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ESSC-ESF POSITION PAPER

Scientific Evaluation and Future Priorities of ESA's ELIPS Programme

Report from the Sasbachwalden Workshops, February 2008

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The European Space Sciences Committee (ESSC), established in 1975, grew out of the need for a collaborative effort that would ensure European space scientists made their voices heard on the other side of the Atlantic. More than 30 years later the ESSC has become even more relevant today as it acts as an interface with the European Spa ce Agency (ESA), the European Commission, national space agencies, and ESF Member Organisations on space-related aspects. The mission of the ESSC is to provide an independent European voice on European space research and policy.
The ESSC is non-governmental and provides an independent forum for scientists to debate space sciences issues. The ESSC is represented ex officio in ESA's scientific advisory bodies, in ESA's High-level Science Policy Advisory Committee advising its Director General, in the EC's FP7 Space Advisory Group, and it holds an observer status in ESA's Ministerial Councils. At the international level, ESSC maintains strong relationships with the NRC's Space Studies Board in the U.S., and corresponding bodies in Japan and China.

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Front cover:
The International Space Station and European Columbus laboratory as seen from the departing space shuttle Atlantis STS-122 mission on 18 February 2008.
Courtesy: NASA.

Foreword

In May 2007 the ESA Directorate for Human Spaceflight, Microgravity and Exploration (D-HME) asked the ESF's European Space Sciences Committee (ESSC) to organise a broad scientific consultation of the users' community in the preparation of the next ESA Ministerial Council (November 2008), in order to evaluate the achievements and define future strategic and scientific priorities of ESA's programme in life and physical sciences in space (ELIPS). This exercise would constitute the follow-on of the assessment studies done at the Bischenberg, Obernai and Evian workshops, which the ESF and ESSC organised in 2000 and 2004/05 to structure and assess the value of ESA's ELIPS programme. The evaluation would look at: the achievements of the ELIPS programme between 2004 and 2007; the expectations and requirements of the users' community with regard to its future and in particular the validity of the Cornerstone scheme which was updated in 2005; and the scientific perspectives of the Exploration programme which are relevant to the ELIPS programme.

A Steering Committee, comprising scientists in life and physical sciences, was therefore formally established in October 2007 and met in Brussels on 16 January 2008 to define the format of the evaluation workshop and agree on the scientists to be invited to this workshop. ESA's ELIPS research plan is split in two main categories: life sciences and physical sciences. The workshop itself was thus also split in two parts, taking place consecutively during the same week, with two 2-day periods dealing separately with physical sciences and with life sciences. Both disciplinary workshops gathered some 80 persons each. A synthesis meeting consisting of the rapporteurs of the various sessions of the two workshops plus a limited number of selected observers then met on 14 April 2008 to finalise and approve the contents of the evaluation report. Following ESF and ESSC rules the report was then independently peer-reviewed.

We are glad to be able to provide this final report to ESA, European national space agencies and the space science community. We hope that it will help Europe better define its strategy for future research in life and physical sciences in space, and in particular reap its investments that led to the realisation of the Columbus laboratory, its launch and attachment to the International Space Station in February 2008.

Jean-Pierre Swings
Chairman
European Space Sciences Committee

September 2008

Executive Summary

General Recommendations

Commonalities and synergies

ESA is to be commended for its support for user-driven research in space and for the opportunities that have been given to European scientists and their international partners to achieve important goals in the disciplines of life sciences and physical sciences. In order to continuously improve European excellence in microgravity research, ESA must emphasise that space experiments should be embedded in strong basic science.

Recommendation G1

The era that began in February 2008 with the attachment of the Columbus orbital laboratory to the ISS, and then the successful docking of the ATV Jules Verne to the ISS, must significantly increase the return on European investment in the International Space Station.

The ELIPS programme is essential for European research in life and physical sciences in space. We fully support ESA in proposing the ELIPS 3 programme at the November 2008 Ministerial Council.

Recommendation G2

The ELIPS programme must be continued through its Phase 3 at the funding level mandated by the fact that science utilisation and return will sharply increase as of 2008 with the Columbus laboratory attached to the ISS and in full operation. Optimum usage of Columbus within the ELIPS programme is mandatory. In order to achieve maximum output and return on investment the funding level has therefore to be raised accordingly.

The full potential of ISS utilisation will not be exhausted by 2018, and the continuation of utilisation beyond that date would deliver enhanced return on investment.

Recommendation G3

Specific investments will have to be made for a new generation of payloads (or new inserts into existing facilities) for the ISS. In parallel, preparatory steps have to be taken for the post-ISS era by looking into alternative payload carriers, ballistic flights and free-flying orbiters. Creative use of the ATV in this context is encouraged.

Topical Teams act as very successful incubators for emerging and interdisciplinary topics, and to prepare for a network of European scientists working for the ELIPS programme. Microgravity Application Promotion (MAP) projects are also considered to be a unique platform to perform in-depth research on complex phenomena that require the teaming of European experts.

Recommendation G4

The present form of the MAP projects should be continued, meaning that these projects would have application-oriented, yet not solely industry-driven, strategic long-term objectives. As promotion is no longer an issue, the programme should be renamed, e.g. Microgravity Assisted Research. Furthermore, Topical Teams as incubators for future research topics should be continued.

The ELIPS programme has demonstrated its high scientific value and relevance to European research ambitions and its balance must be preserved. Hence new programmes on solar system exploration should not be established at the expense of ISS utilisation and ELIPS.

Furthermore, concern was expressed about the impact on the coordination of astrobiology science in ESA as a result of the transfer of ExoMars and Mars Sample Return from the HME/HSF Directorate to the SCI/SRE Directorate. Liaison between ELIPS and Exploration programmes currently occurs predominantly at working level with varying degrees of effectiveness, although clear scientific and technological synergies exist between ELIPS and the Exploration Core programme. The reorganisation between these two programmes, including transfer of key personnel, could alter this relationship.

Recommendation G5

To maintain and foster the high international scientific reputation of European astrobiology research, a strong coordination between the two ESA directorates on ELIPS (D-HSF) and the robotic exploration programme (D-SRE) is thereby mandatory. We further recommend that ESA should have a more specific strategy for coordination between programmes and stress the importance of seriously assessing the consequences of this transfer of programme components.

ESA has contributed to the success of the ELIPS programme by communicating the scientific results of research in space, for example through the Erasmus Experiment Archive, and through ESA's own website. However, although recent years have seen some improvement in ESA's public relations activities, education and outreach are clearly areas where major efforts must be undertaken.

Recommendation G6

A larger education component and budget should be a major objective of the next ELIPS programme. Summer

schools or workshops on various research topics covered by ELIPS could be initiated. ESA should reach an agreement about ECTS credits in these classes in collaboration with interested universities. Thus students could become involved in space sciences early in their career.
Substantial development of Internet resources and particularly the website of ESA is also recommended. A model in that area remains NASA's numerous websites that offer dedicated resources directed at various audiences, from specialists to school pupils. ESA's website should become a reference in Europe, also offering real-time coverage of Europe-specific space events through a web-based 'ESA TV'.

Cornerstones and emergence of interdisciplinary fields

The scientific community is traditionally organised in the 'classical' thematic fields appearing in the various sections of this report. Nevertheless the need for cross-disciplinary discussions and activities is obvious and many synergies exist between the various disciplines of the ELIPS programme, including life and physical sciences. A significant finding of this evaluation is the identification of several potential interdisciplinary areas that cut across the traditional division of research and are of interest to two, three or four of these disciplines (see Table ES1).

Recommendation G7
These cross-disciplinary areas should help define a set of 'orthogonal cornerstones' and therefore provide an innovative approach to the structuring of the Phase 3 of ELIPS. It is therefore recommended to foster cross-disciplinary activities in these domains. This could be achieved by common ELIPS workshops in science and technology to look at corresponding cross-cutting science and technology problems, and/or by setting up Topical Teams in these areas.

Life sciences-specific recommendations

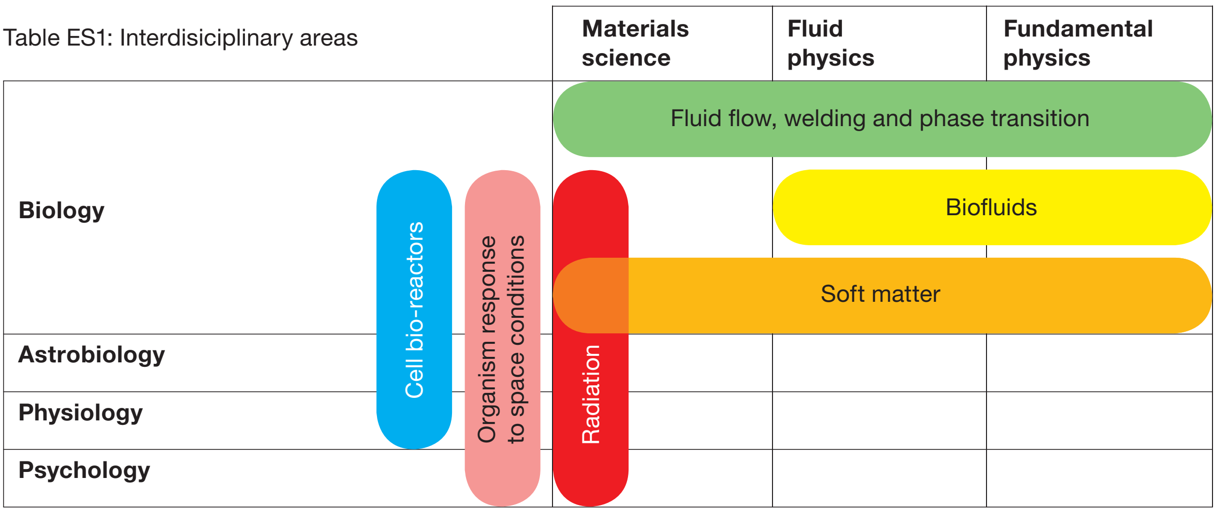
The following summarises the main recommendations in each disciplinary field. Detailed recommendations and the underlying rationales are to be found in section 3.

Biology

The Biology working group has defined new cornerstones. The previous definitions based on science areas (cell and molecular biology, plant biology and developmental biology) were often confusing or misleading because of the vastly overlapping research topics. The new cornerstones focus instead on the underlying basic scientific questions which are common independently from the specific issues addressed.

