of existing materials processing technologies, as well as the development and application of new advanced materials, e.g. glassy ‘supermetals’ and other lightweight and high-strength materials, with controlled micro-or nano-structures.

During the earlier Spacelab missions, the thermo-physical properties of chemically reactive metallic liquids have been measured with a precision that had hitherto been unattainable. Some of the experimental results obtained for this new class of ‘supermetals’ from recent space flights are discussed below.

- *Experimental Results under Microgravity Conditions*

New sophisticated methods of controlled levitation, diagnostics and data analysis have been developed for the study of liquid samples of 7 – 10 mm diameter in microgravity. These methods allow the direct measurement of:

- melting range
- solid-fraction/liquid-fraction during casting
- heat capacity and enthalpy
- density
- surface tension
- thermal conductivity and diffusivity
- viscosity
- total hemispherical emissivity and other optical properties
- electrical conductivity.

Given the limited space available here, only some of the most important results can be presented, in particular for the newly developed bulk metallic glass-forming alloys. Such measurements have not been possible in the past and represent some of the most impressive results from recent microgravity research.

Figure 2.3.3.12 shows the experimental temperature versus time profile for the alloy $Zr_{65}Al_{7.5}Cu_{7.5}Ni_{10}$. This gives the melting range and a liquid under-cooling level of 194 K. Modulation of the power and hence of the resulting temperature allows determination of the specific heat (C_p) of the liquid sample, as shown in Figure 2.3.3.13

From similar experiments during the crystallisation plateau, the enthalpy of crystallisation has been determined, as well as the solid/liquid fraction as a function of time. Furthermore, the electrical resistivity ρ (which relates directly to the thermal conductivity λ, being proportional to T/λ) has been measured as a function of temperature in this alloy for the first time. The results are shown in Figure 2.3.3.14.

The total hemispherical emissivity ε of this multicomponent alloy is shown in Figure 2.3.3.15, where there is an unexpected change (maximum) close to the melting transition. The temperature dependence of the total hemispherical emissivity of the liquid sample, when combined with measurements of the electrical resistivity, allows observation of surface segregation effects or solution of a surface impurity phase, as a function of temperature. This offers a new approach for the investigation of surface-related chemical processes. In another set of experiments on different samples, high-precision measurements have been carried out to obtain the viscosity and surface tension.

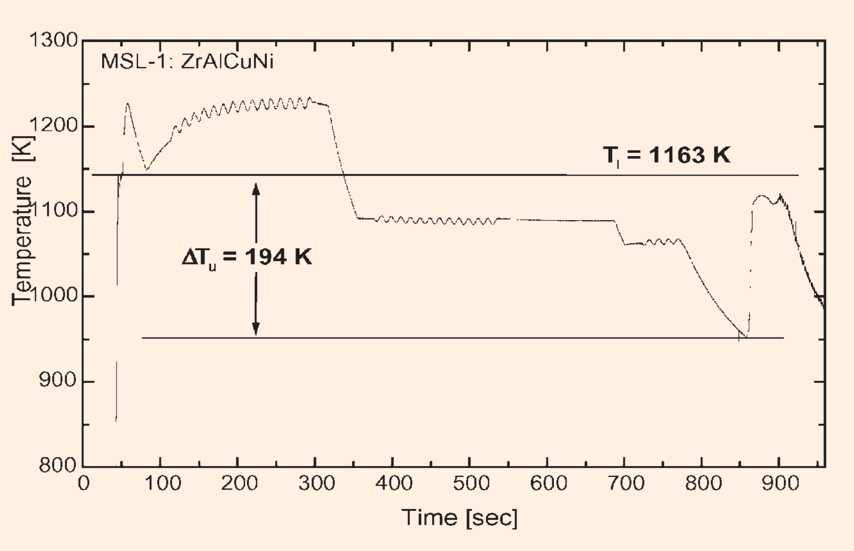


Figure 2.3.3.12. Temperature/time profile of a glass-forming alloy sample with high-precision temperature modulations for heat-capacity measurements in the under-cooled liquid (below 1163 K)

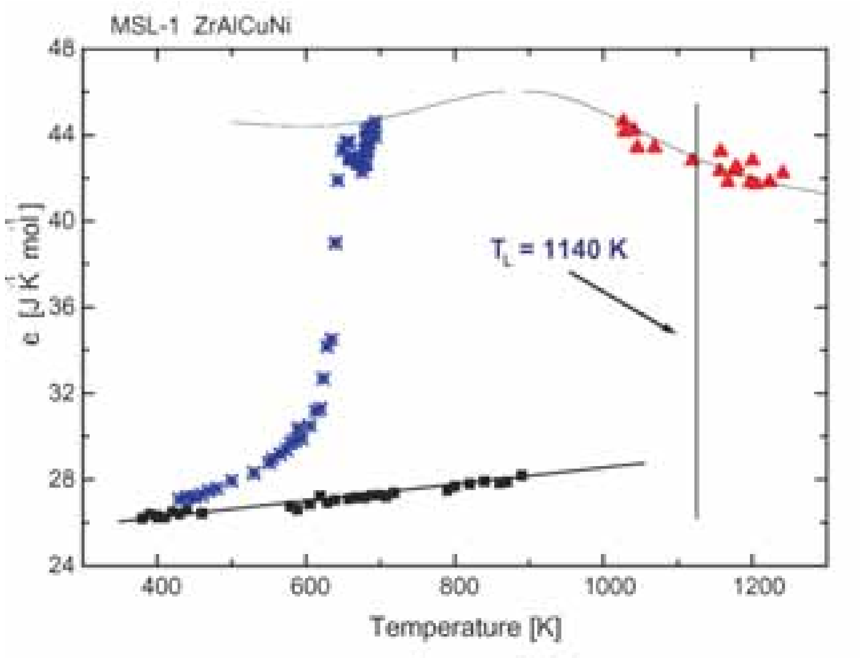


Figure 2.3.3.13. Specific heat (C_p) data for microgravity experiments (liquid sample red) and 1g experiments (crystalline sample black, glassy sample blue)

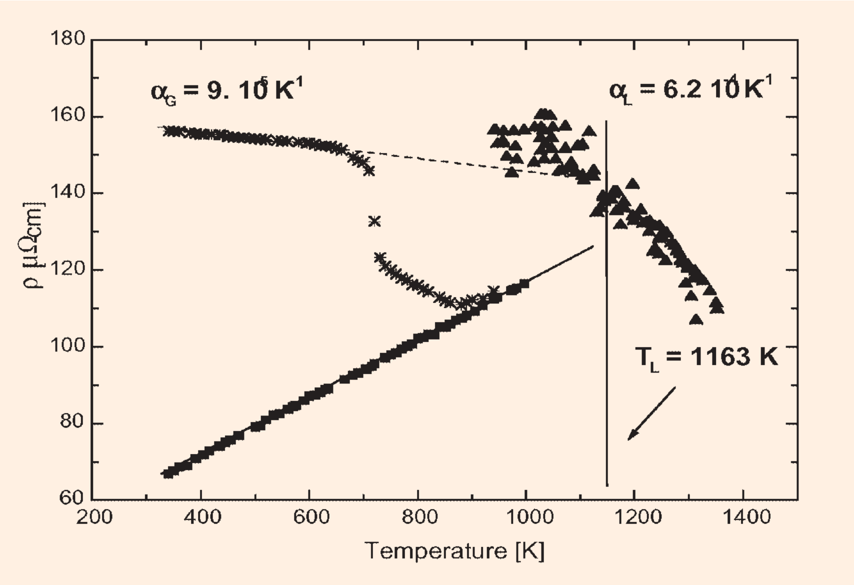


Figure 2.3.3.14. Electrical resistivity of the $Zr_{65}Al_{7.5}Cu_{7.5}Ni_{10}$ alloy in the following states: liquid (triangles), glass (upper) and crystalline phase mixture (lower curve)

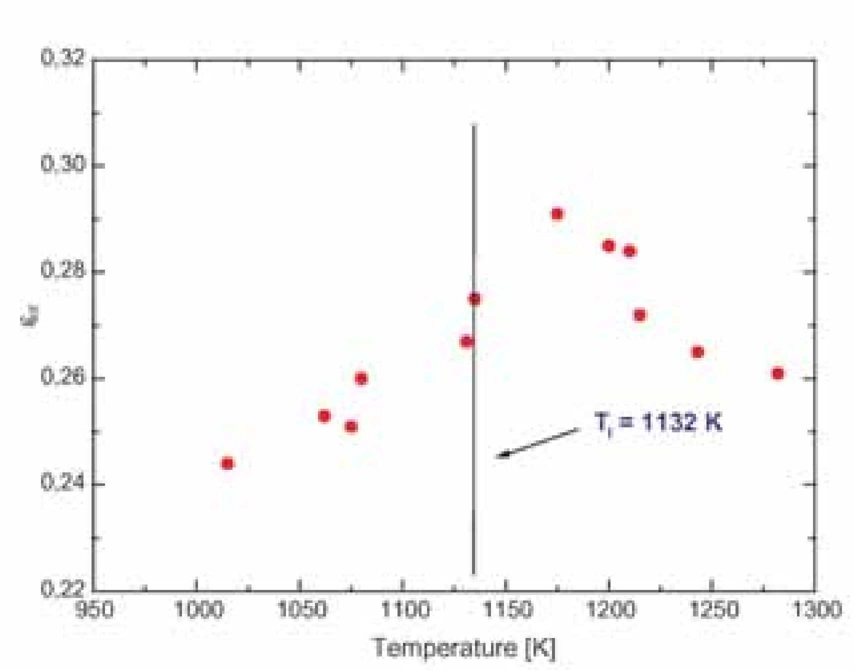


Figure 2.3.3.15. Total hemispherical emissivity (ε) as a function of temperature for a Zr-Al-Cu-Ni-Co sample

One of the most important results has been the determination of the integral driving force for crystallisation for different compositions of glass-forming alloys, based upon the above measurements (specific heat, heat of crystallisation / melting). This is indicative of the stability of these glasses and is shown in Figure 2.3.3.16. Several chemically highly reactive alloys have been investigated in the microgravity experiments. A clear correlation has been established for the first time between the stability of the metallic glass (against crystallisation) and the energetic driving force for crystallisation, based upon selected experiments performed in microgravity. Furthermore, the entropic instability temperature (arrows in Fig. 2.3.3.16) tends to be higher with increasing stability (lower driving force) of the metallic glass.

2.3.3.4 Views from European Industry

Obviously, the improvement of casting control, efficiency and product quality heads industry's wish list. For example, the steel industry uses more than 20 mathematical models in steel production. There are several types of models (predicting thermodynamics, kinetics, fluid flow, etc.), but models combining fluid flow and transfer of heat and species in calculations have proved particularly useful in a wide spectrum of processes involving solidification. They have been applied to the solidification in primary and secondary refining, casting and foundry operations, dip coating and welding operations. Many of the models started out as 'expert systems' correlating known practice information, but more exact models have been developed to provide analytical insight. It is important in all industries to 'get it right the first time', but it is especially important in the foundry and casting industry, in order to minimise working time and material wastage.

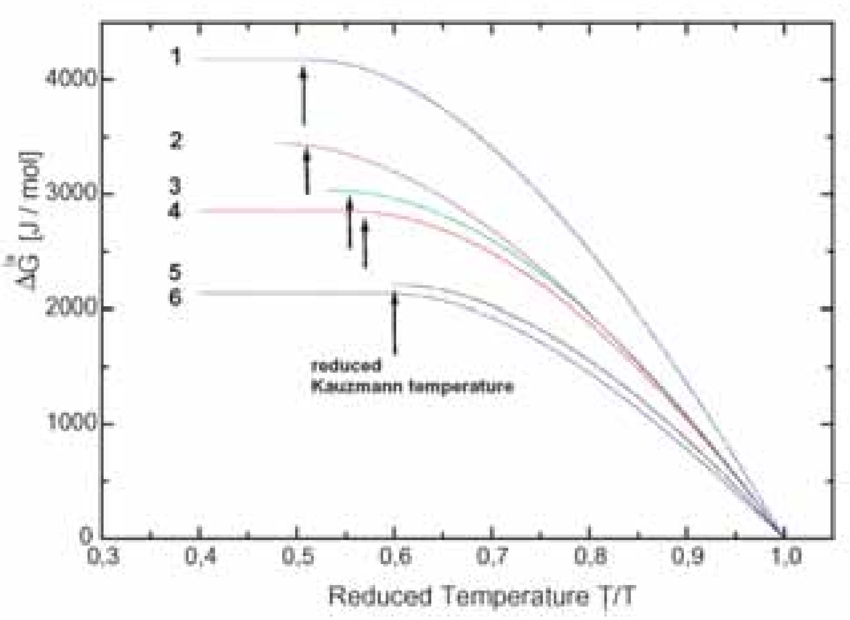


Figure 2.3.3.16. The Gibbs free energy difference of the under-cooled liquid corresponding to the driving force for crystallisation and the relative stability of the bulk glass forming alloys 1 to 6. Curve 1: $Zr_{64}Ni_{36}$ with an estimated critical cooling rate of R_c > 105 K/sec. Curve 2 : $Ti_{34}Zr_{11}Cu_{47}Ni_8$ with $R_c \approx$ 250 K/sec. Curves 3 and 4: $Zr_{65}Al_{7.5}Cu_{17.5}Ni_{10}$ and $Zr_{60}Al_{10}Cu_{18}Ni_9Co_3$ respectively. Curves 5 and 6: $Zr_{57}Nb_5Cu_{15.4}Ni_{12.6}Al_{10}$ and $Zr_{41.2}Ti_{13.8}Cu_{12.5}Ni_{10}Be_{22.5}$ with $R_c \approx$ 10K/sec and $R_c \approx$ 1K/sec, respectively

It follows, therefore, that companies express a real interest in the continuation of model developments and their application to processes. In particular, joint application-oriented efforts with industry on scientifically well-defined problems and on the extension of basic research to materials engineering are spreading rapidly. A striking example is the development within a consortium of industries, with European and North American members, of three-dimensional numerical simulation of the dendritic grain structure at the scale of the whole casting. Also, industry is presently supporting the simulation of the directional casting of large gas-turbine blades. However, it should be emphasised that, although the effects of fluid flow on the formation of microstructure (columnar mushy zone, equiaxed grains) have been incorporated into the models (Fig. 2.3.3.17), their implementation into the predictive software that is used by industry is still in its infancy. This is due to the severe limitations and the hypotheses that have to be made in the interests of tractability. For instance, the type of interaction between a dendritic grain and its surrounding liquid, needed to model the movement of the solid, is poorly described.

Beyond the direct interest emanating from processing, industries also recognise upstream experimental and theoretical research on fundamental points as a mandatory requirement in order to develop conceptual tools. For instance, an aluminium company awarded a grant to a PhD student to merely observe the sedimentation of an equiaxed dendritic grain in a transparent model system. The need for basic research motivated by bottlenecks in applications is further evidenced by the critical topics addressed at the EUROMAT '99 Congress on advanced materials and processes, with a number of sessions chaired by representatives of commercial companies.

Equally, reliable and high-precision thermophysical property data are important for progress in casting. It has been clearly shown recently that the prediction of defects in castings can be significantly improved by replacing estimated thermophysical property data in the software with experimental values for the particular alloy. In general, companies are dissatisfied with the amount of data available for commercial materials and new alloys. This includes primary metals producers, secondary refiners, as well as end users. Furthermore, the response to a questionnaire distributed within European industry has indicated an urgent need for high-quality data on thermophysical properties to: gain a better understanding of solidification, and solve problems encountered with the process in order to improve product quality and

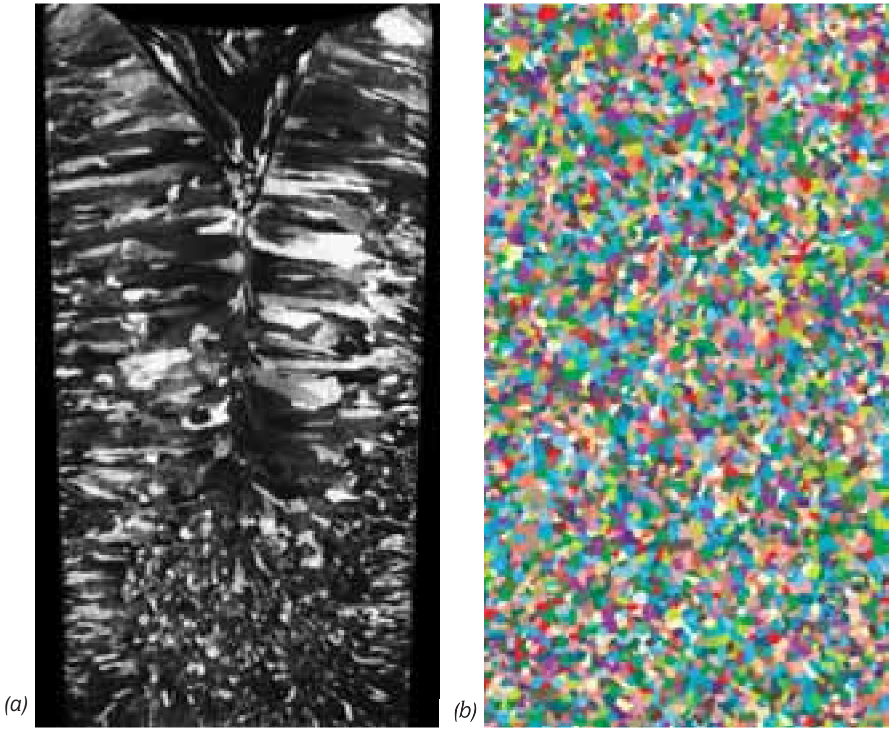
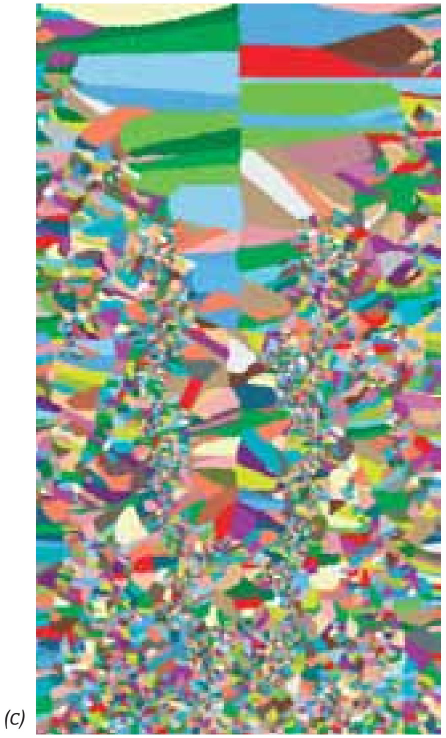


Figure 2.3.3.17. (a) Longitudinal cross-section of an aluminium-base alloy cast in a steel mould (120 mm high and 60 mm in diam.). A sedimentation cone of fine equiaxed crystals is clearly seen at the bottom of the ingot, as in Figures 2.3.3.1 and 2.3.3.7b, and a coarse columnar structure at the top (from N.L. Cupini et al., in 'Solidification and Casting of Metals', Metals Society, London, 1979, p. 193).

(b,c) Numerical simulation of the CET in a conventionally cast Al-7wt%Si alloy (b) without and (c) with grain movement (courtesy of Ch-A. Gandin et al.). When allowed to move, equiaxed grains not linked to the mould wall are transported downwards by fluid flow and by sedimentation, and the picture is in agreement with experiment. (The simulation without grain movement is qualitatively similar to equiaxed growth in microgravity; see Fig. 2.3.3.7a)



minimise waste and energy costs. As a result of this wide survey, the properties cited in Figure 2.3.3.18, which are mostly unknown for commercial materials, are considered important in the corresponding hierarchy. These properties are identical with those measured during Space Shuttle missions on highly reactive materials.

Important examples of relevant industrial processes that must still be improved are:
– Casting processes (Fe-, Ni-, Ti-, Al-, Mg- alloys, refractories, metal-matrix composites).
– Crystal growth of poly- and single-crystalline materials (turbine blades and discs, semiconductors).
– Glass production (metallic and non-metallic).
– Rapid prototyping.
– Spray forming and powder production.
– Surface modification by laser and spraying techniques.
– Welding (conventional, laser, electron).

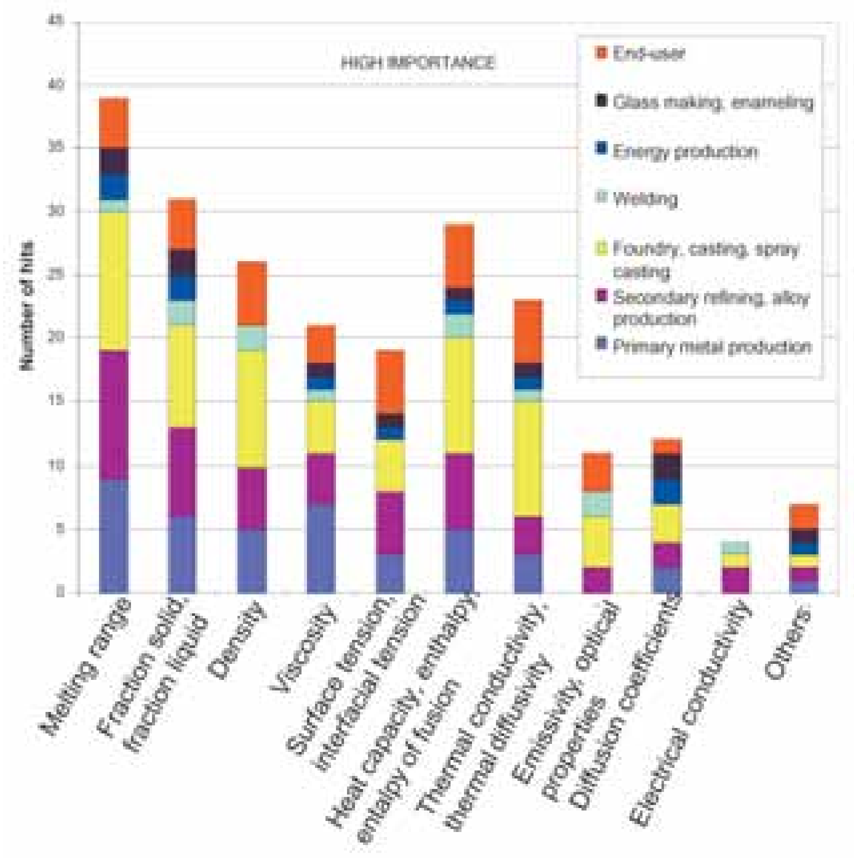


Figure 2.3.3.18. Results of a survey of European (here UK) metal-production businesses concerning the significance of the thermophysical properties of liquid multi-component alloys

2.3.3.5 Conclusions and Perspectives

Due to the extreme complexity of casting processes, their numerical simulation is largely split into several segments at present, each of which is tackled by rather separate communities. In order to advance the use of efficient and user-friendly global numerical simulation of processes with integrated codes, it is essential to strengthen the coupling between those researchers working on the microscopic scale and those working on the macroscopic scale. This might be achieved, for example, by associating in a dedicated research programme physicists working on the microstructure scale, metallurgists and process engineers preoccupied with the whole product, and chemists determining the required thermophysical properties.

The microgravity environment provides the conditions that enable unambiguous reference studies to be undertaken of the basic contributions to the formation of the solidification microstructure, as well as measurements of melt properties, without complicating artefacts from fluid flow. Moreover, the use of the ISS as a laboratory will enable comprehensive studies and flexible experiments. That type of usage will be greatly facilitated by telescience supervision and interactive control of the experiments from the ground.

As far as industry is concerned, they seem ready to finance simulation-based projects on microstructure formation of solidifying melts, and experimental programmes on technical alloy systems, but most remain to be convinced of the need to invest in a microgravity programme per se. The returns from such research are perceived to be too distant on an industrial time scale.

In research terms, the prime goals for the future are:

- *Reliable Determination of the Fundamental Relationships, at Microstructure Scales*

The strategy is based on a joint attack on open questions, using approaches that combine well-defined experiments with theoretical and computational modelling at microstructure and intermediate scales. Furthermore, R&D people are now convinced that the clarifying of the intricate effects encountered in processing necessitates recourse to model processing. By ‘model’ is meant a simpler process (e.g. directional solidification instead of regular casting) or/and a simpler alloy system (e.g. binary Ni-based alloy in place of a real superalloy).

There is undoubtedly a definite advantage to be gained if scientists can start building the future on well-adapted space facilities. Indeed, for the ISS utilisation phase, ESA and national space agencies already have a first series of facilities and diagnostics under development for metallic systems (LGF and SQF for low- and high-melting-point systems, respectively) as well as for transparent analogues melting at about ambient temperature. Moreover, cheap and flexible sounding-rocket experiments on simplified configurations may still be useful for preliminary studies in short periods of microgravity throughout the ISS era.

Among other objectives, two are clearly at the forefront, as they urgently require progress. In columnar growth, the understanding of the dynamics of formation and stability of the dendritic ‘mushy’ zone is a real challenge. Indeed, the time-dependent behaviour of this zone, with fluid flow and formation of solute freckles, is common in most industrial casting processes. It remains badly understood. In equiaxed growth, benchmark data must be generated under purely diffusive through to increasingly convective transport conditions, to validate models for predicting grain structures in castings. The United States is significantly ahead in the preparation of space experiments in which several equiaxed dendrites are interacting.

- *Reliable and Precise Measurements of Thermophysical Data*

These are a prime goal in order to improve the modelling of industrially relevant solidification processes. Although the standard Earth-based techniques appear to work for several materials, they cannot be confidently applied to reactive melts at high temperatures, due to contamination and exothermic reactions from the crucibles required to hold the liquid samples against gravity. New scientific methods, as well as equipment developments, are now available which permit containers to be eliminated. Further increases in accuracy will be possible by carrying out these measurements in the microgravity environment of space, under ultra-high-vacuum conditions.

High-precision experiments have been successfully carried out in an electromagnetic containerless processing facility (EML/TEMPUS) during several Spacelab missions. It has been demonstrated that the reduction of positioning forces in microgravity either leads to a significant improvement in accuracy or permits measurements that are otherwise impossible. These new experiment techniques can be extended to measure the thermophysical properties of liquid materials that are of commercial interest. They open a new research field of high-precision thermophysical property measurements, and their application for high-precision numerical modelling of industrial casting processes. For the future, an experimental programme in a containerless processing laboratory on the International Space Station is planned. This will allow measurements on samples of industrial and technological interest using non-contact diagnostic methods.

The knowledge gained in earlier ground and microgravity studies, taken together with the outcome of the experimental, theoretical and numerical investigations that materials scientists are completing, is now generating an ambitious and coherent programme of critical experiments destined to be carried out in the low-gravity environment of the ISS. By that process of deepening the fundamental understanding and providing highly precise measurements of thermophysical properties, these space studies can confidently be predicted to contribute substantially to the progress of materials development and processing, and thus ensure the future competitiveness of European industry.

Acknowledgements

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Further Reading

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2.3.4 Heat Transfer and the Physics of Fluids

W. Grassi & J.C. Legros

2.3.4.1 Introduction

The study of the science of heat transfer during the latter part of the 19th Century was fundamental to the formulation of the Principles of Thermodynamics. It led towards Planck's radiation theory and was an important factor in the analyses that eventually led to quantum physics. Nowadays, it also plays a key role for terrestrial and for space technology and has a crucial impact on the social and economic development of modern countries. In those countries, there is a growing awareness of the importance of the climate change that can be caused by human activity, particularly with regard to the production of greenhouse gases, e.g. CO_2, CH_4, NO_2, CFCs. These are mostly associated with the products of energy- and heat-transfer technologies.

The 17th Congress of the World Energy Council, held in Houston in 1998, focused on how technology could face the challenges of energy supply and use in the coming decades. Four main mandatory requirements were pointed out by the Council:

- 'increasing the efficiency of both the supply and use of energy, in order to mitigate the environmental impact, including climate change, and to improve the economic competitiveness'
- 'reduction of local pollution ...by using more energetically efficient equipment'
- 'facing the problem of climate change with more efficient technologies for the use of fossil fuels'. It was also stressed that: '..The increased efficiency in the use of energy constitutes the most immediate, wide and economic opportunity of reducing resource consumption and environment degradation', and that 'Efficiency should become mandatory in any aspect of the energy business..'

As most of the energy-dedicated equipment involves heat transfer, the enhancement of the efficiency of heat-exchange performance is a fundamental requirement. Within the field of fluid physics, the most effective heat-exchange technologies are those involving phase changes and, in particular, evaporation, boiling and condensation. Their use on Earth is obviously very widespread and includes power generation plants, cooling of electronics, building air conditioning, food conservation, etc. Consequently, their importance in daily life and their economic impact are clearly enormous.

The question then arises: 'How can fluid-physics research in low gravity contribute to improving energy efficiency for ground-based equipment and thereby reduce environmental pollution?' In order to answer that, the following discussion will introduce some of the basic concepts in heat transfer and the behaviour of fluids in microgravity conditions. It will then consider some of the relevant space experiments that have been performed and the ideas for future experimentation on the International Space Station (ISS).

2.3.4.2. The Physics of Fluids, Heat Transfer and Diffusion

The scientific and engineering motivation for conducting low-gravity experiments on the physics of fluids is either:

- To eliminate (or at least to substantially reduce) the influence of gravity on the motions (convection) in a mass of fluid: this allows the behaviour of fluid systems to be investigated when the transport of mass and of heat are not disturbed by convection (in the so-called 'diffusive or conductive regime').
- To study the motions induced by surface-tension differences along an interface separating two non-miscible fluids, the so-called 'Marangoni convection'. On Earth, in normal laboratory measurements, this contribution is often neglected, mainly because it is difficult to quantify its effect.

- *The Measurement of Diffusion Properties*

The diffusion coefficient is defined as the ratio between the mass flow flux of a component and the concentration difference existing between two points in a system. In a binary liquid solution (the only one considered here), a component is always diffusing from the high towards the low concentration point. Diffusion allows systems to relax any concentration non-uniformity, without resorting to convection flows. It is a slow process. If a concentration difference is established over a distance of 1 cm, it will take typically $10^4 - 10^5$ sec to become homogeneous.

The thermodiffusion (also called the 'Soret effect' in liquids) corresponds to a segregation that takes place in a solution subjected to a temperature difference. The characteristic time is also long (it obeys the same law as diffusion). The density variation resulting from this segregation can be of the same order of magnitude as the thermal expansion.

The long characteristic times associated with these two processes imply that any slow motion (a few microns/sec) can disturb a concentration field. The unique opportunity that is offered by a microgravity environment is to practically eliminate any such disturbing motions inside these non-homogeneous (in temperature and/or concentration) fluid phases. Consequently, researchers have taken advantage of these conditions, to measure the fundamental diffusion properties to an accuracy that is potentially higher than can possibly be achieved under terrestrial conditions.

Various very interesting projects have been carried out in space that have provided accurate measurements of these coefficients in molten salts, in metallic alloys, in isotopic mixtures and in organic mixtures. Such accurate values are needed to try to choose between the many different theories that aim to predict the diffusion behaviour of such materials. The debate between specialists on these different theories is not yet closed. The established (but still not proven) representation of liquid diffusion data in the literature is normally by an exponential 'Arrhenius' equation. Uncontrollable convection, from small temperature gradients or other spurious sources (e.g. Marangoni convection, separation processes, electromagnetic effects, etc.) was supposed to be at the origin of the uncertainties in the data.

Microgravity experiments on liquid diffusion were the first to show that convection could be mostly eliminated by using this highly-reduced-gravity environment, and thus reproducible data with very low scattering (0.5 – 2%) could be obtained. Additionally, these new space results were smaller than the 1g data, as a result of the absence of normal convection that contributed to the disturbance of the classical terrestrial data. Hence, microgravity results are thought now to finally open the way to accurate measurements of the actual atomic diffusion.

Industrial Applications

Reliable atomic liquid diffusion data are vital for computer simulations of, for example, industrial solidification or crystallisation processes or other diffusion-controlled processes, as discussed in Sections 2.3.1.2 and 3 above. There is a great need for such data for many industrial materials. Accurate data are essential, because in modern simulations the convection and the atomic diffusion transport are treated separately.

So far, only microgravity measurements appear to provide the possibility of determining the pure atomic diffusion coefficients, although different teams are investigating the damping influence of magnetic fields in order to curtail the disturbing convection motions in terrestrial experiments. The damping of strong motions is actually observed by this means, but the scattering in the data in those diffusion measurements still persists. This indicates that some slow convection was still present and that this disturbs the measurements. Evidently, this technique has to be further investigated in detail in the future and improved by comparison with microgravity data. Hence, for the foreseeable future (about 5–10 years), accurate diffusion experiments will necessarily have to be performed in microgravity conditions.

The theoretical description of diffusion and thermodiffusion is considerably more difficult in the case of complex systems. Unfortunately, these are often the types of materials in industrial use. In those cases, even a usable phenomenological approach still lies in the future. For materials of that type, the only recourse is to the use of experimental diffusion coefficients, determined using microgravity conditions.

Petroleum exploration and production companies are now requesting highly accurate fluid characteristics, as parameters to be used in increasingly sophisticated computer models. In a technical and financial context, the search for an optimal development scheme for a given reservoir requires knowledge of the effluent composition and its evolution during production. Reliable and accurate values of diffusion and thermodiffusion coefficients for those complex fluids are therefore needed in order to predict the optimal recovery scenario. The lack of data in this field is severe.

In collaboration with Total–Fina–ELF Exploration and Production, a scientific team from Europe and Canada, supported by ESA and the Canadian Space Agency, is conducting an ambitious programme aimed at providing such data for different crude oils. Presently, instruments for carrying out the first experiments to measure diffusion (DCCO – Diffusion Coefficient of Crude Oils) and thermodiffusion (SCCO – Soret Coefficient of Crude Oils) are being developed for a Shuttle GAS (Get-Away Special) independent experiment container campaign. A feasibility study of an instrument to be installed on the International Space Station has begun. This programme will be supported by ESA through its Microgravity Application Promotion (MAP) Programme.

- *Surface Tension and Marangoni Convection*

Surface tension is a force per unit length, acting at the interface separating two non-miscible fluids. It is responsible, for example, for the creeping of liquid along the wettable walls of its container. A meniscus can therefore be observed at the contact line between water and the glass wall of a container. In a glass tube of small diameter, the height of the meniscus results from the balance between surface tension at the edge of the liquid column and the pull of gravity.

Surface tension results from the work that has to be performed to bring, in this example, a molecule from the bulk of the liquid volume towards the surface. Inside the liquid, a molecule is attracted by close neighbours in the three-dimensional space. However, the process of forming a surface creates an imbalance in these forces, since at the surface the close neighbours are attracted only from the liquid side (the gas molecules being in general too far away to generate a significant attraction). It is thus necessary to do some work against this inward attraction, in order to bring molecules towards the surface when its area is increased.

As the compressibility of liquids is generally very small, the surface tension depends only very weakly on the pressure. It generally decreases with temperature. For solutions, changes in concentration can cause rapid and large variations, especially for low-solubility components that are called ‘surfactants’ and are familiar as detergents.

Marangoni convection arises when there is a variation in the surface tension along a liquid surface. It produces motion from regions of low surface tension towards those of higher surface tension, an action that can be compared with the effect of a pressure difference triggering a flow through a pipe. This motion, induced at the interface where the surface tension is acting, is also propagated into the bulk, due to the viscosity (or drag) of the underlying bulk liquid, as shown schematically in Figure 2.3.4.1. The resulting convection flow velocity can be rather large.

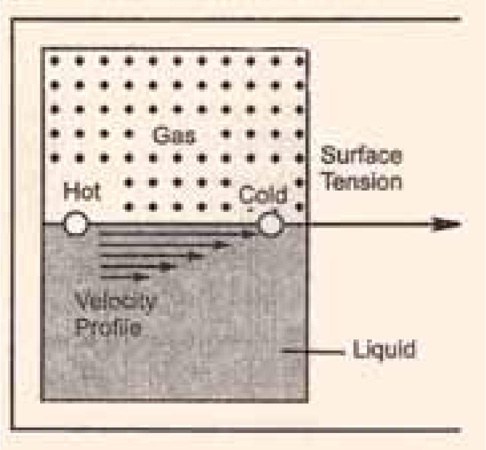


Figure 2.3.4.1. The development of Marangoni convection. A gradient in the surface tension at the gas/liquid interface from the hot (lower surface tension) to the cold (higher surface tension) liquid induces a surface flow that tends to drag the underlying bulk liquid with it. The resulting Marangoni convection flows in the opposite direction to the normal buoyancy(gravity)-induced flow. (courtesy of E. Messerschmid)

An observable example of this process happens in the liquefied wax of a burning candle. It is easy to follow the trajectories of soot particles moving near the surface from the hot region at the wick towards the colder periphery and coming back towards the wick near the bottom of the liquid wax. These particles are following the toroidal cellular Marangoni flow induced by the temperature difference along the liquid/air interface.

Marangoni convection can play an important role in various areas of materials science. It is also important within the technology domain in many processes involving a non-isothermal interface (see Sections 2.3.2 and 2.3.3). A typical example of the research effort in this field is the intensive modelling that is pursued to describe and predict the transport of heat and matter by the convective motions in the molten-zone technique, used for the production of high-quality crystals. There is a direct link between the quality of the produced crystals and the control of the flow, which has to be as steady as possible. Indeed, depending on the thermal constraints imposed on the system, the properties of the flow in the liquid phase are different. They range from the steady to the oscillatory regime, or from a single convection cell to multi-cellular flow or to turbulence. The transitions between these different regimes also give rise to new and fascinating problems linked to the spontaneous organisation of inert materials by fluxes of energy – what Prigogine has called ‘dissipative structures’.

In industrial processes, Marangoni convection reinforces or competes against the normal buoyancy-induced convection. It is very important to analyse accurately the effects of their joint interactions in ground-based processes. Microgravity is a tool well-suited for the careful and accurate study of the surface-tension-induced phenomena that are very difficult to isolate in terrestrial laboratories, and where they are disturbed, even shielded, by gravity effects. This situation will be encountered again in the later discussion of the very important boiling phenomena.

- *Two-Phase-Flow Research*

For a single fluid phase (liquid or gas) flowing in a tube, there are basically two broad categories of flow structures: laminar or turbulent. In the laminar regime, the flow rate is proportional to the pressure difference applied. When a liquid and a vapour phase (gas) are both forced to circulate in a pipe, this two-phase flow presents a wider range of complex regimes, depending upon the relative distribution of the gas in the liquid, e.g. bubbles to slugs to an annular regime where the liquid flows only along the wall, plus all of the intermediate situations. As the gas phase and the liquid have very different densities, their relative positions in the tube depend upon the orientation and amplitude of the gravity field. The total mass flow rate therefore now depends also upon gravity and on these different flow regimes. It is no longer determined solely by the pressure difference.

In the past two decades, several gas/liquid flow experiments have been conducted under microgravity conditions. Space applications, such as in life-support systems and thermal-energy transport, have revealed technical problems that have stimulated the development of two-phase flow research in microgravity. The main topics being addressed are the prediction of flow patterns, pressure drops, heat transfers and phase fractions in thermo-hydraulic systems. Detailed understanding of the flow regimes is necessary in order to design space systems efficiently. This type of research is crucial to the area of heat-transfer technologies. In such processes, the heat produced in one part of the system evaporates some cooling liquid. The vapour is then transported with a very small pressure drop (and thus isothermally) towards a condenser, where the heat is released. In this condenser, vapour and liquid co-exist. The efficiency of the condenser, as mentioned earlier, depends upon the two-phase flow regime that is taking place.

The management of two-phase systems is difficult, especially in a reduced-gravity environment. For high heat-flux transport, such as in the electronics in the next generation of large telecommunications satellites, there is no question of a choice between a single- or a two-phase system. Circumstances will dictate that some form of two-phase system must be accommodated.

A very interesting solution for transferring the degraded electrical energy (heat) from the core of a telecommunications satellite towards external radiators has been developed by a few companies (Matra and Sabca on the European side). The fluid (liquid ammonia) is pumped by the capillary effect, i.e. by virtue of surface-tension forces, in porous evaporators. This system has the considerable virtue that it does not involve any moving parts or consume any energy.

In 1994, a two-phase loop experiment called TPX was flown onboard the Space Shuttle in a GAS canister. Sabca (B) was responsible for the capillary-pumped loop. The objective of this loop test was to demonstrate the loop's heat-transport potential and its behaviour under different heat loads and heat sinks in microgravity. The TPX post-flight analysis showed that the loop worked correctly in microgravity conditions. The capillary pump developed by Sabca was a nickel porous rod with a 2.2 μm pore diameter, a permeability of $5x10^{-14}$ m^2 and a void fraction (porosity) of 71%. Such a capillary material is able to sustain a static head of 6.4 m of liquid ammonia.

The development of such systems is continuing, supported by parabolic-flight experiments and the intended GAS container missions. For instance, two-phase loops are being investigated on the Stentor satellite, supported by a CNES contract and with the participation of Matra and Alcatel. It aims to be a flight demonstrator for new space technologies, one of which is a new active-antenna concept developed by Alcatel, which has to be temperature-controlled. It has also to demonstrate the capabilities of capillary-pumped loops for large satellites in which the dissipated powers are foreseen to be about 20 kW (e.g. Alcatel's Spacebus-4000 line).

Traditionally, the investigation of two-phase flows was conducted by the oil industry, focusing their efforts on flow through long pipelines for the transport of a mixture of crude oil and gas from the well to the treatment plant. The nuclear industry, from its viewpoint, was interested in the stability of the flow to avoid drying out of the heat-exchanger loop. The chemical industries are interested in the investigation of two-phase systems with very complex geometries, for example in two-phase reactors or distillation columns. In these cases, the Marangoni convection can be induced by both temperature and concentration differences.

Pioneering studies were performed already on the Spacelab mission in 1985, with the MACO (Marangoni Convection and Mass Transfer from the Liquid to the Gas Phase) experiment, led by a team from Groningen University (NL). This technologically advanced experiment was followed by investigations using parabolic aircraft and sounding-rocket flights (Maser-1 and Maser-2).

A project supported by ESA (through its MAP programme) is dedicated to studying the influence of evaporation on convection motions. Called 'CIMEX' (Convection Induced by Mass Exchange), it is led by the Microgravity Research Centre of the Free University of Brussels. Five topics will be investigated:

- Identification and understanding of the different mechanisms that result in convective motions in an evaporating liquid phase.

- Investigation of evaporation in porous media, developed in close collaboration with Sabca and Prof. P. Stephan (Darmstadt University). The results could be used to improve the working of capillary pumps in two-phase loops in microgravity.
- Testing of the performance of a two-phase loop by NLR (National Aerospace Institute of The Netherlands).
- Detailed and fundamental study of the evaporation of a drop (Marseille University).
- Evaporation inside a bubble (Marseille University).

The European Commission, via its Research Directorate, also supports the basic effort of this programme through a network called ‘ICOPAC’, which is co-ordinated by MRC (University of Brussels). This is just one example of the huge effort presently developing in order to answer very fundamental and basic questions that are of direct interest in industrial applications.

2.3.4.3 Low-Gravity Research into Boiling Phenomena

The overall heat-exchange performance of thermal equipment is commonly evaluated by using the average value of the so-called ‘heat-transfer coefficient’, which is defined according to the Newton cooling law:

$$\alpha = \frac{q}{(T_W - T_F)}$$

where q is the power exchanged between the wall and the fluid per unit surface, and T_W and T_F are the wall and fluid temperatures, respectively. The various heat-transfer modes give very different (by several orders of magnitude) heat-transfer coefficients and different achievable heat-flux values. For water this is summarised in the following table:

Table 2.3.4.1. The Heat-Transfer Coefficient for Water

Heat-Transfer Mode	Heat Flux Range (W/m²K)
Free convection	100 – 1200
Forced convection in tubes	500 – 1200
Nucleate boiling	2000 – 45 000
Filmwise condensation	4000 – 17 000
Dropwise condensation	30 000 – 140 000

The boiling process involves extremely complicated, non-linear physical processes that operate over length scales ranging from 10 nm to 1 m or more. Strictly speaking, it is intrinsically a non-stationary process, although it shows a sort of ‘regularity’ on a statistical basis. This means that a sufficiently large number of bubbles must exist on the heating surface, so that appropriate time and spatial averages of the phenomenon must be taken into account. In addition, a steady dynamic and thermal regime must exist, both in the bulk fluid and at the heater.

While all of these conditions can be easily attained on Earth (in some cases, like flow boiling, on a large length scale), great care has to be paid to their fulfilment during low-gravity experiments. The physics involved is very complex, as several aspects play a significant role. For example:

- vapour–solid and liquid–solid interactions that occur on the heater, thus implying wettability (static and dynamic), thermal conjugate conditions, liquid and solid effusivities, etc.
- the presence of an ‘elastic interface’ between liquid and solid, with a phase change at the interface and a thermal gradient there that can create Marangoni flows
- fluid-dynamics of deformable bodies (bubbles or, in general, vapour masses) and their reciprocal interactions.

Consequently, a satisfactory description of the whole phenomenon, in terms of conservation and constitutive equations (plus obviously boundary and initial conditions), is not achievable at present. The result is that current industrial engineering design of such systems is based upon simplified correlations of experimental data, with a limited validity range.

No doubt over the next decade an increase in computing power will make it feasible to replace, or at least supplement, the correlations by large-scale models. The development of successful models depends upon gaining a detailed understanding of the physics of boiling. The attainment of that goal can be greatly assisted by experiments in low gravity. In particular, they can play a fundamental role by allowing the balance between gravity-dependent forces and other interacting forces to be varied and the results observed.

According to the classical relations, bubble flow and vapour/liquid interface behaviour are entirely dominated by gravity. As a consequence, the related heat-transfer correlations generally include a dependence on gravity, in almost any pool-boiling regime (see accompanying panel). The experiments carried out in low gravity have demonstrated that this dependence of boiling on gravity is not completely true. Roughly speaking, these experiments have shown that vapour patterns are heavily affected by gravity, as qualitatively predicted. Notwithstanding this, nucleate boiling (see accompanying panel) is affected by gravity at low heat flux, where single-phase convection is still important, while it is largely insensitive to gravity at high heat fluxes (high vapour production). The same thing happens if an electric field is applied. Tentatively, a first conclusion can therefore be drawn: fully developed nucleate boiling is almost insensitive to gravitational and electric force fields. If further confirmation of this conclusion is found by future experiments, then a basic revision of the theory will become mandatory.

Pool and Flow Boiling

‘Pool boiling’ results when a still liquid in a vessel is heated to the boiling point without any bulk liquid motion. Carefully watching the fluid during the heating up process, it is easy to recognise different ‘boiling regimes’. At first a few bubbles are seen (in vertical columns) stemming from the heated surface of the vessel. This is usually called the ‘regime of single bubbles’. Once the power supplied to the liquid increases, the number of bubbles greatly increases, together with the agitation in the liquid. This corresponds to the ‘fully developed nucleate boiling’ regime, or simply ‘nucleate boiling’. If a similar process takes place in a tube with a bulk motion of the fluid, it is referred to as ‘flow (or forced-convection) boiling’.

It is commonly said that water boils at 100°C. More appropriately, it should be said that water, at atmospheric pressure and 100°C, is saturated. Thus, if the heated surface (e.g. of the above vessel) is taken to a little higher temperature, bubbles form on it and move off into the fluid. This is usually called ‘saturated boiling’. But bubbles (and thus boiling) can exist at the heated surface also if the water temperature is below 100°C, provided that sufficient power is supplied to the fluid. In this case, the bubbles can start condensing even in the vicinity of the surface, and no bubbles can be detected within the liquid pool. This situation is termed ‘subcooled boiling’.

The following interpretation of this situation has been given. Nucleate boiling is determined by primary and secondary mechanisms. The primary mechanisms are independent of gravity. They are determined by evaporation in the ‘micro-wedge’ underneath the bubble and by capillary forces. The secondary mechanisms are responsible for vapour transport: they are buoyancy, coalescence processes, momentum of bubble growth and formation, and thermo-capillary flow for subcooled states. The buoyancy can largely be replaced by the other secondary mechanisms in microgravity. Bubbles are definitely larger in microgravity. Furthermore, a phenomenon of lateral coalescence of bubbles along the heater surface has often been observed in low-gravity experiments, leading to a heat-exchange enhancement. This is in agreement with what has been found in Earth-based experiments. On the other hand, it also means that fully developed nucleate boiling is a very effective heat-transfer mechanism also for space applications. This is very good news for space thermal-device improvement, but the question arises of whether it is possible to keep boiling stable without buoyancy, i.e. without a force lifting bubbles away from the heating surface.

In general, the answer is as follows. Steady-state long-term nucleate pool boiling can be attained in microgravity conditions. The possibility is higher with greater subcooling and low heat fluxes. There is still debate about the possibility of maintaining that condition indefinitely and the role played by fluid properties and the size and shape of the solid surface. At the present state of knowledge, it would be advisable to keep the liquid at least slightly subcooled.

A further fundamental argument to be addressed concerns the value of the peak heat flux that is achievable. The mechanism leading to the peak heat flux (also termed ‘burnout heat flux’, as it can even lead to physical destruction of the heater) is not yet well-established. At least four mechanisms have been proposed. Tests in low gravity could play a key role in the effort to achieve a much better understanding of this matter. On the basis of the available results, it is known that this peak heat flux decreases with decreasing gravity. At the gravity levels usually available for low-g tests (g/g_0 in the range 10^{-2} – 10^{-4}) and for the size of the heaters tested, the mechanism leading to ‘burnout heat flux’ proved to be associated with vapour spreading on the surface. Such behaviour was already suggested in the past, in accordance with the rationale that gravity and heater size have a sort of interchangeable role. Thus ‘large’ heaters become ‘small’ at low gravity, and vice-versa.

For large heaters (above a critical value), the proposed mechanism is the vapour/liquid interface instability that proved to be the leading mechanism also for film boiling. For small heaters, hydrodynamics no longer dominates the phenomenon and the vapour-front propagation mechanism comes into play. In this case, the effects of surface tension and liquid and wall thermo-physical properties play a major role. The application of an electric field increased both the peak and the film boiling heat flux several fold, both on Earth and in low-gravity tests. The influence of the gravitational and electric-field forces is briefly described below.

Few experimental studies on flow-boiling (see accompanying panel) in microgravity are reported in the open literature. Sub-cooled forced convective boiling was studied in a 0.6 s drop-tower experiment. The phenomenon was found to have minimum reliance on gravity and is therefore considered to be a feasible and efficient heat-transfer mechanism in microgravity. An adequate velocity field is required to prevent the formation of vapour chunks, which tend to stick to the heater.

Heat transfer and two-phase flow have been investigated in a circular tube during transient quenching in parabolic flight. A thick vapour film on the tube wall, due to the absence of gravity, made the re-wetting of the wall more difficult and degraded the heat transfer. Heat-transfer data on the flow boiling of water in a horizontal annulus with a central heater rod during parabolic flight has been reported. Bubbles were observed to coalesce and move along the heater. The heat transfer was found to be insensitive to the gravity level. Flow boiling of Freon-113 was also studied, using a vertical tube internally coated with a gold film, in parabolic flight. The vertical orientation allowed the examination of the effect of various gravity levels during the flight parabola, with no flow transition. Bubbly, slug and annular flow regimes were examined. As usual, large variations in bubble and slug sizes with gravity level were observed.

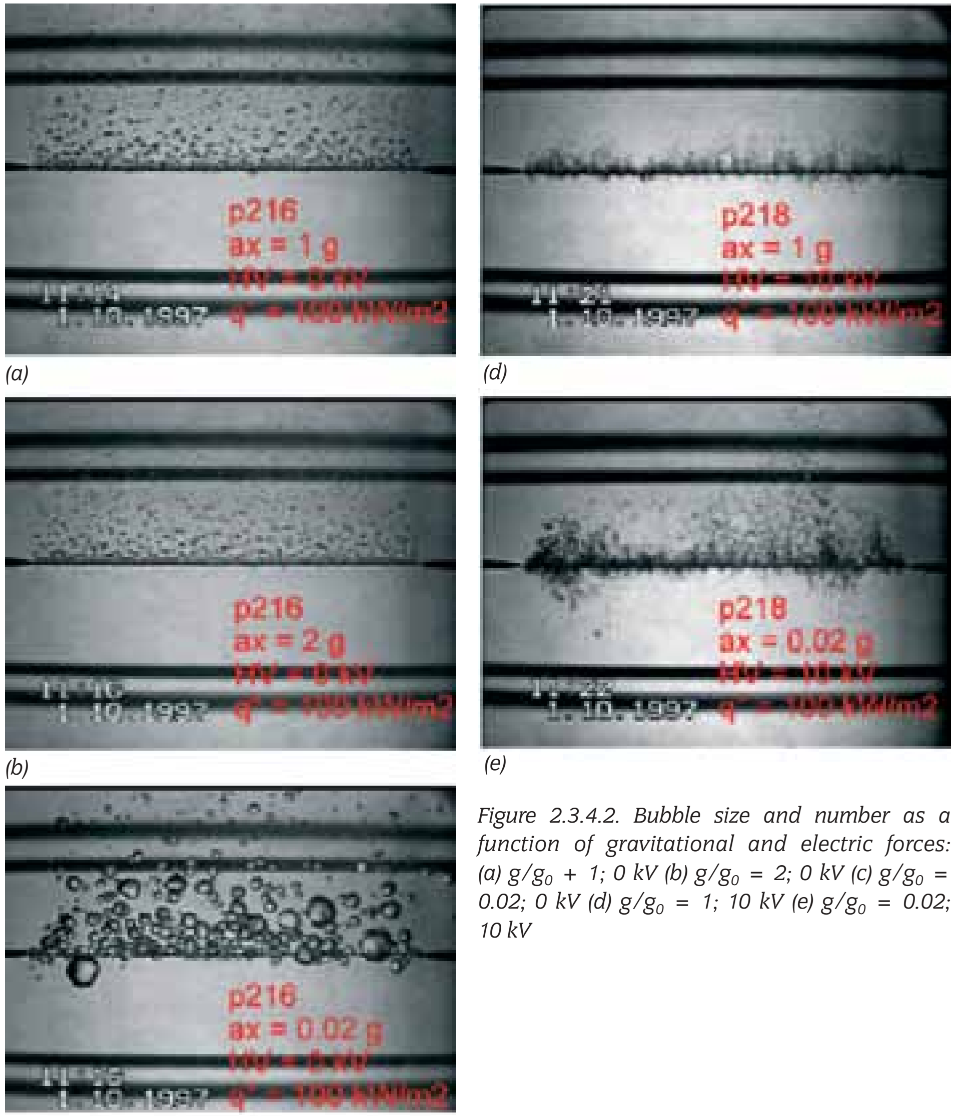
The heat-transfer coefficient was found to be insensitive to the gravity level, with the remarkable exception of annular flow, where boiling is suppressed in the liquid layer. In that case, due to the increase in film thickness and the reduction in turbulence, the heat transfer was degraded in microgravity and enhanced in the subsequent high-g phase of the parabola. It was concluded that, provided boiling is not suppressed at the surface, heat transfer is quite unaffected by the gravity level. Further studies are needed to investigate this boiling transition. Due to the limited amount of work performed so far, it is very difficult to draw definite conclusions on forced convective boiling.

The great importance of this subject has been widely recognised in the recent past by the international research community in this field. As a consequence of this, a Topical Team on Boiling has been established by ESA, composed of European scientists and certain industrial representatives, including Alenia Spazio and DASA. A further MAP project is in progress on boiling, led by LOTHAR (LOw gravity and Thermal Advanced Research laboratory) at the University of Pisa. Last but not least, an International Working Group on boiling and two-phase flow, involving members from Canada, France, Germany, Italy, Japan and the USA, is operating to facilitate joint future activities to be performed on the International Space Station. This group is itself a further confirmation of the need for scientific co-operation between boiling (pool and forced convective) and two-phase-flow specialists.

- *Force Fields Play with Bubbles*

Anyone who shakes a bottle of mineral water can watch either vapour or gas bubbles flowing towards the liquid free-surface, due to buoyancy. What could one expect to see if living on a planet with a different gravity level, or on an orbiting platform like the International Space Station?

Figure 2.3.4.2 can help to provide some answers. The pictures were taken during a boiling experiment with a wire (0.2 mm in diameter), all with the same wall heat flux and with a small liquid sub-cooling. The first three pictures refer to the effect of the (equivalent) gravity acceleration. At 1g, as in (a), all bubbles detach from the wall and rise upwards. If the gravitational force is doubled (b), the bubbles behave in the same way, but their size is smaller as they detach earlier from the wall, thanks to the doubling of the buoyancy force. If the acceleration vanishes, the lifting buoyancy force vanishes as well, leaving surface tension to bind the bubbles to the wall. Thus, if no other buoyant forces are present, bubbles grow at the wall to a bigger size without detaching as in (c), where the residual acceleration is 10^{-2}g. The bubbles are seen to be much larger and tend to accumulate close to the wall and coalesce. Their bulk flow is still directed upwards, but this is only due to a residual acceleration in the opposite direction.



(a) (d) (b) (e) (c)

Figure 2.3.4.2. Bubble size and number as a function of gravitational and electric forces: (a) g/g_0 + 1; 0 kV (b) g/g_0 = 2; 0 kV (c) g/g_0 = 0.02; 0 kV (d) g/g_0 = 1; 10 kV (e) g/g_0 = 0.02; 10 kV

A quite different vapour pattern is shown in the other two photographs, where only very tiny bubbles can be observed, spreading in almost any direction in the direct proximity of the heating wire. Picture (d) refers to a 1g situation, whilst picture (e) refers to the same low-gravity level as before. How can we obtain such an effect?

The answer looks obvious: by introducing a force field other than gravity. In fact, those final patterns were obtained by imposing a radial electric field (the wire is the inner electrode of something similar to a cylindrical electric condenser). Due to the difference between the electrical permittivity of the vapour and liquid and to the presence of electric-field gradients, a net force arises that pushes bubbles (smaller permittivity) towards regions with a weaker field. Liquid drops in a gas would experience just such an opposite force, which would enhance vapour condensation on the wall. If the field is high enough (as in these photographs), the effect of gravity is almost negligible. The electric field proved to be a good means for enhancing heat transfer both on Earth and in low-gravity conditions, and could be a useful means of performing fluid management in space.

2.3.4.4 Conclusion

It is evident that low-gravity experiments are making important contributions to the understanding of the physics of boiling, of heat transfer and of diffusion, and that their potential value for improving the efficiency of industrial processes is very significant. But what should be done in the future? The past activity in low gravity has been fragmentary, as is clearly shown in Table 2.3.4.2. This has been due to some lack of co-ordination, to the large variety of low-gravity platforms, and to the time required for the assessment of any complex scientific process.

The set of available facilities for such low-gravity experiments is very wide. It ranges from drop towers and drop shafts (experiment duration for each shot, 5 to 10 sec) to orbiting platforms (days). The various facilities have different characteristics in terms of available volume, power, energy, support hardware and software. Thus each experiment has to be conceived taking due account of these constraints. This situation can make it difficult to compare results originating from different types of facilities that were used under quite different low gravity regimes.

The International Space Station will therefore provide a unique and welcome opportunity to reasonably relax most of these constraints. It will allow the repetition of measurements under the same conditions and in the same instrument, which is crucial. In addition, the long duration of the tests will ensure the achievement of controlled and steady conditions. The recent Call for Experiments issued by ESA showed that there is strong interest on the part of the scientific community and of industry in investigating applied problems. This should be managed through Topical Teams.

Table 2.3.4.2. Overview of boiling experiments in microgravity

REFERENCE				FLUID	HEATER	NOTES
Snyder & Chung , 2000		PB	DT	FC72	Flat plate: 25x25 mm	Electrostatic field applied, 2 s duration
Di Marco & Grassi	1997	PB	PF	R113	Wire: 0.2 mm diameter	With and without applying electrostatic field
	1998		SR	FC72		
	1999		PF	FC72		
	2000	GB	SR DT	FC72	Cylinder: 1 mm diameter	
Straub and coworkers	1984	PB	SR	R113	Flat plate: 20x40 mm	Saturated and subcooled conditions
	1992		PF	R12	Wires: 0.2, 0.05 mm diameter. 40x20 mm flat plate	
	1996		SR	R113	Wire: 0.2 mm diameter	
	1999		OF	R134a	Wires: 0.2, 0.05 mm diameter	
	1998 1999		OF	R123	1.4 mm diameter hemispherical heater	
Suzuki et al., 1999		PB	PF	Water	Ribbon: 0.1mm thick, 20x5 mm	Subcooled conditions CHF only
Motoya et al., 1999		PB	DT	Water	Wire: 0.2 mm diameter	Effect of scale fouling
Lee et al., 1997, 1998		PB	OF	R113	Flat plate: 19x38 mm	Different subcooling tested. Low heat flux (up to 80 kW/m^2)
Oka et al., 1996		PB	DT	Water and R113	Flat square plate: 30, 40 and 80 mm	
Tokura et al., 1995		PB	DT	Methanol	Wires	
Oka et al., 1994		PB	DT	Water–ethanol mix		
Oka et al., 1992		PB	PF	R113, pentane water	Flat plate	Several flights performed
Merte, 1990		PB	DT	Liquid nitrogen	Disc, upward and downward facing and vertical	
Siegel, 1965		PB	DT	Water, alcohol, 60% sucrose solution	Wire: 0.5 mm diameter, horizontal and vertical	
Kawaji et al. 1991		CB	PF	R113	Circular tube	Quenching experiments
Ohta et al., 1992		CB	PF	R113	Vertical tube	
Saito et al. 1992		CB	PF	Water	Annulus with inner rod	
Wang et al., 1995		CB	DT	R113	Flat plate: 25x25 mm	0.6 s free fall, 0.003 g

Legend:
OF = orbital flight; SR = sounding rocket; PF = parabolic flight; DT = drop tower/shaft.
PB = pool boiling, CB = convective flow boiling, GB = gas bubbling

Acknowledgements

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2.3.5 Critical-Point Phenomena

D. Beysens

2.3.5.1 Introduction

The transition between the vapour and liquid phases of a pure fluid is one of the most fundamental in nature. The reference point, from which all of the transition properties of such a fluid can be derived, is called the 'critical point'. This is the point, characterised by a fixed temperature, pressure and density, at which the distinction between the gas and the liquid phase simply disappears. It was the French baron Charles Cagniard de La Tour, in 1821, who first discovered this critical point, observing the disappearance of the gas/liquid interface of carbon dioxide in a sealed gun. He could not know, at that time, that this new 'state' of matter would lead later on to so many important discoveries for both fundamental science and technology, some of them thanks to exploiting the microgravity environment.

The critical point of carbon dioxide (CO_2) occurs, in fact, at 31°C and at a pressure of 72 bar (atmospheres). That of water (H_2O) is observed at 375°C and 225 bar, and that of hydrogen at 33 K and 13 bar.

In a wide domain around the critical point, important parameters such as isothermal compressibility, the density of the gas and liquid phases, and the surface tension, obey universal power laws. These parameters can easily be varied by using small changes in the temperature. The highly variable properties of near-critical fluids make them very appealing for studying many interesting phenomena that, because of the universality of the power laws, are valid for all

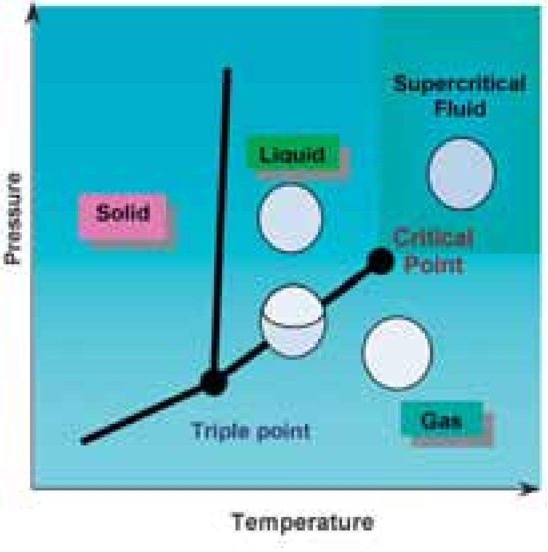

Figure 2.3.5.1. Phase diagram of a pure substance in the temperature/pressure plane. The supercritical 'state' corresponds to a compressed gas that exhibits the density of a liquid

fluids. Above the critical temperature and pressure, such fluids are called ‘supercritical’. In this region, they exhibit a number of specific properties (high density, low viscosity, large diffusivity), which make them intermediate between liquids and gases. In addition, their isothermal compressibility can become extremely large, especially when they approach the critical point.

Fluids in their supercritical state are increasingly used by the food and waste-management industries for their solubilisation properties (e.g. supercritical CO_2), as hosts for ‘cold’ combustion (e.g. supercritical water), in energetics (supercritical thermal or nuclear plants), and in astronautics (e.g. storage of cryogenic fluids). However, their behaviour under both terrestrial (1g) and space (0g) conditions is not well known. Consequently, their current use without such knowledge inevitably raises fundamental questions concerning fluid dynamics, heat transfer, interfacial phenomena and chemical processes. Experimentation on the International Space Station (ISS) is therefore a tremendous opportunity to address these questions and to enhance knowledge in this field, which is of both fundamental and industrial interest.

Fluids in their near-critical or supercritical state are affected by gravity. At the critical point, the compressibility of the fluid is actually infinite and when approaching it is very large. Consequently, gravity compresses the fluid under its own weight and the fluid stratifies. This prevents a very close approach to the critical point. Any measurements made on a cell of finite height will actually measure an averaged property of the fluid at differing densities, rather than the precise property approaching the critical point.

Experimentation in microgravity is not only of value in avoiding the complications due to compression. It also has value because convection and buoyancy are absent. Close to the critical point, fluids exhibit anomalies in the transport of heat. Due to gravity-driven convection and buoyancy phenomena, often turbulent, appear for even minute temperature gradients. In the following, it is shown that experimentation in microgravity has enabled new phenomena to be discovered, thanks to the ability to achieve a close approach to the critical point and the removal of convection and buoyancy. The main characteristics of fluids in the vicinity of their critical point are presented, together with the highlights of previous space experiments. Finally, there is a discussion of the main topics to be addressed in critical-point research using the ISS.

2.3.5.2 Power Laws and Universality

An important aspect of the critical region is that most of the anomalies in the thermodynamic and transport properties can be set in the form of scaled, universal functions (power laws) with respect to the critical-point parameters. This has the very important consequence that any results obtained with one fluid can be immediately re-scaled to describe any member of a whole class of systems, called a ‘class of

universality’. This class is defined by the space dimensionality d (= 3 in normal space) and the dimensionality n, of the fluctuating quantity, the ‘order parameter’. This is the parameter (M) that describes the change in the symmetry of the system at the transition. In fluid systems, the order parameter M is the density.

Density is homogeneous above the critical point (the fluid is supercritical) and inhomogeneous below it, because the two phases (gas and liquid) coexist with different densities. All systems with the same ‘d’ and same ‘n’ show the same asymptotic, universal, scaled behaviour. They all belong to the same ‘universality class’. Fluids belong to the class defined by d = 3, n = 1 (density is a scalar). In addition to pure fluids (order parameter: density), another member of this same class are the partially miscible liquid mixtures (order parameter: concentration). This includes the polymer melts, polymer solutions, micro-emulsions, molten salts, and monotectic liquid metals. Many other non-fluid systems also belong to this class, including the magnetic 3d Ising model (order parameter: magnetisation), which is relatively easy to study theoretically and is often considered a good representative of this class. An example of another class is He_4 near its λ point, which belongs to the class d = 3, n = 2, where the order parameter, a wave function, is a 2D vector. This universality and scaling is fundamental in nature. It stems from the universal behaviour that the free energy must asymptotically obey at the critical point in order to fulfil the conditions of a second-order phase transition. (In such a transition, a specific property changes continuously, rather than discontinuously, on going through the transition). In this sense, universality and scaling are generic to all critical-point phenomena.

By permitting measurements extremely close to the critical point, space experiments have made possible the precise measurements of important, weak power law divergence, such as that of the specific heat at constant volume C_V (Fig. 2.3.5.2). For example, from space experiments, the temperature divergence of the specific heat has been determined with a very high precision.

With the reduced temperature $\varepsilon = T - T_c / T_c$ (where T is temperature and T_c is the critical temperature), the specific heat diverges as $C_V \sim \varepsilon^{-\alpha}$ near the critical point. The ‘critical’ exponent α is universal. Its precise determination was a key

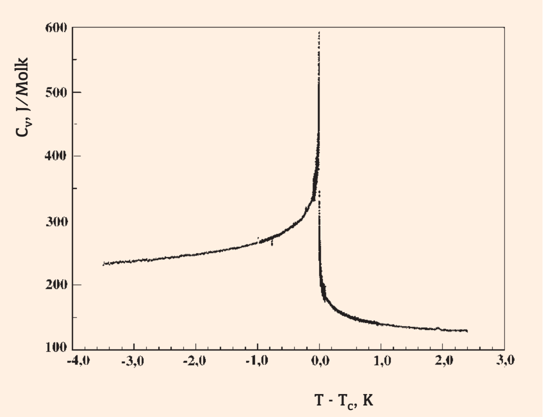

Figure 2.3.5.2. Critical anomaly in the specific heat at constant volume (C_V) measured under 0g in SF_6 (Spacelab-D2, 1993)(from Haupt and Straub 1999, Phys. Rev. E9, p. 1795)

test of the ‘Renormalisation Group’ theory, which has been developed to try to improve on the classical macroscopic description of fluid behaviour close to the critical point. The value deduced from the space experiments, $\alpha = 0.1105 + 0.025 / -0.027$, indeed appears to be very close to the result of the Renormalisation Group theory, $\alpha = 0.110 \pm 0.005$.

2.3.5.3 The Correlation Length of Fluctuations

As the critical point is approached, the fluids become extremely compressible, much more so than ideal gases. Excited by the thermal fluctuations and enhanced by the large compressibility of the fluid, the density fluctuates more and more strongly as the critical point is approached. The vicinity of the critical point is thus characterised by the presence of very-large-scale density fluctuations (or more generally, order parameter fluctuations), which develop throughout the fluid. The density fluctuations give rise to unusually strong light scattering, the so-called ‘critical opalescence’. These order parameter fluctuations are correlated with the correlations having a spatial extent that can be characterised by a correlation length ξ. The specific nature of the critical region therefore involves the appearance of this new characteristic distance, which can become much larger than the inter-particle distance. The correlation length then becomes the natural length scale of critical-point phenomena.

At that point where the correlation length becomes much larger than the range of the intermolecular forces, the specifics of the microscopic interactions cease to be relevant in the description of the critical behaviour. All that matters is the structure of the correlations. That involves the dimensionality of the physical space d, and the dimensionality n of the fluctuating quantity, the order parameter M. These are the only relevant attributes of the system when in this condition. As outlined above, the principal of universality then classifies diverse physical systems according to the values of d and n, with all systems of the same class displaying the same thermodynamic behaviour.

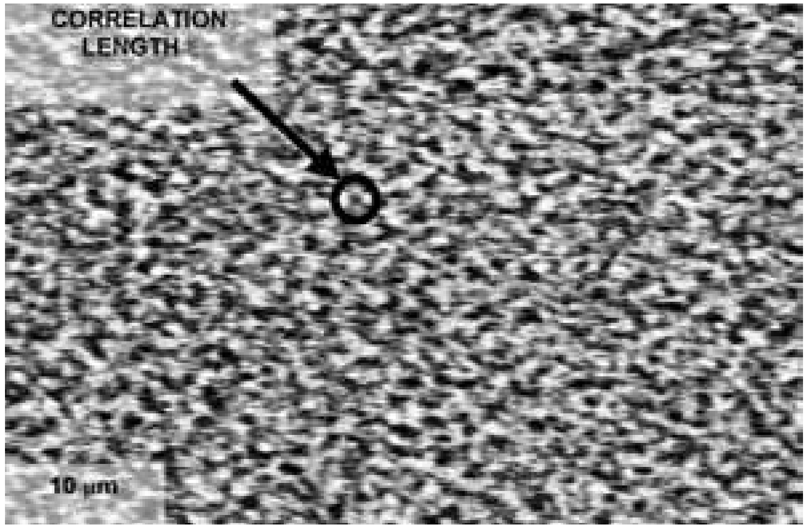

Figure 2.3.5.3. Huge density fluctuations as observed under 0g in SF_6 (Mir, 1996; $T - T_C = 10\ \mu K$). Fluctuations in density diverge at the critical point and their typical size, the ‘correlation length ξ’, determines the length scale of all critical-point phenomena

2.3.5.4 Time Scales

The scaling laws defined for systems in thermodynamic equilibrium are often called ‘static scaling laws’. It is, however, possible also to define universal dynamic scaling laws for the transport coefficients. The dynamics of the density (more generally, order parameter) fluctuations appear to define the natural time scale, much like the correlation length ξ defines the natural length scale for the spatial fluctuations. This natural time scale is the decay time of a fluctuation of size ξ over the length scale ξ Such a fluctuation vanishes by a (thermal) diffusion process, with a diffusion coefficient that can be estimated from the Brownian diffusion of a cluster of size ξ. The typical time t_ξ diverges near the critical point. It follows that the density fluctuations (or order parameter fluctuations) relax more and more slowly as the system approaches its critical point. This is the phenomenon of ‘critical slowing-down’.

In a fluid, pressure equilibrates nearly instantaneously (in fact, at the velocity of sound), so that both density and temperature fluctuations are slowed down. In particular, the thermal diffusivity tends to zero and the time to equilibrate the temperature also diverges. As a practical matter, the time for achieving thermal equilibration can become very long. For example, in the absence of convection (microgravity environment), the time to reach thermal equilibrium, at a temperature which is 1 mK from T_c, for a CO_2 sample with thickness 1 cm, would be more than a month.

Once properly scaled by ξ, the natural length-scale of critical-point phenomena, and t_ξ, the fluctuation lifetime, many phenomena are universal. Thus the critical point enables a zoom (ξ) and a slow-down (t_ξ) of the phenomena to be studied. Rescaling all lengths by ξ and the evolution times by t_ξ, enables the fluid behaviour to be cast on single, universal master curves.

2.3.5.5 The ‘Piston Effect’

Classically, there are three modes for thermalisation to take place: radiation, diffusion and convection. However, in very compressible fluids like near-critical fluids, another thermalisation effect, the ‘piston effect’, is dominant. This thermalisation mechanism – discovered in microgravity experiments – originates from the high compressibility and expandability of a supercritical fluid.

The basic physical mechanisms giving rise to the piston effect are the following (Fig. 2.3.5.4). When a homogeneous bulk fluid enclosed in a sample cell is suddenly heated from one wall, a diffusive thermal boundary fluid layer forms at the wall/fluid interface. Due to the high thermal expansion of the fluid layer and the high compressibility of the bulk, the fluid layer expands and acts as a piston to adiabatically heat the fluid. As a result, a spatially uniform heating of the bulk fluid is produced.

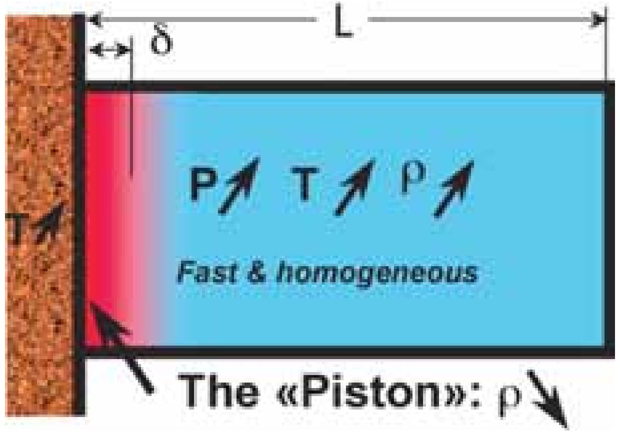

Figure 2.3.5.4. The 'piston effect' mechanism: a thin hot boundary layer expands and compresses the bulk fluid. The corresponding temperature profile exhibits a thin zone of strong gradients near the heated boundary (thermal boundary layer δ), and a homogeneous rise in the rest of the fluid, which settles at the speed of sound

The characteristic time scale for the piston effect is the time t_c to transfer from the boundary layer (thickness δ) the amount of energy that adiabatically heats the remaining fluid. In contrast to the diffusion time t_D that diverges near the critical point, this time tends to zero with the increase in compressibility of the fluid. A striking result of this analysis is the critical speeding up of the piston effect when getting closer to the critical point. As a matter of fact, near the critical point, t_c goes to zero although t_D goes to infinity. This result represents an enormous reduction in the time required for thermalisation. This reduction is obtained at the cost of the formation of a boundary layer that diffuses slowly so that the ultimate equilibration time in pressure, temperature and density still remains the diffusion time-scale.

An additional result shows that the fluid velocity produced by the expansion of the hot boundary layer reaches its maximum value at the edge of the layer. The edge fluid velocity induces the compression of the bulk fluid by a small transfer of matter and makes the boundary layer act as a converter that transforms thermal energy into kinetic energy. This transformation is at the origin of a very particular behaviour when the vapour is in equilibrium with liquid below the critical point (Fig. 2.3.5.5). While heating the cell, the temperature of the vapour becomes greater than that of the wall, apparently violating the Second Law of Thermodynamics.

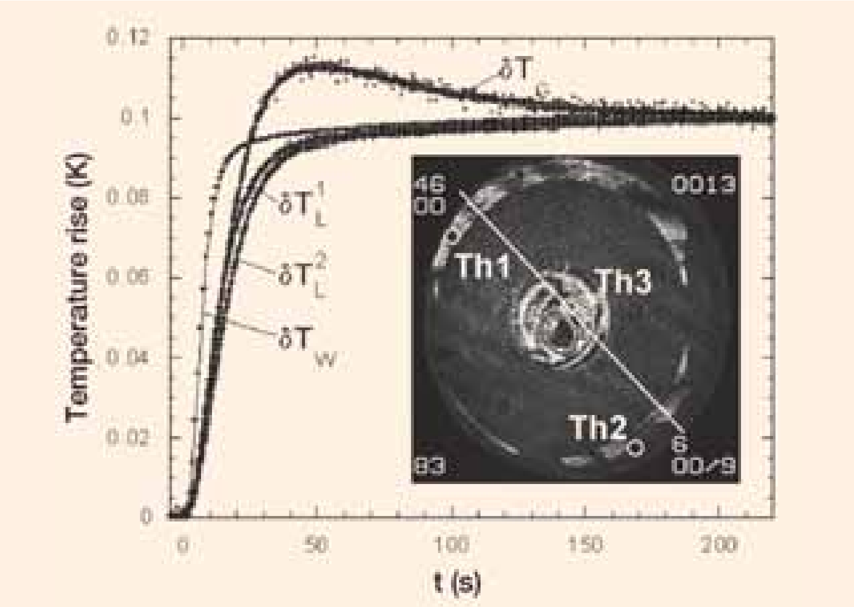

Figure 2.3.5.5. Overheating of nearly 20% in the gas phase of a SF_6 sample at 10 K below the critical point (ALICE on Mir in 1999). A temperature rise of $\delta T_w = 0.1$ K is imposed at the cell wall. The temperature evolution of the gas (δT_C) and that of the liquid at two locations ($\delta T_L^{1,2}$) are shown. In the insert, the sample with the thermistors is shown (from Wunenburger et al. 2000, Phys.Rev.Lett, 84, 4100).

2.3.5.6 Phase-Separation Dynamics

Although phase separation in fluids and liquid mixtures is a common process that occurs in many areas of science and technology, the connection between the morphology of domains and the growth laws is still incomplete. A typical phase-separation experiment consists of quenching the temperature of a sample at the highest possible rate from an initial state (density ρ, temperature T_i) where it is homogeneous to another state (density ρ, temperature T_f). In this latter state, the sample is no longer stable and the process of phase separation occurs (Fig. 2.3.5.6). In the critical region, it is easy to vary continuously the physical parameters. In particular, the temperature quench depth is related to the equilibrium volume fraction ϕ of the minority phase, so that ϕ may be varied.

As discussed above, the 'piston effect' speeds up thermalisation (at the cost of a thin boundary layer) so that thermal quenches very close to T_c are limited only by the thermal response of the thermostat. The critical slowing down is, however, still effective in the droplet growth process and enables a detailed investigation of the mechanisms involved in the separation process.

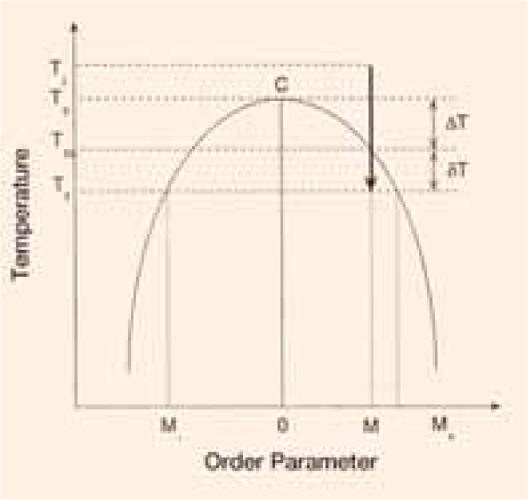

Figure 2.3.5.6. Schematic phase diagram for simple fluids and liquid mixtures in the T – M plane. T is temperature and M is the order parameter ($M = \rho - \rho_c / \rho_c$ for simple fluids, and $M = c - c_c$ for liquid mixtures)

The typical scenario for the formation of a new phase does not correspond to the two classical processes of 'nucleation' or 'spinodal decomposition'. In classical nucleation, only large fluctuations can overcome the energy cost corresponding to the formation of the interface of a nucleus of the new phase. In spinodal decomposition, fluctuations are unstable and grow. Near the critical point, the large fluctuations in the order parameter induce another process called 'generalised nucleation'. In this process, the large order parameter (density) fluctuations of average size ξ grow in amplitude to reach local equilibrium and give rise to droplets of the minority phase. These droplets then grow at the expense of the majority phase, until they reach equilibrium.

Experiments that are free of gravity effects have shown the key role of the coalescence between drops, either by Brownian motion or local flows induced by the coalescence process itself. At very small volume fractions, these interactions should be very rare. Only a diffusive process should take place. However, recent experiments seem to show that, even at very low volume fractions, hydrodynamics still plays a key role.

When the density of the fluid is critical, i.e. when the volumes of vapour and liquid are equal ($\phi = 1/2$), an interconnected pattern of domains that coalesce continuously is formed (Fig. 2.3.5.7a). The characteristic length L_m of the domains can be defined as the pseudo-period between the phases. At late times, $L_m \sim t$. The results obtained in all fluids and liquid mixtures, when rescaled by the unit of length (ξ) and time (t_ξ) as $K_m^* = 2 \pi\xi / L_m$ and $t^* = t/t_\xi$ can be reasonably placed on the same master curve, which obeys scaling and thus strongly suggests universality.

When the volume fraction of the domains is smaller (Fig. 2.3.5.7b), and the gravity effects are negligible, the droplets coalesce and/or grow by Brownian motion. Experiments show that the late stages are always characterised by a 1/3-growth-law exponent. All the data obtained in liquid mixtures and in fluids during the gravity-free experiments, when expressed in the scaled units K_m^* and t^*, can be placed on the same master curve $K_m = 0.9\ t^{*1/3}$, making clear the universality of phase separation in fluids and liquid mixtures.

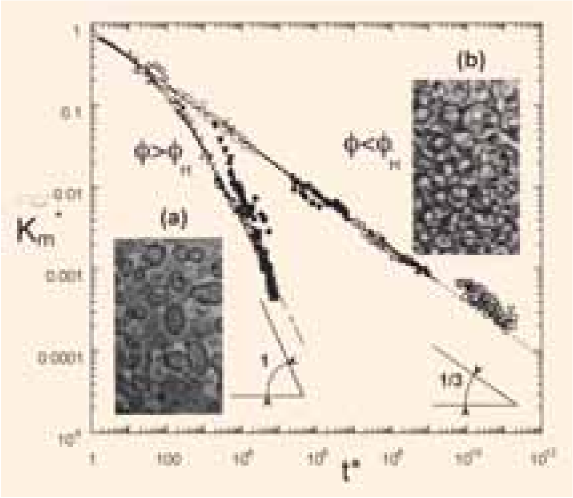

Figure 2.3.5.7. Growth laws in fluids (SF_6, CO_2, data points) and liquid mixtures (partially deuterated cyclohexane and methanol, letters and squares) when gravity effects are absent (from Beysens et al., Proc. 8th Tohwa Intl. Symp. on Slow Dynamics in Complex Sysems, November 1998)

The existence of the two different regimes, their relation to the pattern morphology and the absence of a crossover can be explained as an interplay between the droplet coalescence, as induced by Brownian diffusion, and the hydrodynamics interactions as induced by the coalescence process itself. The transition between the two regimes appears at a well-defined volume fraction, of order 30%.

2.3.5.7 Critical Enhancement of Adsorption

The behaviour of pure fluids and fluid mixtures near a plane wall, which can be considered as a third phase, is also strongly modified by the proximity of a critical point. In particular, in the one-phase region, the adsorption of fluid molecules produces a density variation that scales with the correlation length in a universal, critical adsorption profile. With z the perpendicular distance to the wall, the density varies as $\rho\ (z) \sim z^{1/2}$, at distances $z < \xi$ and $\rho(z) \sim \exp(-z/\xi)$ at $z > \xi$.

Gravity-free experiments, to take advantage of a bulk sample at uniform density, were performed with SF_6 adsorbed on black carbon (a porous material to increase the surface of adsorption). The expected increase in adsorption was measured, as shown in Figure 2.3.5.8. However, when the temperature at which the correlation length of the fluctuations became of the order of the pore size was reached, the phenomenon of 'critical desorption' was observed instead! The finite size of the pores, by limiting the size of the fluctuations, 'killed' the critical character of the fluids and suppressed the excess adsorption caused by the approach of the critical point.

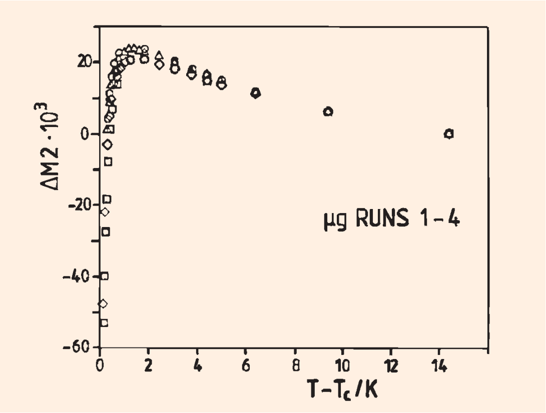

Figure 2.3.5.8. Adsorption excess (arbitrary units) near the critical point of a fluid (SF_6) on a porous material (Vulcan 3-G graphitised carbon black) under 0g (on Eureca-1 in 1992). Although the general increase in adsorption is clearly observed when temperature T decreases towards the critical temperature T_c, when the temperature T is very close to T_c a paradoxical decrease in adsorption occurs (from Thommes et al.1994, Materials and Fluids in Low Gravity, Springer, p. 51)

2.3.5.8 Critical Boiling

When a two-phase fluid is heated, boiling often occurs. When the heat flux is very strong, vapour can spread onto the heater. This is the so-called 'boiling crisis', which can have catastrophic consequences in thermal and nuclear plants, since as a vapour film develops on the heater it prevents heat transfer. Near the critical point, the vapour-liquid interfacial tension σ goes to zero as $\sigma \sim \varepsilon^\nu$. Under zero gravity and near the critical point (where σ is very small), phenomena that are important only at small scale and high heat flux become visible. In fact, the spreading of the dry spot of a bubble vapour has been observed under 0g and it is interpreted as the precursor of the boiling crisis. Spreading occurs under the influence of a recoil force, or a 'thrust', produced by evaporating liquid near the liquid/solid/vapour contact line. When heating the two-phase fluid, the vapour bubble is seen to spread on the cell walls (Fig. 2.3.5.9).

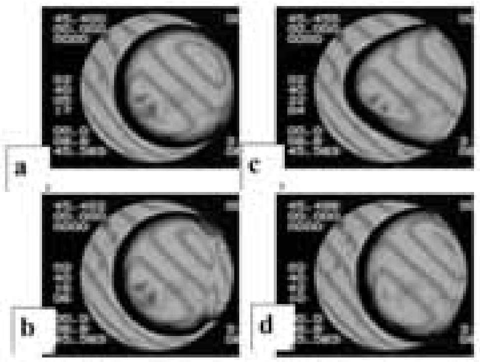

Figure 2.3.5.9. Critical boiling and out-of-equilibrium wetting under microgravity (SF_6, Mir, 1999). Gas apparently 'wets' the wall during heating (a – d). This sequence was taken during a temperature quench from T_c – 0.2 K (a) to T_c – 0.1 K (d). (a) t = 0; (b) t = 11 s; (c) t = 17 s; (d) t = 37 s (from Garrabos et al., J. Chim.Phys., 96, 1066)

2.3.5.9 An Experiment Programme for the ISS

The following is an outline of a possible programme of experimentation in this field, following the recommendations and proposals of the members of the Topical Team for 'Chemical Physics in Near-Critical and Supercritical Fluids'.

This programme, which could extend over about a decade, contains elements that are directed both towards fundamental studies and at industrial applications.

- *A New Hydrodynamics?*

For static phenomena, fluids and liquid mixtures belong to the universality class defined by an ideal magnet (the 3D Ising model). In this model, flows and more generally hydrodynamics are not present. However, hydrodynamics often induces unexpected behaviour in those fluids, especially in heat- and mass-transport phenomena, by convective flows. This occurs even in the absence of gravity. In particular, for supercritical fluids, which are as dense as liquids and more compressible than gases, it is a 'novel' hydrodynamics that has to be considered. This is a developing area and one that will certainly lead to new and unexpected results in the future.

- *Direct Observation of Critical Fluctuations*

The first documented observation by Andrews, in 1869, of critical opalescence in a pure fluid near the critical point was cited as the evidence for large-scale density fluctuations. Although there is much evidence for the existence of critical fluctuations, only a few attempts have been made, including recent experiments on Mir, to observe and analyse fluctuations directly. Future low-g experiments plan to image and study critical fluctuations, both in volume and time, in considerable detail.

Optical measurements within pressurised cells allow the direct observation of such critical fluctuations. Data from within 10 μK of the critical point can be obtained. There, critical fluctuations with a correlation length as large as 15 μm should be observed. A detailed study of the distribution of the fluctuations will allow valuable new information to be gathered. This would include such aspects as the fractal dimension of the fluctuation pattern, the statistics of fluctuations and the expected deviation from Gaussian statistics related to the universal form of the free energy. All of these quantities are fundamental in probing the universal character of the critical point.

- *Phase Ordering*

Knowledge of the mixing and separation of substances has been important to human civilisation for thousands of years. Research into this process of 'Phase Ordering' has been particularly active in recent times, partially motivated by the need for better materials. Phase separation in liquid mixtures and pure fluids is a natural phase-ordering process, and occurs in many areas of natural science, engineering and industry. Moreover, engineering applications are especially important in the two-phase heat- and mass-transfer processes that are used in many industries. Phase separation is also ubiquitous in materials processing for, for example, metallic alloys, polymer alloys, including supercritical elaboration of materials, and flat-panel display technology.

Most of the key experiments in this field have been performed near the critical point of binary liquid mixtures or pure fluids, which provides scaling and, thanks to the critical slowing down, allows the hydrodynamics of coalescence to be observed and measured. The results from such phase-separation experiments have shown that the late stages of phase separation are universal, i.e. the growth laws are described by master curves that are valid for all fluids, within two scale factors. The theoretical study of the late stages of this process has included the use of generic concepts such as scaling and self-similarity, universality, and hydrodynamic percolation.

The accumulation of data under microgravity shows, however, that the behaviour of such fluids, although similar to that observed with liquid mixtures, exhibits a number of significant differences. To understand them, a refined analysis of the local hydrodynamics (at the scale of the domain size) is needed to take into account all possible sources of discrepancy (thermal piston effect, fluctuation effects, turbulent and inertial effects, Brownian motion, etc.). The fluctuation or noise effect (Brownian motion) in hydrodynamics has not been taken into account yet. There is a need to gather data and analyse the growth at very low volume fractions. A new development concerns the investigation of phase transitions induced by mechanical quenches, by using a volume (or density) variation. This is a new way to induce phase ordering, in contrast to the temperature quenches that have hitherto been used.

- *Boiling, Two-phase Thermalisation and Wetting*

A process that is complementary to phase separation (one-phase to two-phases) is boiling (two-phases to one-phase). Boiling in liquid mixtures and pure fluids, like phase separation, is a common process that occurs in many areas of natural science, engineering, and industry. The engineering applications (e.g. supercritical water thermal plants) are especially important in the context of industrial heat-transfer processes. A clearer understanding of the exact physics of boiling is therefore desirable both for improving industrial efficiency and in developing new products. The region in the vicinity of a critical point, under weightlessness, is particularly interesting because it permits a clear observation to be performed thanks to the critical slowing-down and the absence of buoyancy.

Below T_c, the vapour phase co-exists, under low-g conditions, with the liquid phase as a bubble, and the liquid wets the cell wall. However, when boiling occurs, the vapour phase appears to ‘wet’ a large portion of the solid surface and large temperature gradients are measured between the gas and liquid phases. These gradients are related to the two-phase character of the adiabatic fluid heating (diphasic piston effect). Preliminary analyses seem to confirm that the surface-tension gradients are not the main cause. The vapour recoil force, due to momentum transfer at the interface during evaporation, shows a large divergence as T tends to T_c and thus appears as the most probable cause. As the recoil force is suspected to be the cause of the well-known boiling crisis in industrial heat exchangers, it is therefore likely that such experiments will provide new insight into the understanding of this problem. In addition, these recently observed and unexpected results on the interface dynamics open a new field for investigating boiling and two-phase thermalisation by the piston effect.

- *Supercritical Solubilisation*

Fluid systems in the near-critical and supercritical state have a great affinity to dissolve gas, liquid or solid material of other substances. One of the first commercial applications of this phenomenon (in the 1980s) was the decaffination of green coffee. At present, CO_2 extraction processing of coffee is one of the most important applications of supercritical fluids. Another classical application is the treatment of tobacco with supercritical CO_2 or nitrogen. Such treated tobacco contains much less nicotine and the tar condenses when it burns.

A growing interest in supercritical fluids as a reaction medium is also documented in recent literature. Contaminated and poisonous substances can be oxidised and neutralised in supercritical H_2O, or in other supercritical liquids. At present, supercritical fluid processing is achieving greater acceptance in the chemical, petroleum, and food industries. Critical fluids can be used as solvents and reaction mediums with specific properties in terms of density, pressure, and temperature, allowing their application for various purposes. For instance, a variety of substances with different critical parameters are licensed for unlimited use in food treatment.

Although supercritical fluid processing has gained increasing acceptance in many technical applications, the underlying physics is still not really understood. Open questions include: Why are critical fluids such excellent solvents and reaction mediums, and what is the process of mass transport in these fluids? This understanding of its physical nature is necessary for future progress. The solubility of a critical and supercritical fluid is caused by strong density fluctuations, related to the high compressibility of the fluid. This results in local microscopic inhomogeneities in density. One may picture it as ‘a dynamic liquid zeolite’. Thus it has a ‘porous’ structure, similar to that of a zeolite, with similar attractive forces to adsorb other substances within the pores. It is therefore proposed to undertake basic studies of critical fluids, in terms of dimensionless parameters for temperature and density, specifying the distance to the critical point. These would cover the basic nature of the solubility, the mass transport by means of mass diffusion, and the kinetics of the interface mass transport.

- *Supercritical Water Oxidation*

Oxidation in a supercritical water reactor is a powerful tool for transforming complex and dangerous organic compound wastes into their simple constituent components

(CO_2, H_2O and minerals). In addition, these reactors operate at moderate temperatures (about 400°C) and pressures (about 500 bar) in a process that is harmless to the environment. The yields of these oxidation processes are extremely high. Their mechanisms and dynamics involve heat and mass transport by diffusion, convection and possibly thermo-compressible effects associated with the adiabatic piston effect.

Because supercritical water breaks down dangerous organic molecules so effectively into simple and safe byproducts at relatively low pressures and temperatures, chemical reactions in supercritical water, sometimes called 'cold combustion', are of considerable interest to industry. These reactions need very strong convection to mix the reactants. Present and future developments in supercritical reactors, supercritical heat exchangers, and more generally supercritical pilot plants, depend on the way gravity effects are taken into account.

There has been no previous gravity-free investigation of combustion phenomena in supercritical fluids. Here chemical reaction (oxidation) must couple with thermo-compressible effects, like adiabatic heating by the Piston Effect. Experiments that are free of convection effects will provide new insight into the coupling between the diffusion of chemical species and the thermal transport. Consequently, the objective of studying basic reactions in the absence of convection should also contribute significantly to understanding and accommodating the gravity-induced effects.

2.3.5.10 Concluding Remarks

Supercritical fluids are of both fundamental interest (universality of phase transition, supercritical hydrodynamics) and industrial interest (supercritical solubilisation, oxidation, thermalisation, storage). The field of critical point phenomena has achieved major breakthroughs during the past 15 years thanks to microgravity. In particular, a new thermalisation process has been discovered, the 'piston effect', which reveals a special type of hydrodynamics in such near-critical fluids. That study has led to a strong modification of the prevailing view of critical-point phenomena and even of hydrodynamics. Future experimentation on the ISS will certainly lead to further new and unexpected phenomena, which will be of interest for both fundamental and applied science.

Further Reading

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2.3.6 Interfaces, Foams and Emulsions

A. Passerone & D. Weaire

2.3.6.1 Surface Tension

Surface tension is a basic property of all liquid surfaces and interfaces. It expresses the resistance of an interface to stretching. Many manifestations of surface tension and this resistance to stretching can be found in everyday life. For example, a water surface can support small objects, a thin liquid layer tends to form droplets rather than to spread on a solid surface, and liquid drops that hang from taps and soap bubbles are almost perfectly spherical.

Indeed any liquid interface acts more or less as a stretched elastic membrane, so that a force is exerted between the two sides of any imaginary line on the surface or along the contact line between a liquid interface and a solid. Hence water can support an object provided that the force exerted by the surface tension along the contact line is larger than the object's weight. A drop can hang in equilibrium if its weight is smaller than the surface-tension force exerted along the contact line with the solid support.

Surface (or interfacial) tension σ is the force per unit length needed to keep an interface cut along a line in mechanical equilibrium, as illustrated in Figure 2.3.6.1.

As a direct consequence of the existence of the interfacial tension, there is a difference of pressure across any curved liquid interfaces, called 'capillary pressure'. For example, there is a larger pressure inside a droplet than outside. Like a balloon that is stretched by the internal over-pressure, a soap bubble is kept from collapsing by this capillary pressure.

The existence of this pressure was first recognised by Laplace and by Young at the beginning of nineteenth century. The relationship between

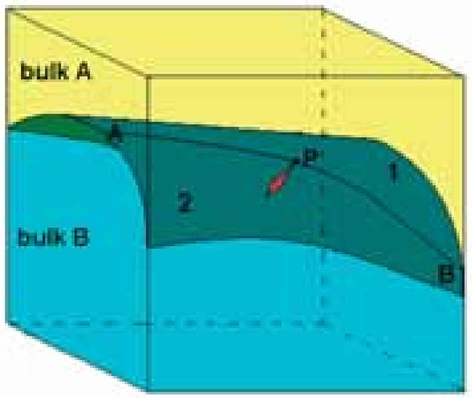


Figure 2.3.6.1. Interface between two immiscible fluids A and B. The interfacial tension σ (red arrow) acts in a plane tangential to the interface at any point P of the interface itself

the capillary pressure P and the interfacial or surface tension σ is thus known as the Laplace equation:

Capillary Pressure P = σ (surface or interfacial tension) x K (surface curvature)

where K is the curvature of the surface (the inverse of its mean radius of curvature).

For common liquids and macroscopic interfaces, the capillary pressure is generally one thousand times smaller than the atmospheric pressure. Nevertheless, it has important effects on the properties of liquids. For example, the shape of pendant drops in the presence of gravity is set by the balance of the capillary pressure and the hydrostatic pressure, the latter being due to the weight of the liquid. At a given height, the curvature of the interface, i.e. the drop (or the meniscus) shape, adjusts itself in order to make capillary pressure consistent with the hydrostatic pressure. Indeed, one of the most used methods for measuring surface tension is based on the analysis of drop shape.

In the absence of gravity, the hydrostatic pressure is zero and so the capillary pressure is constant at each point of the interface, which means that the interface curvature is the same at each point of the interface. The only closed surface of this kind is the sphere, and this is the shape of free drops in microgravity conditions. Liquid surfaces attached to supports or containers have more complex shapes imposed by the contact-angle boundary conditions and the requirement of minimum surface area.

Equilibrium values of surface tension can be established for pure systems in times that are of the order of the relaxation times of atoms or molecules. When dealing with low-viscosity liquids, they are well within the experimentation times. However, whenever multi-component systems are dealt with, the adsorption processes at the interface, which follow their own kinetic laws, have to be taken into account.

Pure substances are important from a theoretical point of view, because the measurement of their surface tension can give valuable insight into their atomic constitution, inter-atomic potentials, bond strength and so on. However, it may be much more rewarding from a technological point of view to study multi-component systems and to find out the behaviour of the surfaces under 'normal' conditions, i.e. in polluting atmospheres, in the presence of trace elements (impurities or deliberate dopants), or in the presence of chemical reactions.

For pure liquids, the surface tension depends on temperature (and pressure), decreasing when it increases, eventually reaching zero at the critical point. For liquid solutions, the magnitude of surface tension depends strongly on the composition of the interface and decreases as the solutes accumulate at the interface. Almost all polar molecules are able to adsorb at the surface and reduce the surface tension of water (or of other polar solvents). However, it has been well known since the last century that some substances are particularly efficient in doing so. In the case of molten metals, particular elements such as oxygen or sulphur have the same effect. These substances are called 'surface active agents' or 'surfactants'. For water or organic liquids, soaps are only the first and most widely known example of a long list of natural and synthetic surfactants. All of these molecules have two ends, which respectively 'like' and 'dislike' to be in contact with water and are therefore called 'hydrophilic' and 'hydrophobic' groups. These 'amphiphilic' (from the Greek for both) molecules segregate at the interface, where they can embed their hydrophilic heads in the water and their hydrophobic tails in the air.

For the so-called 'soluble surfactants', an equilibrium is established between the amount of molecules adsorbed at the interface and the amount in the liquid volume. This equilibrium is reversibly shifted as the solution concentration changes. These phenomena can be experimentally verified by measuring the surface tension of a surfactant solution as a function of the concentration. As shown in Figure 2.3.6.2, beyond a certain concentration the surface tension becomes practically constant.

This reflects an important property of surfactants in solutions. When a critical concentration is reached, the excess surfactant molecules form into aggregates, called 'micelles'. These do not contribute to surface activity. In these conditions, the concentration of free surfactant molecules is constant and, consequently, the number of adsorbed molecules and the surface tension do not change.

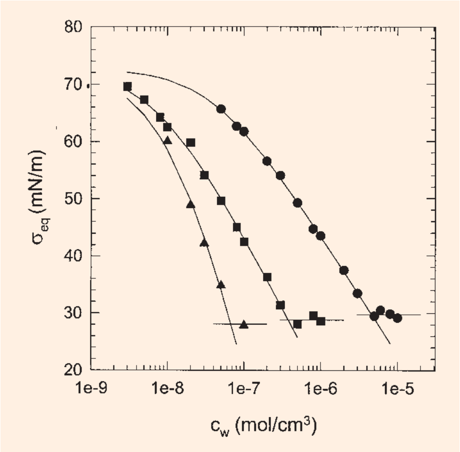


Figure 2.3.6.2. The surface tension of water as a function of C_nDMPO concentration (n = 10,12,13); DMPO = Dimethyl Phosphine Oxide (after Ravera F. et al. 1997, Langmuir 13, 4817)

2.3.6.2 Adsorption Dynamics

The adsorption process is not instantaneous, since the transfer of the surfactant molecules from the bulk to the interface requires a finite time to restore the equilibrium situation. During this process of adsorption kinetics the surface tension varies with time, according to the instantaneous value of the adsorption. A surfactant system can be displaced out of adsorption equilibrium, for example by diluting or compressing the adsorbed layer, thereby varying the interfacial area (Fig. 2.3.6.3). Adsorption kinetics also take place on freshly formed interfaces. At the time of formation, the interface is ideally free from surfactant. A fresh interface can effectively be created by imposing a large and rapid expansion on an existing interface.

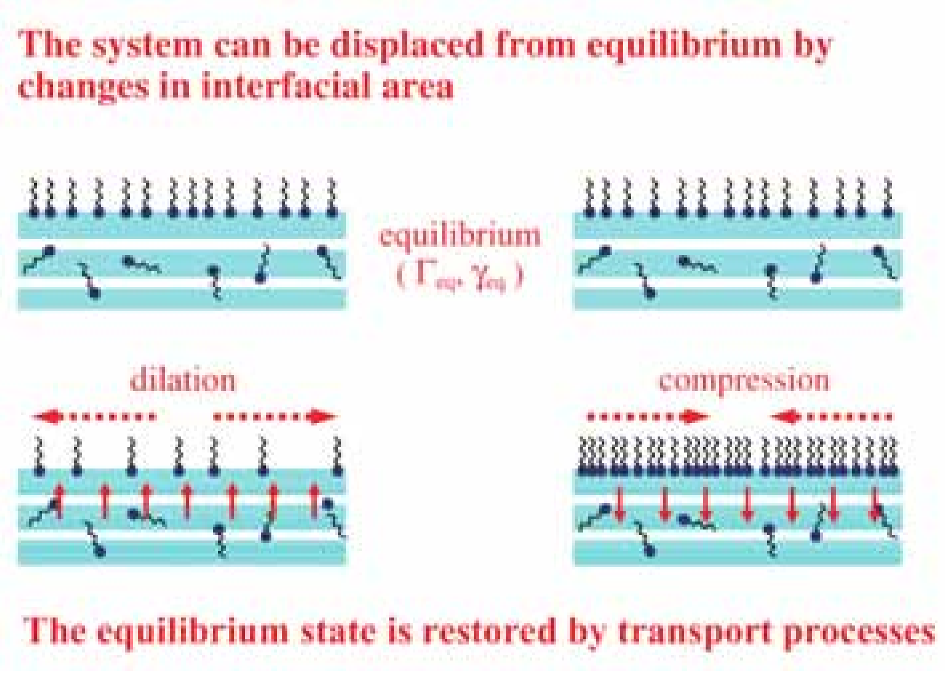


Figure 2.3.6.3. Schematic of adsorbed molecules at a free surface. If the surface is stretched or compressed, molecules are displaced from or to the surface, so that the surface tension changes in a dynamic manner

Two transport mechanisms underlie the progress of the adsorption kinetics. Firstly, there is the interface exchange of molecules with the liquid layer just adjacent the interface: this is the so-called ‘adsorption proper’. Due to the latter, the concentration in the layer adjacent to the interface is changed, so that diffusion of the molecules in the bulk takes place to restore the concentration equilibrium. These mechanisms act at the same time, but develop on independent time scales. Depending on the system, adsorption kinetics can develop on time scales that range from milliseconds, as in the case of short chain alcohols, to days, as is the case of proteins or long polymers.

2.3.6.3 Interfacial Phenomena and Low-gravity Conditions

Microgravity conditions present a unique experimental environment for the study of interfacial and transport phenomena in fluid systems. There is a drastic reduction in the gradient of the hydrostatic pressure. Consequently, the effects driven by capillary forces, differences in chemical potentials and other mechanisms are enhanced or isolated. In particular, in order to adequately study adsorption kinetics at fluid interfaces a simple geometry for the surface is required, together with the absence of gravity-driven convection, which could deform the bulk diffusion profile near the interface. Inter-atomic and molecular forces, which are at the origin of interfacial tension, are much stronger than the forces due to gravity. For this reason, interfacial tension is not expected to change in a measurable way when going from terrestrial conditions to a microgravity environment.

Nevertheless, as explained earlier, bulk effects (such as convection) related to gravity can often obscure phenomena dictated by interfacial tension. The relative strength of bulk and surface forces can be assessed by using the Bond Number, $Bo = \rho g L^2/\sigma$. Here ρ is the density, g the acceleration due to gravity, L is some characteristic length of the system (such as the diameter of a drop) and σ the interfacial tension. On the ground, at large Bond numbers, the contribution of the potential gravitational energy completely overshadows the capillary contribution. Only at small Bond numbers, i.e. when the system dimensions are very small, does the interfacial tension significantly affect the shape of the liquid volume.

In the microgravity conditions of a space platform, the Bond number is always nearly zero ($\rho g \approx 0$), and so all liquid volumes have outer surfaces whose shape is determined by their surface-tension value and by the geometrical boundary conditions. Accordingly, space can be used as an environment in which more sensitive and more precise surface-tension measurements can be made.

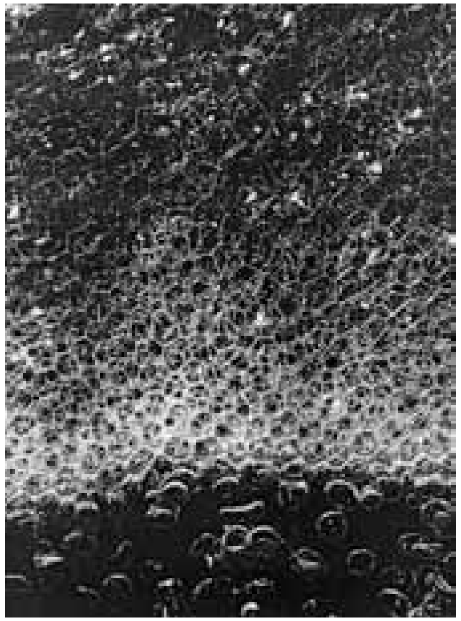


Figure 2.3.6.4. A foam is often formed by bubbles rising in a liquid (photograph courtesy of J. Cilliers, UMIST, UK)

2.3.6.4 Foams

The cellular structure of a liquid foam is made up of gas bubbles surrounded by liquid, which is in the form of a thin film wherever two bubbles press tightly together. It is familiar in everyday life as a feature of cleaning agents and beverages. It is a considerable nuisance in many industrial processes that involve liquid/gas mixtures.

In order to control or optimise the behaviour of foams, it is necessary to better understand the properties of this unique form of matter. Physicists, chemists and engineers can combine their expertise here, because effects on various scales (those of the thin film, the bubble, and the bulk foam) are interlinked. The intricate disordered structure of a typical foam obeys strict rules of equilibrium, which dictate its local geometry. These rules were demonstrated by the Belgian scientist Joseph Plateau in the 19th century.

The foam can never be regarded as entirely static, unless it has been solidified. That is the situation in the common polyurethane foams, or in the more unusual metallic ones, which are described below. As long as it has a liquid component, the foam evolves under the action of three processes: drainage, coarsening and rupture.

'Drainage' is the term applied to the motion of liquid through the foam. Usually, a freshly made foam is left to stand and gravity extracts most of the liquid from it. Eventually, an equilibrium profile of density (or liquid fraction) as a function of height is established. The remaining liquid is held up by surface tension. Only very close to the underlying liquid is the foam 'wet', i.e. with a liquid fraction of more than about 15%. There is a useful approximate rule-of-thumb whenever the foam is in contact with underlying liquid. In equilibrium:

$$\text{Thickness of wet foam layer} = l_0^2 / d$$

where d is the average bubble diameter, and

$$l_0^2 = \sigma / \rho g$$

For example, both l_0 and d might be of the order of 1 mm, in which case only the wet foam consists of only a single layer of bubbles, in normal gravity.

'Coarsening' is the increase with time in the average size of bubbles. This is due to the diffusion of gas through the thin films, due to pressure differences. Generally speaking, this proceeds from small to large bubbles and so continually eliminates the smaller ones. In the final stage of the life history of a foam, the 'rupture' of thin films eventually takes over and causes it to collapse.

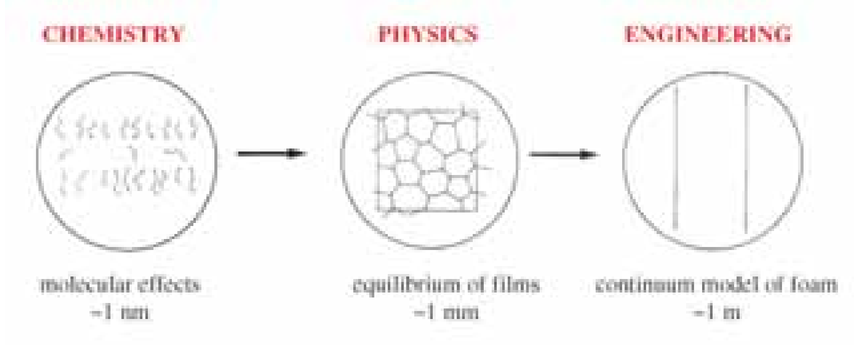


Figure 2.3.6.5. Effects on various scales are interlinked in foams

In recent years, this eventful life history has been chronicled in some detail. It has come to be well understood only in the limit of a static, dry foam. In part this limitation is due to experimental obstacles because a wet foam rapidly drains in normal gravity. Attempts to circumvent this difficulty include the trick of continuous addition of fresh liquid (forced drainage). In that case, a hydrodynamic instability intervenes to limit the effectiveness of the procedure. Another solution is to use very small bubbles, as the above equation would suggest. This is not easy, and speeds up the coarsening process. Uniform wet foams in equilibrium can, however, be made by taking advantage of the microgravity environment of space. By careful measurement of their properties in microgravity, it is expected to be possible to extend the range of present theories. This approach also adds a new dimension to foam technology.

2.3.6.5 Emulsions

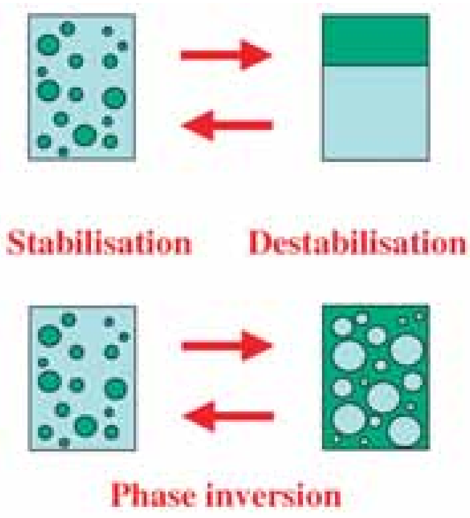


Figure 2.3.6.6. Schematic representation of stabilisation/destabilisation and phase-inversion mechanisms in emulsions

Immiscible liquids are often found in industrial processes. If they are mixed together and shaken, a dispersion of small droplets of one liquid into the other phase is obtained, i.e. an emulsion has been formed (Fig. 2.3.6.6). Emulsions occur in natural products (oil, milk), in foods (mayonnaise), pharmaceuticals, cosmetics, and many other agricultural and industrial products.

In some cases, such as that of foods, emulsions have to be stable, i.e. they have to retain their original properties. In other cases, they have to be destabilised in order to recover the individual constituents, for example in oil recovery. The control of stability is therefore one of the most important problems in emulsion science and technology. Efficient, safe and cheap ways of stabilising (or destabilising) a crude-oil emulsion can make all the difference to the economy of an oil field. Hence, the oil industry actively supports such projects related to crude-oil recovery. The crude oils are emulsions either of water in oil or of oil in water, stabilised by natural surfactants (asphaltenes). Stabilisation/destabilisation is relevant to all production steps, from drilling to refining, as regards both emulsions and foams.

There are many factors and mechanisms at work in emulsion destabilisation. Among them are: 'aggregation', in which different droplets of the dispersed phase aggregate in clusters, 'coalescence', in which two or more droplets fuse together, and 'Ostwald ripening', in which the liquid contained in a smaller drop diffuses to a neighbouring larger one due to the different surface curvatures (Fig. 2.3.6.7). In all cases, the two phases are subject to gravitational forces and tend to eventually ‘cream’ to the surface, or ‘settle’ to the bottom, as a function of their relative densities. Creaming, Ostwald ripening and coalescence are closely analogous to drainage, coarsening and rupture, in the terminology of foam physics.

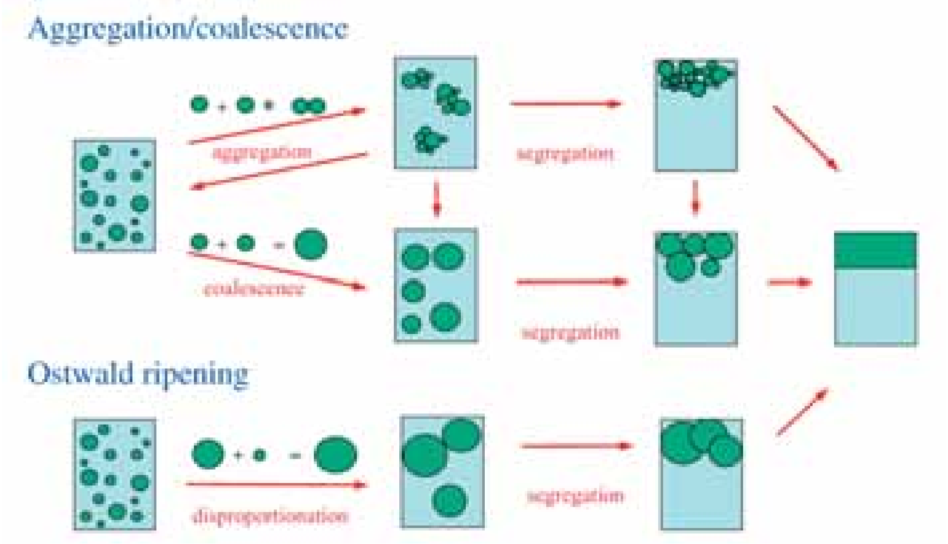


Figure 2.3.6.7. Destabilisation mechanisms in emulsions: segregation occurs in a gravitational environment, due to the different specific weights of the two phases

Advances in the control of emulsion stability can be achieved by increasing our knowledge of the elementary mechanisms already mentioned, and the processes of adsorption and transfer of surfactants that underlie them.

2.3.6.6 Microgravity Projects

- *Foams*

There have been occasional microgravity experiments on foams over recent decades, conducted by American, Canadian and European teams. For the most part, they have been quite preliminary and exploratory. They suffered from the poorly developed state of the theory at the time, which made it difficult to frame precise questions for experiments to address.

In the early nineties, for example, foam flotation in a microgravity environment was investigated using parabolic flights sponsored by NASA. Foam flotation is an important industrial process, in which suspended matter is removed from a liquid by adsorption in a foam. As expected, a strong dependence of the size of recovered particles on the strength of gravity was found, but there was no detailed analysis. Nevertheless, this was a useful pointer to the practical use of this technique in space, for waste treatment or for biological sample processing. Similarly, a number of interesting experiments were carried out on foam drainage, but the interpretation was rudimentary.

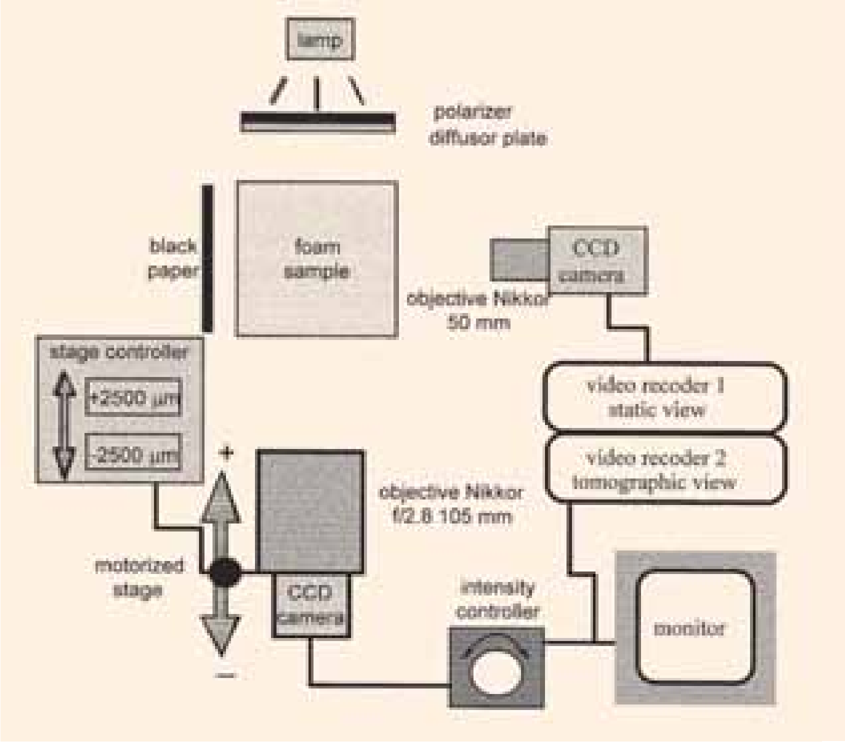


Figure 2.3.6.8. Experimental system used for the observation of foams in microgravity (from C. Monnereau et al. 1999, J .Chim. Phys., 96, 958)

More recently, the Meudon group of M. Vignes-Adler has used parabolic flights to vary gravity while creating and observing aqueous foams. The detailed structure of samples of about 100 bubbles was captured and analysed by optical tomography, so that it was even possible to identify the precise shape of every bubble.

Another European group, at the Fraunhofer Institute in Bremen (D), has embarked on the fabrication of metallic foams in microgravity. Nowadays many substances can be formed as solid foams, among the more surprising being glasses and metals. Fabrication methods have steadily progressed to the point at which a wide variety of alloys may be processed, and there is some limited control over their structure. Further development is motivated by emerging markets for this product, particularly for structural and energy-absorbing automobile components.

Figure 2.3.6.9. Equipment for metallic foam formation used on parabolic flights (courtesy of the Fraunhofer Institute, Bremen, Germany)

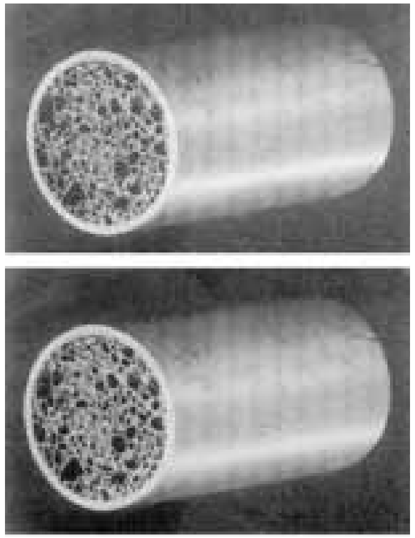
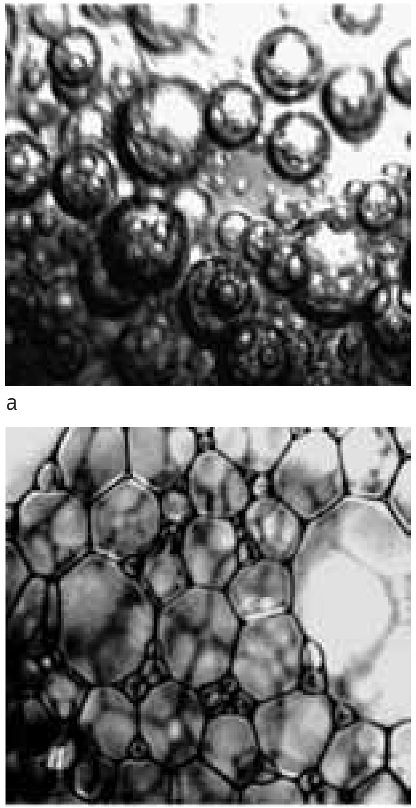


Figure 2.3.6.10. A typical metallic foam encased in a cylinder. This new material offers many advantages in terms of weight, strength and energy-absorbing characteristics (courtesy of J. Banhart)



a

b

Figure 2.3.6.11. Foam sample in two different gravity environments (courtesy of Monnereau et al.)

The creation of a solid metal foam is a race against time. Once formed in the liquid state, it must be frozen quickly enough to avoid drainage and collapse. Again gravity is the enemy. Fabrication in space raises fascinating possibilities: it should be possible to greatly extend the range of alloys, eliminate additives that have served to increase viscosity, and produce superior-grade materials.

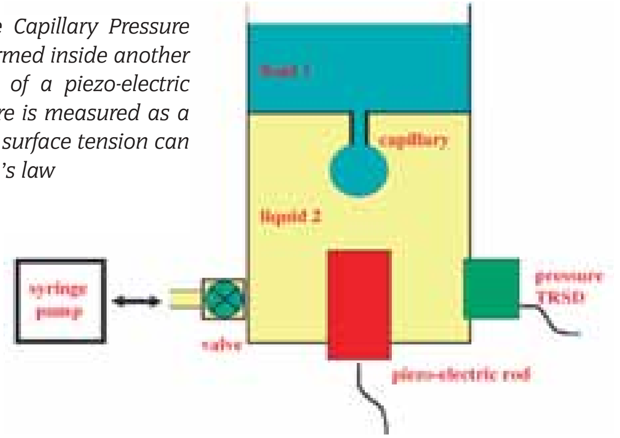


Figure 2.3.6.12. Schematic of the Capillary Pressure Tensiometer. A drop of fluid 1 is formed inside another immiscible fluid 2 by the action of a piezo-electric actuator, and the capillary pressure is measured as a function of the drop diameter. The surface tension can be calculated by means of Laplace's law

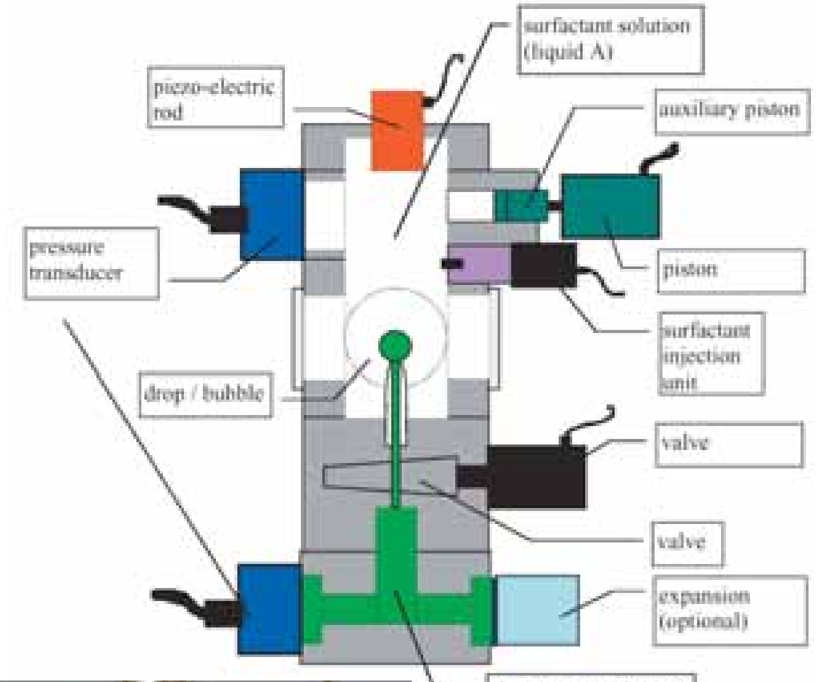
Two international projects were recommended for ESA funding in 2000, under arrangements that allow for terrestrial research in the first instance, and are aimed at the eventual utilisation of the International Space Station. 'Hydrodynamics of Wet Foams' is coordinated by Guy Verbist, of the Shell Research Laboratory in Amsterdam. His team plans to study drainage, particularly of wet aqueous foams. 'Development of Advanced Foams under Microgravity', co-ordinated by John Banhart of the Fraunhofer Institute, is primarily devoted to metallic foams. Both projects are concerned with the development of new methods of monitoring foams in real time, so as to enhance the quality of the data available for comparison with theory.

- *Emulsions*

The ESA 'FAST' and the subsequent 'FASES' projects aim to establish a quantitative link between emulsion stability and the physical chemistry of droplet interfaces. Research groups from Italy, Germany and France are co-operating at three levels of investigation. These are:

(a) the study of adsorption dynamics with transfer of matter and interfacial rheology of liquid/liquid interfaces
(b) the study of drop–drop interactions and of the physical chemistry of the interfacial film
(c) the study of the dynamics of phase inversion in model emulsions.

The projects, supported also by the ESA Topical Team 'Progress in Emulsion Science and Technology', co-ordinated by R. Miller of the Max-Planck Institut, Berlin, include



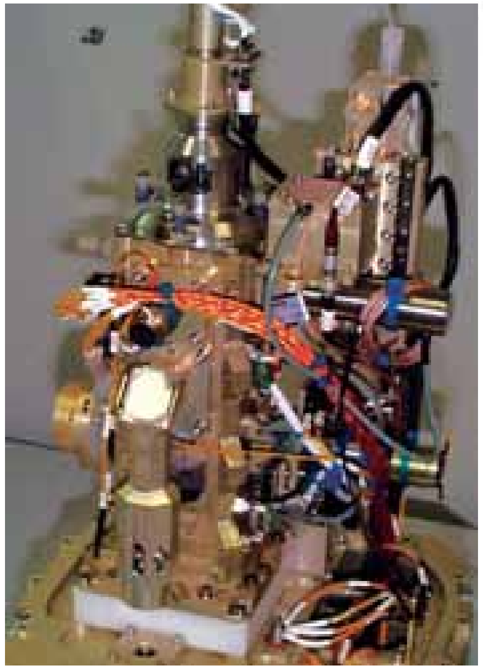


Figure 2.3.6.13. The layout of the Capillary Pressure Tensiometer, constituting the core of the FAST facility

Figure 2.3.6.14. The FAST facility, flown on Shuttle mission STS-95 in October 1998

experiments in the laboratory, on sounding rockets (Texus, 1993), and on Shuttle-Spacehab missions (1998, 2001) (Figs. 2.3.6.13 and 14). Continuing work on the International Space Station is envisaged.

Drop deformations have also been studied in drop-tower experiments, whilst programmes aimed at developing new theoretical models and space experiments are being conducted in the United States and financed by NASA. The rheology of interfaces and of concentrated emulsions, the mobility of bubbles and drops, as well as thermocapillary/Marangoni effects, drop formation/break-up and phase separation, are increasingly attracting the attention of researchers.

In addition, emulsions play an extremely important role in metallurgy, when dealing with metallic systems that show miscibility gaps in the liquid state. Experiments with metallic Al-In emulsions have shown that other mechanisms can exist that may destabilise the emulsion, in particular Marangoni motions and wall effects. These effects were confirmed on metallic Cu-Pb emulsions in 1993. Sounding-rocket experiments had also been conducted in 1982 to test acoustic mixing devices to prepare Pb-Zn emulsions directly in microgravity conditions. It is worth noting that the Marangoni studies in microgravity conditions have led to important improvements in industrial metallurgical processes, particularly in the case of metallic emulsions for bearing alloys. Marangoni effects, with specific parameters evaluated in microgravity, can be used to counteract the gravitational pull on the ground. This procedure allows homogeneous dispersions of the softer (lubricating) phase to be obtained during continuous casting processes.

Acknowledgements

This contribution has benefited from discussions with members of the ESA Topical Teams:
- ‘Foams and Capillary Flows’, co-ordinated by D. Weaire. Members: J. Banhart, V. Bergeron, B. Kronberg, D. Langevin, P. Georis, G. Verbist, M. Vignes-Adler, D. Wantke, K. Lunkenheimer and J-C. Legros.
- ‘Equilibrium and Dynamic Properties of Adsorbed Layers’, co-ordinated by A. Passerone. Members: L. Liggieri, R. Miller, G. Pétré, G. Loglio, A. Steinchen and A. Sanfeld.

Further Reading

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2.3.7 Combustion

C. Eigenbrod

2.3.7.1 Introduction

Combustion is the process of transforming chemical energy into thermal energy. It is still the most important process for delivering energy to industrial processes, for electrical power generation, for the propulsion of cars, ships and aircraft, and last but not least, for the heating of homes, which ensures the existence of mankind outside the tropical and subtropical regions.

In most cases, combustion leads to a temperature rise and is accompanied by a decrease in the local density, generally by a factor of two to ten. This density change gives rise to buoyancy effects in many terrestrial combustion processes. By eliminating buoyancy and thus reducing the number of degrees of freedom, microgravity experiments can be of great benefit for the observation and understanding of basic combustion phenomena.

Numerical calculations, taking advantage of the increasing capacities of modern computers, have become the most important tool for developing new or better combustion technologies. However, the quality of the results from such calculations depends upon the quality of the basic input data, as well as the accuracy of the model. Consequently, the data derived from microgravity experiments can assist in the development of simulations by offering an improved material-properties database, in particular by providing validational help at a stage in development where natural convection-driven buoyancy has not yet been included.

Energy generation through the combustion of fossil fuels can and will be replaced by other energy sources to a substantial degree in the future, for example for electrical power generation. Nonetheless, mankind will need to rely upon such fuels for propulsion purposes for the foreseeable future. The combustion of these fossil fuels is inherently connected to both the consumption of finite resources, and the production of pollutants. Some major exhaust byproducts are themselves poisonous, such as CO, N_2O and soot. For others, like CO_2, SO_x and NO_x, the interaction with the global climate is more complex. Even though the energy consumption per capita will drop significantly in industrialised countries in the future, overall world consumption will actually rise, as the EC prognosis depicted in Figure 2.3.7.1 shows. This is due to the combined effect of the increase in population and the rise in per-capita energy consumption in the newly industrialising countries.

Figure 2.3.7.2 reveals that almost three quarters of the greenhouse emission effectively originates from industrial combustion, power generation and traffic. Since the CO_2 emissions from combustion (Fig. 2.3.7.3) can really only be lowered through the use of more efficient systems, a reduction in the use of fossil fuels is generally required.

2.3.7.2 Activities and Results in the Different Branches of Combustion Studies

In accordance with the three main types of combustion, the activities and results reported here are divided into three sub-areas: premixed, diffusion-flame and condensed-matter combustion. Each of these represents different, typical terrestrial energy-conversion processes. Whilst premixed and diffusive combustion deal with gaseous fuels, condensed matter first needs to be vaporised before combustion is possible. In some cases, there is technical overlap between these branches. The recent introduction of a fourth sub-area, that of non-intrusive diagnostics, acknowledges the major developments in this area that have been triggered by the specific demands of microgravity research facilities. These have led to inventions that have proved of great terrestrial benefit research, both in laboratories as well as in industrial applications. These diagnostics are increasingly finding their way into the closed-loop control systems that serve to optimise combustion processes.

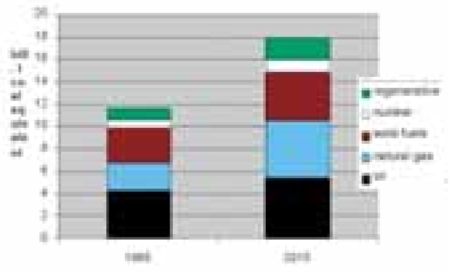

Figure 2.3.7.1. European Commission (EC) prognosis for future worldwide energy consumption

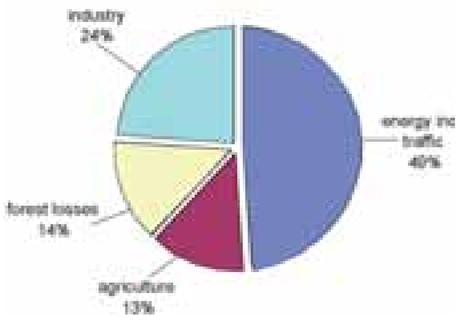

Figure 2.3.7.2. The origins of, and percentage contributions to, the greenhouse effect (courtesy of the World Resources Institute)

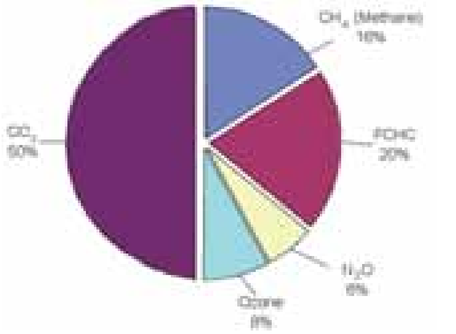

Figure 2.3.7.3. The percentages of trace gases driving the greenhouse effect (courtesy of World Resources Institute)

- *Premixed Combustion*

In premixed combustion, the reactants are well mixed prior to initiation of the combustion process. The majority of technical processes in gaseous combustion fall into this category. The temperature of premixed flames can be adjusted by changing the fuel-to-oxidant ratio. Usually, premixed flames are of low luminosity and are therefore more suitable for turbines than for heat exchangers. In a turbine, advantage is taken of the thermal expansion of the gas, while a heat exchanger requires radiative heat transfer from the luminous flame to the separating walls in order to be efficient. An important example of this is the gas turbine, used in natural-gas-fired power stations. The biggest single gas turbines currently in use have an electrical power output of about 300 MW. When operated in a combined cycle with steam turbines that use the steam generated from the gas turbine's exhaust heat, such power stations achieve efficiencies of about 60%. Centralised power generation will continue to be needed for the foreseeable future and, with the demand for higher profitability, even bigger assemblies will be required to optimise the installation costs per MWh.

The formation of nitric oxides (NO_x), which are both poisonous and environmentally harmful, is mainly determined by the combustion temperature. Therefore, this temperature should never exceed 1500°C, which is the onset temperature for the formation of thermal NO_x through the Zeldovich-mechanism. Operation below this rather low combustion temperature requires very lean mixture ratios (i.e. much air – little fuel), close to the flammability limits of natural gas.

This then leads to the first issue, which is addressed by research in microgravity. When trying to determine experimentally the flammability limits of a fuel gas/air premixture on the ground, the results are different for upward- and downward-propagating flames due to buoyancy effects. In microgravity, where buoyancy does not affect the diffusive process, it was possible to determine the true minimum air/fuel ratios. These values are below those found under terrestrial conditions (Figs. 2.3.7.4 and 5). These results supported the validation of chemical kinetics equations that were to be implemented in terrestrial combustion simulation. Microgravity experiments also revealed the tendency for propagating lean methane/air flame fronts to wrinkle and maybe later to form independent cellular flames. These phenomena were first observed by P. Ronney in hydrogen/air flames in microgravity.

Operation of a gas turbine at air/fuel ratios close the flammability limits is only possible if the mixture is perfectly premixed, but in reality this is hard to achieve. It would require a long duct to allow complete turbulent mixing of the separately injected reactants. As the air coming from the compressor is as hot as 400 to 600°C, self-ignition of the mixture could occur prior to its arrival at the combustion chamber. Thus the mixture has either to be richer, in order to avoid it being locally below the flammability limits, or the turbulence must be high enough to guarantee a homogeneous mixture even with short mixing lengths. Turbulence also leads to longer, wrinkled flame fronts. This would then result in the desired side effect of more flames per unit volume and thus smaller combustion chambers. As can easily be imagined, a lean flame, propagating slowly and just barely 'alive', is rather sensitive to both fluctuations in mixture ratio as well as to turbulence. Put simply, blowing into a flame will augment the combustion, at least until the local velocity becomes so high as to separate the flame from the unburnt fuel. Extinction, at least locally and temporarily, is then the outcome.

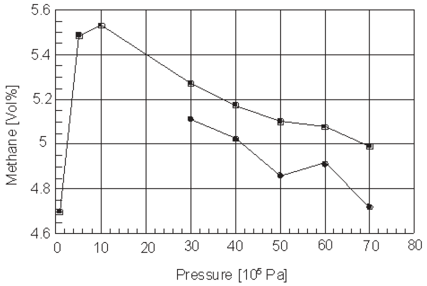

Figure 2.3.7.4. Flammability limits for methane/air under 1g (top) and μg (courtesy of Hyvönen & Peters)

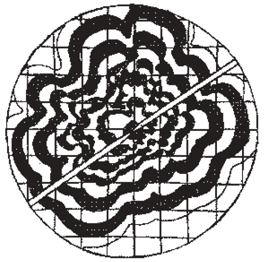

Figure 2.3.7.5. Flame propagation for 60 bar and 5.01 vol% methane (front recorded at 0.05, 0.1, 0.2, 0.3, 0.4, 0.5, 0.7, 0.9, 1.1, 1.3, 1.5 sec). 50 mm diameter Schlieren image (courtesy of Hyvönen & Peters)

Another gas-turbine-specific problem is related to periodic combustion phenomena that are assumed to be based upon design criteria, such as the number of revolutions per minute, the number of individual burners, the periodicity within the swirl-stabilised burners, and also the contours of the combustion chamber, serving as a resonant body. Because of that, these engines tend to fall into a noise-generating, oscillating operation mode, with associated pressure waves that can limit the lifetime of the engine and possibly even destroy it.

This touches on the second microgravity aspect, as it is not yet well understood how a lean, more or less premixed flame interacts with high levels of turbulence. High turbulence intensity in this case means small, highly energetic vortices. These vortices are so small that they are not only assumed to transport reacting layers through a given volume, but can also interact directly with a flame front with a typical thickness of the order of a tenth of a millimetre. If this interaction leads to local flame extinction, there will be fluctuations in local heat release. That in turn might lead to pressure fluctuations and, inside a resonant body, to the well-known 'humming' phenomenon. It is an open but important question whether such flame-vortex interaction is the source, or at least the amplifier, of combustion-induced oscillations. The interaction of a premixed flame with rather large turbulence eddies is well understood, but the effect of small eddies, having the dimensions of the flame-front thickness, is unknown.

The most basic experimental configuration needed to investigate this phenomenon is a lean, premixed propagating flame, running into an artificially produced vortex with well-defined properties. As the freely propagating flame on Earth is affected by buoyancy, as explained above, microgravity is needed to establish the required experimental conditions. Research teams in the USA and in Europe are preparing such microgravity experiments, with participation by industry. An ESA-supported Topical Team of experts has formulated the appropriate questions and the experimental hardware is being prepared within the framework of a Microgravity Application Promotion (MAP) project.

Modelling and simulation of turbulent combustion is a rather well-developed and integral part of commercial Computational Fluid Dynamics (CFD) tools. The inclusion of information on small eddy interactions can become an important enhancement, leading to better predictability of the behaviour of future highly efficient engines.

- *Diffusion Flames*

In diffusion flames, the fuel and oxidiser are unmixed prior to the initiation of combustion. Consequently, they must diffuse towards each other in order to react. The flame is always established close to the stoichiometric region within the concentration-gradient field. Stoichiometry is the equivalence ratio where the oxidiser concentration is exactly that which is necessary to completely burn the fuel. Stoichiometric flames are the hottest possible for the given fuel and the temperature is always beyond 2000°C.

Therefore, a priori control of the NO_x emissions is not possible. On the contrary, as such flames are used technically for, for example, process heat generation, a certain amount of particulates is often needed. These particulates are radiation emitters. They make a flame luminous and therefore serve to provide for efficient heat exchange from the flame to the walls of, for example, a steam generator, or to the material to be heated when producing melts of glass, ceramics or steel. In order to control polluting emissions, engineers are thrown back to an appropriate but costly post-treatment of the exhausts. To optimise such a system in terms of the highest efficiency coupled with the lowest or least harmful amounts of exhaust pollutants, detailed knowledge of the kinetics of diffusive combustion is required.

Another technical application of diffusion flames that is of increasing importance concerns the flame products. Carbon particulates, for example, are used for printing toner or serve as filler for tyre production, not only to colour them, but also for performance adjustment. Diamond thin films and coatings for hardening tool surfaces can be combustion generated and deposited on metal surfaces. The same is true for other carbides, for example those based on silicon that can be flame-generated and deposited. In all of these cases, the physico-chemical processes of diffusive combustion are the controlling factors. Despite their importance, there remains a lack of fundamental knowledge of these processes.

Microgravity provides an ideal environment in which to study these basic diffusion-controlled processes of combustion and particulate formation, without the masking effects of natural convection. The well-developed flamelet concept, used for modelling real turbulent combustion processes, is based upon superposition of the diffusion-controlled basic reactions with a turbulent transport. Thus, the accuracy of numerical calculations applying this widely used method depends upon the accuracy of the fundamental data. Microgravity experimentation and modelling is therefore the appropriate way to move from semi-empirical methods to a knowledge-based simulation.

Compared to 1g flames, the microgravity gas-jet diffusion flames have much greater tendencies to emit soot or other particulates. This is due to longer residence times and thus greater time for particulate formation, plus broader regions in which composition and temperature are favourable for particle formation. Recent quantitative measurements show peak soot-volume fractions about twice as high in microgravity as in 1g, for 50% acetylene/50% nitrogen-air flames. In addition, in microgravity the particles can agglomerate to form much bigger aggregates. This is because with weak convection, thermophoretic forces, which move particles towards lower temperatures, are an important effect. If the convection and temperature gradients are in the same direction, the convective and thermophoretic forces may balance at some location. This leads to soot accumulation inside the flame front in microgravity.

In order to study the formation mechanisms of soot and other particulates, microgravity experiments have been proposed within another ESA MAP project, applying a laser-based method to measure, in-situ, the sizes and growth rates within flames. Figure 2.3.7.6 shows the local size distribution of primary soot particles formed in a laminar ethane/air jet-diffusion flame under 1g conditions. Applying this quantitative method in microgravity conditions promises to yield much deeper insight into the formation process.

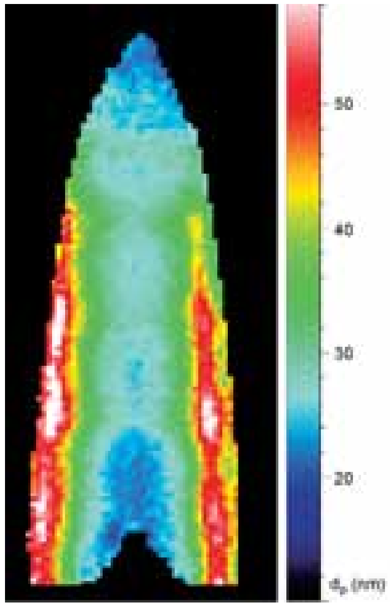

Figure 2.3.7.6. Size distribution and location of primary soot particles formed in the upper section of a laminar ethane-air jet-diffusion flame at 1g (courtesy of Prof. S. Will)

- *Condensed-Matter Combustion*

The term ‘condensed matter’ refers in this context to fuels that are initially liquid or solid. As the combustion process itself can only happen in the gas phase, heating and vaporisation or gasification processes must be introduced. Whether the subsequent combustion is of the premixed or diffusion type depends upon the uniformity of the fuel-gas/oxidiser mixture that can be established, prior to initiation of the combustion process. The majority of technical combustion systems fall into this category, including internal combustion engines (petrol and diesel), aircraft turbines, rocket propulsion, heating-oil burners, coal-fired power stations, etc.

Another important aspect that falls within this sub-area is fire safety. Dust explosions and smouldering combustion, with subsequent flash-over, are just two examples. The interaction with flames of the water sprays used for fire fighting, aiming at flame quenching through heat deprivation, is a kind of inverse combustion, but it follows identical rules.

An aircraft-type kerosene-fuelled gas turbine is pretty much comparable to the gas-fired power generators type discussed above. Several European Commission (Brite Euram, Low NO_x III) and various national research programmes are directed towards achieving a reduction in NO_x emissions from aeroengines.

Whenever a fuel spray is injected into a flame, the combustion will be of the diffusive type, because the droplets cannot vaporise straight away. After heating up and during vaporisation, the droplets’ surface temperature remains close to boiling temperature. The already gasified fuel burns at the stoichiometric concentration area in the vicinity of the droplets. The result is high local temperatures and thus high NO_x emission values, even though the overall mixture ratio was in the lean regime. The aim is therefore to ensure that the local mixture ratios are the same as that of the overall mixture, which is only possible with premixtures. One intended technical approach is the LPP (Lean Pre-vaporised Premixed) combustor, with each burner equipped with an additional premixing duct where vaporisation and turbulent mixing occurs before the mixture enters the combustion chamber. As state-of-the-art compressors deliver inlet temperatures of 600°C or more, and the trend in development is to exceed 800°C, the time for vaporisation and mixing is very limited before self-ignition occurs. In the case of a lightweight and thus comparatively fragile aeroengine, a resulting flashback, or even worse, a stabilised flame inside the premixing zone, is unacceptable. Detailed knowledge of the auto-ignition behaviour of a spray is therefore a prerequisite for effective design. Knowledge is definitely lacking in this area.

If a droplet could be followed from the injection nozzle, through the premixing area and into the combustion chamber until burnout, accompanied by the non-invasive diagnostics needed to answer the related questions, microgravity research would be dispensable. But since terrestrial diagnostics can only be applied to the spray in total, and since even the most sophisticated non-intrusive laser diagnostics fail when applied to a dense spray, microgravity is the most promising way out. This research has already found that under engine operating conditions, droplets can ignite in a staged regime with exothermal precursor reactions affecting the total induction time until hot ignition. Figure 2.3.7.7 shows the refraction-index distribution, which is linked to the temperature distribution, observed around an igniting droplet at different stages. These results led to the definition of new model kerosene and light-oil fuels, including staged-ignition behaviour. The model fuel data are needed to enable numerical simulations to transfer those findings into process simulations.

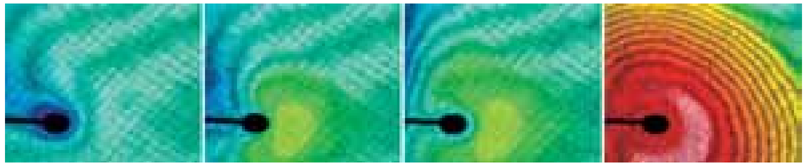

Figure 2.3.7.7. False-colour interferograms of a self-igniting, suspended n-heptane droplet in microgravity. From left to right: cool vapour area around the droplet, bright-green cool flame above ambient temperature, cool flame expanding, and hot ignition

In addition, the droplet spacing obviously plays a role. Droplets in a spray do not necessarily ignite individually, but when auto-ignition occurs at a preferred point the associated heat release might induce ignition of the whole volume. Figure 2.3.7.8 shows results from microgravity experiments, where development of the cool flame is indicated by the very weak chemo-luminescence of formaldehyde, which is a stable product of the cool-flame burning prior to hot ignition. For the given conditions, the 5 mm distance causes ignition to happen first, while the single droplet does not undergo hot ignition. This is assumed to result from a balance between the droplets sheltering each other (delaying ignition) and the fuel-vapour concentration rising more in the space between the droplets (impelling ignition). Numerical studies are required to find out which kinetic aspects are really responsible for this complex nonlinear behaviour.

As the translation of data from microgravity experiments into technical applications will be achieved through numerical simulation, knowledge of the detailed physical and chemical process is much more important than the question of whether or not experimental and technical conditions are directly comparable. In this respect, the ability to produce large droplets, which are very different from those in real applications in terms of size and thus induction times, is not a drawback, but a perfect condition for studying the whole process.

In another recently started ESA MAP project, partners from universities and the European gas-turbine industry will together investigate these issues. This project enhances the value of both the microgravity and ground-based experiments. These experiments will serve to validate the 'numerical pathway' from the space research to the practical engine application.

Coal combustion still plays the predominant role in electrical energy generation. Optimisation of the combustion process is all the more important because coal is inherently linked with comparatively high polluting exhaust contents. Unlike fuel droplets, the coal dust particles used in boilers for steam turbines are not spherical and are heterogeneous in consistency. Ignition of a particle exposed to the hot environment in a combustion chamber happens first at the surface of the coke pores. A noticeable temperature rise is first observed in the gas phase, following pyrolysis of the volatiles released by the particles. The remaining coke burns longest and contains the majority of the primary energy. In contrast to droplets, coal particles strongly absorb infrared radiation. Thus, particle heating is controlled by radiation instead of by heat conduction, as occurs with droplets. Radiation is absorbed at the surface, and so it is easy to imagine that the corners heat up quicker than the flat regions. As a sphere exposes the smallest surface per unit volume, the heating process is expected to be shorter the more the particle's shape differs from a sphere. For a given origin-dependent coal property, the efficiency of combustion as well as the composition of the primary exhausts is determined by the initialisation process – the ignition of both the volatiles and the coke.

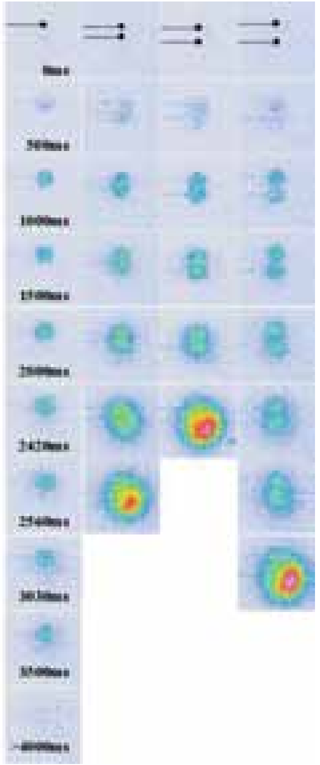

Figure 2.3.7.8. Chemi-luminescence of formaldehyde forming around self-igniting n-decane droplets at 1 bar and 430°C. Droplet initial diameter 1.5 mm. From left to right: a single droplet (no ignition); 3.5 mm centre distance; 5 mm centre distance; and 6.5 mm centre distance. The pictures were taken with an intensified high-speed CCD imager

In order to develop particular numerical coal-combustion models, detailed information about the initial phase of combustion is required. The first experiments on specifically shaped particles of Assam brown coal in microgravity revealed the expected dependency of induction times on specific surface (Fig. 2.3.7.9).

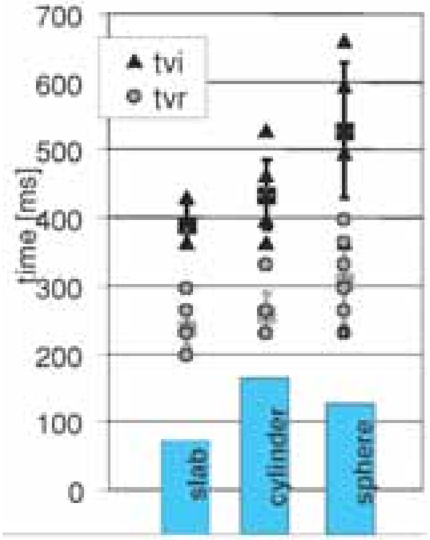

Figure 2.3.7.9. Comparison of induction times until release of volatiles (tvr) and until volatile ignition (tvi) for different basic particle shapes. Each data column represents 10 experiments, performed at the HNIRI 10 m drop facility in Sapporo. Coal: Assam brown. Heating: ~ 1000 K/s (with spot heaters)

The transformation from microgravity experiments on single particles to technical combustion will follow the same numerical pathway as from droplets to sprays.

Another example of condensed-matter combustion is fire. It is the worst thing that can happen onboard a spacecraft, because there is no easy way to escape from it and its poisonous combustion products. Fire prevention is therefore an extremely important issue in space.

On Earth, the energy released by a fire strongly depends upon buoyancy. In microgravity, buoyancy is absent and the only convection process driving a fire is that induced by the air-conditioning system. Thus, fires in space are usually much less vehement than on the ground. However, what looks like an advantage at first sight is particularly dangerous when looked at more carefully. Experience shows that fires in space can remain undetected until they have propagated and spread over wide areas. Besides the direct hazard, the fire can inflict a lot of damage, maybe even affecting the life-support systems.

All materials used in space vehicles need to meet specific flammability requirements that, in NASA's case, are provided in the document 'Flammability, Odor, Offgassing and Compatibility Requirements and Test Procedures for Materials in Environments that Support Combustion' (NASA-NHB 8060.1) This document specifies two tests that need to be performed before a material is qualified for use in a space vehicle: the upward flame-propagation test (Test 1) and the heat- and visible smoke release rates test (Test 2). These two tests are expected to properly assess the flammability of material in microgravity conditions. Experimental and numerical research conducted on the basic items have questioned the reliability of the results obtained with that protocol. In fact, behaviour has been found that is the reverse of that originally predicted. However, it is clear that the methods currently applied are not based on a true understanding of the phenomena, but rather on a semi-empirical strategy.

Joint project groups of scientists from Europe and the USA have defined an experimental approach to study systematically the role of the different modes of heat transfer and the influence of flow pattern and oxygen content in the gas phase. The mechanism of ignition, flame spreading and stability, as well as quenching, blow-off and other modes of extinction, will also be studied in a configuration corresponding to Test 1. The results will be incorporated into the existing body of theory. The aim is to define a new protocol to classify the potential fire hazards of specific materials based on fundamental understanding, rather than empirical worst-case scenarios. The results may therefore affect current regulations regarding material selection for microgravity environments, and this research also has the potential to improve fire prevention and fire fighting on Earth as well as in space.

- *Non-Intrusive Diagnostics*

Diagnostic methods, most of them laser-based and more or less non-intrusive, have been developed during the last fifteen years. These methods have provided impressive insight into the basics of physical chemistry in combustion. The unique properties of coherent laser light and its interactions with matter make it possible today to measure flame temperatures, short-lived chemical intermediates, flow patterns, concentration fields, and even the temperature distribution inside heating droplets. Not least, this can be done without probing, and therefore without affecting the process of interest. These developments are mainly the result of work by physical-sciences institutes in Europe and the USA in close co-operation with combustion researchers.

Fundamental combustion research in general, and particularly that performed under microgravity conditions, requires diagnostic methods that are able to present data with an accuracy and resolution appropriate to the exacting conditions. However, the transformation of these techniques from terrestrial laboratories to microgravity facilities has been slow. As a result, the methods applied to microgravity combustion were restricted for a long time simply to photographic or video observation, due partly to the mass and power limitations inherent in orbital facilities. It was also due to the complexity and sensitivity of the optical installations and the potential hazards associated with lasers that had to be dealt with. It is not surprising, therefore, that the drop towers in Bremen (D) and in Cleveland (USA) were the first facilities to adapt the techniques to microgravity combustion research.

One of the reasons why drop towers are used extensively for combustion research is that combustion processes generally have short time scales and thus suffer less from the limited microgravity time available in such facilities. The other is that the largest, most sensitive and most electric-power-consuming elements of laser diagnostics need not be dropped together with the experiment. The laser light can be either mirrored (Bremen) or fibre-transmitted (Cleveland) into the falling capsule.

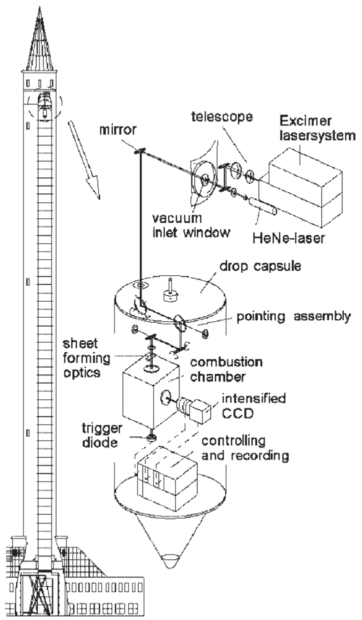

Figure 2.3.7.10. The laser diagnostic system at the Bremen drop tower. The 1 ton excimer laser system remains attached to the top of the drop tube. The pulsed laser is mirrored into the falling capsule

Figure 2.3.7.10 is a schematic of the laser diagnostic system at the Bremen drop tower. This installation was used for two-dimensional diagnostics of species concentrations. The hydroxyl radical was used as an indicator of the reaction area in flame, whilst the formaldehyde molecule, a stable product of low-temperature reactions, provided information on the processes preceding ignition. The method applied is Laser-Induced Fluorescence (LIF), a scattering technique in which only the molecules of interest are excited to fluorescence by highly energetic light with an extremely narrow spectral distribution, coinciding with the energy difference between the excited state and the equilibrium state of the specific species.

Both the limited time available in a drop experiment, as well as the transient nature of the combustion process itself, led to the development of a diagnostic system with comparably high repetition rates of up to 250 frames/second. As an example, Figure 2.3.7.11 shows selected OH-LIF images of a methane/air jet-diffusion flame during transition from the flickering 1g shape to the quasi-steady tulip-shaped microgravity flame. From this experiment, it was learned that microgravity flames are associated with surprisingly high rates of radiative heat loss. These can even lead to a flame outline that is not necessarily closed, but can build an open tip.

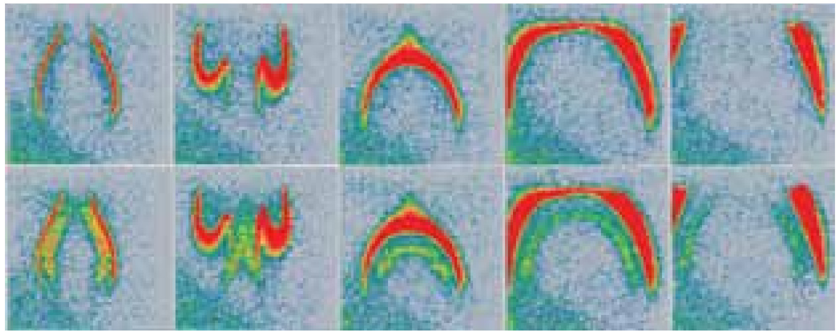

Figure 2.3.7.11. Selected OH-LIF images of a methane/air jet-diffusion flame during transition from 1g (left two images) to microgravity. Each image in the upper row was taken 4 ms before the corresponding image in the lower row (courtesy of L. Sitzki)

This diagnostic system, which resulted from microgravity requirements, has already been used successfully in industrial research. For example, it has provided the first visualisation (appearance and localisation) of combustion-induced oscillations in power-station gas turbines. Even though it was possible to measure the trend of these oscillations in terms of pressure waves and noise, it had never previously been possible to observe the inducing phenomena. This was due to the fact that lean natural-gas flames are invisible when viewed in front of a 1200°C chamber wall.

Such observations and measurements are necessary in order to learn how to design burners properly and avoid wasting time on costly trial and error experiments at the customer's site. A diagnostic system based on a solid-state laser of a completely new design, with repetition rates up to 2 kHz, is to be used on the International Space Station. Doubtless such a system will also find its way into terrestrial applications.