Recommendation BIO1
The existing concept of cornerstones should be modified, focusing on the following three science questions.
1. The perception of gravity, the effect of radiation and the respective adaptation processes at the cellular level.

Table ES1: Interdisiciplinary areas



2. Relation of single cells to extracellular matrices, other cells, tissues, organs and the whole organism.
3. How is gravity shaping organisms?

In addition to these cornerstones, the following general recommendations are made:

Recommendation BIO2

The selection of model organisms has to be science-driven. We deliberately do not recommend particular model organisms and/or cell culture systems. In a diverse field such as biology it is necessary to choose the best system for the best science. However, wherever and whenever possible, sample-sharing should be encouraged, preferably in the context of multilab experiments. This, of course, enforces the use of 'common sense' model systems, but 'uncommon' model systems must not be discouraged.

Recommendation BIO3

Preflight hardware has to be provided in sufficient quality and quantity early enough to allow the PIs/USOCs to perform ground tests in order to prepare for any possible necessary countermeasures. Ground-based studies are needed in support and an optimisation of experiment collection and assembly of different experiments during an enhancement onboard ISS should be enforced.

Recommendation BIO4

For the use of transgenic organisms ESA should develop rules based on national and European laws.

Recommendation BIO5

Other recommendations focus on communication (ESA-scientist, scientist-scientist in an interdisciplinary context) which should be improved, the implementation of the ESF/ESSC recommendations (ESA should inform ESSC of any implementations on a yearly basis), programme coordination (regarding an improvement of funding by national agencies/EU programmes in the context of multinational experiments) and technological restrictions (development of hardware, design of alternatives to be used after the era of ISS). The details of these recommendations are to be found in section 3.

Physiology

The Physiology working group stressed that future research strategy should build upon the themes highlighted in the previous 2005 ESF report.

Recommendation PHY1

The Physiology working group recommended that physiology research programmes should be based upon three principle pillars:
1. Fundamental science
2. Applied science
3. Exploration-driven science

The working group further recommended that the following themes should be superimposed upon this foundation:
- Radiation
- Human performance
- Microbial safety
- Systems homeostasis and adaptation
- Life-support systems
- Countermeasures

The nature of space physiology research demands a holistic approach to studies, considering the interactions between whole-organ systems. Microgravity physiology remains one of the few areas of research, outside terrestrial medicine, in which whole-body integrated physiology is central. It is this potential for an integrated approach to research that is the greatest strength of the current ESA programme. However, to date, ESA has not taken full advantage of this asset.

Recommendation PHY2

Resources should be committed to more fully exploiting the potential for integrated, cross-disciplinary physiology research programmes.

Much of the research undertaken in support of human spaceflight operations has relevance to terrestrial applications.

Recommendation PHY3

Further resources should be committed to translating space physiology research for application in multiple fields of human activities on Earth. This includes the development of new, advanced diagnostic techniques, therapeutic and rehabilitation techniques, learning and training methodologies as well as non-invasive and minimally invasive biotelemetry. For this to succeed, small well-focused multidisciplinary teams should be assembled and tasked with specific solutions.

The nature of whole-body physiological research leads to the generation of large, complex data sets which, coupled with the long-term nature of studies of human physiology, demand a new approach to data analysis and processing.

Recommendation PHY4

Resources should be committed to exploring how data mining techniques can be deployed on these complex data sets such that the maximum benefit can be obtained. Secure, high-integrity data archiving techniques should exist, which allow anonymised records to be held in perpetuity and accessed by future research teams or for the purposes of longitudinal health monitoring. Finally, there should be better communication between the operational aspects of human spaceflight and the science side such that medical data with potential scientific value do not remain hidden indefinitely.

Future plans regarding planetary exploration require a better understanding of partial gravity environments/ artificial gravity. The study of physiology under conditions of microgravity provides a unique tool with which to probe physiological systems, yielding new data which could not have otherwise been obtained. This provides a sufficient case to continue the parallel pursuit of both discrete and multisystem countermeasures.

Recommendation PHY5

ESA has an advantage in this area having inherited earlier, and now abandoned efforts, from the United States. This, coupled with the multidisciplinary approach highlighted above, provides a new and unique opportunity that should not be missed.

Astrobiology

ESA's life sciences programmes have been the historical home of astrobiology (previously termed 'exobiology') for more than 30 years.

Recommendation AST1

This highly evolving multidisciplinary area of space life sciences shall remain an active part of ESA's ELIPS programme.

The Astrobiology group expressed concern about the impact on the coordination of astrobiology science in ESA as a result of the transfer of ExoMars and MSR from the Human Space Flight to the Science and Robotic Exploration Directorates.

Recommendation AST2

To maintain and foster the high international scientific reputation of the European astrobiology research, a strong coordination between the two directorates is mandatory.

The Astrobiology working group saw the possibility for clear scientific and technological synergies between ELIPS and the Aurora Core programme. However the group urges careful assessment of the merger and its consequences so that these synergies may be achieved.

Recommendation AST3

An in-depth discussion should occur with the European astrobiology community prior to any related decision. It is further recommended that ESA prepare an astrobiology 'roadmap' clearly identifying required synergies between programmes, identifying flight opportunities (Earth orbit and planetary missions), ground-based studies and field studies. This could be done through the organisation of a workshop in coordination with existing organisations, e.g. EANA, ESF.

The availability of the Columbus module at the ISS is an important milestone for future astrobiology research in Low Earth Orbit (LEO).

Recommendation AST4

ESA should therefore provide further long-term experimentation opportunities on board the ISS with advanced external exposure facilities (e.g. sun-pointing, low temperature, in situ analysis) as well as bioreactors with sophisticated analysis devices inside the Columbus module.

Recommendation AST5

ESA should continue to provide frequent short-term missions in LEO for astrobiology experiments using free-flying satellites. Such experiments are required for (i) increasing the statistical significance of the results by repetition of the experiments, (ii) defining experimentation conditions in the preparation of long-term experiments on board the ISS, and (iii) testing astrobiology space hardware in the preparation of astrobiology experiments on board the ISS or planetary missions.

Recommendation AST6

ESA should foster astrobiology activities with regard to the exploration of Mars, with emphasis on the timely realisation of the astrobiology missions ExoMars and Mars Sample Return. Mars is one of the prime targets meeting the overarching scientific goal 'Emergence and co-evolution of life with its planetary environments', as defined by the ESSC-ESF position paper Science-Driven Scenario for Space Exploration (ESF, 2008).

Several moons of the giant planets (e.g. Europa, Titan, Enceladus) carry a large potential for astrobiology research.

Recommendation AST7

Whereas missions to these bodies are properly located within the new ESA science and robotic exploration programme, preparatory laboratory and field studies to determine the habitability of those bodies should remain part of the ESA ELIPS programme and be conducted, in a coordinated fashion within ESA.

If Europe becomes further involved in robotic or human missions to the Moon, several areas of astrobiology may benefit from such missions.

Recommendation AST8

Provision of relevant astrobiology facilities should be included in the ELIPS programme.

Recommendation AST9

ESA should set a certain budget aside for astrobiology laboratory and field studies. The experience gained from such studies is vital for the success of astrobiology studies in LEO, on Mars and on other bodies of the solar system relevant to astrobiology.

Recommendation AST10

As already stated in the 2005 evaluation of the ELIPS programme (ESF, 2005) ESA should continue to foster its planetary protection activities. These activities include the development of its own planetary protection programme (e.g. an ESA handbook for planetary protection measures, training of space engineers involved in planetary missions, and development of sample-receiving and curation facilities).

Recommendation AST11

ESA should foster the establishment of a Virtual Institute of Astrobiology with a strong education programme in order to teach students and scientists interested in the multidisciplinary field of astrobiology and to augment public perception of astrobiology.

Psychology

Recommendation PSY1

In the short term, the Psychology working group recommended focusing on the following research priorities, the details of which are laid out in section 3.4.1.
- **Psychological health and wellbeing**
- **Interpersonal relationships**
- **Cognitive and psychomotor performance**

Limitations of previous research have been the intractable problems of small sample sizes as well as a lack of methodological consistency. Comparison of data collected from space with those from simulation studies will be essential to assess the value of the information with regard to different aspects of space missions beyond the characteristics of the physical environment. Any attempt to transfer experiences across settings requires a thorough evaluation of the variables of crew member characteristics, crew size, crew tasks and overall mission objectives.

A mission to Mars will add a new dimension to the history of human expeditions regarding the distance and duration of travel. Such missions might not be comparable to any other undertaking humans have ever attempted because of the long distance of travel, the duration of permanent living dependent on automated life-support systems, the degree of isolation and confinement, and the lack of short-term rescue possibilities in case of emergencies. Current knowledge about human adaptation under these conditions is very limited, although predictions about the emergence of certain psychological issues might be extrapolated from Earth-based analogues and studies and previous spaceflights.

Recommendation PSY2

Specifically, more research in the following areas is needed in the longer term.
- **Research on, and development of, effective training tools in order to prepare crews for exploratory missions;**
- **Research on, and development of, effective support tools in order to provide the best possible psychological in-flight support of crews during exploratory missions:**
  - **establish countermeasures for monitoring and dealing with social problems and individual stress reactions;**
  - **establish countermeasures for reducing the impact of boredom and monotony on performance and psychological health;**
- **Research on safety management in space organisations.**

Physical sciences-specific recommendations

The following summarises the main recommendations in each disciplinary field. Detailed recommendations and the underlying rationales are to be found in section 4.

Fundamental physics

Fundamental physics research objectives fall under three headings: (i) fundamental research for understanding the systems under study; (ii) transfer of know-how into other fundamental and applied research areas; and (iii) transfer of know-how for industrial application(s).

Recommendation FUP1

In contrast to Phase 1 and Phase 2 of the ELIPS programme, three major fields of interest have been identified:

1. Fundamental interactions and quantum physics in space-time.
2. Soft matter physics (covering the fields of complex plasma physics, dust physics, and vibration and granular matter physics).
3. Environmental physics (covering mainly the research activities with regard to the Atmosphere-Space Interaction Monitor to be mounted on ISS).

Recommendation FUP2

The existing and planned facilities should be used (or brought into use) as quickly as possible to gain the maximum scientific return. New research subjects must be implemented without further delay. In order to continuously improve European excellence in microgravity research, ESA must emphasise that space experiments should be embedded in strong basic science.

Recommendation FUP3

It is also recommended to establish the new and emerging field of 'matter wave interferometry with super-massive particles'. Although the quantum superposition principle is well established in the microscopic domain, we have at present no indication whether it still holds in the macroscopic world. A viable way to test this experimentally is to bring increasingly massive particles into a macroscopically distinct superposition state of their position, as is done in matter wave interferometry.

Recommendation FUP4

The following implementation plan for Fundamental Physics is recommended:

- Completion of the Phase C/D and final implementation of the ACES atomic fountain clock until 2013;
- Strong support of cold atom physics research under weightlessness with emphasis on Phase A/B studies and pre-developments of space hardware, in particular the developments of:
  - Space Atom Interferometer
  - Facility to process Bose-Einstein condensates and atom lasers
  - Space Optical Clock
  - Space Optical Frequency Comb
  - Space-QUEST (for quantum entanglement experiments);
- Support of the emerging field of Super massive Particle Interferometry;
- Continuation and completion of the Phase C/D development of the PK(Plasma Crystal)-4 facility;
- Start of the Phase C/D for the IPE-Facility;
- Start of the Phase C/D for the VIPGran-Facility for granular physics;
- Strong support of the Phase A/B development for the double rack facility IMPACT consisting of the IMPF-Facility for Complex Plasma Research and the ICAPS-Facility for research on dust agglomeration;
- Strong support of the Phase C/D activities for the development of the ASIM observation platform.

Recommendation FUP5

The Fundamental Physics working group has identified a number of key critical technologies that should be developed and supported for fulfilling the programme's objectives in those fields, and also technologies that are of benefit for general application and in particular for adaptation in ESA´s Exploration and Aurora programmes. These technologies are listed in section 4.2.1. In addition, some interesting impacts for fundamental research are expected from the planned Exploration programme. In particular, for gravitational physics, the possibility of precise deep space ranging to satellites and planets as well as Very Long Baseline Interferometry (VLBI) will be of great benefit in order to be able to carry out various tests of special and general relativity (e.g. experiments to measure the Shapiro time delay).

Recommendation FUP6

Commonalities between fluid and material physics are substantial. Fundamental research topics of common interest are phase transitions, critical point studies, non-Hamiltonian and non-Newtonian fluid behaviour, tribology, origin of turbulence at the kinetic (individual particle) level, two-stream flows, wave propagation, solitons, kinetically resolved shocks, etc. In fact all fundamental problems associated with stability, flows, self-organisation and structure formation, thermodynamic equilibrium and non-equilibrium phenomena may be included.

Fluid physics and combustion

Recommendation FLP1
A number of activities in fluid physics and combustion are currently running and should be continued throughout Phase 3 of the ELIPS programme, with corresponding support.

Concerning future activities, and to make the fluid physics and combustion research activities more efficient, it is proposed that ESA considers the following recommendations.

Recommendation FLP2
ESA should foster an interdisciplinary research programme with life science teams, with bearing, for instance, on the Exploration programme. Two examples can be given: the case of micro-biofluidics and the recycling of wastes by cold combustion in supercritical water waste, in connection with the life support MELiSSA project.

Recommendation FLP3
A significant hiatus exists in Europe between the funding mechanisms for space experiments by ESA and the mechanisms for funding of researchers, ground-based work, data exploitation etc. at national or EU level. It is recommended that a way be found to harmonise the approval cycles and funding processes of ESA and national agencies. In addition ESA should support ground-based experimental and simulation activities and aim at a better consolidation between 1g and 0g research. Together with national agencies and the EU, ESA should seek to establish a more harmonised selection process.

Recommendation FLP4
It is recommended that ESA aims at re-utilising or re-designing existing facilities rather than spending funds for new facilities in fluid physics and combustion.

The science of fluids and combustion in space aims at investigating the behaviour of fluids and chemically reacting fluids in a reduced gravity environment. Some objectives are then already clearly application-oriented.

Recommendation FLP5
The Fluid physics working group has identified a number of application-oriented fields which will need emphasis and adequate support throughout the Phase 3 of the ELIPS programme, such as:
- More efficient cooling/heating systems;
- Better understanding of emulsion flows, especially drainage and phase separation in micro-channels with application to micro-fluidic machinery;
- Waste treatment;
- Biofluidics for health and life science;
- Better understanding of flame propagation on solid walls, methods of fire suppression;
- New standards on the definition of materials flammability based on fundamental knowledge rather than on empirical data gained from 1g-experiments;
- New functional materials (e.g. sensors, catalysts etc.) through thin-film deposition of combustion synthesised nanoparticles.

Recommendation FLP6
Several links have been identified between fluid physics and combustion and the Exploration programme. These fields will require adequate support:
- Investigation of fluid and combustion behaviour at Moon and Mars gravity, using e.g. dedicated parabolic flights. Experiments using a centrifuge on drop-tower experiments or the use of magnetic fields on the ground would also be needed;
- Life support and waste treatment (MELiSSA project);
- Fire safety research;
- Energy production using Lunar and Martian resources.

Materials science

Basic research in materials science is a prerequisite for applied research. However it is also true that the area of materials science is, by definition, application-oriented. This is manifested, for example, through the active participation of more than 40 industrial companies in related ESA-MAP research programmes.

Recommendation MAT1
The cornerstones of materials science, as defined in the previous evaluation, remain:
- Thermophysical properties of fluids for advanced processes
- New materials, products and processes

The consolidated list of topics related to these two cornerstones has been identified to sustain the design of new and improved materials in space with better performance. These topics are detailed in section 4.3.1.

Recommendation MAT2
In addition to these two main cornerstones, two specific topics have been highlighted in the domain of crystal growth, namely:
- Containerless and Solution growth (intermetallics, THM growth of CZT, SiGe)
- Impact of convection on nucleation and self organisation

Recommendation MAT3
The area of 'soft matter' will become a major topic for the materials science community within the next 10 years. This includes fractal aggregates, aerosols, aerogel, foams, proteins, colloids, and granular material that closely relate to many other areas in ELIPS.

With the availability of Columbus, the research capabilities will increase dramatically as compared with previous years. Drawbacks and funding shortages during the Phase 2 of ELIPS are well known and documented (work packages cancelled, MAPs delayed or on hold etc.) and had a negative impact on the return on investment.

Recommendation MAT4
Full utilisation of the available resources on ISS requires a proportional increase in the envisaged budget for setting up a sensible research programme with corresponding manpower in order to achieve the ambitious scientific and programmatic goals.

Microgravity-assisted materials science can substantially contribute to the Aurora programme by supporting the required materials development for future human space missions. This activity may become one of the future priorities of the present programme.

Recommendation MAT5
The development of materials science activities related to exploration is considered as a service to the Aurora programme and would consequently require funding from that source. Critical topics in this regard are reliability, life-time under space conditions and the design and development of new materials such as:
- **Light-weight and high-strength structural materials (crystalline, nanocrystalline, quasi-crystalline, non-crystalline)**
- **Energy-related materials (for heat exchangers, catalysts, liquid metal coolants, heat pipes)**
- **Radiation-resistant materials**
- **Sensor materials**

One of the key ISS facilities under development is the Electromagnetic Levitation device (EML). The EML permits containerless melting and solidification of alloys and semiconductor samples, either in ultra-high vacuum or high-purity gaseous atmospheres.

Another ISS facility in the field of materials research is the Materials Science Laboratory (MSL). The furnace inserts allow both directional and isothermal solidification experiments to be performed under microgravity conditions.

Recommendation MAT6
- **The completion of EML is critical for a number of top-priority materials science projects.**
- **Concerning MSL, additional multi-user inserts such as a diffusion furnace should be developed. In addition, the existing furnaces should be upgraded with regard to their maximum operating temperatures.**

Acknowledgements

In memory of Roberto Marco Cuéllar

This strategy report has been reviewed by individuals chosen for their diverse perspectives and expertise, in accordance with procedures used by the European Science Foundation (ESF). The purpose of this independent review was to provide additional critical comments to assist ESF and the European Space Sciences Committee (ESSC) in making the published report as sound as possible and to ensure that it meets standards for objectivity, evidence and responsiveness to the study charge. The contents of the review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their participation in the review of this report:

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- Steering Committee members.
- All participants to the Sasbachwalden workshops.
- Observers and ESA national delegates.

Contents

1. Framework of the evaluation

1.1 Background and approach

At the request of the European Space Agency (ESA), the European Science Foundation's (ESF) European Space Sciences Committee (ESSC) organised two workshops in Sasbachwalden (Black Forest, Germany) to evaluate ESA's programme in life and physical sciences in space (ELIPS). These workshops gathered some 160 scientists and agency representatives. This document constitutes the final report from this evaluation exercise. It was delivered to ESA in advance of the ESA Ministerial Council of November 2008.

The aim of this exercise was to evaluate the achievements and to define future strategic and scientific priorities of ESA's ELIPS programme. This is the third time that ESSC-ESF has carried out such an evaluation exercise on the ELIPS programme, the other two instances being the Bischenberg (ESF 2001) and Obernai/Evian (ESF 2005) workshops. This time the evaluation looked at the achievements of the ELIPS programme between 2004 and 2007; the expectations and requirements of the users' community with regard to its future; the validity of the Cornerstone scheme which was updated in 2005; and the scientific perspectives of the Exploration programme which are relevant to the ELIPS programme.

A Steering Committee formed of independent scientific experts in life and physical sciences was therefore formally established in October 2007 and met in Brussels on 16 January 2008 to define the format of the evaluation workshops and agree on which scientists to invite to this workshop. The committee also included the Chairman and the Executive Scientific Secretary of ESSC, ESF Standing Committee representatives (PESC, LESC and EMRC), as well as ESF and ESSC appropriate staff members.

The two workshops took place consecutively during the same week, with two 2-day periods dealing separately with physical and life sciences. A synthesis meeting consisting of the rapporteurs of the various sessions of the two workshops plus a limited number of selected observers then met on 14 April 2008 to finalise and approve the contents of the evaluation report. Following ESF and ESSC rules, the report was then independently peer-reviewed. The balance between disciplines was adequate. The physical sciences part was subdivided into three general themes: fluid physics, materials science, and fundamental physics; the life sciences part was also subdivided into three general themes: biology, physiology and astrobiology. A general introduction to each workshop was provided by ESSC-ESF, detailing the objectives and expected outcome. ESA also prepared a series of general and disciplinary overviews and briefings. This input derived from a document prepared by ESA, *Outlook for the ELIPS-ARISE Programme Proposal*, which constitutes a draft proposal for the Phase 3 of ELIPS that ESA submitted to ESSC-ESF and to the workshop participants for appraisal and comments. This document generated substantial discussion regarding whether or not the research cornerstones defined in 2004 were still adequate for Phase 3 of the ELIPS programme. Table 1.1 depicts the research cornerstones defined in 2004 in Obernai and Évian.