2.3.7.3 Conclusions

Reduced-gravity combustion experiments and modelling have led to a new understanding of the basic phenomena in many cases. In particular, the role of the different heat- and mass-transfer parameters in convection, diffusion and radiation is now much better understood. Consequently, the combustion research community at large has never called into question the value or validity of combustion research under reduced-gravity conditions.

However, there are still many inconsistencies to be clarified between results from state-of-the-art modelling and experiments. The problem with microgravity research has been that experiment opportunities have been so limited. Thus the data are also limited in number and often too scattered for new theories to be verified in a statistically acceptable manner. On the other hand, in microgravity, combustion researchers are in a good situation compared to other branches of science. As time scales in combustion are generally short, comparatively cheap and easy accessible drop towers have proved well suited to, and have been extensively used for microgravity experiments. With the advent of the International Space Station and its more extensive facilities and access, combustion research will receive a major boost. Such a facility with continuous microgravity access will definitely assist in changing the current situation as regards paucity of data. This fact that the combustion experiments can still be developed and evaluated at drop towers, before selection and preparation for space flight begins, will be a significant aid in using the Station and its facilities effectively.

ESA's Topical Teams, as well as the initial projects derived from the Team's discussions, have proved to be a very suitable means of ensuring focussed, user-driven research. By nature, this kind of research tends to be closer to fundamental research than to applications, but history has shown that such investment in the fundamentals does pay off. In most cases, the microgravity combustion research issues are far from immediate application, which means that a single company cannot be expected to bear all of the research costs. In specific cases, it might be different for a pool of European companies. In general, however, the outcome of microgravity combustion research, at least initially, will be in the form of publications, which need to be carefully surveyed and fostered.

Perhaps one example may serve to illustrate here the point concerning the benefits that adherence to a long-term programme can bring. At present, no turbine manufacturer in the world, in either the power-generation or propulsion business, could stay in the market without using monocrystalline turbine blades. However, every such manufacturer has to rely on the knowhow of a US-based monopoly. Costly, extensive trials by European manufacturers to catch up in this knowledge have failed. Even though the US initiative had a military background, the critical knowhow was gained from a long-term research programme financed through NASA. Fundamental research in microgravity played a dominant and vital role within that long-term programme.

Further Reading

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2.3.8 Complex and Dusty Plasmas

G.E. Morfill & H.M. Thomas

2.3.8.1 Introduction

The field of complex and dusty plasmas has been one of the fastest growing research areas in physics in recent years (Fig. 2.3.8.1).

It was the rapid development of this field that recently prompted the American Institute of Physics to introduce corresponding identification codes (complex plasmas, dusty plasmas, plasma crystals, PACS 25.52.Zb). The term 'Complex Plasmas' was chosen by analogy with fluid physics, where 'Complex Fluids' are liquids enriched with small nano- or micro-particles, resulting in a rich spectrum of new physical processes – the physics of colloids. Accordingly, 'Complex Plasmas' are defined as fully or partially ionised gases, which are enriched with small nano- or micro-metre-sized particles. The inclusion of such particles in the plasma introduces a wealth of new phenomena and exciting physics.

The difference between these complex plasmas and the more historical 'dusty plasmas' is that the latter includes the huge field of contaminated (by dust) plasmas, with research ranging from astrophysics to the laboratory, and where the interactions between the species are mostly due to binary collisions.

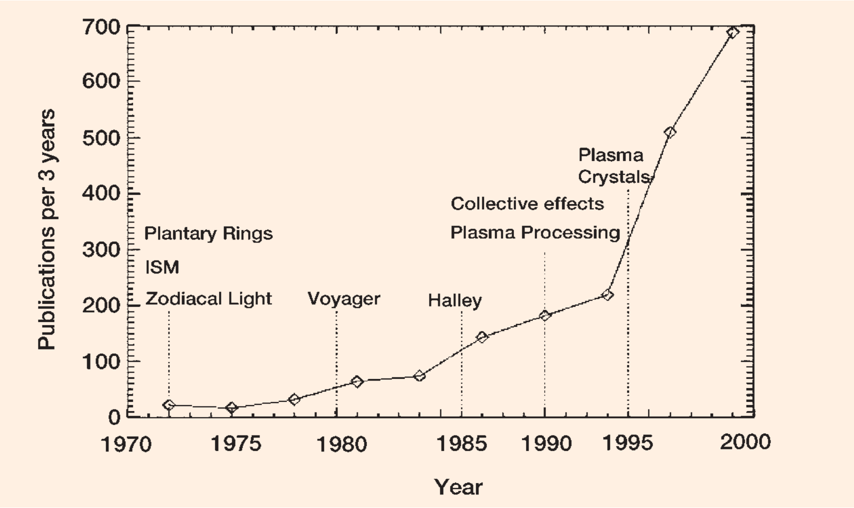

Figure 2.3.8.1. Publications in the field of 'Complex and Dusty Plasmas' (from A. Mendis)

By contrast, and by definition, the complex plasma contains the particles (or microspheres) as one of the active plasma components, participating in – and even dominating – the plasma physics, both by binary and by collective interactions.

Outstanding examples are the recently discovered liquid and crystalline plasma states. In the limit of very weak ionisation, for example in the Earth's atmosphere or in star- and planet-formation regions, other interactions may become dominant. These include condensation, coagulation, evaporation, and surface chemistry. But there may also be important processes such as collisional charging, which may introduce plasma-electromagnetic effects into the system, including possibly quite substantial effects such as lightning.

The subject of this Section necessarily covers a wide range of topics of broad scientific interest. Accordingly, the potential and scope of this field is first discussed and an overview of the diverse research interests is presented. The major fundamental processes that are the subject of current and (especially) future research efforts are introduced and summarised. This is followed by a discussion of the role that microgravity experimentation plays in these investigations, and the connections with terrestrial laboratory programmes. This naturally leads to a consideration of future industrial interests and the requirements for an integrated research effort in microgravity.

2.3.8.2 The Scope and Potential of the Field

In the Introduction, mention was made of some of the general processes occurring (e.g. binary, collective), without being very specific. In order to assess the importance and potential of this field, it is expedient to take a subject-oriented approach. Accordingly, some of the major research topics and the role played by complex (dusty) plasmas will be briefly summarised, subdivided into two broad areas: first the interdisciplinary aspects of complex (dusty) plasma science, including its applications, and then the fundamental research into the new liquid and crystalline plasma states that were discovered just a few years ago.

- *Interdisciplinary Studies*

Astrophysics
Dusty plasmas are ubiquitous in the field of astrophysics. They are found in interstellar clouds (ionisation fraction smaller than 10^{-2}, dust/gas ratio about 1% by mass), in star-formation regions, protoplanetary disks, circumstellar shells and in expanding, cooling nova and supernova shells.

Research has focused upon the basic processes of nucleation – i.e. How are the dust particles formed? – and on surface chemistry – e.g. What is the role of dust in H_2-molecule formation? It includes radiation transfer – in particular the radiative cooling of contracting clouds during star formation. Also included is the charge state: surface recombination on dust dominates over gas phase recombination above a certain threshold density and the cloud may then evolve independently of the magnetic field.

Coagulation studies investigate how particles grow by collision. Do they form fractal aggregates? Dust-gas interactions concern frictional coupling, mass loading of turbulence, turbulence damping, and so on.

The role of dust is spectacularly illustrated by two images taken with the Hubble Space Telescope (HST). Figure 2.3.8.2 shows the Eagle Nebula, which is irradiated by nearby hot stars and slowly evaporates. However, there are local inhomogeneities – density condensates that survive this evaporation process due to more efficient cooling by the dust. These inhomogeneities are seen as coherent clumps at the outer perimeter of the nebula, and may evolve into the birth-sites of stars.

Figure 2.3.8.2. HST image of the Eagle Nebula. Note the compact features at the top, which could evolve into protostellar clouds (from J. Hester & P. Scowen, Arizona State Univ., HST, NASA)

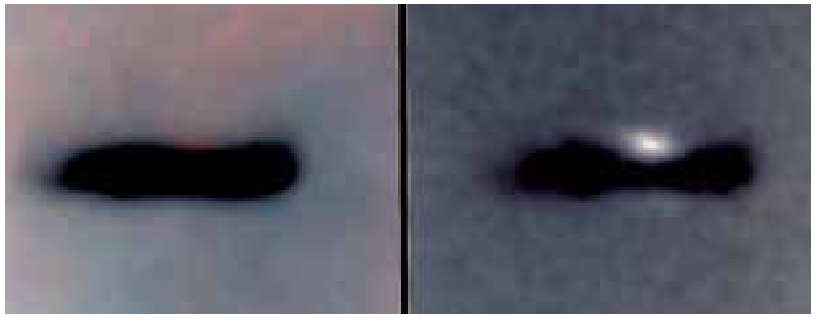

Figure 2.3.8.3. HST images of a circumstellar disc, which is believed to be the birth region for planet formation (from M.J. McCaughrean, MPIA, and C.R. O'Dell, Rice Univ.)

Figure 2.3.8.3 shows an image of a young star still embedded in its protostellar disc. The object is seen silhouetted against the Orion Nebula in the background. It is the dust that obscures the background light and makes the disc appear dark. Such discs are believed to be the birth places of planets. The dust particles are micron-sized and the extent of such discs is typically 100 AU.

Solar-System Science

Dusty plasmas are found practically everywhere within the Solar System. The Zodiacal Cloud, a tenuous distribution of particles (largely in the 10 to 100 micron range) is made visible by the reflected sunlight and also through its infrared signature. The origin of the zodiacal particles is probably cometary, although some contribution from the asteroids and the minor bodies in the Kuiper Belt is also expected. The major questions are the source and transport, i.e. the radial evolution. The latter involves knowledge of the charging by electrons and ions from the solar wind as well as solar UV photons. Collisional and Coulomb drag and – for the very small particles in particular – radiation pressure and electromagnetic forces are also important.

The planetary rings have been a topic of great interest in dusty plasma physics ever since the detailed measurements by the Voyager missions were made available. The discovery of the existence of huge numbers of small micron-sized particles in planetary magnetospheres was, of course, a surprise. So too were the many significant and unexpected effects that these particles have. As representative examples of the new discoveries just two are mentioned here: the injection of sub-micron-sized particles into Jupiter's magnetosphere, due to the volcanic activity of the moon Io, and the dark triangular evolving features found in Saturn's rings, the 'spokes' (Fig. 2.3.8.4).

Major questions in dust-magnetosphere interactions involve the role of: mass loading (particle sputtering, photo-sputtering), impacts (particulate and plasma ejecta), momentum and angular-momentum transfer (ring evolution, instabilities, structure formation), regolith formation, cohesion of particles in a regolith and disagglomeration or electrostatic disruption and levitation, respectively.

There are also novel collective effects. For instance, small dust particles will orbit their planet with Keplerian velocity, modified somewhat by electromagnetic and radiation pressure forces. The magnetic field of the planet co-rotates, of course. This implies that inhomogeneously distributed charged dust particles produce local currents. These currents have to be closed and this therefore leads to new forms of collective dust-magnetospheric interactions that allow the exchange (ultimately) of gravitational and electrodynamic energy.

Comets, as already mentioned, are copious suppliers of small dust particles. As they approach the Sun, the more volatile materials start to evaporate. This leads to a number of interesting interactions involving particles, neutrals, the solar wind and

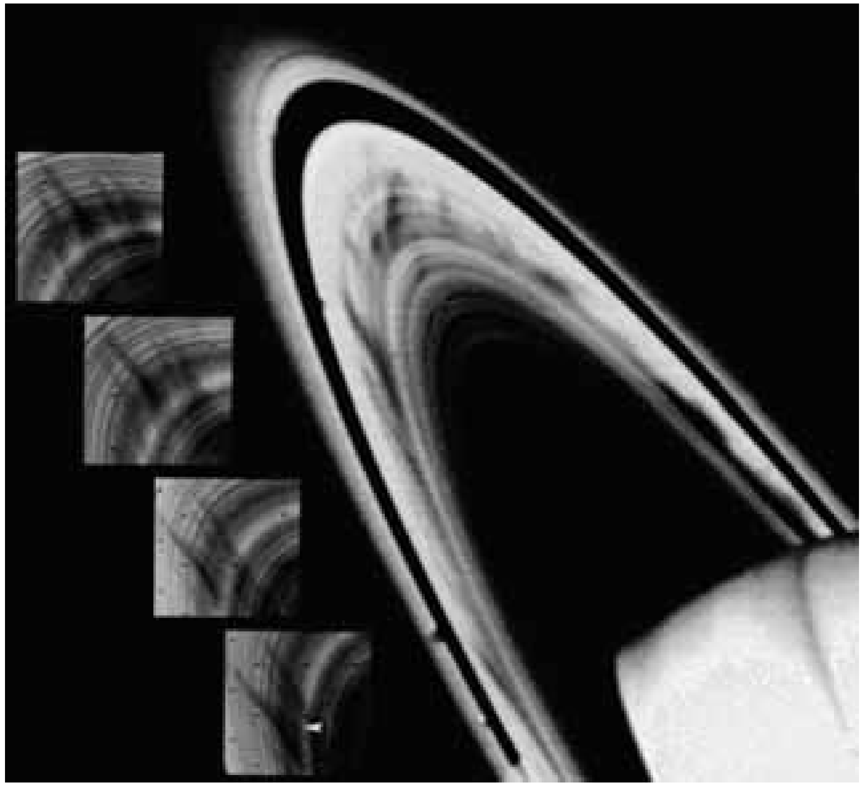

Figure 2.3.8.4. Image of Saturn's rings, including the dark 'spokes' (courtesy of NASA)

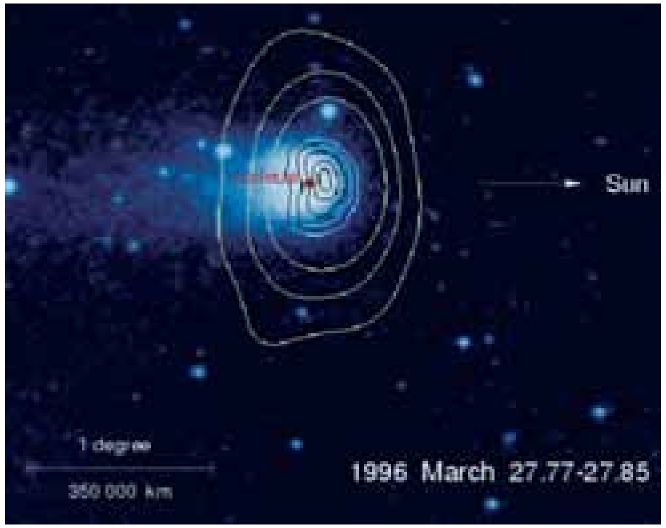

Figure 2.3.8.5. Contours of the X-ray and extreme-ultraviolet emissions of Comet Hyakutake, superimposed on an optical image. The inner five contour lines show the intensity distribution of the X-ray emission, observed with the Rosat High-Resolution Imager (HRI), while the outer three contours refer to the extreme-ultraviolet emission, measured simultaneously with the Rosat Wide-Field Camera (WFC). The optical image was taken during the Rosat observations. It is evident that the X-ray emission is coming mainly from the sunward side of the coma and not from the cometary nucleus (courtesy of K. Dennerl, Max-Planck Institut für Extra-terrestrische Physik)

sunlight. In addition, it is believed that comets contain essentially unmodified 'cold stored' material from the time of formation of the Solar System. Much of the information about comets has come from spectroscopic measurements and, of course, from ESA's spectacularly successful Giotto mission, confirming the notion of a 'dirty ice ball' containing mostly light and volatile material. A recent, totally unexpected result was the discovery that comets can also be detected in X-rays (Fig. 2.3.8.5).

The physics behind the X-ray emission lies in the interaction of the solar wind with the neutral gas and dust. Highly ionised solar-wind particles (in particular 'heavy' ions – carbon to iron) collide with the cometary ejecta and cause charge exchange. Recombination then produces photons of several hundred eV, which ultimately lead to the observed X-ray signatures.

- *Atmospheric and Environmental Science*

It was mentioned earlier, in the context of impact ionisation, that even very weakly ionised gases – such as the Earth's atmosphere – can nevertheless exhibit strong electromagnetic disturbances, such as lightning. This phenomenon occurs during thunderstorms, sandstorms, as well as in volcanic plumes – in fact everywhere where gas and dust are present and where free energy of motion exists. The surprise is that a few percent of the available energy in a thunder cloud, for instance, is released via lightning, which makes this non-linear process very efficient.

The physical processes of greatest interest are, as expected, the charge generation, the charge separation, the charge transport (in particular large-scale separation), the energy storage and dissipation. Dust, or water droplets, play an important role in all of these processes. This is easy to see, because free electrons would be too mobile to allow electric fields of the required magnitude for electrostatic breakdown to be built up. Hence, present efforts concentrate on dust (water droplets) as charge generators, as charge separators, and for the charge transport, e.g. size sorting during sedimentation or in convection cells via inertial effects.

Within the context of Solar System formation, lightning may have played a role too. One particular question of interest here is the charge generation during disruption of a conglomerate particle. Regarding other environmental issues, one could mention cluster-ion formation and the role of aerosols in the upper atmosphere, or the recently discovered particle layer in the mesosphere, which may be of man-made origin (a pollution effect) or may be 'natural' (e.g. due to meteor ablation). One could also invoke catastrophic events such as huge volcanic eruptions, major meteorite impacts or even the scenario leading to a 'nuclear winter'. Whatever the issues for research are, they all require a good understanding of the complex interactions involving dust particles, gases, plasmas, electromagnetic fields and radiation.

- *Industrial Processing*

Plasma technology is an important branch of industry, involving deposition as well as etching, and active as well as inactive gases. It is used in the manufacture of computer chips and solar cells, in surface treatments and coatings, and it has great potential in the design and manufacture of complex composite materials, to name but a few of the applications. Needless to say, the inclusion of nano- or micrometre-sized particles in a controlled process of manufacturing opens the possibility for new products. A promising programme involving 'polymorphous' (= amorphous plus nanocrystallite) solar cells has been started by the European Union. First results indicate an improvement in efficiency by a factor of approximately two compared with amorphous cells, as well as long-term stability.

Other application-related research, in particular controlled particle growth and surface treatment, is in progress in various laboratories, with applications ranging from pharmacy to printing.

- *Fundamental Research*

The discovery in 1994 of liquid and crystalline (complex) plasma states triggered a worldwide avalanche of research activities. Some six years later it is still continuing, with a growing number of researchers engaged in the diverse new science that has been opened up. There are some simple reasons for this continuing and growing interest:

- The strongly coupled liquid and crystalline plasma states can be investigated at the kinetic level – by direct microscopy of individual particle positions and velocities – which has not been possible before in plasma physics.
- The characteristic plasma time scales are 'slowed down' in these systems, due to the large masses of the microspheres. The microsphere masses are typically a hundred billion times heavier than the plasma ions. This brings the plasma frequency down from the usual MHz regime into the 10's of Hz, which are then easily measurable.
- Control and manipulation of particles is relatively easy using electrostatic, magnetic, mechanical or radiation forces, and hence many active experiments can be designed to investigate new phenomena occurring in these systems.
- Many principally different systems can be assembled and investigated – homogeneous, inhomogeneous, anisotropic, coulombic and paramagnetic systems being the most obvious – with different properties of interest for both fundamental and applied research.

The principal interactions in a complex plasma can be summarised as follows. The microspheres become highly charged through collisions with the ions and electrons. They therefore form a separate, massive, plasma component, which contributes to overall charge neutrality and which exchanges momentum and energy with the other plasma components (ions and electrons). The mobile ions and electrons are redistributed in the electric field around the individual charged microspheres, forming a charge 'cloud' of opposite polarity around each particle. This cloud has the effect of shielding (or neutralising) the microsphere charge over a characteristic distance – the shielding distance. Microspheres can interact with each other only if they approach to within a few of these shielding distances. If such interactions are frequent, the complex plasma is 'strongly coupled'. It may even become liquid or crystalline, yet it retains its plasma character.

- *Plasma Crystals*

The discovery of crystalline plasma states, the 'plasma crystals', was quickly recognised as a major advance in plasma physics, although the theoretical possibility had been discussed almost ten years earlier. A plasma – normally viewed as the most disordered form of matter – that was able to organise itself into a regular structure seemed remarkable at first glance. The promise of unexplored scientific territory and new physics was very powerful, and it is not surprising, therefore, that a large number of researchers have taken up the investigation of this new plasma state. Among the main regions of interest in this relatively new field are the following:

- Detailed investigation of self-ordering phenomena at the kinetic level for two- and three-dimensional systems (Fig. 2.3.8.6) – the kinetics of phase transitions.
- Investigation of the transition from 'Coulomb Clusters', containing small numbers of microspheres, to large macroscopic crystals – including the energetics of the binding forces.
- Surface-phenomena investigations at the kinetic level for different systems.
- Thermodynamics of plasma crystals, using measurements at the kinetic level, for both two- and three-dimensional systems.
- Three-dimensional structure of lattice defects, defect migration, annealing.
- Wave propagation in plasma crystals, compressional and shear waves, dispersion damping, microscopic physics at critical frequencies (e.g. the Debye frequency).
- Shock propagation in plasma crystals, detailed shock structure at the minimum (inter-particle distance) scale (Fig. 2.3.8.7).
- 'Manufacture' of glass-like plasma crystals, using suitable mixtures of different microsphere types, and the investigation of their properties.

These research topics are only a selection of those currently being studied. Each topic will require many experiments, using sophisticated plasma-chamber designs, imaging and data-analysis systems, before an advanced understanding of the process and basic principles is achieved.

It is important to note not only that the complex plasma systems are very different from the liquid-colloid (complex liquid) systems, but also that they complement the

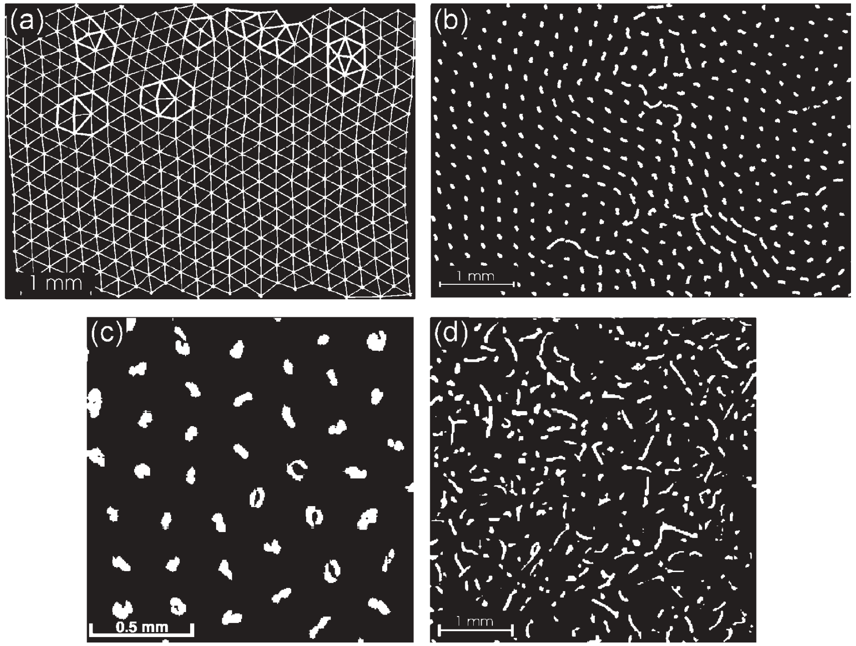

Figure 2.3.8.6. Phase transition from crystalline to disordered states of a strongly coupled complex plasma (from Thomas & Morfill 1996, Nature, 379, 806). The phases shown are: (a) crystalline, (b) co-existence of crystalline 'islands' and liquid states, (c) a vibrational phase that exhibits large-scale order and excited particles, and (d) disordered state

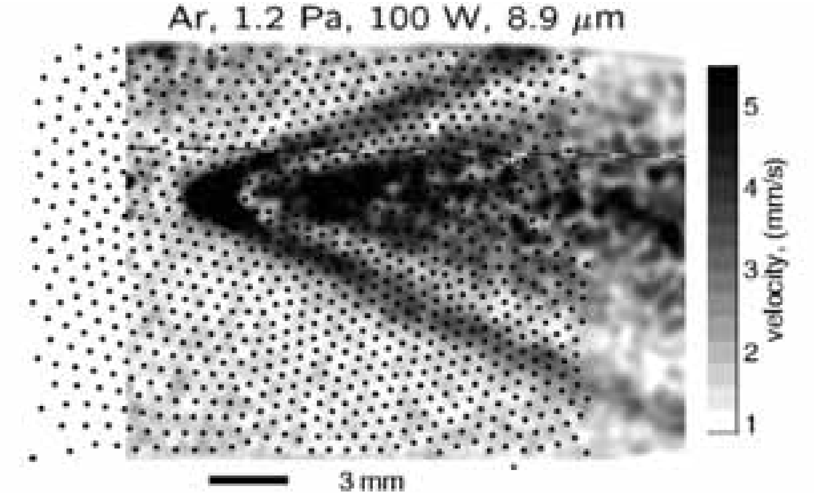

Figure 2.3.8.7. Mach cones observed in a two-dimensional plasma crystal. The complex structure resulting from inter-lattice forces (compression, rarefaction) is normally not discernible in macroscopic systems, where the scales exceed the inter-particle distances by many orders of magnitude. The figure shows particle velocity (grey-shaded) as well as particle positions (a snapshot), illustrating the relationship between shock structure and lattice separation (adapted from Samsonov et al. 1999, Phys. Rev. Lett., 83, 18, 3649)

research performed with the latter. The main reason lies in the response time scales. Since the neutral and ionised gas has virtually no mass compared with the microspheres, the damping due to friction between species in complex plasmas is typically 100 000 times smaller than that in complex fluids. This implies, among other things, that rapid processes can be investigated using complex plasmas, something that is impossible with complex fluids.

- *Liquid Plasmas*

Complex plasmas, as mentioned earlier, offer the possibility to observe a liquid practically at the 'molecular' (or kinetic) level. This has already resulted in many laboratory experimental efforts, since here is a good chance to study the thermodynamics and hydrodynamics from the most basic viewpoint – the motion of individual interacting particles. Among the fundamental processes of interest are:

- Shear flows and momentum exchange at the kinetic level. Derivation of 'macroscopic' fluid properties (e.g. viscosity) from microscopic particle measurements.
- Transition from laminar to turbulent flows at the kinetic level. Identification of new ordering parameters.
- Surface physics – microprocesses responsible for surface tension in different systems.
- Fluid interfaces at the kinetic level, flows, perturbations, instabilities.
- Impacts between liquid-plasma bubbles, including the full kinetics and energetics of the momentum transfer and energy dissipation.
- Study of convection cells at the kinetic level, self-organisation and structure formation (Fig. 2.3.8.8).
- Kinetics of guided flows (constriction, obstacles, redirection) to investigate inertial terms, for instance.
- Investigation of the response to oscillations, global mode excitations, etc.

Again, these research topics are just some examples of the current research. There are many more projects in preparation worldwide, particularly in the areas of active experiments, and it is practically certain that the forthcoming research will yield new questions that require even further studies. It therefore seems reasonable to assume that 'liquid plasmas' will contribute significantly to the detailed understanding of a range of nonlinear problems in fluid physics.

- *Some Basic Physics Issues*

There are several principal issues that have not yet been resolved, even after many decades of research. Complex plasma investigations may be able to make contributions here and initiate further advances. Among the currently unresolved questions are the following:

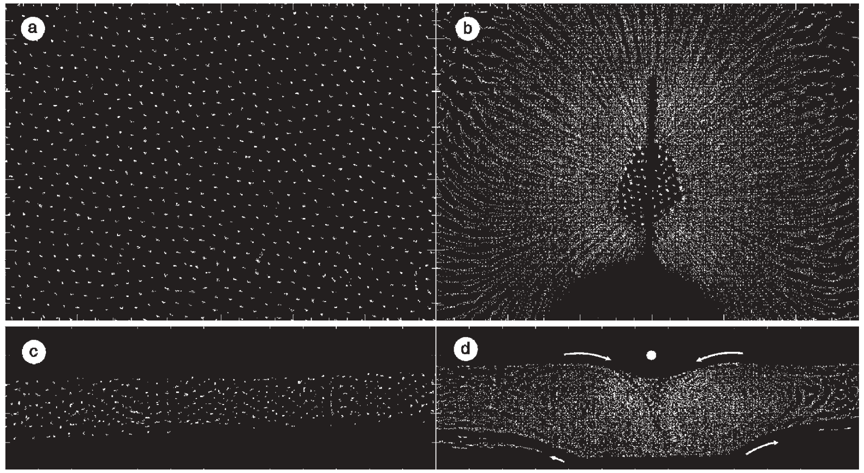

Figure 2.3.8.8. Convection patterns induced in strongly coupled complex patterns (from Law et al. 1998, Phys. Rev. Lett. 80, 19, 4189)

- Charging of objects in a plasma is an old topic, which is still the subject of intensive research. New approaches (e.g. binary collision experiments) have already been very valuable (Fig. 2.3.8.9). New activities could involve the investigation of different plasmas including composition and streaming as well as different particle shapes and ultraviolet radiation.

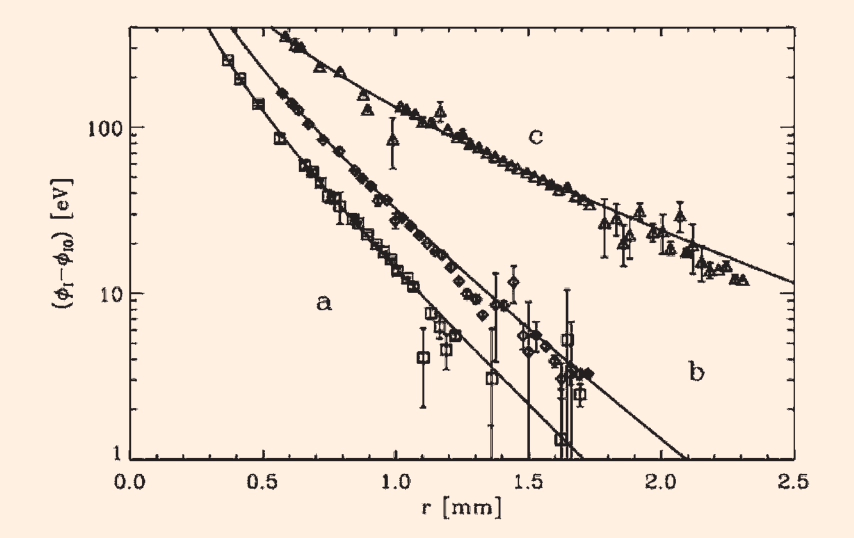

Figure 2.3.8.9. Electrostatic potential around an isolated spherical particle in a plasma, derived from collision experiments for three different plasma conditions. The solid line is the Debye-Hückel potential, i.e. the theoretically predicted form. Discrepancies from this theory are predicted to occur at larger distances (possible attractive potentials) and at small distances (from Konopka et al. 2000, Phys. Rev. Lett., 84, 891)

- Parasitic charge depletion, caused by high concentrations of particles in a plasma, is a topic of fundamental interest. It includes the spatial charge distribution in a particle cloud – in particular, the transition to a solid, where the charge is located at the surface.
- Dust–gas friction for single particles can be described quite well with, for example, the Epstein drag law (provided the conditions apply). For particle clouds, shielding (from the flow) may become important – the Bernoulli effect – so that the momentum exchange with the gas is less effective. This process is important in astrophysics, atmospheric physics, combustion, pollution control, etc.
- The physics of granular media is observable (usually) only in terms of surface effects. Complex plasmas provide special interacting ‘granules’ – pseudo-particles with a size governed by the shielding length, where the ‘visible’ particle inside may be substantially smaller. This allows (in principle) the analysis of granular media in three dimensions – subject of course to the limitations imposed by the forces of interaction.
- Radiation pressure acting on single particles of different composition and structure (e.g. conglomerates) can be investigated in detail. This is of importance in astrophysics, but possibly also for industrial applications. Wavelength dependencies can be studied using different laser light sources.
- Radiation pressure acting on particle clouds is another interesting topic, which is again of wide interest wherever particle inhomogeneities occur.

This list of process-oriented research is by no means exhaustive. Even so, it illustrates the enormous potential of the field and the new possibilities for making precise quantitative studies of different effects that have been opened up. It also highlights some of the obvious uses of the new knowledge to be gained.

2.3.8.3 The Microgravity Requirement

It has been mentioned already that the individual particles of the micro-particle component of complex plasmas are typically one hundred billion times heavier than the plasma ions. This implies that gravity is an important force and has an important influence on the behaviour of the system. For many research and application purposes this is useful and desirable; on the other hand, for a large number of topics it is not. The latter are typically of the following generic type:

- Investigations into fundamental properties of complex plasmas.
- Investigations where natural phenomena in space are simulated experimentally.
- Investigations involving small changes in energy levels or surface properties.
- Three-dimensional systems.

As can easily be seen, in some ways practically all of the research topics mentioned in Section 2.3.8.2 are involved. Consequently, in order to avoid repetition, it is simply pointed out that by the very nature of this research – operating with particles that are very heavy relative to the plasma ions and electrons – microgravity is likely to be an important requirement for many study topics.

Another issue is how long, how stable, and how small, should the ‘micro’-gravity conditions have to be? The possibilities for continuous reduced gravity are:
– Drop towers: ~ 5 seconds
– Aircraft: ~ 20 seconds
– Rockets: ~ 6 minutes
– Space Station: ~ hours – months.

The quality and stability of the reduced-gravity conditions vary as well, but it is the extent and continuity of the available experimentation time that is the dominant factor. It is clear that most of the research summarised in Section 2.3.8.2 requires long periods of microgravity for careful experimental work, leading to the following requirements:

(i) *A Research Facility on the Space Station*, which can be reconfigured to suit individual experimental requirements. It should be flexible, through being computer-operated, have variable experiment control, and contain an adequate diagnostics and data-handling capability. This is the most important requirement. Estimates of the total operating time for such a facility, based on the research programmes discussed earlier, are in excess of 10 years.

(ii) *A Complementary Laboratory Development Programme*, which works in two ways – firstly, to develop new hardware for space-operated science platforms, and secondly to transfer knowhow obtained from microgravity research back to terrestrial laboratories. This can then be used to improve basic knowledge or provide possible applications.

(iii) *Test Facilities on Parabolic-flight Aircraft*, to pre-calibrate and test newly developed hardware for the Space Station in a reduced-gravity environment. Experience has shown that such tests are absolutely necessary in a research area that deals with highly nonlinear processes, where in many cases the outcome (even of simple issues) cannot be predicted.

(iv) *Provision of Rocket Flights*, for systems that require a longer uninterrupted reduced-gravity period for testing and even preliminary results.

(v) *Adequate Manpower Support*, for data handling, archiving and data distribution and, most important of all, for understanding the science.

In short, the requirement for this new and rapidly growing field of Complex Plasmas is an integrated space and laboratory programme. The first steps in this direction have already been taken already, as is illustrated by two results. The first example (Fig. 2.3.8.10) comes from the Plasma-Kristall-Experiment (PKE). The measurements were made on a sounding rocket and show stable regions as well as rotating cells. Interest focuses on the sharp boundaries of the system (in particular the inner ‘void’), the interface between stable and rotating layers, the differential shear motion, etc. These aspects will have to be among the topics for future experiments, which will be performed on the International Space Station. They are one of the first natural-science experiments to be conducted on the ISS in a joint German/Russian research co-operation, and are an important step for the development of a possible International Microgravity Plasma Facility.

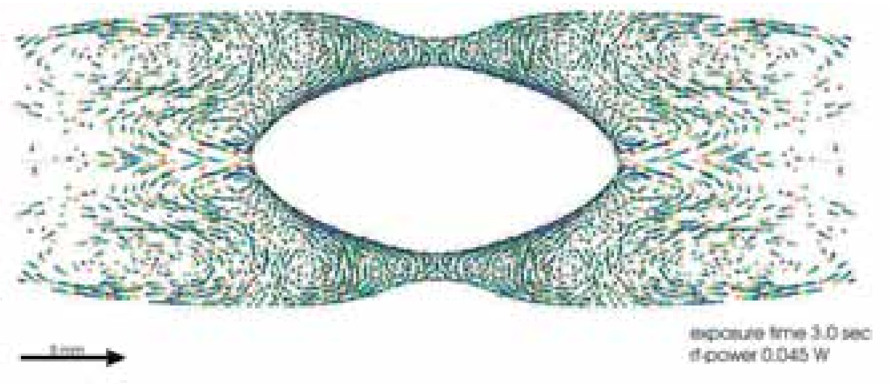

Figure 2.3.8.10. Microsphere distribution observed in the first microgravity experiments in complex plasmas using an RF plasma chamber. Note the sharp boundary towards the central ‘void’, the convective-type outer envelope, and the steady near-crystalline portions of the system (from Morfill et al. 1999, Phys. Rev. Lett. 83, 1598)

The second example (Fig. 2.3.8.11) comes from an experiment designed to measure coagulation of microscopic particles under astrophysical (microgravity) conditions – the ‘Cosmic Dust Aggregation Experiment’ (CODAG) – which was flown on Space Shuttle mission STS-95 in October 1995. Mono-disperse spherical SiO_2 (glass) dust grains were dispersed into a neutral gas ($T = 300$ K, $P = 0.75$ mbar) and allowed to coagulate.

The particles appear to cluster in long strings, with the conglomerates appearing needle-shaped. This result agrees quite well with astrophysical observations that often show that starlight that has passed through a certain column density of gas and dust on its way to our Solar System is polarised. The polarisation is interpreted as being due to the alignment of needle-shaped dust particles with the magnetic field. If the needle shapes are caused by coagulation, as the CODAG data suggest, then this information can be used to determine collision rates and hence the source and age of the particles in interstellar clouds.

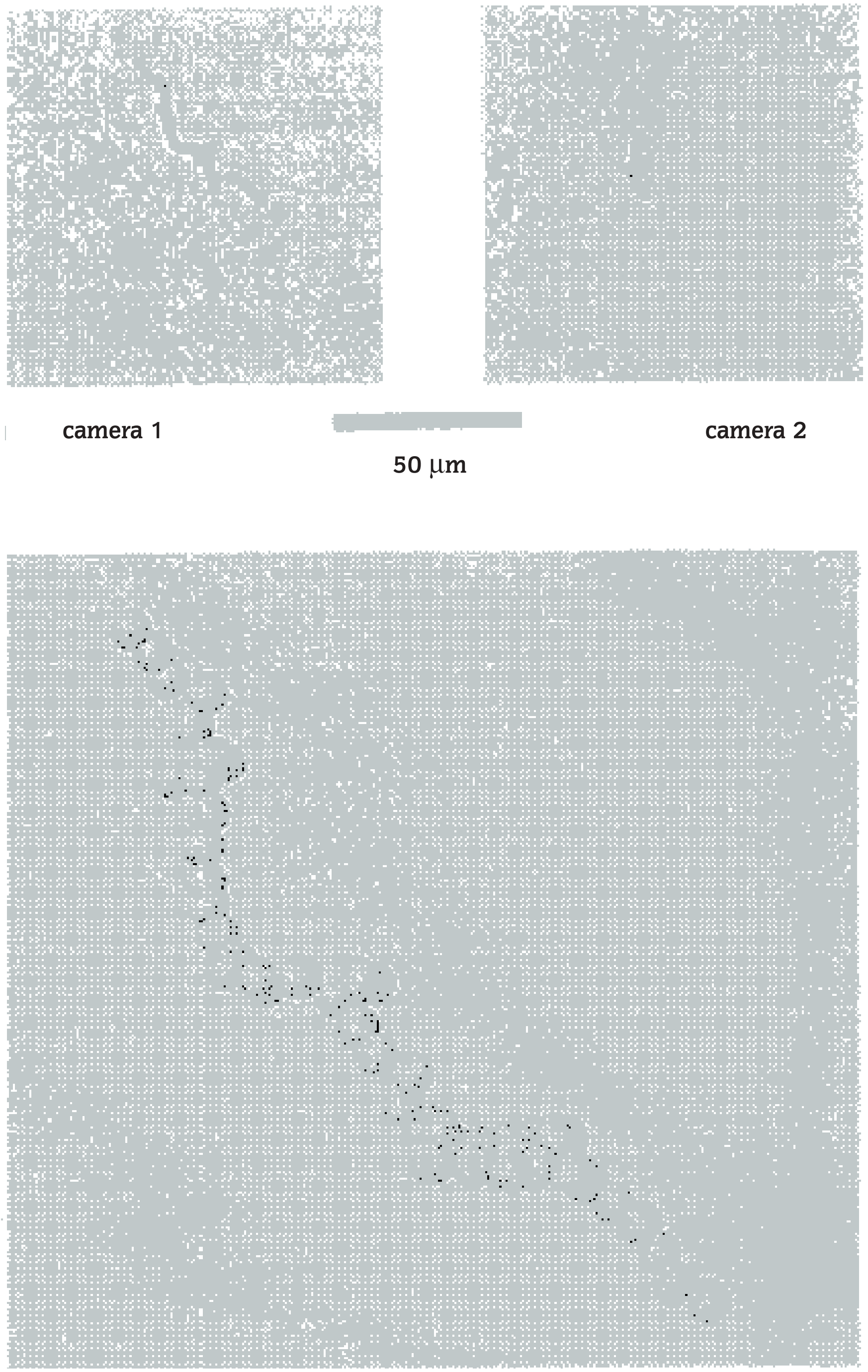

Figure 2.3.8.11. Coagulated particles observed under microgravity conditions in the CODAG experiment (from Blum et al. 1999, Meas. Sci. Technol., 10, 836)

2.3.8.4 Conclusion

In the foregoing, the huge diversity of the research in the field of complex plasmas and its enormous potential has been outlined. The research includes the physics of strongly coupled plasmas (liquid and crystalline states) and the microscopic analysis – on a scale of ‘crystal lattice’ or individual-particle separations – of phenomena such as the transition to turbulence, momentum transfer in shear flows, shock structure, wave propagation, the physics of interfaces, etc. All of these can be observed on a kinetic level for the first time. It extends to astrophysical, environmental and Solar System phenomena, which are directly relevant to the understanding of the formation of planets, comets and asteroids, as well as to pollution problems.

The basic knowledge obtained from this research is also expected to yield significant benefits for industrial purposes. Plasma technology and colloid technology are the basis for important branches of industrial production. The combination – plasma colloid technology – has great potential as a future manufacturing process, as it combines speed, control and precision. This might benefit in particular the area of complex ‘designer’ materials.

Looking to the future, an integrated research programme, which uses a multi-purpose ‘International Microgravity Plasma Facility’ (IMPF) and also a facility to study the ‘Interactions of Cosmic and Atmospheric Particle Systems’ (ICAPS), is needed to provide continuous research opportunities in space on the ISS. This should be allied with appropriate terrestrial laboratory programmes that include transfer of knowhow to industry. These are the next logical steps for this growing and important field of research and their implementation will ensure the continuing growth in Europe of the basic understanding of these complex processes and will provide the link to exploit possible applications.

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2.3.9 Vibrational Phenomena in Fluids and Granular Matter

D. Beysens

2.3.9.1 Introduction

Vibrations in matter act on inhomogeneities, which generally tends to direct them perpendicular to the acceleration direction. The inhomogeneities can be due to the granular structure of the matter itself, acting as if it is an assembly of hard beads; they can be density inhomogeneities, such as those induced in a simple fluid by temperature gradients; or they can be created by the coexistence of two phases (e.g. liquid and vapour). In a sense, vibrations can play the role of an artificial gravity, inducing flows, structuring the gas/liquid interfaces, and eventually helping to control fluids when in space.

The phenomena associated with such vibrations form a rich collection of situations, whose diversity has yet to be fully investigated. It is, however, a subject of considerable importance, not only for discovering new phenomena, but also, within the space context, for evaluating the effect of the unavoidable vibrations occurring in spacecraft structures. These may, in some cases, considerably perturb fluid and material-science experiments and are likely to be of concern for the International Space Station.

Investigations into the behaviour of inhomogeneous materials submitted to vibrations under microgravity conditions have started only recently. However, a certain number of significant results have already been obtained and these are reviewed below. The effects in fluids are first reported. There, the critical point plays an important role, since simply by inducing a change in the proximity to the critical point the properties can be modified in a scaled, universal way. Following that discussion, the effect of vibrations on granular matter are analysed.

2.3.9.2 Vibration Effects in Fluids and Near-Critical Fluids

- *Why Study Vibrating Fluids under Microgravity?*

Vibrations applied to mechanical systems can cause destabilisation or stabilisation, depending upon the characteristic features of the vibrations, i.e. the frequency, or the angular frequency, the amplitude, and the direction of vibration. Many equilibrium and non-equilibrium phenomena can be affected by the presence of high-frequency vibrations.

The periodic acceleration due to vibrations can have a marked influence on the behaviour of fluids near to their critical point. Different phenomena are presently under consideration, including induced thermal instabilities, analogous to viscosity/diffusion moderated convection, and ordering of the gas/liquid interface below the critical point. The question of how the acceleration can be transmitted to the compressible fluid through a mechanical boundary layer will not be discussed here. It is simply assumed that the fluid is submitted in bulk to a periodic acceleration.

A number of theoretical aspects have been considered in some detail by Russian scientists. They conclude that the suppression of the uniform steady gravity field is mandatory in order to evaluate the phenomena induced by vibration.

- *Interface Deformation and Localisation*

On Earth, the usual effect of vertical vibrations in a fluid is to modulate the local effective gravity force, via the time-dependent acceleration applied to the system. Under microgravity, the response can be markedly different and concerns not only the shape and localisation of the gas/liquid interfaces, but also the evolution and morphology of the drop pattern during a phase transition.

A plane liquid-vapour layer, vertically vibrated parallel to gravity, displays two different regimes. Far from the critical point, a square wave-pattern deformation is formed. At a temperature T_0 close to the critical temperature ($T_c - T_0 \approx 20$ mK for CO_2), a transition occurs to a new pattern configuration of lines. This transition is due to the increase in dissipation near the critical point. This is a rather unique example of strong coupling between two different critical-point phenomena. These are the critical point of interface instability and the thermal critical point of the liquid–vapour phase transition.

When, in gravity, the acceleration is parallel to the interface, an instability is observed with the interface modulated as a 'frozen' roll wave pattern (Fig. 2.3.9.1b). This phenomenon corresponds to the formation of waves on the sea under the influence of the wind. As yet, it has been only poorly investigated for the present case, where the 'wind', i.e. the gas phase, exhibits a periodic velocity relative to the 'sea', here the liquid. The instability mechanism is due to the relative motion of two fluids induced by vibration. The perturbation becomes unstable if the velocity is larger than a threshold velocity, determined by the gas–liquid surface tension and the densities of the liquid and vapour. This destabilisation is due to the increasing effect of the Bernoulli-type pressure, arising from the velocity difference between gas and liquid. The experiments conducted recently are consistent with this model, with the velocity as the relevant parameter governing the instability.

The only available results in microgravity are preliminary data gathered in a sounding-rocket experiment. Three samples of different gas volume-fractions and distances from the critical point, were vibrated at different amplitudes and frequencies ranging from 0.1 to 5 mm and 0.1 to 60 Hz. Although the initial state of the sample was a vapour drop emulsion or a unique drop, the final state was the same: vapour and gas phases forming alternate layers perpendicular to the acceleration vector (Fig. 2.3.9.1c). The instability develops as liquid fingers from the cell walls and then coalesces with the droplets in the bulk and/or with the fingers that have grown from the opposite side.

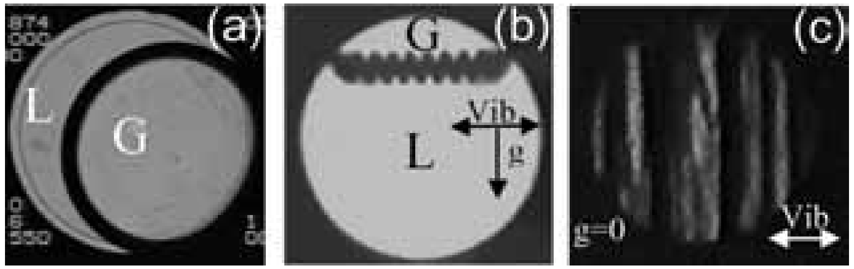

Figure 2.3.9.1. Gas-liquid phases, which show up under 1g as a vapour phase above the liquid phase separated by a flat meniscus, and under 0g as a vapour bubble surrounded by a liquid phase (a), can order in a different way when submitted to vibration. Illustrated in (b) are frozen waves under 1g, and in (c) gas-liquid ordering under 0g (Mini-Texus-5, February 1998) (from Beysens et al. 1998, Micrograv. Sci. & Techn., 11, 113)

These observations suggest that, under some circumstances, a periodic excitation can act as a kind of artificial gravity to localise the liquid and vapour phases perpendicular to it. This occurs irrespective of the initial configuration (emulsion of vapour droplets or a unique vapour drop). These are preliminary studies of the phenomenology of one- or two-phase fluids, subjected to oscillatory accelerations under microgravity. At present, there is little theoretical understanding of these phenomena.

- *Vibrational Thermal Effects*

Consider a planar fluid layer under a vibrational acceleration field, which is subjected to a thermal gradient by heating from below. Convection is able to start when the buoyancy effect of the hot lower density fluid can overcome the energy dissipation due to viscous drag and heat diffusion (this is the well-known Rayleigh-Benard instability). As the temperature of the fluid gets closer to the critical temperature, the density change due to heating is increasingly important and the fluid becomes extremely sensitive to the vibration-induced acceleration.

Measurements of flow velocities performed on the Mir station in CO_2 and in SF_6, confirm this expectation. A heat flux was sent into the fluid from a point-like source (thermistor). Depending on the oscillation velocity, two regimes of heat propagation were observed: (i) at low frequency, heat is convected during one oscillation period to form symmetrical hot layers perpendicular to the vibration (configuration hot–cold–hot, Fig. 2.3.9.2b); and (ii) at high frequency, heat is convected by convection rolls perpendicular to the direction of oscillation (opposite configuration, cold–hot–cold, Fig. 2.3.9.2c).

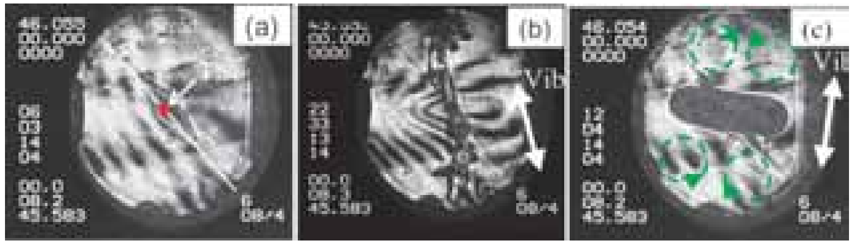

Figure 2.3.9.2. The spreading of the hot boundary layer during the heating of the thermistor (Th1, supported by a thread): (a) without vibration (hot region underlined in white); (b) under low-frequency vibration; and (c) under high-frequency vibration, where convection rolls form (ALICE on Mir, 1999)

2.3.9.3 Vibrations in Granular Matter

Although studied for several centuries due to their various industrial applications, granular media have recently received renewed attention from physicists. Granular media indeed exhibit a wide range of behaviours – solid-like, gas-like and liquid-like – depending upon the dynamic coupling of the particles with the surrounding media and the intensity of the mechanical excitation. Dynamic decoupling between the particles and the surrounding media is achieved by using a low-pressure, low-density fluid, such as air at atmospheric pressure, or even vacuum. In such a fluid, the solid particles can be considered as isolated bodies between each collision, and one of the most interesting properties is the dissipative nature of the particle–particle interactions (inelastic collisions). The usual techniques and results of statistical mechanics can then be used to analyse the thermo-statistics of a dissipative gas.

- *Low Gravity for Granular Media Studies*

From an experimental point of view, in order to study its properties in a steady state, it is necessary to bring to the gas a steady amount of kinetic energy that balances the dissipative losses. Mechanical vibrations are a common way to keep the temperature of such a macroscopic gas constant. On Earth, the energy of the particles depends on their relative height, and stratification occurs at all levels of vibration. Observation of a 'phase transition' in granular media is therefore uncertain, and the experimental tests of theoretical predictions problematic. Although it is possible to immerse the particles in a liquid of comparable density, this situation induces strong dynamic coupling between the particles and the fluid, leading to liquid-like behaviour of the granular media. In contrast, a low-gravity environment eliminates stratification, even at high density ratios, and produces an effectively isolated gas of particles.

- *Phase Transition in a Granular Gas*

The first experiment with slightly dissipative granular media was carried out on parabolic low-gravity flights, on board CNES's Caravelle aircraft in 1991. It tested the $PV = nRT$ law of a perfect gas, using a collection of macroscopic stainless-steel spheres. Its purpose was mainly information gathering and showed reasonable agreement between pressure and temperature equivalence, and with the Boltzmann statistics.

The first experimental evidence of a phase transition in a granular gas was provided by a Mini-Texus-5 sounding-rocket experiment in 1998. Although this collapse was predicted by numerous theoretical and numerical studies, it had never been observed, even in two dimensions. It was found that the formation of a dense cluster of particles in a 'liquid' or cluster regime (low velocity, small free mean path) in equilibrium with a fraction of the particles in a 'gaseous' regime (high velocity, large free mean path) occurred above a well-defined threshold in particle number density (Fig. 2.3.9.3). The observation of such a dissipative collapse has important consequences in astrophysics, particularly for the analysis of the formation of planetary rings (see also Section 2.3.8).

The difference between the two kinetic regimes, homogeneous and clustered, is also apparent in the pressure signals. In the dilute case, the pressure of the granular gas scales like the 3/2 power of the vibration velocity. This is quite surprising, since the basic argument predicts a power of 2. So it seems that this result can only be explained by some special dependence of the collision-restitution coefficient upon velocity.

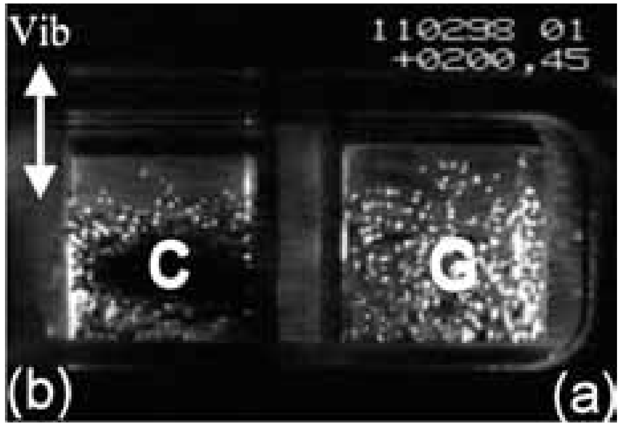

Figure 2.3.9.3. 'Gas–liquid' transition for granular matter subjected to vibration under microgravity conditions (ESA Mini-Texus-5, 1998): (a) gas behaviour (G); (b) cluster behaviour (C). In the most dilute case (a), the particles move erratically and their distribution is roughly homogeneous in space. In the denser cases (b), a 'motionless' dense cluster (in black, C) is surrounded by regions of lower particle density (from Falcon et al. 1999, Phys. Rev. Lett., 83, 440)

2.3.9.4 Prospects for the ISS

It is a remarkable fact that the effect of vibrations on inhomogeneous media under microgravity conditions is largely unknown. Detailed data on this phenomenon are still lacking. Non-linear vibrations may induce new forces, which may help to control the flow of fluids in space, and that in turn can be used for the phase separation of heterogeneous media in the space environment. It seems very likely that this study will lead to new processes in applied science and technology.

In the future, the members of the ESA Topical Team on 'Vibrational Phenomena' propose to enlarge the preliminary investigations that were performed with fluids and granular materials. What is basically needed is a vibration set-up whose amplitude ranges from 0.1 to 50 mm and frequency from 0.1 to 100 Hz, with maximum acceleration in the range 1 – 10 g.

- *Fluids and Near-Critical Fluids*

The first objective is to understand the coupling between heat transfer and high-frequency vibration. Since no buoyancy forces exist in microgravity, the only possible heat-transfer mechanism in the absence of vibration is thermal diffusion (and the Piston Effect for near-critical fluids). A well-controlled method for investigating the change in the heat-transfer mechanism is to use a single-phase fluid under a thermal gradient and to submit it to controlled oscillatory acceleration. The main effect of high-frequency vibrations would be to restore convection, as reported above in Figure 2.3.9.2, thereby behaving as if they induce an artificial gravity.

Concerning the behaviour of a two-phase fluid, the main scientific objectives are to understand the interface deformation and ordering/organisation mechanisms, in particular the roles of density ratio and interfacial tension, and in addition to determine the coalescence laws of dispersed two-phase fluids, when submitted to such oscillating accelerations. A goal of this study will be to achieve sufficient knowledge of the ordering mechanism to be able to control and predict the localisation of the fluid interfaces under microgravity conditions.

Another objective is to understand how vibrations can induce ordering mechanisms in a dispersed system, such as a metastable gas–liquid dispersion. It should be interesting to analyse the effect of alternating accelerations on phase separation in the same way as the effect of shear on phase-separation kinetics, i.e. in terms of the anisotropic law of domain growth, domain deformation, growth acceleration and final equilibrium state.

The understanding of these effects is important in the control of gas/liquid interfaces and the enhancement of heat transfer in microgravity. It will also furnish information on the spurious and destabilising effects of ISS structure vibrations on the numerous experiments using heterogeneous media.

- *Granular Matter*

An intensive study of dissipative collapse is the natural goal of the research programme on granular matter, in order to build up an experimental phase diagram of granular matter under vibrations. From a thermodynamic point of view, vibrations are used to maintain the kinetic energy of the gas, whereas the granular pressure is measured by simple sensors and the temperature evaluated via the velocity of the particles.

For this purpose, systematic experiments have to be conducted to determine the number-density threshold where the collapse occurs. The influence of the coupling between the surrounding fluid through viscosity or compressibility also needs to be studied in detail, as should the perturbing effect of electrostatic forces. In this sense, an exhaustive programme of ground-based experiments combining various fluids, among them supercritical fluids and granular media, should be carried out in order to extend the recent theoretical and experimental results on fluidised granular media. An extended range of excitation intensities and longer experiments should allow the kinetics of the collapse process to be investigated. Improvements in the detection of the particles and larger sample cells should also permit the formation of multiple clusters to be detected and their coalescence studied. In parallel, the pressure fluctuations should be measured and modelled, in order to determine the free energy of the granular matter.

Another subject of interest is the segregation mechanism of binary mixtures (particles species of different sizes, shapes or densities). On Earth, segregation is frequently observed, but there is no unified theory for this phenomenon. Even the pertinence of the description in terms of minimisation of interaction energy is still an open question. This 'hot' scientific problem is presently the object of a few microgravity experiments funded by NASA and the Japanese Space Agency, in an industrial context. Since the NASA experiment consists of shearing a binary granular mixture in low gravity, the experiments proposed here, involving vibrating a granular medium, are complementary in nature.

Further Reading

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Falcon E., Wunenburger R., Evesque P., Fauvé S., Chabot C., Garrabos Y. & Beysens D. 1999, Cluster Formation in a Granular Medium Fluidised by Vibrations in Low Gravity, Phys. Rev. Lett., 83, p. 440.

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2.3.10 Cold Atoms in Space and Atomic Clocks

C. Salomon

2.3.10.1 Introduction

The research field of atom manipulation by the use of laser light has experienced considerable growth over the last 20 years. From the initial demonstration experiments in the early 1980s, it has evolved into a mature domain with a wealth of new applications, as demonstrated by the awarding of the 1997 Nobel Prize for Physics to S. Chu, C. Cohen-Tannoudji and W. Phillips. Applications such as ultra-stable clocks, matter-wave interferometers, Bose-Einstein condensation and atom lasers have developed rapidly, and it is now conceivable to fly such systems in space.

For cold atoms, space brings two major advantages. Firstly, it offers the state of weightlessness. Atoms can now be cooled down to such low temperatures that the Earth's gravitational force represents a major perturbation to their motion. Take, for instance, a gaseous ensemble of rubidium atoms, which is cooled in an 'atom trap' to a temperature sufficiently low that a Bose-Einstein condensation occurs (Fig. 2.3.10.1).

In this spectacular quantum phenomenon, nearly all of the atoms accumulate in the lowest energy state of the trap, and they all behave in exactly the same way. In this system, the atoms have, on average, a speed of barely 30 μm/sec. On Earth, however, as soon as the trap is switched off the atoms acquire a speed of 1 m/s under the effect of gravitational acceleration, and they do so in just one tenth of a second. This exceeds their initial velocity by a factor 33 000 ! In one second, these atoms will have dropped by 5 m and have usually hit the bottom of the vacuum chamber in which they were cooled. In space, this problem disappears because of the microgravity conditions. The atoms can then be retained within the observation volume for periods ranging from several seconds to tens of seconds.

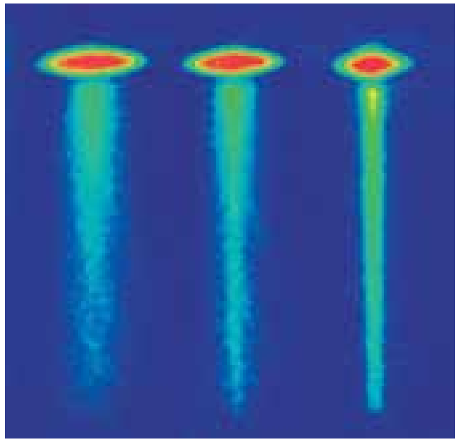


Figure 2.3.10.1. An atom laser: atoms are extracted from a cold rubidium gas (left) or from a Bose-Einstein condensate (right). The intense, low-divergence, coherent atomic beam is affected by gravity (courtesy of Munich University)

The second advantage stems from the fact that space constitutes a unique laboratory in which to test fundamental physical laws with great precision. It is well known that a conflict exists today between general relativity, which describes classical gravitation well, and quantum mechanics, which describes microscopic phenomena well. As yet, there is no satisfactory quantum theory of gravitation. Theoreticians are still seeking to unify all four fundamental interactions of nature into a single theory.

In space, the Equivalence Principle (the universality of free fall), which forms the basis of Einstein's general-relativity theory, can be tested with orders-of-magnitude improvement over ground-based experiments. Similarly, the famous gravitational red-shift effect (whereby a clock in Earth orbit is seen to run faster by an Earth-based observer!) can be tested with unprecedented accuracy by comparing ultra-stable clocks orbiting around the Earth with companion clocks on Earth. Other fundamental predictions of general relativity and of modern physical theories can be tested in space and will constitute a crucial search for new interactions or new forces.

These two aspects will be illustrated here using the specific example of atomic clocks. Firstly, the main methods for cooling atoms to very low temperatures, i.e. less than one millionth of a degree above absolute zero, will be reviewed. The principle of an atomic clock is then introduced and the advantages of using space are discussed. The current PHARAO and ACES projects, which will fly on the ISS in 2005, are then described. Finally, some perspectives for cold atoms for other future space missions are outlined.

2.3.10.2 Cooling Methods

- *Laser Cooling*

In laser-cooling experiments, photons are used to exert forces on the atoms. When an atom absorbs or emits a photon its speed changes, so that the total (atom + photon) momentum is conserved. This change is called the recoil velocity and is usually very small. For caesium atoms illuminated with light at a wavelength of 0.852 μm, the recoil velocity is 3.5 mm/s. However, the atom is able to absorb and emit at typically 10 million times per second, so that the net force that a laser beam can exert on an atom can be very large. Typically, the force can exceed that of gravity by five orders of magnitude. This force exerted by a laser beam is called the 'radiation pressure'.

Cooling a gas of atoms consists of reducing the thermal fluctuations in the atoms' velocity around their mean velocity. The mean velocity can be zero, in which case the gas is at rest in the laboratory. In the case of an atomic beam, the mean velocity is not zero and can be adjusted. Several laser cooling mechanisms have been invented and the simplest of them is called 'Doppler cooling', because it relies on the Doppler effect.

It was proposed by T. Hänsch and A. Schawlow, in 1975. The atoms are illuminated by two counter-propagating lasers of equal intensity and the same frequency ν_L (Fig. 2.3.10.2a).

The frequency of the lasers is chosen to be slightly below the frequency at which the atoms absorb when they are at rest. When an atom moves, it sees the frequency of the laser propagating against its motion as up-shifted (just as the sound of a police car coming towards you has a higher pitch) and it absorbs photons from this wave. Conversely, the atom sees the laser beam that propagates in the same direction with a frequency that is down-shifted (more red). The atom then absorbs many less photons from this beam. Thus the net misbalance between the two radiation pressures leads to a slowing of the atom.

This mechanism is very efficient. When the laser beams are oriented along the three directions of space, the atoms are rapidly cooled and viscously confined within the laser beams, forming an optical 'molasses'. The average speed of the atoms is then damped to about 10 cm/s. At this stage an even more efficient cooling mechanism takes over. It lowers the speed to a mere 1 cm/s, corresponding to a temperature of about 1 μK.

An interesting variant of the optical molasses combines the previous cooling force with a trapping force. It is called a 'magneto-optical trap' and it is the workhorse in cold-atom manipulation. In this process, an inhomogeneous magnetic field, created by two coils located on each side of the experimental cell, is added to the molasses. With a suitable choice of the laser-beam polarisations, a restoring force can be created that attracts the atoms towards the point where the magnetic field is zero, at the centre of the laser beams. This force accumulates the atoms in a ball of a few cubic millimetres (Fig. 2.3.10.2b) at a temperature of a few micro Kelvin.

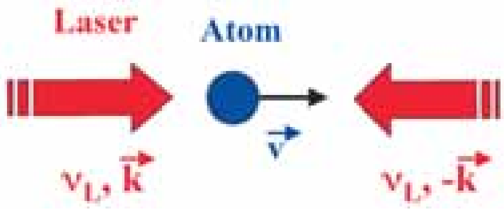


Figure 2.3.10.2. (a) The principle of laser cooling. Two counter-propagating laser beams exert a radiation pressure force on an atom. When the atom moves, because of the Doppler effect, the laser that opposes the atom's velocity has a larger radiation pressure than the beam that co-propagates with the atom. Therefore the atom's velocity is damped. If this beam configuration is used along three orthogonal directions in space, all three velocity components are damped. This is an optical 'molasses', in which atoms are viscously confined

(b) A magneto-optical trap. In this glass cell, the red ball at centre is the fluorescence of a billion atoms, cooled and trapped by six laser beams. The two white rings hold the magnetic-field coils

- *Evaporative Cooling*

Cooling of dilute gases has been pushed even further by a totally different technique, well known to everybody who tries to drink a cup of coffee that is too hot! You blow air on it! This cooling is not due to the difference in temperature between the air and the coffee, but to the evaporation of the coffee that is enhanced by blowing on it. Removing a molecule from the liquid takes up energy that is extracted from the remaining liquid. The liquid then cools down.

The cooling process for atoms is the same. The atoms are confined in a magnetic trap, in which they oscillate and collide with other trapped atoms. The magnetic trap has a bowl-shaped potential energy form that possesses a minimum and has a 'rim' at a finite potential-energy 'height'. If the 'height' of the rim is reduced to a value that slightly exceeds the average kinetic energy of the atoms, the fastest atoms will escape from the bowl. The remaining atoms then re-thermalise through collisions to a temperature that is lower than the initial temperature. It can be shown that, despite the loss of atoms in this process, the density of atoms at the centre of the trap increases and the temperature continuously decreases. Typically, a factor of ten decrease in atom number brings a factor of ten reduction in temperature. Using this method, in 1995 the group of E. Cornell and C. Wieman at JILA and the University of Colorado (USA) succeeded in producing a very peculiar new state of matter: a Bose-Einstein condensate of rubidium atoms.

2.3.10.3 Bose-Einstein Condensation and Atom Lasers

According to quantum mechanics, one can associate a wave with each particle of matter. The period of this wave is inversely proportional to the particle's velocity v, and is called the 'de Broglie wavelength': $\lambda_{DB} = h/Mv$, where h is Planck's constant and M the mass of the particle. When the velocity of the particle becomes very low, as is achieved with laser and evaporative cooling methods, the de Broglie wavelength can exceed 1 μm, which is the typical wavelength of visible light.

In 1925, inspired by the work of the young physicist S. Bose, A. Einstein predicted an extraordinary property for a gas of identical particles at low temperature and high density in a confining box. This was that, when the mean separation between the particles becomes of the order of their de Broglie wavelength, a large fraction of the atoms will condense into the lowest energy state of the system. This is the state with zero velocity, if the size of the box becomes arbitrarily large. In the magnetic trap of the JILA experiment, about 100 000 rubidium atoms condensed into the lowest state of the trap, forming a macroscopic quantum system at almost zero temperature.

In a Bose-Einstein condensate, all atoms occupy the same quantum state. They therefore behave in exactly the same manner. By switching off the trap, the condensed atoms are easily seen by laser-imaging as they correspond to a peak of ultra-cold atoms on a background of uncondensed atoms (Fig. 2.3.10.3).

These condensates possess very peculiar quantum properties that are now being actively investigated by more than 50 groups in the world. They have interesting coherence properties that, in some respects, are analogous to those of lasers. In a laser, a very large number of photons occupy the same mode of the electromagnetic field, and this property is at the origin of the high brightness and low divergence of laser beams.

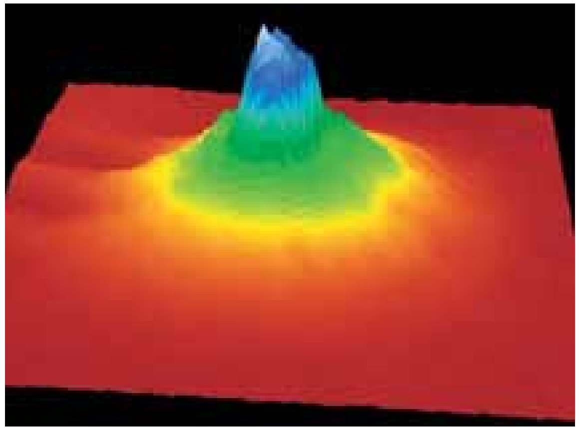


Figure 2.3.10.3. The velocity distribution of a Bose-Einstein condensate of rubidium atoms. The condensate forms an ultra-cold peak (in blue) and the non-condensed atoms form the green pedestal. At very low temperatures, only the condensate exists (courtesy of Ecole Normale Supérieure, Paris)

Atom lasers have just been produced. Figure 2.3.10.1 shows such a atom laser, developed by a group at the University of Munich, led by Prof. Hänsch. The very low divergence of the beam of atoms extracted from a rubidium condensate is clearly visible in that figure. As mentioned above, the main problem with these atom lasers on Earth is that as soon as the atoms leave the trap they are accelerated by gravity and very quickly acquire a high speed. Obviously, the microgravity conditions of space should be able to help in solving some of the fundamental questions that these quantum systems raise. A second difficulty is the relatively low flux of atoms that a condensate can currently produce. Typically, a condensate of one million atoms is produced in 30 seconds. Depositing these atoms on a 1 cm^2 area will require about 30 years! New methods for improving this situation are being actively investigated and one can expect, as for lasers, a considerable gain in output flux in the coming years.

2.3.10.4 Atomic Clocks

From the early days of atom manipulation using laser light, it was recognised that the very low velocities of laser-cooled atoms would be of benefit in improving atomic clocks. As illustrated in Figure 2.3.10.4, in an atomic clock a very stable radio-frequency source is used to probe a transition between two energy levels in an atom. Since 1967, the primary time standard relies upon caesium atoms and the atomic transition is between two hyperfine states of the electronic ground-state.

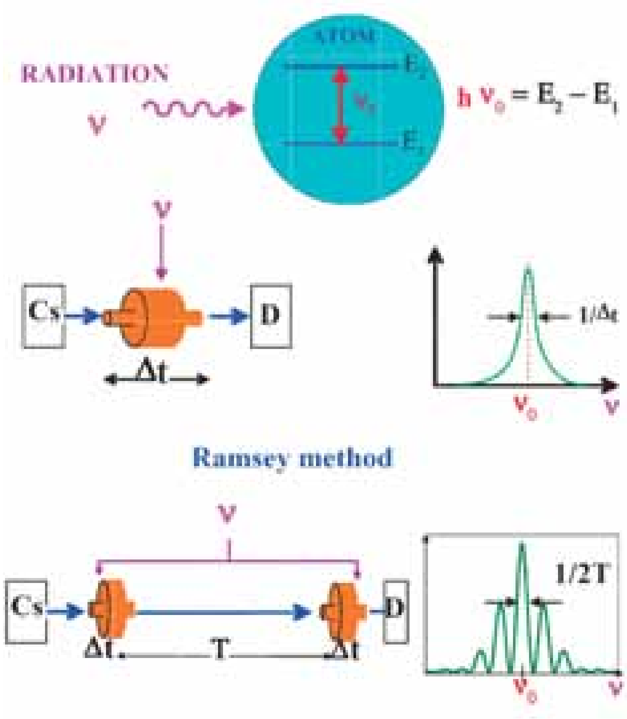
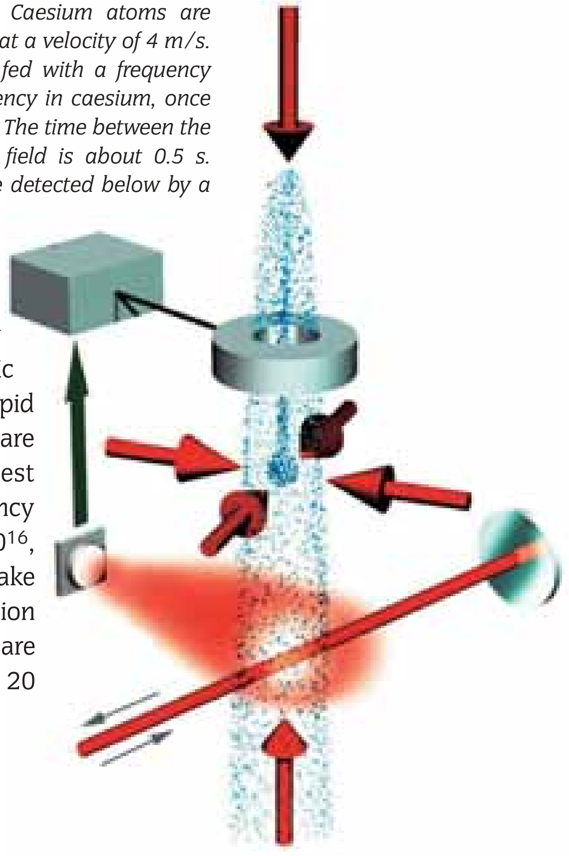


Figure 2.3.10.4. The principle of an atomic clock. An electromagnetic radiation of frequency ν is tuned near the atomic frequency ν_0 and transfers the atom from the ground-state energy E_1 to the excited state E_2. The width of the resonance curve is inversely proportional to the duration Δt that the atoms spend in the interaction zone with the radiation. The method proposed by N. Ramsey uses two separated zones, in which case the width of the resonance is inversely proportional to the time of flight T of the atoms between the two zones. Slow atoms produce a longer T

By definition, the frequency of this transition is ν_0 = 9 192 631 770 Hz. When the radio frequency is scanned around the atomic transition, it excites the atoms and a resonance curve is obtained. The narrower the resonance curve, the more accurate the frequency determination, and hence the better will be the clock.

In practice, the radio frequency is electronically locked to the peak of the resonance. As the width of this resonance is simply the inverse of the time taken by the atoms to cross the radio-frequency interaction zone, slow atoms will allow longer transit times and hence a narrower width. Commercial clocks use atoms travelling at an average speed of 100 m/s. Laser-cooled caesium atoms move at a speed of 1 cm/s. Consequently, the gain in interaction time for a fixed device length could reach a factor of 10 000! Because of the Earth's gravity, this gain is 'only' 100, and one uses a fountain geometry as shown in Figure 2.3.10.5. In space, a further factor of 10 is expected.

Figure 2.3.10.5. An atomic fountain. Caesium atoms are cooled to 1 μK and launched upwards at a velocity of 4 m/s. They twice cross a microwave cavity fed with a frequency close to the hyperfine transition frequency in caesium, once on the way up, once on the way down. The time between the two interactions with the microwave field is about 0.5 s. Atoms that are excited by the field are detected below by a laser beam, in which they fluoresce



Atomic fountains have already improved the accuracy of atomic time by a factor of 10, and rapid progress in stability and accuracy are currently expected. The best fountains have a relative frequency instability of only 5 parts in 10^{16}, which means that these clocks make an error of about 1 s every 50 million years! Today, 10 atomic fountains are in operation worldwide and about 20 others are under construction.

2.3.10.5. Atomic Clocks in Microgravity: PHARAO

In an atomic fountain, the downward pull of gravity obviously imposes a limit to the interaction time, which is typically of the order of 1 s. Increasing this duration by a factor of 10 would require a clock height of 125 m. Such a size is not realistic, given the technical problems such as shielding of residual magnetic fields, and thermal stability. In microgravity, however, long interaction times can be achieved in a reduced volume. It is sufficient to launch the atoms slowly in the clock device and to use the scheme for normal clocks shown in Figure 2.3.10.4, but with a launch velocity 1000 times smaller. The principle of the PHARAO microgravity clock is summarised in Figure 2.3.10.6. The resonance curves in a conventional clock, a cold-atom fountain and a microgravity clock are compared in Figure 2.3.10.7. It clearly illustrates the gain in resolution that is made possible when laser cooling is used in conjunction with a microgravity environment.

The relative frequency stability of the PHARAO clock onboard the International Space Station (ISS) is expected to be better than 10^{-13} for a 1 second measurement time, 3×10^{-16} for 1 day, and 1×10^{-16} for 10 days. This accuracy is three orders of magnitude beyond that of the clocks currently flying on GPS satellites.

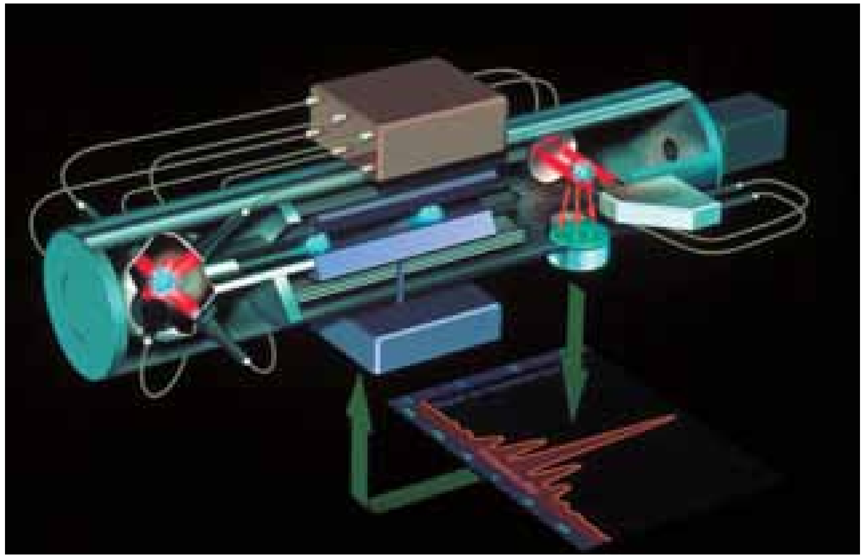


Figure 2.3.10.6. The principle of the PHARAO cold-atom clock in microgravity. An optical bench (top) provides light to a caesium tube for cooling and detecting the atoms, using optical fibres. Atoms are collected in 'optical molasses' in a first chamber (left), cooled below 1 μK, and launched into a second chamber. They enter a cavity in which they experience the two successive Ramsey interactions with a microwave field tuned near to the 9 192 631 770 Hz caesium frequency. Atoms excited by this field are detected downstream by fluorescence. The resonance signal is used to lock the oscillator's central frequency to the caesium transition. For a launch velocity of 5 cm/s, the expected resonance width is 0.1 Hz. This is ten times narrower than in Earth-based fountains

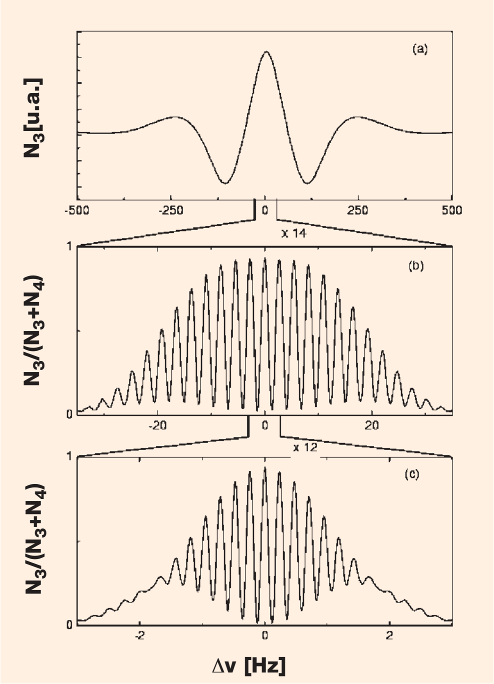


Figure 2.3.10.7. The advantage of measuring cold atoms in microgravity.
(a) A measured resonance signal in an Earth-based conventional thermal-beam caesium clock. The resonance width is 100 Hz.
(b) A measured resonance signal with laser-cooled atoms in a 'fountain' on Earth. The resonance width is 1 Hz.
(c) The expected signal in the PHARAO space clock, for an atom launch velocity of 5 cm/s. The resonance width narrows to 0.1 Hz

A prototype of a cold-atom clock, developed by French laboratories with CNES support, was tested in the reduced gravity of aircraft parabolic flights in 1997 (Figs. 2.3.10.8 and 9). This prototype is now a transportable cold-atom clock with an accuracy of 1x10^{-15}, which is presently the highest accuracy atomic clock. The satellite version of PHARAO, developed by CNES, completed its detailed design phase in 2000 and will go forward to industrial development in early-2001.