The discussion led during a specific 'achievements' session addressed: (i) the major ELIPS scientific achievements; (ii) whether the ESF 2005 recommendations had been implemented by ESA and, if so, what the outcomes were; (iii) whether new fields were appearing on the scene; and (iv) if more prioritisation should be advocated by the science community, for instance by defining model scenarios, model organisms or streamlined processes.

Other background documents were made available to participants in advance of the workshops (e.g. ESA 2005a, 2005b, ESF 2008, Nederhof et al. 2006). Working sessions in each theme identified above as well as cross-thematic plenary sessions took place during each two-day period, introduced by a series of keynote

Table 1.1: Cornerstones defined in 2005 in Obernai and Évian

Physical sciences research cornerstones	Life sciences research cornerstones
Fundamental physics • Physics of plasmas and solid/liquid dust particles • Cold atom clocks, matter-wave interferometers and Bose-Einstein condensates	**Physiology** • Integrative gravitational physiology • Non-gravitational physiology of spaceflight • Countermeasures
Materials science • Thermophysical properties of fluids for advanced processes • New materials, products and processes	**Biology** • Molecular and cell biology • Plant biology • Developmental biology
Fluid physics • Fluid, interface and combustion physics	**Astrobiology** • Origin, evolution and distribution of life • Preparation for human spaceflight exploration

presentations. The chairpersons and rapporteurs of the sessions were members of the Steering Committee (see Table 1.2 and Appendix 6.1).

Finally, the field of psychology is becoming increasingly important, both for human space flight in low-Earth orbit and for future exploration missions with humans. Only a few experts in this domain attended the Sasbachwalden life sciences workshop and it was therefore deemed necessary to implement an additional consultation after the workshop to ensure that the community's viewpoints were adequately represented. As a result a section on psychology including achievements as well as research priorities for the future has been added to this report. That part of the report was compiled by Gro Mjeldheim Sandal, Bob Hockey and Dietrich Manzey, who also considered additional input from Gabriel de la Torre and Berna van Baarsen.

1.2 Evaluation guidelines

Prior to the workshops, ESSC-ESF had sent each invitee a set of questions, both general and thematic, and asked them to provide a written set of comments. The comments received were integrated, sent to the chairs and rapporteurs who used this information to structure the discussion in their sessions, and also made it available to all workshop participants. This set of questions, detailed below, served as evaluation guidelines for the workshops.

1.2.1 Current and upcoming research priorities

- What are the top level scientific priorities?
- What are the specific objectives to be reached?
- What is the state of development of this field, what is its potential to grow?
- To what extent or in what field can we benefit from cooperative programmes and projects with international partners? Are there specific expertise and competencies missing in Europe and, if so, where? What are the opportunities in terms of flights and payloads? What is the status of research on ISS/STS?
- In what fields is interdisciplinary cooperation wanted or mandatory?
- What would be the main constraints with regard to scientific achievements?
  - what are the gaps in terms of competencies and expertise?
  - technological: what are the critical technological needs and developments, including infrastructures?
  - programmatic?
  - schedule-wise?

1.2.2 Long-term research priorities

- What are the top level emerging scientific fields and priorities?
- What are the critical technological needs and developments, including infrastructures?
- Is there a need for additional platforms?

1.2.3 Potential spin-off applications and societal importance

- What is the main spin-off potential of current research?
- What are the main potential spin-offs and application fields of societal importance of short- and long-term research?
- What is the impact of MAPs, their importance and future?
- Outreach, education and training.

Table 1.2: Chairpersons and rapporteurs

Physical sciences workshop	Life sciences workshop
Chair: Jean-Claude Legros	**Chair: Monica Grady**
Fundamental physics Chair: Gregor Morfill Rapporteur: Hans-Jörg Dittus	**Physiology** Chair: Helmut Hinghofer-Szalkay Rapporteur: Kevin Fong
Materials science Chair: Hans Fecht Rapporteur: Ivan Egry	**Biology** Chair: Michael Lebert Rapporteur: Ralf Anken
Fluid physics Chair: Daniel Beysens Rapporteur: Christian Eigenbrod	**Astrobiology** Chair: Charles Cockell Rapporteur: Petra Rettberg

1.2.4 Thematic issues discussed in workshops

- Where are the interfaces and synergies of ELIPS with the other ESA programmes, e.g. exploration, science, etc?
- How can my research field benefit from these programmes?
- How can these programmes benefit from my research field?
- What concrete steps and decisions should be taken to optimise and/or streamline research activities, e.g. by an agreement on model organisms, by management and exploitation of data, development and funding of large interdisciplinary projects, coordination of national efforts, etc?
- How to efficiently implement ESF-ESSC recommendations?

After the workshops, chairs and rapporteurs produced final reports from their sessions; these session reports constitute the backbone of this document.

1.3 Workshop participants

Participating scientists were the key elements of this evaluation. It is important that the participants' scientific expertise and knowledge in their specific domain are well assessed and recognised within the scientific community. The workshops attracted space scientists as well as researchers who are usually not actively engaged in space projects. Concerning the latter, the aim of having such mainstream scientists was to provide us with a different outlook on those space activities which had to be evaluated. Indeed projects undertaken in space or using space tools and assets should ideally be evaluated against other projects in the same mainstream discipline, although not using space, in order to assess their relevance and interest to the whole field.

A list of some 600 scientists was established to this end, using the suggestions made by:

- The Steering Committee
- ESF's Standing and Expert Committee members (PESC, LESC, EMRC, ESSC, EPB, MB)
- The European Space Agency
- National delegations to PB-HME, the corresponding ESA programme board

A complete list of all workshop participants is provided in Appendix 6.2.

A synthesis meeting of the Steering Committee and a few observers took place in Brussels on 14 April 2008. This meeting summarised the conclusions and findings of the first two workshops, extracted general findings and recommendations, and produced an integrated report. This report then went through the normal approval cycle of all ESF reports, namely. independent peer-review and formal approval by ESF's governance. The final report was approved and delivered to ESA.

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2. Achievements of the ELIPS programme

2.1 General remarks

ESA's ELIPS programme began in 2002, following plans drawn up by ESA in response to scientific developments and after a prospective evaluation by the ESF in 2000. In 2004 the progress made with ELIPS was assessed through an ESF-driven consultation of the community and priorities for the future were also established, including the definition of research cornerstones. Four years later, another such evaluation of the achievements, opportunities, impact, and future directions of ELIPS 3 is needed with a view to advising the responsible bodies (ESA, Ministerial Council, national agencies) on their future course of actions and investments.

Overall, ESA is to be commended for its support of user-driven research in space and the opportunities that have been given to European scientists and their international partners to achieve important goals in the disciplines of life sciences and physical sciences. Over the years Europe has secured a position of excellence in these areas; in some of the latter Europe is even the only place where certain ISS-related research can be carried out.

Overall, Europe receives a substantial return on its investments in the space station, and the era that began in February 2008 with the attachment of the Columbus orbital laboratory to the ISS must significantly increase this return on investment.

ESA has contributed to this success by its support of the ELIPS programme, the fostering of networking between interdisciplinary Topical Teams, communicating the scientific results of research in space, for example through the Erasmus Experiment Archive, and through ESA's own website. However, although recent years have seen some improvement in ESA's public relations activities, education and outreach are clearly areas where major efforts must be undertaken.

Courtesy: ESA/NASA

Figure 2.1: View of the European Columbus laboratory attached to the ISS.

2.2 Life Sciences

The three working groups that comprised the Life Sciences workshop covered the fields of human physiology, biology and astrobiology. Presentations in all three subject areas stressed the importance of the successful addition of the Columbus module to the ISS, and it was apparent that usage of Columbus would play an increasingly prominent role in future research projects. However, all three groups also made it clear that without supporting ground-based facilities, life sciences research in the next phase of the ELIPS programme would be seriously constrained.

The achievements of biological research carried out within the ELIPS programme can be divided into results from 'macro' investigations, which are experiments undertaken at the systemic/organismal and/or the cellular level level, and 'micro' investigations, undertaken at the molecular level. In systemic/organismal, cellular and molecular biology, there are stress responses, visible as changes in growth and development that are a result of the general space environment; there are also more specific variations in response to the low gravity environment of the ISS. Over the period covered by this report, there have been significant advances in distinguishing between effects from the two stressors, radiation and microgravity. Astrobiology is currently a high profile subject, not just in Europe, but internationally, and ESA's forthcoming ExoMars mission is eagerly awaited. The Astrobiology working group identified an area where the ELIPS programme could make a significant input into preparative studies for ExoMars (and other Mars missions), if it were to coordinate or support field studies in terrestrial analogues of Martian environments. The working group also highlighted advances made in understanding the effects of radiation on organisms in the space environment, making use of the EXPOSE facility on the ISS. They report advances obtained through use of several different facilities in addition to the ISS, including the short-term exposure experiments carried out on the BIOPAN facility. Waste recycling is recognised as an important issue for human spaceflight, and progress has been achieved with various different bacterial strains during spaceflight experiments to investigate closed-loop recycling and regeneration, for future use in life-support systems. The third working group, Physiology, covered a wide diversity of specialities, including basic human physiology, medical and health studies and psychology. All areas benefited from research undertaken on the ISS, from investigations of motor, nerve and cardiovascular systems, to the socio-psychological effects of working in confined quarters in stressful conditions. Study of human physiology under microgravity has direct relevance to human health issues, particularly when related to degenerative bone and muscle conditions. The population of Europe is ageing, and advances in treatment of syndromes associated with ageing are increasing in significance; it is in this field that some of the most valuable contributions from research using the ISS have been made. Results from research into psychological issues surrounding working in stressful conditions can be applied to environments other than the space environment. However, given the recent Global Space Exploration initiative, and its declared intent to plan for international lunar activities involving human occupation of the Moon, psychological research is likely to become an expanding field.

Alongside scientific and technical advances, all three working groups reported on their experience of public outreach and education within the ELIPS programme. There was strong agreement that public outreach was a vital part of ESA's remit; unfortunately, there was equally strong agreement that ESA was not achieving the visibility that it should within Europe for the achievements of its investments. All groups recommended that future models of the ELIPS programme should have a directed outreach programme based on a clear and readily-navigable website. They recognised that this would have resource implications, but felt that without a more visible and identifiable European human spaceflight programme, ESA would always be regarded as a poor second to NASA as far as the European community was concerned.

2.2.1 Biology

Life sciences have undergone dramatic changes in the past decades. The genome projects not only revealed the knowledge of the building blocks of the cells but also provided the pathway towards unravelling the function of the many genes, their interactions with other genes and with the environment. Space research has benefited from these developments highlighting these endeavours by finding the first key components of gravity-mediated signalling in various model organisms and integrating them into pathways. Systems biology will be a logical follow-up in the forthcoming years yielding greater insights than do piecemeal contributions by separate fields. Such multidisciplinary approaches will integrate the fields of mathematics, chemistry, physics, informatics, engineering and others to enhance the understanding of biological processes affected by gravity. To understand the complexity of these processes, new tools need to be developed for quantitative data capturing and integrating this into computational modelling, simulation and ground- or space-bound experiments.

General

- A good understanding has been reached about the differences between stress responses arising from the specific space environment and specific gravity-related effects. Substantial progress was made in the analysis of gravity sensing by non-specialised cells.
- The use of artificial microgravity (2D and 3D clinostat/random positioning machine RPM, magnetic levitation) and hypergravity has brought deeper insights in gravity-induced biological phenomena. In particular, several important studies, published in leading cell biological journals, were performed based on the application of microgravity simulations (e.g. using clinostats) or hypergravity systems. Although not directly included in ELIPS, they were related to ELIPS flight experiments (e.g. van Loon 2007a, b, c, van Loon et al. 2004, 2005a, b, c, 2007, Pardo et al., 2005, Loesberg et al., 2005, 2006a, b, 2007, 2008, Bacabac et al. 2007a, b, Hughes-Fulford et al., 2005, Walther et al., 2005, Morbidelli et al., 2005, Boonyaratanakornkit et al., 2005, Infanger et al., 2006a, b, 2007, Monici et al., 2006, Grimm et al., 2006, Babbick et al., 2007, Anken, 2006).

Cellular and molecular biology

- Recent research demonstrated that in micro-/hypergravity the gene expression profile of pro- and eukaryotic cells including multicellular organisms (from plants to mammalian species) changes and the alterations involve numerous important pathways. On the cellular level, much progress has been made in understanding cytoskeleton-related organisation processes (including the role of the cytoskeleton in graviresponding) as well as concerning gravity-related genes, the signal transduction of gravity involving, for example, calcium signalling.

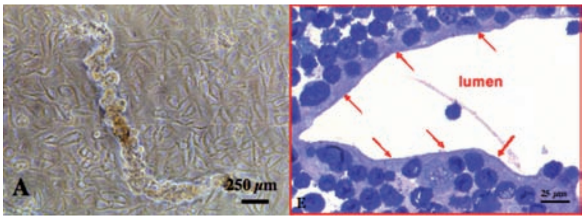
After the pioneering discovery of A. Cogoli and co-workers on the first Spacelab-Mission 20 years ago, it is known that the proliferative response of lymphocytes after mitogenic stimulation is suppressed in microgravity. Whereas it is well known that gravity can be perceived by gravireceptors (statocyst-like organelles or gravisensitive ion channels in the cell membrane) in unicellular organisms where it strongly influences intracellular signal transduction and behaviour, the molecular mechanisms of gravisensitivity in mammalian cells remain widely unknown.

Regarding another cellular model system (human epidermal A431 carcinoma cells) significant changes in cell morphology were observed under microgravity conditions. During a number of sounding rocket flights it was demonstrated that the amount of F-actin increased under microgravity conditions, indicating that either actin polymerisation increased under microgravity conditions or that actin depolymerisation was inhibited.

It is a main scientific objective to study the effect of microgravity on the actin morphology of mammalian cells, activated or not with growth factors. A wide variety of proteins – amongst them proteins of the Rho and Rac family, profilin, gelsolin and many others – have been demonstrated to play a regulatory role in actin polymerisation or actin depolymerisation, but it has not yet been elucidated the expression, activity and localisation of these proteins under different microgravity conditions.

- The cell cycle and cell proliferation in real and simulated microgravity has been further studied and, for instance, the motility and interaction of human immunocells in microgravity has been analysed (a study in the course of the 10th DLR Parabolic Flight Campaign, for example, addressed the effect of microgravity on the cytoskeleton and calcium signalling of immune cells during cell migration); in immunology, also the role of cytokines and growth factors with regard to the gravitational environment has been raised as an issue of importance. Such studies on cells led to an increased knowledge on cellular mechano-transduction, particularly regarding the role of the cytoskeleton.
- Radiation issues have been successfully analysed (e.g. Rabbow et al., 2004, Rettberg et al., 2006) and an experiment (Triple-Lux; gene, immune and cellular responses to single and combined spaceflight conditions: Triple-lux assay), will be flown on Columbus within the BioLab facility in 2009.
- Three-dimensional growth of normal cells and tumour cells in vitro is an established cell culture model with a variety of advantages in many research applications. Three-dimensional cultures, often referred to as 'multicellular spheroids', represent an experimental model that is intermediate in its complexity between monolayer cultures and tumours grown in vivo. As spheroids form three-dimensional intercellular contacts, they usually show radial gradients of oxygen, metabolites, and nutrients with low values in the centre and high values in the periphery. So far, the liquid-overlay method and the spinnerflask technique have been used to trigger cells to assemble in a three-dimensional manner. Recently, D. Grimm and her co-workers observed that cells switch from two- to three-dimensional growth, when monolayers were cultured on a random positioning machine, which mimics microgravity. Rounded spheroids were obtained when thyroid cancer cells were clinorotated (Grimm et al., 2002, Kossmehl et al., 2003), but tube-like structures arose, when endothelial cells of the cell line EA.hy926 were cultured under conditions of simulated microgravity (Infanger et al., 2006, 2007). Thus, they concluded that the kind of cell aggregates formed under microgravity depends on the type of cells. Therefore, endothelial cells are currently clinorotated with the aim of studying the development of new blood vessels.

    The SPHEROIDS team (D. Grimm) tested the relevance of simulated microgravity on endothelial cells and thyroid cancer cells using a three-dimensional random positioning machine (RPM; Collaboration Egli, ETH Zurich, and Zero-g LifeTec GmbH A. Cogoli, Zurich, Switzerland; numerous experiments using the RPM have been performed at the ETH Zurich in collaboration with several institutes in Europe and USA: Hughes-Fulford et al., 2005, Walther et al., 2005, Morbidelli et al., 2005, Boonyaratanakornkit et al., 2005, Infanger et al., 2006a, b, 2007, Monici et al., 2006, Grimm et al., 2006). Today, we know that exposure of both types of cells to simulated microgravity triggers cells living within monolayer cultures to turn spontaneously into three-dimensional cell aggregates with remarkable new features. It is certain that, under simulated microgravity, human thyroid cancer cells of the cell line ML-1 form rounded three-dimensional aggregates, while endothelial cells of the type EA.hy926 cell line assemble to tube-like structures. These three-dimensional aggregates exhibit various biological and histological features of their originating tissues but rather often also an altered expression of interesting cell components. Amongst the biochemical changes observed, enhanced apoptosis and different production of growth factors and hormones as well as alterations of cytoskeletal and extracellular matrix components are the most predominant ones.



Courtesy: M. Infanger

Figure 2.2.1.1: The pictures show an example of engineered vascular endothelial tubes. (A) Phase contrast microscopy of a multicellular tubular structure obtained under conditions of simulated microgravity (RPM). This tube-like structure has a length of 1.8mm. (B) Semi-thin section of a tubular structure with a length of 1.8mm, collected after 72h culture under simulated microgravity. A lumen is visible and an artificial endothelium layer is formed along the extracellular matrix (arrows).

- Apoptosis, that is, programmed cell death is an issue of major concern regarding manned spaceflight. Contributions to the closer understanding of the initiation of apoptosis by the space environment have been provided.
- Progress was gained in understanding/differentiating indirect from direct effects of altered gravity on cells. Identified neurons within the nervous system of developing and adult insects (E. Horn) (crickets *Acheta domesticus*: Eneide mission and RPM; fruitfly *Drosophila sp.*: RPM; R. Marco) were not affected with regard to their basic patterns. Proliferation of identified neurons was not affected even after in-orbit fertilisation (Eneide mission).
- The objective of FLOWSPACE is to define the bone cell mechano-sensitive characteristics and experiment

Courtesy: M. Cogoli-Greuter

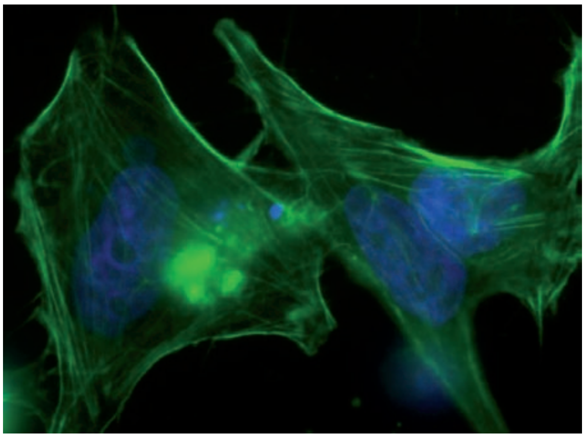


Figure 2.2.1.2: F- ACTIN in J-111 cells in KUBIK Bio1.

Courtesy: J. van Loon

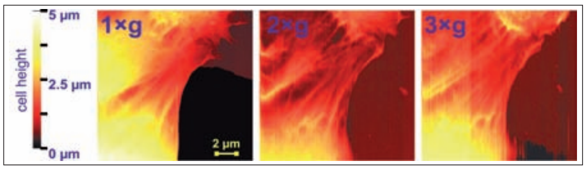


Figure 2.2.1.3: An Atomic Force Microscopic (AFM) picture of part of the same single mammalian cell cultured on a glass substrate at 1xg (left), 2xg (middle) and 3xg (right). This is the first on-line measurement of a mammalian cell showing that cell height is directly changed in altered gravity conditions, The higher parts of the cell, about 1.2µm, are in the bright yellow domains. Clearly visible is the reduction of height in this part of the cell with increasing g. In the remaining lower parts of the cell at 2xg and 3xg one can clearly identify cytoskeletal bundels.

requirements to be used for the development and use of a cell culture module for gravitational biological experiments. The specific aim is to test whether gravity, simulated and real microgravity and hypergravity modulates the sensitivity of bone cells for mechanical stress.