Figure 2.3.10.8. The PHARAO prototype under test on the CNES Zero-G Airbus in 1997

Figure 2.3.10.9. The PHARAO caesium tube (total length 1 m). Bottom: cooling zone. Middle: interaction zone. Top: detection zone and vacuum pump

2.3.10.6 The Atomic Clock Ensemble in Space: ACES

- *The ACES mission*

PHARAO was proposed to ESA in 1997, within the framework of a more general mission called 'ACES'. Selected by ESA to fly on the ISS as part of its early utilisation programme, ACES consists of two clocks, PHARAO and a hydrogen maser (SHM, Neuchâtel Observatory, Switzerland). There are also optical and microwave communication links for time and frequency transfer to ground-based users on the Earth (Fig. 2.3.10.10). Both links are high-performance systems, designed to transfer the very high stability of the space clocks to the ground without degradation by propagation through the atmosphere. The projected performance of the links is a time stability of 10 ps over one day, more than two orders of magnitude beyond the present GPS timing-signal accuracy.

The optical communication link has been developed by the Côte d'Azur Observatory and CNES (F). Called T2L2 (Time Transfer by Laser Link), it is based on laser pulses that are synchronised to a ground clock and emitted, using a telescope, towards the satellite. The arrival times of the laser pulses are dated onboard the ISS and part of the light is retro-reflected towards the emitting ground station by corner cubes on the ACES platform. The retro-reflected signal is also dated in the ground clock's time scale. This round-trip of the light pulses enables one to cancel the fluctuations of the atmosphere in the comparison between the ground and ISS time scales.

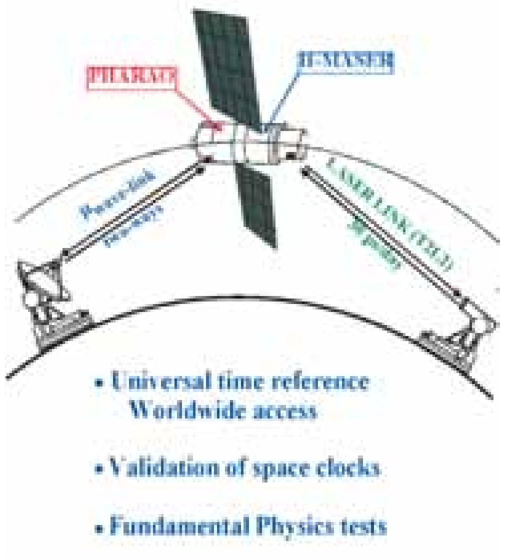


Figure 2.3.10.10. The operating principle of ACES

Figure 2.3.10.11. Mock-up of the ACES Pallet

The microwave link transmits high-frequency signals between the Earth and the ISS. As in the case of T2L2, these signals are synchronised to the ground and to space clocks, respectively, and allow one to compare these clocks. Unlike an optical link, which cannot operate in cloudy conditions, the microwave link is weather-independent.

This equipment will fit on a nadir-oriented Express Pallet Adapter, with dimensions of 863x1168x1240 mm^3. The total mass will not exceed 227 kg and the electrical power requirement is 500 W. A mock-up of the ACES Pallet is shown in Figure 2.3.10.11.

- *Scientific Objectives of ACES*

These are twofold:

- The first objective is to operate the PHARAO clock with the level of performance mentioned above, i.e. a frequency stability of better than $3x10^{-16}$ for one day, and to study the effect of the reduced gravity on the clock's stability and accuracy.
- The second objective is to use the very high stability of the PHARAO-SHM combined time scale, onboard the ISS, to perform time comparisons between ground clocks, to a 30 picosecond level of precision. This represents an improvement over the best current GPS comparisons by a factor of 100. Frequency comparisons between these clocks will be performed with a relative accuracy of 10^{-16}, whereas at present frequency comparisons between distant clocks have not been performed below 10^{-15}.
- The third objective is to perform several fundamental-physics tests with increased precision. The gravitational red-shift will be measured with a $3x10^{-6}$ accuracy, a 25-fold improvement over the NASA 1976 Gravity Probe-A mission. Better tests of the isotropy of the speed of light and a new search for a possible drift in one of the fundamental physical constants, the fine-structure constant α, will also be performed.

Figure 2.3.10.12 illustrates the progress made in the last forty years with atomic clocks in the microwave and optical domains. In 2005, ACES is likely to be near to the crossing point of microwave and optical clocks, providing a very interesting space option for comparing these ultra-stable clocks on the ground.

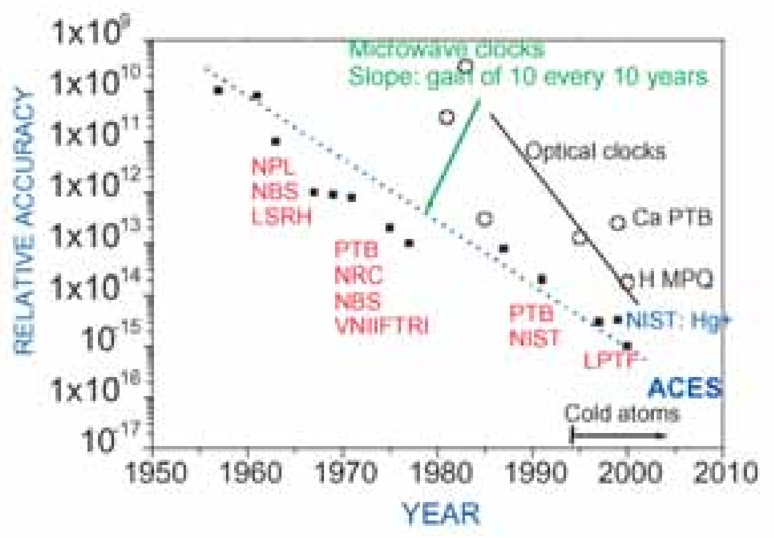


Figure 2.3.10.12. Evolution in the accuracy of atomic time, comparing microwave and optical clocks

2.3.10.8 Future Prospects

PHARAO and ACES will probably constitute the first demonstration of the benefits of space for cold atomic gases and their application to ultra-stable atomic clocks. PHARAO's performance could be improved still further by using a better interrogation oscillator, a better microgravity environment than that of the ISS, and by replacing the caesium atoms with rubidium atoms, which display fewer collisional interactions. Frequency stability and accuracy in the 10^{-17} range can then be envisaged. The associated time- and frequency-transfer techniques will need to include several higher order relativistic corrections in order to compare distant clocks adequately. Such ideas are already under development at NASA (PARCS, SUMO and RACE projects).

Of particular interest then would be a clock mission in the strong gravitational potential of the Sun, rather than that of the Earth (SORT). This mission could bring several orders of magnitude improvement in tests of general relativity, such as the Shapiro delay. Third-generation navigation systems are likely to benefit from advances made in the time-transfer techniques validated with ACES. Totally new concepts for global positioning systems based on a reduced set of ultra-stable space clocks in orbit, associated with simple transponding satellites, could be studied.

More generally, on the ground clocks operating in the optical rather than in the microwave domain are making rapid progress. The frequency of these clocks is four to five orders of magnitude higher than that of microwave standards. With an equivalent line width, the quality factor of the resonance then exceeds that of caesium clocks by the same factor. Using laser-cooled atoms or ions and ultra-stable laser sources, these optical clocks will likely open up the 10^{-17} – 10^{-18} stability range. Using the wide frequency comb generated by femtosecond lasers, it now becomes possible to connect virtually all frequency standards together throughout the microwave to ultra-violet frequency domain. The simplicity of this femtosecond laser comb, which fits on a small optical bench, makes it conceivable to qualify it for space.

Clocks are not the only devices that can benefit from the space environment. Atom interferometers would also have increased sensitivity with increased interaction times. In these systems, matter waves rather than light waves interfere, bringing an enormous gain in potential sensitivity over light interferometers. After just a few years of existence, matter-wave gyroscopes on the ground have now surpassed their optical counterparts in terms of their ability to detect very feeble rotation signals. This opens up a whole new field for inertial sensors, accelerometers, and gradiometers, both on Earth and in space.

In January 2000, the HYPER project was submitted to ESA by a group drawn from several European laboratories, in answer to the Agency's Call for Flexi-mission (F2/F3) Proposals. HYPER is designed to measure yet another effect predicted by general relativity, namely the Lense-Thirring effect, and also to measure the fine-structure constant with at least one order of magnitude gain in precision. HYPER would also be the first satellite to be monitored and controlled using matter-wave inertial sensors, rather than classical accelerometers and gyroscopes.

The technology for producing Bose-Einstein condensates and atom lasers is also progressing rapidly. Space would offer the possibility to produce coherent atomic waves in the picokelvin temperature range. In addition to the interesting fundamental many-body physics that this quantum matter would offer on a truly macroscopic scale in space, atom lasers would constitute ideal sources for atom interferometers with long interaction times.

Clearly, cold atoms open up several new and fascinating prospects for space applications!

Acknowledgements

The author wishes to thank many European and US colleagues for fruitful discussions on the above topics. The support received from ESA, CNES, CNRS, Region Ile de France, Bureau de Metrologie, and the Paris Observatory is also gratefully acknowledged.

CHAPTER 3

FROM BASIC RESEARCH TO COMMERCIAL APPLICATIONS

3.1 The Scope and Impact of the Information and Technology Transfer

G. Seibert

Research and development programmes stimulate the production capacity of the economy through the development and introduction of new technology. This can be particularly the case for space-related programmes, which require technical solutions for an extreme environment. New technology can make existing production methods more efficient and it can create new products, instruments and services. These not only stimulate new markets, industries and opportunities, but can also improve the way people do things and the overall quality of life.

These benefits and their impact on the economy are not immediate; it often takes many years for a new idea to be transformed into a marketable product or service. Economic success will also generally require large-scale manufacturing capacity, marketing effort, advertising, and product support.

Within the framework of the European space effort, some 4 billion Euros per year have been pumped into the economy, resulting in the creation of jobs and the stimulation of income throughout Europe. Of that amount, the ESA programmes have contributed some 2.6 billion Euros annually over the past decade.

The basic role of ESA is to carry out approved space programmes on a Europe-wide basis. An important part of that task involves the development of leading-edge technology to support those programmes. The developments may be in areas such as launchers and space systems, in communications, or in support of the diverse scientific and applications payloads.

Inevitably, some of these advanced technology developments find their way into applications other than just the space application originally intended. The result may simply be a use in some other highly specialised system of no great commercial consequence. On the other hand, it may also be adapted to find widespread and valuable commercial application. Consequently, the ESA programmes provide not only a direct return in the shape of successful space endeavours and a stimulation of Europe's economy and its space technology, but they also add indirect benefits. One of these is the process of 'spinning-off' advances in technology to create new, commercially valuable products.

The total extent to which this process operates is difficult to quantify. Knowledge is like a freely flowing fluid that can take many routes, so that the eventual destinations of the transferred knowledge can be difficult to trace. Nonetheless, ESA has initiated studies to try to get a measure of this so-called 'spin-off' effect. These Spin-Off and Technology Transfer Studies are intended to provide concrete examples that illustrate advances made as a result of space-technology research and development. They cover areas such as medical instrumentation and services, new and better materials and processing techniques.

In addition to that action to look back at what has happened and how various spin-offs have occurred, ESA and several European national space agencies have also taken the initiative to actively encourage and to promote this technology-transfer process from space programmes. A Space Link Group composed of transfer agents from ESA Member States has been formed to support these activities, and the major space programmes are now routinely examined for possible technology-transfer candidates.

The cost of the ESA Microgravity Programme amounts to less than 3% of the total ESA budget. Consequently, it had not been in the focus of this general ESA initiative to identify and define technology-transfer candidates. In fact, it was not until late 1999 that the Microgravity Programme was included in these activities and the task begun of identifying the spin-offs from the microgravity research and its associated experimental facility developments. In this task, and that of trying to estimate the potential markets, ESA was assisted by industry (Novespace/Beta).

The outcome of this review revealed an extraordinary success. Fourteen technical items, derived from microgravity life-science and materials/fluid-science activities, were either already on the commercial market, or about to produce large quantities of terrestrial equipment in newly built factories. Several space companies have recently created spin-off companies. For the year 2001, the commercial value of these spin-offs from the microgravity programme is estimated to be in the order of 50 – 60 million Euros. In 2002, it is expected to be in the range 90 – 100 million Euros, with further increases for the following years. The annual revenue associated with these spin-off developments from the microgravity programme will actually exceed the annual public funding spent on the ESA microgravity space activities.

The large number of spin-off developments from the microgravity space life sciences, which have found medical applications on Earth, is especially rewarding. It takes about 5 years to perform the necessary clinical tests and to obtain the related safety certificate for medical application. That points to an early and rapid application of the original space technology.

It was observed that the applications were often developed through the combined initiative of the Principal Investigators and those companies that were involved in the original microgravity hardware development. The main reason for the great success of this microgravity spin-off process is probably the fact that research activities in microgravity life- and physical sciences are closely linked to terrestrial research in the materials industry and in medicine. The space programme therefore acts as a catalyser for the development of innovative instruments and technologies.

In the following Sections, some of the most notable spin-off developments that were identified in this study are reviewed and their commercial relevance indicated.

3.2 The Commercial Spin-Off from European Microgravity Research

G. Seibert

3.2.1 Glaucoma Diagnosis: the 'Selftonometer'

Glaucoma is a widespread eye disease. It afflicts about 70 million people in the industrialised world and has led to blindness in about 10% of patients. It is caused by elevated pressure within the eye. If this intra-ocular pressure exceeds the vascular pressure within the arteries of the retina, the blood flow is suppressed. Consequently, the blood supply to the nerves may then become inadequate and the nerves of the retina die, producing blindness. If, however, the glaucoma is regularly checked through pressure measurements (six times per day) to detect pressure peaks, medication can be used at the appropriate time in order to lower and regulate the eye pressure. This can substantially reduce the risk of blindness occurring.

- *Space-Related and Technical Aspects*

It was believed that the fluid shift observed in astronauts when they enter the microgravity environment of space would have a strong effect on their intra-ocular pressure. The quantitative measurement of this pressure and its time dependence was the subject of various space experiments by Prof. Draeger of the University of Hamburg.

On the German D-1 Spacelab mission in 1985, the eye pressure of an astronaut was measured. This could only take place one hour after launch (i.e. too late to measure the peak) and it needed an additional astronaut to act as the operator. The drastically increased pressure that occurs during the launch itself could not be measured. Therefore the development of an automatic selftonometer device was needed and one was subsequently developed. This new device enabled an astronaut to measure his own eye pressure anywhere and at any time, even during launch and landing.

The main objective of the new development was to obtain a simple, one-man-operated instrument for astronauts. Different sensors were tested. Finally an optical infrared-surface detector was chosen, allowing for precise definition of the applanated corneal surface whilst performing tonometry. This light and precise instrument allowed self-tonometry to be performed under microgravity conditions for the first time. It was used during the Mir-92 mission and on the German D-2 Spacelab mission in 1993. A rapid increase in intra-ocular pressure, to 100% above the normal value, was measured. Fortunately, there was also an early (within a few hours) re-adaption to normal levels. After landing, a marked drop in intra-ocular pressure was recorded.

- *Spin-Off 'Selftonometer'*

The next step was the application of this technology to clinical medicine. An even lighter, smaller, more precise one-hand instrument was developed from the space model. Using the same IR-detector and the same technology proven in space flight, an automatic Selftonometer for use by glaucoma patients was developed in co-operation with Elektronik Präzisionsbau Saalfeld (EPSa) at Jena-Saalfeld (D). Following calibration, extended clinical tests and instrument certification (CEN) in 1999, this instrument could be made available to glaucoma patients.

Figure 3.2.1. The 'Selftonometer', an instrument for routine monitoring of intra-ocular pressure in glaucoma patients, derived from a self-operated instrument used by astronauts (courtesy of EPSa)

- *Economic Aspects*

Originally part of the East-German Zeiss-Kombinat in Jena, today EPSa is a private company with 140 staff, working mainly in the fields of small medical equipment and traffic telemetry using GPS. The research and space-hardware developments were supported by the German Space Agency, but EPSa has invested about 1 million DM in the development and commercialisation of the Selftonometer, plus 0.5 million DM in the large-scale production tools. The commercial activities started in 1999, with the sale of 500 Selftonometers at a unit price of 2000 DM. In 2000, 1000 units were sold, and for 2001 sales of 5000 units are envisaged. A contract with the German association of pharmacists has been concluded. They have taken over the task of instructing patients in how to operate the device. Also, the health-insurance companies have agreed to take over a major part of the procurement costs for the patients. The medical instrument company SMP markets the Selftonometer worldwide.

In 1999, marketing also started in Italy, Austria and Switzerland. It also started in 2000 in the USA, where a very large market exists. In Germany there are 1.5 million glaucoma patients, about 500 000 of whom are expected to buy a Selftonometer device. In addition, another 500 000 units are planned to be sold in other European countries. The eventual largest market is expected to be in the USA, with a likely requirement for several million Selftonometers.

There is also a version that allows eye-doctors to treat babies and handicapped people (costing 3000 DM). The Selftonometer has been patented in all major countries of the world. A follow-up development, compatible with telemedicine, is being tested at the University of Erlangen (D).

3.2.2 Osteoporosis Diagnosis: the 'Osteospace'

The absence of weight in the microgravity of space gives rise to changes in those tissues that normally support the body and propel it. The result of this unloading is a progressive reduction in bone and muscle mass. (see Sections 2.1.4/5). These processes are known from long-duration space missions, such as Skylab (lasting up to 84 days) and Mir (lasting up to one year).

Bone has two basic components, living and non-living. The living element is made up of osteoblast cells,which help to form new bone, and osteocast cells that resorb old bone. The non-living component is a matrix of collagen multiple fibres, combined with crystalline salts of calcium and phosphates. The former provide the bone with great tensile strength, while the latter give high compressional strength.

The rates of bone deposition and absorption are essentially equal in a normally functioning body on Earth, so that the total bone mass remains constant. This equilibrium is influenced by a number of factors, such as nutrition, physical exercise, exposure to sunlight (vitamin D), and hormonal secretions from numerous body glands. When the osteoblastic activity in bone is less than normal, the disease known as 'osteoporosis' develops (i.e. porous bone), which afflicts many women after the menopause and also the elderly. The bone loss can amount to one third of the original bone mass in women and half of that in men, the latter having about 30% more bone mass to start with. Osteoporosis makes bone brittle and more susceptible to fractures. The low bone mass and structural deterioration of bone tissue lead to an increased susceptibility to fractures of the hip, spine and wrist. A similar effect to osteoporosis develops in astronauts during spaceflight, but in an accelerated form. It is primarily the result of the disuse of the weight-bearing bones in the microgravity environment.

In order to study the rate of bone mass loss in astronauts and to determine whether countermeasures (physical exercise), medication and nutrition are sufficiently effective, a number of European scientists were selected to perform research during ESA's two Mir-based missions in 1994 (duration 30 days) and 1995 (duration 179 days). In support of these bone studies in space, via contracts with industry (Matra Marconi Space) ESA developed a Bone Densitometer device, which was based on a quantitative ultrasound technique. This technique was chosen to avoid the use of ionising radiation in a manned spacecraft, as would occur with the normal Dual X-Ray Absorptiometry technique.

Figure 3.2.2. The Osteospace, a bone densitometer derived from a space instrument uses ultrasound to determine bone density and structure, rather than the X-rays of conventional systems, thereby avoiding radiation exposure for the patient (courtesy of DMS/Medilink)

The ultrasound Bone Densitometer determined the speed of sound and the broadband ultrasound attenuation in the bone at the heel (calcaneus), and later at the tibia. From these two parameters, accurate information on bone mineral density and on bone structure can be derived.

The small French company Medilink, a subsidiary of Diagnostic Medical Systems, has developed the terrestrial spin-off of this Bone Densitometer, called 'Osteospace', under a licensing agreement with GIP-Ultrasons and Matra.

In 2000, around 100 Osteospace units were sold to clinics and practitioners, at a price of 18 000 Euros. Over the next two years, DMS foresees sales of this unit doubling. An improved version will be a portable unit, with new and improved probes. The world market for bone densitometers is currently worth about 600 million Euros/year. In Europe, some 5000 units were needed in 2000 by radiologists, rheumatologists and orthopaedists.

3.2.3 Video Oculograph

Within the framework of the visual-vestibular research performed in microgravity on the German and ESA missions to Mir (1992–96), the German national space programme has supported (since 1987) the development of a Video Oculograph (VOG) by Prof. Scherer, of the FU Berlin. That original instrument was later extended to a Binocular Video Oculograph (BIVOG), and used as a research instrument by Mir astronauts from Germany, ESA and Russia.

Making use of the technology and operational knowhow developed from the space missions, SensoMotoric Instruments (SMI) was founded in 1991 to concentrate on the development of VOG systems for terrestrial applications. The performance of this instrument was also improved and its innovative features extended. This resulted in minimising the inertial load on the head by the use of lightweight components for the Head Unit, and an extension of the field of view.

The applications for these instruments (2D-VOG and 3D-VOG) are in the medical diagnostic area, such as ophthalmology, neurology, physical therapy and in the related clinical and psychology research, such as brain research, human factors and marketing. So far, more than 500 of the eye-movement systems have been sold and installed in Europe, America and Asia, where the company has set up subsidiaries or organised a distribution network with competent partners.

Figure 3.2.3. The Video Oculograph, an instrument derived from research on the human vestibular system in space. The measurement of eye orientation and movement finds application in clinical practice in ophthalmology, in neurology and in psychology research (courtesy of SensoMotoric Instruments)

The 3D-VOG instrument, which also measures the torsional movement of the eye, is so far only used in a small number of international research institutes, eye clinics and by the German Air Force. Recently, SensoMotoric Instruments launched a new product (STRABS) based on this technology, which enables on-line binocular measurements and squint angle evaluation in three dimensions (horizontal, vertical and torsional), needed for strabismus (squint) analysis. Both instruments are based on a face mask, which includes two high-resolution infrared cameras mounted on the sides of the mask, to which the eye images are reflected using visible-light translucent IR mirrors in front of the eyes. The video image of the eye is digitally processed and the squint angle calculated. A large variety of visual stimuli can be applied by displays in front of the patient, using a video projector.

SensoMotoric Instruments has specialised in the development and system integration of video and sensor technology associated with digital image and signal processing for eye-tracking systems. Whereas the 2D-VOG has had great success in clinics for vestibular examination of patients (nystagmography analysis), the 3D-VOG is mainly used for research purposes. Other products include 'EyeLink', which is the leading research product for eye-movement analysis, and 'iView', used for human-factor analysis.

The German national microgravity research programme supported the VOG space project in the period 1987–1996. A follow-on development of an Eye Tracking Device, based on VOG and BIVOG, for research on the Space Station, is presently being supported by DLR at FU Berlin. The world market in this field of video-oculography and eye-movement measurement products is US$15 million, of which SMI has approximately 30 to 40%. SensoMotoric Instruments presently has a staff of more than 30 people. It is the technology leader in eye-tracking solutions for research, medical applications, human-factor analysis, as well as industrial applications.

3.2.4 Ozone Disinfection: the 'Sterilite'

Bradford Engineering (NL) have developed a safe disinfection system that is based upon flush cleaning with ozone gas. It was originally designed for use in the Biolab, a multi-user facility for biological research on the International Space Station. This

particular method of sterilisation was preferred due to its lower technical resource requirements and better safety features, when compared to conventional disinfection facilities such as autoclaves.

Bradford have derived a commercial version of this Biolab disinfection system, known as the 'Sterilite'. This ozoniser box is available in two versions: one is a portable unit, whilst the other is intended for permanent installation for all types of sterilisation and disinfection work. It can replace the traditional and cumbersome steam autoclaves, which work at high pressures and at 120°C. The chemically aggressive ozone that does the disinfection is generated by the ionisation of oxygen in the air, using a thin wire at a high electrical potential (7 – 8 kV). After the disinfection treatment, the ozone is easily dealt with because it decays naturally to normal oxygen with a half-life of 5 minutes.

There is a large potential market for this system, ranging from hospitals and clinics through to biochemical laboratories and dentists' facilities. Bradford's market analysis and production capability (large-scale production planned to start in autumn 2000) projected 1000 units for the year 2000, equivalent to 2.3 million Euros. After introduction of the ozoniser to the market, it is estimated that the total world demand for Sterilite could be as high as 100 000 units. Bradford anticipates that sales will increase further in 2001 and 2002, to 6 and 10 million Euros, respectively.

3.2.5 Triple-Containment Glovebox

Bradford Engineering developed various versions of a triple-containment biological glovebox for ESA in the early 1990s, which were intended for the USML-1 and USML-2 Spacelab missions. It also extended this design, to develop the larger glove boxes that were sold to NASA and to the Japanese space authorities. These were flown on several Spacelab and Spacehab missions. In modified versions, this glovebox has found customers worldwide for various space programmes.

A commercial development of these very safe, triple-containment space gloveboxes was made by this company, aimed at the much wider non-space market. These units provide for the control of gas composition and pressure, temperature and humidity. They allow

Figure 3.2.4. The Bradford Triple-Containment Glovebox. Originally used in space for ESA microgravity research, these units have been bought by NASA and the Japanese Space Agency. A design for terrestrial use has found application in medical areas and for the handling of toxic materials (courtesy of Bradford BV)

for the provision of a video system and internal microscopes and for the handling of toxic substances. The glovebox allows the partial pressure and the mixture of gases to be set and accurately controlled. Since body cells in-vivo see a 4 to 5% oxygen partial pressure, rather than the 21% as in air, this facility has become a very desirable tool for cancer research and for artificial- insemination studies. (in the USA there are 4 million artificial inseminations per year). Cancer-research institutes are already working with a terrestrial version of this glovebox.

The market for the triple-containment glovebox is potentially large and already increasing. After the first 8 units were produced and sold for 1.6 million Euros in 2000, sales will increase to 6 million Euros in 2001, according to Bradford's business plan. In order to manufacture the Ozonisers and Gloveboxes in large quantities, Bradford BV created a sister company, Bradford Medical, in 1999.

3.2.6 Heat Exchanger

In another commercial application of its space work, Bradford Engineering has developed a terrestrial version of its space component the 'Flat Swinging Heat Pipe', for application by the aviation industry. This unit is a direct derivation of the cooperative development by Bradford and the Dutch institute NLR of a two-phase temperature-control system. Its technical performance was first demonstrated in an ESA General Supporting Technology Programme experiment and it was later used in space for a combined ESA/UK project.

The commercial derivative of this component has gained acceptance by the military aviation authorities. From 2002 onwards, it will be used in large quantities for a new military aircraft, i.e. about 20 units per fighter plane. Some 3000 such planes will be produced by Boeing/Raytheon, as a successor to the Starfighter.

However, Bradford is also active in finding customers in the non-military sector, in which it expects significant sales already in 2000/2001. The initial annual sales target is 2.5 million Euros (unit price 400 Euros). An investment of 1.2 million Euros is planned by Bradford, which includes the setting up of a production line. The low and high business scenarios vary between 4000 and 20 000 units per year.

3.2.7 Respired Gas Analyser

Prof. D. Linnarsson of the Karolinska Institutet in Stockholm, and Prof. M. Paiva of the Free University of Brussels, in co-operation with cardiopulmonary scientists from the USA and Australia, wanted to study whether the upper and lower parts of the lung have different air- and blood-flow patterns when in space, compared to those when on the Earth. In other words, are these patterns induced by gravity on Earth and therefore absent in microgravity, or are these patterns a natural property of the lungs? In support of these lung experiments, ESA charged the Danish company Innovision with the development of a Respiratory Monitoring System (RMS).

Innovision's space work began in 1986 with the development of an early respiratory monitor that used a bulky mass-spectrometer as the gas analyser. It was flown as a major element of the ESA Anthrorack on the German D-2 Spacelab mission in 1993. The principal purpose of the monitor is to analyse the composition of respired gas mixtures.

A second generation of this monitor was subsequently developed. For the analysis of the respired air, it used the smaller Photo Acoustic Spectrometer (PAS) gas analyser, developed and patented by Bruel and Kjaer (DK). This instrument was flown with all its peripheral equipment on ESA's Euromir '95 mission.

The third generation of this respiratory gas monitor, with an improved performance and reduced resource requirements, is being developed for the STS-107 Spacehab mission in 2002. In addition, Innovision is currently developing for ESA a Photo-Acoustic Module for the pulmonary function instrument of the Human Research Facility. This will be installed in the International Space Station.

- *A Commercial Respired Gas Analyser*

Stemming directly from the respired gas analyser developed under an ESA contract, Innovision has derived a commercial instrument, the AMIS-2000, which is intended for use in pneumonology, cardiology, intensive care and sports medicine. A second instrument, the AMIS-2001, uses the photo-acoustic gas analysis method and has been clinically evaluated in Denmark, Germany, the United Kingdom, Sweden and Italy. The market for such gas analysers for clinical applications is potentially very large. Heart/lung failure is the most important health problem of the industrialised world, and a non-invasive technique to determine the condition of both the cardiac system and the lungs is highly desirable.

With this technique, measurements are made of the contents and flow of a person's respired gas. From these it is possible to determine the volume of blood pumped per minute (the cardiac output), lung diffusion capacity, lung volume, and the rates of oxygen uptake and of carbon-dioxide excretion. This provides much of the basic information needed to guide medical diagnosis and the appropriate treatment.

Innovision has therefore put a major effort into developing third-generation gas analysers for non-invasive measurements of cardiac output, etc. The new analysers will be dramatically improved in terms of technical capabilities compared with the AMIS-2000: 8 kg instead of the 100 kg of the AMIS-2000, 30 W instead of 800 W, signal-to-noise ratio of 2000 instead of 400, and a two times better response time than the AMIS-2000. The price is also very much lower, at 15 000 instead of 70 000 Euros.

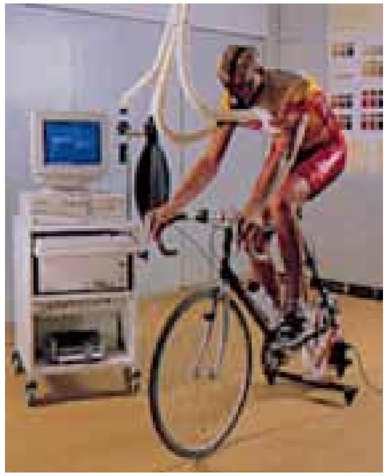


Figure 3.2.5. The Innovision Respired Gas Analyser. Derived from a space instrument for ESA, it provides a non-invasive method of determining cardiac output and lung characteristics and functions (courtesy of Innovision)

In addition, the maintenance requirements and complexity of operation of the new instruments are greatly reduced. The portable version of this device can be placed in the patient's home to monitor cardiovascular and respiratory parameters routinely. This is valuable in that it avoids hospitalising patients, for example those with pacemakers, dialysis, and critical care needs.

The market for this third-generation commercial instrument is probably very large. The main clinical application focuses on the measurement of cardiac output (pumping capacity of the heart) by a non-invasive method. It is very likely that this new method will replace the presently applied invasive methods, which are costly, inconvenient for the patient, and involve risks. The new technology is expected to contribute towards reducing the mortality rate from cardiovascular diseases, one of the most common causes of death in the industrialised world.

- *Spin-Off Ergonometer*

The Bicycle Ergonometer developed by Innovision for ESA was intended to be used as stimulus equipment for cardiopulmonary research. However, Innovision has subsequently sold 15 such units (100 000 Euros each) to NASA, for use by Shuttle astronauts for exercising whilst in space. It has also found use in several research centres and in the anaesthesia and intensive-care departments of hospitals/clinics.

3.2.8 Waste-Management Devices

In the early 1990s, CNES carried out a research programme in space using Rhesus monkeys. Within the framework of this programme, it was necessary to develop a system to collect the monkeys' waste under microgravity conditions. The technical requirements for the development called for a simple system, having a low mass and volume.

The small French company 3IS and Soterem took up this challenge and designed and developed a dry toilet system that collected and packaged the urine and faeces in sealed plastic bags.

- *Spin-Off 'Dry Toilet'*

The company 3IS identified a significant terrestrial application for this space waste-management device in various transportation vehicles such as buses. It is very suitable for use in campers/caravans and also on airplanes, both large and small, where water is scarce and expensive to transport. Boats in harbour are another potential user, since the fouling of harbour waters is a serious problem with present water toilets.

In such applications, the dry toilet has had to meet government regulations forbidding the open discharge of pollutants. The dry toilet meets both the technical requirements (minimum mass/volume), by avoiding the need for large amounts of water, and the regulatory requirements of` disposal, by using plastic-bag containment, perfectly. It is to be preferred also from the hygiene point of view.

3IS has patented the dry toilet in 12 countries, including the USA and Canada. Under licence from 3IS, the company Actia has started industrial manufacture of the Dry Toilet for camper vans and buses. It has installed test units in buses in France, Spain and Mexico.

Actia has invested some 300 000 Euros in the installation of an industrial production line and has concluded delivery contracts with the car industry (Renault) and caravan producers for the installation of the dry toilet. The unit cost for buses is 2000 Euros, whereas the unit cost for a simpler, lower capacity system for a camper van costs just 200 Euros.

The overall European market for new camper vans is about 20 000/year. It is therefore expected that, including the boat market, some 2000 units will be sold in 2001. That should increase strongly by 2002. The present market for buses is 200 units/year and is expected to increase to 300 by 2002.

In addition, 3IS is presently developing a modified dry-toilet version for hospitals, called 'Hospack'. A further application is its use by customs authorities for the collection of faeces from people suspected of having ingested tiny plastic bags filled with drugs.

The market for dry toilets is therefore expected to become a multi-million Euro business in the near future.

3.2.9 Three-Dimensional Eye Tracker

In the early 1990s, the German national space programme supported Dr. Clarke and Prof. Scherer in the development of their Video-Oculography (VOG) and Binocular Video-Oculography (BiVOG) measurement technology for vestibular research. With the help of industrial partners, these image-based eye and head-movement measurement

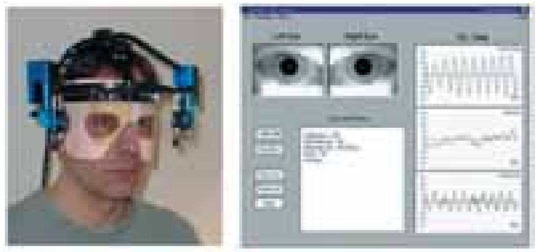


Figure 3.2.6. The Chronos Vision 3D Eye Tracker head unit. Originally developed for the German Space Agency and flown on German and ESA Mir missions, it offers binocular eye-movement recording, using integrated, intelligent cameras. The design gives a free field-of-view and the face-mask provides a comfortable fit that eliminates slippage. It is used for ophthalmological and neurological examinations, in corrective eye surgery, and in eye-guided interactions in virtual environments (courtesy of Chronos Vision)

systems were implemented for deployment on the German and ESA missions to Mir. Based upon this space technology, the company SMI (as discussed in Section 3.2.3) developed a first commercial spin-off. This was based upon standard video technology, which permitted off-line analysis of eye-movement recordings. Now Chronos Vision, which is a small enterprise founded by Dr. Clarke and Dr. Baartz of the FU Berlin, has developed the next-generation VOG, the 3D Eye Tracker. This provides for fully digital measurement of eye movement. This new system is based upon state-of-the-art, programmable, CMOS image sensors and dedicated digital processing devices.

The 3D Eye Tracker is designed as a portable instrument, being intended in the first instance as an integral part of the Human Research Facility on the ISS. However, it is also being developed as a commercial instrument for neurological and ophthalmological examinations. The Eye Tracker provides on-line and off-line binocular measurement of horizontal, vertical, and torsional eye position, based upon digital recordings of image sequences. Important new features include a selectable sampling rate of up to 400/second, reconfigurable processor units to allow software upgrades, and an ergonomically designed head unit.

The main market areas for the ‘Chronos 3D Eye Tracker’ include:
- medical research and diagnosis in neurology and ophthalmology
- monitoring of eye movements after corrective retinal surgery
- monitoring of eye position during laser refractive surgery
- neuro-psychology research and rehabilitation
- multimedia applications, such as eye-guided interactions in virtual environments
- ergonomic studies.

Preliminary clinical tests are now being performed in neurology clinics and vestibular research institutes in the USA, Canada, Germany, France, and Switzerland. The 3D Eye Tracker will be marketed worldwide by the experienced Dutch company Skalar Medical BV. The initial market for these units is estimated to be in the order of 60 – 80 per year. The unit price is about 35 000 Euros.

3.2.10 Ultrasonic Components

In 1979, Prof. L. Pourcelot and Dr. Patat of the medical faculty of the University of Tours started to develop, in co-operation with Matra Espace, an ultrasound sensor to perform heart echography during spaceflight. This work was carried out within the framework of the CNES Premier Vol Habité programme. The first French astronaut, J.L. Chretien, used this echograph in 1982 in orbit. A follow-on development of this device, the ‘As de Coeur Echograph’, was used in 1986/87 by the second French astronaut P. Baudry, on Mir and on Shuttle mission STS-51.

Matra itself did not want to enter the terrestrial medical-equipment market. However, two spin-off companies were created: Vermon (1984, Tours) by the Faculté de Médecine de Tours, and Imasonic (1989, Besancon), by Vermon engineers involved in the space projects. The intention was to manufacture and commercialise ultrasonic Doppler probes and transducers for the medical-equipment industry.

In addition, a Groupement d’Interet Public called GIP-Ultrasons was created in 1990 at the University of Tours by several of the university’s research institutes, CNES, Matra and a number of academic, governmental and private institutions. This GIP had the objective of compiling, advancing and transferring ultrasonic technology, including high-resolution ultrasound imagery. Matra transferred its ultrasound know-how from the ‘As de Coeur’ space project to GIP-Ultrasons. This group participated in several space ultrasound projects in the 1990s, e.g. in the design and development of the ESA Bone Densitometer and in ESA technology studies in this field. In addition, it started to derive the spin-off ‘Osteospace’ (see Section 3.2.2) and UBIS 3000, a device that enabled the mapping of parts of the bone at different times.

In 1997, experienced GIP-Ultrasons engineers created the small company ‘Ultrasons Technologie’, which produces and markets ultrasonic equipment for diagnostic imaging and components. The ultrasound Doppler transducers and probes for these are produced by the company Vermon.

The company Imasonic is specialised in the techniques that are used for non-invasive medical diagnostics and therapy and in non-destructive testing and control of materials and parts in industry. It provides piezo-components made from composite materials for large frequency ranges, wide temperature ranges and acoustic power devices.

Together, these three companies, Vermon, Imasonic and Ultrasons Technologie, employ more than 100 people. In 1999 they had an annual turnover of 10.5 million Euros, at least 50% of which was directly derived from the space life-sciences-facility developments.

3.2.11 Mobile Photogrammetric Measurement System

Within the framework of ESA's fluid-science activities in microgravity, there was a need to measure the motion and shape of transparent liquid bodies, e.g. the liquid columns investigated with the Fluid-Physics Module and also with the Advanced Fluid-Physics Module flown on the German D-2 Spacelab mission in 1993.

The traditional measurement technique used to determine both the geometrical shape and the volume was the so-called 'light sheet method', which provides successive measurements of the cross-sections. This technique is limited to steady-state phenomena or to a single cross-section.

In order to remove these limitations and the risk of microgravity disturbances by a mechanical scanning system, ESA placed a technology study to develop a technique to observe the dynamic behaviour of arbitrarily shaped fluid bodies in a fluid matrix. This was to be based upon the use of a three-dimensional photogrammetric method.

In the period 1993 to 1996, the small company AICON in Braunschweig (D), translated an idea of Mr J. Becker (ESTEC) into hardware and software that could measure the changing shapes of liquid columns, droplets and bubbles. AICON's expertise led to the creation of a 3D Photogrammetric Measurement Head for the measurement of position co-ordinates throughout the whole object space, i.e. throughout the whole experiment volume (typically 100x100x100 mm^3) with a spatial resolution of 15 microns.

This non-invasive optical diagnostic tool can be applied, for example, to the Fluid-Science Laboratory for the Space Station, in order to study dynamic phenomena from one viewing direction, whilst leaving the second orientation open to other diagnostic tools. The system is also able to perform the three-dimensional reconstruction of objects. The front end, towards the object to be measured, consists of a 'camera bundle' of three CCD cameras that provide different views of the object. Using these three different views, the position co-ordinates can be calculated on the basis of a system calibration. This calibration includes the orientation of the cameras and the 'multi-media optical path' (e.g. air–windows–media–bubble).

- *Spin-Off 'Pro-Cam'*

AICON has used its experience from space-related work and from earlier photogrammetric work to develop an industrial 3D measurement system, the Pro-Cam^3. The industrial version of this mobile 3D-probe has been accommodated in a handy solid housing connected via a cable to a portable PC, which directly displays the co-ordinates. Exchangeable probe tips (touch sensors) have been provided.

The measured shapes and volumes range from some centimetres to 10 metres, with an accuracy that is about 1/10 000 of the size of the object. Calibration of the system can be performed in the field and takes only a few minutes.

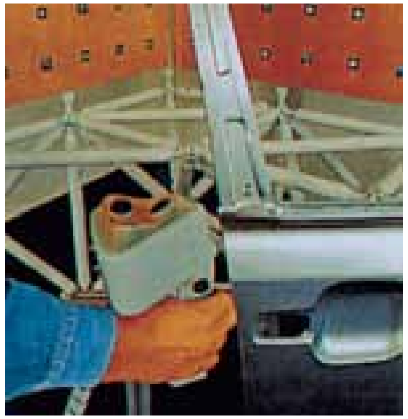


Figure 3.2.7. The AICON Pro-Cam^3. Originally developed to measure the 3D motion and shape of transparent liquids in ESA fluid-physics facilities, this commercial derivative finds ready application in many industries where simple, yet accurate, three-dimensional measurements and image reconstitutions are required (courtesy of AICON)

- *Economic Aspects*

There is a rapidly growing demand for accurate and mobile three-dimensional measurements in many industrial areas, such as the automotive, aircraft, ship and tool industries. Efficient and very precise production monitoring, quality control and assurance is essential in modern industry.

The Pro-Cam^3 system has advantages over competitive techniques such as Stationary Co-ordinate Measurement Machines, Mobile Measurement Arms and Stereo Videogrammetry with regard to handling, mobility, setup time and portability. The accuracy is slightly lower than with these alternative techniques, but it is generally sufficient. In addition, the cost is lower.

The expected annual market volume is 50 Pro-Cam^3 systems from the year 2001 onwards, following introduction in 2000. The unit cost is 65 000 Euros. It is expected that the market for this unit will increase annually by about 30%.

Among the initial users are Daimler Chrysler and BMW in the car industry and Airbus Industrie. The Pro-Cam system has been patented in Germany and patent applications have been made by AICON in other European countries and in the USA.

3.2.12 Crash Tester for the Car Industry and Railway Electrical Monitor

Kayser Threde GmbH, of Munich, has been involved in the Texus Sounding-Rocket Programme since it started in 1976 in Germany. The Texus Programme was initially dedicated to short-duration microgravity experiments in materials science, fluid physics and later also biological experiments.

These experiments were performed with a set of experiment modules, such as furnaces, process chambers, biological incubators, etc., equipped with an integrated electrical supply, command and data-management system, telemetry, and g-level

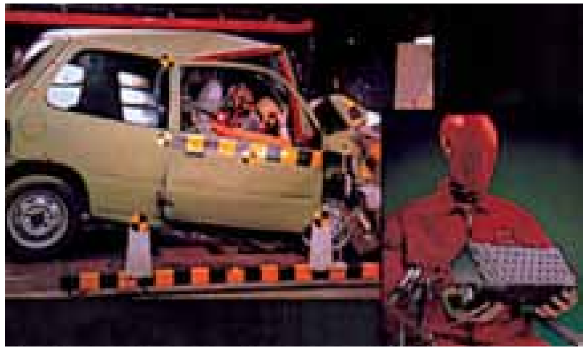


Figure 3.2.8. Crash-testing equipment, one terrestrial application of Kayser-Threde's expertise in system measurement and data management for the Texus sounding-rocket payloads

measurement. All of these standard services to the experiment modules were accommodated in the Texus Service Module. Kayser-Threde developed, maintained, and upgraded these Service Modules and provided the computer-based electrical ground checkout equipment, as required for the integration and monitoring of the Texus payload.

From the start of its space-research-related activities, which cover some 30 years, Kayser-Threde has looked for terrestrial applications of its space know-how. This has been derived from work on the development of scientific facilities, satellite subsystems, and elements of space transport systems, as well as the activities in the Texus Programme. It has found those applications mainly with the German railways and in the car industry. Today, about 50% of Kayser-Threde's business is independent of any space programme, but is all derived from the original space activities. It now covers high-speed data acquisition, coding, handling and transmission systems, GPS-based location techniques for rail, car, and truck traffic, and crash-test facilities.

Kayser-Threde is a major supplier to the German railway system of the autonomous electronic supervision and control equipment needed to control the electrical energy supply and distribution.

The value of Kayser-Threde's space-derived spin-offs in 1999 was about 6.5 million Euros, and averaged about 5 million Euros per year over the period 1994–1999. Kayser-Threde expects the non-space part of the company's activities to increase still further in the future.

3.2.13 Body-Fluid Monitoring with Multi-Frequency Impedance Measurements

In early 1995, the Spanish company NTE received a contract from ESA covering 'Body-Fluid Monitoring with Multi-Frequency Impedance Measurements'. This contract included the development of five units of the Multi-Frequency Impedance Measurement System (MUFI), capable of measuring the distribution of intra- and extra-cellular fluid in the whole body and in segments of it such as the head, thorax, abdomen, arms and legs.

ESA's plan was to have a measurement device to determine the well-known shift of about 2 litres of body fluid that occurs in astronauts when they enter the microgravity environment. This NTE contract also covered the performance of two MUFI calibration and application campaigns, which were carried out with the involvement of several medical teams with expertise in body-fluid shift mechanisms and in different methods of determining segmental and global total and extra-cellular water volumes.

The MUFI measurement technique uses the fact that the electrical impedance of biological tissue is a function of frequency. The impedance has a real and an imaginary (typically negative) part, with the latter indicating capacitative effects originating from cellular membranes. When the frequency of the current injected into the 'circuit' of the biological tissue is low (below 20 kHz), the capacitor C (of the membranes) has a high impedance and current flows only through the extra-cellular medium (R_e). If the frequency is high, (i.e. over 100 kHz), then the capacitor C becomes almost a short-circuit and the electrical current flows not only through R_e, but also in parallel through R_i (the resistance of the intracellular medium) via the capacitor C. This means, in simple terms, that at frequency zero the extra-cellular fluid volume can be determined, whereas at infinite frequency the total fluid volume (extra-plus intra-cellular) can be measured.

The calibrated MUFI instrument has indeed been able to measure the intra- and extra-cellular water contents successfully. As a result of this success, NTE has also invested its own money in the development and certification of a commercial product, which is a derivative of the MUFI instrument.

At present, those physicians dealing with healthy people such as sportsmen, fighter and test pilots, people requiring diet control, scientists performing bed-rest studies simulating microgravity conditions, etc., are potential customers for the commercial MUFI instruments. Calibration of the MUFI technique for different diseases will be started in the near future.

The total investment to date in the MUFI project by PNE (Plan Nacional del Espacio of Spain), ESA and NTE amounts to 1.3 million Euros. The expected sales, on the basis of conservative assumptions by NTE are: 180 kEuros in 2001, 420 kEuros in 2002, and 780 kEuros in 2003.

In addition to the MUFI instrument, NTE has developed a spin-off for biomass monitoring, from an ESA TRP study on life-support systems. It has also developed a device to measure the quality of meat, based upon the electrical-impedance spectroscopy technique discussed above. This particular development has been supported by the European Union.

3.2.14 Posture Platform and Locomotion Measurement System

Within the framework of Franco-Russian missions to Mir, the Laboratoire de Physiologie of the Medical Faculty of Toulouse Rangueil (Profs. Bessou, Depui and Montoya) has conducted research on human balance, posture and locomotion in microgravity, using pre- and post-flight measurements as a reference.

Balance regulation involves the transfer of signals from specialised nerve sensors to the central nervous system, with the aim of maintaining good balance and harmony of body movements (see Section 2.1.6).

In order to measure and analyse the postural regulation of a standing subject, the company SATEL, in co-operation with the Laboratoire de Physiologie, has developed a 'force-platform'. This force-platform enables the recording of statokinesigramme plots of successive positions of the centre of pressure exerted by the subject's feet on the platform with respect to a reference axis. These measurements are performed with 'eyes open' and 'eyes closed', because the ability of individuals to balance in static conditions is quite different in the two cases. A computer associated with the force-platform displays the statokinesigramme in real time on a screen and makes an assesment of the subject's ability to maintain orthostatic balance.

This balance platform is now increasingly used in the clinical evaluation of posture in the fields of neurology, ENT, gerontology, traumatology, sports physiology and physiotherapy. A large portion of the population has posture deficiencies or disturbances.

A second apparatus, the 'mobile platform', was also developed by SATEL, in co-operation with the Laboratoire de Physiologie at Toulouse. It measures and analyses the dynamic-balance function of human subjects during walking. This mobile platform enables therapists to identify the patient's sector of balance deficit using visualisation of the measurements. Based on these measurements, the therapist can develop for the patient a physiotherapy programme using postural biofeedback. Simultaneous recording of both feet during human walking is used for the analysis of locomotion, with the aim of accurately assessing spatial and temporal parameters of that locomotion and identifying deviations from normal locomotive behaviour.

- *Economic Aspects*

The company SATEL was founded in 1981 with the objective of supporting the development and promote the utilisation of medical equipment. As far as therapeutic application of the SATEL posture and locomotion diagnostics and therapy instruments is concerned, the French Social Security Dept. has recently approved coverage of up to 10 sessions (at 100 FF each).

The unit cost of the locometer platform, including software, amounts to 70 kFF. The posture-analysis platform costs 56 kFF. SATEL's recent and projected sales figures are as follows: 7/98–6/99: 70 000, 7/99–6/2000: 210 000, 7/2000–6/2001: 400 000 and 7/2001–6/2002: 610 000 Euros.

3.2.15 Future Developments

Besides those applications and technology transfers that were described above and are summarised in Table 3.2.2, a number of other space-derived commercial applications were identified. These are presently either at an early stage of commercialisation or are at the component level, making an assessment concerning their future commercial prospects more difficult. A number of them are outlined below.

- *Shape-Memory Alloys for Implanted Medical Devices*

Previous developments of prototype equipment for use in space, undertaken under a series of contracts awarded by ESA to Brunel Institute for Bioengineering (UK) facilitated the spin-off of Anson Medical Limited, a UK-registered company manufacturing implanted medical devices.

The specific technology associated with the development of space equipment focussed on the dynamic properties of Shape-Memory Alloys (SMAs). The rationale for the use of these materials was to try to simplify the complex mechanical devices, such as actuation mechanisms, that were to be used on-board 'Biosample', an experimental plant-research facility. The Biosample module was originally intended as an automated life-science facility for the unmanned European Retrievable Carrier (Eureca).

Shape-memory alloys were used for:
- optical-mirror actuation
- a plant-cutting actuation mechanism
- a miniature rotary-drive engagement mechanism, to shield delicate electro-mechanical devices

Anson Medical Ltd. produces implanted medical devices for use in cardiovascular and orthopaedic surgery and treatment. These devices are made wholly or partly from shape-memory alloys. The products currently under development and undergoing trials are vascular stents, vascular stent-grafts, and endoscopic instruments for cardiovascular intervention and orthopaedic trauma.

The sales of Anson Medical should be about 900 kEuros in 2001 and are expected to increase rapidly in subsequent years.

- *Back-Pain Diagnosis and Therapy Device*

Contrary to expectations, most astronauts have suffered from back pain whilst in space. In order to try to determine its origin, Prof. Baum of the Deutsche Sporthochschule, Cologne, developed a six-channel ultrasound device. This instrument measures the distances between eight electrodes (each with one ultrasound receiver and one transmitter) on the skin. The information is recorded with a sampling frequency of 1 Hz over 56 hours (accuracy better than 1 mm) for later evaluation, in terms of body attitude, muscle movements and recommendations for therapy measures.

In the experiments, both distance changes at selected points of the back and the electric potentials (EMG) were measured simultaneously. The resulting conclusion was that back pain is mainly due to insufficient movement of back muscles. It is not due to spine length changes or atrophy of spinal discs, as had been assumed originally. The pain results from an isometric contraction of low intensity of muscles on both sides of the spinal column if the body does not move sufficiently. Bed-rest studies have confirmed this conclusion.

Based on the experimental results of these projects on the German Mir '97 mission and on two French Mir missions in 1998 and 1999, the small company Orthoson (Jena) has developed a very small, portable Ultrasound Sensoric Device, for which it has obtained a worldwide patent. All clinical tests are complete and were successful. However, up to two years are estimated to be needed to develop a commercial unit, which will also be able to provide instructions for therapy countermeasures (i.e. defined muscle exercises).

In the industrialised world, about a third of all sick-leave days, and one third of all early invalidity cases, are related to back pain. It is estimated that in Europe, where the annual medical and rehabilitation expenses exceed 1000 billion Euros, about 20% of the costs are spent on back-pain-related medical treatments and rehabilitation. Consequently, an instrument such as this is likely to find a significant market.

- *'Mamagoose', a Monitor to Reduce the Incidence of Sudden Infant Death Syndrome*

This spin-off is derived from the 'Respiratory Induction Phethysmograph' (RIP) experiment of Prof. Paiva (Université Libre de Bruxelles). The space version of it was developed by the company Verhaert Design and Development. It was first flown as an element of the large ESA human physiology research facility Anthrorack, on the D-2 Spacelab mission in 1993. The clinical tests on the RIP-derived 'Mamagoose' have already been performed.

The Mamagoose is a suit for babies, whereas the RIP suit was specifically designed for astronauts. It measures rib-cage and abdomen movements during respiration and it gives an alarm if these movements stop. The Mamagoose had to be made watertight and designed to limit the possibility of frequent false alarms. Completion of the Mamagoose development and testing effort will require up to two years.

It is estimated that the US market for FDA-approved Mamagoose suits would be about 10 000 units per year, with a substantial market also in Europe.

- *A Bioreactor for Biomedical Applications*

Prof. A. Cogoli of the Space Biology Group at the ETH in Zurich (CH) has worked since 1977 on gravitational and space-biology subjects. In particular, he has worked on cell biology (signal transduction, cell differentiation and proliferation), immunology, bioprocessing and technology in space. He participated as Principal Investigator in five Spacelab missions, several sounding-rocket flights, Mir, Foton and Spacehab, and will be the PI on the Biopack STS-107 mission in 2002. The ETH team has developed the following hardware for space missions:

- Cell-culture incubators and cell-culture flasks.
- Blood kits and immuno-test kits for immunology experiments in microgravity.
- Mini-bioreactors with automatic medium replacement.
- Bioreactors for Biorack Type-2 Containers.

Of this space research hardware, the Space Bioreactor for Biomedical Applications is the most application-oriented development. However, it is expected that it will require a further five to ten years of research in space and on Earth for it to become a commercially viable product. This project was selected as an ESA Microgravity Applications Project (MAP) early in 1999. The Bioreactor project team, led by Prof. Cogoli, consists of five co-investigator teams and the company Sulzer Medica of Winterthur (CH).

The production of artificial tissues and organ-like structures is one of the most innovative and timely technologies. Understanding of the molecular and biological mechanisms regulating the growth and survival of such structures is a necessary prerequisite for medical applications. It is believed that microgravity may contribute in two respects to progress in this field. Firstly, it is a useful tool for investigating important biological events at the cellular and molecular levels (e.g. signal transduction, genetic expression and cell proliferation) from a new and non-invasive standpoint. (i.e. avoiding inhibitors or other biochemical agents). Secondly, low-g conditions may also favour the mass production of cells, by obtaining higher cell densities per unit culture volume, and enable smooth cell-cell aggregation and three-dimensional organogenesis, in the absence of gravity or of damaging sheer forces due to agitation.

Sulzer Orthopedics is a medical-device company that is investing heavily in biotechnology to develop the next generation of implants, i.e. implants leading to tissue repair and regeneration. Their R&D programme comprises biological implants to regenerate meniscus and articular cartilage in the knee, as well as to develop growth factors for the induction of new bone. Sulzer Orthopedics' expertise lies especially in providing implants containing autologous cells of the patient.

The first phase of applied research focuses on the understanding of biological processes of cartilage tissue formation in-vitro, followed by the application of this knowledge to the industrial process of cartilage production. It is expected that the advanced bioreactors to be developed will form the basis of automatic cartilage production. The automatic process will also be used to grow organs such as liver, thyroid, pancreas, etc.

The implants are in-vitro-developed organ-like structures that are implanted into the body, where they then develop to fully functional tissue organs.

The company owns a patent on the production of cartilage in-vitro, using free cells. The literature demonstrates the importance of microgravity for in-vitro cartilage production (improved 3D growth), due to the reduced mechanical load in microgravity. The bioreactor will allow the production of mass cell cultures for pseudo-tissues and pseudo-organs by in-vitro organogenesis. The use of viable autologous cells in the bioreactor will allow the utilisation of the body's own repair and remodelling mechanism.

Tissue engineering is an expanding field of medical research, which will potentially lead to relevant clinical applications in the near future. The present world market for artificial tissue-engineered products amounts to about 5 billion Euros, and is increasing by about 25% per year.

- *Novel Bearing Alloys for Car Engines*

On Earth, a number of alloy systems exhibit two immiscible phases when they are liquid. The fact that each phase has a different density can lead to separation by gravity-induced sedimentation, both before and during solidification. What is needed for applications is a homogeneous distribution of the two phases. In the case of materials for bearings, a soft metal in the matrix of a hard metal is desired.

It was originally assumed that, because of the absence of sedimentation in microgravity, the solidification of such alloys under those conditions would result in a homogeneous distribution. That did not occur, however, because of the effect of a gravity-independent mechanism called 'Marangoni migration'. This migration is driven by interfacial tension gradients on the surfaces of droplets, caused by local temperature gradients in the melt. Dedicated microgravity experiments led to the measurement and the characterisation of the Marangoni effect. Theoretical studies by Prof. Ratke (DLR, Cologne) led to the validation of numerical models and finally to the possibility of controlling the direction and velocity of this Marangoni-induced migration.

The next step was the use of this knowhow to counterbalance – in production processes on Earth – the gravity-induced sedimentation of the higher density droplets by a reverse Marangoni migration. By applying this balancing method in terrestrial laboratories, it was possible to obtain homogenous dispersions of particles of a soft metal (which provides the lubrication) in the matrix of a hard metal.

The application of such new and better lubricating materials in cars would have major economic benefits in terms of the lifetime of the bearings and of fuel consumption, since many sliding bearings are employed in every car. The DLR Space Simulation Institute is trying to obtain a European Union research contract to cover the investment needed to procure a Strip Cast Machine (1 million Euros). This would be used for the optimisation and model validation of different bearing materials, and to obtain the automotive industry's support for performing the expensive lifetime tests.

If the validation and further quantitative and lifetime tests are successful, there would be a large potential market for this type of sliding bearing, especially in the car industry.

- *Astrium-Dornier Spin-Offs*

Of all the European space companies, Astrium-Dornier was in the past the one most involved in the development of microgravity experiment facilities for the ESA and German national microgravity research programmes. In addition, Astrium-Dornier was for many years the main contractor for the ESA Technology Research Programme 'Space Materials Sciences'. This involvement, in co-operation with a number of European subcontractors, has led to several technological advances and component improvements, which have already or which will find spin-off applications in various non-space industrial fields.

Examples of such applications are:

- Miniquarium, derived from Biorack, is outfitted with various integrated and individual micro-sensor packages for pO_2, pCO_2, pH, nitrate, glucose, flow, relative humidity and temperature. In addition, there are gas/water/nutrient/medium exchangers, feeding systems, micro-pumps, and an optical observation capability, i.e. all components that are useful for advanced bioreactors.
- A novel technique for detecting the solid/liquid interface in solidification processes, developed in cooperation with Access eV (Aachen) and the University of Leipzig. The method is based on the application of longitudinal, guided ultrasonic waves,

supplied from a transducer/receiver at the cold end of the sample. The position of the solid/liquid interface is determined by a time-of-flight measurement for the fraction of the wave that is reflected at the interface. The resolution of this method is better than 0.01 mm, which is ample for terrestrial and space solidification research. At present this technique, derived from an ESA TRP development, is used by the companies RWE and Heidelberger Druckmaschinen, and by the glass industry.

– The use of Vacuum Insulation Panels (VIP) as structural wall elements with strongly increased insulation performance. Astrium-Dornier has made the Refrigerator Freezer Racks for ESA for use on the International Space Station, for which such VIPs have been developed. The VIPs thermal conductivity is about 10 times lower than that of conventional insulation. VIPs are already utilised for high-end commercial freezers and allow energy savings of up to 30% compared to conventional designs. The VIP spin-off is especially interesting for rail, ship, road and air transportation.

A number of further potential Spin-Offs from space fluid-physics experimentation are listed in Table 3.2.1.

- *Telemedicine and Health-Telematics*

The European Commission defines 'Telemedicine' as a specific part of telematics application for healthcare or 'Health-Telematics', the latter term being derived from the combined use of telecommunication and informatics technologies in the healthcare system in general.

These telematics technologies find application in the medical services, as well as in the associated support services. They will therefore be used by doctors, as well as by nurses, pharmacists and other 'health agents'. Applications will include the direct medical treatment processes as well as the prevention, general care and rehabilitation activities. Telemedicine in this context is understood to be the use of health-telematics technologies in the direct care process, in situations where the patient is located at a distance from the source of the requisite medical expertise.

Health telematics is used for medical diagnostics and consultation. A simple application would be the consultation of on-line computer databases, such as a search for abstracts of publications on relevant medical cases. The advances in the capacity of today's communication links and technology, via satellites or fibre optics, allow the provision of medical services to patients at remote sites where no medical experts are available. The wide-bandwidth transmission of digital signals, in conjunction with computer services, allows the transfer of ECG, digital X-ray images, and high-resolution motion pictures from remote sites to medical centres for diagnosis and consultation. The most relevant applications of video-telemedicine are those that do not require face-to-face contact between the physician and the patient.

Table 3.2.1 Potential Spin-Offs from Space Fluid-Physics Experiments

Name	**Original Microgravity-Related Project**	**Potential Non-Space Application**	**Potential for New Commercial Application**
Astrium/Dornier and subcontractor Ferrari SpA	Bubble, Drop and Particle Unit (BDPU) TC3 Mini Gas Compressor	Car engine control	Sports- and racing cars (BMW)
Astrium/Dornier + consultant TU Munich	Bubble, Drop and Particle Unit (BDPU) TC3 Mini Thermistor Sensors	Advanced temperature sensoric instrumentation (gas/liquid applications)	Ultra-small and fast object/media instrumentation
Astrium/Dornier + subcontractor Laben SpA	Bubble, Drop and Particle Unit (BDPU) TC1/7 Liquid Separation Sheets	Crystal growth from liquids, diffusion and chemical processes	Miniaturised ultra-precise process-control device
Astrium/Dornier + subcontractor Officine Galileo	Bubble, Drop and Particle Unit (BDPU) TC2/6/8 Gas & Liquid Extraction System	Binary physico-chemical processes with trapped gas bubbles of liquid drops	Liquid/liquid and liquid/gas separation without loop
Astrium/Dornier + supplier Univ. Libre Brussels	Bubble, Drop and Particle Unit (BDPU) TC1/3/7 Liquid Tracers	Advanced measurement of liquid flows (esp. LDV and PIV applic.) using silvered nanospheres	Chemical process control and two-phase flow
Astrium/Dornier + subcontractors Kayser-Threde and Labor Steinbichler	Holographic Optics Laboratory (HOLOP): Thermoplastic Camera	Compact/automatic holographic camera for industrial applications (liquid/gas processes, object deformation)	3D flow and object measurements in research and industry
Astrium/Dornier	Holographic Optics Laboratory (HOLOP): ISIS-GVI (Glass Fibre Vac. Isolation)	Advanced thermal insulation (with hot/cold application potential; also for rough chemical environments)	Railway, road, aircraft transportation Passive transport (20x lower heat conduction)
Astrium/Dornier +subcontractor Nucletron/Marlow	Refrigerator/Freezer Rack (RFR) Thermoelectric Cooler Assembly	Advanced thermoelectric coolers for mobile applications (e.g. ships, aircraft, trucks) or high demands concerning noise, vibration, reliability	Mobile thermal-conditioning applications, noise and vibration-sensitive thermal conditioning and low-temperature cooling
Astrium/Dornier +subcontractor Verhaert	Refrigerator/Freezer Rack (RFR) Defrosting and Humidity Management	Humidity management, within non-gravity environment or without active pumps	Enhanced cooling device defrosting (refrigerator/freezer)

Telematics is considered to be the key to overcoming the dilemma that all healthcare systems in the developed countries are facing: i.e. increasing demands being placed upon decreasing or stagnating resources. The widespread use in the future of telematics should improve, or at least maintain, the quality of health care for the general population. It can provide increased access to medical specialists, reduce transportation costs and increase the overall cost efficiency.

Telemedicine can allow home-monitoring of patients who are still recuperating after early discharges from expensive stays in hospitals after surgery. It allows home-monitoring of old people, at a time when they are forming an increasing portion of the population. Such a monitoring system will enable the elderly to live longer in their own homes, under conditions of 'controlled, self-determined autonomy'. Telemedicine is a new field that provides major opportunities. It has a large market potential, running to billions of Euros, once general acceptability by physicians and patients has been achieved.

The two leading nations in manned spaceflight, the USA and the Soviet Union/Russia, have used tele-monitoring and video-conferencing to monitor the health of their astronauts. With the start of regular, long-duration, manned missions on the International Space Station, and later of manned missions to Mars, it will be essential to develop autonomous decision-support systems with the combined use of telemedicine and robotic devices/instrumentation. Even more than in the past, the space programme will have a lead role in the development of advanced telemedicine and the qualification of the associated new technologies. Other potential applications of this new healthcare technology include its use in battlefield surgery, during wilderness expeditions, and in connection with emergencies during air and sea transportation.

In the early 1990s, the Health Telematics and User Support Division of the DLR Institute of Aerospace Medicine carried out the Baseline Data Collection (BDC) for the Anthrorack human-physiology experiments for ESA. (Anthrorack was ESA's largest life-sciences facility, flown on the German D-2 Spacelab mission in 1993).

Based on this BDC experience, the DLR team has continued to use and to improve informatics and telecommunication technologies for applications in healthcare activities. They became involved in a number of telemedicine research and development projects, nine of which were supported by the European Union in the 4th and 5th Framework Programmes in the period 1996–2001. In addition, DLR's telemedicine projects were promoted by government organisations such as the Federal Armed Forces (Deutsche Bundeswehr), and industrial organisations such as Deutsche Lufthansa.

The total third-party funding for DLR's telemedicine projects in this period was more than of 2.5 million Euros, of which 0.7 million were contributed by the European Union. Over the past 7 years, DLR has acquired a co-ordinating and moderating role in the process of introducing telematics into healthcare systems.

In addition to these telemedicine collaboration projects, which are supported by the G-7 countries, WHO and the European Union, there is a very interesting initiative at German national level. It concerns the development of a Health Telematics Platform, with the establishment of virtual electronic health records and electronic prescriptions for regional healthcare networks that will finally merge into a federation of networks within Germany and beyond. Presently, negotiations on the implementation of such systems are being undertaken with communication and e-business providers, such as Deutsche Telekom.

3.2.16 Spin-Offs: Impact on Jobs and Company Creation

Another type of benefit derived from ESA and national microgravity research programmes is the creation of some 20 small companies in the last two decades in various European countries. These have subsequently used their acquired microgravity-related knowledge to broaden their activities into other space disciplines and into non-space industrial developments. There were a further 20 existing Small- and Medium-sized Enterprises (SMEs) that have extended their activity strategy to include microgravity developments and to exploit them in their terrestrial branch or to create spin-off companies for this purpose.

The following is a non-exhaustive list of these new or reoriented SMEs and the larger space companies where new jobs have been created due to their involvement in microgravity work:

Belgium: Chevalier Photonics, Lambda-X, Logica, OIP, Verhaert, Trasijs Space
Denmark: Damec, Innovision
France: Aerospatiale, Cadmos, Comat, Diatecnic, DMS, Matra, Medes, Medilink, Novespace, SEP, Soterem, Vermon, 3IS
Germany: Access, AICON, Astrium, Chronos Vision, DLR Musc, EPSa, Intospace, KT, OHB, Orthoson. SMI, ZARM
Italy: Alenia, Carlo Gavazzi, Ferrari, Laben, Mars, Officine Galileo, Tecno System
Netherlands: Bradford, Comprimo, Fokker
Norway: Prototech A/S
Spain: Crisa, NTE, Sener
Sweden: Saab Ericsson Space, SSC
Switzerland: CIR, Contraves, ETEL, HTS, Mecanex
UK: Anson, BAe, BIB, Sira.

It is estimated that as a consequence of microgravity-related developments and their terrestrial exploitation in these smaller companies, and in the large space companies such as Aerospatiale, Alenia, Astrium and Matra, almost 1000 new jobs have been created. In addition, there are several hundred scientists in European universities and research institutes who are involved in microgravity research work.

3.2.17 Conclusions

As was already mentioned in the Introduction to this chapter, the results of this special review are not based on a comprehensive and systematic evaluation of the technical and economic aspects of all microgravity spin-offs. They are based only upon a limited sample of identified projects that are just entering the commercial market, mainly in the medical service and research sectors. There are many other developments, especially at the component and materials-processing levels which, due to the difficulty in identifying and assessing their economic impact, have not been addressed in detail in this review. Nevertheless, whilst concentrating on spin-offs at the instrument level, this review has shown clearly that large sales benefits have already been achieved and that the market expectations for the coming years are excellent.

The main results of the review are summarised in Table 3.2.2. From this table and the information provided in the various sections on the individual spin-offs, it can be concluded that the market for these selected examples of ‘Microgravity Spin-Offs’ will be:

– 50–60 million Euros in 2001, and
– 90–100 million Euros in 2002

with a likelihood of increasing still further in subsequent years.

These figures do not include the important aspect and value of knowledge transfer to terrestrial production lines. Such transfers may be to the space companies, often with new daughter companies being created for the production and marketing of such spin-offs. They may also be to other companies, to which both knowhow and new technology has been transferred. In this context, it is important to mention that the majority of the companies in this survey stressed that what they learned in their space projects in terms of scientific principles, methods and technical and managerial knowhow was particularly important as a basis for future non-space technical developments. This is especially the case in the field of materials/fluid sciences, where in general the sophisticated and expensive space equipment, such as furnaces or fluid-science facilities, cannot be directly used in the terrestrial factory. However, the experience acquired in terms of novel processing and control techniques is relevant. So too is the knowledge concerning the design, development and qualification of novel equipment with high reliability and reproducibility properties. These are considered by the large space companies to be of very high value, and by the smaller companies as vital for the success of their non-space activities.

Coming back to the selected spin-off instruments listed in Table 3.2.2, most of them were originally built to monitor the health of astronauts or to perform biological experiments in space. These instruments can often be used, with some adaptation, in the bio-medical equipment market. A further feature of the ‘Microgravity Spin-Offs’ is that most of them were derived by the smaller firms, rather than by the larger well-known space companies. For the latter, the development of microgravity research facilities represents only a ‘small project’, from which the company management is less interested in deriving terrestrial spin-offs or performing technology transfers. Their ‘core activities’ lie in spacecraft development and integration, and mission operations. Life- and materials/fluid-science activities and the associated hardware are often considered to be too far from their company’s core competences and objectives.

However, the large space companies did acknowledge deriving some benefits from the smaller microgravity projects. These included the interaction with a new scientific community, interdisciplinary projects, the application of new principles of organisation and the management of new small companies as subcontractors, with different areas of knowledge and competences required for life and physical sciences, and with cross-fertilisation between the science teams, the small companies and the large space firms taking place.

For their part, the smaller companies involved in the development, production and marketing of spin-offs often had to cope with other difficult aspects. These included trying to obtain funds to build a production line or to find an appropriate commercial partner to sell the spin-off product in a given niche market. There are also sometimes fears that large non-space companies would either take them over or fight commercially against the success of a competitive instrument in ‘their’ market.

Another feature of several small companies was that they accepted the development of a space instrument only if they could exploit their existing terrestrial technical knowhow to a significant degree. These small companies always had a terrestrial spin-off of the space instrument in mind, and this demanded low unit costs to make it sellable on the terrestrial market. This in turn led to the application of existing terrestrial technology and fabrication methods, which had to be upgraded to meet specific space requirements, such as reliable functioning in a hostile space environment, and to survive the launch phase. This was a kind of ‘spin-in’ from normal terrestrial techniques, which made the space products less expensive and the later spin-off more competitive on the terrestrial market. It was a time- and cost-effective ‘spin-in – upgrading – spin-off’ mechanism, which avoided unnecessary duplication of development effort and investment.

There are several potential future spin-offs in the wings, such as the Backpain Diagnostic and Therapy Device and the Bearing Alloys for cars, which have very large potential markets. Yet it remains to close the financing gap between the prototype and the necessary follow-on development, to set up a production line, and to seek an introduction into the terrestrial market.

In conclusion, it can be said that this ‘Microgravity Spin-Off Review’, which concentrated on just a small sample of spin-off facilities and equipment and their economic aspects, has yielded an unexpectedly large harvest. The systematic promotion of technology transfer and support for the creation of commercially viable products in the future is therefore fully warranted. Without such promotion, several identified economically interesting developments might not find their way to the market. The approach adopted within the European Union’s Framework Programme is a good example of the promotion of and support to small and medium-sized companies.

Table 3.2.2. Selected Spin-Offs from Microgravity Life- and Physical Sciences

Name and Type of Spin-Off/ Technology Transfer	Company/ Institution	Original Space Project or Mission	Unit Price of Spin-Off	Present and Future Annual Markets (MEuro)	Assessment of Overall Economic Sector
1. **Ocuton S: Selftonometer for Glaucoma Patients**	Prof. Draeger EPSa (Jena, D)	Tonometer on D-1, D-2 and Mir	1 kEuro	99/00: 1000/1.0 2001: 5000/5 2002: 10000/10	2M units in Europe (=2BEuro), several million units in USA
2. **Osteospace: Device for the Diagnosis of Osteoporosis**	Medilink/DMS Started by MMS/Gip-Ultrasons	BDM on Euromir ’94 and ’95	18 kEuro	99/00: 100 units/1.8 2001: 150 units/2.7 2002: 200 units/3.6	Ultras. Bone Densitometer Market in Europe: 2500 in 99, 5000 in 00. In world: 600 MEuro/year
3. **Video Oculograph for Eye Clinics (VOG)**	Senso Motoric Instruments (Berlin, D)	VOG on D-1, D-2 and Mir Missions	65 kEuro	99/00: 4 2001: 4-5 2002: 5	World Market: 11 MEuro, 35% of of this covered by SMI Extension with 3D-VOG
4. **Sterilite: an Ozonizer Box for Disinfection/ Sterilisation**	Bradford (Heerle, NL)	Biolab for Columbus Lab. on ISS	2.3 kEuro	2000: 1000 units/2.3 2001: 2700 units/6.2 2002: 4400 units/10	100000 total market potential in Europe + USA, clinics, doctors, dentists, and laboratories
5. **Triple Containment Glovebox for Medical Research and Services**	Bradford (Heerle, NL)	7 Biorack + several other missions	100–150 kEuro	2000: 8 units/1.6 2001: 60 units/6 2002: 200 units/30	Cancer + other biomedical research, artificial insemination (200 unit batch planned for production)

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Table 3.2.2. Selected Spin-Offs from Microgravity Life- and Physical Sciences (continued)

Name and Type of Spin-Off/ Technology Transfer	Company/ Institution	Original Space Project or Mission	Unit Price of Spin-Off	Present and Future Annual Markets (MEuro)	Assessment of Overall Economic Sector
6. **Flat Swinging Heat Pipes for Aviation Industry**	Bradford (Heerle, NL)	ESA-GSTP and Atlid Satellite Programmes + Others	0.4 kEuro	2002: 6000 units/ 2.5 per year with increasing tendency	Use in civil and military aircraft (JSF) 3000 planes, 20 units in 4 years
7. **Respired Gas Analyser for Cardiopulmonary Diseases (Breath Analyser)**	Innovision (Odense, DK)	Anthrorack - D-2 Euromir ’95, Spacelab + ISS	15 kEuro (70 kEuro)	2000: 10 units/0.15 2001: 300 units/4.5 2002: 600 units/9	Very large medical market, heart and lung sector
8. **Dry Toilet, Waste Management Device**	3IS (Toulouse, F) Transfer to Actia	Rhesus Res. Progress, Bion Missions	0.2 kEuro (caravans) 2.0 kEuro (buses)	2000: 400 caravans, 50 buses/0.2 2001: 2000 caravans, 200 buses/0.8 2002: 3000 caravans, 300 buses/1.2	600 buses, 20000 caravans + boats + customs ports (10 units, 0.5 MEuro total) + potential for small planes + clinical version in development
9. **3D-Eye Tracker, for Strabismus and Other Eye Surgery**	Chronos Vision/ FU Berlin (D)	3D-VOG on D-2 and Mir missions	35 kEuro	99/00: 30 units/1.0 2001: 70 units/2.5	Marketing via Skalar Medical (NL) and IVP (S)
10. **Ultrasonic Components Sensors, Probes, etc.**	Vermon (F) Imasonic (F) Ultrasons (F)	PVH, As de Coeur (CNES), Bone Densitometer (ESA)	N/A (differs for each company)	In 1999, the space derived components had a value of 5.7 2000/01, not less than 5.7 annually	
11. **Pro-Cam^3, a 3D Photogrammetic Mobile Measurement System for Industrial Quality Control**	AICON (Braunschweig, D)	ESA Techn. Res., Progr. Studies for AFPM on D-2	65 kEuro average	2000: 10 systems/0.7 2001: 50 systems/3.3 (annual increase 30%)	Strongly growing market in car, airplane and ship industry, at least until 2005
12. **Body Fluid Monitoring using Multi-Frequency Impedance Measurements**	NTE (Barcelona, E)	ESA Techn. Research Progr. Studies for Human Physiology	10 kEuro	2001: 0.2 2002: 0.4 2003: 0.8	Used by physicians treating sportsmen, pilots, people on diets, and by research physiologists.
13. **Posture Platform and Locomotion Measurement System**	Satel (Toulouse, F)	French missions to Mir, Research at Physiol. Lab. of Univ. of Toulouse	8.5 kEuro Post. Platf. 10.7 kEuro Loc. Plat	2000: 0.3 2001: 0.5 2002: 0.7	Neurology, ears/ nose/throat, gerontology, traumatology, sports physiology psychotherapy
14. **Crash-Tester Data Acquisition System for Car Industry – Railway Electric Supply Control**	Kayser-Threde (Munich, D)	Texus Sounding Rocket Electronic Check-Out Equipment	Varies, because system adapted to specific needs	1994-99: 5/year 1999: 6.5 2000 onwards: 6.5/year or more	Growing market in car industry, 60% of railway needs, constant market

3.3 European Industry and Microgravity Experimentation

H.J. Sprenger

3.3.1 Introduction

One of the major objectives for the operational phase of the International Space Station (ISS) is to provide a basis for its utilisation for scientific and technological research. A large part of that utilisation will come from those disciplines that can benefit particularly from the continuous presence of a manned infrastructure in orbit. Besides the disciplines of Space Science and Earth Observation, the Space Station will be mainly used for experiments under microgravity conditions and for the demonstration and validation of new space technologies.

In order to exploit the potential of this unique environment for both scientific and commercial purposes, ESA has initiated several utilisation preparation and promotion programmes. Particular emphasis has been devoted to the identification and attraction of new users and to the supply of information, since the capabilities, the rules and the procedures for the exploitation of the Space Station are not widely known to potential users. In addition to these promotional activities, the programmes need to provide practical support for the preparation and operation of experiments on the Space Station.