The laboratory setup for testing bone cell response to mechanical loading, as used in the regular research of the FLOWSPACE group around J. Klein-Nulend/J. van Loon, has been thoroughly characterised and was downscaled to comply with spaceflight requirements. The response of bone cells to mechanical loading by fluid flow was also tested. It was found that bone cells respond to flow in a rate-dependent manner. These results were used for the FLOW experiment flown to the International Space Station (via the DELTA mission or Dutch Soyuz Mission). Preparations for the FLOW experiment provided experience for an actual spaceflight involvement, in terms of developing spaceflight-approved hardware and optimising primary bone cell cultures for robust pre-flight environmental conditions.

Further experiments on bone cell responses to different mechanical stress conditions revealed that bone cell response to vibration stress is linearly rate-dependent, and that noise enhanced the response of bone cells to fluid shear stress loading. It was also found that bone cell mechanical compliance is frequency dependent. New findings on the effects of mechanical stress on bone cells provide relevant experience and information for the final experiment FLOWSPACE. Numerous papers have been published relating to Flow and Flowspace (Bacabac et al., 2004, 2005a, b, c, 2006a, b, c, 2007a, b, Klein-Nulend et al., 2005, 2008, Mullender et al., 2006).

- After the successful start and implementation of Columbus, BioLab on ISS is now a major achievement for gravitational biologists. The first experiment (WAICO 1; PI G. Scherer) has been on orbit since early 2008. The protocol was successful and the recovery of fresh samples yielded unexpected insights (pers. com. PI to rapporteur). This experiment is intended to gain a closer understanding of the connection between gravitropism and circumnutation in plants (Arabidopsis).

Developmental biology

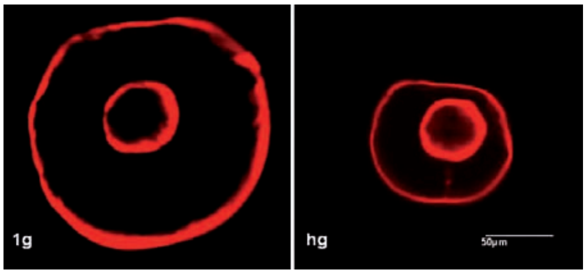
There is an apparent lack of effects from the space environment on the overall development of a large series of biological systems that have been exposed to these conditions. On the other hand, specific processes have been shown to be affected but they are eventually compensated. Many of the properties of the compensation mechanisms are unclear.

- Regarding the development of arthropods (Drosophila), R. Marco and his group (in collaboration with further international groups) have studied the overall behaviour of the Drosophila genomic expression in pupae developed and fixed in the ISS in real microgravity and compared them with the data obtained in the Random Position Machine (simulated microgravity) in the Dutch Experiment Support Centre (DESC – J. van Loon) in Amsterdam. A high number of genes changed expression levels in Drosophila pupas developing in microgravity and, just as important, these changes could be reproduced in the simulated microgravity in the RPM. Details on Drosophila investigations (‘Ageing’ and ‘Gene’ Experiment) in the context of the Spanish Soyuz mission Cervantes are provided in Herranz et al. (2005, 2007), Leandro et al. (2007) and de Juan et al. (2007).
- Experiments employing aquatic vertebrates have yielded an improved description of critical periods for vestibular development (e.g. Horn, 2004, 2005, 2006, Horn et al., 2006). Especially, new perspectives on the existence of critical periods during development of the vestibuloocular reflex have been raised by the comparison of the amphibians *Xenopus laevis* and *Pleurodeles waltii*

that differed in their developmental velocity (experiment AMPHIBODY; Soyuz taxi-flight TMA8) (E. Horn).

- Numerous adaptive effects of altered gravity on the neurovestibular system in aquatic vertebrates during development have been found, especially regarding the adaptive neural control of inner ear otolith mineralisation in fish (for review: Anken, 2006). Because of their aquatic lifestyle, fish are affected by altered gravity especially regarding the development of the inner ear (which may cause an aberrant behaviour, see below). Ear stones, the otoliths, are calcified structures in the inner ear, where they enhance its sensitivity to gravity. They are composed of the calcium carbonate polymorph aragonite and a small fraction of organic molecules. The latter form a protein skeleton, which determines the morphology of an otolith as well as its crystal lattice structure. The deposition of (calcium) carbonate is mainly based on the action of carbonic anhydrase (Beier and Anken, 2006a, b., Beier et al., 2004a, 2006) with the supply of calcium having been attributed to macular tight junctions (Ibsch et al., 2004a, b) (the latter model is under discussion; probably calcium transporters play their role here). In contrast to the otoconial masses of higher vertebrates, the physical capacity of compact fish otoliths can be directly assessed by weighing, measuring their size or by determination of their calcium content. Last but not least, fish otoliths continue growing during the entire life-span of the animal. Fish are therefore highly suited to investigate whether altered gravity affects otolith growth and in what way such an adaptation is effected. Fish otoliths grow slower under 3xg hypergravity than under normal 1xg Earth gravity and the activity of carbonic anhydrase is affected (Beier et al., 2004b, c). Opposite effects are obtained when fish are kept under orbital microgravity or under simulated microgravity within a fast rotating 2D clinostat. Moreover, calcium incorporation and thus otolith mineralisation stopped after vestibular nerve transaction (Edelmann et al., 2004). This clearly indicates that the otolithic calcium uptake is regulated neurally, most likely via the efferent vestibular system (vestibular ganglia, for example, show a response to hypergravity, Kempf et al., 2006, and efferent pathways seem to be involved, Anken, 2006).

Thus, otolith calcification is the only hitherto known biomineralisation process that requires neuronal input. Although numerous data on the neuronal control of otolith mineralisation have been collected, studies at (simulated or actual) microgravity are almost completely lacking. Otolith growth at (actual) microgravity is being analysed in the course of an experiment on the Foton-M3 mission, which was successfully flown in September, 2007. The 2D clinostat as well as an RPM are fully capable of providing data on otolith development at simulated microgravity (stimulus-deprivation), which will well complement results gained in the Foton mission.



Courtesy: R. Anken

Figure 2.2.1.4: Fish otoliths under fluorescent light: The fish bearing these inner ear stones were fed with a calcium-tracer once at the beginning of an experiment (inner circular labelling) and once again after some days (outer labelling). Note that an otolith grown at hypergravity (right image, hg, 3xg) has a core as small as in a control grown under Earth gravity (left image, 1xg), but did not grow that large under hypergravity. This adaptation to altered gravity is under neuronal control as has been shown by further studies.

- A closer understanding of the reasons for (human) motion sickness susceptibility/neurovestibular issues has been gained using aquatic vertebrates (especially fish) as a vertebrate model system. In general, the findings support the ‘otolith asymmetry hypothesis’ in the context of related vestibular behaviour (a number of, mostly earlier, studies on humans suggest a correlation between otolith asymmetry and space motion sickness and the space adaptation syndrome (SAS); convincing data from a recent study by S. Nooij on humans exposed to hypergravity also suggest that the paradigm of otolith asymmetry is related to SAS. Employing fish, R. Hilbig, R. Anken and their group have put forward the notion that in vertebrates (including humans) altered gravitational environments such as weightlessness induce changes in the central and peripheral interpretation of sensory input leading to alterations in motor behaviour (e.g. intersensory-conflict theory). Such disturbances include space motion sickness (SMS, a sensorimotor kinetosis normally accompanied by malaise and vomiting). Susceptibility to SMS is probably related to the otolithic organs, especially regarding the issue of otolith asymmetry; namely, differences in the size or weight between the left and the right inner ear stones; malformed/carboanhydrase defective sensory cells may, however, also play a role (Bäuerle et al., 2004, Schönleber and Anken, 2004). According to a hypothesis, otolith asymmetry is the basic cause of an intersensory conflict at diminished gravity. Due to technical reasons, otolith asymmetry and its possible role in SMS susceptibility cannot be *directly* assessed in human subjects.

Interestingly, some fish of a given batch show a kinetotic behaviour (especially so-called ‘spinning movements’ and ‘looping responses’) at the transfer from hypergravity (centrifuge) to 1xg as well as at the transfer from 1xg Earth gravity to diminished gravity in the course of drop-tower (DT) (Anken and Hilbig, 2004b, Anken et al., 2006) and parabolic flight (PF) experiments. By means of the DT experiments, the threshold for kinetotic behaviour in a stepwise diminished gravity was determined (Anken and Hilbig, 2004a). Also, it could be elucidated by DT and PF that otolith asymmetry is higher in kinetotic animals as compared with controls. Susceptibility to kinetosis thus depends: (i) on the level of otolith asymmetry; as well as on (ii) the individual animal preference for either visual or vestibular cues; and (iii) on the dimension of gravity or linear acceleration.

Overall, experiments at altered gravity clearly showed that fish are highly suited in the context of clarifying the basic causes of kinetosis susceptibility and of the regain of normal behaviour in the course of an adaptation process.

- Effects of altered gravity on human neuroscientific parameters have also been found in support of the otolith asymmetry hypothesis. Numerous experiments on fish as a model system (conducted by Anken/Hilbig) have shown that particular neuroscientific issues put forward by the Physiology working group can be resolved by using aquatic vertebrates.

Plant sciences

Gravity is one of the most important environmental cues plants use to adapt to their environment in order to optimise exploitation of resources. Gravity-sensing mechanisms have evolved early in the history of plants. Aquatic organisms, such as photosynthetic flagellates are part of the largest ecosystem of the world, the sea. They serve as primary producers and use light and gravity as cues to reach and stay in regions optimal for growth and reproduction.

The gravitropic responses of higher plants are of considerable importance for many aspects of plant breeding and agriculture. Gravitropism enables storm-flattened crops to grow up again and it therefore prevents crop losses. Plant-breeding companies, on the other hand, would like to switch off gravitropism of ornamental plants in order to avoid upward bending of horizontally transported flowers. Therefore, understanding the molecular and cellular basis of gravitropic mechanisms would be of utmost interest, but possibilities for investigating the multicellular and complexly organised higher plants tissues on the molecular and cellular level are very limited.