One of the stated intentions of the ISS utilisation strategy is to concentrate on application-oriented research. This means attracting the interest of industry to invest in the utilisation of the microgravity environment. The long-term goal is to achieve a substantial contribution to the operating costs of the ISS from these commercial users. According to the expected return on investment, they would be considered as paying customers with a shared financial commitment to the utilisation cost. However, this objective can only be achieved by the appropriate promotional means, which are presently being developed within the Agency’s utilisation preparation programmes.

Recent analyses, from studies carried out by independent business and marketing experts, have made it clear that the private sector is not yet ready to submit major proposals for self-financed research on the Space Station. The principal reasons cited are the unacceptably high cost and risk connected with full payment for access to the space infrastructure. However, the studies also revealed that, at present, the private sector is hardly aware of the possible benefits that the utilisation of space would give them in return for their investment. Moreover, the examples discussed in these studies were considered as typical of the kind of applied research that would be subject to public funding from European and national research funding schemes, rather than originating from industry.

Evidently, a commitment from industry to take over a substantial part of the operation and utilisation cost of the ISS can only be seen as a long-term goal. In order to shorten the period of time required to reach that goal, suitable means have to be established to facilitate the increasing involvement of industry. These are presently under discussion among the ISS partners, i.e. the space agencies, space industry and the scientists interested in the procurement of applied research for industrial purposes. It is obvious that a suitable background has first to be created. This should be created in an ESA-supported programme in which the advantages of microgravity can be demonstrated through experiments based on the requirements of industry.

The programme concerned is the Microgravity Application Promotion (MAP) Programme. From a number of proposals received by the Agency from co-operating research teams from industry and academia, a selection of projects was made by a peer-review process organised by ESA. This peer review not only considered the scientific merit of the proposals. It also emphasised the potential contribution to the solution of industrial research problems, as demonstrated by the industrial partners in the proposal. Such an approach forms a first but important step in the process of achieving the desired involvement of non-space user industry in space-related programmes.

The Programme includes various aspects and it targeted the means to identify those of industry’s problems that could be solved more efficiently and effectively by the use of microgravity experimentation on the ISS as an additional research tool. This participation by industrial firms in selected co-operative research ventures at an early stage will contribute to their familiarisation with the space environment. It will also demonstrate the potential value of the unique environment of space. In so doing, it will assist in convincing the private sector that the benefits that accrue can justify the financial investment.

In order to demonstrate the possibilities of the ISS for industry, this Section will outline those applications that have already been identified as being of interest. It will also provide an overview of the programmatic aspects intended to promote the involvement of industry in space-related research. Finally, an attempt will be made to give recommendations for further activities in this area.

3.3.2 Applied Research in Space of Industrial Interest

Existing experience indicates that the space environment is unlikely to be used as a fabrication site for high-value products, as was too readily assumed in the earliest days of Spacelab utilisation. Those expectations were based upon highly unrealistic estimates of the costs of space transportation and operations.

More realistically, it can now be predicted that the environment of space, and in particular the ISS with its permanent manned presence, will be utilised as a research site where the most important property, the almost complete absence of gravity, will be used for both fundamental and applied research. Industrial interests are likely to be served by both of these activities, since industrial research generally contains elements of basic research, e.g. if improved physical models are needed for the inclusion into numerical simulations of industrial processes involving the controlled transport of liquid or gaseous phases.

Chapter 2 has shown that research in microgravity can indeed be used as a tool to obtain information that may otherwise not be available in a terrestrial laboratory. There is no doubt that such fundamental research can also be exploited to provide information that may be useful for the development of products and processes of interest to industry.

The individual Sections of Chapter 2 have already identified the main research areas in the physical and life sciences in which possibilities exist for research that is useful for industry, at least according to presently available results. Several examples have been presented that are either the subject of ongoing research or are potential new projects. It is clear from those that microgravity research can be applied to solve particular aspects of industrial research problems that will be of importance for increasing industry's competitiveness in future global markets. It is presently not clear, however, whether industry will seize upon those opportunities and demand to participate actively in space-related research.

Major applications areas can be deduced from the existing research objectives of certain industrial sectors, in particular those that are aiming to use advanced structural and functional materials in new constructions, in applications leading to improved efficiency or miniaturisation, or in biotechnological processes that are presently under development in the chemical and pharmaceutical industries. It has to be realised, of course, that industry will seek the benefits from research on the ISS only if no terrestrial (cheaper) alternative means are conceivable to achieve similar research results.

A second potential major beneficiary from the ISS are the developers of technologies and facilities that are designed for use in space. This is of major interest not only for space companies, but also for suppliers who are interested in the miniaturisation or in the improvement of terrestrial technologies for securing their function under extreme conditions (e.g. tele-operation), as well as for industry fabricating sensors, detectors, etc. These sectors would have the opportunity to achieve a competitive advantage in the supply of products or technologies that could be used on satellites and their power aggregates. Other examples would be the deployment testing of solar arrays in space, increasing the efficiency of cooling loops in heat rejectors, or the optimisation of the

surface-tension tanks needed for the liquid-fuel boosters used on telecommunication satellites.

A few selected examples are presented here of where knowledge and data derived from microgravity experiments are believed to be contributing substantially to the success of ongoing research and development aimed at advanced products and processes for commercial use. Based on the actual research objectives of today's microgravity projects and experiment results to date, the following areas have the highest priority for experimental studies in terms of existing and possible future involvement of the private sector:

- thermo-physical properties of melts and other fluids
- solidification behaviours of metals and alloys
- crystal growth of semiconductor and sensor materials
- combustion phenomena and processes
- study of complex multiphase fluids
- crystallisation of bio-molecules (proteins) for structure determination
- cell science and bioreactor technology
- human physiology and medicine.

Moreover, the recent developments in nanoscience and particle technologies point to microgravity being a very useful tool for the study of the self-organisation of very small particles into ordered and disordered structures in the absence of convection and sedimentation. Sections 2.3.8 and 2.3.9 deal with some aspects of that topic. Such research is certainly relevant to applications, for example, in soot formation, the fabrication of powders having ultra-small sizes, in chemical vapour deposition processes and for studies of the encapsulation of pharmaceutical materials.

· *Measurement of the Thermo-physical Properties of Melts and Other Fluids*

In melt-processing applications such as casting, welding, etc., the heat flow and the fluid flow must be known and controlled. To understand and to predict transport phenomena by modern methods of numerical simulation, knowledge of the thermo-physical properties of the molten materials is required. A certain accuracy of these properties is essential for the understanding and subsequent modelling of metallurgical processes, thermodynamic phase equilibria and phase-diagram evaluation. Thus, precise input data have to be measured on the stable liquid and at different levels of liquid under-cooling.

The demand for more accurate determinations of the thermo-physical data of reactive metallic melts at high temperatures is a result of the experimental difficulties that arise from the unwanted reactions of melts with containers. For example, the viscosity measurements reported for pure iron vary by ±100 % around the average. Also, a recent survey of available data for the surface tension of pure liquid metals

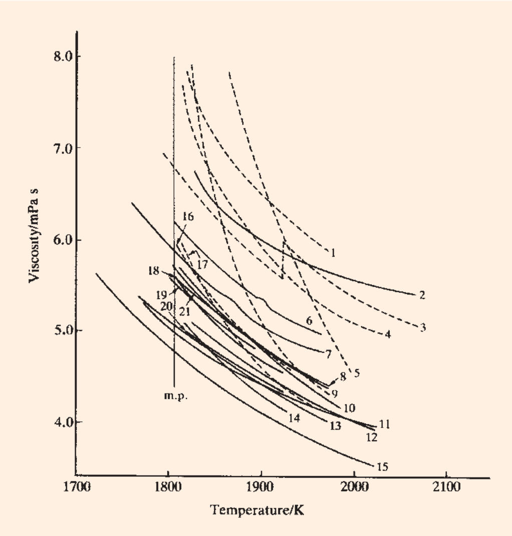

Figure 3.3.1. The very large spread in measured values for the viscosity of molten iron, indicating the need for better thermo-physical data (from T. Tanaka, K. Hack, T. Lida & S. Hara, Z. Metallkunde 87, 380, 1996)

demonstrates that while values are known for pure metals to an accuracy of about ±5%, the temperature coefficient, which is the relevant quantity controlling Marangoni convection, is only known to an accuracy of less than ±50% for most pure metals. For alloys, and in particular for multi-component commercial alloys, the situation is even worse.

The thermo-physical properties of interest are melting range, solid fraction, density (thermal expansion), viscosity, specific heat, Gibbs free enthalpies, diffusion coefficients, thermal (electrical) conductivity, surface tension and emissivity. Some of these data can be obtained reasonably accurately by conventional methods. However, high-precision measurements on chemically highly reactive melts and fluids at the temperatures of interest require the application of containerless processing, using non-contact diagnostic tools. By eliminating the contact between the melt and a crucible, accurate surface nucleation control and the synthesis of materials free of surface contamination becomes possible.

Under microgravity conditions, further advantages are expected from the significantly smaller electromagnetic fields needed to stabilise the containerless melts. This was shown on several Spacelab missions, where the results clearly demonstrated an improvement in accuracy over terrestrial measurements, even on pure metals. This is an indication that the electromagnetic levitation technique can provide a suitable environment for the accurate measurement of the thermo-physical properties of metallic melts of industrial interest on the ISS also.

For the measurement of non-conducting fluids, the situation is different. If containerless techniques are needed to determine data for numerical simulation of combustion and other chemical processes (e.g. for evaporation, chemical reactions, etc.), other methods, such as acoustic levitation, have to be used. Those techniques also give more accurate results when applied in microgravity, because of the greatly reduced forces required to keep the samples in a stable position.

- Solidification Behaviour of Metals and Alloys

It is well known that most properties of metals and alloys, such as mechanical strength, creep resistance, ductility, and wear resistance, are determined by their microstructures. The microstructural control, in turn, is very important for quality control and the design of new advanced materials for specific technological applications. In particular, during melt processing, for example for casting, welding, single-crystal growth and directional solidification, the control of crystal nucleation and growth is absolutely essential. This is achieved by numerical simulation of mass and heat transport in the solidifying melt, allowing calculation of the temperature variation (cooling curves) at each location of the processed sample or part. This, in turn, permits prediction of the actual solidification behaviour. The parameters can then can be modified and tailored to the requirements to achieve the desired microstructure. The knowledge obtained from these calculations can be used to shorten significantly the design and development time for a casting, thereby reducing the costs that would otherwise accrue as a consequence of experimental trial and error.

The study of solidification processes, with the objective of gaining a better understanding of the relationship between processing parameters, microstructure and the resultant mechanical properties, already started during the early days of microgravity experimentation. On Earth, convection has a substantial influence on fluid flow, which is responsible for the distribution of elements and particles in the melt near the solidification front and for their degree of homogeneity after solidification. Furthermore, the thermal analysis of these processes, including multi-component phase changes and dendritic growth, could be of interest to improve the possibilities for better control of microstructure in the present models. In particle-containing alloys, the effects of gravity can lead to sedimentation and can cause increased agglomeration, resulting in unwanted separation of the different constituents in the solidified part. Under microgravity conditions, heat and mass transport can occur by diffusion only, so that study of those effects can be used for a better and more quantitative understanding of separation mechanisms. This knowledge can, in turn, be used to increase the accuracy of the models used for controlling the casting and solidification processes.

Early experiments concentrated upon determination of the influence of convective melt flow upon the geometry and regularity of the microstructure. With strongly reduced convection, smaller distances between the solidifying dendrites and between the eutectic phases are generally observed. Those results have confirmed that convective flow should be minimised also on Earth to achieve the desired fine and regular distribution that results in improved mechanical properties. These findings also contributed to the development of a new casting process that is already being used for the fabrication of cast nodes in aluminium frames for automobiles and corner fittings for aeroplane structures.

Other investigations concentrated on particle distributions in metallic melts, the regularity of which is responsible for the improved quality of metal matrix composites. It was found that even without convection the particles in the melt were agglomerating into chains and networks, which led to an unwanted viscosity increase and to an increased risk of entrapment of impurity inclusions or gas bubbles. In the near future, experimental investigations are planned to quantify the influence of convection at dendritic solidification fronts in this so-called 'mushy zone'.

Recently, the use of magnetic fields for damping convection has been studied as a precursor for microgravity research. This is an efficient way to control the flow of liquid matter by avoiding unwanted turbulences. However, the interaction between electromagnetic and convective flows is not well understood. It was found that even the physical models used in numerical simulation do not correctly describe the experimental observations.

This is important for the development of industrial metallurgy and metal processing, in which magnetic fields are used as part of the processing itself. This leads to better control over the material properties compared to conventional technologies. This is achieved by using the different effects of electromagnetic fields, such as heating, braking of convection, stirring of the melt motion, shape control and levitation. Although the principles have been known for more than two decades, their industrial use is constrained by several problems, even for well-established processes. This is due to the fact that most of the existing turbulence models cannot predict or reproduce the experimental observations in the numerical simulations. Therefore, they cannot be used to optimise the process parameters and the geometrical conditions for the use of the electromagnetic fields. There are clear demands from industry for a better understanding of the effects of convection on the microstructure. This could be the subject of future combined terrestrial and microgravity research and would consist of:

- more detailed analysis of the physics of the mushy zone, the segregation behaviour in the alloys and the related material parameters
- development of 3D numerical codes that use realistic boundary conditions
- obtaining a better understanding of interface phenomena, to improve the existing processes; this requires improved knowledge of the physics and chemistry of free-surface problems, entrapment or removal of inclusions, melt mould interaction, etc.
- development of new or more robust sensor technologies, e.g. measurement of flow velocities or measurement of thermo-physical properties; this is necessary both for experimental verification and testing of theoretical models and numerical simulations, and for better control of the industrial process
- definition and execution of well-defined benchmark experiments to observe specific phenomena and to validate theoretical predictions.

- *Crystal Growth of Semiconductor and Sensor Materials*

In inorganic-material crystal growth, structural perfection is one of the most important goals. This has been achieved to a certain degree via a better understanding of the influence of flow in the solidifying melt and by the ability to calculate the flow by numerical simulation. In the last 25 years, crystal growth has advanced from an art to a science, by co-operation with fluid scientists and by the introduction of fluid-mechanics knowledge into the different growth technologies. Study of the influence of the different kinds of convection under microgravity also helped in the development of growth methods.

Experiments using microgravity to study fluid flow caused by surface-induced (Marangoni) convection (see Section 2.3.2/4), which is important for the growth of semiconductor crystals, were an area of intensive research during the past decades. These experiments contributed to quantifying the influence of different convection modes on the fluid flow, and they showed that Marangoni-driven flow can be of the same order as flow induced by natural convection. In addition, due to the absence of hydrostatic pressure in space, attempts were made to grow crystals from the melt with larger diameters than is possible on Earth. This was successfully demonstrated with GaAs crystals of 20 mm diameter, grown using a float-zone process during the D-2 mission. This was significantly larger than was possible on Earth (about 8 mm). It was, however, difficult to transfer these results to significant improvements in the industrial growth of these semiconductor materials. Numerical simulation and accompanying terrestrial research showed in fact that the flow during the crystal growth can be well controlled using magnetic fields. Moreover, the most difficult problems causing unwanted defects in the grown crystals occur during the cooling in the solid state. Therefore, microgravity research was dropped as a means to seek quality improvements in materials such as silicon or GaAs.

The situation is different for materials like CdTe and related compounds. These have potential applications as highly sensitive sensors and detectors for the identification of flaws in materials or for medical purposes, e.g. for low-dosage X-rays. So far, these materials have not been used in practice because the current quality of the single crystals is not sufficient to allow economic applications. To be able to grow material of the required size and quality, a better understanding of mechanisms leading to deterioration of the crystals is needed and suitable measures have to be developed to avoid those defects.

For growing large single crystals with high homogeneities, two different processes are envisaged and are under development, both of which could benefit from research in microgravity. In melt growth, relevant experiments on Shuttle missions have demonstrated that avoiding or strongly reducing the contact with container walls by applying non-wetting conditions leads to decreasing tensions in the solid material.

This, in turn, leads to a significant reduction in defects in the grown crystal. Moreover, the application of weak rotating magnetic fields is responsible for the setting up of a laminar flow, which favours relatively uniform transport of the components in the melt towards the advancing solidification front.

- *Growth of Protein Crystals and of Other Large Biomolecules*

Protein crystallography is a method of determining the three-dimensional structure of proteins by the analysis of X-ray diffraction data. The results provide the keys for basic structure studies, drug design and protein engineering. Crystallisation of proteins and nucleic acids with the required homogeneity and size is therefore one of the key issues for the analysis of the three-dimensional structure and the determination of functional groups of proteins and similar large organic molecules.

The growth of such crystals in a terrestrial laboratory is, in many cases, a difficult or even impossible task. Though a number of experimental techniques have been developed, they often fail to produce crystals of sufficient size and quality. It has been observed that several different parameters influence the crystallisation process, one of them being the action of gravity. Though the exact mechanisms are still not known, it is believed that the nucleation and growth processes suffer from the presence of convection and sedimentation. Further problems stem from the non-reproducibility of experiments and the lack of rational (empirical) methods to predict under what conditions a certain protein may or may not crystallise.

Positive results on early Spacelab missions stimulated worldwide attempts to carry out systematic experiments in the field of protein crystal growth. Those experiments partly involved the participation of a number of pharmaceutical companies, particularly in the United States. In Europe, several attempts were made to grow protein crystals on unmanned spacecraft, with a view to commercial production. For certain substances (especially lysozyme, a generally accepted test substance), the growth of larger, more uniform crystals with higher order at the molecular level is possible in space.

All of the various methods used are believed to benefit from microgravity experiments. The parameters that affect the crystallisation of proteins are diffusion rate, convection, density (sedimentation) and wall/interface effects. The goal is to find conditions that favour the nucleation of a small number of crystals, which should then grow to larger sizes and with greater crystallographic perfection (see Section 2.3.1).

Growth experiments by the University of Alabama in the USA have received substantial contributions from the pharmaceutical industry. Among those proteins that could be grown in microgravity to larger sizes, displaying more uniform morphology, and yielding diffraction data to significantly higher resolutions than the best crystals of these proteins grown on Earth, were porcine elastase and gamma interferon D, bovine and human serum albumin, malic enzyme, proline isomerase and HIV-1 reverse transcriptase. Recent space experiments on human insulin (by Eli Lilly Co.) gave an improvement in resolution from 2.0 (ground) to 1.4 Å, allowing the crystal structure to be determined.

In European programmes, the efforts have primarily concentrated on increasing the basic understanding of the influence of gravity on nucleation and growth of proteins through experiments on Spacehab-1 and IML-2, in the ESA-developed Advanced Protein Crystallisation Facility (APCF). The results, similar to those supported by NASA, showed a certain portion of crystals that were better and diffracted to higher resolution than the best samples grown on Earth. The relevant experiments are designed to achieve better-ordered crystals from growth in space, as well as to improve the Earth-based methods by learning about the influence of gravity through space experimentation. Industrial participation focuses on proteins for structure-based drug design and protein engineering. The final goal is to develop pharmaceuticals that are important in combating diseases, or for the production of special enzymes that may be used as detergents in separation processes.

After about ten years of protein crystal growth research in space, the facts are that in about 20 to 25% of the experiments under microgravity the crystals grew larger or were better ordered than their best counterparts in terrestrial laboratories. So far, the strongest increase in resolution has generally been observed in those proteins that also crystallised on Earth, but did so with a slightly disordered structure (mosaic), attributed to the presence of convection and sedimentation.

Further research will improve our understanding of the mechanisms and the conditions that lead to better-ordered proteins in the absence of convection and sedimentation. Consequently, there is a good chance that the crystallisation of proteins with the size and structural order needed for the analysis of the three-dimensional arrangement of functional groups, can be successfully achieved in space.

There are more than a million different proteins, only a small fraction of which could be analysed so far for their three-dimensional structure. For industry, the most important target is to determine an unknown structure as fast as possible, in order to gain an advantage over possible competitors. The resolution of de-novo protein structures normally requires 3 to 6 months, but in particularly difficult cases up to a year may be spent on a single protein. The ISS will provide an environment in which protein crystallisation can be routinely carried out with short turnaround times. The industrial demand will be based on the possibility to conduct a large number of trials in parallel with extremely small sample sizes (in the micro-litre range). This requires only relatively small pieces of hardware, with an arrangement of hundreds of identical chambers. To be able to obtain the structural data as fast as possible, the operation of a low voltage X-ray facility onboard the Space Station is being considered. This would greatly facilitate the transfer of results to the ground, because the delicate transport of the newly-grown tiny crystals would be avoided.

- *Combustion Research*

For as long as spaceflight technology has existed, it has been necessary, due to safety requirements, to investigate how fires would start and flames would spread in gaseous mixtures (diffusion and premixed flames), in insulation (smouldering combustion) or in flammable liquids (flammability limits, evaporation rates), under microgravity conditions. The results have shown that combustion processes under those conditions differ from those in normal 1g conditions. Furthermore, the reaction products of the combustion process must be known. These are highly toxic in some cases and, more remarkably, are different if produced in a space or in a 1g environment. Due to these differences, alternative methods of fire detection and fire fighting have to be developed for and used in space.

The reason for the different behaviours is the presence of buoyancy convection on Earth. Under 1g conditions, convection is the determining transport process in combustion – much more so than diffusion and radiation. In a microgravity environment, where free convection is nearly zero, the heat and mass transport is determined mainly by diffusional transport, the magnitude of which is comparatively small. Therefore radiation, which is not directly affected by gravity, starts to play a more important role. Because of these differences for the three transport parameters, combustion in space is weaker and the diffusion rate and the material consumption are lower than in normal terrestrial combustion.

Combustion research under microgravity conditions has contributed significantly to our understanding of its basic characteristics. However, priority is not given to the possible applications of those combustion processes. Rather it is seen as an opportunity to acquire knowledge about the influence of gravity on the different transport parameters.

The examples described in Section 2.3.7 have shown how detailed investigations under microgravity can be applied to improve numerical models and also to gather more precise data to be implemented in the models. These models have been developed in order to increase the efficiency of technical combustion processes applied in transport and energy technologies. Major R&D objectives are reductions in fuel consumption and a decrease in carbon dioxide in exhausts and in atmospheric pollution. These developments go hand-in-hand with attempts to use fuel with low sulphur contents.

The development of three-dimensional simulation tools has to take into account a wealth of parameters, such as convection, diffusion (thermal, solutal), radiation and reaction kinetics in three dimensions, and an excess of different species. The latter are produced, or vanish, in chemical reactions on a very short time scales. Hence, these simulations have had up to now to be made with simplifying assumptions, which often lead to incorrect calculations because of the sensitivity of the method. One possibility for overcoming this problem is to neglect one of the main parameters, namely convection.

If convective effects can be neglected, the simulation of single-fuel-droplet combustion can be treated as a one-dimensional problem instead of a three-dimensional one, and the simulation of droplet array combustion will be reduced from three dimensions to two. Therefore, data from convection-free experiments conducted in a microgravity environment can be used for the validation of the basic simulation model. This will be an important step in validating the whole process simulation model.

Fuel-droplet research has shown the existence of multi-step ignition, which influences the mean ignition delay time. Based on this, new binary models have been developed that allow much more exact simulation of the behaviour of technical fuels (e.g. decane/trimethylenebenzole for kerosene). Numerical simulation of microgravity droplet-ignition experiments showed the large differences between the simplified models, based on reaction kinetics in a homogeneous gas phase, and the real behaviour.

Microgravity combustion research therefore involves both fundamental research and applied basic research. Without the stimulus of and the volume of data gathered from microgravity experiments, the improvement of simulations of industrial combustion processes would not be feasible.

- *Ceramic and Metallic Powders*

Advanced ceramic materials constitute an emerging technology with a very broad base of current and potential applications and an ever-growing list of material compositions. Advanced ceramics are inorganic, non-metallic materials with different combinations of fine-scale microstructures, purities, complex compositions and crystal structures, together with accurately controlled additives. Such materials require a level of processing science and engineering far beyond that used in making conventional ceramics. This new generation of high-performance materials holds the promise of a total market worth billions of dollars. Collectively, they represent an enabling technology, the development of which is critical to advances in a host of high-technology applications, ranging from modern microelectronics to future car engines and superconductors.

The outstanding properties possessed by advanced ceramics are achieved through special compositions and microstructures that require very careful control throughout the successive stages of processing: powder synthesis, powder sizing, rheology control, consolidation and forming processes, sintering, final machining and inspection.

For most advanced ceramic components, the starting powder is a crucial factor, because their performance characteristics are greatly influenced by the precursor powder's characteristics. Among the most important are the powder's chemical purity, particle size distribution and the manner in which the powders are packed before sintering. Powders with a narrow size distribution can be compacted into ordered arrays and, when in the submicron region, these powders are sintered at reduced temperatures. Consequently, in the processing of advanced ceramics, there is a growing need to develop synthetic techniques capable of producing submicron, chemically pure powders with a narrow size distribution. However, cost is again a factor, since the new synthetic processing techniques are comparatively more expensive than today's manufacturing methods.

Current research concentrates on the vapour-phase synthesis of fine powders and thin films, with a special focus on nanoparticles and on nanocrystalline powders. The processes of interest include vapour condensation, gas-phase chemical reaction, flame synthesis, plasma reactions, aerosol decomposition, spray pyrolysis and chemical-vapour deposition. The role of nanoparticle formation and growth on the surfaces during thin-film growth is a rapidly growing topic. Basic aspects of interest include particle formation, growth and crystallisation. Practical aspects are also important, including gas-flow profiles and temperature distributions, powder-deposition control, reactor design and powder collection. Other important practical issues include reactor modelling with combined CFD-aerosol modelling tools, as well as the in-situ and ex-situ characterisation of particles for process optimisation and control. Synthesis of nanocrystalline particles and films for various applications including pigments, ceramics and electroceramics, conductive agglutinants, catalysts, advanced pharmaceuticals and nanoelectronic devices such as single-electron transistors, are all topics of ongoing research.

It is evident that microgravity can be used as an efficient tool for applied research in this area. The simple reason is that gravity causes sedimentation of the particles and natural convection accelerates agglomeration. To study details of the reaction processes, in particular to observe critical mechanisms under slow-motion conditions, the use of microgravity is absolutely essential.

- *Micro-encapsulation*

Many biological systems in their natural state are immobilised. For example, without retention, cells would be washed away by flowing water. Therefore, most functions of living systems are based on the confinement of reactions within a limited space. The membrane also provides the protection for the internal material.

Many biotechnological processes need to be carried out using immobilisation of the biocatalysts. Encapsulation is considered a powerful method of immobilisation. There are many examples of applications of this technique in various fields:

- Plant cell cultures allow the production of different metabolites used for medical, pharmacological and cosmetic purposes. Cell immobilisation improves the efficiency of the cultures by imitating the cell's natural environment.
- Immobilisation seems to be the technique of choice in many industrial processes in food, and especially in beverage, production. Beer, wine, vinegar and some other production processes have traditionally used immobilisation procedures with adhesion culturing (e.g. acetobacter in vinegar production) and in the modern approach, with entrapment of yeast biomass (e.g. sparkling wines).
- Continuous fermentation produces a higher overall performance than batch fermentation. To avoid wash-out of the biological catalyst from the reactor, it is necessary to immobilise it. This principle is applied in ethanol and solvent production, sugar conversion and waste-water treatment.
- Implantation of endocrine cells is one of the most promising treatments for diseases such as diabetes. However, without the protection provided by a microcapsule membrane, cells would be rejected in just a few days.
- In pharmaceutical treatments, a single application of a drug would ensure a very efficient procedure. This could only be realised with a microencapsulated drug.

It therefore appears that micro-encapsulation has strong potential in the biotechnology and biomedical fields (it may even be extended to 'non-biological' systems).

Though the actual market for microcapsules in biotechnology and medicine is still limited, one might expect a very large growth in encapsulation technologies in the coming decades. To give an idea, the treatment of diabetes with encapsulated pancreatic islets represents a real solution for 7 million sufferers in the USA, and hence a potential cash flow of US$ 2.5 billion per year. Many small companies have been created in North America in the two last decades, with impressive capital investments (often more than US$ 30 million), to develop micro-encapsulation methods. Similar progress has been made in Japan.

It is therefore important that European industries develop similar background expertise in order to be able to compete with Japan and the USA. In the past, most research has been directed towards improving processes through an empirical approach by trial and error. Our fundamental understanding of microcapsule formation is therefore still limited.

One of the main limitations in the study of microcapsule formation is that, under gravity, droplets or particles must be subjected to movement during the encapsulation process to avoid sedimentation and coalescence. Droplet speeds may reach several metres per second, and it is then quite difficult to observe the microcapsules during their formation. Process analysis is therefore mainly based on the final microcapsule characteristics. The initial stage of capsule formation in particular is very difficult to observe. Mixing of the particles leads to high convection, and the processes at the droplet interface are then speeded up and considerably modified by this effect. High convection movement may even occur inside the droplet itself. Microgravity observations will allow greater flexibility to study the effects of the different parameters that control microcapsule formation.

A recently established Topical Team, supported by ESA, has been tasked to acquire the necessary knowledge about industrial needs in this area and, in collaboration with industrial partners, to develop new or improved processes using microgravity as one of the key tools. The intention is to give European industry a leading role in the micro-encapsulation field.

- *Tissue Engineering*

The business of creating spare parts for the human body is becoming ever more refined. Scientists are now engineering living human tissue in the laboratory, which may one day be used to replace human organs such as the liver and kidneys, as well as bone, cartilage or skin.

About 18 000 human organs are transplanted annually in the USA, while an estimated 100 000 Americans die whilst waiting for a spare heart, liver, kidney, or other organ. Ultimately, the commercial availability of laboratory-grown tissues may make the expensive organ harvesting needed for traditional transplantation and reconstructive surgery obsolete. The overall market for engineered tissues has been estimated to be in the US$ 400 billion range, of which US$ 80 billion is estimated to be the value of the engineered tissues themselves.

Many experimental data, obtained in micro- to hyper-gravity conditions or in microgravity simulation studies, indicate a change in cell function that is related to the gravity level. Subtle modifications in the mechanical and biochemical micro-environment trigger changes in cell-cell relations or in the cell function within differentiating tissue (see Sections 2.2.1/2).

Investigation of these minute changes will benefit from the increased stability of fluid systems in space bio-cultivators and from the reduced mechanical loading under microgravity conditions. It will be particularly important for an improved understanding and definition of the environmental factors needed to mimic organo-typical culture conditions.

A better knowledge of the metabolic control of the growth and differentiation can therefore be achieved from experiments with the culturing of animal cells and tissues in space. This can lead to improved artificial organs and bioreactors.

Most of the experiments have been performed on Earth since the beginning of the 1990s under ‘simulated’ microgravity conditions, using the rotating-wall culture vessel developed by NASA. Various tissues, such as animal heart cells, bovine cartilage cells or tumour cells, were used. However, this system is not well adapted to the cultivation of complex tissues; it is more suited to the growth of spheroids or cell clumps for use in cancer research.

A well-documented space experiment on cartilaginous constructs, flown during Shuttle/Mir missions, has shown that the space samples were smaller, more spherical and mechanically weaker than their terrestrial equivalents. These findings have been attributed to the absence of gravitation-induced effects in space on the growth and development of the engineered tissue.

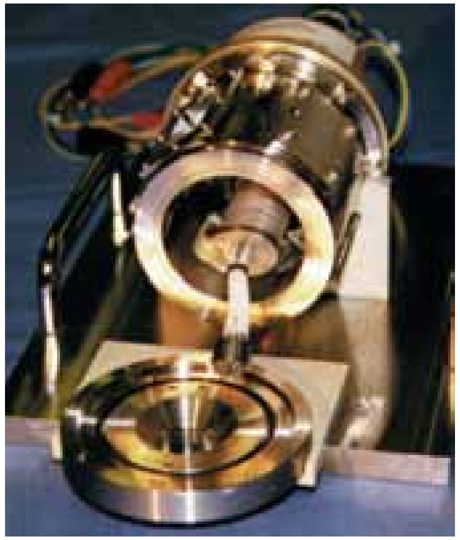

Figure 3.3.2. ESA’s Space Bioreactor for suspension culturing of sensitive cell and multi-cellular systems

3.3.3 Industry’s Attitude to Research in Space

Industrial research generally aims at the development of new or improved processes or products that have to be brought to market in a timely fashion. In order to be competitive, industry will only invest in research and development if it foresees a demand from customers who would be interested in buying these products. The utilisation of space within relevant research and innovation efforts can be expected if benefits can be identified which would counterbalance the required investment.

The research that industry believes is needed to overcome the technology barriers in manufacturing and process technologies generally falls in the following areas:
- fundamental understanding
- design aids
- processing technologies
- sensors for in-situ monitoring and control.

A critical area of research that will rely heavily on public funding is the development of a better fundamental understanding of processes like solidification, chemical processing, energy production and transformation and biotechnological production (cell factory, tissue engineering). These are processes in which the influence of convection can play a role, but one that often cannot be quantified. Research can provide the information to enable engineers to improve the design and productivity of industrial products. This is increasingly being achieved by numerical simulation, for which better models and more precise input data are needed. In certain areas, this might be achieved by the utilisation of space. Successful research in these areas would help industry make progress towards three goals:

- improved productivity
- reduced time-to-market, and
- reduced energy consumption.

To identify the industrial interest in using the International Space Station for those purposes, a number of representatives from industry were recently asked, in different studies executed on behalf of ESA, if they would be interested in considering it as a site for targeted applied research and, if so, under what conditions. Although the majority of the answers were rather disappointing with respect to possible near-term investment, it was accepted by a number of the industrial scientists that some participation in projects dealing with research in the microgravity environment could be of advantage. Even so, they had almost no concrete ideas about the purposes for which such research could be applied in product research and development. The general opinion was that using the weightlessness of space would be the subject of basic research, the results of which might lead to a better understanding of the physical phenomena that take place in processes involving molten metals, multi-phase fluids (consisting of liquids, gases and particles), or the interaction and aggregation of cells and bio-molecules.

The major reasons why industry, at present, tends to eschew the opportunities that could arise from the utilisation of space for applied research and development stem from three areas of concern:

- Because research under microgravity is a new discipline and, particularly, because the experiment opportunities have been so scarce compared to those of ground-based research, the results achieved so far are few and often rather basic. The visibility of the industrial potential and the possibilities for direct commercial applications still remain to be elaborated through suitable promotional means.
- The access conditions for industry-related research in space are presently in conflict with some of the requirements of a straightforward approach directed towards the inclusion of microgravity in on-going (terrestrial) application-oriented research programmes and projects.

- The experimentation cost is too high. This is true for the flight iself and also for the construction of facilities and the efforts necessary for experiment preparation. The announcement policies and selection procedures of the various agencies are seen as prohibitively slow and inflexible by the private sector. Consequently, they prefer to spend their money on the terrestrial research alternatives.

The outcome of discussions with representatives from the private sector showed, at first glance, that the kind of research that had been identified as benefitting from the inclusion of microgravity was, in the majority of cases, considered useful. On the other hand, the areas and topics identified were characterised mostly as basic research. They did not reflect the possible contribution of microgravity to the solution of a particular industrial research problem.

This means that the usefulness of microgravity as a new tool for research is generally not questioned. However, a great number of the problems that could be solved using microgravity would belong mainly to the category of fundamental or application-oriented research. In industry's opinion, this kind of research should be carried out by academic researchers using publicly funded research budgets. To attract industry, applied-research tasks need to be based strictly upon the requirements of the industrial-product-driven research and development. In addition, there needs to be a highly visible calculable benefit from the possible results for the improvement of a marketable product. This has appeared to be lacking in many of the projects or proposals identified.

Most of the industry researchers contacted explained that this attitude reflects a change in the companies' research strategies compared to the situation even just a few years ago. Research managers of large companies active in the automotive and engineering sectors, for example, could not even be motivated to discuss the topic with their scientists. This was because the research possibilities offered by the inclusion of microgravity were considered too basic to warrant near-term consideration. They also explained that, for economic and commercial reasons, the kind of application-oriented research that was the subject of past EC-funded projects, and was carried out with their participation, is no longer actively pursued within the strategic aims of their companies. The main reason is that those tasks were often only indirectly related to the development of a marketable product.

Consequently, a number of the industrial research activities previously performed in collaboration with scientists from universities have been terminated by industry and are no longer considered future topics for industrial applied research. It is expected that henceforth this kind of research will only be carried out by universities and research institutes, and that direct industry involvement will only occur if potential profits from that direct investment are clearly visible.

The conclusion is that to involve industry in gravity-related research and ensure its participation in the utilisation of microgravity in the long-term, the specific research needs of the individual companies have to be addressed. The development of products and processes has to be analysed in much more detail than was possible hitherto, and these needs and requirements have to be taken as the basis for future projects.

3.3.4 The ESA Microgravity Application Promotion (MAP) Approach

It is realistic to assume that benefits from using the International Space Station could be the harvesting of results or data that:

- are not otherwise available from research on Earth
- would speed up the innovation process and the time to the market
- could put the enterprise in a unique position to sell its products.

The results of this research can be considered as a kind of 'added value', which would justify the investment of going into space. Areas to be addressed are:

- on-going industrial research where gravity-influenced phenomena could be relevant
- industrially relevant research problems or questions
- the use of microgravity as a tool to solve those questions
- quantification of the 'added value' of microgravity's contribution
- non-space funding programmes (e.g. European Commission)
- possibilities for industrial sponsorship.

From the experience gained so far, it appears that the possibilities offered by the ISS for industrial research will be limited, but some of the fields for its utilisation can already be clearly identified. To do this, it is necessary to study the needs of industrial research carefully and to identify areas where the utilisation of the space environment as a tool could bring further advantages. It is also apparent that suitable methods have to be developed for including the expected results in the industrial process and product development. It has also been shown that for industry to consider using the space environment in such an innovation process, a certain promotional approach is needed to overcome the obstacles that have so far have limited its involvement.

The industrial research possibilities can be categorised into:

- processes improved by data and knowledge from space (e.g. numerical simulation)
- products developed from new ideas generated from space results
- shortening time to market through space-research contributions
- saving on development costs by use of space
- products processed in space and sold on Earth.

Several approaches have been started to promote the industrial utilisation potential of the International Space Station. The aim was to initiate suitable efforts to encourage European industry to use the space environment and the related infrastructure for innovative purposes, in order to increase and strengthen its competitiveness. These activities are mostly related to the transfer of available results and ideas from previous fundamental experiments into more application-oriented and industry-driven research efforts.

The Microgravity Application Promotion (MAP) Programme is directed at preparations for the utilisation of the ISS. Almost ten years ago, ESA launched a programme to involve industry in applied research on the Space Station. Rather like the NASA 'Centers for the Commercial Development of Space' (CCDS) programme, an approach was initiated in which groups of scientists would team up with industry. The objective was to identify those areas in which the utilisation of space could be one important element in the research and development of an industrial programme. Originally called RADIUS (Research Associations for the Development of the Industrial Utilisation of Space) programme, it was later supplemented by broadening the approach through the establishment of Topical Teams (TT). In these Teams, new space-environment applications were discussed in a series of workshops with industrial participation. Covering the different fields and disciplines of materials science, fluid sciences and biotechnology, these workshops proved to be an important step in identifying applied-research problems that could usefully be solved by using microgravity as one of the key tools.

To get the MAP Programme started, an Announcement of Opportunity (AO) was issued in 1998. It asked for proposals in which researchers and research teams, with partners from industry, suggested ideas and new approaches to include the utilisation of microgravity in their overall product-oriented and market-driven applied-research activities. Out of the 150 proposals submitted and evaluated by a peer-review process, about 50 were ranked as 'recommended'. Many of them were ranked as 'highly recommended', or even 'outstanding', in terms of their scientific quality and potential for solving significant industrial-research questions. It could be clearly shown that, contrary to frequently heard statements, the proposals presented represented a set of initial nuclei, needed to prepare and to promote the desired industrial involvement in the utilisation of the ISS in the long term. Details of currently accepted proposals are to be found in the Tables in the Appendix (Chapter 6.8).

To illustrate the industrial potential of the MAP approach, several of the recently selected project proposals are described below, which fall into the following industrial research sectors:

- advanced casting technologies
- crystal growth of semiconductor and sensor materials
- industrial combustion
- multiphase fluids in chemical processing
- biotechnology
- medical applications and health care.

3.3.5. Selected MAP Projects

Presently some 48 projects have been approved by ESA, most of which were started during 2000. Mainly ground-based research will be financed for the first two years, during which the industrial questions for future microgravity research to address should be identified. Thereafter, precursor experiments are planned in selected research areas using either early opportunities on the ISS, or Spacehab and sounding-rocket missions.

The following are some of the most advanced project topics:

- *High-Precision Thermophysical Data for Liquid Metals*

This project is based on the fact that the accuracy of measurement of thermo-physical data for metallic melts is limited with the methods usually applied in ground-based laboratories, as discussed above in Section 3.3.2 and earlier in Section 2.3.3. It has been shown that by using advanced methods such as the containerless processing of reactive melts of high-temperature materials (iron, nickel, titanium alloys), the melts' reaction with the crucible materials can be avoided. This can lead to more accurate values for the properties to be determined. This precision can even be further increased if convection effects can be suppressed under microgravity conditions. It is therefore expected that the outcome of the research will benefit the numerical simulation of liquid-metal forming processes, such as casting, welding and metal spraying.

In contrast to earlier microgravity research in the field, which already provided proof of concept, the ongoing project is concentrating on alloys of technological and commercial interest. The industrial partners are the market leaders in the application of numerical simulation, representing materials producers and end users, software code developers and producers of measurement equipment. It is expected that the benefits resulting from the project will improve the predictability of casting processes (investment casting, directional and single-crystal solidification, continuous casting), leading to micro-structural improvements and improved quality and reliability of the cast components and parts. Examples are turbine blades for static and aircraft gas turbine engines, bone replacement parts made from titanium, and cast aluminium and magnesium casings for mass-produced products such as laptop computers and mobile phones.

- *Microstructure Formation in the Casting of Technical Alloys*

There are two projects in this domain:
– Columnar-Equiaxed Transition in Solidification Processing, and
– Control of Convection by Magnetic Fields

which are aimed at improving the physical models that are the underlying basis for the numerical simulation of advanced casting technologies. The research work complements that in the 'determination of thermophysical properties' project. It was industry itself that clearly voiced the need for improvement of the presently used physical models, particularly for the transition stage of cooling between liquid and solid (mushy zone). In this range, the competition between the growth of columnar and equiaxed grains is not well-understood, and therefore these phenomena will be investigated by comparing the heat and mass flows in the presence and absence of convection. This will lead to a more quantitative understanding of the basic physical principles that govern the formation of microstructures in modern solidification technologies.

The knowledge gained from this research is expected to contribute significantly to improvement of the integrated modelling of the grain structure in technically important castings, based on the demands from the industrial partners in the project. The main emphasis will be on frequently used Al- and Cu-alloys, supported by fundamental investigations of transparent model systems. A primary goal is to improve the so-called CAFE (Cellular Automaton Finite Element) 3D model, developed and applied by several of the industrial research partners to predict the dendritic grain structure of directionally solidified parts or components.

The second project has the objective of identifying the interaction of magnetic fields and fluid flow in continuous casting. This process is used to fabricate long material for further hot and cold working to sheets, bars and wires. Industry has been using magnetic fields to brake and to control the liquid-metal flow for more than two decades, but the models applied for numerical simulation are already at their technical and physical limits in terms of validity. To enable more economic processing and to improve the processing speed used in casting slabs and billets to a few metres/second, it is necessary to understand the complex interactions in the melt better. This in turn will lead to the desired quality improvement in the numerical simulation and to further optimisation of the continuous casting of steel and aluminium alloys.

- *Crystal Growth of CdTe and Related Compounds*

Semiconductors like cadmium telluride (CdTe), and related compounds such as (Cd,Zn)Te, are required as highly perfect single-crystal materials for advanced applications in X-ray detectors and photo-refractive devices (e.g. ultrasonic sensors), and as substrate material for infrared detectors and electro-optical devices. However, the quality of those materials produced with current single-crystal-growth process techniques does not match the level required for the applications envisaged. In addition, the low production yields have made use these expensive materials unattractive from an economic viewpoint also.

Figure 3.3.3. A space-grown cadmium-telluride crystal, suitable for high-sensitivity X-ray detectors. The limited size of Earth-grown crystals has held back their application

The project aims to develop new growth techniques, based upon the experience gathered with space experiments. It was shown that the containerless growth methods tested in space provided single-crystal material of unprecedented quality and yield. The reason for the improvement is the strongly reduced level of stress on the material due to the lack of direct contact with the container walls. The aim is to transfer those benefits to processing on Earth, through the development of ‘quasi-containerless’ processes in which the grown material is in contact with the supporting crucible or ampoule at a few points only. This will be achieved by the development of advanced growth techniques using proper geometric wall design and non-wetting conditions in the melt.

Eleven European companies with different commercial interests are participating in the project. Their aims are to develop and to apply new material testing methods, to test the performance of the grown materials for the envisaged applications, and to fabricate model devices allowing them to estimate the economic potential of the materials in X-ray detectors for medical and non-destructive testing, or in the electro-optical switches used in modern communication technologies.

- *Technical Combustion Processes*

It is becoming clear that society needs to reduce the rate of consumption of fossil fuels in order to contain the threat posed by atmospheric pollution and the accompanying ‘greenhouse’ effect. That leads to the need to improve the efficiency of power and energy production and conversion processes in both transport and power-plant technologies. These requirements have not only triggered the development of new and lighter materials, but have also initiated efforts to reduce fuel consumption through a better understanding of the physico-chemical processes needed for the development of more effective combustion systems.

Though gravity appears to be insignificant in the case of technical combustion processes, which are mostly turbulent, combustion data from microgravity research can still contribute to further improving efficiency. The reason is that the development of technical combustion systems is today based more than ever on simulations. Experience is still important, but costs and competition require an increasingly rapid innovation process, with as little experimentation as possible. The simplified numerical simulation models are, however, only as good as the respective basic knowledge. The understanding of these basic relations is, as explained above, mostly achieved by microgravity-based research activities (see Section 2.3.7).

In addition, data on material properties applied in simulation processes are of great importance in order to check the correspondence between simulation results and the actual behaviour. Since material data contain no gravity-related parameters, microgravity laboratory is the only way to obtain these data accurately, without any masking or distorting external influences (normally of convective, but also of a systematic-industrial nature). These data affected by external influences may cause, by an accumulation of mistakes, considerable deviations between the simulation and the real behaviour.

The objectives of two related projects are directed towards improvement of the numerical simulation tools and codes that are presently under development by industry. Efforts are also directed towards studying the influence of water sprays on the processes, with the goal of using the acquired knowledge also in fire-fighting applications. Major developments are the design and construction of new laser diagnostic systems allowing one to study details of the experimental investigations in space and on Earth.

- *Bioreactor in Space*

ESA has recently recognised the need for a 3D bioreactor in space, in order to study tissue function and reaction to gravitational stress. A Tissue Engineering project has just started, with the selection of research topics and the development of the appropriate instrumentation. One of the aims is to develop a Biotechnology Mammalian Tissue Culture Facility (BMTC), which is presently being considered for use on the International Space Station.

The utilisation of ‘bionic’ organ models in tissue culturing will allow the elucidation of the role of weightlessness on (human) cell and organ function in space. Benefits from tissue-engineering experiments in space, for use in terrestrial industrial applications, are expected to come from the following areas:

– Improved knowledge will be gained of the 3D growth of organ tissues. The reduced shear stress or tissue pressure will help in the precise regulation of the micro-environmental conditions necessary to establish and maintain polarity in tissues, with the potential for future development of artificial organs.
– New organo-typical culture models, replacing animals, will help in monitoring the health of humans in space (astronauts) and will allow the prediction of health risks.

- New in-vitro models for use in drug screening and for the development of artificial organs will be developed for space-physiology studies, which will also be of interest for terrestrial use.
- Better understanding of the influence of mechanics and weightlessness on intracellular interactions may lead to the discovery of new modes of drug action and new compounds. This can be applied in the development of new molecular targets/drugs for the pharmaceutical industry.

The development of innovative technologies (microsystems, optical diagnostics), leading to improved bioreactor technology for organ tissue culture, will result from constraints like limited volume and power, and possibly find application in commercial markets.

- *Osteoporosis and Bone Remodelling*

The topic of this project was one of those themes that were selected in the early phase of promoting the industrial utilisation of space and, in particular, the application of microgravity for human health issues. The observation that a loss of bone mass occurs in astronauts and animals under long-duration weightless conditions has led to the idea to study this effect in a more quantitative manner. Furthermore, it has been suggested to use the results achieved in space not only to develop methods for countermeasures during human space travel, but also to transfer the knowledge to solve the Earth-related problems of osteoporosis, which has developed into a disease of major concern for elderly people.

In Europe, there are more than one million osteoporotic-related fractures each year. The costs of associated treatments are a significant factor of interest for the pharmaceutical and biomedical industries. It is therefore not surprising that the private sector is interested in the results of studies conducted in space, which could be used to simulate bone loss under strongly accelerated conditions. The testing of possible treatments and countermeasures could also be performed on the ISS, thus allowing significantly quicker proof of their efficiency.

Given these considerations, the ESA-sponsored Osteoporosis Project is based on several application-oriented and industry-driven objectives:

- quantitative study of bone loss during spaceflight and transfer of the results into a physiological model by in-vivo observation and in-vitro samples, to be used also for drug screening
- investigation of the influence of gravity/microgravity on bone cell cultures
- development of a high-resolution instrument for the quantitative characterisation of bone density and bone architecture
- testing of the efficiency of pharmaceuticals and specific exercises for the prevention or deceleration of osteoporosis.

Industrial participants in the project include suppliers of biomedical instrumentation and pharmaceutical companies.

3.3.6 Industry-Oriented Space Research and the European Commission

The scope of the research proposed in the MAP projects is limited to use of the microgravity environment as a tool for achieving 'added value' in the approach to solving industrial research problems. Since the Agency's funding possibilities are limited, it would be desirable to get additional financial support from non-space sources, such as the 5th Framework Programme (FP) of the European Commission (EC). Previous experience showed that co-funded projects, in which the cost of ground-based research is funded jointly by industry and public research programmes, leads both to a reduction in ESA's costs and a substantial increase in the usefulness of the results for the development of industrial processes or products.

Most MAP projects are eligible for additional funding from the European Commission (EC), provided their objectives coincide with the research topics and time frames (calls for submissions in different programme areas) of the EC's 'Growth' and 'Life' programmes.

It is generally expected that, at least at the beginning of the Space Station utilisation phase, most of the experiments will be based on the existence of such joint projects between industry and applied-research institutes. The research will mostly be pre-competitive in nature, falling within the typical conditions associated with the Commission's Framework Programmes. Because these conditions require a substantial contribution from industry (generally 50%) and a market-oriented research exploitation plan, such projects can be considered as a model for the future industrial utilisation of space.

The concept of 'virtual institutes' within the EC's Framework Programme is based on the grouping of projects with similar industrial research objectives. It would allow joint ESA- and EC-funded industrial research efforts in selected application fields. It would also allow the streamlining of related research objectives, through the distribution of tasks and an intensive exchange of information and results. This would allow the harmonisation of applied research in the pre-competitive stage.

The project selection would include:
- themes of outstanding/highly-recommended MAP projects
- incorporation of space-based experiments into the overall research activities
- use of the results for the improvement of industrial processes and products.

Another important aspect is that EC funds could be used for space-related activities, which has not been possible so far at a programmatic level.

Industrial research will either be conducted in multi-user facilities developed primarily for more fundamental research, or in dedicated experiment facilities provided by the users themselves or by contracting space-experienced companies. Users coming from industry and bringing their own payloads to the Space Station may well not be familiar with ISS operating procedures and safety considerations. Access arrangements tailored to the specific needs of individual industrial users, including the confidentiality and proprietary rights issues, will therefore need to be developed. These issues will be handled on an individual user basis by the ISS operator.

3.3.7 Conclusions and Outlook

Non-space industry's interest in using the ISS for applied research is expected to centre mainly around taking advantage of its weightless environment. The results of their combined space- and Earth-based research efforts can then be used to improve their existing processes and/or products, thereby gaining them a competitive advantage. In some cases, specially formed small companies (spin-offs from institutes or universities, funded by venture capital) will conduct the space-based research under contract to industry and with partial support from public funding programmes.

Given the nature of the space experiments carried out in the past, industrial demand for using the ISS for applied research is expected to come primarily from the following areas:
- materials processing and fabrication
- optimisation of process technologies
- increasing of efficiency in energy conversion
- data for numerical simulation needed by code developers and users
- development of new biotechnology processes
- design and testing of new pharmaceuticals.

More results from space experiments need to become available to stimulate significant involvement by industry in the International Space Station. Greater industrial participation in ISS utilisation for commercial benefit will therefore depend on the establishment of a promotion programme geared to convincing industry of the potential benefits. The industrial possibilities mainly rely on using the microgravity environment as an application-oriented research tool to gather more accurate data on, or a much improved understanding of specific physical and biological phenomena, leading to benefits for industrial, environmental or medical applications.

In addition, study and validation of the behaviours of certain process steps under microgravity may be of interest. This would ensure that such technologies could be used to generate additional business from the exploitation of Earth-bound technologies in space applications (e.g fluid loops, heat exchangers, etc).

ESA's approach to promoting future involvement of the private sector in the use of the ISS is the MAP programme, which focuses on two major themes. The first is the definition and preparation of experiments within previously selected networks having industrial participants. The second involves the so-called 'ESA Topical Teams', co-ordinated by experienced scientists coming from basic research. They have the task of using the developing knowledge on gravity-related phenomena to identify and solve industry-related research questions. Based on these existing activities, the promotion programme is able to fulfil the industrial users' demands by providing information, establishing a dialogue with industry and making available attractive research conditions.

Industry is generally not aware of the kinds of benefits that it can obtain from the utilisation of the ISS. Moreover, the results of previous microgravity missions are not easily available to 'outsiders'. Because flight opportunities have tended to be rare and the most significant results have generally been published at space-related conferences, information about experiment results and their possible benefits for industry tends to be fragmented. Experience has shown that industrial scientists would not develop their own research proposal merely as a result of seeing brochures and learned publications.

One major aspect of the information approach must be participation by industry in the setting up of Europe-wide teams and networks involving researchers from both academia and industry. Since it is expected that applied research on the ISS will start on pre-competitive projects, industrial researchers will be motivated to work jointly on the identification of industrially relevant questions for which the ISS and its environment can be used as a 'tool for research'. A further objective is to initiate industrial projects in which ground-based research would be supported by the EC's Framework Programme. In that event, ESA would finance the space-related ground-based activities and the flight opportunities, along with the participation of researchers from universities. Only in the long term would industry be asked to contribute to the space-related costs, provided a clear return-on-investment for them can be identified.

This new approach is aimed at generating continuous demand for industrial research on the ISS in the medium and long term. This will be achieved by initiating ground-based industry/institute networks on selected research topics. The idea is that those networks, or 'Virtual Institutes', should cover a broader range of related projects, based on industrial research demand. They would perform co-operative research, combining the originally separate scientific and applied research goals. It is anticipated that once such networks have been established, further interest from industry will be created as a consequence of the quality of the data and results received from space.

Major elements of this approach are to:
- establish industry/academia research networks
- initiate research networks with combined ground and space research
- apply for funding from industry and non-space funding programmes
- generate continuous demand for industrial research on the ISS in the medium and long term.

The experiments on the ISS will be designed to solve key research questions and acquire data and knowledge not available from research on Earth. This approach of including space results to achieve ‘added value’ for solving industrial problems would be based on a business plan in which the expected risk must be taken into account, and from which the potential return-on-investment could be calculated.

Because of the different uses envisaged for the ISS as a site for non-R&D related purposes, it is suggested that applied research be combined also with activities that tend to fall into the public-relations category. Many companies use symbols and pictures from space to demonstrate progress and competence in high technology. On the other hand, TV broadcasts on advanced research tend to have high viewing ratings within the educated public. TV transmissions from the ISS could therefore be used by companies to improve their image and to relate their product to ongoing research and the facilities in which the research is being conducted. Other similar opportunities include using space research and demonstrations, including astronauts, as a basis for questions and answers related to the research being performed aboard the ISS. Such an approach would have the added advantage of helping to create/preserve a positive image of the ISS, thereby enhancing industrial interest for its future use for applied research.

CHAPTER 4

THE GROWTH OF MICROGRAVITY RESEARCH

– From Skylab to the International Space Station

G. Seibert

4.1 The Origins of Microgravity Research in Space

4.1.1 Early US and Soviet Activities

During the 1970s, only the USA and the Soviet Union had access to the microgravity environment that exists in a freely drifting spacecraft or an orbiting satellite. There was no European manned spaceflight or satellite programme that included microgravity experimentation at that time.

- The Skylab Programme

The objective of the Apollo Programme, to land an American astronaut on the surface of the Moon before 1970, was achieved in July 1969. Five further successful Moon landings, extending through to 1972, followed.

The Apollo capsule had been constructed to accommodate three astronauts during their flight to the Moon. It was not designed as a laboratory for microgravity studies in the life and materials sciences. Consequently, there was insufficient space to accommodate sophisticated research equipment. Nevertheless, the first exploratory space microgravity experiments were performed on these missions, including low-temperature composite casting, some simple fluid-physics experiments and electrophoresis experiments.

By 1972, after six Moon landing missions and the return of almost 400 kg of Moon rocks and soil to Earth, American public interest in further Moon missions was waning. There were other national concerns. NASA decided to cancel the three further Apollo lunar missions that had been planned. Instead, it was decided to use the Saturn-5 rocket hardware that still existed to construct a manned orbiting station that was called ‘Skylab’. Following the termination of the Apollo Programme, the development of Skylab became the core space activity of NASA.

Skylab consisted of a third stage of the Saturn-5 rocket, modified to act as an orbital laboratory. It had a length of 15 m, a diameter of 6.6 m, and could accommodate three astronauts and their necessary life-support equipment. It was also able to accept a number of microgravity research facilities for life-sciences and materials processing, together with instruments for Earth observation and astronomy.

The 99 ton orbital station Skylab was launched in May 1973, into a 400 km orbit of 50 deg inclination by a 2-stage Saturn-5 rocket.

This first manned Skylab mission lasted 28 days. Just five weeks later, a second crew of three astronauts was sent to Skylab for a stay of almost 60 days. The Skylab manned activity was concluded with a third mission launched on 16 November 1973. The three-crew members spent 84 days in space. Skylab stayed in orbit, but unoccupied, until July 1979, when a controlled re-entry occurred.

During these three manned Skylab missions, pioneering microgravity experiments in the life- and physical sciences were performed, covering biomedical studies, the behaviour of fluids and the solidification processes of materials. There were 21 experiments in the space processing of materials. These dealt with metal melting, exothermic brazing, sphere forming, vapour growth of IV-VI compound semiconductors, immiscible-alloy processing, radioactive-tracer diffusion, microsegregation in germanium, growth of spherical crystals, whisker-reinforced composites, indium antimonide crystal and mixed III-V crystal growth, alkali-halide eutectics, silver grids melted in space, and copper-aluminium eutectics. There were also a number of investigations in biology (bacillus subtilis, human lung cells), biotechnology, human physiology and medicine. Studies were also made of the effects due to the combined influence on living matter of the particle-radiation, vacuum, low-temperature, and microgravity environment of space.

Figure 4.1.1. The Skylab orbital station (courtesy of NASA)

These pioneering life- and physical-sciences microgravity experiments on Skylab attracted worldwide interest in many research fields. They led to the start of dedicated microgravity materials-processing and of space life-sciences research programmes in the USA. It became obvious that research in microgravity would lead to advances in the fundamental understanding of the properties of materials and the discovery of new life-sciences phenomena.

An important objective of the American, and later also of the European Microgravity Programmes, was to provide a sound appraisal of the probable medium- and long-term value of microgravity studies to industrial applications. However, it became apparent that the detailed scientific information required for this appraisal would only be forthcoming after a series of fundamental investigations, which required the sophisticated instrumentation becoming available during the Shuttle/Spacelab era.

The reason why a full appraisal of materials processing and life sciences in space was not possible after the Skylab missions was the following:
- The experiments on Apollo and Skylab were hastily prepared and instrumentation such as furnaces, crystallisation chambers, and biomedical instruments, was rudimentary compared with the experimental facilities developed later and used during the Spacelab era.
- In addition, many potential research areas in the life sciences and materials processing were not explored in the Skylab programme. For example, the area of protein crystallisation, which became one of the most investigated research fields during the later Shuttle/Spacelab period, was not addressed on Skylab.

Unfortunately, those early results from the Skylab experiments gave rise to overly optimistic predictions for the potential industrial benefits from space processing. The NASA-supported studies, for example those performed by the Centre of Space Policy in Cambridge (Mass.), made projections predicting extremely large benefits from materials processing in space factories.

Subsequently, more realistic reviews attempted to correct these predictions, by stating that short-term economic benefits were unlikely. Instead, the scientific and technological problems should first be addressed so as to gain a detailed understanding of the fundamental aspects. These could then lead later to an application-oriented programme.

- *The Apollo-Soyuz Test Project (ASTP)*

In 1972, the Soviet Union and the USA agreed on a space mission that was intended to demonstrate to the world that, despite the Cold War, scientific and technical co-operation should be possible. From the Soviet side, it was agreed that the man-rated transfer vehicle 'Soyuz', which since 1971 had routinely serviced the first Soviet Orbital Station 'Salyut', would be launched and ultimately docked with an American Apollo command capsule. The latter was launched in July 1975 using a Saturn-1B rocket.

This ASTP mission was not only a techno-political success, which culminated in handshakes between three American and two Russian astronauts in space on 17 July 1975, but it was also a welcome opportunity to perform further microgravity experiments in physical- and life sciences after Skylab. These were mainly follow-on investigations of Skylab and Apollo experiments in metallurgy, crystal growth and electrophoretic separation of organic samples:

– four metallurgy experiments in the fields of surface-tension-induced convection, growth of LiF-NaCl eutectica, processing of monotectic (PbZn) and syntectic (AlSb) alloys, and processing of permanent-magnet materials (MnBi and others)
– three crystal-growth experiments: from the solution and from the vapour and a germanium single-crystal experiment
– two electrophoretic-separation experiments, one of which was an American 'static zone electrophoresis' experiment, which was tried earlier on Apollo-14; the (Another was a German 'Free-Flow Electrophoresis' experiment. This sought to avoid the gravity-induced convection currents that disturb the separation quality of organic samples (e.g. red blood cells, kidney cells, lymphocytes, erythrocytes).

These experiments worked quite well and they extended the database of knowledge of research under microgravity conditions. It was, however, only a simple 'stand-alone' mission. There was no related follow-on research opportunity to broaden the research base and to provide continuity of experimentation, as was desired by the scientific community.

- *The Soviet Salyut Orbital Station*

The Soviet Union took the first step in the direction of a space station in April 1971, with the launch of the Salyut-1 orbital station. It consisted of a cylindrical module, 13 m long and 3.6 m in diameter. After Salyut-1, several further improved Salyut versions were launched, until 1982.

Ten different crews visited Salyut, using the Soyuz transfer vehicle. The final visit lasted 100 days. It was also visited 15 times by the cargo vehicle Progress, which carried about 170 different instruments. However, the Soviets did not communicate or publish the results of these missions, which were predominantly dedicated to life- and materials-science research in space.

- *The Mir Space Station*

In February1986, the Soviet space station Mir was launched. This had an 'unlimited' mission-duration capability and was the first true space station. It continued to circle the Earth, at an altitude between 350 and 400 km, and with an orbital inclination of 51.6 deg, until March 2001.

Mir's configuration consisted of a core module, about 13 m long and with a maximum diameter of some 4 m, together with five scientific modules. These were:
– Kvant, a module for astrophysics, launched in 1987
– Kvant-2, housing scientific and technology equipment, plus an airlock for extravehicular activities, launched in late 1989
– Kristall, launched in 1990, and dedicated to materials and biological science
– Spektre, launched in 1995, and used for astronomy and atmospheric research
– Priroda, launched in 1996, and dedicated to Earth observation.

The total Mir complex was T-shaped, with a length of 33 m and height of 28 m. Its overall mass was 70 tons.

Figure 4.1.2. The Mir space station

The many visits by international crews to Mir in the period from 1986 through to 1999 have provided invaluable mission experience in operating a space station and in supporting the crew during extended stays in space. In so doing they have prepared the way for the operation and the utilisation of the International Space Station (ISS).

In the Soviet Union, public information concerning the life- and materials-science research in space was always limited. However, it became obvious in the 1980s that the Soviets considered this field an important means for developing novel or advanced materials with unique properties that they needed to make progress in strategic technologies. The Soviet programme was always applications-oriented. Their research was directed towards enhancing the properties of materials such as compound semiconductors, super-conducting alloys, magnetic alloys, laser materials, infrared optics, sensors, etc. It is now known that about 2000 samples have been processed in Soviet orbital stations, and that hundreds of kilogrammes of samples/specimens were returned to Earth.

In addition to these orbital missions, both NASA and the Soviet space authorities carried out numerous materials processing studies with drop towers, parabolic airplane flights and sounding rockets. These started long before Europe began such short-duration microgravity experiments in the late 1970s.

- *Guidelines for Microgravity Research in the USA*

The early optimism regarding the commercial possibilities of microgravity (e.g. factories in space) was dampened when, in 1978, a report by the Scientific and Technical Aspects of Materials Processing in Space Committee (STAMPS) of the US National Academy of Sciences was published. This concluded that the prediction of commercial benefits should not be exaggerated and that the scientific aspects and technological problems should first be addressed. Only when a detailed understanding of the fundamental aspects had been achieved could one decide on setting up an industry-oriented research programme.

NASA followed the guidelines and recommendations of that report during the 1980s. It concentrated on the field of materials processing/fluid physics and the areas of electronic materials, metals and alloys, glasses and ceramics, transport phenomena, fluid dynamics and biotechnology. In life-sciences research, the field of human physiology and the survival and well being of astronauts in the space environment (microgravity and radiation) received the highest priority.

4.1.2 Early European Microgravity Activities

The motivation that led to the decision to develop Spacelab as Europe's contribution to the US Shuttle Programme was described in Section 1.3, where there is also an overview of Europe's involvement in Spacelab missions between 1983 and 1998. The decision taken by ESA in 1973 to develop Spacelab caused Europe to review and take stock of the early American results of microgravity studies. The interest was to define the future European microgravity research activities in the life and physical sciences. In order to facilitate this process, ESA organised in 1974, just after the Skylab missions, and again in 1976 after the Apollo-Soyuz Test Project (ASTP), two symposia at which US scientists and NASA reported on their preliminary research results. Consultations were also held on promising future research areas. The results of the early life-sciences experiments demonstrated that the initial hypothesis, to extrapolate from hyper-gravity through 1 g to microgravity effects, could not be sustained. Many of the experimental results were seen to contradict the models and theories in physiology and biology textbooks.

The Spacelab Agreement between ESA/Europe and NASA/USA specified that the first Spacelab mission would have as its primary objectives the verification of the Spacelab system, the Shuttle/Spacelab interface compatibility, and the measurement of the induced radiation environment. The secondary objective was to obtain scientific, application and technology data from the joint European/US multi-disciplinary payload and to demonstrate, to the potential user community, the broad capability of Spacelab for research.

The joint ESA/NASA payload required ESA to select experiments from different disciplines and to procure or develop the necessary hardware. This would use 50% of the technical resources available to the first Spacelab payload. An acceptable resource allocation to payload elements from the different disciplines had to be found after competitive experiment selection.

ESA received many proposals for experiments in the new discipline of microgravity research in materials/fluid sciences and life sciences. It was obvious that they would constitute the major portion of the multi-disciplinary payload of the first Spacelab. In response to the need to advise and guide this new research activity, in 1975 ESA set up a Life-Science Working Group and a Materials/Fluid-Science Working Group. The latter was subsequently renamed the Physical-Sciences Working Group. Two years later, the senior advisory group known as the Microgravity Advisory Committee (MAC) was established.

- *The Joint US – European First Spacelab Mission*

The evaluation of the requirements of the selected microgravity experiment proposals revealed the need not only for new multi-user research facilities, but also to perform a number of subsequent Spacelab missions. Many of the proposed experiments were in fact experimental programmes, having parameter variations as part of the study. Consequently, they needed the results of the first experiment in order to set the experimental parameters for the follow-on experiments. This interactive and sequential experimental research process is, of course, very similar to the procedure followed in terrestrial laboratories.

However, the US–ESA Spacelab Agreement only provided for the first joint mission to be free of flight costs to ESA. NASA had decided unilaterally that from the second Spacelab mission onwards, the missions would not be joint events. They would be either totally NASA missions or from agencies that would pay the Shuttle/Spacelab launch and operating fees.

ESA started to study in detail two European Spacelab missions, the so-called 'Demonstration Missions'. One of these was dedicated to microgravity studies in the life and physical sciences, and the other to atmospheric physics (a pallet-only mission). The scientific, technical, operational and cost aspects of these two missions were repeatedly presented to the ESA Spacelab Programme Board and proposed as an additional slice to the Spacelab Programme. However, the Board, comprised of Delegations from the ESA Member States, decided not to perform any further Spacelab missions under ESA management. The two main reasons for this refusal were the large cost overruns on the Spacelab Programme, and the fact that the majority of the Member States did not want to spend major European funds on US Shuttle flights.

In the absence of an ESA Spacelab Utilisation Programme, Germany decided to carry out two German national Spacelab missions, D-1 and D-2. The German decision was motivated by a desire to utilise the European built Spacelab, towards which Germany had contributed 53% of the development costs of almost one billion Euros. It also wanted to have direct national access to space to perform materials-processing experiments of industrial relevance. The German space authorities invited ESA and interested Member States to participate in these German-led missions, in return for a contribution towards the Shuttle launch fees, based upon the proportional use of resources.

In the end, it was only ESA that took up this offer, once it had an approved Microgravity Programme. It participated in the D-1 mission with about 38% and in D-2 with about 25% of the payload. ESA also provided one of the three Payload Specialists for the D-1 mission (Wubbo Ockels).

- *Early European Spacelab Experiment Facilities*

From the overview of the Skylab and ASTP experiments and the replies to the European Call for Experiments for the first Spacelab flight, it became evident that many experimenters required the same experimental facilities. For example, different experimenters required very similar furnaces, or they needed a 36°C incubator for cell and developmental biology. To avoid the duplication of facilities and their accommodation requirements, it was evident that such facilities would have to be developed with capabilities satisfying many users. These Multi-User Facilities, as they were called, could therefore best be developed centrally. On the other hand, it seemed that selected Principal Investigators (PIs) should develop any experiment-specific hardware or stand-alone experiments that were needed. They would obviously need financial support for this task, because the design, development and space qualification of flight hardware was expensive.

Consequently, ESA studied several multi-user research facilities at Phase-A level (conceptual design and cost estimate). These were destined to be accommodated, together with nationally planned facilities, in the Materials-Science Double Rack of the first Spacelab mission. ESA also studied the Vestibular Sled. These facilities had to be qualified with respect to the launch accelerations and vibration, had to meet electromagnetic-interference requirements, and had to be compatible with Spacelab's technical resources, constraints and interfaces.

The studies showed that, contrary to the earlier optimistic views, the commercial instruments used in the terrestrial laboratories could not be used for a manned mission such as Spacelab without major modifications. They normally did not meet the environmental constraints of the launch, had outgassing problems, were not optimised regarding power consumption, and their thermal-control systems usually relied upon convection cooling, which of course is absent in microgravity. In addition, the facility/instrument technical performance requirements of the investigations were at the edge of technological progress and often exceeded the performance of the equipment that the investigators used in their own terrestrial laboratories.

This situation led to the development of a new generation of space-qualified and high-performance experimental facilities/instruments based on an extension of existing technology. However, the unit costs of these new facilities by far exceeded those of their terrestrial counterparts. These costs were often a factor of 5 to10 higher. The reasons for that high unit cost stem from the advanced technology that was needed, the stringent testing required for equipment to be accepted onto a manned space vehicle, and the fact that each unit was unique.

The European and the NASA 'Call for Experiments' for the first Spacelab mission resulted in several hundred experiment proposals, from which 70 were selected for flight. The selection criteria were based on guidelines from the ESA/NASA Joint User Requirements Group (JURG), which periodically reviewed the performance and resource provisions of Spacelab for the users. JURG's guidelines for the peer selection included the following for this first payload:

- ESA and NASA experiments should be complementary
- the payload should be open to science, applications and technology experiments
- the experiments should take advantage of Spacelab's unique capabilities and its broad potential
- the experiments should capitalise on man's presence
- payload crew selection and training should permit the evaluation of future selection and training criteria.

The principal selection criterion was, of course, scientific merit.

As shown in the accompanying table, the seventy experiments originated from Principal Investigators in Europe (57), the USA (12) and Japan (1). The reason that many more experiments from Europe were selected was mainly due to the fact that NASA withdrew all of its material/fluid-science experiments from that first flight. They were scheduled for flight 9 months later on a US national Spacelab mission. The reason for this change was formally the low amount of electrical energy and crew time available for the first flight. Also, at this time NASA considered materials-science experiments to be sensitive investigations.

	Materials & Fluid Sciences	**Life Sciences**	**Atmosph. & Solar Physics**	**Plasma Physics**	**Astro-physics**	**Earth Observation**	**Technology + Environment**	**Total**
Europe	36	9	5	3	2	2	-	57
USA	-	7	2	1	1	-	1	12
Other	-	-	-	1 (J)	-	-	-	1
Total	36	16	7	5	3	2	1	70

The European experiments came from 10 ESA Member States.

Analysis of the selected European materials-science and fluid-physics experiments showed that three types of furnaces would be needed. These were an isothermal furnace, for the execution of 15 experiments, a gradient furnace for 5 experiments, and a novel mirror furnace for a further 5 experiments. A Fluid-Physics Module (FPM) would be needed for the execution of 6 experiments. ESA therefore initiated a detailed design study in industry with the objective of accommodating these three furnaces and the FPM, together with power- and data-management equipment, in one double rack, called the Materials-Science Double Rack (MSDR).

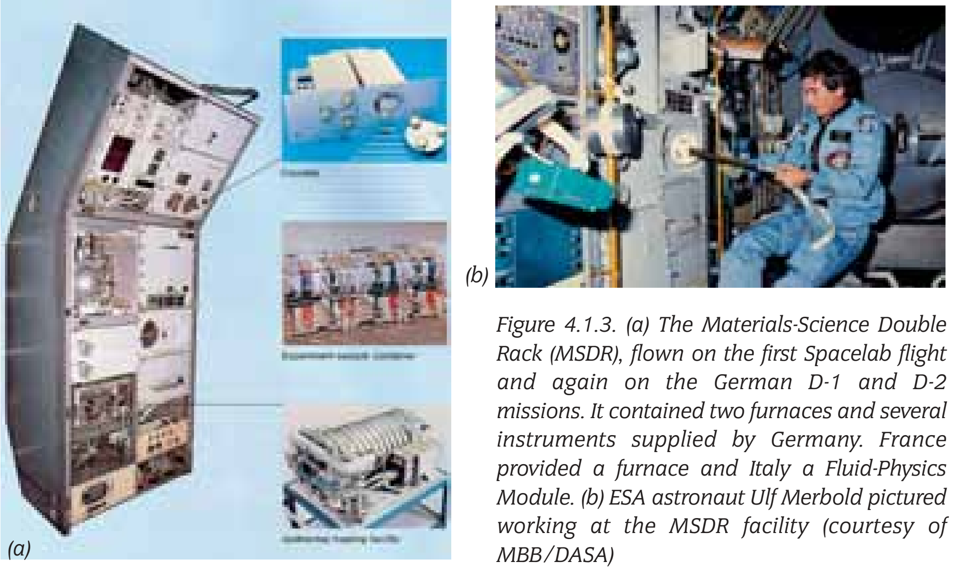

Figure 4.1.3. (a) The Materials-Science Double Rack (MSDR), flown on the first Spacelab flight and again on the German D-1 and D-2 missions. It contained two furnaces and several instruments supplied by Germany. France provided a furnace and Italy a Fluid-Physics Module. (b) ESA astronaut Ulf Merbold pictured working at the MSDR facility (courtesy of MBB/DASA)

The selected life-sciences experiments had a more heterogeneous technical requirement, because they belonged to very different life-science disciplines. These included radiation biology, cell biology, plant biology, a number of different cardiovascular measurements and vestibular research experiments.

The vestibular experiments requested the most sophisticated facility, a Vestibular Sled. On the recommendation of the Life-Science Working Group, a conceptual design study of the Sled was performed by ESA with the help of industry. All other experimental hardware was to be provided by the Principal Investigators themselves, supported by their national space authorities.

After completion of the conceptual designs of these facilities, ESA proposed to the national delegates of the Spacelab Programme Board that the development phase of these two multi-user facilities should be funded in one of two ways: either by creating a new small microgravity research programme, or via a special new budget within the existing Spacelab Programme. However, the Delegations could not agree to this proposal and recommended that other solutions be sought by ESA.

A complicated solution eventually emerged, with the development of the Materials-Science Double Rack infrastructure taken over by Germany, together with two of the three furnaces (isothermal and mirror furnaces). The Gradient Furnace was then to be provided by France and the Fluid-Physics Module by Italy. Despite its many parents, this complex mix of equipment making up the Materials-Science Double Rack became the most important materials/fluids-science facility so far. It was flown on the two German Spacelab missions, as well as on the first flight of Spacelab.

Figure 4.1.4. ESA astronaut Wubbo Ockels testing the Vestibular Sled, used to study motion and orientation perception in weightlessness

The solution found for the development of the Vestibular Sled was an ESA internal one. The conceptual and detailed design of the Sled was covered financially by the ESA General Budget, whereas the actual development was, exceptionally, financed by the ESA Space Science Programme.

The Sled was designed to perform selected studies on man's perception of orientation and motion in the microgravity environment, from cues provided by the vestibular receptor system, the visual system and the mechano-receptors in the skin and joints. It was a movable sled mounted on 3.2 m-long rails and provided linear acceleration stimuli as a result of pre-programmed velocity trajectories. The astronaut riding on the Sled wore a Vestibular Helmet, which included a small television screen and an infrared camera to record the astronaut's eye movements.

In fact, the Sled did not fly as planned on the first Spacelab mission, but on the subsequent German Spacelab flight D-1. The reason was that the final payload mass for that first flight was going to exceed substantially the allowed mass. A large facility had to be removed and the Sled was chosen. Although its flight was thereby delayed for two years, it did ultimately provide valuable results for the 11 European and 10 US/Canadian researchers.

4.1.3 The European National Programmes

The difficulties and delays associated with the creation of the ESA Microgravity Research Programme have been outlined above. At the national level, however, several of the ESA Member States had been developing their own microgravity research programmes since the 1970s. This was especially the case for Germany, and to a lesser extent for France and also for Sweden (only sounding-rocket missions). Germany and France developed microgravity research communities, designed and developed experimental facilities and executed Spacelab missions (Germany), and/or sounding-rocket flights (Germany and Sweden). They also used Soviet flight opportunities (France, Germany and Austria) to fly microgravity experiments and astronauts. France and Germany also used the Russian Foton unmanned retrievable capsule.

There is one key difference between the ESA Microgravity Programme and those of the USA, Japan, Canada or the national programmes of the ESA Member States. That is, it does not include any means to provide substantial support to perform ground-based preparatory research for the experiments of ESA-selected Principal Investigators/Co-Investigators (PIs/CoIs). This PI/CoI-funding responsibility normally falls upon the national space programmes or upon other national research funding institutions such as Ministries, Universities, etc. This means that ESA's microgravity activities, which include the definition of priority research fields, the solicitation and selection of flight experiments, provision of flight opportunities, and flight hardware at multi-user facility level, have to be complemented by national funding for the work of the PIs/CoIs. This division of responsibility, which is desired by ESA's Member States on all ESA programmes, makes it necessary at the European level to co-ordinate the content and timing of ESA's programme with those of its Member States. It also requires the ESA-selected PIs to look for financial support in their home country. That has often meant a more severe experiment-selection process at ESA level, and additionally selection at the national level for the financial support for the scientists.

The most recent national microgravity programme started in Europe is that of Italy. Due to Italy's national contribution to the ISS infrastructure, in the form of the Multi-Purpose Logistics Module, it has acquired independent utilisation rights for the use of the ISS. As a result, the Italian initiative is principally concerned with the national microgravity experiments that are to be performed on the ISS. The focus of microgravity research in Italy has been on fluid physics, and that emphasis tends to be reflected in the type of experiments destined for the ISS. An Italian centre dedicated to microgravity research (MARS) has been established in Naples. In addition, Italy plans to develop a mouse holding facility for use on the ISS. Italy has always been a major investor in the ESA Microgravity Programme. Its industry has been very active in developing ESA's multi-user facilities in the fluid-physics field, and in the development of sounding-rocket payloads for ESA.

In Sweden, the national microgravity programme has evolved around the sounding-rocket activities. Flight-hardware development has focused on experiment modules for the nationally initiated Maser sounding-rocket projects, and on launch-operations support for the Texus and Maxus sounding-rocket flights. All of the European microgravity-dedicated sounding rockets are launched from the Esrange centre, near Kiruna in the north of Sweden. The Karolinska Institutet continues to carry out space experiments in the life sciences, particularly on respiratory physiology.

Belgium has always strongly supported ESA's Microgravity Programme phases. It has promoted, within the framework of the ESA General Supporting Technology Programme, several microgravity-dedicated projects at the national level. A Microgravity Research Centre has been established at the Université Libre de Bruxelles.

Switzerland, Denmark and Spain have always contributed to the various phases of the ESA microgravity programme. At present, the emphasis of microgravity-related research in Switzerland has been put on cell and developmental biology, together with biotechnology. In Denmark, the emphasis is on human physiology, at DAMEC. In Spain, the interest lies largely in fluid science, protein crystallisation and developmental biology.

In the Netherlands, there has been continuing active scientific interest in the ESA programmes, with varying levels of financial support. The United Kingdom and Norway have each supported the programmes at various times and at modest levels.

Recently, this situation seems to be changing as far as the UK is concerned, with the inclusion of applications-oriented research (MAPs) in the ESA programme.

Austria did not participate in ESA's Microgravity Programme phases. It did, however, carry out a life-sciences-dedicated mission to Mir, in co-operation with the Russian space authorities.

The national microgravity programmes of both Germany and France are large. They have carried out national missions, built substantial dedicated facilities and equipment, and selected and supported their experiments. The following is an outline of the relevant major activities in each of those countries.

- *The German Microgravity Programme*

Germany started its first microgravity research activities in 1972, with programmatic studies and the preparation of some experiments in the fields of biology, materials science and biotechnology. The early development of the experiment 'Biostack', in the field of radiation biology, is noteworthy. This device was first flown on Apollo-16 and -17, with many subsequent re-flights. Derivatives of this outstanding facility are still in use. In addition, several materials-science experiments have been performed on Skylab.

A principal motivation for Germany to create its own Microgravity Research Programme was the European decision, in 1973, to develop Spacelab as its contribution to NASA's post-Apollo Programme. Germany contributed 53% to the Spacelab Programme. Consequently, it intended to prepare for the scientific and applications-oriented utilisation of Spacelab. Already in 1975, the Federal Ministry for Research and Technology (BMFT) established five discipline-oriented planning groups of scientists from academia and industry to prepare plans for the utilisation of Spacelab in materials/fluid sciences and applications. Three planning groups were similarly established to cover the life sciences. The outcome was that the BMFT approved a broad Spacelab utilisation promotion programme. Some 50 projects were contained within that programme, including the preparation of experiments.

Another milestone in the early German microgravity programme was the performance of three free-flow electrophoresis experiments on the Apollo-Soyuz mission in 1975, as mentioned earlier.

In these early days of microgravity research, German scientists participated in the American Spar sounding-rocket programme. Experiments were concerned with investigating the separation process in monotectic alloys. It was as a result of these experiments that the important role of Marangoni convection in such processes was discovered.

After detailed studies of short-duration flight opportunities, the decision was taken in 1976 to set up the Texus sounding-rocket programme, as a preparatory endeavour for the upcoming Spacelab utilisation era. The Texus programme actually exceeded, in terms of reliability and experimental facilities, the contemporary American Spar and Japanese TT-500A sounding-rocket programmes. Texus is still going today and is the 'workhorse' of the German microgravity programme, being continuously used by both ESA and DLR. The Texus programme holds a record of 36 successful flights since 1977, the year of the first lauch. It has developed into an independent research opportunity in microgravity. Advanced operational features like remote tele-operation/telescience were introduced at an early stage in 1983, enabling experiment control to be performed from the Microgravity Support Centre (MUSC) at DLR, Cologne, to the launch site at Esrange in northern Sweden.

As part of its contribution to the effective utilisation of Spacelab (see Section 4.1.2), the German national programme provided major multi-user facilities to the Spacelab-1 (FSLP) flight in 1983. One was the Materials-Science Double Rack (MSDR), which was also re-flown as a major payload element on the two German D-1 and D-2 Spacelab missions in 1985 and in 1993, respectively. The MSDR was the first materials-science payload element developed in Europe, and it contained the following German-developed facilities:

- Isothermal Heating Facility, dedicated to metallurgical investigations
- Mirror Heating Facility, for the crystallisation of semiconducting materials
- High-Temperature Thermostat, for diffusion studies in metallic melts
- Cryostate, for protein-crystallisation experiments.

In addition, the Gradient Heating Facility from France and the Fluid-Physics Module developed in Italy were accommodated in the MSDR. For all of these experimental facilities, the MSDR provided joint power conditioning, heat rejection, and data management.

The MSDR (Fig. 4.1.3) was developed within the German Microgravity Programme and offered to ESA for European utilisation. It accommodated 'Cryostate', in which the first protein crystals were grown in space, an event that initiated a worldwide protein crystal-growth programme in space.

Another contribution to Spacelab-1 was the 'Integrated Helmet', for vestibular research, using a video-oculograph method. Vestibular research, as part of neurological sciences, is an important field of emphasis within the German Programme. An advanced version of this facility is presently under development for the International Space Station.

Highlights of the German Microgravity Programme have been the two German Spacelab missions D-1 and D-2, which were primarily dedicated to microgravity research. These missions provided research opportunities not only to German scientists, but also to other European investigators, mainly via ESA's participation.

Based on scientific requirements, Germany has developed equipment especially for investigations in the following research fields:

- *Fundamental Physics:* Capillarity, Marangoni Convection, Diffusion, Critical Point and Heat Transfer
- *Materials Science:* Solidification Front Dynamics, Composites, Crystal Growth Undercooling and Nucleation, Technologies
- *Life Sciences:* Neurophysiology, Cardiovascular System, Pulmonary System, Endocrinology and Metabolism, Cognitive Behaviour, Bioprocessing/Biocrystals, Cell Cultivation, Gravisensitivity, Radiation Biology and Exobiology.

The outcome of these missions included important new findings, which are published in the relevant scientific literature and in special publications on the D-1 and D-2 missions. Both missions were performed with the intensive application of tele-science and tele-operations from the German Mission Control Centre at DLR.

After D-1 and D-2, Germany participated in the international NASA Spacelab missions IML-1 (1992) and IML-2 (1994), with major contributions. In the field of gravitational biology, a multi-user facility with novel features was developed. In 'NIZIMI', a microscope is accommodated on a slowly rotating centrifuge, allowing measurements of the biological threshold of gravity sensitivity. Also for this mission, and since re-flown twice on MSL1/1R (1997), the technologically very complex Tempus facility (see Section 5.2) was developed for the accurate determination of the thermo-physical properties of alloys of industrial relevance and for undercooling experiments. This unique Tempus facility (see Fig. 4.1.5) is the predecessor of the MSL-EML (Materials-Science Laboratory - Electromagnetic Levitation facility) planned for accommodation in the Columbus Laboratory. In co-operation with ESA, the German programme is providing a key part of the MSL-EML facility in the form of the automatic experiment-exchange chamber (see Section 5.2 for details).

Figure 4.1.5. The German 'Tempus' Experiment Module. Electromagnetic levitation allows high-temperature reactive melts to be studied without having to use a container. An ESA follow-on development of this system will be used in the ISS/Columbus Materials Science Laboratory (courtesy of Astrium/Dornier)

For the last Spacelab mission, Neurolab in 1998, Germany provided a collapsible Lower-Body Negative-Pressure Device for co-operative research on this mission. In addition, the Aquatic System CEBAS, first flown on STS-89 in1998, was re-flown. CEBAS is a nearly closed, aquatic ecological system with water plants, fish and snails, which allows investigations in developmental biology and ecological stability. It is to make a third flight on the STS-107 Spacehab mission in 2002.

Two German missions to Mir were performed in 1992 and in 1997. German astronauts were also flown on these missions, mainly to support research in human physiology, which was their focal point. Medex, a cardiovascular research facility, should be mentioned in this context. Germany also provided the Titus furnace and vestibular research equipment (VOG) for the Euromir '94 and '95 missions.

Germany has participated with experiments (about 10% of the payloads) in seven Foton missions, starting with the Foton-7 in 1991. Since 1982, the German programme has also flown 19 'Maus' facilities, which are small autonomous standardised experiment facilities carried in the Shuttle's cargo bay.

Spacehab was used for the first time in 1996 (on STS-77) with a modified Mirror Heating Facility (ELLI) in a German-Canadian co-operation. The next experiments were performed in 1998 (on STS-89 and STS-95), and further experiments are planned on two future Spacehab missions (on STS-107 in 2002 and STS-112 in 2003).

In addition, further short-duration experiment facilities, such as the Drop Tower in Bremen and the Microba (Payload Drop Facility from a 40 km altitude balloon), were developed as part of the German microgravity research programme. The Bremen tower has become the most extensively used drop facility in Europe.

Germany contributed 53% of the cost of the ESA Eureca development programme. A large portion of the 28 European experiments on Eureca also came from Germany, i.e. the German national programme supported many Eureca PIs (see Section 6.7).

Utilisation of the ISS within the German national programme is supported by developing a number of instruments. These include the Lower-Body Negative-Pressure Device (LNBP), a second-generation eye-tracking device for vestibular research, and Cardiolab, in co-operation with CNES, a major element of the European Physiology Module (EPM). The EPM is one of the four large ESA facilities under development for accommodation in the Columbus Laboratory. One of the first experiments on the International Space Station is the German– Russian Plasma Crystal Experiment (PKE), which has been developed in the German Programme. PKE is a pilot experiment for the planned International Microgravity Plasma Facility (IMPF) for the ISS (see Section 2.3.8). Germany will also contribute a key element of the Materials Science Laboratory (MSL–EML) facility, as detailed later.

From a programmatic point of view, it is noteworthy that, in the 1980s and early 1990s, the financial envelope of the German national microgravity programme (excluding the mission costs for Spacelabs D-1 and D-2) was larger than that of ESA's microgravity programme. However, this envelope was reduced from about DM 100 million/year in 1990 to about DM 40 million/year in 1998, and is planned to remain constant until 2003. This reduction in the national microgravity research budget is compensated by an increasing German contribution to the ESA microgravity programme in the 1990s, so that the overall level of activity in the German scientific community and in the relevant space industry was not reduced. In the 1990s, European space industry and especially German space industry, which developed sophisticated experimental facilities for the ESA and German microgravity programmes, was recognised as a world leader in this field. German industry created the European entity 'Intospace' in the mid-1980s, which was later supported by nearly 60 European firms, to facilitate industry's access to flight opportunities.

- *The French Microgravity Programme*

The financial envelope for France's space activities, consisting of its contribution to ESA's space programmes and the national space projects, makes it the largest investor in space in Europe. Within the ESA framework, France contributes the largest share of all ESA Member States to Ariane, the biggest of the European space programmes. Also at the national level, France's space programme, which is administered by the French space agency CNES, exceeds that of any other European country.

France's leading position in terms of European space expenditure is not, however, fully reflected in its funding of microgravity research. The French contribution to ESA's Microgravity Programme has, on average, been about half that of Germany and about the same order of magnitude as that of Italy. The financial envelope of the national microgravity programme in the 1980s was considerably smaller than that of Germany. This situation changed somewhat in the first half of the 1990s, but during the second half the national microgravity activities had a low priority amongst the French space programmes. Only in 2000 was this low-priority status revised.

Despite these political and financial circumstances, a motivated and competitive physical- and life-sciences community has developed in France. The national programme was predominantly oriented in the past towards basic research. The scientific projects selected were co-ordinated with ground-based preparatory research and only clearly space-relevant topics were selected for in-orbit experiments. This

resulted – at moderate cost – in a growing number of research teams with excellent scientific expertise.

In the *Physical Sciences*, French national microgravity research concentrated mainly on the following areas:
- solidification (improvement of the microstructure due to the absence of gravity and study of instabilities at the liquid/solid interface)
- crystal growth (especially from solutions, protein crystallisation)
- measurements of thermo-physical coefficients
- critical-point research
- combustion.

In support of this research, CNES has used ESA flight opportunities and ESA's experiment facilities, such as the Advanced Gradient Heating Facility (AGHF), the Critical-Point Facility (CPF), the Advanced Protein-Crystallisation Facility (APCF), etc. (see Table 6.2) and ESA sounding-rocket experiment opportunities. In addition, however, at the national level CNES developed some highly sophisticated research instruments and flew them under bilateral arrangements with NASA and with the Russian space authorities. The most important of these nationally developed instruments are:
- Mephisto, a furnace in which the Seebeck effect is used to characterise the status of the solid/liquid interface. This instrument was flown several times on NASA Spacelab pallet missions in the 1990s.
- Alice-1, an instrument with capabilities similar to those of ESA's earlier developed Critical-Point-Facility (CPF) for Spacelab and sounding rockets. It was accommodated on Mir, in the framework of French missions in the period 1992 – 96. Alice-2 was used from 1996 onwards. Alice-1 and -2 employed optical and very precise thermal diagnostics to support critical-point research. These studies resulted in the discovery of a new heat-transfer mechanism, which is due to the adiabatic heating of fluids by dilatation of limited thermal layers. It is called the 'Piston Effect' (see Section 2.3.5). This new heat-transfer mechanism has already found industrial application (Air Liquide) in the storage of cryogenic fluids on Ariane-5.

In addition, CNES has supported the development of two short-duration flight opportunities:
- the Drop Tube in Grenoble, to support mainly short-duration solidification and combustion studies
- parabolic aeroplane flights, using first a Caravelle and later an Airbus-300 aircraft (flights managed by Novespace, a company set up by CNES).

In the *Life Sciences*, the French national programme did not simply limit its activities to supporting its science teams that were using ESA flight opportunities and experimental facilities. CNES also concluded – especially after the Challenger accident

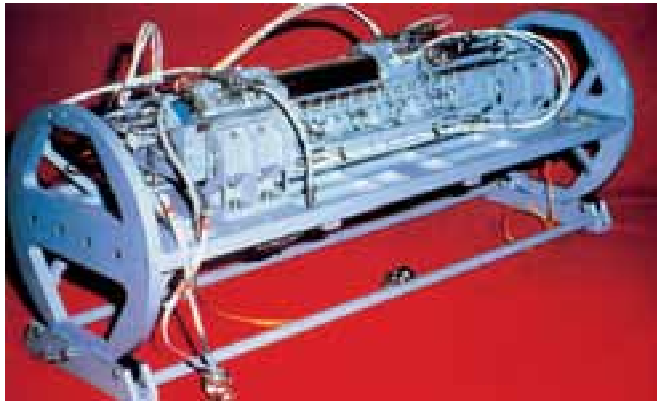

Figure 4.1.6. The French 'Mephisto' furnace, used for detailed study of the solidification processes at the melt solid/liquid interface and flown on several Spacelab pallet missions (courtesy of CNES)

in 1986 – bi-lateral arrangements with the Soviet/Russian space authorities to perform joint missions to Mir.

There was a first mission, with the first French astronaut, to Salyut-7 in 1982. This was followed by several missions to Mir between 1988 and 1999:
- Aragatz, 1988, 25 days duration
- Antares, 1992, 14 days duration
- Altaïr, 1993, 21 days duration
- Cassiopée, 1996, 16 days duration
- Pegase, 1998, 20 days duration
- Perseus, 1999, 6 months duration.

These missions were predominantly used to perform human-physiology studies on French and Russian astronauts, but some gravitational biology, exobiology, and critical-point studies were also conducted.

In addition, some nationally selected life-sciences experiments were performed on NASA's Spacelab missions IML-1, IML-2 and LMS, and on Russian Foton/Bion retrievable pressurised-capsule missions.

The major scientific topics addressed during these space missions on man and animals were:
- in neurosciences: the adaptation of the sensori-motor functions, movement and posture, cognition aspects such as perception, memory and spatial orientation.
- in cardiovascular physiology: cardiovascular deconditioning, with studies in haemodynamics, control of arterial blood pressure, hormonal mechanisms in blood and total body-fluid loss, cerebral fluid, etc.
- in the field of bone modifications and muscle degradation: bone-density changes in astronauts and osteoporosis in animals, muscle atrophy and modifications of muscles in microgravity

- in gravitational biology, radiation biology and exobiology: developmental biology studies on, for example, amphibian eggs (pleurodels), plant gravitropism and gravimorphism, physical and biological dosimetry, induction of lesions at the genomic level and their mutational consequences.

For many of these studies, special experimental hardware was developed within the French national microgravity programme. These items included 'Cognilab' (perception), 'Physiolab' (cardio-vascular physiology), 'Kinelite' (movement problems), 'Fertile' (developmental biology), and 'Ibis' (cell and developmental biology).

Utilisation of the International Space Station within the French national microgravity research programme is planned in the physical- and life-sciences areas. In continuing research on critical-point phenomena in the ISS, the CNES will develop the 'Declic' instrument, which is designed to study high-temperature critical fluids and the crystallisation of transparent materials.

As is explained in Section 5.2, CNES, in co-operation with DRL, will develop an important element called 'Cardiolab' for the ESA ISS laboratory's European Physiology Modules (EPM). Cardiolab is derived from the French Physiolab and the German Medex, both of which were developed for and flown on Mir.

A long-term plan of CNES is the development of a Neurosensory Research Laboratory (SENS), which will include existing instruments such as the Kinesigraph, the Occulometer, Cognilab and new stimulation devices

4.2 The ESA Microgravity Programmes

4.2.1 Towards the First ESA Microgravity Programme (Phase-1)

By 1980, the lack of a coherent overall European strategy and programme for the development of microgravity research and the use of the European-developed Spacelab was clearly unsatisfactory and becoming untenable. The solution to the problem of funding the facilities for the first Spacelab flight with a complicated mix of national funds and ESA funds from other programmes, was not a viable arrangement for the future, for several reasons:

- Interest in performing life- and physical-sciences experiments in space increased in the late 1970s in all of the ESA Member States, as evidenced by the fact that the experiments selected for the first Spacelab flight came from 10 different Member States. During the discussions on future Spacelab missions, the national delegations had considered it fair that all Member States from which Principal Investigators had been selected should contribute to facility development/refurbishment costs and to integration and operation costs. However, when Germany offered other ESA Member States the opportunity to participate with their own national experiments in the D-1 mission on a cost-reimbursable basis, none were willing to make use of this opportunity. There were, however, a few co-operative experiments flown without a contribution to the D-1 mission costs.
- Apart from the Vestibular Sled, the multi-user facilities that were developed for the first Spacelab flight did not serve the important but crew-intensive research fields, such as cell and developmental biology or the broad field of cardio-vascular and cardio-pulmonary research. This was because the crew time available for the scientific payload on the first verification flight was limited to 100 hours. Consequently, the centralised development of the multi-user facilities, such as Biorack and Anthrorack, which were needed to support such research, was postponed to later missions. Yet neither Germany, nor any other Member State, was willing to develop such facilities at a national level, if they were to be used by Principal Investigators from other Member States on later missions.
- A similar situation existed for the case of certain sub-disciplines in fluid physics and materials sciences. Based upon the requirements of proposed experiments, there was a need to develop a Critical-Point Facility, a Bubble Drop and Particle Unit and a multi-user Protein-Crystallisation Facility. For these facilities also, no nationally funded developments were offered.
- Since 1977, German scientists had been able to prepare for microgravity experiments on Spacelab by conducting precursor experiments on short-duration rocket flights. The German national space programme funded those Texus rocket flights. Principal Investigators from other Member States usually did not have access to such preparatory flight opportunities, apart from a few bilateral cooperative experiments.

In order to improve the situation and to provide a strategy and plans for the future, ESA again proposed to its national Delegations the creation of a Microgravity Research Programme. Among its stated intentions was the selection of investigations according to scientific-merit criteria, the development of the necessary multi-user facilities and the payment of space mission costs (i.e. payload integration, launch fees and operation costs).

In the ensuing discussions, the ESA-proposed budget to cover those activities over several missions was substantially reduced by the Delegations. It was limited to a programme to cover just an ESA participation to supply and fly certain multi-user facilities on one Spacelab mission, namely the German D-1 mission, and to prepare the related experiments on the equivalent of four Texus sounding-rocket missions with ESA payloads, spread over seven Texus flights. Nonetheless, it was a step in the right direction, as it opened a way ahead for microgravity research on a European basis.

This Phase-1 of the ESA Microgravity Programme formally got underway in January 1982, with a financial envelope of 48.6 MAU spread over the years 1982 to 1986 (the AU was roughly equivalent to 1 US Dollar; it was an ESA internal budget predecessor of the Euro). The participating Member States were: Germany (38.2%), France (21.4%), Italy (10.4%), Belgium (6.2%), Sweden (5.9%), Switzerland (5.6%), the Netherlands (5.5%), Denmark (3.5%), the United Kingdom (1.9%) and Spain (1.4%)

There were three Phase-1 programme elements:

- Biorack, a multi-user facility to be built for investigations in the field of cell and developmental biology and flown on the D-1 Spacelab mission. During that flight, Biorack supported the execution of 14 experiments. It later became the multi-user facility with the highest flight frequency, flown on three Spacelab and three Spacehab missions.
- The Improved Fluid-Physics Module (IFPM), an improved version of the original Fluid-Physics Module flown on the first Spacelab flight. It was designed to study mainly phenomena connected with the hydrodynamics of floating zones and Marangoni convection. It was flown on the D-1 mission and eight selected experiments were conducted.
- The Sounding-Rocket Programme Element, which involved ESA in developing the experiment modules equivalent to four Texus payloads, each weighing 240 kg. This began with the Texus-6 mission in 1982.

In parallel with these Phase-1 programme elements, ESA developed the Vestibular Sled, as mentioned earlier.

The flight of the three ESA facilities – the Vestibular Sled, Biorack and the IFPM – amounted to 38% of the total payload of the German D-1 Spacelab mission, in terms of utilisation of the critical resources (mass, crew time and electrical energy). The ESA

Figure 4.2.1. The ESA 'Biorack', which accommodated 14 cell and developmental biology experiments on the Spacelab D-1 mission and was later used on the two further Spacelab and three Spacehab missions. ESA astronaut Wubbo Ockels is seen here working at this facility

Figure 4.2.2. TEM-EVA, one of the experiment modules for Texus sounding rockets (Texus-38)

Phase-1 programme paid the NASA launch fees for Biorack (15%) and the IFPM (5%), based upon the use of these critical resources during the D-1 mission. The launch fee for the Sled (18%) was paid by the German space programme, under an earlier agreement.

4.2.2 Phase-2 of the ESA Microgravity Research Programme and Its Extensions (EMIR-1)

The few facilities that were developed within the framework of Phase-1 of the ESA Microgravity Programme could serve only a small part of the interests of European microgravity research scientists. ESA therefore continued to study the technical and cost aspects of additional multi-user facilities in detail during the period 1982–84. These facilities included:
- an Advanced Gradient Heating Facility (AGHF)
- a Critical-Point Facility (CPF)
- a Bubble Drop and Particle Unit (BDPU)
- an Advanced Protein Crystallisation Facility (APCF)
- an Autonomous Fluid-Physics Module (AFPM)
- a facility for human-physiology research (Anthrorack)
- a Botany Facility (BF).

The reflight, upgrading, and refurbishment costs for the Biorack and Sled were also examined.

In meetings at that time, ESA explained to NASA that the very high Shuttle/Spacelab transportation costs, representing more than half of the Spacelab utilisation costs, posed a major barrier to the further development of the European microgravity research programme. It made it impossible for ESA to obtain agreement from its Member States for the funding of a reasonable European Microgravity Research and Spacelab Utilisation Programme, despite the fact that ESA had spent about 1 billion AU (Euros) on the development of Spacelab, which NASA was using. The Member States were simply unwilling to spend huge amounts of money on Shuttle launch fees.

These ESA–NASA discussions finally led to the generation of a series of NASA Spacelab missions called 'International Microgravity Laboratory' or IML missions, in which ESA could participate. The IML agreement required that ESA would develop some multi-user facilities of a high technological standard for Spacelab that fulfilled NASA's technical performance requirements as well as those of the ESA-selected experiments. NASA and ESA would then use the resulting facilities on a 50/50 basis, and in return NASA would fly these ESA facilities on an IML-mission at no cost to ESA. However, agreement had to be reached for each facility separately. NASA would accept them only if it had no equivalent facility type, or if the ESA facility had a higher performance. Also, for the ESA facilities for which there were no NASA-selected experiments, ESA had to pay the Shuttle mission fees.

This agreement was a major breakthrough in the process of establishing a new, larger, and more coherent ESA Microgravity Research Programme. It was an agreement that also applied later for NASA's LMS and Neurolab Spacelab missions. The result was that ESA could establish the larger Phase-2 Microgravity Programme. It was approved in February 1985, with a financial envelope of 131 MAU, to cover four years. Two subsequent large extensions to this Phase-2 Programme took place in 1988 and 1991, as discussed in detail below, and led to an envelope of almost 600 MAU, spread over the period 1986 – 1998.

This Phase-2 Programme permitted the development of all of the facilities (except the Botany Facility) that had previously been studied:
- AFPM, BDPU and CPF in the fluid-sciences field
- AGHF and APCF in the materials-science field, and
- Anthrorack in the human-physiology field

together with the reflight of Biorack and the Vestibular Sled and also three further programme elements:
- short-duration flight opportunities (mainly sounding-rocket flights)

– 20% use of German multi-user facilities on the D-2 Spacelab mission
– a Microgravity Supporting-Technology Programme.

The Phase-2 Programme was supported by 11 ESA Member States, with the following individual participations: Germany 35.00%, Italy 17.00%, France 16.80%, Belgium 4.50%, The Netherlands 4.00%, Switzerland 3.87%, Sweden 3.44%, Spain and the United Kingdom each 2.00%, Denmark 1.98%, and Norway 0.50%.

Since there was still an under-subscription of about 9% in terms of the total programme cost, it was agreed to shift the planned development of the Botany Facility to a later programme phase. In addition, the proposed reflight of the Sled was cancelled, after NASA refused to fly it under the IML agreement. The problem was that this large 550 kg facility would have disturbed the microgravity environment needed by other experiments when it moved along Spacelab's aisle.

During 1985, ESA had placed the development contracts with industry for most of the new multi-user facilities. Then in January 1986, the Challenger disaster occurred. The result for the ESA Programme was a gap in Shuttle flight opportunities that lasted almost six years. It was not until January 1992 that ESA again had access to Spacelab, when the IML-1 mission with some ESA microgravity-science payloads was flown. The German D-2 mission had to be postponed from its planned launch date in 1988 until April 1993, a delay of about five years.

To try to reduce the negative impact of the Challenger accident on the microgravity research of the European science community, ESA stretched the on-going industrial development contracts and restructured Phase-2 of its Microgravity Programme as follows:
– It increased the short-duration flight opportunities, by doubling the flight frequency of sounding rockets and by adding preparatory parabolic airplane flights and by enabling experiments on drop towers.
– It started to perform biological experiments on the Soviet Bion (later called Foton) unmanned, but pressurised, retrievable satellites. (The Soviet space authorities did not offer the use of Mir or Bion/Foton for ESA materials/fluid-science experiments at that time).
– ESA began a 'General Activities Programme Element' to cover the Phase-A and -B (design and costs) studies of microgravity research facilities for the ESA Columbus Laboratory of the International Space Station, i.e. the preparation of the later MFC-Programme.

A Phase-2 Programme Extension was an evident requirement, due to the delays in the launch dates for the Spacelab IML-1 and D-2 missions. When, in November 1988, the extent of these delays became firmer, Phase-2 was extended financially from the original 131 MEuro to 203.8 MEuro (at 1983 economic conditions). This was to cover the above Programme elements and the stretching of the development of the Phase-2 multi-user facilities. The duration of the combined Phase-2 plus First Extension was prolonged by 3.5 years, until the end of 1992.

A Phase-2 Second Extension took place in late 1990, because new flight opportunities became available on:
– NASA Spacelab missions (IML-2, USML, LMS)
– the German D-2 Spacelab mission
– Russian retrievable satellites (Foton)
– Maxus sounding rockets (from 1993 onwards, with a large payload-carrying capability of 440 kg and up to 13 min of microgravity conditions)
– Spacehab (offered as part of the barter agreements with NASA for Biorack and APCF use)
– Get-Away Specials (GAS) in the Shuttle's Cargo Bay.

These Spacelab missions meant flight opportunities for the multi-user facilities then under development, like CPF, BDPU, AGHF, and re-flights for Biorack, as well as opportunities for new multi-user facilities to be developed such as:
– Biobox, Biopan and autonomous experiments for Foton missions
– a Respiratory Monitoring System (RMS) for the D-2 Spacelab mission and a second generation of it (RMS-2) for Euromir '95
– Bone Densitometer as well as blood kits and stand-alone physiology and radiation experiments on the Euromir missions
– Glovebox for the USML-2 Spacelab mission
– Torque Velocity Dynamometer for the LMS (Life and Microgravity Sciences) Spacelab mission
– Diffusion-Coefficient Measurement Facility for a GAS (Get-Away Special) payload on Shuttle flights.

This Second Extension of Phase-2 further prolonged its duration until the end of 1995, i.e. by another 3 years, and increased the approved financial envelope from 203.8 to 336.2 MEuro (at 1983 economic conditions). With the consent of the Microgravity Programme Board, this envelope was later exceeded by a cost overrun of 14%. This was due to further delays in Spacelab missions, the need to cover further development of Euromir equipment, and the payments for a part of the mission costs for Euromir '95 (ESA Euromir missions were not yet planned when the Phase-2 Second Extension was approved).

From 1993 onwards, this Phase-2 and its two extensions were formally known as EMIR-1, or European Microgravity Research Programme 1. The total financial envelope for the EMIR-1 programme, invested over a period of about 14 years (1985 – 1999), was 598 MEuro at current price levels (i.e. in the economic conditions of the year in which the money was spent).

4.2.3 The ESA EMIR-2 Programme, Its Extension and Applications Projects

The objective of the EMIR-2 programme was to maintain an active microgravity user community until the start of utilisation of the International Space Station. At the time in 1995 when the EMIR-2 programme was proposed, ISS utilisation was foreseen to commence in 2001.

The proposed EMIR-2 basic programme consisted of a number of specific activities such as:

- continuation of Mini-Missions, including sounding rockets, parabolic airplane flights, drop-tower/tube experiments
- experiments for retrievable carriers (e.g. Foton) using Biobox, Biopan, Fluidpac and furnaces
- utilisation of manned systems (Spacelab, Spacehab, Mir and, when launched, the US-Lab of the ISS). The facilities to be developed for these research opportunities included:
  - the European Modular Cultivation System (EMCS) for plant and cell biology
  - the Protein-Crystallisation Diagnostics Facility (PCDF)
  - the Space-Exposure Biological Facilities (Matroshka and Expose)
  - the Advanced Respiratory Monitoring System (ARMS)
  - the Facility for Absorption and Surface-Tension Studies (FAST)
  - the reflights of the Advanced Gradient Heating Facility (AGHF) and the Advanced Protein-Crystallisation Facility (APCF)

ESA's programmatic proposal for EMIR-2 was only partially approved at the 1995 Council Meeting at Ministerial Level. Nevertheless, an amount of 153 MEuro (1995 economic conditions) was approved. This enabled the continuation of the basic utilisation activities, at a reduced level of about 35 MEuro/year, for a period of 4 years, i.e. until 2001.

The basic EMIR-2 utilisation programme had an annual financial envelope only about half that of its predecessor programme EMIR-1, during the first half of the 1990s. However, the start of the ISS routine utilisation phase was successively delayed, being moved finally into the 2005 time frame. Consequently, in 1999 ESA tried to obtain an increase in the financial envelope of the EMIR-2 programme to cover this gap, by proposing an EMIR-2 Extension. At the request of its Member States, ESA reduced the cost of this Programme Extension several times, so that the final approval covered only an amount of about 50 MEuro.

The consequence of this neglect of flight/research opportunities in the pre-Columbus era is demonstrated in Figure 6.5.1, which shows many fewer experiments being performed each year in the period 1999 to 2002, compared with the mid-1990s. As shown in the Appendix, in Table 6.7, the number of experiments flown in the four-year period 1993 – 1996 was 226, whereas the corresponding number for the four-year period 1999 – 2002 is only 72. This is a drastic reduction in experimental activities, which has hampered progress in ISS utilisation preparations. This effect was aggravated by the fact that no co-operative NASA/ESA agreements existed, such as those for the Spacelab missions between IML-1 (1992) and Neurolab (1998). All flight costs for sounding rockets, Foton and Spacehab missions had to be covered by the EMIR Programme.

The halving of the annual budget for EMIR-2, compared to the mid-1990s, and the need to procure all flight opportunities after the termination of co-operative Spacelab flights by NASA in 1998, proved to be a major drawback in terms of adequate preparation for the utilisation of the ISS.

However, a positive effect on the preparation of ISS utilisation in the years 1999 – 2002 is being provided by the Columbus Utilisation Promotion Programme. The microgravity part of this programme addresses researchers from industry and academia for developing relevant Microgravity Application Promotion (MAP) projects. MAP is intended to develop pilot projects demonstrating that the ISS is a unique tool with which to advance terrestrial research with industrial objectives. MAPs are supported by ESA, national space agencies and industry. The funding share of industry is unexpectedly high, i.e. about 1/3 of the total funding requirements of about 40 MAP projects selected in the frame of two Announcements of Opportunity (AOs) for MAP projects in the physical and life sciences. The residual funding is shared by ESA (one third) and the institutes/national agencies (one third each).

The contribution from ESA's Columbus Utilisation Promotion Programme to MAP projects is about 28 MEuro. This Columbus Utilisation Promotion budget approval was a single event, which was not continued by a follow-on approval of a promotion budget at the Brussels Ministerial Conference in 1999. Consequently, this very promising active co-operation of non-space industry might come to an end after 2002, i.e. some years prior to the start of the routine phase of ISS utilisation. Therefore, an ESA contribution to MAP projects needs to be continued after 2002, if industrial research on the ISS is to be seriously encouraged.

Figure 4.2.3 shows in graphical form the annual budgets of the various microgravity-research-related programmes from 1982 onwards. It also demonstrates that, considering that the development of experimental facilities takes about 3 to 4 years, a decision on a microgravity follow-on programme is needed in late-2001.

Since the completion of ISS assembly is presently expected at the end of 2004/early 2005, routine utilisation will not start before 2005. With present approved funding (Figure 4.2.3), there will be a three year gap in ESA's microgravity research prior to ISS utilisation, unless a new life- and physical-sciences programme is approved to allow

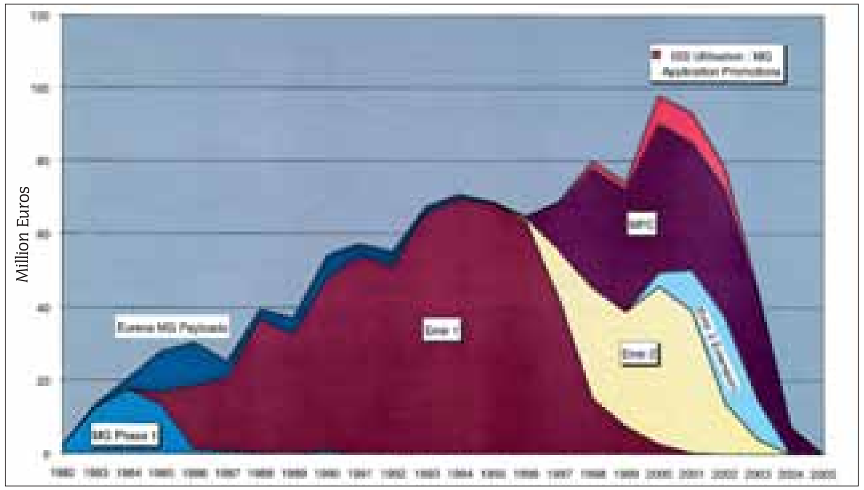

Figure 4.2.3. ESA annual budgets for the various microgravity programmes

further research activities in that period. (The MFC Programme, discussed below, covers only facility hardware costs, not research activities). If a budget is not allocated for such activities in this interim period, the most important European ISS user community could largely disappear.

4.2.4. The ESA 'Microgravity Facilities for Columbus' (MFC) Programme

During the 1980s and the first half of the 1990s, ESA performed design and cost studies of Columbus, the European contribution to the ISS. During this period the Agency's Member States repeatedly requested reductions in the technical content and financial envelope of the Columbus Programme. Finally, in September 1995, when the corresponding decisions of the other ISS partners, i.e. the USA, Japan and Canada, had already been taken, an ESA Council Meeting at Ministerial Level took place to decide on the development of Columbus, and its utilisation preparation and promotion. At this time it was planned to utilise the ISS for multi-disciplinary research, applications and technology for a period of 15 years after the completion of the Station's orbital assembly.

In parallel with the Columbus definition studies, ESA conducted ISS utilisation studies and issued Preliminary Calls for Experiments. These showed that the major ISS utilisation areas would be research and applications in the fields of life and physical sciences and applications, and potentially industrial and commercial applications.

In the second half of the 1980s, the European microgravity user community defined (at ESA's request) a number of multi-user facilities for the Columbus Attached Laboratory (known until then as the Attached Pressurised Module) and for the Columbus Free-Flying Laboratory. These facilities were afterwards studied technically and from a cost point of view by ESA, with the support of European space industry.

The multi-user facilities for the Columbus Attached Laboratory and the Columbus Free-Flying Laboratory studied at the time were as follows:

Columbus Attached Laboratory	Columbus Free-Flying Laboratory
– Anthrolab (AL) – Biolab (BL) – Biotechnology Facility (BF) – Fluid-Science Laboratory (FSL) – Combustion Facility (CF) – Low-Temperature Materials Processing Laboratory (LTMPL) – High-Temperature Materials-Processing Laboratory – Containerless Processing Laboratory	– Automated Biolab – Crystallisation Facility – Thermophysical Properties Facility – Central Robotic System for Sample/Specimen Supply to Facilities – Sample/Specimen Storage Racks – Protein-Crystallisation Facility – Low-Temperature Vapour Crystal Growth Facility

As a result of a cost-reduction exercise, the size of the Columbus Attached Laboratory was reduced from an originally 12.8 m-long cylinder, to one 6.4 m in length and 4 m in diameter. The Columbus Free-Flying Laboratory was totally deleted from the Programme. In addition, the adoption of the ISS ESA/NASA Memorandum of Understanding (MOU) meant that only 51% of the technical resources allocated to the Attached Laboratory would be available for European utilisation. Consequently, the above list of facilities studied far exceeded the accommodation now allocated to ESA. They had to be reduced to four microgravity-dedicated facilities, each the size of one International Standard Payload Rack (ISPR), i.e. 1.05 m in width, 2.03 m high and 1.01 m deep. The utilisation-preparation part of the Columbus Programme included a European Drawer Rack for small, standardised payloads from various user disciplines, and a European Storage Rack (ESR) and Laboratory Support Equipment.

The allocation of the technical resources, such as the number of racks, power and heat rejection, crew time, data transmission and upload/download capacity has been based on the value of the contributions of the ISS Partners to the overall Space Station Programme. If the later-added Russian ISS contributions are not taken into account, then the European Columbus contribution represents 8.3% of the 'western part' of ISS. NASA is the major ISS Partner with 76.6% of the western part, followed by Japan with 12.8%, ESA with 8.3% and Canada with 2.3%.

The four racks selected for development within the framework of a separate 'Microgravity Facilities for Columbus' (MFC) Programme were the following:
- Biolab
- Materials-Science Laboratory (MSL)
- Fluid-Science Laboratory (FSL)
- European Physiology Modules (EPMs).

The scientific and technical aspects of these microgravity multi-user facilities are described in Chapter 5.2. The MFC Programme includes the development of these four facilities for the ISS. It also includes a programme element called 'User Support', covering the development of standardised experiment containers for Biolab and FSL and cartridges for MSL users. Another programme element called 'Second-Generation Facility Studies' covers design and cost studies for a second generation of microgravity facilities for ISS. The MFC Programme was approved together with the Columbus Programme in September 1995.

The approved financial envelope for the MFC Programme is 202.6 MAU (MEuro) at 1995 economic conditions. Only eight ESA Member States contribute to the MFC Programme: Germany (40.8%), France (23.3%), Italy (16.1%), Belgium (10.2%), Switzerland (4.1%), Spain (2.0%), Denmark (2.0%) and The Netherlands (1.5%). Since the detailed design studies (Phase-B) of the MFC elements were still financed by the EMIR-1 Programme, the MFC Programme began with the first hardware development in 1997. It is planned that hardware development and qualification of all MFC facilities will be concluded by 2003.

CHAPTER 5

THE FUTURE OF MICROGRAVITY RESEARCH

5.1 Microgravity Experimentation in the Space-Station Era

M. Heppener

5.1.1 Introduction

Research in the life and physical sciences in space began in the late 1950s, with early experiments in drop towers, and progressed in the 1960s with Russian capsules and the Apollo flights. After the early concerns as to whether humans could even survive spaceflight, the emphasis began to turn towards more fundamental research on the influence of gravity on physical and biological processes. Those early experiments led to enough interesting results and theories to warrant a more concentrated effort.

The survey of the current status of microgravity research, presented in Chapter 2, shows clearly that a solid body of valuable results and a well-based programme of ongoing research now exists. However, the rate of scientific progress in this field has been slow relative to that of comparable terrestrial-based research. This is almost entirely due to the very limited amount of actual experimentation time that has been available in space in the past.

It should be recalled that in the early days of the development of the Space Shuttle, in the seventies, official NASA expectations were that some 50 flights would take place annually. In reality, not more than nine Shuttle flights have been realised in any given year, largely due to the cost and complexity of flight preparations and operations. The greatly increased cost, over that originally presented by NASA, has further restricted European flight opportunities. In addition, the Challenger accident in 1986 meant not only a hiatus of about five years, but also led to an important increase in safety requirements and, consequently, in the mission preparation time. Although for some experiments alternative flight solutions could be found, for example by boosting the European effort in sounding rockets, this cannot compare to the scientific return that can result from routine long-duration human missions.

The International Space Station (ISS) will be a quantum leap in this respect. This will be the first time that European scientists will have access to a permanently functioning and well-equipped laboratory in space. Consequently, microgravity research will finally have the opportunity to firmly establish itself as a valid and important scientific endeavour in its own right. The ESA plans to enable this opportunity to be translated into reality are outlined in the following discussion of the utilisation of the ISS for microgravity research.

5.1.2 The ISS: an International Endeavour

From the outset, the ISS has been designed to be an international collaborative project between the partners. For researchers who want to use the ISS, it should really become a 'station without walls'. In other words, it should be irrelevant in which module of the ISS an experiment is to be performed or who is the formal owner of the facility that is used. In practice, the international partners in the ISS programme are trying to accomplish this by setting up International Working Groups, to deal with various aspects of the Station's utilisation. Three such working groups are presently active: the International Strategic Life-Sciences Working Group (ISLSWG), the International Microgravity Strategic-Planning Group (IMSPG), and the Multilateral Consultative Working Group for Commercial Programmes (MCWG-CP).

The first two groups are particularly active in streamlining and defining the complement of available facilities. In addition, they organise the international Announcements of Opportunity (AOs) for experiments and the subsequent global experiment selection process for their respective disciplines. The selection is performed by international, independent peers who use a set of agreed criteria that focus on scientific merit. After the scientific review by the peers, a technical review of the feasibility is organised. By this means, it is intended to guarantee that ultimately the best international projects will be performed on the ISS.

- *Scientific Research*

For those scientists with past experience of performing experiments in space, the International Space Station will differ markedly from the earlier missions. The ISS is a platform with a planned lifetime of 15 years. For that reason, its operational scenario is completely different from other manned missions on the Space Shuttle, let alone unmanned carriers or short-duration flights on sounding rockets. The best comparison might be the Russian space station Mir, on which non-Russian experiments were also performed during co-operative, but cost-reimbursable, missions with NASA, ESA and several individual countries during the past decade.

Having more regular and routine access to space means that, for the first time, scientists will be able to set up comprehensive research programmes. Such a programme could consist of possibly several space experiments. These will be centred on the ISS, but may also utilise sounding rockets or unmanned carriers, depending upon the requirements. They are also likely to be complemented by continuous ground-based research. In such an approach, the separation between the research to be carried out in space and that of the traditional scientific discipline will be diminished. Rather than delivering only one data point after years of preparation, a comprehensive research programme can be expected to yield several publications over its lifetime. Such an approach also has the important consequence that it makes research in space more compatible with the average duration of normal research projects, and also with the typical four-year duration of a PhD.

In order for this future vision to become reality, it is a top priority to make access to space as simple as possible and to reduce the preparation time and paperwork to a minimum. That will definitely require some learning and adapting from the various space agencies involved with ISS operations.

- *Application-Oriented Research*

In recent years, an additional demand has emerged for easy access to space, which is a result of the onset of application-oriented research. ESA is stimulating this development with a specific Microgravity Application Programme (MAP), as discussed in Section 3.3, that has the possibility to support these projects financially. In response to recent AOs, ESA has received numerous proposals describing projects that are relevant for society or industry. These have included research projects in the medical field, in the casting and petrochemical industry, and in energy production and environmentally relevant processes. After rigorous evaluation of the proposals, ESA has accepted 48 of these projects. Within those accepted, there are some 125 European companies participating. In all cases, the funding of these projects can be described as a public-private partnership in which industry, academic institutions and ESA each pay roughly an equal share of the total project costs. It is clear that there is a very promising interest by industry in research in space and this needs to be further encouraged and nurtured. However, in order to make the ISS a really interesting industrial research environment, its operations must become compatible with the typical 1 – 2 year planning cycle that is customary in industrial R&D, and the associated costs firmly restrained.

- *Operational Considerations and Constraints*

In the past, almost all space missions were prepared in a 'batch mode', i.e. one in which planning, testing and training were performed extensively on the ground beforehand, in order to ensure a flawless performance in space. For manned missions, this meant that the crew's activities were more or less prescribed from minute to minute.

For the Space Station, the operational scenario will be different. The basic planning unit is called an 'Increment' (Fig.1.8), each of which covers approximately three months. It begins as a new crew arrives at the Space Station and new experiment-specific equipment, such as samples, consumables and inserts for the MFC and EDR facilities, are delivered, together with software updates for all equipment. The preparations for each Increment form a step-wise process, which starts approximately two years earlier. During this period, the requirements of the different payloads will be matched up and a complete simulation of the activities to be conducted during the Increment will be performed, in order to identify potential incompatibilities. At this time also, a complete overview will be made of the resource requirements during the Increment. Some of these resources, in particular the up- and down-loads, are rather scarce. Indeed, they may well be the limiting factors that determine the total number of experiments that can be performed within each Increment.

In Europe, an important role is given to the various User Support and Operation Centres (USOCs), located in different participating ESA Member States. It is here that the direct contact with the experiment team is established. The communications with the ISS will also be made through the USOCs, since they are connected into the ISS ground infrastructure. A selected USOC has responsibility for one of the European facilities that is on-board the ISS. Each USOC maintains the technical and scientific knowledge necessary to operate its designated facility.

Once in orbit, experiments will be performed in the various facilities that are available in that particular Increment. Remote operation of the payloads and 'telescience', which allows the Earth-based scientist to oversee and control the experiment in progress, will be applied.

The resources set aside for experimentation are accommodated within the overall resources, the main part of which actually goes into the operation of the Space Station itself. It is to be expected that during a mission Increment, unforeseen events may arise that will require adaptation of the planning.

The above brief outline of the operational aspects of experimentation on the ISS reveals that there are certain conditions that have to be met in order to enhance its scientific output. These include:

- Reducing experiment preparation time and flight costs. Special 'fast-track' access possibilities need to be created.
- Specific attention should be given to in-orbit sample preparation and analysis.
- Increment planning should allow sufficient flexibility to absorb unforeseen events without necessarily sacrificing experiments.
- Maximising the amount of resources that can be made available to experiments must be the top priority in the planning process.

It is expected that already after the first few Increments, a lot of experience will have been gathered on the real constraints of ISS experiment planning and operations. With time, therefore, the ISS will grow into its role of a flexible, well-equipped, multi-purpose, research laboratory in low Earth orbit.

- *Complementarity with Other Research Opportunities*

Although the ISS will be the platform of choice for most experiments, there will remain a continuing need for other, complementary research platforms. Ground-based research, as has been said before, is an essential ingredient in most research programmes. The use of facilities that simulate microgravity to different degrees, such as clinostats, random-positioning machines, free-fall machines, together with the use of hyper-gravity centrifuges, will be of interest, since they can be used to help tailor and optimise the experimental conditions of the space experiment.

Parabolic flights will continue to be used as a very useful, low-cost preparatory research facility. Drop towers and especially sounding-rocket flights provide additional, very flexible research platforms, which can be used for complete scientific studies, provided that the phenomena occur fast enough. Sounding rockets, together with unmanned retrievable capsules such as the Russian Foton, have undeniable advantages over human missions in that they demand much lower safety standards and are therefore amenable to experiments with more hazardous materials. Then there is the Shuttle, which can provide rapid access to astronauts to obtain biomedical samples directly after the onset of microgravity, which for some studies is essential.

The ISS, on the other hand, offers long-duration microgravity access to a large number of test subjects, advanced facilities and in-orbit analysis facilities. It will also allow for experiment repeats with different parameters, when a first run does not yield the expected results. This will make research on the ISS more comparable to the normal practices used in terrestrial laboratories.

In summary, ESA intends to continue to provide research projects with various types of flight opportunities, tailored to specific schedules and needs.

- *The First Experiments on the ISS*

In recent years, ESA has issued AOs in which the ISS facilities have also been offered. As a result, there now exists a list of approved experiments that will be performed initially on the Space Station. In the period before the Columbus Laboratory is launched, these experiments will be executed under agreements with NASA for the so-called 'Early Utilisation of the ISS'. More details of these arrangements are given in Section 5.2.2

The facilities that are planned to fly in this time frame are the Advanced Protein-Crystallisation Facility (APCF), the European Modular Cultivation System (EMCS), the Matroshka experiment, the Expose facility and the first version of the Material- Science Laboratory (MSL).

The first of these to be delivered to the ISS will be the APCF (reflight; see Table 6.2), presently foreseen for a launch in 2001. The nine experiments planned for this facility are expected to benefit from the much longer time available on the ISS for growing the large-sized protein crystals that are required for X-ray diffraction experiments to unravel their molecular structure.

The European Modular Cultivation System (EMCS) will be launched to the ISS in 2003. The six EMCS experiments presently selected (including two from the USA) are designed to study the effect of gravity and radiation on plants, algae and simple organisms.

Matroshka and Expose will be housed at external locations on the ISS. Matroshka is a human ‘phantom’ model, which will be placed on the outside of the Russian Zvezda module, in 2003. It is intended to allow the radiation doses received at different locations in the human body to be quantified. Expose will be launched in 2004 and will be used for exobiology experiments that study the effects of space conditions (vacuum, radiation, etc.) on spores and other biological substances. Presently, eight experiments from multi-national teams are foreseen.

The first Material-Science Laboratory (MSL-1) will be launched in 2003. The MSL Furnace Facility will have two European and two American exchangeable furnace inserts. Nine experiments have been selected at the present time. They are intended to study both fundamental and application-oriented themes in the solidification of metals and alloys and crystallisation of semiconductors.

In addition to these experiments that are to be performed in ESA facilities, ten ESA experiments in the area of human physiology have been selected for flight during the first years of ISS utilisation. They will be performed in the NASA Human Research Facility (HRF). In co-operating with NASA on the HRF, ESA is contributing the Muscle Atrophy Research and Exercise System (MARES), the Percutaneous Electrical Muscle Stimulator (PEMS), the Hand-Grip Dynamometer (HGD), and a major part of the Pulmonary Function System. These experiments will focus on the effects of gravity on the human body, in particular the cardiovascular system, sensorimotor co-ordination and the muscle system. The findings of these studies are important for the health and functioning of astronauts, but are also very relevant to the understanding of human health problems and diseases on Earth.

- *Future Outlook*

In response to several AOs in the past, a large number of experiments have been proposed. These have been analysed and subjected to peer group review.

As explained earlier, ESA is stimulating specifically application-oriented research. This is done especially within the framework of the Microgravity Application Promotion (MAP) programme. A list of the presently approved MAP Projects, with some details about their objectives and future implementation, is given in the Appendix (Chapter 6.8)

Although European facilities and experiments will be flown during the build-up phase of the ISS, the major European utilisation of the Space Station will only start when the Columbus Laboratory is in orbit. At that point, the four ESA Microgravity Facilities for Columbus, namely the Biolab, Fluid-Science Laboratory (FSL), the second Material-Science Laboratory (MSL-2) and the European Physiology Modules (EPMs), will also be available. In addition, a fifth facility, the European Drawer Rack (EDR), will be available to offer flexible accommodation for smaller payloads that can be exchanged at each Increment.

Since the launch of the Columbus Laboratory is now expected only in late 2004, no specific selection of experiments for those facilities has yet been made. However, several proposals received in response to recent AOs, dealing with both basic and application-oriented research, have asked for the development of new facilities or specific upgrades to existing ones. To give an impression of what can be expected in the future, a few examples will be described below.

Measurement of Thermo-physical Properties
Knowledge of the thermo-physical properties of molten metals is not only of interest from a purely scientific point of view, but also has many practical implications. For the modelling of processes in the casting industry, for example, these data essentially determine the accuracy that can be obtained, and thereby the precision with which these processes can be finely adjusted to maximum effectiveness. Clearly, this is a topic of significant economic impact.

However, it is not easy to measure these parameters. The reason is that many metals only reach their molten state at such elevated temperatures (1500°C or higher) that the material of the crucible in which the sample is held starts to dissolve into the metal, thereby invalidating the measurement. By performing these measurements in space, samples can be heated and processed without a crucible by containing them in an electromagnetic field. In this way, the thermo-physical properties of pure metals can be studied, and in addition very detailed solidification experiments on under-cooled melts can be performed.

Following the receipt of several very-high-quality proposals from teams that include a large number of industrial companies, ESA is now studying the development of an electromagnetic levitation furnace for the Material-Science Laboratory, namely MSL-EML. A more detailed discussion of this topic can be found in Sections 2.3.2. and 5.2.2.

Three-Dimensional Tissue Culturing
A major activity in present-day biotechnology is the study of methods to develop artificial human tissue and organs. Unfortunately, attempts to grow functional tissues from human cells on Earth are limited by the fact that the cells tend to grow only in two dimensions. Therefore, experiments in space have been proposed to study the specific conditions that are important for cellular growth in three dimensions in the absence of gravity. As a first step, an attempt will be made to grow artificial cartilage. If successful, the technique can be extended to determine the specific growth conditions needed for more complex tissue.

Over the past two decades, many experiments have been performed on mammalian cells in space, and therefore the technology needed to grow these cells in space is now well-developed. The next step is to develop a specific Bioreactor for Mammalian Tissue Culture (BMTC). For this, again based on a proposal with some medical companies involved, a study is now being performed. It is the intention that a future BMTC will be developed to be compatible with the European Drawer Rack. More information on the subject of tissue engineering is given in Section 3.2.15.

Foams
Under terrestrial conditions, foams can form as an unwanted by-product in chemical reactions, or as a specifically desired end-result. Both cases are interesting from a theoretical and a practical point of view. The study of foams on Earth is influenced by the fact that the drainage of liquid through foam takes place under the influence of gravity, which creates a natural gradient in wall thickness. In certain cases, this can be a handicap when measuring foam properties. In addition, solidified foam made of molten metal can be a very interesting new material whose properties will be a function of wall thickness. A more detailed discussion of foam physics can be found in Section 2.3.5.

Two MAP proposals, submitted by teams comprising leading industries and specialist university researchers, therefore aim to study foams directly in a space environment. For the foams based on water or organic solvents, a special insert for the Fluid-Science Laboratory is being studied. For foams made of liquid metal, the intention is to develop an insert for the Material-Science Laboratory or the European Drawer Rack.

Equipment for Treating Physiological De-conditioning
It is a well-established fact that astronauts in space experience physiological de-conditioning effects that closely resemble health problems on Earth related to ageing, immobility or disease. Examples are bone mass loss, muscle atrophy, and effects on the cardiovascular, equilibrium and breathing systems. A great number of experiment proposals address these issues. Specific equipment is proposed to arrive at more advanced diagnostic techniques and also to find adequate physical countermeasures.

Presently under development or study are: a portable gas analyser to check lung function, a portable device that monitors several cardiovascular parameters simultaneously, advanced diagnostics of bone structure, and an exercise machine that has proven in preliminary studies to be very effective against these de-conditioning effects.

Since there is clearly a close link between research in space and the eventual clinical application, these proposals are co-ordinated by teams comprising medical doctors and medical companies. Chapter 2.1 gives more information on the subject of space medical research.

Other Equipment Studies
Additional studies are being performed on possible inserts for the EDR, FSL or MSL. The present list includes:

- a facility to study interactions in cosmic and atmospheric particle systems
- a microgravity plasma facility
- a facility for thermal-transport phenomena in magnetic fluids
- a facility for diffusion and Soret coefficient measurements
- an insert for space combustion research (for inclusion in the NASA Combustion Facility)
- a facility for the study of emulsions
- an insert to study geophysical flows
- a small-rodent research facility
- a facility to study life-support systems.

It is to be expected that even more studies will be initiated following future Announcements of Opportunity. Of course, this does not imply that all of these studies will eventually lead to development and flight. However, it is already evident that the ISS and its facilities will allow for the flexible accommodation of the research needs of the user community both now and in the future.

5.2 Major ESA Microgravity Facilities for the ISS

G. Seibert

5.2.1 Introduction

At the end of 1998, the first two elements of the International Space Station, 'Zarya' and 'Unity', were launched and subsequently joined together in space. The third ISS element, the Russian service module 'Zvezda' (star), was launched on 12 July 2000 and later docked with the Zarya-Unity complex. Zvezda not only provides for the first human habitation of the ISS, but it also accommodates the two European experiments:

- the Global Transmission System (GTS), which broadcasts accurate timing and data signals to multiple users on Earth, and
- a German Plasma Krystall Experiment (PKE, see Section 2.3.8).

Furthermore, within the framework of a bi-lateral agreement between the Russian Space Agency and ESA, the 'Matroshka' radiation experiment will be accommodated on Zvezda in the early-2003 time frame.

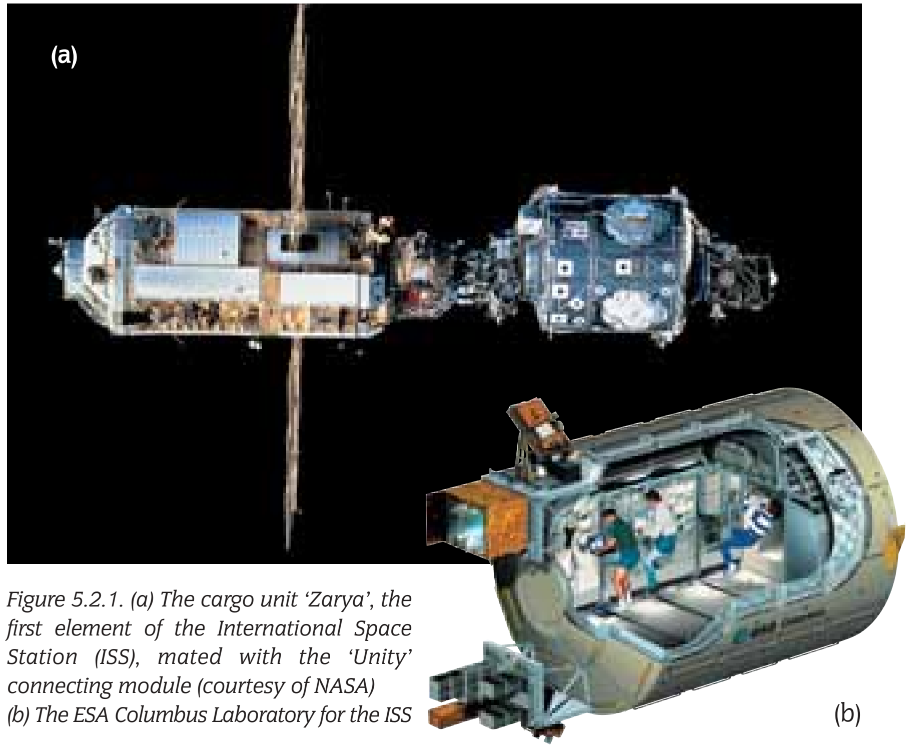

Figure 5.2.1. (a) The cargo unit 'Zarya', the first element of the International Space Station (ISS), mated with the 'Unity' connecting module (courtesy of NASA)
(b) The ESA Columbus Laboratory for the ISS

As mentioned in Section 5.1, prior to the launch of the Columbus Laboratory, a number of other ESA-selected early European experiments/facilities will be accommodated on the ISS, either in the US Laboratory as from 2001 or on the external viewing platforms.

- *ESA Research Facilities in the US Laboratory*

The facilities to be located in the US Laboratory are in most cases follow-on developments of EMIR-1 equipment, such as the Muscle Atrophy Research and Exercise System (MARES), PEMS-2 (a muscle stimulator device), a Hand-Grip and Pinch-Force Dynamometer (HGD-PFD) and the European Modular Cultivation System (EMCS) for plant research. All of these life-sciences facilities will be described briefly below.

In addition, the first facility of the Materials-Science Laboratory (MSL), including the ESA Solidification and Quenching Furnace (SQF) and the Low-Gradient Furnace (LGF) as inserts, will be accommodated for two years in this US Laboratory.

- *ESA Payloads on the External Platform of the ISS*

These will include payloads from the fields of space science (payloads 'Solar' and 'Sport'), Earth Observation (planned payload: Focus, an intelligent Fire Detection and Characterisation Infrared Sensor System) and Technology (payload: EUTEF, a European Technology Exposure Facility). There will also be two payloads that have been selected by ESA for external accommodation, from the areas of life sciences and physical sciences. These are:

- Expose, a Sun-pointing exposure platform for exobiology experiments
- ACES, a microgravity 'Atomic Clock Ensemble in Space' payload, the core of which is a laser-cooled caesium atomic clock.

Both Expose and ACES are briefly described below.

- *European Payloads in the Columbus Laboratory*

By far the most important of the ESA contributions for the utilisation of the ISS by European scientists are the Microgravity Facilities for Columbus (MFC), i.e. Biolab, the Fluid-Science Laboratory, the European Physiology Modules (EPMs), and the Material-Science Laboratory (MSL). The second MSL facility, an Electro-Magnetic Levitation heating facility (MSL-EML), will be accommodated in the Columbus Laboratory.

In addition to the MFC laboratories, the European Drawer Rack (EDR) is also planned to be permanently accommodated in the Columbus Laboratory. It provides the infrastructure for four standardised experiment drawers and four standardised ISS lockers (MDLs). Both can be exchanged in orbit. The EDR is not dedicated to a specific discipline. It offers a quick turnaround and thereby increased flight opportunities for the microgravity user community. A typical EDR payload, the ESA Protein-Crystallisation Diagnostics Facility (PCDF), is described below.

Table 5.2.1 provides a summary of the main European facilities to be provided for the ISS, their locations, start of operations, and the main areas of research for each facility.

Table 5.2.1 European Life- and Physical-Sciences Facilities on the ISS

Experiment Facilities	**Research Area**	**Location on ISS**	**Ops. Begin**	**Funding Programme**	**Comments**
Biolab	Cell and developmental biology, biotechnology	Columbus Laboratory	2005	MFC	Microgravity Facilities for Columbus (MFC)
Fluid-Science Lab. (FPM)	Fluid dynamics, capillarity, phase transitions, critical-point phenomena, bubble physics	Columbus Laboratory	2005	MFC	
Materials-Science Lab.-1 (MSL-1)	Solidification physics, diffusion, crystal growth	Columbus Laboratory	2005	MFC	Furnace inserts: 2 from ESA, 2 from NASA, 1 from DLR
Materials-Science Lab.-2 (MSL-2)	Electro-Magnetic Levitation Furnace, to study nucleation, metastable phases, thermo-physics properties	Columbus Laboratory	2006	MFC & DLR	An ESA–DLR co-operation, MSL-2 will be the first exchange of a large Columbus facility
European Physiology Modules (EPMs)	Human physiology, muscles, bone, cardiovascular, neurology, vestibular, fluid regulation	Columbus Laboratory	2005	MFC	Modules are supplied by ESA, Germany, Denmark, France and Italy
Protein-Crystal. Diagnostic Facility (PCDF)	Study of nucleation and growth of protein crystals, using various optical diagnostic systems	Columbus Laboratory	2005	EMIR-2	The PCDF is the first payload located in the European Drawer Rack
European Drawer Rack (EDR)	Accommodates sequentially, life- and physical-sciences payloads, e.g. the PCDF, MTCS, MAPs, etc.	Columbus Laboratory	2005	Columbus Utilisation	Payload from EMIR-2 Prog. and future life/physical-sci. and appl. programmes
Biotechnol. Mammalian Tissue Cult. Facility (BTMC)	Cell and tissue growth and differentiation	Columbus Laboratory	2006	Future life-sci. and phys. sci. programmes	European Drawer Rack payload for tissue engineering
European Mod. Cultiv. System (EMCS)	Multi-generation studies in plants and fungi, and the study of gravity perception	US Laboratory	2003	EMIR-2	Containers are larger than in Biolab, to facilitate growth studies

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5.2.2 ESA Microgravity Facilities in the Columbus Laboratory

The programmatic aspects of the ESA Microgravity Facilities for Columbus (MFC) Programme approved in 1995 are described in Section 4.2.4. The major experimental facilities being developed within that MFC programme for accommodation in the Space Station are discussed here, together with the characteristics of the Protein-Crystallisation Diagnostics Facility (part of the EMIR-2 Programme).

Table 5.2.1 European Life- and Physical-Sciences Facilities on the ISS (cont'd)...

Experiment Facilities	**Research Area**	**Location on ISS**	**Ops. Begin**	**Funding Programme**	**Comments**
Photoacoustic Analyser Module (PAM)	The PAM and PFM are part of the Pulmonary Function	US Laboratory	2002	MFC	The Pulmonary Function System will be accommodated in the NASA Human Research Facility
Pulmonary-Function Module (PFM)	The Pulmonary Function System was developed in co-operation with NASA for studies of lung and cardiovascular behaviour	US Laboratory	2002	MFC	
Muscle Atrophy Res. and Exercise Syst. (MARES)	Muscle, skeletal and biomechanical studies	US Laboratory	2002	EMIR-2	An ESA contribution to the NASA Human Research Facility
Percut. Elec. Muscle Stimulator (PEMS)	Neuro-muscular research, in association with the Muscle Atrophy Research System	US Laboratory	2002	EMIR-2	An ESA contribution to the NASA Human Research Facility
Handgrip & Pinch-Force Dynamometers	Muscle atrophy in the hand and fingers. Stressor for the cardiovascular system	US Laboratory	2001	EMIR-2	Used also in NASA's crew health-care system
'Matroshka'	Space-radiation depth-dose measurement in human model	Exterior of Zvezda	2003	EMIR-2	Simulation of human tissue
Atomic Clock Ensemble in Space (ACES)	ACES is a laser-cooled caesium clock, with an H-maser reference clock	ISS External Platform or Columbus Platform	2004	Columbus Utilisation and CNES	ESA-CNES co-operation Switzerland provides H-maser clock. GPS improvement in microgravity
'Expose'	Exobiology. Effects of the space environment on organisms	ISS External Platform or Columbus Platform	2004	EMIR-2	Survival of organisms in interplanetary space

In the early 1990s, the MFC Programme, as then proposed, comprised a large number of facilities, consistent with the technical envelope for Columbus as it existed at that time. It consisted still of a 12.8 m-long pressurised laboratory, originally called the APM (Attached Pressurised Laboratory, later renamed the Columbus Orbital Facility (COF), and today called the Columbus Laboratory). In addition there was the Columbus Man-Tended Free-Flyer (MTFF).

The ESA Member States eventually demanded that the cost of the Columbus development programme – and with it also the cost of European participation in the ISS exploitation phase (planned to last for 15 years after the completion of ISS assembly) – be substantially reduced. Consequently, plans for the MTFF were cancelled and the Columbus Laboratory reduced to half of its original design length, i.e. from 12.8 to 6.4 m. In addition, the NASA/ESA ISS Memorandum of Understanding determined that only 51% of the outfitting and use of the Columbus Laboratory was to be allocated to Europe, an agreement that was in line with the value of the European contribution to the ISS. This corresponds to 8.3% of the 'western' part of the ISS, or 5.6% of the overall ISS.

A further modification to the ESA Columbus Programme's content was the inclusion of a Robotic Arm and of the Automated Transfer Vehicle (to be launched about once per year by an Ariane-5). This further contribution was introduced in order for ESA to participate in the ISS logistic activities. A further important objective of this move was to provide what is principally a hardware contribution to the ISS exploitation phase, thereby minimising or totally avoiding European cash payments to NASA during that phase.

This major reduction in the size of the ESA laboratory and the allocation of almost half of the effective volume to NASA meant that only five International Standard Payload Racks (ISPRs) would be available for European utilisation in the Columbus Laboratory, after allowing for the racks needed for system requirements. Of these five racks, at least one was needed for storage.

Lengthy discussions ensued with the European microgravity user community on the full implications of this drastically reduced utilisation capability. There was clearly a minimum need for four multi-user facilities, in order to cater for the four major microgravity disciplines of biology, human physiology, fluid physics and materials science. The real problems, however, lay in the details of the types of equipment that should go into each of these four facilities, and the timetable for their deployment. Eventually, the following recommendation regarding the initial outfitting of the Columbus Laboratory and the technical content of the MFC Programme was agreed upon:
Of the five ISPR racks (four lateral, one on the ceiling) available for Europe in the Columbus Laboratory, three were to be used for the Biolab, the Fluid-Science Laboratory (FSL) and the European Physiology Modules (EPMs). The remaining position would be used for a European Drawer Rack (EDR). This was designed for the accommodation of smaller, quick-turnaround experiments. The fifth ISPR was planned as a European Stowage Rack (ESR), for the storage of experiment containers, samples/specimens and payload-support equipment.

This arrangement was only acceptable because ESA had negotiated with NASA that the first ESA Materials-Science Laboratory (MSL-1) would be accommodated for two years in the NASA Materials-Science Research Rack (MSRR-1) in the US Laboratory of the ISS. That provided earlier access to space experimentation for the European materials scientists, since the MSRR-1 comes into operation some two years before the launch of Columbus. It also reduced the pressure on accommodation in the Columbus Laboratory. Under this agreement, NASA would bear the transportation and operations costs, in return for a 50% NASA usage of this first element of the planned ESA MSL. In addition, this preliminary ESA/NASA agreement allowed access for European Principal Investigators to the NASA-developed furnaces, i.e. within the 50% technical resources allocated to the ESA MSL for ESA usage.

Regarding the distribution of facility-development tasks, it was decided that the main scientific facilities, the Biolab, FSL, EPM and MSL (consisting of two furnace facilities) would be part of the Microgravity Facilities for Columbus Programme, whereas the development of the European Drawer Rack and the European Storage Rack would be covered by the utilisation-preparation part of the Columbus Programme.

The four facilities designed and built under the Microgravity Facilities for Columbus (MFC) Programme are:

- *Biolab*

The technical configuration of the Biolab, intended to carry out research in fundamental and applied biology, is based upon the pioneering experiments performed by European and US scientists using the ESA Biorack on Spacelab (and later on Spacehab). It has been elaborated in consultation with the relevant science community (Facility Science Team) and within the framework of pre-Phase-A and Phase-A design studies in industry. Taking into account the low level of crew time that was to be available on the ISS for payload operations, the Biolab had to operate in a highly automated mode, despite the fact that automated facilities have very much higher development costs. The compromise concept found for Biolab was that it would operate automatically only after manual loading of the biological specimens, such as small plants, cell cultures, micro-organisms, insects, and small aquatic systems. Also, the operations within the Bioglovebox are to be performed manually.

In the presently developed Biolab, the biological specimens will be contained in standard experiment containers, which can be accommodated in the incubator on a

Figure 5.2.2. The ESA 'Biolab' multi-user facility for biological research. The loading of samples and operations in the Bioglovebox are conducted by a crew member. Thereafter, the experiments are performed automatically, with the possibility of remote guidance/ intervention from a ground-based scientist

1g centrifuge (there are two of these in Biolab). Both 1g centrifuges are installed in the incubator to enable simultaneous operation in microgravity (i.e. one centrifuge not running) and under 1g conditions. This allows the same experiment to be performed simultaneously in 1g and in microgravity conditions, under identical environmental conditions in other respects, for comparison purposes.

An Experiment Preparation Unit installed in the Bioglovebox enables controlled thawing of those specimens transported into orbit in a frozen state. Biolab's major diagnostic instruments are a microscope and a spectrophotometer, to which the biological specimens are moved with the help of a handling mechanism. A telescience capability allows the Principal Investigators on the ground to follow and interact with the diagnostic operations. The Bioglovebox, a follow-on development of the Biorack's glovebox, provides for both further diagnostic work and also manual liquid-handling and fixation. There are two cooler systems for specimen preservation. There is also the possibility to store the biological specimens in a separate – 80°C freezer (called MELFI) using small vials. These are manually transported between MELFI and Biolab.

- *Fluid-Science Laboratory (FSL)*

Figure 5.2.3. The ESA Fluid-Science Laboratory, to be located in the Columbus Laboratory

Studies in fluid dynamics under microgravity conditions have provided an important means for testing the theories that describe three-dimensional laminar, oscillatory and turbulent flows generated by forces other than gravity, such as surface tension. The absence of fluid static pressure, together with the lack of gravity-driven convection, provides optimal conditions for the investigation of capillarity phenomena, phase transitions and critical-point phenomena. The investigations include condensation studies and bubble formation, growth and motion experiments.

In order to continue and to extend this type of research, the fluid-science community requested the development of a Fluid-Science Laboratory (FSL) for the Space-Station era. In the past, such research had been supported by the Spacelab multi-user facilities, known as the Advanced Fluid-Physics Module (AFPM) and the Bubble, Drop and Particle Unit (BDPU).

Following the establishment of the scientific priorities recommended by ESA's Microgravity Advisory Committee, the technical requirements for the FSL were defined by a Facility Science Team. They were elaborated in pre-Phase-A and Phase-A studies in industry, which finally led to the current FSL hardware-development phase.

The FSL consists of a core Central Experiment Module, into which the experiment containers are sequentially inserted and operated, together with an Optical Diagnostics Module (ODM). All functional subsystems are accommodated around these two core elements.

The ODM's optical diagnostic equipment provides for:

- visual observation (photographic and electronic imaging) in two axes, with a variety of illumination options
- interferometry in two axes by convertible interferometers, such as holographic-, Wollaston/shearing-, speckle pattern interferometers and a Schlieren mode combined with shearing
- infrared thermographic mapping of free surfaces
- particle image velocimetry.

For each experiment category, dedicated Experiment Containers will be developed, with standardised interfaces. These containers are inserted manually by the crew into the Central Experiment Module. They accommodate the experimental fluid and additional experiment specific diagnostics. The FSL has a full telescience capability, which allows the operating mode to be changed from the ground (in addition to the possibility of interaction by the flight crew). However, fully automatic experiment processing is planned to be the routine operating mode.

- *European Physiology Modules (EPMs)*

The scientific priorities in the field of human physiology for the Space-Station era were defined by the ESA Microgravity Advisory Committee/Life-Sciences Working Group in 1994. They included research topics such as bone remodelling and demineralisation, muscle degradation, blood pressure and volume regulation, blood components and fluid/electrolyte regulation, lung ventilation and perfusion and the human sensory and balance system.

During the Spacelab era, human-physiology research was performed with the help of the large multi-user facilities Anthrorack, Sled, and the Torque Velocity Dynamometer, together with the experiment-specific equipment. In the context of ESA's Euromir mission and the Mir missions of certain ESA Member States, a number of physiology subdiscipline-dedicated instruments were developed. ESA developed a Bone Densitometer and a second-generation Respiratory Monitoring System. ESA's Member States developed Medex (DLR) and Physiolab (CNES) for cardiovascular research, and Elite (ASI) and Kinelite (CNES) for the quantitative analysis of human kinematics in microgravity.

After taking account of the scientific priorities established by the advisory groups and the past results of space human-physiology experiments, the ESA EPM Facility Science Team defined the EPM's technical content.

Contrary to the technical layout of the other MFC facilities, the EPM is not a single large multi-user facility. Rather, it is composed of a number (up to nine) of exchangeable Science Modules (SMs), plus the facility infrastructure needed to support their coordinated operation. These Modules are accommodated in two types of standard-rack container.

Figure 5.2.4. The European Physiology Modules, to be located in the ESA Columbus Laboratory. The NASA Human Research Facility will be co-located there to allow combined experimentation

Based upon the recommendations of the EPM Facility Science Team, the initial EPM configuration consists of the following Science Modules:

- *Multi-Electrode EEG Measurement Module (MEEMM)*
  This module provides facilities for non-invasive research into brain functions. Up to 128 electrodes can be placed on the subject's head and various stimuli and stressors (e.g. muscle stimulators) introduced. In combination with another science module, the Elite-S2, simultaneous measurements of body movements and brain activity can be performed. The MEEMM will also take measurements during sleep or other bodily activities.

- *Elite-S2*
  This science module is an ASI/CNES contribution. It is a follow-on development of the Elite equipment originally developed by ASI for experiments on Mir and of the Kinelite equipment developed by CNES for experiments on the Space Shuttle. It enables quantitative analysis of human kinematics in microgravity, by applying four cameras for 3D-photogrammatic measurements of crew movements.

– *Xenon Skin Blood-Flow Measurement Instrument and Physiological-Pressure Measurement Instrument*
These two instruments, contributed by the Danish space authorities, will be used to measure skin blood flow and physiological pressures, such as the central venous and oesophageal pressures.

– *Cardiolab*
The Cardiolab is a follow-on development of the French Physiolab and the German Medex. A joint contribution by CNES/DLR, it comprises various equipment elements to support cardiovascular research and the health of astronauts on short- and long-term flights, and it provides the means for operational medicine/prevention and diagnostics. The research objectives are fluid-volume regulation, haemodynamics and surveillance of the main organs in the thorax/abdominal region.

– *Bone-Analysis Module (BAM)*
The BAM enables an evaluation of the efficiency of countermeasures against bone demineralisation, bone loss and deterioration in microgravity to be carried out. It is derived from the Bone Densitometer developed for and flown by ESA on the Euromir ’95 mission. It measures ultrasound transmission delays and broadband ultrasound attenuation in weight-bearing bones.

– *Sample-Collection Kit*
This is similar to the blood, urine and saliva kits flown on the Euromir missions. It allows the collection of samples of body fluids in a controlled environment, for later transport to the ground for analysis. The kit includes waste-management utilities for the disposal of bio-hazards or sharp items.

- *Materials-Science Laboratory (MSL)*

As already explained in the Introduction (Section 5.2.1), the first of the two MSL facilities, with associated infrastructure, will initially be accommodated for two years in NASA’s US Laboratory, from 2003. Thereafter, it will be located in the Columbus Laboratory.

This first MSL facility will be able to accommodate:
- the ESA Solidification and Quenching Furnace (SQF)
- the ESA Low-Gradient Furnace (LGF)
- the NASA Quench-Module Insert (QMI) and Diffusion-Module Insert (DMI).

The decision to develop the SQF and the LGF within the framework of the MFC Programme was based upon the recommendation of the European material-science community and the results of the seven Phase-A studies that were performed with the help of European industry.

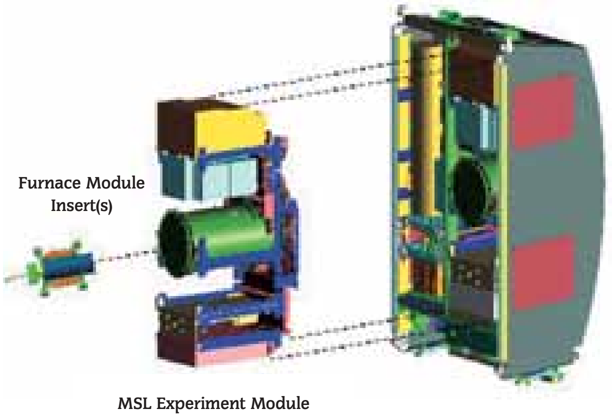

Figure 5.2.5. The ESA Solidification and Quenching Furnace and Low-Gradient Furnace, which are the first two components of the ESA Materials-Science Laboratory

A Science Team addressing materials-science furnaces for the ISS had initially defined the following seven furnaces, for which design and cost studies (Phase-A) were performed by industry:

– High-Precision Furnace	HPF
– Solidification and Quenching Furnace	SQF
– Materials-Processing Furnace	MPF
– Bridgman High-Temperature Furnace	BHF
– Gradient-Freeze Furnace	GFF
– Zone-Melting Furnace	ZMF
– Floating-Zone Facility	FZF.