- Considerable progress on the basic knowledge of plant gravity-sensing and gravitropism has been achieved regarding especially the basic knowledge of the effects of altered gravity (gravitational stress) on essential cellular functions related to plant growth and development, such as cell proliferation and cell growth. Experiments performed in microgravity have greatly contributed to the progress that has been made in the understanding of how plants sense the direction of gravity and properly respond to it. Gravireceptors have been characterised and localised in specialised gravity-sensing cell types and the mechanisms of how the gravireceptors are activated have been investigated. Concerning the signalling chain, increased knowledge of cellular mechano-transduction in plant cells has been gained (also with regard to the plant cell wall as a mechanical force acting on the cell itself), particularly regarding the relation between mechanosensing and the cytoskeleton.
- Whereas other species have been intensively used in the past to investigate the gravity response in higher plants, Arabidopsis is now taking the leading position in view of the knowledge concerning its full genome sequence and the dramatic advances experienced in proteomics, transcriptomics and metabolomics (Teale et al., 2006). Effects of microgravity on, for example, cell proliferation and nucleolar activity in this model system have been investigated in the context of the Spanish Soyuz Cervantes mission (Matia et al., 2005, 2007). Microgravity-related changes in gene expression after, for example, short-term exposure of *Arabidopsis thaliana* cell cultures have been reported by Martzivanou et al. (2006).

Arabidopsis thaliana seedlings were sent into space (AT-SPACE) in 2007 to elucidate the mechanisms of plant root gravity perception and signal transduction, and to identify gravity-related genes and localise gravity-related proteins using a gene expression by microarray postflight. This investigation will address questions such as does gravity drive the expression of particular classes of genes or does gravity influence the expression of the same genes in different organs, such as roots and shoots? Another important question that will be addressed is whether the same genes are regulated by gravity on the ground and in space-grown plants.

Remarkable studies helped to understand the mechanisms of how lateral plant roots enable efficient exploration of the underground environment. It was shown that gravitropic curvature induces the *de novo* formation of lateral organs. A few hours after a change in the gravity vector, auxin-sensitive gene transcription is localised to developing xylem cells at the incipient site of lateral root initiation preceded by a subcellular reorientation of the auxin transport protein PIN1, thereby revealing an important relationship between the physical environment and organogenesis.

A comprehensive overview on the perspectives of using Arabidopsis as a plant model for gravity research can be found in Potters et al. (2007) and Palme (2005) and Palme et al. (2006).

Courtesy: K. Palme.

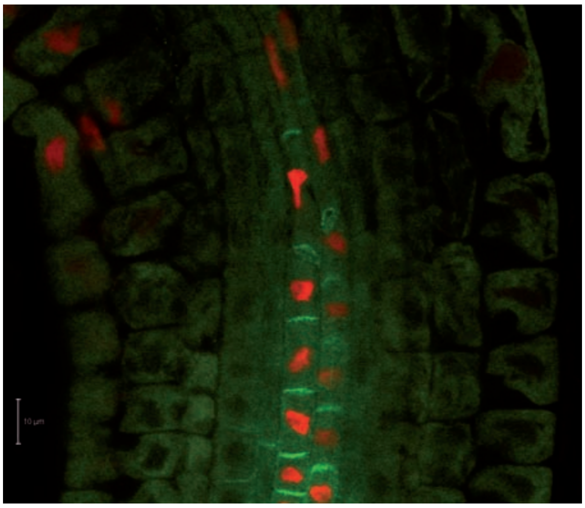


Figure 2.2.1.5: Arabidopsis lateral root formation.

Courtesy: M. Braun

Figure 2.2.1.6: *Characean algae*.

- The first experiment in the BioLab facility (WAICO; PI G. Scherer) has been on orbit since early 2008. This experiment is intended to gain a closer understanding of the connection between gravitropism and circumnutation in plants (*Arabidopsis thaliana*).
- Additional evidence for the understanding of gravitropism was supplied by studies related to Characean algae (group of M. Braun), which are the most closely related algae to land plants (Braun, 2007, Braun and Hemmersbach, 2007, Braun et al., 2007). They provide two well-established single celled and tip-growing model cell types, the positively gravitropic rhizoids and the negatively gravitropic protonemata (Hemmersbach and Braun, 2006, Braun and Limbach, 2007, Braun et al., 2007). Breakthroughs in the understanding, especially of the early processes of gravity sensing, resulted from experimentation in microgravity; namely, Texus and Maxus-missions, Space Shuttle-missions and parabolic aircraft flights, complemented by studies on 2D clinostats, 3D clinostats and magnetic levitators. In Chara as well as in higher plant statocytes, statoliths are actively kept in a resting position by myosin motor proteins that interact with the dense filamentous actin cytoskeletal meshwork (Braun et al., 2004, Braun and Sievers, 2004, Braun and Limbach, 2005). Any changes in the orientation of the cells with regard to the gravity vector result in the sedimentation of statoliths which activates gravireceptors and eventually elicits the gravitropic reorientation of the growth direction.

  Detailed analysis of the movements of statoliths in microgravity (NIZEMI, Maxus) and of artificially displaced statoliths revealed the surprising complexity of the actomyosin forces that control statoliths positioning and the graviresponse mechanism (Braun and Sievers, 2004, Braun and Limbach, 2005). The molecular forces that act on statoliths can be precisely determined by analysing the threshold value of centrifugal forces that are required for statolith displacement in microgravity (Braun, 2007, Greuel et al., 2007). Similar interactions of statoliths with cytoskeletal elements have recently been confirmed in higher plants.

  First insights into the mechanism of gravireceptor activation were obtained by recent parabolic flight experiments (Limbach et al., 2005). It was found that statoliths do not activate gravireceptors mechanically (mechanoreceptor). Activation rather relies on specific interactions of components of the statoliths surface with the receptor molecules.

  Additional microgravity experiments and applications of ground-based facilities such as clinostats, levitators and centrifuges promise to further increase our knowledge of these decisive early processes of plant gravity sensing.
- Concerning unicellular organisms (i.e. gravisensitive protists), a clear hypothesis of graviperception exists, which has largely been developed recently (Groups D.-P. Häder/M. Lebert and R. Hemmersbach). Because of current knowledge, graviperception is based on mechanosensitive ion channels in the cell membrane which are stimulated by the mechanical load of the cytoplasm. This hypothesis is supported by different experimental approaches: electrophysiological studies, studies under isodensity conditions, application of specific blockers and studies of mutants. As revealed by electrophysiological experiments, Paramecium bears two species of mechanoreceptor channels incorporated in the cell membrane in a gradient-like distribution – Ca-mechanoreceptors prevail in the anterior hemi-

sphere, K-mechanoreceptors dominate posteriorly. Since the mechanical load of the cytoplasm stimulates the lower region of the membrane, the resulting change in membrane potential depends on the orientation of the cell in regard of the gravity vector. In an upward-swimming cell, K-mechanoreceptors open, resulting in a hyperpolarisation and an increase in swimming rate. Correspondingly, a downward-swimming Paramecium is depolarised by an increase of Ca-conductance.

- With regard to Euglena, stretch-activated gravireceptor channels are located asymmetrically in the anterior cell membrane. In an upward-swimming cell the channels are closed; they open if the longitudinal axis deviates from the vertical or if the cell swims downwards. The resulting depolarisation induces an intracellular signal chain and reorientation of the cells is started. Further steps in the signal transduction chain in both species include second messenger cascades which finally lead to a reorientation and fine tuning of the movement organelles – the cilia or flagella (see Richter et al. 2006) for review. Most recently, substantial progress was made in the molecular identification of key players in signal transduction in unicellular organisms (e.g. in *Euglena gracilis*). A gravity response-specific TRP-like calcium channel, as well as a calmodulin were identified (unpublished results).
- A comprehensive account of findings on unicellular organisms regarding their behaviour at altered gravity including models for graviperception in such organisms and even evolutionary aspects on gravisensing has been provided in a monograph by Häder et al. (2005).

Courtsey: M. Lebert

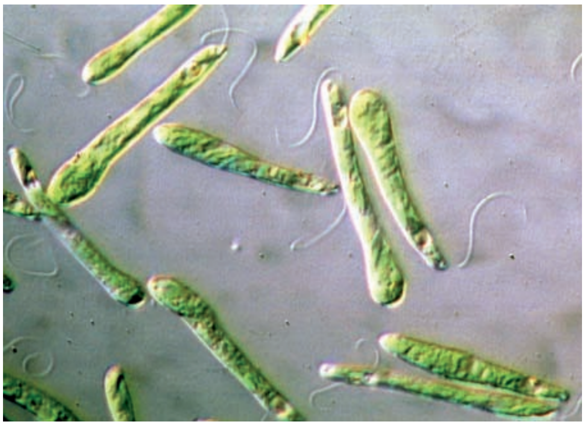


Figure 2.2.1.7: *Euglena gracilis*, a unicellular, motile flagellate. Euglena is a model system for the understanding of gravity effects on single cells.

Technology

Life-support systems are developed mainly for waste removal and recycling (solid and gaseous). One example would be MELiSSA, a complex system developed for long-duration spaceflights including microbial and higher plant compartments. The system allows the recycling of carbon dioxide as well as solid and liquid waste, all produced by astronauts. In contrast, controlled environmental systems (CES) are designed to replicate in an artificial way a small habitat and by this means support the survival of organisms. The purpose is to study the complex interaction of different species as well as the specific organismic responses in an artificial ecosystem under space environment conditions.

In addition, many other hardware platforms have been developed and successfully tested in different contexts.

- In the context of controlled environmental systems, aquatic, bioregenerative life-support systems were developed (i.e., for experiments using aquatic organisms) and successfully flown on the recent Foton-M2 and -M3 mission (OMEGAHAB (R. Hilbig, R. Anken, M. Lebert, D.-P. Häder) on Foton-M3 as well as Aquacells (M. Lebert, D.-P. Häder) on Foton-M1 (lost due to problems during launch) and M2). OMEGAHAB is one successful example of a multilab experiment where one experiment supplied two groups in a combined experiment with valuable data and biological material.
- The experiment MULTIGEN-1 was developed in the broad context of the achievement of long duration space exploration; in this respect, a renewable food source for the astronauts must be available. Through the MULTIGEN-1 experiment, the possibility of sustainable plant growth for long duration space exploration by growing several generations of plants in orbit will be examined. MULTIGEN-1 is thus a multigeneration seed-to-seed experiment. Details on ground-based studies have been published (Kittang et al., 2004).
- A mouse telemeter was developed which monitors activity, temperature and heart rate for animal research on the ISS (van Essen et al., 2005).