The Science Team concluded, following a special Workshop, that the Gradient-Freeze Furnace should have the highest priority. However, this was recommended on condition that European materials scientists would be allowed to utilise the other furnace types that were to be developed by NASA and the Japanese space authorities. Unfortunately, such a commitment could not be obtained from NASA and the Japanese Space Agency at that time. Furthermore, the industrial study of the GFF showed that it resulted in the highest risk in terms of meeting the very exacting technical requirements set for it. The Science Team therefore agreed to the compromise of two furnace inserts (SQF and LGF), but a single furnace infrastructure, and the option of further insert developments by national space authorities. Also, NASA had a preference for the Solidification and Quenching Furnace.

The MSL Science Team defined the stimuli/diagnostics measurements for the SQF as follows:
- measurement of supercooling by the Seebeck effect
- phase-boundary demarcation by the Peltier effect
- solidification-front position and planarity to be evaluated by an ultrasound device
- various temperature measurements.

In addition, the furnace should move and the cartridge should be fixed. The displacement rate was selectable over four orders of magnitude. Also, an accelerometer to be accommodated near to the furnace was requested.

The major characteristics for the Low-Gradient Furnace (LGF) were defined as the short-term temperature stability (±0.01 K) and the drift. The stimuli and diagnostic requirements were similar to those of the SQF. Furthermore, a rotating magnetic field, variable in strength up to about 20 mTesla, was made a performance requirement for the LGF.

In addition to these two furnace inserts, which form the first element of the Materials-Science Laboratory, a further insert is under development by DLR, namely a floating-zone furnace with a rotating magnetic field.

The SQF is optimised for solidification experiments requiring large thermal gradients and fast sample quenching. The latter is realised by coupling the experiment cartridge via a liquid-metal sleeve to the water-cooled zone of the furnace. The LGF is optimised for crystal-growth experiments using the Bridgman technique.

The SQF and the LGF will operate at temperatures of up to 1550°C. The required temperature stability and uniformity of heating for these two furnaces are at the limit of the associated technology. The diagnostics (Seebeck voltage measurement, Peltier and thermocouples) and the stimuli are accommodated in the facility infrastructure and are thus independent of the choice of furnace insert.

- *Electro-Magnetic Levitation Furnace (MSL-EML)*

This is the second facility in the Materials-Science Laboratory and is a follow-on development of the German Tempus levitation facility. Tempus has been flown on three Spacelab missions: IML-2, MSL-1, and MSL-1R. The two main objectives of the MSL-EML facility are the following (see Section 2.3.2 also):

– Measurement of the thermo-physical properties of industrial alloys, to the high accuracy needed as input to calculations intended to improve casting processes. On Earth, those measurements are not sufficiently accurate, because most metallic melts become chemically aggressive at their melt temperature and react with crucible materials. In microgravity, greatly reduced electromagnetic forces can be used for levitation control in containerless conditions, allowing a large extension of the temperature range of the measurements and a reduction in impurity effects.
– Generation of new metallic glasses by strong under-cooling below the melting temperature, without the immediate start of solidification. Since there is no contact between the melt and container walls, heterogeneous nucleation is avoided. Crystallisation is therefore avoided and the solidification is delayed. Amorphous forms of metallic glass are obtained, with novel technical properties.

A more fundamental objective of experimentation with the MSL-EML is the general study of metastable states and phases, mainly:
– under-cooling, nucleation kinetics and non-equilibrium solidification
– nucleation and growth of metastable crystalline phases

The use of electromagnetic levitation in the terrestrial laboratory is limited because of the high levitation fields needed to counteract the gravity fields. On Earth, this type of levitation requires high power absorption by the sample, which is accompanied by strong heating. This limits its application to high melting alloys and refractory metals. In space, the positioning forces to compensate disturbing accelerations are about three orders of magnitude smaller. This enables the performance in space of new classes of experiments that involve slow under-cooling without heterogenous nucleation. On Earth, it is necessary to use very rapid cooling (quenching) in order to bypass the undesired heterogeneous nucleation kinetically. This quenching alternative is not, however, suitable for the production of bulk material in a metastable state.

The MSL-EML facility, presently under co-operative ESA-DLR Phase-A/B study, is largely based upon the MSL-SFQ/LGF for all supporting functions (power, data handling, etc). The main difference is that the SQF and LGF inserts are replaced by the EML system, with its dedicated electronics and video system.

The samples to be processed are contained in exchangeable experiment containers, i.e. each container magazine groups together 15 samples with comparable properties and process requirements. During processing, the samples can be viewed via the video system. The MSL-EML rack also houses the peripheral infrastructure elements, such as pyrometers, vacuum pumps and cooling modules.

Levitation of the samples is performed in oscillating magnetic fields that produce eddy currents within the samples. In MSL-EML (as in Tempus), a quadrupole field for positioning and a dipole field for heating are superimposed in a coil system. Sample temperatures and solidification speeds are measured by three-colour pyrometry. Video cameras control the positioning and permit the measurement of surface tension and viscosity from the sample oscillations. In the Phase-A/B study of MSL-EML, DLR is concentrating (via a contract with the industrial developers of the Tempus facility) on the design and breadboarding of the automatic experiment-exchange chamber.

- *European Drawer Rack (EDR)*

In addition to the four main facilities described above, ESA will be outfitting the Columbus Laboratory with a rack designed principally for stowage, together with a Drawer Rack. The latter is designed to accommodate three standard experiment drawers (8 panel units, 73 litres, 48 kg net user mass) and four standardised Shuttle-type (57 litres, 28 kg net user mass) ISS lockers, all of which can be exchanged whilst in orbit. The intention is to provide a facility that allows quick-turnaround experiments to be performed within a standardised accommodation package. One of the items to be located in the EDR is a facility designed for the study of the growth of protein crystals:

- *Protein-Crystallisation Diagnostics Facility (PCDF)*

Since the first successful European attempts to crystallise biological macromolecules (of which proteins are one type) on sounding rockets, and later in 1983 on the Spacelab-1 mission, some 400 protein crystal-growth experiments have been performed under microgravity conditions by European scientists, and some 4000 by US scientists. Protein crystals of high structural perfection are needed in order that X-ray diffraction may be used successfully to reveal the structures of these macromolecules. Once the detailed structure is unravelled, it then becomes possible to understand their function. On Earth, proteins often either do not crystallise or, if they do, they fail to achieve sufficient structural perfection to allow successful X-ray diffraction analysis.

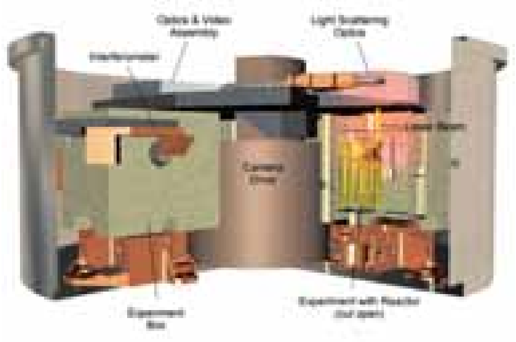

Figure 5.2.6. The ESA Protein-Crystallisation Diagnostics Facility, designed for the detailed study of macromolecule crystallisation and to provide high-quality crystals for subsequent X-ray analysis (courtesy of Astrium/DASA)

European protein-crystallisation experiments in microgravity conditions have mostly been performed with the ESA Advanced Protein-Crystallisation Facility (APCF). This was a very reliable facility, but it only allowed 'blind' experiments, in which the initial conditions and the final results (when returned to Earth) are known. Only about 25% of the space experiments yielded larger and more perfect crystals than those grown on Earth. Interestingly, some displayed a different morphology to those grown under 1g conditions. Why only a fraction of the space-grown crystals were better and indeed resulted in improved structural analysis is not known. Hence, the science community involved requested that a new facility, the Protein-Crystallisation Diagnostics Facility, be built for use on the Space Station.

The PCDF is presently under development as part of the EMIR-2 Programme. It will allow observation and study of the actual crystallisation process of proteins over long periods in orbit, using advanced diagnostic instruments such as video microscopy, dynamic light scattering and Mach-Zehnder interferometry. It is planned to accommodate the PCDF in the European Drawer Rack on Columbus.

Since biological macromolecules, including proteins, nucleic acids, viruses, etc., are of the utmost importance for living systems, progress in this field is of the highest interest for basic research and for the pharmaceutical, medical and nutrition industries. Space research in this field has the potential to yield scientific breakthroughs if, for example, proteins can be crystallised under microgravity conditions that do not crystallise on Earth.

5.2.3 ESA Facilities and Equipment in the US Laboratory

The co-operative design, development, operation, utilisation and management of the ISS is based on an Intergovernmental Agreement (IGA) between the five ISS Partners – the USA, Russia, Japan, Canada and Europe (11 ESA Member States) – concluded in January 1998, and on a NASA-ESA Memorandum of Understanding (MOU). These top-level legal agreements define the objectives and technical capabilities, and also the rules of operation and utilisation of the ISS. These rules spell out that the utilisation rights of ISS Partners start with the launch of their hardware contributions. Since the European decision to participate in this programme was taken very late, the launch of the Columbus Laboratory was put at the end of the ISS assembly sequence. This means that European utilisation rights start only in late 2004, after the launch of the Columbus Laboratory.

In order to compensate, to a certain extent, for this disadvantage for the European space user community, ESA has concluded a bi-lateral 'no-exchange of funds' agreement with NASA. This permits ESA to participate with some experimental equipment and experiments in the so-called 'Early Utilisation' (i.e. in the limited utilisation during the ISS build-up phase) in the US Laboratory and in the use of the Station's external platforms. This bi-lateral agreement is partly based upon scientific co-operation in ESA experimental hardware, for joint ESA/NASA use in the US Laboratory, as discussed below. It is also based upon the delivery by ESA of Laboratory Support Equipment, i.e. the Microgravity Science Glovebox (MSG), the MELFI –80°C freezer, and the Hexapod pointing platform for external experiments (Fig. 5.2.7), to NASA. In exchange, ESA has also been granted experiment accommodation on the ISS's external Truss structure, as discussed in Section 5.2.4. The LSE barter agreement was later extended to give ESA 8.3% of the MSG and MELFI utilisation rights in return for the extension of MSG's technical capabilities.

Figure 5.2.7. ESA Laboratory Support Equipment: the Glove Box, – 80°C Freezer, and Hexapod instrument-pointing platform

- *ESA Life-Sciences Equipment*

The equipment that has been developed for joint use by ESA and NASA includes the following:

Muscle-Atrophy Research and Exercise System (MARES)
The MARES facility is a follow-on development of the Spacelab Torque-Velocity Dynamometer (TVD) facility flown on the LMS Spacelab mission in 1996. For the International Space Station, ESA is seeking to develop a new muscle-research instrument that should allow the investigation of atrophy in isolated muscle groups in the trunk, in joints at the limb extremities, and in complete limbs.

MARES will be used to carry out research on muscle-skeletal, biomechanical, neuromuscular and neurological physiology, to study the effect of microgravity on the human being, and to evaluate the effect of countermeasures to microgravity-induced physiological effects. MARES can therefore be used to evaluate the efficiency of exercise protocols. It enables measurement of the strength of isolated muscle groups around joints or complete limbs by controlling and measuring the inter-relationship between position/velocity and torque/force as a function of time. Torque and angular position/velocity measurements and training are supported for the following joint movements: flexure/extension of the knee, ankle, trunk, hip, shoulder, elbow and wrist. It also supports force and linear-position/velocity measurements and training for multi-joint linear movements, including whole-arm and whole-leg linear presses. MARES is able to support exercise motions/profiles in the isometric, isokinetic (concentric and eccentric) and isotonic (also concentric and eccentric) modes. It is a large aisle-mounted facility, which has a mass of some 200 kg.

Figure 5.2.8. The Muscle-Atrophy Research and Exercise System (MARES)

NASA is very interested in MARES's capabilities and has offered to fly it as part of the NASA Human Research Facility, located initially within the US Laboratory Module. Launch is planned for June 2002, in conjunction with the Multi-Purpose Logistics Module.

Percutaneous Electrical Muscle Stimulator (PEMS)
PEMS is a muscle-stimulator device that was originally developed by ESA for the LMS Spacelab mission, where it was used in combination with the Torque-Velocity Dynamometer, the predecessor of the MARES facility. For the ISS, an improved version called PEMS II, with a mass of about 10 kg, is presently under development. It will also form part of the NASA Human Research Facility.

PEMS II will support human neuro-muscular research in space by eliciting muscle contraction, using electrodes on the skin. It will permit direct activation of the skeletal muscles, bypassing the central nervous system's control. Applying this PEMS mode of stimuli, it is possible to study changes in muscle function independently of neural-control changes. By applying repeated contractions with PEMS, in combination with a dynamometer like MARES, force-frequency curves, fatigue ability, and the force-length and force-velocity characteristics of muscle capacity can be obtained. PEMS allows the stimulation of single muscles (e.g. the adductor pollicis) as well as entire muscle groups (e.g. the triceps surae), in combination with MARES.

As a stand-alone instrument, PEMS enables countermeasure protocols of precise intensity, frequency and duration to be applied, with the objective of preventing muscle atrophy under microgravity conditions. By evaluating muscle functions, PEMS will also be used to judge the efficiency of such countermeasures against the deconditioning induced by the microgravity environment.

PEMS produces square waves of constant-current stimuli, with a negative post-stimulus lag to ensure charge neutrality. It is programmable to produce sequences of pulse trains spaced by selectable intervals. The number of pulses in a given pulse train, their duration, amplitude and repetition rate are freely selectable. This complete pre-defined sequence of pulse trains, selected by the medical experts monitoring the health of astronauts in orbit, is called the 'PEMS protocol'.

Hand-Grip Dynamometer and Pinch-Force Dynamometer (HGD-PFD)
This device was originally developed by ESA for the LMS Spacelab mission. A rebuilt instrument was handed over by ESA to NASA in February 2000 for use in the Space Station as the first ESA contribution to the Human Research Facility. It will help in evaluating the muscle atrophy in the hands and fingers caused by weightlessness. It will also be used for isometric exercising of the hand muscles and as a stressor for the astronaut's cardiovascular system. Launch of the HGD-PFD is currently planned for April 2001, but it might be used earlier as part of the ISS Crew Health-Care System. In particular, it could be used to evaluate the hand strength of astronauts involved in Extra-Vehicular Activities (EVAs).

European Modular Cultivation System (EMCS)
The EMCS and Biolab are complementary ESA biological research facilities. The EMCS will be launched in 2003 in the US Laboratory, where it will operate for a minimum of two years. Biolab, on the other hand, will be launched as part of the initial outfitting of the Columbus Laboratory in late 2004.
Both facilities support research that continues and extends the biological experiments performed using Biorack on six Spacelab/Spacehab missions, including research on protoplasts, fungi, callus cultures, algae and seedlings.

In order to provide a better-defined environment for plants, both facilities are equipped with a dedicated life-support system. This provides a closed atmospheric environment, with concentration and pressure control for O_2, CO_2 and N_2 and with ethylene-pollutant removal. Humidity, temperature and illumination are also actively controlled.

Figure 5.2.9. The European Modular Cultivation System (courtesy of Astrium/ DASA)

Both facilities use standard experiment containers installed on two centrifuges of 0.6 m diameter. These provide controlled accelerations that range between 10^{-3} g and 2g, for g-response threshold measurements. However, the EMCS experiment containers are considerably taller (160 mm) than those of Biolab (60 mm), allowing research on larger specimens of fungi, mosses and vascular plants. Planned experiments with this cultivation system on the ISS include multi-generation seed-to-seed studies, studies on the influence of gravity on plant development and growth, and g-threshold measurements, as well as experiments on perception and signal transduction in plant tropism.

There are two moveable zoom video cameras on each of the two EMCS centrifuges, which can be used both for high-resolution observation and down-linking of the pictures for remote analysis.

Within the US Laboratory, the EMCS will occupy the space of four adjacent lockers in the NASA Express Rack. The long-term continuous operations that will be possible will give a new dimension to this type of experimentation and considerably broaden plant research under microgravity conditions.

Biotechnology Mammalian Tissue Culture Facility
This facility, designed for cell and tissue-culturing research, will be developed by ESA as part of its future life- and physical-sciences programme. The primary scientific interest is in studying the influence of the cell micro-environment on cell growth and differentiation. The core of the system will allow concentration gradients and mechanical forces to be controlled using fluid-distribution tools, micro-sensors and micro-actuators. The emphasis will be on mimicking organo-typical conditions and on the acquisition of data to be used for guided tissue development and differentiation under both space and terrestrial conditions. In addition to this core cultivation sub-unit, a diagnostic system allows the use of dedicated tools adapted to the particular tissue undergoing testing.

The facility is a modular system, composed of three main components:
- An Experiment Sub-unit, which is the core of the system, where the cultivation is performed under controlled conditions. This sub-unit can be adapted to suit the specific tissue to be cultivated.
- A Diagnostic Sub-unit, which is a powerful tool for characterising the physiological and biological status of the cultivated tissue. This is likely to include a fluorescent microscope, combined with laser scanning. For the evaluation of trabecular-bone-tissue evolution, the µCT developed within the on-going Osteoporosis MAP is also a likely candidate.
- The Biotechnology Mammalian Tissue Culture Bench, which provides the interface with the Experiment and Diagnostic Sub-units, assuming that the facility is to be accommodated in the European Drawer Rack.

The development of this facility will build upon the technologies that have been developed for the Gradient Bioreactor, the Advanced Sensor technologies, and the Laminar Flow Bench technology.

Pulmonary-Function System (PFS)
As part of the MFC Programme, two other life-sciences modules have also been developed by ESA for early accommodation on the US Laboratory. Forming part of the NASA/ESA Pulmonary-Function System, they are:
– the ESA Photo-Acoustic Analyser Module (PAM)
– the ESA Pulmonary-Function Module (PFM).

The PFS is a ESA/NASA collaborative development in the field of respiratory physiology and cardiovascular instrumentation, which will be integrated into the US Laboratory. NASA's contributions to the joint PFS are:
– the NASA Gas-Analysis System for Metabolic-Analysis Physiology (GASMAP)
– the NASA Gas-Delivery System (GDS).

Through in-orbit reconfiguration of the interconnections between the four units, it will be possible to create two different respiratory instruments. The first, called MAS (Mass-spectrometer-based Analyser System), uses the building blocks of GASMAP, PFM and GDS. The second, called PAS, involves the use of PAM, PFM and GDS.

The PAS configuration will be portable, permitting it to be used not only in the US Laboratory, but also in other ISS modules, such as the Russian Zvezda habitation module.

GASMAP will be used to measure and analyse the inhaled and exhaled breath of human subjects. At its core is a random-access mass-spectrometer, which allows the concentrations of the various gases in the mixtures being breathed to be analysed.

GDS provides the special gas mixtures needed to calibrate GASMAP and PAM. It consists of a part that remains permanently in orbit, and a re-supply part consisting of a high-pressure cylindrical reservoir, a pressure regulator, a stop valve and a mechanical pressure gauge.

PAM is a further developed and miniaturised version of the Respiratory Monitoring System-2 flown on the Euromir '95 mission. It will provide the means to determine the concentrations of O_2, CO_2, CO, SF_6, methane and freon in the respired gas mixture. This mixture may also contain significant amounts of N_2 and water vapour.

The PFM consists of the Respiratory Valve Unit (RVU), flow meters, a re-breathing bag and an electronics unit, all accommodated in a transportable standard drawer to enable the PAM to be used outside the NASA Human Research Facility accommodated in the US Laboratory. The PFM will initially be a core element of the US Laboratory, supporting a wide range of respiratory and cardiovascular measurements.

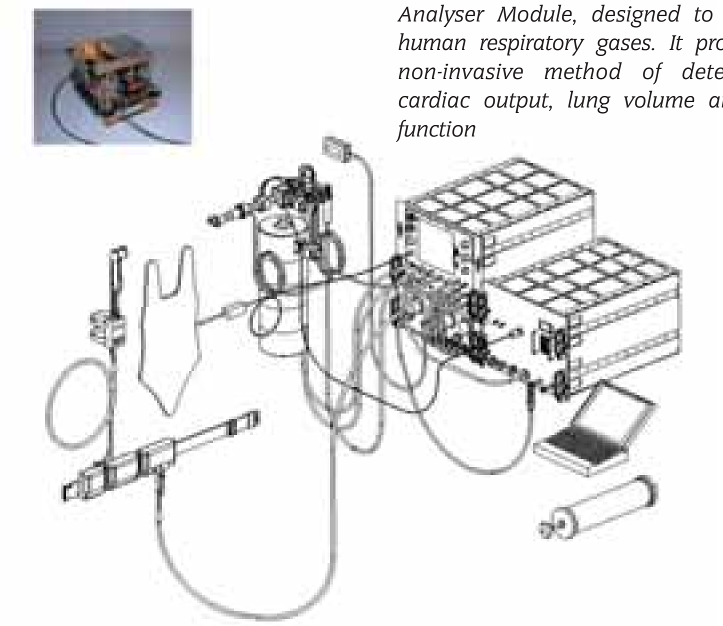

Figure 5.2.10. The ESA Photo-Acoustic Analyser Module, designed to analyse human respiratory gases. It provides a non-invasive method of determining cardiac output, lung volume and lung function

This co-operation is a first important step towards the principle that all research facilities on-board the ISS should be available for use by all ISS Partner scientists, regardless of which agency developed the facility. The wide application of this principle would avoid the duplication of hardware development and lead to a cross-fertilisation of the Partners' research programmes.

Another step towards optimisation of the research output from the ISS is the agreed co-location of all ESA and NASA human-research equipment, i.e. the ESA EPM and the NASA HRF, in the same ISS laboratory. These plans foresee the concentration of the NASA and ESA life-sciences facilities within the Columbus Laboratory, which will simplify matters when experiments require the use of scientific instruments belonging to both ISS Partners.

A similar arrangement should be concluded for other disciplines. For example, all gravity-disturbance-sensitive experiments, such as fluid- and materials-science investigations, should really be performed in the US Laboratory which, because it is located at the centre of gravity of the overall ISS, has the best steady-state microgravity levels.

- *Physical-Sciences Equipment*

The first element of the ESA Materials-Science Laboratory (MSL-1), will be temporarily located in the US Laboratory. Its characteristics have been discussed in detail in Section 5.2.2, together with the arrangements made with NASA for it to be accommodated for the first two years (from 2003) in the US Laboratory.

Table 5.2.2 summarises the planned major NASA research facilities to be accommodated in the US Laboratory 'Destiny' and in the Centrifuge Accommodation Module (CAM). It also lists the ESA contributions accommodated in 'Destiny' and the CAM.

Table 5.2.3 lists the planned Japanese research facilities to be accommodated in the pressurised Japanese Experiment Module (JEM), recently renamed 'Kibo'.

Table 5.2.2 Planned Major NASA Research Facilities for the ISS

Payload Element	Research Area	Launch	ESA – Contrib. or Barter Comments
Human Research Facility-1	Biomed Research. Human Physiology + Psychology	2001	Contrib.: Handgrip Dynamometer
4 Express Racks	Multidisciplinary	2001	–
Microgr. Science Glovebox	Biotechn., Combustion Mat. Sci.	2002	} Dev. by ESA as barter
Minus 80°C Life Sci. Freezer	Life Sciences	2002	} for early flight opportunities
Windows Observational Fac.	Earth Observation	2002	–
Human Research Facility-2	Biomedical Research	2002	ESA Contrib.: Pulmonary Funct. Module PAM, MARES, PEMS
Alpha Magnetic Spectrometer	Space Physics (Anti-Matter Physics)	2003	International Sci. Cooperation
Habitat Holding Rack-1	Gravitational Biology	2004	Europ. Mod. Cultiv. Syst. (EMCS)
Material Science Res. Fac.-1	Materials Sciences	2004	ESA Mat. Sci. Lab.-1
Fluids and Combustion Fac-1	Combustion Science	2004	–
Life Sciences Glovebox	Biomed. Res., Biotechn., Gravit. Biol., Ecology	2004	–
Biotechnology Res. Fac.	Protein Crystalisation, Bioreactors	2004	Accommodation in JEM
X-ray Crystalography Fac.	Prel. Structure Determin. of Proteins	2004	–
Advanced Human Support Technology	Testbed for Long-duration Flights	2004	Accommodation in JEM
Habitat Holding Rack-2	Gravitational Biol. + Ecology	2005	–
Fluid and Combust. Fac-2	Fluid Physics	2005	–
Stratosph. Aerosol & Gas Exp.	Atmospheric Physics, Earth Science	2005	–
Express Pallets 1 and 2	Multidisciplinary	2005	Accom. of ESA Ext. Payload incl. Hexapod Platform
Fluids and Combust. Fac-3	Fluid Physics	2005	–
Express Rack	Multidisciplinary	2005	–
Express Pallet 3	Multidisciplinary	2005	Accom. ESA External Payload

Table 5.2.3 Planned Research Facilities for the Japanese 'Kibo' module (JEM)

Payload Element	Research Area	Technical Features
Gradient Heating Facility (GHF)	Directional Solidification Semiconductor Growth from Vapour Phase	Automatic exchange of sample cartridges (max. 15) 3 independent heating zones Max. Temperature: 1600°C
Adv. Furnace for Microgr. Expts. with X-ray Radiography (AFEX)	Semiconductor Crystallisation and Study of Marangoni Convection with X-Rays in Gas Atmosphere	Ellipsoidal Mirror Furnace, Observation in real-time, isothermal and gradient heating modes, up to 1600°C
Fluid-Physics Experiment Facility (FPEF)	Study of Marangoni Convection to remove Air Bubbles in Floating-Zone Semiconductor Crystal Growth	3D flow-field observation surface – flow rate determination
Solution-Growth/Protein-Growth Facility (SPCF)	Crystal Growth from Solution Growth of Large Protein Crystals for Structural Analysis on Earth	2 Sub-Units: Solution Crystallisation Observation Fac. (SCOF) with Interferometers, and Protein Crystallisation Res. Fac. (PCRF)
Cell Biology Experiment Facility (CBEF)	Effects of Space Environment on Cells, Tissues, Small Animals, Plants and Micro-organisms	Variable g-levels provided by turntable for reference experiments. Samples accommodated in canisters on turntable and incubator
Clean Bench (CB)	Provides Aseptic Operation for Life Sciences and Biotechnology Expts.	CB has disinfection/sterilisation chamber using UV-lights and Cell Experiment Unit (CEU)
Biological Experiment Units (BEU) installed in CBEF or CB	Plant Life-Cycle Experiments, Cell Culture Expts. using Phase Contrast and Fluorescence Microscopes	BEU exists in 2 versions: Plant Experiment Unit (PEU) and Cell Experiment Unit (CEU)
Minus Eighty Degree Freezer (MELFI)	Support Life Science and Biotechnology Experiments with Storage at +4°C, –26°C and –80°C	MEFI is developed by ESA and bartered with NASDA for ISS Payload Racks.

**Kibo means Hope. Kibo is planned for launch with payloads in 2004*

5.2.4 ESA Microgravity Experiment Equipment for ISS External Platforms

As a result of the bilateral agreement with NASA, some ESA-provided viewing/exposure experiments can be accommodated on three 'Express Pallet Adaptors' at NASA's external viewing sites. These are located on the Station's truss structure and can be used during the early-utilisation phase.

Since there is a large demand in Europe for external experiment accommodation on the Space Station, as shown by the replies to the 1997 Announcement of Opportunity, ESA decided to add to the Columbus Laboratory four standard Express Pallet Adaptors. Each of these has a 1 m^2 mounting surface and a mass-carrying capability of 225 kg.

However, these ESA external viewing sites will only be available after the launch of the Columbus Laboratory in late 2004.

The Russian ISS modules also offer the possibility to attach external experiment equipment. A contract has therefore recently been concluded with the Russian space authorities to accommodate the ESA radiation biological facility ‘Matroshka’ on the outer surface of the Russian service module ‘Zvezda’ in early 2003.

The ESA external payloads Expose and ACES, which will be mounted on NASA Express Pallets (a Pallet houses six adaptors, each with about 1 m^2 of mounting surface for experiment accommodation), and the Matroshka facility are described below.

- *Exobiology Experiment Unit (Expose)*

Expose is to be mounted, together with the European space-science payload Sport, on one Express Pallet Adaptor, oriented towards the Sun. The unit accommodates eight selected exobiology experiments on a coarse-pointing mount that tracks the Sun, the direction of which changes rapidly as the ISS moves through its orbit with a gravity-gradient orientation.

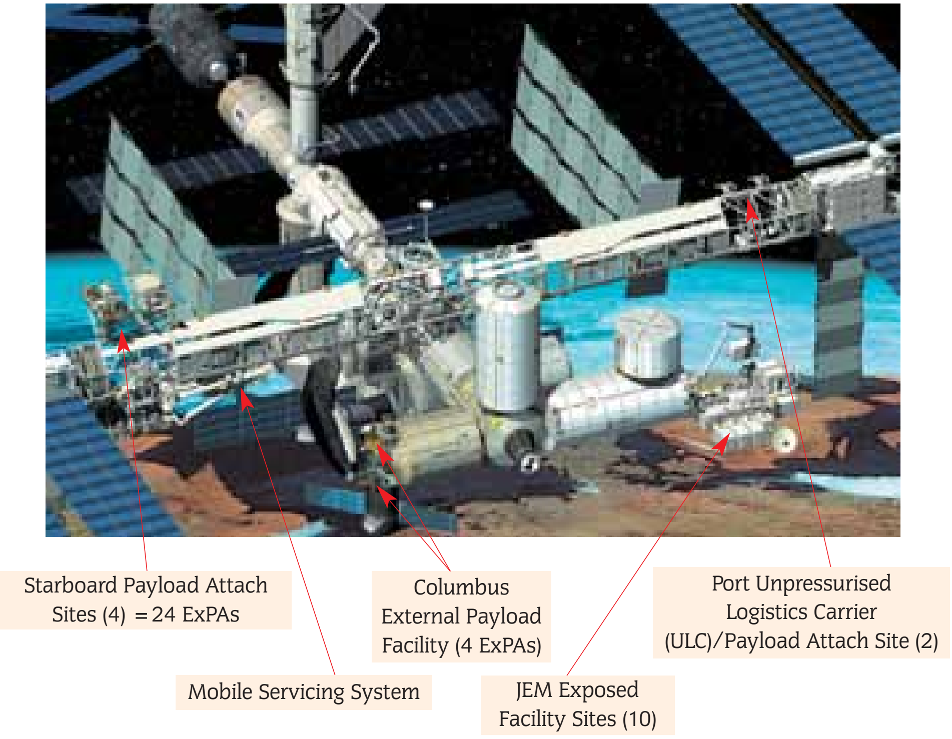

Figure 5.2.11. The locations for attaching external payloads to the ISS

The exobiology experiments will expose a large number of biological specimens for up to 1.5 years to free-space conditions and/or selected space parameters such as solar UV radiation, cosmic radiation, space vacuum and temperature extremes. Expose will also support long-term in-situ studies of microbes in artificial meteorites, as well as those of microbial communities from special biological niches (see Section 2.2.3). The experiments include studies of photo-biological processes, in simulated planetary radiation environments (Mars, early Earth, ozone layer) as well as studies of the probabilities and limitations of life in the Solar System.

The results from Expose experiments are expected to provide a better understanding of the processes regulating the interactions of life with its environment on Earth.

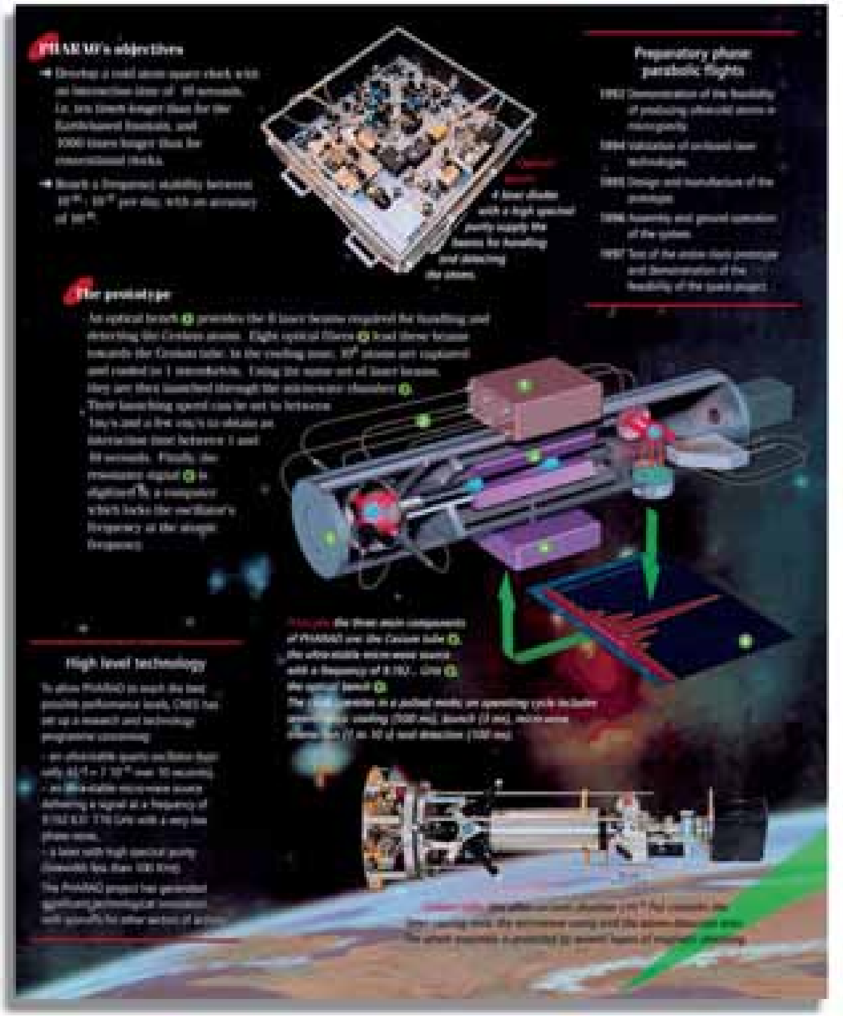

Figure 5.2.12. The core Pharao element of the ACES atomic clock (courtesy of CNES)

Figure 5.2.14.

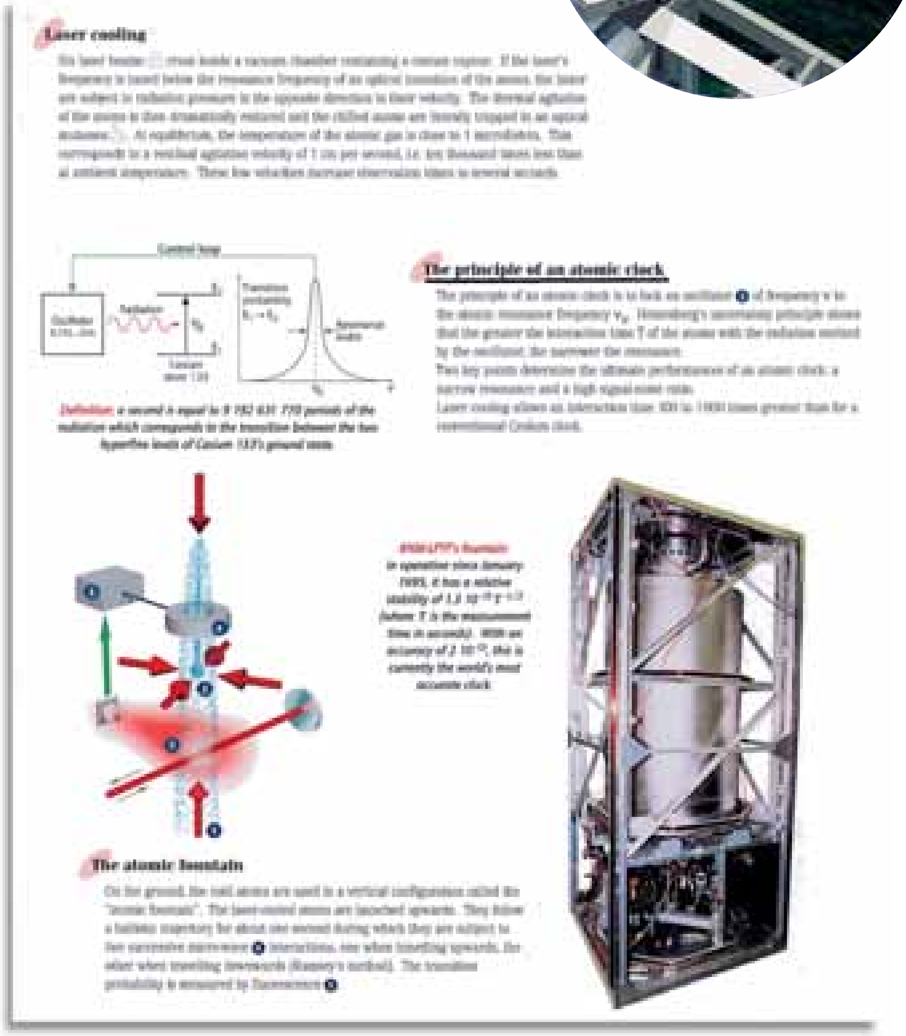

Figure 5.2.13. The ACES package to be installed on the ISS (courtesy of CNES)

- *Atomic-Clock Ensemble in Space (ACES)*

ACES is a co-operative CNES/ESA project under ESA management, the core element of which is a laser-cooled caesium clock (Pharao). This is a French contribution, designed by the Ecole Normale Superieure, for which Neuchatel Observatory (CH) is providing a space version of a hydrogen-maser clock (SHM) to act as a reference. Other ACES elements are Time Transfer by Laser Link, for the synchronisation of remote clocks with an accuracy better than 50 picosec, an All-weather Microwave Link, which is to be used for time and frequency comparison to picosecond accuracy, and a Precise Orbit-Determination Device to provide altitude and velocity determination for the ISS. Further elements are a Frequency Comparison and Distribution Package, allowing Pharao and SHM phase comparison and signal transfer to the time-transfer systems.

ACES exploits the combination of laser cooling (Fig. 5.2.12) and microgravity to produce slow-moving atoms, which allows 10 times longer interaction times than are possible on Earth. This, in turn, leads to a narrower resonance frequency width, an increased signal-to-noise ratio, and thus greatly increased measurement precision. A factor of 100 improvement, to 10^{-16}/day, is expected. A major goal of the ACES project is the characterisation of Pharao by comparison with the on-board space hydrogen-maser clock (SHM) and with primary ground clocks via a laser or microwave link.

ACES opens up not only new opportunities in fundamental research, such as the measurement and testing of relativistic effects, but also important applications in atmospheric propagation, high-precision geodesy, navigation (improved GPS) and advanced communications. It is planned to install ACES on a nadir-viewing (Earth-looking) ISS Express-Pallet Adapter for a three-year period (Fig. 5.2.14).

- *Body Radiation-Dosage Measurement Unit (Matroshka)*

Matroshka is a tissue-equivalent phantom representing the upper part of the human torso. It is to be used to study the depth-dose distributions for different components of the particle and radiation fields in orbit, looking at the different positions that correspond to the organs of astronauts. The dummy is equipped with user-provided passive and/or active detectors for ionising radiation.

The body phantom consists of commercial ‘Rando’ phantom parts, familiar in the field of radiotherapy, i.e. various types of tissue simulating the human organs in terms of size, shape, mass, density, orientation and nuclear interaction. Knowledge of the radiation dosage to which the sensitive organs of astronauts’ bodies are exposed is very important for evaluating the risks from radiation on the ISS, including extra-vehicular activities, and for future long-duration space missions.

Matroshka will be launched in early 2003 on a Progress spacecraft and accommodated for one year on the outside of the Russian ISS service module Zvezda.

5.3 A Future European Life- and Physical-Sciences Research Programme

M. Heppener

5.3.1 Introduction

European life- and physical-sciences research in space stands at the threshold of a new era. Over the next few years, there will be a progressive build-up of research activities on the Space Station, culminating in the introduction of science operations in the ESA Columbus Laboratory. At that point, the facilities will be in place for ESA to mount a long-term scientific research programme in space. It will finally become possible for Europe to embark upon a programme that has both depth and extent, and one that can be carried out at a rate and with a quality that can stand direct comparison with its terrestrial-based counterparts.

To support such a programme, it will be necessary for ESA to seek approval and funding from its Member States both for the exploitation of the ISS as a whole, and for the proposed Life- and Physical-Sciences and Applications Programme. Discussions and decisions on these topics are due to take place in the course of 2001.

In looking towards that future of an enlarged activity and increased scientific output, ESA is now concerned to ensure that such an activity takes place within a framework that closely co-ordinates both European and national endeavours in this field. In defining the plans that will lead to the appropriate scientific output, ESA intends to continue and to expand its close consultations with an enlarging user community. It will also give increasing support to processes that will further facilitate the transfer of life- and physical-sciences research results into the mainstream of relevant terrestrial research programmes, as well as into potential applications and industry. Those links between research and applications that already exist, together with the programmes designed to support increased industrial involvement, will be strengthened even further. Last but not least, greater efforts will be made to involve the general public in these developing activities and to increase public awareness of the benefits to life that flow from space research. The manner in which these changes will be brought about is outlined below.

5.3.2 A User-Driven Programme

The starting point for the future programme is provided by the inputs from the user community. Figure 5.3.1 is a graphical representation of the essential ingredients of this user-driven approach.

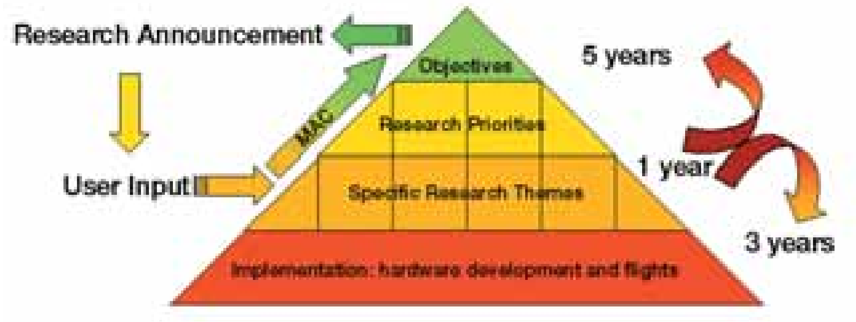

Figure 5.3.1. Schematic of the principal ingredients of the future programme

Formal Announcements of Opportunity (AOs) will be published regularly, soliciting proposals from the user community for specific research topics. These topics are represented at the lower levels of the pyramid in Figure 5.3.1. The typical time scale for the updating of user inputs is one year, which means that changes in topics of interest can be introduced rather rapidly. These topics are then synthesised, under the guidance of the ESA expert advisory groups, into research priorities and top-level objectives. These will have a typical variation time scale of 3 – 5 years, i.e. the duration of the programme itself. These top-level objectives are again used as inputs for the AOs, thereby creating a programme-stabilising feedback loop.

The user inputs at the base of the pyramid are used to define the specific activities being carried out within the programme, including defining the need for flights of existing facilities or the development of new ones. It is the intention that each of these proposals should encompass a complete research programme, including any necessary ground-based research, rather than just describing an individual flight (ISS Increment) experiment.

At present, the time required for the development of a new facility is in the order of 3 – 5 years. It is the goal in the ISS era to shorten the time span between the submission of a proposal and the execution of an experiment to 1 – 3 years, depending upon the specific hardware requirements. In exceptional cases, such as experiments with a highly competitive element or with high industrial or commercial interest, this time should even be reduced further.

5.3.3 The Selection of Research Objectives

The definition of the top-level research objectives is a continuous process, in which all of the parties mentioned above play a role. In particular, several meetings have recently taken place with the ESA advisory teams, the European Science Foundation (ESF) and the national delegations. The selected future research objectives have been presented to the scientific community at large at an ESF-organised workshop and, following a critical appraisal, the list will now be finalised. Presently, four top-level objectives have been identified, which are briefly described below.

- *Exploring Nature*

In any scientific discipline, unbiased curiosity is the starting point for progress. Generally, the results of basic research will lead to new ideas both in the area of the pure sciences and in the process of finding new applications. The research priorities that have been established in this area follow from recently received proposals, as well as common trends in the respective disciplines. In the life sciences, the emphasis is on understanding gravity's influence on basic biological processes, such as cell growth and differentiation, gravitaxis, developmental biology and tissue organisation. In the physical sciences, topics include the study of solidification processes, the organisation of matter (supercritical fluids, strongly coupled plasmas, cosmic and atmospheric dust, diffusive mechanisms) and non-classical physics, such as quantum liquids and their application in atomic clocks and relativity tests.

Special attention will be given to the human exploration of the Solar System, which will be one of mankind's great endeavours in the 21st century. Motivations for this will be the search for extraterrestrial life and the desire to explore the unknown. In response to recent AOs, proposals have been received that address this domain, such as exobiology studies and the development of life-support systems. In addition, specific topics will be promoted for future study, including areas such as human-physiology and psychological aspects, radiation studies and the development of in-situ production technologies.

- *Improving Health*

A major part of the proposals, and of the human-physiology experiments supported by the Agency today, deal with health-related topics. In particular, the space environment provides a good tool with which to study the effects of disease and ageing and the underlying mechanisms, to identify suitable clinical treatment methods, and to develop advanced diagnostic equipment. Several projects already approved by ESA address the study of physiological adaptations as a result of reduced loads and immobility, such as blood-pressure control, muscle atrophy, balance control, osteoporosis and cognition. Also, specific attention will be given to the influence of environmental conditions, atmosphere, nutrition, and radiation on health and safety. Several diagnostic tools are presently under development, building upon non-invasive techniques, miniaturisation, advanced sensors and tele-monitoring, which will be employed during future spaceflight missions. Clinical countermeasures for rehabilitation, including exercise devices, drug tests and special food will also be tested.

- *Innovating Technologies and Processes*

With the progress made in life- and physical-sciences research in space during the past two decades, research topics have emerged that have a clear relevance for industrial production processes and the development of new technologies. In the life-sciences area, this is the field of agriculture and biotechnology, genetic improvement of plant growth, analytical bioreactors, gene chips, reconstituted tissues for drug screening and artificial organs. In the physical sciences, there is a need for understanding gravity-dependent processes in order to be able to model and improve the production methods. Examples include improved knowledge of critical parameters for the oil and casting industries, modelling of combustion and crystallisation processes, and the development of advanced materials such as metallic foams. Also, techniques that are presently employed for their basic research potential, such as high-precision cold-atom based systems and advanced plasma-based technologies, will be stimulated to further develop them into practical applications.

- *Energy and Environment*

Several of the topics addressed in projects that are currently running have relevance for understanding, or even improving, processes that have an environmental impact, address safety issues, or deal with energy-production techniques. Examples include the studies of atmospheric dust and geophysical flows, both of which have a clear impact on the modelling of the Earth's climate. The safety of the nutrition cycle is also a very relevant present-day application, which is being studied within the framework of developing closed-loop life-support systems. Finally, a lot of attention is devoted in some selected proposals to a better understanding of combustion and heat-transfer processes. Here, researchers and industries hope that a better understanding of the basic chemical and physical aspects of combustion will lead to higher efficiency energy-production techniques and/or cleaner engines.

5.3.4 The Alignment of Strategic Objectives with Other European Institutions

An important aspect of the future programme will be its integration within a larger European scheme. In particular, it is the intention to identify common objectives with the most important institutions dealing with research in Europe. By using common objectives, and even common terminology, it should be possible to achieve:

- a continuous dialogue with the major European players on strategic and implementation issues
- increased embedding of space-based research into ground-based research programmes
- easier access to other funding sources for scientists active in space-based research
- increased appreciation and underpinning at the level of science policy makers.

The various National Research Councils decide the policy for basic scientific research at the national level. Almost all of the national organisations responsible for supporting scientific research are associated with the European Science Foundation, which has as its prime objectives to:

(a) advance co-operation in basic research
(b) examine research issues of strategic importance
(c) give advice on science policy matters
(d) promote the mobility of researchers and the free flow of information and ideas
(e) facilitate co-operation in the use of existing facilities and in the planning and provision of new facilities
(f) plan and, where appropriate, manage collaborative research activities.

The ESF is therefore judged to be a valuable counterpart for strategic discussions on basic research objectives. Contacts were established in 2000 and agreement has already been reached that the ESF will participate in this process and also organise relevant workshops to review the proposed objectives.

In the area of applied research, the European Commission (EC) is the obvious counterpart for ESA. The Framework Programmes (FPs) define the EC's strategic priorities for research, technological development and demonstration activities. The present Framework Programme No.5 covers the period 1998 – 2002, and the definition of the next programme (FP6) is underway.

The current programme (FP5) has been conceived in order to help solve problems and to respond to major socio-economic challenges such as increasing Europe's industrial competitiveness, job creation and improving the quality of life for European citizens. Emphasis is placed throughout on the process of innovation, so as to ensure that the output of EU research is translated into tangible results. A total budget of 14.96 billion Euros has been allocated to implementing FP5, which comprises four 'Thematic Programmes' and three 'Horizontal Programmes':

- Quality of Life and Management of Living Resources
- Promoting a User-Friendly Information Society
- Competitive and Sustainable Growth
- Energy, Environment and Sustainable Development
- Confirming the International Role of Community Research
- Promotion of Innovation and Encouragement of Small- and Medium-size-Enterprise Participation
- Improving Human Research Potential and the Socio-Economic Knowledge Base.

There are obvious overlaps at several points with the objectives of the future ESA programme in life- and physical-sciences research in space. For example, one of the key actions of the Quality of Life theme is called 'The Ageing Population and Disabilities'. Research projects receiving funding here have the same themes as projects in human physiology and medical applications carried out in the ESA programme, such as osteoporosis studies and countermeasures. Other examples are the ESA projects in applied material, fluid and combustion sciences, which may lead to important competitive advantages for European industry.

5.3.5 Consolidation of a European Strategy with the National Authorities

Given the budgetary pressures in Europe in the area of space activities, it is essential that the contents of the future ESA programme be agreed upon by the national space authorities. Duplication of activities should not only be avoided on a case-by-case basis, but its avoidance should also be a key driver in designing both the ESA and the national programme activities. Already today, the need for a unified European approach is evident from the increasing number of bilateral agreements between NASA and individual Participating States. This trend ultimately weakens European-wide space efforts and runs counter to the political processes represented by the European Union. It will clearly also lead to sub-optimal use of European resources and is not in the long-term interests of the European taxpayer.

Therefore, the goal is that ESA's research activities and those carried out by the national space agencies must find their place within the framework of a European Research Strategy. The partners in this overall strategy will still be able to recognise their own contributions and priorities. However, they will now be part of an integrated approach. This not only creates greater clarity towards the funding authorities, but is also of advantage in, for example, discussions with the Space Station partners. Finally, the implementation of this European Research Strategy will also lead to an overall European approach towards the definition and development of future payloads and facilities, based on user inputs.

5.3.6 The Role of European Industry

Traditionally, European industry was active in the fields of life and physical sciences as developers of advanced facilities and instrumentation. This has led to a very impressive technological knowledge base, with European space-research facilities among the most sophisticated presently available. Within the framework of a user-driven programme, this will be a very important asset, since here the developing industries will have to have a thorough understanding of the scientific requirements and translate them into engineering specifications. A specific challenge will be to reduce the time from initial conception to flight of an experiment to something in the order of two years, and to do so with significantly lower budgets than were available in the past.

The reason for this is that only by applying these two conditions can the ISS become the high-throughput laboratory that everybody wants it to be. In view of the relatively small scale of individual facilities, this work is of particular interest for space companies in the smaller ESA Member States, or for Small and Medium-sized Enterprises (SMEs). This makes the programme of life- and physical-sciences research in space also very attractive in the context of European industrial policy.

A new class of industries previously not involved in space research are non-space companies that are interested in using space as a tool. Within the framework of recent AOs, more than 48 Microgravity Application Project (MAP) proposals with a high application value and with industrial researchers as part of the teams have been accepted. In total, more than 125 companies are involved in these projects, including several major international companies and a number of small, high-technology companies aiming for specific markets. This very promising development is regarded as the first sign of truly industrial research being conducted in space.

5.3.7 Explaining to the General Public

The objectives of the future programme have been established by analysing the requirements of the four categories of parties that are directly involved, i.e. the active users who have submitted proposals, the European research community at large, the various national space agencies, and European industry. It should not be forgotten however, that in the end the support for this activity depends upon the ability to explain its usefulness to the general public. Since the sixties, there has been a continuing interest from the general public in space activities, which actually seems to be growing stronger in recent years. However, for the moment astronomical topics and flights by astronauts attract the greatest attention. As has been amply demonstrated above, both in the life and physical sciences excellent examples exist of research results that are of direct relevance for health problems, to the welfare of the environment, or for the development of new materials and processes.

It is the future responsibility not only of ESA, but of all those involved, to make the results of these efforts known, to explain and demonstrate that the life- and physical-sciences research that is carried out in space is not some esoteric exercise, but is for the ultimate benefit of life on Earth.

CHAPTER 6. APPENDIX

6.1 Programmatic Structure of ESA's Microgravity Activities

G. Seibert

Research in materials science/fluid physics and life sciences is a basic scientific activity, although the results are often later applied in industrial processes or in medical treatments on Earth. At the time of each decision on ESA's Microgravity Programme phases, therefore, the question of whether the programme should be added to the mandatory traditional Science Programme (astrophysics, astronomy, atmospheric physics), or whether it should be an optional programme in its own right, has been discussed.

In ESA terms, 'mandatory' means that every Member States must participate in the programme with a contribution proportional to its Gross National Product (GNP). The current ESA Mandatory Programme includes the Science Programme and the General Budget, which covers the Technology Research Programme (TRP) and a number of administrative activities needed for the functioning of the Agency. The other ESA programmes, such as Launchers (Ariane), Earth Observation, Communication/Navigation and Manned Spaceflight and Microgravity, are so-called 'Optional Programmes'. These allow 'à la carte' participation, with each Member State free to determine the size of its contribution (as a percentage or an absolute amount) to the programme's financial envelope, with no obligation to participate in a follow-on programme or even a small extension of the programme envelope. An Optional Programme can also find itself with a cumulated Member State subscription of less than 100% of the ESA-proposed budget envelope. Such a situation is only acceptable if a proposed programme consists of a number of independent elements, where the deletion of one element, in order to match the available level of subscription, does not affect the others.

Although the adoption of a mandatory status for ESA's Microgravity Programme was requested by several smaller Member States at each programmatic decision point, this status was never achievable. The reasons for this were the following:

- Not all ESA Member States wanted to participate in this programme, e.g. Ireland, Finland, Norway (except for EMIR-1).

- A few of the larger Member States (like the UK) did not want to contribute to a level corresponding to their GNP.
- Besides their participation in the ESA Microgravity Programme, the two largest contributors to other ESA programmes, Germany and France, had their own national microgravity research programmes. During the 1980s and early 1990s, the German national programme was actually larger than the ESA programme.
- Europe did not possess and was not developing its own man-rated launcher system, nor had it mastered the re-entry techniques needed for retrievable satellites. This made the major elements of ESA's Microgravity Programme dependent upon US or Soviet launch and retrieval systems, a fact that made the long-term planning and financing of microgravity research opportunities uncertain.

The consequence of this situation at European level was that a large number of partially overlapping phases of the ESA Microgravity Programme, with only limited durations and different Member-State percentage contribution levels, were approved.

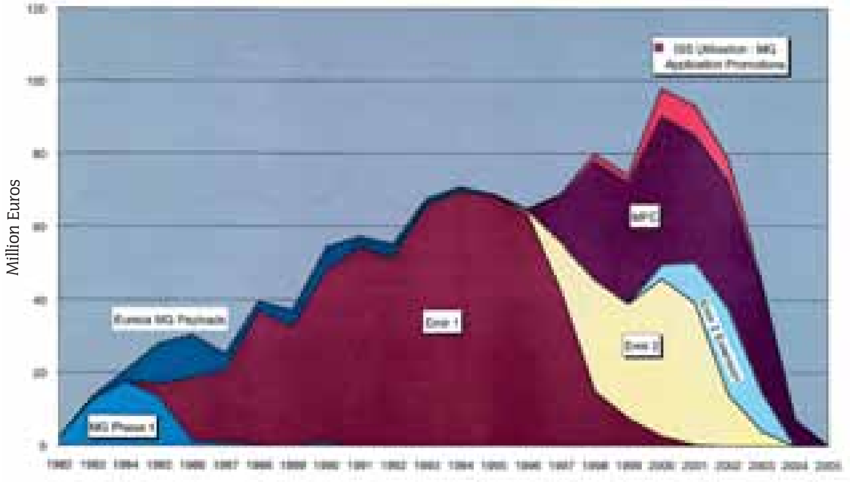

Figure 6.1.1. Development of ESA's budget for microgravity research and facilities

Figure 6.1.1 shows that seven, programmatically different, microgravity activity phases were approved and executed, some of which are still on-going until 2004. It also shows that:

- In parallel with the Phase-1 of the Microgravity Programme, the Eureca Programme, which included a microgravity core payload, was approved in 1983. Due to the delays caused by the Challenger accident, the development of this core payload was stretched over many years and Eureca was eventually flown only once, in 1992/93.
- The EMIR-1 programme is by far the largest ESA Microgravity Programme phase.

- At the ESA Ministerial Conference in September 1995, two different and independent Microgravity Programme phases were approved, which started in 1997: (i) The utilisation programme EMIR-2, as the follow-on to EMIR-1, providing research opportunities in the pre-Columbus era, and (ii) The Microgravity Facilities for Columbus (MFC) programme, in which ESA's major microgravity multi-user facilities for the ISS utilisation phase (presently planned to start in early 2005) are being developed.
- The EMIR-2 programme phase was extended in 1999 (EMIR-2 Extension) by a small amount (about 50 MEuros) to compensate somewhat for the original low financial envelope and to cover some flight opportunities in the pre-Columbus era, which was still further extended to 2003 and 2004.
- The Columbus programme content includes a 'Utilisation Promotion' element, which was foreseen to promote ISS utilisation by all user disciplines, such as space science, Earth observation, technology and microgravity research and some user information activities. The microgravity share of this promotion budget is used to support microgravity application projects in which industry is actively participating in the applied research.

6.2 ESA Facilities on Spacelab and Spacehab

The most important research opportunities supported by the ESA Phase-1, EMIR-1 and EMIR-2 programmes in the 1980s and 1990s were the eight Spacelab missions and later the Spacehab missions.

A short description of Spacelab and the commercially offered Spacehab is provided in Section 1.2. For 15 years, from 1983–1998, the manned laboratory Spacelab was the workhorse of microgravity research for the 'western' world. It provided adequate technical resources, acceptable microgravity levels (10^{-4} g) for the great majority of microgravity experiments, and up to seven astronauts for the operation and repair (if needed) of the experiments. The crew were also available as subjects for human physiological studies. Several of the astronauts on each Spacelab flight, the so-called 'Payload Specialists', were competent and trained in the subjects of the experimentation.

The 7 to 17-day duration of Shuttle/Spacehab missions was also adequate for the first generation of space experiments, which did not yet require a series of experimental runs with parameter variations, as normally applied in the terrestrial laboratory. However, the Shuttle/Spacelab flight frequency was too low, at least for the European scientists who had, at best, one flight opportunity for their experiments every two years.

Table 6.1. Multi-User Facilities on Spacelab Missions Used to Perform ESA-Selected Experiments

Mission	**SL-1/FSLP**	**D-1**	**IML-1**	**D-2**	**IML-2**	**USML-2**	**LMS**	**Neurolab**
Launch	28-11-83	30-10-85	22-01-92	26-04-93	08-07-94	20-11-95	20-06-96	17-04-98
Mission	10 days	7 days	8 days	10 days	15 days	16 days	17 days	16 days
ESA Share of Payload	50%	38%	25%	25%	35%	10%	35%	25%
	Mat. Science Double Rack, including: • Isothermal Heating Facil. (D) • Gradient Heating Facil. (F) • Mirror Heating Facility (D). Fluid Physics Module (I) + other PI instruments in MS/FS. 3D-Ballistograph (I) Biostack (D) Echocardiograph (F) Lymphocyte Proliferation Instrum. (CH)	Biorack Space Sled Fluid-Physics Module (FPM) + several German facilities Biorack	Biorack Biostack Critical Point Facility (CPF)	Anthrorack Biostack Lymphocyte Instrument Advanced Fluid-Physics Module Microgravity Measurement Facility (MMA)	Biorack Biostack NIZEMI (D) Advanced Protein Crystallisation Facility (APCF) (2 flight units) Bubble Drop and Particle Unit (BDPU)	Glove Box APCF (2 flight units)	Torque Velocity Dynamometer Percutaneous Electrical Muscle Stimulator (PEMS) Advanced Gradient Heating Facility (AGHF) BDPU APCF (2 flight units) MMA	Visual and Vestibular Investigation System (VVIS) with Human Off-axis Rotator + several European PI Instruments
Total No. of Expts.	**70**	**82**	**36**	**88**	**79**	**30**	**43**	**26**
Phys.Science Experiments	36	54	8	38	24		24	-
Life Science Experiments	16	26	28	41	53	LS+ PS only	16	26
Others	18	2	-	9	2		3	-

(D), (F), (I), (CH) mean that the payload element was provided by these ESA Member States.

Table 6.2 ESA Microgravity Multi-User Facilities for Spacelab/Spacehab

Facility/Missions	**Field of Research**	**Size of Facility**	**Special Technical Features**
1. Biorack: (6 missions) SL : D1, IML-1 & IML-2 Spacehab: MM3, MM5 and MM6	Cell and developmental biology on bacteria, unicellular organisms, human cells, plant gravi-perception and gravi-tropism. Embryogenesis, organogenesis	1.5 Standard Racks 350 kg	Incubators (2), glove box, cooler/freezer, 1g centrifuge, standard experiment containers, late-access Mid-Deck Lockers
2. Vestibular Sled: SL-D1	Vestibular receptor system, visual system, somato-sensory systems, i.e. mechano-receptors in skin, joints and other tissue	3.5 m long Sled structure on SL centre aisle, plus 2 SL single racks for control and storage. 550 kg	Performs pre-programmed velocity trajectories with sinusoidal and triangular waveforms plus oscillating motion. Vestibular helmet with optical stimulation and IR-TV recording
3. Improved Fluid-Physics Module: SL-D1	Study of static and dynamic liquid columns of different viscosity, characterisation of Marangoni convection, study of capillary forces	80 kg, accom. in Materials-Science Double Rack	Rotates axisymetrically and non-axisymetrically different shapes of liquid bridges. Applies lateral movements, vibrations, electrical fields and has heating capabilities
4. Advanced Fluid-Physics Module: SL-D2	Capillarity, wetting, liquid floating-zone stability, Marangoni convection	96 kg 1/2 of an SL Standard Rack	Visualisation of shape and fluid motion. Surface temperatures measured with thermographic cameras
5. Critical-Point Facility: SL: IML-1 SL: IML-2	Phase transitions, phase separation and compressibility near the critical point of SF_6. Interfacial phenomena in microgravity	1/3 of an SL Standard Rack 90 kg	Very accurate temperature control of 0.1mK, in temp. range 30-70°C. Optical diagnostic, with interferometry and light scattering when passing through the gas-liquid critical point
6. Anthrorack: SL-D2. Parts of it on Neurolab Spacelab Mission	Cardiovascular, cardio-pulmonary and endocrinology research in humans	2 SL Standard Racks 610 kg	Used often in combination with the Lower-Body Negative Pressure Device and Ergometer. AR elements: breath analyser with mass-spectrometer, echo-cardiograph, ECG, EOG, EEG, high-speed blood centrifuge, gas supply for pulmonary research
7. Bubble Drop and Particle Unit: SL: IML-1 SL: LMS	Study of particle, drop and bubble dynamics and growth in transparent liquids. Steady and oscillatory Marangoni-Bénard convection, thermo-capillary instability, nucleation/condensation	1 SL Standard Rack 270 kg	Injection of bubbles and drops in fluid cells. Optical diagnostics. Application of temperature gradients and electric fields. Sophisticated individual experiment containers

Table 6.2 (cont'd) ESA Microgravity Multi-User Facilities for Spacelab/Spacehab

Facility/Missions	Field of Research	Size of Facility	Special Technical Features
8. Advanced Gradient-Heating Facility: **SL: LMS** **Spacehab/STS-95**	Alloy-solidification studies, semiconductor crystal growth. Planar-front solidification, cellular and dendritic growth. Miscibility-gap studies, phase-separation studies, composite materials	1 SL Standard Rack 180 kg + cartridges	Advanced high-performance Bridgman-type surface. Standardised cartridges. Cartridges are stationary, furnace moves, to minimise microgravity disturbances. Max. temp 1400°C. Gradient 100°C/cm
9. Torque-Velocity Dynamometer (TVD): **SL: LMS**	Muscle-disuse atrophy studies. Efficiency of countermeasures (isokinetic exercise better than isotonic ergometry training). Muscle force, velocity of movements and endurance tests	Partly floor-mounted in Spacelab 130 kg	TVD measures force, torque and velocity of various human limbs/joints in an adjustable and reproducible way, i.e. muscle-strength changes in orbit
10. Visual and Vestibular Investigation System (VVIS): **SL: Neurolab/STS-90**	Human neuro-physiological research. Sensation of centrifugal forces without Earth gravity. How sense of space orientation is organised in the brain	Centre-aisle mounted 160 kg	VVIS's most important element is a human off-axis rotating chair. Includes binocular 3D video eye-movement recording system. Centrifugal force reaches 1 g when rotating at 45 rpm
11. Advanced Protein-Crystallisation Facility: **SL: IML-2 (2 units)** **USML-2 (2units)** **LMS (2 units)** **Spacehab-1 (1 unit)** **Spacehab/STS-95 (2 units)**	Growth of large protein single crystals, for 3D structure determination of protein macro-molecule with X-ray diffraction analysis	2 flights units exist 2 x 27 kg	Three crystallisation methods possible: dialysis, interface diffusion, vapour equilibrium. Each model consists of 48 crystallisation reactors. 20 reactors observed/recorded by video prior to re-entry
12. Glovebox: **SL: USML-1** **USML-2**	A facility for preparation, handling, and performance of simple experiments in physical- and life-sciences fields. Handling of toxic materials	Spacelab Double Locker size 54 kg	Safe cabinet, in which partial gas pressures and temperatures are controlled. Provides illumination and video recording
13. Morphological Transition and Model Substances (MOMO): **Spacehab: MM-6/STS-84** **Spacehab: STS-101**	In-situ observation of directional solidification in organic alloys used to model metallic melts	Self-standing drawer 65 kg	One experiment cell used repeatedly for solidification studies at different temperature gradients (Bridgman furnace). The cellular structure of the solidification fronts monitored by video and recorded on internal digital tape recorder
14. Facility for Absorption and Surface Tension (FAST): **Spacehab/STS-95**	Measurement of the dynamic response of surface tension to a model surfactant, for various forcing functions over a range of temperatures and surfactant concentrations	2 Spacehab Lockers 55 kg	Two independent experiment cells. Fluid/fluid and fluid/gas interfaces can be studied. Video system and image processor tracks meniscus for fluid-control loops and measures radius of droplet/bubble. Forcing frequency: 0.01– 600 Hz

6.3 ESA Experiments and Facilities on Bion/Foton

In 1987, ESA started a co-operation with the Soviet Institute for Biomedical Problems (Moscow) to fly biological experiments on the Soviet retrievable satellite Bion (also called Biocosmos or Biosputnik), which had been flown since 1973. Technically speaking, Bion was the same as the 'Foton' spacecraft, which is now offered commercially as a retrievable satellite. The ground landing of these spacecraft is smoothed by a retro-rocket system. The spacecraft itself consists of three sections: a descent module, a battery package as the main energy source for spacecraft and payload, and an attitude and orbit control module, with gas thrusters and a rocket engine used for re-entry. The payload-carrying capability of Bion/Foton is about 500 kg, with an average power provision of 400 W (peak 700 W) for a typical mission duration of two weeks.

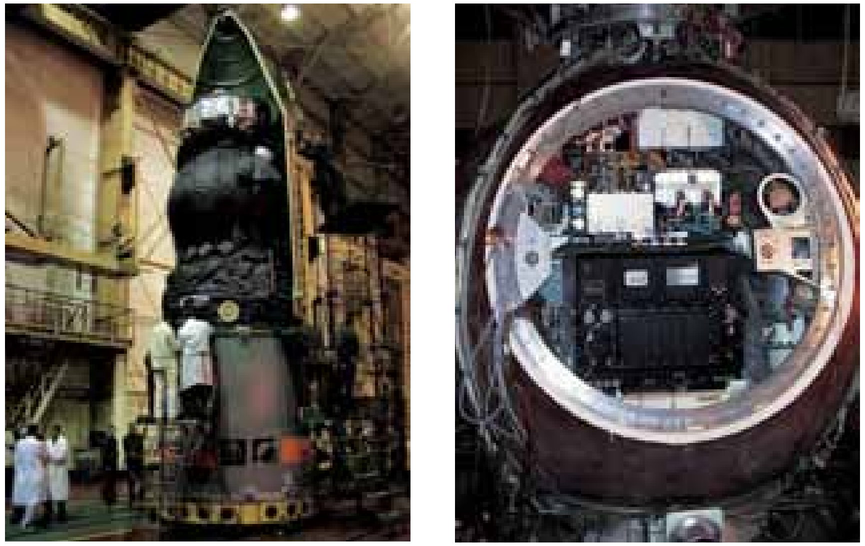

Figure 6.3.1. The Russian Bion/Foton retrievable capsule system, used by ESA for biology and exobiology research

Three autonomous experiments were provided by selected ESA and Soviet Principal Investigators for the Bion-8 flight in 1987. ESA then participated in the Bion-9 mission in 1989 with five joint experiments. For the co-operation on Bion-10 in 1992, ESA developed the Biobox multi-user facility to support cell and developmental biology experiments. During its first flight on Bion-10, the Biobox was used by four experiments, and in addition six autonomous joint ESA/Soviet experiments were performed on this mission.

To ease the effects of the gap in Shuttle/Spacelab flight opportunities, from 1990 onwards ESA increased its use of these Soviet retrievable satellites, also on a commercial basis. This started in 1990 with Foton-8 and continued in 1993 with Foton-9, in 1995 with Foton-10, in 1997 with Foton-11 and in 1999 with Foton-12.

For these flights ESA developed two further multi-user facilities:

- Biopan for radiation biological, dosimetry and exobiological experiments
- Fluidpac for various fluid-science experiments.

The technical capabilities of, and the missions and experiments performed with, Biobox, Biopan and Fluidpac, as well as the other autonomous experiments, are listed in Table 6.3.

Figure 6.3.2. The ESA Biobox and Fluidpac payloads for the Russian Foton capsule

The Biobox facility was flown later on the Spacehab/STS-95 mission in October 1998, following its use on the Foton flights. It is planned to re-fly it on Spacehab in 2002 (STS-107).

Table 6.3 ESA Multi-User Facilities and Experiments Flown on Bion/Foton Missions

Biobox:

Incubator with 1g centrifuge, 24 experiment containers, temperature control in the range 6 - 37°C, telemetry/command capabilities, total mass 40 kg.

Biobox-1(Bion-10, 1992), Biobox-2 (Foton-10, 1995) and Biobox-3 (Foton-11, 1996) experiments:

- Bones (Bion-10): Growth and mineralisation of fetal mouse bones in microgravity
- Fibro (Bion-10, Foton-10 and -11): Morpho-physiological properties and differentiation of cell-culture fibroblasts under microgravity
- Oblast (Bion-10, Foton-10 and -11): Osteoblastic cells (cell culture from rat) in weightlessness: morpho- and biochemical response
- Marrow (Bion-10, Foton-10 and -11): Effect of microgravity on in-vitro cultures of pre-osteoblast cells and on MG-63 human osteosarcoma cells.

Biopan:

Cylindrical pan-shaped container mounted on external surface of Foton, deployed in orbit and closed prior to re-entry to provide exposure of biological specimens to measured levels of space/solar radiation, vacuum and microgravity. Surface area 1080 cm^2, mass 30 kg. temperature control in the 15 - 25°C range.

Biopan-1 (Foton-9, 1994), Biopan-2 (Foton-11, 1997), Biopan-3 (Foton-12, 1999) experiments:

- Base (Foton-9 and -11): Base damage induced by cosmic radiation in cellular DNA
- Shrimp (Foton-9 and -11): Radiation effects in gastrulae from the brine shrimp Artemia
- Vitamin (Foton-9, -11 and -12): Radiation effects and efficiency of radio-protective substances in biological acellular systems
- Mapping (Foton-9 and -11): Radiation measurements behind defined shieldings
- Survival (Foton-9, -11 and -12): Effect of the harsh environment (of solar UV) on micro-organisms
- Shutter (Foton-9 and -11): Biological UV dosimetry
- Dust (Foton-9 and -11): Processing and stability of biomonomers in artificial dust grains
- Dosimap (Foton-12): Dosimetric mapping
- Yeast (Foton-12): Radiation damage in yeast: interaction of space-radiation components

Fluidpac:

This instrument accommodates 3-4 experiments, for which it provides diagnostic interferometers, IR and CCD cameras with data compression, a variety of sensors for in-situ measurements, and a Telesupport Unit for operations from the ground, scientific data transmission, and 5 Gbyte of data storage. Total mass is 185 kg. It handles 400 W, has a large volume of 1700 litres. It provides accurate ±0.1°C temperature control in the range of 3 – 40°C and good stability (±0.01°C/hour) During the first flight of Fluidpac on 12 February 1999, the following three experiments were performed:

- Magia: Marangoni-Grown Instabilities in an Annulus
- Bambi: Bifurcation Anomalies in Marangoni-Bernard Instabilities
- Tramp: Thermal Radiation Aspects on Migrating Particles.

Autonomous ESA-selected experiments flown on Bion/Foton missions:

- **Caraucos**
  Bion-8 and -9: Study of the effects of microgravity and HZE particles of cosmic radiation on embryogenesis of the stick insect
- **Dosicos**
  Bion-8 and -9: Radiation dosimetry inside and outside the spacecraft; radiation damage in plant seeds (lettuce seeds).
  Bion-10: Identification and quantification of incident radiation particles during orbital space flight
- **Seeds**
  Bion-8 and -9: Biological effects of higher and lower ionising cosmic heavy particles in genetically variable (embryonic) plant tissues
  Bion-10: Analysis of chromosomal damage of marker lines in Arabidopsis seed by cosmic heavy particles, including protons
- **Flies**
  Bion-9: Effects of microgravity and radiation on fruit-fly development, ageing, rate of mitotic recombination and adaptation to the space environment
  Bion-10 and Foton-10: Test of the metabolic hypothesis of accelerated ageing in space in Drosophila Melanogaster
- **Protodyn**
  Bion-9: The effect of the microgravity environment on the regeneration of plant protoplasts
- **Kashstan**
  Foton-7: Protein crystallisation in microgravity: HIV reverse transcriptase
- **Algae**
  Bion-10, Foton-10 and -11: Changes in cell-division cycle of Chlamydomonas Monoica caused by microgravity
  Foton-12: Effect of microgravity on cell-cycle kinetics in the unicellar algae Chlamydomonas Monoica
- **Cloud**
  Bion-10: The impact of pre-flight gravity stress on in-flight fitness in Drosophila Melanogaster
- **Wolffia**
  Bion-10: Radiation damage in Wolffia Arrhiza caused by heavy ions of cosmic rays
- **Beetle**
  Foton-10 and -11: Biological clocks of beetles: reactions of free-running circadian rhythms to microgravity
- **Stone**
  Foton-12 and IRDI-Demonstrator flight in 2000: Thermal processing of artificial sedimentary meteorites during atmosphere re-entry
- **Symbio**
  Foton-12: Plant-bacterial symbiosis in microgravity

6.4 ESA Microgravity Experiments and Facilities Flown on Mir

At the beginning of the 1990s, several ESA Member States chose to strengthen their international co-operation with Russia in space activities, as part the dramatic geopolitical evolution that had just taken place. This was partly realised by establishing bilateral research programmes, and also by sending French, German and Austrian astronauts to the Russian Mir space station in order to carry out research. A UK astronaut was also sent to Mir, although that mission was in the context of a privately funded project.

In view of this changed political situation, the ESA Council in November 1992 approved a Columbus Precursor Flight Programme, the main elements of which were two ESA missions to Mir in 1994 and 1995 (designated Euromir '94 and '95). The main objectives of these missions were:

(i) the flights to Mir and the experience obtained there by two ESA astronauts
(ii) the preparation of the European space user community for the Space Station/Columbus era by providing long-duration experiment possibilities
(iii) the acquisition of experience in the operation of manned systems and experimentation support areas.

Euromir '94 was a 31-day mission, from 3 October to 4 November 1994, which involved Ulf Merbold as the ESA astronaut. It included the uploading of a 110 kg ESA payload, and the downloading of 10 kg to be brought back to Earth in the Soyuz manned transfer vehicle, together with the astronauts. The selection of experiments for Euromir '94 took place in early 1993 and it was clear that, because of this tight schedule, no new research facilities could be developed in time. Therefore only existing experimental equipment developed for previous missions, or Russian, French, German and Austrian hardware already onboard Mir, could be used.

The ESA experiments selected for Euromir '94 were predominantly life-sciences experiments from the human-physiology field. 21 European and 1 US life-science experiment were selected, of which six were 'ground experiments', i.e. requiring only pre- and post-flight measurements. In addition, four materials-science experiments and two technology experiments were selected and flown.

The four materials-science experiments that had planned to use the Russian CSK-1 furnace already on-board had to be postponed due to its malfunctioning. The life-science experiments used either small ESA-provided hardware items, such as blood, urine and saliva kits, a cooler/freezer and a hematocrit centrifuge, or they were PI-provided small instruments, pharmaceutical drugs or onboard Mir instruments. The two selected technology experiments were a crew PC and an ion-emitter experiment.

The ESA life- and materials-science experiments performed on the Euromir '94 mission are listed in Table 6.4

Table 6.4 The Euromir '94 Life- and Materials-Science Experiments

- Circadian Rhythm and Sleep
- Fluid and Electrolyte Balance
- Magnetic Resonance Spectroscopy and Imaging of Human Muscles (GE)
- Radiation Health during Prolonged Spaceflight
- Chromosomal Aberrations in Peripheral Lymphocytes of Astronauts (GE)
- Fluid-Volume Distribution and Tissue Thickness
- Effects of Changes in Central Venous Pressure on the Erythropoietic System (GE)
- Spatial Orientation and Space Sickness
- Posture and Movement
- Spatial, Temporal and Mental Process/Cognitive Changes
- Volume Regulation and Heart-Rate Variability
- Changes in Mechanical Properties of Human Muscle as a Result of Spaceflight (GE)
- Bone Mass and Structure Changes and Bone Remodelling in Space
- Influence of Spaceflight on Energy Metabolism
- Adaption of Basic Vestibulo-Oculomotor Mechanisms to Altered Gravity
- Gastro-enteropancreatic Peptides
- Non-Invasive Stress Monitoring in Spaceflight by Hormone Saliva Measurement
- Otolith Adaptation to Different Levels of Gravity (GE)
- Biomechanical and Bioenergetic Changes of Human Muscles (GE)
- Osmo- and Volume Regulation in Man (Dynamic Response)
- Immune Changes after Spaceflight
- Eye Torsion Changes during Space-Adaptation Syndrome

- Liquid–Liquid Phase Separation in Glasses by Microgravity
- Research on Bulk Metallic Glasses
- Thermophysical Properties of Undercooled Melts
- Reaction and Solidification Behaviour of In-Situ Metal Matrix Composite

GE = Ground Experiment

The Euromir '95 mission was originally planned to last 135 days, but was later prolonged to 179 days, with launch on 3 September 1995 and landing on 29 February 1996. The ESA astronaut on this mission, Thomas Reiter, was not only trained as a science astronaut, but also as flight engineer with prescribed responsibilities for Mir operations, including extravehicular sorties. This mission gave 'western' European scientists their first opportunity to perform investigations of prolonged periods in weightlessness.

The Call for Experiments for the Euromir '95 mission resulted in the selection of 19 life-science, 8 materials-sciences, 10 technology and 4 space-science experiments. The life- and materials-science experiments are listed in Table 6.5.

For this long-term space mission, ESA developed two multi-user facilities: the Bone Densitometer (BDM) and the second generation of the Respiratory Monitoring System (RMS-2). The technical resources originally available to ESA for Euromir '95 were 200 kg of upload with the unmanned Progress transport vehicle, plus 10 kg of upload and download with the manned Soyuz TM vehicle. After the development of all of the microgravity experiment hardware, including RMS-2 and BDM as major facilities, the required ESA upload had increased from 210 kg to 367.4 kg and the (marginal) download from 10 kg to 22.6 kg. Since the Columbus Precursor Flight Programme had paid the Russians for the Euromir '94 and '95 missions on the basis of a firm fixed price of 50 MEuro, and since the excess mass stemmed from the microgravity hardware, the additional 5 MEuro needed to cover the excess upload and download costs was provided by the EMIR-1 programme. Looking back, this was an extremely cost-effective investment for a six-month duration manned space mission, particularly as both multi-user facilities (BDM and RMS-2) were later developed into very lucrative terrestrial 'spin-offs', as reported in Chapter 3.

The two Euromir missions certainly fulfilled their political, technical and operational objectives. Their scientific returns were also very satisfactory, given that the download capability was extremely limited and that none of the experimental facilities could therefore be brought back. The data-transmission capabilities were also limited: it was not possible to transmit high-speed experiment data rates, nor was full orbital coverage achieved.

- *The Bone Densitometer (BDM)*

Figure 6.4.1. The ESA Bone Densitometer used on the Euromir '95 mission resulted in development of this spin-off version for normal clinical use on Earth

This was the first instrument capable of monitoring bone-density changes in astronauts during the actual mission. The new feature of the BDM was that it was not an X-ray instrument, as in a normal bone densitometer, but an ultrasound measurement device, which presents no hazard to the crew due to repeated exposure and requires no radiation shielding. To evaluate the loss of mass or the demineralisation in weight-bearing bones (the astronaut's heel was used), the BDM measured the speed of sound (transmission delay) and the broadband ultrasound attenuation in the bones. The accuracy and reproducibility achieved for these two measurements – 0.3% and 2%, respectively – were sufficient to satisfy the analysis. Other experiment objectives were to determine in how far drugs and specific exercises can counteract the effects of weightlessness. Figure 6.4.1 shows the commercial clinical version of the Bone Densitometer spun-off from the Euromir '95 BDM experiment.

Table 6.5 The Euromir '95 Life- and Materials-Science Experiments

- Influence of Microgravity on Renal-Fluid Excretion in Humans
- Non-Invasive Monitoring of Drug Metabolism and Drug Effect during Prolonged Microgravity
- Effect of Otolith Input on Ocular and Neck Reflexes and Perceived Vertical
- Eye-Torsion Change Correlation to Space-Adaptation Syndrome
- Chromosomal Aberrations and Repair in Peripheral Lymphocytes (GE)
- Radiation Health during Prolonged Spaceflight
- Influence of Gravity on Preparation and Execution of Voluntary Movement (GE)
- Effect of Microgravity on the Bioenergetic Characteristics of Human Skeletal Muscles (GE)
- Changes in Mechanical Properties and Reflex Responses in Human Muscles (GE)
- Human-Muscle Magnetic-Resonance Spectroscopy and Imaging (GE)
- Central Venous Pressure during Weightlessness
- Cardiovascular-, Pulmonary Control and Pulmonary Gas Exchange (Rest + Exercise)
- Pulmonary Function in Microgravity
- Regulation of Cardiovascular Responses to Exercise in Humans
- Interstitial Fluid Balance under Microgravity and Pulmonary Mechanics
- Influence of Vitamin-K on Bone Metabolism
- Bone Mass and Structure Measurement with BDM and Bone-Stiffness Measurement Device
- Effect of Venous Pressure on Bone Mineral Density in Weightless Conditions
- Mechanical Stimulation to Prevent Loss of Bone Mass using Heel-Strike Transients

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- Equi-axed Solidification of Al
- Reaction and Solidification Behaviour in Metal-Matrix Composites
- Specific Heat of Undercooled Melts
- Investigation of Chemical-Vapour Transport
- Liquid-Liquid Phase Separation in Glasses
- Thermosolutal Convection in Ge-Si
- Metallic-Glass Research
- Casting of Hypermonotectic Alloy

GE = Ground Experiment

- *The Respiratory Monitoring System (RMS-2)*

The first-generation respiratory monitoring system was developed for the D-2 Spacelab mission. A traditional gas analyser is based on a mass-spectrometer and requires a high vacuum in order to operate, making it a heavy and bulky instrument. To overcome these undesirable (for spaceflight) features, a new gas-analysis technique, namely the photo-acoustic method for poly-atomic gases (developed and patented by Bruel and Kjaer, Denmark) was used, supplemented by a magneto-acoustic method for detecting oxygen. This new method allowed a drastic reduction in terms of mass, volume and power needs, but had the potential disadvantage of not being able to measure all gases. For the Euromir '95 experiments, it was acceptable that the RMS-2 would measure continuously the oxygen, carbon-dioxide, nitrous-oxide and hexafluoride concentrations in the respired gases. In addition to the basic gas analyser, the RMS-2 on Euromir '95 included an ECG module, a continuous blood-measurement device to monitor the subject's physical condition, a Respiratory Inductance Plethysmograph (RIP), which measures the movements of the thorax and the abdomen during normal breathing, and PI-provided instruments: handgrip dynamometer, infrared pulso-oximeter and haemoglobin photometer. The complete RMS-2 instrument package, including a considerable amount of consumables such as 480 litres of experiment-specific gas in a pressurised system (needed for the long mission duration), had a mass of 130 kg.

Figure 6.4.2. The Respiratory Monitoring System, used on the 179-day Euromir '95 mission to monitor the cardiovascular system and pulmonary performance

The RMS-2 experiment programme also included pre- and post-flight Baseline Data Collection (BDC). This required that the crew repeated the measurements after the mission, to study the re-adaptation to gravity following a long space mission.

6.5 Summary of Missions, Facilities and Experiments

Table 6.6 lists all missions on which ESA payloads have flown (apart from the short-duration flight opportunities offered by sounding rockets, parabolic aircraft flights, and drop tubes/towers); it therefore includes Spacelab, Bion/Foton, Eureca, Euromir '94 and '95 and Spacehab, together with the facilities flown, and the numbers of ESA experiments in the physical and life sciences performed on each of these missions. Slightly more than half of the total of 412 experiments are life-science related.

Table 6.6. The ESA Physical- and Life-Sciences Experiments performed on Spacelab, Bion/Foton, Eureca, Euromir '94 and '95 and Spacehab

Mission/Year		Physical Sciences	Life Sciences	Subtotal	Experiment Facilities Used
1.	**Spacelab Missions**				
1.1	SL-1 (1983)	36	8	44	
1.2	D-1 (1985)	6	20	26	
1.3	IML-1 (1992)	4	16	20	See Table 6.1
1.4	D-2 (1993)	9	19	28	
1.5	IML-2 (1994)	25	18	43	
1.6	USML-2 (1995)	14	-	14	
1.7	LSM (1996)	27	5	32	
1.8	Neurolab (1998)	-	7	7	
	Subtotal Spacelab	*121*	*93*	*214*	
2.	**Bion/Foton Missions**				
2.1	Bion-8 (1987)	-	3	3	Stand-alone Experiments
2.2	Bion-9 (1989)	-	5	5	Stand-alone Experiments
2.3	Foton-7 (1991)	1	-	1	Kashtan (Protein Cryst. Fac.)
2.4	Bion-10 (1992)	-	9	9	Biobox
2.5	Foton-9 (1994)	-	7	7	Biopan
2.6	Foton-10 (1995)	-	6	6	Biobox
2.7	Foton-11 (1997)	-	13	13	Biopan, Biobox
2.8	Foton-12 (1999)	4	7	11	Fluidpac, Biopan, Agat Furnace
	Subtotal Bion/Foton	*5*	*50*	*55*	
3.	**Eureca (1993)**	22	6	28	AMF, SGF, PCF, MFA, ERA
4.1	**Euromir '94 (1994)**	4	21	25	Freezers, Blood Kit
4.2	**Euromir '95 (1995)**	8	18	26	RMS-2, BDM, Blood Kit
5.	**Spacehab**				
5.1	SH1 (1993)	10	-	10	APCF
5.2	SH/MM3 (1996)	-	8	8	Biorack
5.3	SH/MM5 (1997)	-	7	7	Biorack
5.4	SH/MM6 (1997)	1	8	9	Biorack, MOMO
5.5	SH/STS-95 (1998)	26	3	29	AGHF, APCF, FAST, MOMO, Biobox
5.6	SH/STS-101 (2000)	1	-	1	MOMO (Morphological Model Substances)
	Subtotal Spacehab	*38*	*26*	*64*	
Total No. of Experiments		**198**	**214**	**412**	

* PS = Physical Sciences. LS = Life Sciences.

Table 6.7 shows the annual distribution of ESA-selected experiments performed on these missions, in the period 1983 – 2000, and the planned experiments and missions for the years 2001 and 2002.

Table 6.7. Annual Distribution of ESA-Selected Experiments performed on Spacelab, Bion/Foton, Eureca, Euromir '94 and '95 and Spacehab

Year	No. of Expts.	Mission
1983	44	Spacelab-1 (SL-1)
1984	-	-
1985	26	Spacelab D-1
1986	-	-
1987	3	Bion-8
1988	-	-
1989	5	Bion-9
1990	-	-
1991	1	Foton-7
1992	29	Spacelab IML-1, Bion-10
1993	66	Spacelab D-2, Eureca, Spacehab-1
1994	75	Spacelab IML-2, Foton-9, Euromir '94
1995	45	Spacelab USML-2, Foton-10, Euromir '95
1996	40	Spacelab LMS, Spacehab MM3
1997	29	Foton-11, Spacehab MM5 and MM6
1998	36	Spacelab Neurolab, Spacehab STS-95
1999	12	Foton-12
2000	1	Spacehab/ STS-101 (MOMO)
2001 (planned)	29 (LS:21 + PS:8)	Spacehab /STS-107: ARMS(8), Biopack(7), Biobox(4), Osteo(2), APCF(6), Fast(2)
2002 (planned)	30 (LS:23 + PS:7)	Foton M1: Biopan(4), IBIS(3), Stone(1), Fluidpac(4), Agat Furnace(3) (mission to be confirmed). Spacehab-R2: ARMS(8), Biopack (7)
Total incl. planned	**471**	**Of which 258 are life-sciences and 213 physical-sciences experiments**

LS = Life Sciences, PS = Physical Sciences.

Figure 6.5.1. Annual distribution of ESA microgravity experiments conducted in space, including the six-year hiatus in flight opportunities after the Challenger accident

The major findings of the life- and physical-sciences experiments are presented in the discipline contributions in Chapter 2. The annual number of publications in both life and physical sciences under microgravity conditions has increased strongly over the last 15 years (by a factor 3) and the so-called 'impact factor', a measure of the quality of the journals in which the publications have been accepted (from the journal Citations Reports issued by the Institute for Scientific Information), has also strongly increased (by a factor 3.5 over the last 15 years).

6.6 Short-Duration Flight Opportunities

From the start of Phase-1 of ESA's Microgravity Programme, short-duration flight opportunities were always a solid programme component, amounting to about 25% of the financial envelope. They started in May 1982, with ESA's participation in the Texus-6 sounding-rocket flight. Some 25 experiments were performed between 1982 and 1986. In 1987, during Phase-2 of the Programme, the frequency of ESA sounding-rocket flights was doubled to two per year. This increase was introduced to compensate for the six-year hiatus in Spacelab flight opportunities caused by the Challenger accident. ESA provided further short-duration flight opportunities from 1984 onwards with the introduction of parabolic aircraft flights, supplemented later with research opportunities in the drop tube at Grenoble (F) and the drop towers at Bremen (D) and near Madrid (E).

- *Sounding-Rocket Flights*

The sounding-rocket activities, which presently consist of the Texus, Maser, Maxus and Mini-Texus projects, have represented by far the largest element of the short-duration flight opportunities:

– Texus (Technologische Experimente unter Schwerelosigkeit): 360 sec of microgravity, about 250 kg of scientific payload
– Maser (Materials-Science Experiment Rocket): 360 sec of microgravity, about 250 kg of scientific payload
– Maxus (name derived from Maser and Texus): about 780 sec of microgravity, about 450 kg of scientific payload
– Mini-Texus (using a smaller rocket, but the same payload diameter as Texus): about 180 sec of microgravity, 100 kg of payload

The rocket missions provide reasonably good microgravity levels (better than 10^{-4}g), and use autonomous experiment modules developed for ESA or DLR by industry. Maxus can carry up to five experiment modules, Texus/Maser three to five modules, and Mini-Texus one or two modules, always in addition to a service module supplying data management via real-time telemetry/commanding and TV modules providing real-time video observation. The scientists are able to interact with their experiments during the flight (tele-science), a feature that has been available since 1983.

Sounding rockets provide reliable and frequent flight opportunities, with ESA currently performing typically two flights per year. They offer a short-preparation/turn-around time of 1.5 – 2.5 years between experiment selection and flight. In addition, the safety and documentation requirements for the experiments are very much lower than those for payloads on manned missions. It has turned out that sounding-rocket experiments are not only very useful as precursor experiments for later Spacelab/Spacehab and Mir missions or for the verification of the functioning of technical designs in low gravity, but they also provide several sub-disciplines with results that constitute a high scientific return in themselves.

Figure 6.6.1. Launch of a Maxus sounding rocket from Esrange, in Sweden

By mid-2000 ESA had supported flight opportunities on 41 sounding-rocket flights. With the help of industry, the Agency has developed a multitude of experiment modules and has frequently upgraded the service modules providing the telemetry down-link and telecommand up-link for the individual experiment modules.

Most of the flights have been performed within the framework of the Texus project, which was originally initiated (in 1976) by DLR, but later industrialised by the company MBB/ERNO-DASA. The Maser project was started in 1987 by the Swedish Space Corporation (SSC) and its last three missions were used exclusively by ESA on a commercial basis. Maxus, a joint venture between DASA and SSC, is also used by ESA on a commercial basis. The Mini-Texus programme was initiated by DASA in 1993, to provide cheaper flight opportunities for those investigations that can be performed in about 3 minutes of microgravity. This is of particular interest for combustion experiments. The launch campaigns for all four types of rocket take place at Esrange, near Kiruna in northern Sweden, as this launch site allows land recovery of the scientific payload.

By mid-2000, 38 Texus flights had taken place, of which 25 were used by ESA experiments (the others were used solely by DLR and SSC). A further 8 Maser flights, 4 Maxus flights (Maxus-1 had a rocket failure) and 4 Mini-Texus flights have also taken place. The ESA experiments performed on each of these rocket missions, together with their scientific themes, are listed in Tables 6.8 (Texus), 6.9 (Maser), 6.10 (Maxus) and 6.11 (Mini-Texus).

Table 6.8 Texus Sounding-Rocket Flights Carrying ESA Experiments

Launch	Flight	No. ESA Expts.	Research Topics of Experiments Performed
May 1982	Texus-6	4	Metallic composites. Diffusion in cast iron. Striations in germanium. Eutectic solidification.
May 1983	Texus-7	3	Metallic components with particles, immiscible AlPb alloys, single crystals of $CeMg_3$.
May 1983	Texus-8	2	Liquid-phase sintering, surface-tension/Marangoni effects
May 1984	Texus-9	4	Metallic composites, containerless solidification, thermal Marangoni convection, surface-tension minimum
May 1984	Texus-10	4	Critical point of H_2O. Ga-doped Ge crystal growth. Tungsten composites. Floating-zone injection
April 1985	Texus-11	1	Phase separation at critical point
June 1985	Texus-12	4	Liquid bridge. Critical point of H_2O. Rare-earth crystal growth. Ge crystal growth
April 1986	Texus-13	3	Salt crystallisation. Repeat of Marangoni experiment of Texus-8. Repeat of critical-point experiment of Texus-11
May 1987	Texus-14 B	6	Containerless alloy undercooling. Fluid-dynamics expt. Solidification of ZnBi Metal composites, dispersions, Ge crystal growth
May 1988	Texus-17	3	Ultrasound adsorption in salts. Colloid chemistry. Role of gravity in dorsal-ventral axis of amphibian embryos
May 1988	Texus-18	1	Freezing of long liquid column
Nov. 1988	Texus-19	5	Tungsten-composite sintering. Refractive-index change by ion exchange. Electrostatic positioning. Marangoni experiment reflight
Dec. 1988	Texus-20	1	Metal matrix composites
April 1989	Texus-21	2	Benard-Marangoni instabilities in circular and rectangular cells
Nov. 1989	Texus-23	3	Critical Marangoni flow. Rotational instabilities of liquid columns. Coagulation of dispersions
May 1990	Texus-25	1	Density and temperature relaxation near the critical point of CO_2
May 1990	Texus-26	1	Liquid-phase sintering of tungsten composites
Nov. 1990	Texus-27	6	Remelting of Fe-C-Si alloys. Heat-storage model. Liquid-phase sintering. Pressures in supercritical salt solutions. Visualisation of electrophoresis. Gravity's role in spatial orientation of biological cells
Nov. 1991	Texus-28	2	Reflight of Texus-27 electrophoresis expt. Reflight of orientation of biological cells
Nov. 1993	Texus-31	4	Wetting of GaInSb. Nucleation bubble growth/evaporation/condensation. Coagulation of suspensions. Marangoni instabilities
May 1994	Texus-32	2	Marangoni convection by evaporation. Differential wetting of GaInSb melts
Nov. 1994	Texus-33	3	Acceleration of liquid columns. Convection instabilities in phase separation of mixed fluids. Adsorption and surface tension
March 1996	Texus-34	1	Reflight: Interactive Marangoni convection

Table 6.8 cont'd . Texus Sounding-Rocket Flights Carrying ESA Experiments

Launch	Flight	No. ESA Expts.	Research Topics of Experiments Performed
March 2000	Texus-37	1	Critical velocities in open capillarity flow
April 2000	Texus-38	3	Droplet combustion evaporation. Flame spreading and forced flow convection. Signal transduction in osteoblasts
		70	**Of these 70 experiments, 4 were from the life sciences**

Table 6.9 Maser Sounding-Rocket Flights Carrying ESA Experiments

Launch	Flight	No. ESA Expts.	Research Topics of Experiments Performed
March 1987	Maser-1	5	3D-Marangoni convection. Thermo-capillarity. Drop motion. Thermal conductivity, meniscus stability if immiscible metals
Feb. 1988	Maser-2	7	3D Marangoni convection. Thermo-capillarity. Drop motion. Bridgman growth of Ga-doped Ge (2 expts). Directional solidification of immiscible alloy ZnPb. Adhesion of metals on ceramics. Precipitation in Zn-Bi alloys
April 1989	Maser-3	8	Metal-matrix composites. Particle agglomeration. Thermo-capillarity. Drop motion. Protein crystal growth. Membrane functions in green algae. Regulation of cell growth (growth-factor receptor for interaction). Binding of Concavalin A to Lymphocytes. Dorsoventral axis development in amphibian embryos
March 1990	Maser-4	5	Measurement of interfacial tensions. Orientation of DNA molecules during electrophoresis. Fertilisation of urchin eggs. Embryogenesis lymphocytes in microgravity. Regulation of cell growth and differentiation
April 1992	Maser-5	6	Wet satellite model. Solutal Marangoni effect. Marangoni effect due to evaporation. Refl. of expt.: Fertilisation of urchin eggs and embryogenesis. Plasma-membrane fusion in human fibroblasts. Nuclear response to protein. Kinare C signal transduction
Nov. 1993	Maser-6	5	Solutal Marangoni effect. Interaction on Marangoni migration. Cleavage stage development of urchin eggs after microgravity exposure. Development of Xenopus eggs fertilised in space. Cell-growth regulation and differentiation
May 1996	Maser-7	7	Enzyme catalysis. Liquid-phase epitaxial growth of SiC. Pool boiling with/without electric field. Signal transduction mechanisms in microgravity in immobilised neuroendrine cells. In-vivo culture of differentiated functional epithelial follicular cells from the thyroid gland
Jan 1998	Maser Tech. Flight	1	Convective boiling and condensation of ammonia in microgravity
May 1999	Maser-8	4	Cosmic-dust aggregation. Thermal-radiation forces in non-stationary conditions. Pool boiling with/without electric fields. Jet growth motions in aerosol
		48	**Of these 48 experiments, 18 were from the life sciences**

Table 6.10. Maxus Sounding-Rocket Flights Carrying ESA Experiments

Launch	Flight	No. ESA Expts.	Research Topics of Experiments Performed
Nov. 1992	Maxus-1B (Maxus 1 rocket failed)	7	Directional solidification of LiF-LiBaF3 eutectics. GaAs floating-zone growth. Floating-zone processing of fluoride glasses. Oscillatory Marangoni convection. Electrophoretic orientation. Marangoni convection. Lymphocyte experiments
Nov. 1995	Maxus-2	8	Marangoni instability in liquid containers. Marangoni instability near the critical-point. Continuous-flow electrophoresis. Influence of acceleration on spatial orientation of paramecium and loxodes lymphocytes. Behaviour of liquids in corners and at edges. Instability of multi-layered systems
Nov. 1998	Maxus-3	5	Pulsation and rotating instabilities in oscillatory Marangoni flows. Electrodynamic distortion during electrophoresis. Perception and ligual transduction in microtubule solution. Mechanism of gravitactic signal perception. Experiments in Chara Phizoids
		20	**Of these 20 experiments, 4 were from the life sciences**

Table 6.11. Mini-Texus Sounding-Rocket Flights Carrying ESA Experiments

Launch	Flight	No. ESA Expts.	Research Topics of Experiments Performed
May 1994	Mini-Texus 2	2	Marangoni Benard instability. Freon boiling experiment
May 1995	Mini-Texus 3	1	Influence of forced convection on flame-spreading processes over solid fuels
Feb. 1998	Mini-Texus 5	1	Piston effect in model fluids submitted to an oscillatory acceleration
Nov. 1998	Mini-Texus 6	1	Laminar-diffusion flames established over a flat fuel surface
		5	**No life-sciences experiments**

Table 6.12. Annual Distribution of ESA Experiments on Sounding Rockets

Year	Texus	Maser	Maxus	Mini-Texus	Total
1982	4				4
1983	5				5
1984	8				8
1985	5				5
1986	3				3
1987	6	5			11
1988	10	7			17
1989	5	8			13
1990	8	5			13
1991	2	-			2
1992	-	6	7		13
1993	4	5			9
1994	5			2	7
1995	-		8	1	9
1996	1	7			8
1997	-				-
1998	-	1	5	2	8
1999	-	4			4
2000	4				4
Total	**70 expts.**	**48 expts.**	**20 expts.**	**5 expts.**	**143 expts.**

Table 6.12 shows the annual distribution of all microgravity experiments on sounding rockets sponsored by ESA.

It clearly shows how ESA increased (at least doubled) the average number of experiments each year after the Challenger accident in 1986. A total of 143 ESA microgravity experiments were performed on sounding rockets between May 1982 and mid-2000, of which about half used the Texus flight opportunities. 25 of these 143 experiments were from the life sciences.

A sounding rocket can accommodate a number of experiments, not necessarily provided by the same space agency. In particular, many Texus flights (consisting of 3–5 experiment modules) were shared between DLR and ESA. The costs are also then shared pro-rata, according to the respective payload masses.

In total, ESA has flown about 6 tons of scientific payloads and associated service modules on sounding rockets, conducting many highly successful experiments in the fields of diffusion, electrolysis, interface phenomena, alloy solidification, crystallisation, critical-point research, combustion and biology. The results of these experiments have been published in the ESA Special Publication series: ESA SP-1132 for the physical-science experiments and ESA SP-1206 for the life-sciences experiments, available from ESA Publications Division.

- *Parabolic Flights on Aircraft*

Aircraft parabolic flights provide up to 20 seconds of low gravity (about 10^{-2}g). They are used to conduct short microgravity investigations in the life and physical sciences, to test instrumentation, and to train astronauts prior to a space flight. A campaign comprises typically three flights, each flying 30 parabolas.

In the past, ESA used various aircraft for precursor investigations and for the functional testing of Spacelab, Mir and Spacehab experiments:

– KC135 (provided by NASA): 1984 – 1989, 6 campaigns in the USA, and 1996, 1 campaign near Bordeaux
– Caravelle 234 (provided by CNES/Novespace):
1989 – 1995, 15 campaigns in Bretigny near Paris
– Ilyushin IL-76MDK (provided by Russian Space Agency):
1 campaign in July 1994 near Berlin in preparation for the Euromir '94 and Euromir '95 missions
– Airbus A300 (CNES/Novespace):
Since October 1997, with an average of 2 flight campaigns per year for ESA, near Bordeaux

The main advantages of parabolic flights are their short turn-around times of a few months, their low cost and their geographical proximity within Europe. The possibility for direct intervention by the investigators on board the aircraft is also a major advantage. By mid-2000, ESA's Microgravity Programme had supported 26 parabolic flight campaigns, during which a total of 360 experiments were performed.

Figure 6.6.2. The Airbus A300 during a parabolic-flight manoeuvre, which creates low-gravity conditions lasting about 20 seconds (courtesy of Novespace)

- *Drop Towers and Drop Tubes*

Drop tubes and drop towers are ground-based research facilities in which up to 10 sec of free-fall conditions can be achieved. Such facilities are being used for microgravity research in the USA, Japan and Europe. In line with the ESA Microgravity Programme's objective of providing practical opportunities for conducting experiments under low-gravity conditions, it offers experiment time free of charge for selected experiments at the drop tube in Grenoble (F) and at the drop towers in Bremen (D) and Madrid (E).

The 47 m-high drop tube in Grenoble (F) provides about 3 sec of microgravity at a level of 10^{-8}g. It has an internal diameter of 20 cm and is operated under ultra-high vacuum, which allows containerless processing of metal droplets for solidification studies, nucleation research, etc.

Figure 6.6.3. The drop tube in Grenoble (F), which provides 3 sec of weightless, free-fall conditions for solidification experiments (courtesy of CENG-Grenoble)

The drop tower in Bremen (D) is a multi-purpose facility for short-duration combustion, fluid-sciences and bio-technology experiments. It is an evacuated system, 110 m high and 3.5 m in diameter, which provides 4.7 sec of microgravity (10^{-5}g) for experiment packages of up to 170 kg. To double the microgravity duration, the tower is presently being fitted with a catapult system delivering a controlled acceleration. During its 10 years of existence, this drop tower has been used for about 3000 free-fall experiments. An average of about 30 drops are performed per experiment.

Figure 6.6.4. The Bremen drop tower, which can accommodate free-fall experiment packages of up to 170 kg (courtesy of ZARM)

The drop tower at INTA, near Madrid, is a 21 m-high facility, which provides 2.1 sec of free-fall conditions. As the fall occurs in the open air, the experiments are subject to aerodynamic drag. This can be avoided by using a drag-shield technique, whereby the experiment is released to fall freely inside an all-enveloping dropping capsule.

The experiment-support services provided at the drop towers/tube are already of a high technical standard and are continuously being upgraded.

6.7 The European Retrievable Carrier (Eureca) and Its Payload

The ESA Microgravity Programme's Phase-1, and later EMIR-1, provided microgravity research opportunities with durations ranging up to a maximum of 17 days on Spacelab missions. Analysis of the requirements of the experiments being proposed revealed that a number of them called for:

- Longer missions (especially for gravitational biology research and multi-generation plant growth).
- Better microgravity levels than were achievable on Spacelab (10^{-4}g) missions. The movements of astronauts induced considerable disturbances in the microgravity environment on Spacelab.

In 1980, therefore, ESA began studying a re-usable free-flying platform, initially called Mireca (Microgravity Retrievable Carrier), which would be launched by the Shuttle into a 250 km orbit, boosted to a 500 km-altitude orbit by its own propulsion system, and then retrieved again by the Shuttle after a 6 – 9 month stay in orbit. The name Mireca was subsequently changed to Eureca, to make it clear that investigations from other disciplines could also be flown.

Following a Call for Experiments, which was extended to all other disciplines such as space science, applications and technology, the Eureca programme was approved in 1982 and the first mission was scheduled for 1987. Unfortunately, due to the Challenger accident and the subsequent interruption of Shuttle flights, Eureca's maiden flight had to be postponed until 1993. Due to the large interest from the various microgravity disciplines, the Eureca development programme also included five microgravity multi-user facilities:

- The Automatic Mirror Furnace (AMF), for crystal growth of semi-conductors.
- The Solution-Growth Facility (SGF), for low-temperature crystal growth from the solution.
- The Protein-Crystallisation Facility (PCF), for protein crystallisation in 12 growth reactors.
- The Multi-Furnace Assembly (MFA), using 10 different furnaces for metal and alloy solidification studies.

- The Exobiology and Radiation Assembly (ERA), for exposing about 1000 specimens to selected features of the space environment.

Due to financial limitations, the originally planned botany facility with a closed ecological life-support system could not be developed for the first Eureca mission.

The Eureca platform had a payload mounting surface of 4.3 m by 2.2 m. The total mass of the platform was 4.5 tons, of which 1 ton was available for payload. The in-orbit hardware consisted of a core payload of the above listed five multi-user facilities, and a number of microgravity, space-science and technology add-on experiments. The ESA core payload was made up of processing chambers for crystal growth (inorganic and protein crystals) and furnaces for metallurgical experiments, and it allowed the study of the impact of the space environment – solar and cosmic radiation, weightlessness and vacuum – on organic molecules, membranes, bacterial spores, etc. The Eureca core payload's technical features and the experiments using the multi-user facilities of the core payload are summarised in Table 6.13.

The Eureca programme, which was originally planned to consist of a series of missions, was terminated after the first 11-month flight (launched 31 July 1992). Despite strong interest from the relevant user community, and although excellent microgravity levels (10^{-5} – 10^{-6}g) were achieved during that first mission, it proved impossible to get the participating ESA Member States to agree to any re-flights of the platform.

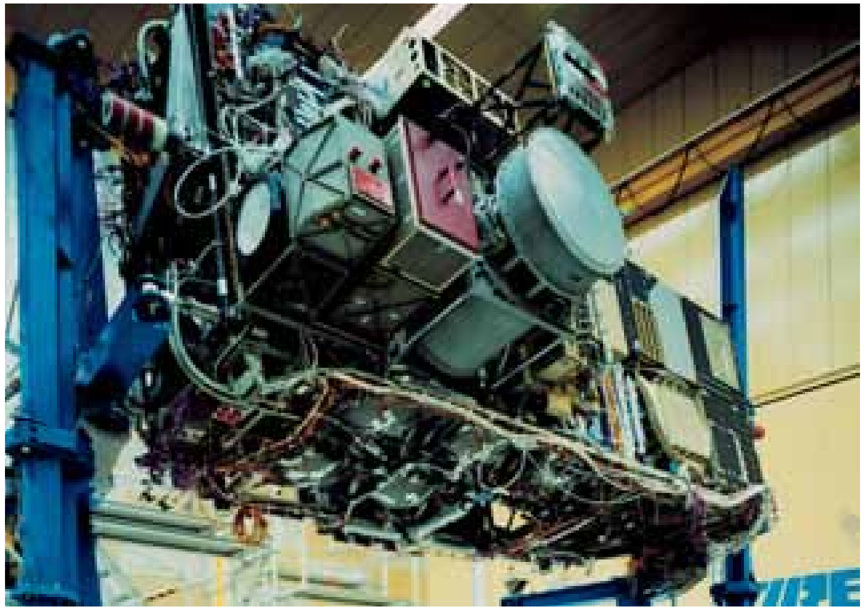

Figure 6.7.1. The Eureca retrievable carrier, which carried a 1 ton experiment payload and was launched and retrieved by the Space Shuttle

Table 6.13 The Eureca Core Payload, with Its Five ESA Multi-User Facilities

Multi-User Facility	Scientific Use	Technical Features
Automatic Mirror Furnace, AMF	Vapour crystal growth of II-VI semiconductors CdSe, CdTe Solution crystal growth of II-VI semiconductors CdTe with Travelling Heater Method (THM) THM solution growth of III-V semiconductors: InP, $Ga_{0.8} Al_{0.2} Sb$ THM growth $Pb_{1-x} Sn_x Te$ compounds Solution growth of ternary sulphides by THM: $Ag Ga S_2$ THM growth of $Ca In_2 Te_4$ Solution growth of Ga Sn (In)	Mass: 162 kg, incl. the 23 cartridges processed. Typical process temperature: 1000°C (depends on sample) Furnace consists of ellipsoidal cavity with halogen lamp at one focus and the sample to be processed at the other. The focussing of the lamp's radiation melts the samples at a transverse section. By slowly pulling the sample cartridge out of the furnace, directional solidification is achieved. For homogenous temperature distribution, the sample is slowly rotated
Solution-Growth Facility, SGF	Formation of amorphous tricalcium phosphate by solute diffusion crystal growth of $CaCo_3$ Synthesis of Zeolite crystals Soret diffusion-coefficient determination in binary organic mixtures and electrolyte solution	Mass: 75 kg. Consists of 4 reactors, operating in controlled temperature range 35° – 90°C independently (± 0.1°C) There are 3 isothermal reactors and 1 Soret diffusion reactor, consisting of 20 tubes in which thermal gradients are applied
Protein-Crystallisation Facility, PCF	12 independently controlled low-temperature solution-growth experiments of different proteins in 12 reaction chambers. Proteins include: Lysozyme, Beta-Galactosidase, Rhodopsin, Plasminogen, Fibrogen, Alpha Crustacyanime, tRNA, Asp/Aspartit tRNA Synthethase Complex, Bacterio Rhodopsin.	Mass: 145 kg. Temperature control: 0° – 25°C. Growth activation by connecting protein chamber with salt chamber via a buffer chamber in which crystallisation occurs. At the end of the growth process, connecting growth chamber with fourth reservoir containing fixation salt increases the salt concentration. In-flight video observation and interaction with experiments is possible
Multi-Furnace Assembly, MFA	5 experiments in solidification, diffusion and crystal growth: liquid-phase sintering, Ostwald ripening and diffusion, thermo-migration in liquid alloys, $Pb_x Sn_{1-x} Te$ and GaAs vapour growth, wettability of ceramic materials	Mass: 160 kg. Sequencial operation of 12 furnaces, due to power limitations. MFA consists of 12 furnaces, processing 33 samples for 5 experiments. Total processing time in orbit is 2 months. Temperature control in range up to 1000°C. 6 single-zone furnaces, 4 three-zone furnaces, 2 isothermal furnaces
Exobiology and Radiation Assembly, ERA	Exposure of biological specimens to the space environment. Interaction of HZE atomic nuclei with tissues. Exposure of spores and organic material to the space environment, effect of UV radiation on molecule formation and destruction, measurement of the composition of the cosmic radiation in the Eureca orbit, inactivation and mutant induction by solar irradiation	Mass: 57 kg. ERA consists of deployable and fixed experiment trays containing biological objects such as spores, seeds or eggs, alternated with radiation and track detectors. The periods of exposure are predetermined by the PIs and are controlled by means of shutters. Different space-radiation components are selected using optical band-pass filters

The main reasons why reflights were not approved were:

- The Shuttle launch and retrieval costs had increased dramatically after the Challenger accident in 1986, compared with the first Eureca flight, for which the ESA/NASA Shuttle-launch agreement had been concluded in 1983/84.
- Due to the Shuttle-imposed delay of more than 5 years on the first Eureca mission, the latter's development costs had considerably exceeded the original financial envelope. The Eureca microgravity core payload, however, represented less than 15% of the overall Eureca programme costs.
- Eureca was, to a certain extent, seen as a predecessor of the Columbus Free-Flying Laboratory. However, the financial limitations that ESA's Member States imposed on the Columbus Programme led to the Free-Flying Laboratory being deleted in the early 1990s.

From a scientific point of view Eureca's first mission was a great success. It also increased European technical know-how in retrievable free-flying satellites, their integration, fast disassembly after flight, and mission operations and, last but not least, it reinforced international co-operation.

6.8 Future Experiments and Microgravity Application Projects

- Life Sciences

The concept of Topical Teams (TT) for the identification and definition of research programmes and related experiments was already mentioned in Section 3.3.4. In order to prepare the future European life-sciences activities, ESA originally set up 10 TTs, of which five were dedicated to space biotechnology/bioengineering subjects.

Since 1996, ESA has been participating, together with other ISS Partners and national space agencies, in issuing international Life-Sciences Research Announcements (LSRAs) on an annual basis. These international, mainly ISS-related announcements have resulted – after review, analysis and rating of the submitted proposals – in 84 basic-research programmes being selected. In addition, 27 life-sciences Microgravity Application Projects (MAPs) from Europe have been selected by ESA. Non-space industry participates in these MAPs in different ways and with different levels of contribution. The degree to which ESA provides financial support to selected MAPs depends directly on the degree to which a research proposal is considered applications-oriented (from 0% for purely basic research, to 100% of an allocated maximum annual amount for a dedicated industrial applications-oriented research project). Financial support is provided by ESA only to the non-industrial partners in a project, with industry providing additional contributions in kind or in cash. Experience shows an average contribution by ESA of about one third of the total value of a project.

Not all of the experiments related to these basic-research and MAP projects involve an ISS flight opportunity; they cover the whole range of precursor and preparatory studies extending from ground-based bed-rest investigations to short-duration microgravity experiments, involving drop towers, parabolic aircraft flights and sounding-rocket flights. Experiment opportunities on Spacehab missions (7–16 days) using life-sciences facilities such as the ARMS (Advanced Respiratory Monitoring System), Biobox, Biopack, etc. are also required. Although the routine use of ISS facilities will only become available in several years' time (2005), a number of research programmes are already requesting the use of ISS laboratories, in addition to other earlier flight opportunities. Also, a number of exobiology experiments have been selected for flight on a Mars-Lander mission.

- Physical Sciences

For the physical sciences also, special Topical Teams (TTs) are being formed, with 16 already active at the end of 2000, as a result of earlier calls and selections. The Announcement of Opportunity (AO) for research-programme proposals released by ESA in 1998 and covering the fields of physical sciences and biotechnology resulted in 68 proposals being selected, 21 of which are financially supported by ESA as MAPs,

Table 6.8.1. Future Basic-Research and MAP Experiments in the Life Sciences

Flight/Research Opportunity	**Facility***	**Flight Year**	**No. of Basic Expts.**	**No. of MAP Expts.**	**Total No. of Expts.**
Ground-Based Research	Bed rest	-	11	1	12
Sounding Rockets	Maser-9	2001	2	1	3
	Maxus-5	2002	2	-	2
	Maser-10	2003	3	-	3
Spacehab:					
STS-107	Biobox-5	2002	4	-	4
STS-107	ARMS	2002	8	-	8
STS-107	Biopack-1	2002	8	-	8
STS-107	Osteo	2002	-	2	2
ISS Increments 1-2, STS-102	Dosimeter, Mapping	2001	1	7	8
ISS/US Laboratory	Human Research Facility + PI Equipment	2001/03	5	1	6
	EMCS	2003	5	2	7
	MARES/PEMS/HGD	2003	-	1	1
	Animal Research. Facility	TBD	1	-	1
Shuttle Missions to the ISS	MAP-supplied dedicated equipment, like sensors, etc.	TBD	-	7	7
ISS/Columbus Laboratory	Biolab	2005/6	1	1	2
	EDR	2005/6	-	3	3
	EDR-BMTC	TBD	-	3	3
ISS TBD (recent MAPs) (probably US Laboratory or Columbus Laboratory)	TBD (not EPM, Human Research Facility, partly ground expts.)	TBD	-	8	8
ISS Externally Mounted Expt.	Expose	2003/4	8	-	8
	Matroshka	2003	4	-	4
Total			63	37	100

** Technical descriptions of the facilities can be found in Sections 5.2, 6.2, 6.3 and 6.6.*

Table 6.8.2. Future Basic-Research and MAP Experiments in the Physical Sciences

Flight/Research Opportunity	Facility*	Flight Year	No. of Basic Expts.	No. of MAP Expts.	Total No. of Expts.
Sounding Rockets	Maxus-4	2001	6	-	6
	Maser-9	2001	1	1	2
	Maxus-5	2002	3	-	3
	Maser-10	2003	1	1	2
Shuttle-Get-Away Special (GAS)	PI-provided Equipment	2001	1	1	2
		2002/3	2	-	2
Spacehab, STS-107	APCF	2002	10	-	10
	FAST	2002	3	-	3
ISS External Platform (UF-6)	ACES	2005	1	-	1
ISS US Laboratory	MSL	2003	3	4	7
	APCF	2001	11	-	11
	Declic (CNES)	2005/6	1	1	2
ISS Columbus Laboratory	FSL	2004/5	4	4	8
	EDR	2004/5	-	5	5
	MSL-EML	2006	3	5	8
Total			**50**	**22**	**72**

** Technical descriptions of the facilities can be found in Sections 5.2, 6.2, 6.3 and 6.6.*

with funding proportional to the degree to which they are application-oriented, as for the life sciences.

The first international AO for physical sciences, released in 2000, with a submission deadline of January 2001, offers scientists the use of all experimental facilities on the ISS, independent of which ISS Partner is developing them or in which ISS laboratory they will be accommodated. The international coordination of this AO is aimed at avoiding duplication of facility development, ensuring maximum utilisation of the facilities themselves, and promoting the teaming up of researchers at international level (i.e. beyond European level).

Tables 6.8.1 and 6.8.2 list the numbers of basic-research experiments and MAPs selected in the life and physical sciences, together with the required flight opportunities, facilities and desired flight periods.

Tables 6.8.3 and 6.8.4 provide details about the life- and physical-sciences MAPs in the form of a short description of each MAP's objectives. The project coordinators and partners and the facility requirements are also listed. Table 6.8.5 lists the names of the industrial companies participating in the MAPs.

Table 6.8.5 Industrial Companies Participating in the Microgravity Application Projects (MAPs)

Belgium:	Sabca
Canada:	C-Core, Millennium Biologix
Denmark:	Damec Research
France:	Aubert & Duval, Cezus, Cime-Bocuze, Creusot Loire Industrie, Crismatec, ELF-EP, Institute Français du Petrole, Irsid, Nicox, Pechiney, Reosc, Satelec, S & CC, Schlumberger, Scometal-Creas, Sinters Robotics, Snecma, Sofradir, Three-Five Services
Germany:	AEG-IM, BMW-Rolls Royce Aero Engines, Celler Pflanzen und Gewebekultur, Clondiag Chip Technologies, Cortex Biophysik, Daimer Benz Aerospace, Degussa Huels, Deutsche Affinerie, Dornier GmbH, EFU, Eisenwerk Brühl, Richard Wolf Endoscope GmbH, Escube GmbH, Esytec Energie und Systemtechnik, Federal Mogul, Helmholtz Institut für Biomedizinische Technologie, Institut für Giessereitechnik, Intospace, IP & P, La Vision GmbH, Magma, MAN-Nutzfahrzeuge, MTU, Netzsch Geraetebau, Novocontrol, Novotec Maschinen, Pari GmbH, Sacher Lasertechnik, Schunk Sintermetal Technik, Schwermetall GmbH, Siemens AG, Siemens KWU, Speed Form GmbH, TFB-Feingusswerk Bochum, Thyssen Krupp Stahl, Tital, Vacuum Schmelze, VAW Aluminium, Verein Deutscher Giessereifachleute, WAV-Giesserei, Wieland-Werke
Hungary:	Duanferr Acelmuvek, Magyar Aluminium
Israel:	Advanced Metal Technologies
Italy:	Alenia Spazio, Bruckner Italiana, Burratto Advanced Technology Srl, Cantoni Engineering, Casti Imaging Srl, Corecom, DTM-Technologies, ENEA, ENI-Tecnologia, Ferrari SpA, Technogym Group SpA, Weidmann Plastics Technology
The Netherlands:	Amersham-Pharmacia Biotech, Bioclear, Clair Techn. Monsanto, Hoogovens R & D Corp. Service BV, Organic Waste Systems BV, Shell Research and Technology Centre, Stork
Norway:	Ergotest Technology, VESO Vet Research
Sweden:	Aerocrine AB, Ancra ABT AB, Copytec Film Original, Erikssons Mekaniska AB, Fabri AB, HG Foton, Saab Oxelund Production Department, Sigma Design & Development, SKF Nova AB, Swedish Space Corporation, Topis AB, Westermalms Metallgjuteri AB, YoYo Technology AB
Switzerland:	ABB Corporate Research, Calcom, Scanco Medical, Seyonic SA, Sulzer Medica, Swiss Metal SA
United Kingdom:	Alcan, British Steel, Cyto Science, GEC Marconi IR, Gentronix Ltd., Liquids Research Ltd.,Osprey Metals, Rolls Royce Universal Technology Centre, Sandvik Steel

Many of the companies listed above are participating in two or more MAPs. 65 companies are participating in the 27 life-sciences MAPs, and 87 in the 21 physical-sciences MAPs.

Table 6.8.3 Microgravity Application Projects (MAPs) in the Life Sciences

Proposal Number *Peer Evaluation*	**Coordinator**, *Partners*, **Company**, *(Country)*	**Title**	**Description**	**Facility**	**Flight Year**	**Status**
AO-LS-99-LSS-019 (MAP)	J. v. d. Waarde (NL), *P. Groot Koerkamp (NL),* *A. D'Amico (I),* *J. C. Nieuwland (NL),* *F. Eckhard (NL),* *F. Godia (E),* *M. A. Dixon (CND),* *A. B. Darlington (CDN)* plus 3 Dutch companies	Biological Air Filter for Air Quality Control of Life-Support Systems in Manned Spacecraft and Other Closed Environments	The project aims to develop a microbial-based biofiltration system to treat contaminated air emissions from animals housed in cages. The intention is to connect such a biofiltration unit to the higher-plant compartments of advanced life-support systems currently used in the MELISSA system. The system can be used to remove volatile organic compounds from all closed systems where release into the environment is not possible (e.g. submarines, spacecraft, etc.). Biosafety aspects will be addressed. The active converting organisms will be selected *Pseudomonas* strains. The project will also cover the development of a miniaturised electronic-nose concept to monitor and control atmospheric quality.	Shuttle/ISS	TBD	Ground phase
AO-99-122 (MAP)	D. Jones (D), *A. Mitchell (UK),* *B. v. d. Schoot (CH),* *J. v. d. Sloten (B),* *P. v. d. Wal (CH),* *U. Zanger (D)* plus 1 company from Germany, 1 from Switzerland, and 1 from the United Kingdom	Bone Metabolic Studies in a Combined Perfusion/Loading Chamber	This project will permit simulating in-vivo mechanical and perfusion conditions on bone samples and on engineered bone-tissue constructs. The proposed test hardware will allow synchronous mechanical stimulation and determination of the mechanical properties of living bone samples, as well as the determination of metabolic parameters, and the evaluation of signal transduction phenomena. There is a demand for such an instrument for orthopaedics on the ground. Commercial partners are involved in the instrument development.	BMTC in EDR	TBD	Ground phase
AO-99-030 (MAP)	W. Gowin (D), *A. Boshof (D),* *D. Felsenberg (D),* *P. Saparin (D),* *J. Kurths (D),* *L. Mosekilde (DK),* *J. Thomsen (DK)* plus 1 German company and 1 from Switzerland	2D & 3D Quantification of Bone Structure and its Changes in Microgravity Condition by Measures of Complexity	It is planned to improve microcomputer tomography hardware to the theoretical maximum resolution limit, and to develop novel image-reconstruction algorithms. This method will be of extreme significance for bone diagnosis. For this project, medical doctors will collaborate with mathematicians and physicists to optimise synergy.	Shuttle/ISS bone explants/ astronauts	TBD + F65	Ground phase
AO-99-121 (MAP)	M. Hoffmann (D), *F. Eckhard (NL),* *D. Jones (D),* *K. Meerholz (D),* *J. McInerney (IRL),* *J. Sacher (D),* *H. Voges (D)* plus 2 German companies and 1 Dutch company	Ballistic and Holographic 3-D High-Resolution Imaging of Bone	The imaging of bone using ballistic and holographic 3-D high-resolution imaging methods has a high potential to overcome the radiation problems associated with series of measurements in space and on the ground. In addition, the potential for developing a small, compact, and versatile instrument is very high. Since the submission of the proposal in February 1999, the team has managed to attract the interest and participation of additional leading companies in the complementary fields of laser technique, holographic films, and bone microstructure analysis.	Shuttle/ISS	TBD	Ground phase
AO-99-003 (MAP)	A. Cogoli (CH), *F. Ambessi Impiombato (I),* *A. Bader (D),* *P. Bruckner (D),* *W. Mueller (CH),* *R. Poertner (D),* *F. Saverio (I),* *I. Walther (CH)* plus 1 Swiss company	Modular Bioreactor for Medically Relevant Organ-Like Structures	The major objectives are the production of cartilage, without using any scaffold structure, and of blood vessels. Because of the extremely high content of exopolymeric material in cartilage, this may be the only means for in-vitro production of a functional cartilage analogue. Only microgravity conditions will allow an appropriate cell contact that is stable in position, while loose in cohesiveness. The highest effectiveness is expected for tissues organised primarily by extracellular matrix structures (cartilage and blood vessels).	Maser-9 Biolab/ EMCS BMTC in EDR	2001 TBD TBD	Ground phase To be approved To be approved
AO-LS-99-LSS-006 (MAP)	S. Bradamante (I), *J. Maier (I),* *J. W. de Jong (NL)* plus 1 Italian company	Vascular Endothelial Cells in Microgravity: Gene Expression, Cellular Energy Metabolism and Differentiation	The proposed studies of gene expression and energy metabolism modifications by microgravity conditions are very timely, and are expected to lead to new insights into tissue possibilities engineering. They could also provide new leads for the intense and ongoing research effort to tie endothelial tissue development to cancerous diseases. The group is purely academic, but even the lack of industrial partnership does not seriously detract from the potential of the project for health on Earth.	Biolab, otherwise EDR or Biopack	TBD	Ground phase

AO-LS-99-LSS-015 (MAP)	W. H. Verstraete (B), *H. Märkl (D),* *G. Brünner (D),* *C.-G. Dussap (F)* plus 1 Dutch company	A Total Converting and Biosafe Liquefaction Compartment for MELISSA	In the MELISSA model (Microecological Life-Support System Alternative), it is essential to convert all solid wastes to basic liquefied components. To this effect, the project proposes innovative solutions, based on recent developments obtained within the team. Adequate techniques for gas/liquid separation in a fermentation broth will be developed to support space experiments. Industry will contribute relevant expertise; it is expected to transfer the results to biowaste treatment processes on Earth.	TBD	TBD	Ground phase
AO-LS-99-LSS-017 (MAP)	L. Boarino (I), *M. Maffei (I),* *G. Sberveglieri (I),* *R. Arens-Fisher (D),* *W. Benecke (D)* plus 2 Italian companies	Closed-Habitat Environmental Control Sensors	This project aims to build a complete system for monitoring the environmental conditions for growing plants in space. The important factors are: light, CO2, ethylene (an important signalling molecule released by plants), and stress sensing by leaf-colour determination. Sensing will be based on thin-film porous silicon technology. This project will be an important contribution to life-support systems under microgravity conditions. Applications in manned spaceflight can be complemented with future applications in the food industry and with the monitoring of plant growth.	Shuttle/ISS	TBD	Ground phase
AO-LS-99-LSS-018 (MAP)	J. Krooneman (NL), *H. J. M. Harmsen (NL),* *J. E. Degener (NL),* *G. W. Welling (NL),* *P. Landini (CH),* *W. Koster (CH)* plus 2 Dutch companies	Molecular Tools for Monitoring and Control of (Pathogenic) Bacteria in Advanced Life-Support Systems	Because of the human organism's reduced immuno-reactivity under prolonged microgravity conditions, pathogen monitoring and reduction will be a must. The plating methods generally used reveal only but a small fraction of the bacteria present. Therefore, molecular detection techniques will be utilised and adapted for space use. The results of this work will be very interesting for Earth applications in environmental and health monitoring, and for basic research as well, i.e. for the development of a "dry PCR" which can be easily handled. An innovative element will be the introduction of non-pathogens to outcompete pathogens in biofilms.	Shuttle/ISS	TBD	Ground phase

AO-LS-99-LSS-034 (MAP)	R. M. Walmsley (UK), *S. Wolfl (D),* *N. Goddard (UK),* *P. Fielden (UK),* *T. Hammond (USA)* plus 1 British company and 1 from Germany	A Biosensor to Monitor Radiation Induced DNA Damage on the International Space Station: Risk Assessment for Astronauts	The project aims to further develop an existing yeast-based biosensor system. It will act via modification of the expression of the Green Fluorescent Protein (GFP) system in response to DNA damage. The existing system will be modified to assess radiation-induced DNA damage through the construction of genetically engineered yeast strains with enhanced sensitivity to radiation. The team will develop both a novel tape-based sensor system for continuous monitoring of radiation exposure, and a badge-based system for the detection of occasional high-risk exposure.	Shuttle/ISS	TBD	Ground phase
AO-LS-99-LSS-003 (MAP)	R. Goerlich (D), *P. Ahleström (N),* *J.-M. Hein (D),* *E. W. Knapik (D),* *K. Piepenbreier (D),* *M. Schartl (D),* *C. Winkler (D)* plus 1 Norwegian company	Investigation of Developmental Pathways Leading to Bone Formation and Bone Homeostasis by Genetic Dissection and Functional Analysis of Osteoprotegerin in a Transgenic Fish Model on Earth and in the Microgravity Environment	Induction of osteoporosis constitutes one of the major medical problems under spaceflight conditions. The team proposes a strategy to identify key regulatory elements of conserved eukaryotic signalling pathways controlling bone formation under normal and microgravity conditions. The researchers plan to use highly efficient molecular, immunological, and cytological techniques in combination with transgenic fish models to identify functions affected by microgravity in bone formation. In combination with pharmacological studies, the proposed project may lead to the development of novel strategies for better control of osteoporosis.	Shuttle/ISS	TBD	Ground phase
AO-99-098 (MAP)	K.Palme (D), *M. Bennet (UK),* *H. Hammerle (D)* plus 3 German companies	Perception of Gravity, Signal Transduction and Graviresponse in Higher Plants by Innovative Genomic Technologies	The aim of the proposal is to unequivocally identify genes which are activated, or in some way regulated, by gravity. This knowledge can have an impact on practical agronomic issues; e.g. architecture of root and shoot systems, as well as realising this potential for regulating plant growth in space. Significant interest and support from industry is demonstrated, especially in the analytical genomic sector.	EMCS	TBD	Ground phase
AO-99-091/01 (MAP)	ERISTO - led by C. Alexandre/L. Vico (F)z plus 2 Swiss companies and 1 from Canada	ERISTO - Effect of Space Flight on Osteoblasts/Matrix Interaction	Study the origin of the mineralisation impairment process in the hypothesised association between the observed short-term space-related adhesion change in osteoblastic cells and a change in the extracellular matrix production and/or organisation.	OSTEO (Canadian prog.)	2001	STS 107 Phase-D

AO-99-091/02 (MAP)	ERISTO - led by A. Zallone (I) plus 2 Swiss companies and 1 from Canada	ERISTO - Influence of Microgravity on Osteoclast Formation from the Bone Marrow	Study the origin of the space-induced osteoporotic conditions in a change in the osteoclast formation rate by differentiation from cells of the monocytic lineage.	OSTEO (Canadian prog.)	2001	STS 107 Phase-D
AO-99-091/03 (MAP)	ERISTO - led by R. Cancedda (I) plus 2 Swiss companies and 1 from Canada	ERISTO - STROMA 2 Human Bone Marrow Stromal Cell Proliferation and Differentiation in Microgravity: Analysis of mRNA	Study the evolution of the differentiation potential of HBMSC towards osteoblasts under growth factor and hormone stimulating conditions and under unstimulated control conditions. Extracted RNA will be analysed for genes related to osteogenesis.	OSTEO (Canadian prog.)	2001	R 2 Definition Phase + backup for STS 107
AO-99-091/04 (MAP)	ERISTO - led by P. v. d. Saag (NL) plus 2 Swiss companies and 1 from Canada	ERISTO - Oestrogen or NFkappaB Response of the Osteoblastic U2OS-Engineered Cell in Microgravity	Investigate the respective role of oestrogen receptors, alpha and beta, in signal transduction using cells that have been engineered with a reporter gene.	Biopack	2002	R 2 Definition Phase
AO-99-091 (MAP)	L. Braak (F), *R. Cancedda (I),* *C. Drummer,* *M. Heer (D),* *B. Koller (CH),* *S. Pugh (C)* *P. Ruegsegger (CH),* *P. v. d. Saag (NL),* *K. Vaananen (FIN),* *L. Vico (F),* *C. Alexandre (F),* *A. Zambonin (I)* plus 2 Swiss companies and 1 from Canada	ERISTO - Osteoporosis	"ERISTO-Osteoporosis" constitutes the second phase of an activity initiated as a MAP Project in 1997. A major objective is the 3-D culturing of the three main types of bone cells in a biodegradable matrix for the production of bone analogues. The cell growth and remodelling will be characterised by a microcomputer tomography visualisation technique, also part of the development. Animal models, including genetically engineered mice, will be studied and compared. A set of models will be selected for use within the project. State of the art molecular biological methods will be utilised to explain cell behaviour.	OSTEO (Canadian prog.) BMTC in EDR	2001 TBD	Ground phase To be approved

AO-99-058 (MAP)	E. Messerschmidt (D), *S. Fasoulas (D),* *D. Essfeld (D),* *R. Hemker (D),* *U. Hoffmann (D),* *C. P. Kretschmer (D),* *D. Linnarsson (S),* *M. Paiva (B),* *F. Ritthaler (D),* *R. Stoll (D),* *N. Stoll (D),* *M. Sauer (D),* *E. Sommer (D),* *R. Stangl (D)* plus 3 German companies	Development and Application of a Miniaturised Sensor System for Respiratory Investigations	This proposal intends to expand on a new technology that has emerged from the development of small, solid electrolyte oxygen sensors for environmental monitoring. This sensor can be incorporated in miniature, portable measurement devices for the simultaneous determination of total gas flow rates, and of oxygen and carbon dioxide concentrations, without the need for additional pumps, tubing, or valves. The applications are in the fields of cardiopulmonary physiology, sports medicine, and rehabilitation medicine.	ISS	TBD	Ground phase
AO-99-081 (MAP)	P. Norsk (DK), *N. J. Christensen (DK),* *B. Pump (DK),* *A. Gabrielsen (DK),* *J. G. Nielsen (DK),* *Ch. Drummer (D),* *M. Kentsch (D),* *N. Gadsboll (DK)* plus 1 Danish company	Long-Term Microgravity: A Model for Investigating Mechanisms of Heart Disease with New Portable Equipment	This proposal addresses cardiovascular phenomena observed in cardiac patients and astronauts alike. The team wishes to develop a portable monitoring system to simultaneously determine a number of cardiovascular parameters. Besides its applications in the care of ailing patients, this equipment would also be useful to study adaptive changes in humans during prolonged spaceflight.	ISS	TBD	To be approved
AO-99-013 (MAP)	D. Felsenberg (D), *G. Armbrecht (D),* *L. Mosekilde (DK),* *J. S. Thomsen (DK),* *J. Rittweger (D),* *D. F. Stegeman (NL),* *G. Wilhelm (D),* *G. Tysarczyk-Niemeyer (D)* plus 1 German company	Vibration Exercise as a Countermeasure for Muscular Atrophy and Bone Loss	Vibration exercise is known to effectively enhance muscle strength via reflective, non-voluntary contractions. This work focuses on the use of a vibration exercise device during a set of ground-based experiments (human bed rest and hind limb suspension of rats); and later, during spaceflight, on both humans and rats. It is postulated that vibration exercise can effectively prevent bone loss and muscle atrophy. The beneficial effects of any strategy potentially capable of limiting or counteracting osteoporosis and muscle atrophy, will be paramount for the development of countermeasures for prolonged spaceflight complications, ageing human problems, and neuromuscular diseases.	Bed rest	TBD	

AO-LS-99-MED-030 (MAP)	H. E. Berg (S), *P. Tesch (S),* *R. Merletti (I),* *M. Narici (UK),* *O. M. Rutherford (UK),* *J. Zange (D)* plus 8 Swedish companies, 1 company from Italy, and 1 from Norway	Resistance Training Using Fly-Wheel Technology for Crew's Stationed in Space	This project deals with the physiological deconditioning during spaceflight. In order to combat bone loss, muscle atrophy and muscle function, it is proposed to use resistive exercise based on fly-wheel technology. The proposal focuses on performing ground-based experiments to design flight-ready hardware, and for the prescription of in-flight protocols. The applications are in the field of rehabilitation medicine for elderly people and injured patients, as well as in home gyms for healthy people.	Fly-wheel exercise device ISS	2001 TBD	R 2 To be approved
AO-LS-99-MED-027 (MAP)	P. Di Prampero (I), *G. Antonutto (I),* *R. Merletti (I),* *C. Orizio (I),* *F. Bodem (D),* *F. Cassese (I),* *A. Malagoli (I),* *R. Fenech (I),* *D. Santachiara (I),* *M. Zotele (I),* *F. Solieri (I)* plus 2 Italian companies	Effects of Simulated and Actual Microgravity on Muscle Function During Explosive Efforts	This team plans to design and construct a special ergometer for the assessment of explosive muscle power. This device will be used to define to what extent changes in the central and peripheral motor control system are involved in the drastic decrease in explosive power (50-70%) observed after spaceflight. The introduction onto the market of this novel device (for non-space application) is also envisaged.	Pre-/post-flight crew time	TBD	Ground phase
AO-LS-99-MED-031 (MAP)	D. Linnarsson (S), *L. E. Gustafsson (S),* *C. G. Frostell (S),* *M. Carlson (S),* *J. Mann (S)* plus 2 Swedish companies	Airway Nitric Oxide in Microgravity	This work belongs to the field of pulmonary research. It is proposed to improve a technique for Nitric Oxide (NO) analysis to unmask NO physiological actions in humans under microgravity. These changes may indeed not be apparent when lung deformation and movements are influenced by gravity. The applications are in clinical research and potentially in monitoring asthmatic patients.	TBD	TBD	Ground phase

AO-LS-99-MED-024 (MAP)	L. Braak (F), *R. Cancceda (I),* *W. Mueller (CH),* *A. Zallone (I),* *Ch. Alexandre (F),* *P. Del Soldato (I),* *P. Ruegsegger (CH),* *B. Loller (CH)* plus 1 French company and 2 from Switzerland	ERISTO: Transgenic and Normal Mice as Models to Study Osteoporosis Mechanisms and to Test Drugs	This is a research programme complementing the existing ERISTO (European Research in Space and Terrestrial Osteoporosis) project. It focuses on the influence of microgravity-induced and immobilisation-induced remodelling of bone using animal models (mice). This research is expected to improve the understanding of mechanical constraints in bone remodelling and to provide models to support osteoporosis-targeted drug screening in space and during ground simulations.	TBD	TBD	Ground phase
AO-LS-99-MED-007 (MAP)	L. De Marco (I), *V. Vicente Garcia (E),* *R. Perris (I)* plus 2 Italian companies	A Novel System for In-Vitro Detection of Gravity Effects on Primary Haemostasi	This research is in the field haemostatis and thrombosis. The programme will develop a novel, in-vitro system for low-cost automated diagnostic analysis, having minimal invasiveness, for use in space and on the ground. In addition, since this analysis is prone to alterations by gravitational forces, the microgravity environment may help to improve the process on Earth. The clinical applications are widespread; for example, the monitoring of anti-neoplastic therapies.	TBD	TBD	Ground phase
AO-LS-99-MED-028 (MAP)	R. Merletti (I), *P. Di Prampero (I),* *G. Antonutto (I),* *P. Tesch (S),* *C. Orizio (I),* *C. Dario Farina (I),* *A. Rainoldi (I),* *M. Pozzo (I)* plus 1 Italian company	Microgravity Effects on Human Skeletal Muscle Function Investigated by Surface EMG and Mechanomyogram	The proposal focuses on the upgrading of prototypes of electromyographic (EMG) and mechanographic (MMG) techniques for the non-invasive characterisation of human skeletal muscles. The two techniques, used jointly, are a powerful tool for quantitative monitoring of muscle deconditioning due to spaceflight. These techniques are complementary to the ESA MARES, PEMS and HGD hardware. The applications are in quantitative monitoring of muscle deconditioning/ reconditioning during exercise, for age-related muscle atrophy, and injured patients.	TBD	TBD	Ground phase
AO-LS-99-MED-023 (MAP)	Ph. Arbeille (F), *P. Marche (F),* *P. Vieyres (F)* plus 1 French company	Echographic and Doppler Diagnostic Guided by a Robotic Arm (Telemedicine)	This work deals with remote diagnostics of diseases by standard ultrasound echography and Doppler technology, remotely operated by a specialist via a robot. The proposal focuses on the improvement of a prototype to be used on the International Space Station, and in remote areas. No funding has been requested from ESA in this proposal.	TBD	TBD	Ground phase

Table 6.8.4 Microgravity Application Projects (MAPs) in the Physical Sciences

Proposal Number *Peer Evaluation*	**Coordinator**, *Partners*, **Company**, *(Country)*	**Title**	**Description**	**Facility**	**Flight Year**	**Status**
AO-99-075 (MAP)	J. Banhart (D), *D. Langevin (F),* *S. Odenbach (D),* *D. Weaire (IRL),* *H. Frederiksson (S),* *B. Kronberg (S),* *F. Baumgaertner (D),* *D. Schubert (D)* plus 1 German company and 1 French company	Development of Advanced Foams under Microgravity	This proposal addresses both Metallic Foams and Aqueous Foams. The metallic foam experiments will concentrate on improving production methods, with special regard to the quality and reproducibility of the foams. The investigators will utilise molten metals in microgravity to generate foams. They will monitor the foaming process, analyse the foams produced and their properties, and apply magnetic fields to control the bubble distribution during foam production. The team will also develop novel foam structure analysis tools. The aqueous foam investigations aim to increase the physico-chemical understanding of the mechanisms that affect foam film rupture. Thus, fluid motions in the liquid films between foam bubbles will primarily be studied here.	PF FSL EDR or MSL insert	Yearly 2004 TBD	Phase-A/B EC in 2001 (with AO-99-108) Phase-A in 2001 MAP contract started 1 July 2000
AO-99-108 (MAP)	G. Verbist (NL) *D. Weaire (IRL),* *D. Langevin (F)* plus 1 Dutch company	Hydrodynamics of Wet Foams	A study in the absence of gravity-driven instabilities will result in a broader experimental characterisation of wet foams than is possible on Earth. This, in turn, will lead to an improvement of the operational window design for foam handling in industrial processes, for example, in gas/liquid contacting, floatation, pumping, etc. Better foaming systems may then be selected using film properties and foam stability criteria derived from this work.	PF FSL	Yearly 2004	Contract in negotiation Phase-A/B EC in 2001 (with AO-99-075)
AO-99-022 (MAP)	H.-J. Fecht (D), *L. Battezzati (I),* *I. Egry (D),* *K. Mills (UK),* *A. Passerone (I),* *P. Quested (UK),* *S. Seetharaman (S),* *B. Vinet (F)* plus 7 German companies, 3 from the United Kingdom, 1 from the Netherlands, and 1 from Sweden	High-Precision Thermophysical Property Data of Liquid Metals for Modelling of Industrial Solidification Processes	Numerical simulations are increasingly used as a tool for the microstructural optimisation of high-quality castings. However, due to the inherent difficulties stemming from the high temperatures, and to the aggressive nature of the melts, the precision of the models is often not sufficient. Thanks to the successful development of containerless processing, measurements at high temperatures of critical and reactive materials are now possible. The proposed research will focus on the determination of thermophysical properties of metals and alloys of industrial relevance (Ni-, Fe-, Cu-, and Ti- based alloys and superalloys).	Dtube PF	2001 TBD	MAP contract in negotiation
AO-99-031 (MAP)	G. Mueller (D), *D. Camel (F),* *H. Jones (UK),* *Y. Fautrelle (F),* *L.Ratke (D),* *A. Roosz (H),* *G. Zimmermann (D)* plus 4 German companies, 2 from Hungary, and 2 from the United Kingdom	Microstructure Formation in Casting of Technical Alloys under Diffusive and Magnetically Controlled Convective Conditions	The goal is to study microstructure formation during casting of technical alloys under diffusive and magnetically controlled conditions. The experimental results obtained with this programme, together with parametric studies using numerical simulations, will be used to optimise industrial casting processes.	MSL	2003/4	Phase-A/B cartridges in 2001 -To be approved- MAP contract start 1 September 2000
AO-99-094 (MAP)	Ch. Eigenbrod (D), *Th. Sattelmayer (D)* plus 3 German companies, and 1 from Switzerland	Combustion Properties of Partially Premixed Spray Systems in the Fields of Droplet and Spray Combustion	The experiments will study the vaporisation, auto-ignition, and combustion of fuel droplets in a controlled environment, as well as the generation of greenhouse polluting byproducts such as NO_x. This work has direct applications to the improvement of aircraft-engine and gas-turbine efficiency.	DTower PF NASA's CIR	2000/1 Yearly TBD	DT contract COA2 placed Phase-A in 2001 MAP contract started 1 April 2000

AO-99-117 (MAP)	B. Billia (F), *A. Gandin (F),* *D. Camel (F),* *J. Hunt (UK),* *K. Kassner (D),* *A. Wheleer (UK),* *G. Zimmermann (D)* plus 6 French companies, 3 from Germany, 2 from Switzerland, and 2 from the United Kingdom	Columnar-Equiaxed Transition in Solidification Processing	The research programme's ultimate objective is to improve the integrated modelling of grain structure in industrially important castings. This will be achieved by increasing the quantitative understanding of the basic physical principles governing microstructure formation in solidification processes, under diffusive conditions, and with fluid flow in the melt.	MSL	2003/4	Phase-A/B cartridges in 2001 -To be approved- MAP contract in negotiation
AO-99-052 (MAP)	A. Passerone (I), *D. Clausse (F),* *L. Liggieri (I),* *G. Loglio (I),* *R. Miller (D),* *A. Steinchen (F),* *A. Di Lullo (I)* plus 1 Italian company	Fundamental and Applied Studies of Emulsion Stability	These studies will address single and multiple interfaces, as affected by various surfactants. An important part of the programme aims at establishing links between emulsion stability and physico-chemical characteristics of droplet interfaces. Further experiments are planned to investigate droplet dispersion in emulsions and phase inversion. On the basis of these studies, the team will generate a model of emulsion dynamics to be transferred to industrial applications.	FSL EDR	2004 TBD	Phase-A/B EC in 2001 Phase-A in 2001 MAP contract started 1 October 2000
AO-99-021 (MAP)	S. Odenbach (D), *R. W. Chantrell (UK),* *P. Fannin (IRL),* *K. O'Grady (UK)* plus 1 German company and 1 from the United Kingdom	Thermal Transport Phenomena in Magnetic Fluids under Microgravity Conditions	The focus of this research is the quantitative investigation of the influence of magnetic fields on ferrofluid transport phenomena under the influence of a thermal gradient. A ferrofluid is a fluid containing magnetic particles; it is sensitive to temperature gradients and to magnetic fields. The proposed experiments will lead to advances in the technologies to magnetically control the position of the fluid bulk, as well as its heat- and mass-transfer properties. This will have important applications for the future design of thermal management devices.	PF EDR	Yearly TBD	Phase-A in 2000 MAP contract started 1 August 2000

AO-99-023 (MAP) *merged with* AO-99-025 *and with* AO-99-036	A. L. Greer (UK), D. Herlach (D), *R. Cochrane (UK),* *A. García-Escorial (E),* *A. Mullis (UK),* *P. Sahm (D)* plus 6 German companies and 3 from the United Kingdom	Non-Equilibrium Solidification Modelling for Microstructure Engineering of Industrial Alloys Dendrite Growth Velocities in Dilute Alloy Melts: Tests of Solidification Theory on Technologically Relevant Materials Dendrite Growth Velocities in Aluminium-Based Alloys	The investigations will concentrate on crystal-growth conditions, and on their impact on microstructure development for industrial materials (Ni-, Al-, Ni-, Al-Fe, Al-Cr, Fe-C, Fe-C-Si, and Fe-C-Si-Mn-P-S based alloys). The team will develop models of crystal growth for these materials. An interesting feature of dendrite growth is that small solute additions to otherwise pure systems can lead to enhancement of the growth velocity. Dendrite growth velocity will be studied and compared between pure Ni, a dilute binary Ni alloy, and a commercial Ni superalloy. Suitable models will be developed for dendritic growth. The goal is to study dendrite growth velocities in solidifying Al alloys, using the magnetic levitation technique, and to develop suitable models.	MSL-EML Phase-A/B in cooperation with DLR		MAP contract in negotiation
AO-99-110 (MAP)	J.-Cl. Legros (B), *G. Lebon (B),* *P. Cerisier (F),* *M. Bestehorn (D),* *P. Stephan (D),* *A. Delil (NL)* plus 1 Belgian company	Convection and Interfacial Mass Exchange	This programme is devoted to the study of mass-transfer processes through interfaces, and their coupling with surface-tension-driven (Marangoni) flows and instabilities. The modification of mass-transfer efficiency by interfacial flows and instabilities is of the uttermost importance in a variety of chemical-engineering applications, e.g. phase separation, absorption/desorption, liquid-liquid extraction, etc. This work will also concentrate on addressing some of these industrial concerns.	Maser 9 Fluidpac FSL	Autumn 2001 2002 2004/5	Approved -To be approved- Phase-A/B EC in 2001 MAP contract started 1 October 2000

AO-99-114 (MAP)	D. Herlach (D), M. Kolbe (D), *A. Ludwig (D),* *L. Granasy (H),* *W. Kurz (CH),* *W. Loeser (D)* plus 3 German companies, 1 from Switzerland, and 1 from the United Kingdom	Metastable Solidification of Composites: Novel Peritectic Structures and In-Situ Composites	The aim of this project is to improve the processing of commercial peritectic alloys through microstructure control, e.g. through the development of a phase selection model, and of a model predicting the pushing/engulfment of particles by a growing dendritic front. The output of these microstructure models will be compared to experimental data obtained in 1- and in 0-g environments.	MSL MSL-EML Phase-A/B in cooperation with DLR DECLIC	2003/4 2003/4	Phase-A/B cartridges in 2001 -To be approved- Phase-A cell in 2001 (with AO-99-046) MAP contract 1 November 2000
AO-99-111 (MAP)	J.-Cl. Legros (B), *E. Stenby (DK),* *J. P. Caltagirone (F),* *Z. Zaghir (F),* *D. J. Hart (CDN),* *F. Montel (F)* plus 1 Canadian company and 1 from France	Diffusion and Soret Coefficient Measurements for Improvement of Oil Recovery	This work consists of three stages: (a) the determination of diffusion data requirements for petroleum reservoir models; (b) the simultaneous measurement of the Soret diffusion coefficients in binary and in tertiary systems; and (c) the refinement of a multicomponent transport model applied to petroleum reservoir evaluation.	GAS in cooperation with CSA EDR	2001 TBD	Approved Phase-A in 2001 MAP contract started 1 January 2000
AO-99-007 (MAP)	S. Will (D), *A. Leipertz (D)* plus 3 German companies	Investigations on Soot Concentration and Primary Particle Sizes by Advanced Laser Induced Incandescence	Soot formation is a sign of energy losses during combustion. Furthermore, soot particles are pollutants. This research will concentrate on the mechanisms of soot nucleation, growth, and oxidation during combustion processes. The microgravity experiments will specifically study the effects due to fuel flow rate, and to the relation between fuel and air flow during combustion. Laser-induced incandescence and electron microscopy are expected to provide the data necessary for modelling soot growth in the phase after the nucleation of primary particles. An additional goal will be to study the production of carbon black and other nano-particles having very desirable industrial properties.	Dtower PF NASA's CIR	2000/1 2001 TBD	DT contract COA2 placed -To be approved- MAP contract started 1 July 2000
AO-99-095 (MAP)	Ch. Eigenbrod (D), *H. Ciezki (D),* *W. Koschel (D),* *A. Taylor (UK),* *W. Triebel (D),* *Th. Sattelmayer (D),* *Th. Van der Meer (NL),* *A. Veyssiere (F),* *J. Jarosinski (PL),* *A. Giesen (D)* plus 1 German company	Flame Vortex Interaction in the Fields of Turbulent Gaseous and Heterogeneous Combustion	The aim is to study the effects of high-turbulence intensities on flame propagation velocities, flame-front distortion, wrinkling, and flame-front break-up. The work will also address the interaction of propagating gaseous flames with a dispersed, inert water spray.	DTower PF NASA's CIR	2000/1 Yearly TBD	DT contract COA2 placed -To be approved- MAP contract in negotiation

AO-99-035 (MAP)	K. Benz (D), *M. Fiederle (D),* *T. Duffar (F),* *J. L. Santailler (F),* *P. Dusserre (F),* *J. C. Launay (F),* *T. Arnoux (F),* *X. Lagoueyte (F),* *G. Roosen (F),* *Ph. Delaye (F),* *E. Dieguez (E),* *L. Zanotti (I),* *C. Paorici (I),* *J. P. Collette (B)* plus 5 French companies, 2 from Germany, 1 from Italy, and 1 from the United Kingdom	Crystallisation of CdTe and Related Compounds	The objective of this experiment is to develop new growth technologies for producing high yields of large, high-quality CdTe crystals for electro-optical applications, e.g. X-ray detectors, photo-refractive devices, and infrared sensors.	MSL	2003/4	Phase-A/B cartridges in 2001 -To be approved- MAP contract started 1 July 2000
AO-99-010 (MAP)	I. Egry (D), *D. Herlach (D),* *R. Abbaschian (USA),* *W. Bender (D),* *L. Ratke (D),* *D. Chatain (F),* *S. Dietrich (D),* *B. Groh (NL)* plus 1 German company	Undercooling and Demixing of Cu-Co Alloys	It is proposed to undercool Co-Cu alloys in the miscibility gap by electromagnetic levitation, and to investigate their liquid/liquid separation behaviour, the correlation between undercooling and microstructure evolution, the surface and interfacial tension before and after demixing, the wetting properties, and the magnetic ordering at deep undercooling.	MSL-EML Phase A/B in cooperation with DLR		MAP contract in negotiation

AO-99-083 (MAP)	S. C. Mueller (D), *K. Eckert (D),* *A. de Witt (B),* *J. P. Boon (B),* *D. Salin (F).* *H. A. Dijkstra (NL)* plus 1 French company	Chemo-Hydrodynamic Pattern Formation at Interfaces	The two main goals in studying "chemical fronts" are to understand the interplay between viscous and density fingering, and autocatalytic reactions. The work will also centre around "chemical reactions at liquid-liquid interfaces," where the processes are due to chemically-driven interfacial convection. In both instances, the focus will be on quantifying the dynamics and the products. The results of this work are of interest for multiple industrial/environmental applications, including efficient oil recovery, ground water remediation, and reactive liquid/liquid extraction.	PF Maser 10	Yearly 2003	-To be approved- MAP contract in negotiation
AO-99-026 (MAP)	L. Ratke (D), *A. A. Wheeler (UK),* *A. Ludwig (D)* plus 1 German company	Solidification Morphologies of Monotectic Alloys	Monotectic and peritectic solidification are emerging areas of research. The monotectic reaction is observed in a wide class of alloys exhibiting a miscibility gap in the molten state. This liquid decomposition at the monotectic reaction front, into a solid and a liquid, is subject to convection, even in microgravity, due to Marangoni effects. The goal of this project is to obtain a thorough theoretical understanding of monotectic solidification morphology.	MSL	2003/4	Phase-A/B cartridges in 2001 -To be approved-
AO-99-045 (MAP)	W. Grassi (I), *P. Di Marco (I),* *D. B. R. Kenning (UK),* *B. Roux (F),* *I. Iakovlev (RUS),* *F. Stoian (RO),* *L. Tadrist (F)* plus 1 Italian company	Study of an Imposed Electrostatic Field on Pool Boiling Heat Transfer and Fluids Management	The presence of an electric field has proved to remarkably enhance the heat transfer in single-phase convection, and in pool boiling processes. However, the mechanisms responsible for this enhancement are not yet well understood. The purpose of this project is to address this deficiency. It will also explore the possibility of utilising electric fields to improve fluid-management and heat-transfer equipment in space.	PF Fluidpac	2000 2002	Phase-A/B -To be approved- MAP contract in negotiation

AO-99-053 (MAP)	G. P. Celata (I), *F. Lanzetta (F),* *L. Tadrist (F),* *M. Zell (D),* *G. Zummo (I)* plus 1 German company and 1 from Italy	Two-Phase-Flow Heat-Transfer Experiments in Small Tubes under Steady Microgravity Conditions	The objective of this programme is to design efficient two-phase heat-transfer components for cooling high thermal loads in space systems. The proposed work will examine different two-phase flow regimes: subcooled, and saturated-flow boiling. The space activities will include: heat-transfer and pressure-drop measurements, critical-heat-flux experiments, and flow-pattern visualisation for the various flow regimes. New models will be developed.	PF EDR		Not supported by the MAP programme
AO-99-101 (MAP)	B. Vinet (F), *W. Loeser (D),* *P. J. Desre (F),* *N. Eustathopoulos (F),* *A. Pasturel (F),* *B. Drevet (F),* *L. Granasy (H),* *R. Hermann (D),* *D. Holland-Moritz (D),* *T. Volkmann (D),* *A. Mullis (UK)* plus 5 French companies, 1 from Germany, and 1 from Israel	Study and Modelling of Nucleation and Phase Selection Phenomena in Undercooled Melts: Application to Magnetic and Refractory Alloys of Industrial Relevance	Controlling the formation of metastable structures is a promising novel way of developing application-tailored materials. The objective is hence to establish phase-selection phenomena in undercooled magnetic alloys (Nd-Fe-B, Fe-Co) for composition ranges useful in industrial applications; and to determine the critical parameters for phase selection and metastable phase formation.	Dtube (National Prog.) MSL-EML Phase-A/B in cooperation with DLR	2000/1	MAP contract in negotiation

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