  Molecular analysis of plant gravity sensing by using high-resolution video microscopy was successfully demonstrated and a novel rapid freeze fixation technique has been introduced (DLR, 10th Parabolic Flight Campaign). The suitabilty of this freezing method compared with other standard fixation methods was demonstrated in the case of the concentration of RNA extraction of Arabidopsis. This technology was also successfully used in the 12th Parabolic Flight Campaign (DLR) to establish mechanisms of gravity perception and transduction using DNA and peptide-based array technologies.
- Also further hardware was developed or/and successfully flown/used again in the course of orbital flight

(especially, regarding national ESA Soyuz missions such as Andromede, Marco Polo, Odissea, Cervantes, DELTA and Eneide; for review, see van Loon et al., 2007) as well as ground-based experiments, for example miniaquaria (E. Horn), parabolic aircraft container (PAC) (R. Hilbig, R. Anken), KOF (kinetoses of fishes-hardware; the ZARM drop-tower in Bremen; R. Anken, R. Hilbig), VOCAV (video observation centrifuge for aquatic vertebrates; R. Hilbig, R. Anken), OMNIHAB for Texus (R. Hilbig, R. Anken), Kubik, MAMBA (e.g. R. Marco), Plungerboxes, BioPack (van Loon 2004) and others.

Educational outreach

Pupils and students have been especially integrated in ground-based experiments in relation to space experiments and also took part in ground-based experiments under simulated or actual microgravity (e.g. drop-tower and parabolic aircraft flight experiments). In the course of the Dutch Soyuz mission (DELTA), a 'seeds-in-space' educational experiment was extremely successfully carried out (all together, some 90 000 children took part in the Netherlands and in Germany; van Loon et al., 2005b, Weterings et al., 2007). An overview of educational experiments can be found in a special issue of the journal *Microgravity Science and Technology* (vol. XIX/5-6, 2007) covering six European Soyuz missions; Marco Polo, Andromede, Odissea, Cervantes, DELTA and Eneide.

Achievements – programmematic/ implementation issues

- Multidisciplinary collaboration. ELIPS is building on a ground that has been prepared. The best thing that all ESA and related programmes can do is to bring scientists from different laboratories together in the preparation and execution of experiments. The opportunity to bring together scientists from different disciplines working in astrobiology/exobiology would be a major advance.
- Development of equipment to support the use of the Columbus module on ISS. Namely the BioLab facility was – based on scientists´ requirements – specified, developed, tested successfully launched and commissioned.
- Information dissemination to interested parties regarding forthcoming opportunities in space missions has been much improved.
- Support of parabolic, drop-tower and sounding rocket flights, albeit somewhat limited by logistic constraints, have been crucial for valuable short-term measurements and observations as well as for flight hardware development.

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2.2.2 Astrobiology

The following text provides a review of astrobiology achievements within ELIPS and other ESA programmes since 2004.

During the ESF-ESSC consultation workshop that took place in 2004 in Obernai, France (ESF 2005) the following research goals for astrobiology were identified: (a) the detection of signatures of life on other planets and moons; and (b) the provision of supporting information required to enable human exploratory missions. These two goals were covered by the two cornerstones:

- Origin, Evolution and Distribution of Life
- Preparation for Human Planetary Exploration

To reach these research goals, the following recommendations for ESA were formulated:

(i) Continuation of the exploration of Mars with emphasis on the ExoMars mission to search for past and present life, and to investigate potential hazards to humans;
(ii) Exploration of Europa's sub-ice ocean and its potential for habitability;
(iii) Intensification of ESA's planetary protection activities;
(iv) Provision of advanced exposure facilities on the ISS and on autonomous free-flying satellites for exobiological experiments;
(v) Interdisciplinary cooperation within the ELIPS programme and with other relevant ESA programmes for the development of life-support systems including bioregenerative approaches, the detection, control and prevention of microbial contamination, and investigations of the radiation field in space and its biological effects;
(vi) Support of research using ground-based facilities;
(vii) Support of field studies in regions which are suitable terrestrial analogues of extraterrestrial habitats;
(viii) Continuation and extension of the ESA activities in outreach and education.

A review of each of these recommendations and their achievements are discussed below.

(i) ExoMars is the first mission in ESA's Aurora Exploration programme. In addition to an orbiter, ExoMars will deploy a rover carrying analytical instruments dedicated to astrobiology and geology research, the Pasteur payload. The Pasteur payload is equipped with a multispectral, stereoscopic camera, an electromagnetic subsurface sounder to identify local water/ice deposits, a drill capable of reaching a depth of 2m, and also of collecting specimens from within surface rocks, a sample preparation and distribution unit, an optical microscope, an oxidation sensor, and a variety of instruments for the characterisation of organic substances and minerals. It will be complemented by the Humboldt payload in order to study the environment and measure planetary geophysics parameters. The scientific findings to be expected from the ExoMars mission will be important for understanding Mars's evolution and habitability in comparison to that of our Earth and to astrobiology in general.

(ii) The exploration of Europa's sub-ice ocean and its potential for habitability has not been approached in the ELIPS programme in the past. This might be addressed in the future by ESA's Cosmic Vision in its science programme.

(iii) ESA's planetary protection activities encompassed the ongoing work of ESA's Planetary Protection Advisory Committee, ESA's Ethical Working Group on Planetary Protection and Astrobiology, ESA/NASA Planetary Protection courses for scientists, instrument/hardware providers, AIV and QA engineers, and project managers, and the participation in COSPAR symposia and colloquia on planetary protection as well as in IAA congresses. In addition, working groups with ESA participation in the European Cooperation for Space Standardization started to develop standards for procedures necessary for ensuring the compliance with international planetary protection rules. Research and development projects have been continued to determine the bioburden and microbial diversity of different spacecraft assemblies, testing and launch facilities where the European satellites are being built. In the frame of these projects, for example BioDiv, measurements with qualitative and quantitative detection methods for non-cultivable microorganisms are also taken in order to get insights into the 'real' bioburden of a spacecraft. This also contributes significantly to the overall organic contamination (species diversity). This is in addition to the collection of baseline data on fluctuations in bioburden and biodiversity in spacecraft assembly facilities (seasonal changes) and resistance tests of microorganisms isolated in spacecraft assembly facilities against environmental space or planetary parameters, for example ionizing radiation, UV radiation, low pressure/vacuum, temperature extremes (functional diversity). New faster methods for bioburden and biodiversity determination are under evaluation in comparison to existing standard methods.

(iv) A major achievement of the ELIPS astrobiology activities of the previous years is the successful launch, installation and commissioning of the European Columbus laboratory launched on 7 February 2008 with the STS-122 Shuttle mission on Space Shuttle Atlantis. Columbus is now an integral part of the International Space Station with the external payload EuTEF, the European Technology Exposure Facility, carrying the EXPOSE-E facility of a set of biological and chemical experiments requiring long-term exposure to the space environment. In the experiment ADAPT, the capability of bacteria to adapt to qualitatively and quantitatively different UV regimes, such as those in LEO and on Mars, as well as to other 'extreme' environmental space parameters is tested. LIFE investigates the survivability and photosynthetic activity of lichens, cryptoendolithic microbial communities and cryptoendolithic meristematic black Antarctic fungi after exposure to space vacuum, solar UV and cosmic radiation. The in situ resistance of selected bacterial spore-formers isolated from spacecraft surfaces and/or assembly facilities to the space environment of LEO is determined in the experiment PROTECT. In SEEDS the bio-/chemical basis for UV resistance in Arabidopsis seeds is examined. The aim of the experiment PROCESS is to improve the knowledge of the chemical nature and evolution of organic molecules in extraterrestrial environments with exobiological implications by photochemical studies of molecules in the gaseous phase as well as in the solid state. With R3D-E the actual doses of visible and UV radiation is measured in addition to the dose rate and energy deposit spectra of the cosmic ionizing radiation. The dosimetry experiments DOBIES and DOSIS are using passive radiation detectors for the determination of the dose of the exposed samples inside EXPOSE and the dose gradient in very thin shielding layers. Further, on total absorbed mission dose, linear energy transfer (LET) spectra and total dose equivalent is measured applying a combination of thermoluminescent dosimeters (TLDs) and nuclear track etch detectors. The experiment Advanced DOSTEL on EuTEF continuously monitors temporal variation of the charged particle count rate, the dose rate, charged particle and LET spectra.

Courtesy: ESA

Figure 2.2.2.1: The Foton M-2 capsule after successful landing in Kazakhstan.

In the frame of the Foton M-3 mission the series of successful utilisations of the ESA facility BIOPAN for short-term exposure experiments was continued. On BIOPAN-6, different species of bacteria, yeast cells, rotifers, tardigrades and nematodes, lichens and endolithic microbial communities have been exposed to single and combined space parameters and are being analysed.

The next major exobiological activity will be the launch of the EXPOSE-R facility, which is a designed analogue to EXPOSE-E, but with exchangable experiment trays, and which will be accommodated on the Russian module of the ISS. Different physical, chemical and biological experiments are being prepared for the launch scheduled for the end of 2008. The main goal of the experiment AMINO is to investigate the possibility of the delivery of extraterrestrial amino acids via micrometeorites and the photochemical processing of amino acids in Earth orbit.

Courtsey: DLR

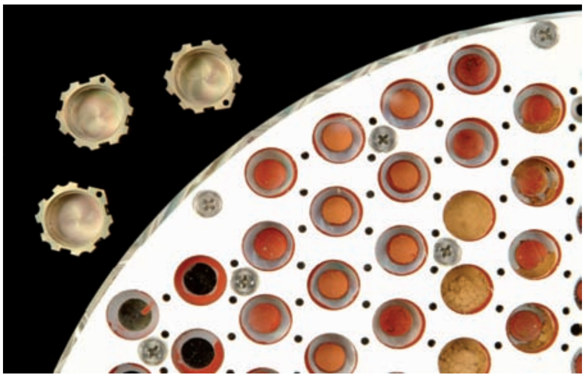

Figure 2.2.2.2: *Bacillus subtiltis* spores and Mars analogue minerals accomodated in the flight hardware of the MARSTOX experiments exposed to space in the ESA facility BIOPAN on the Foton M-2 and M-3 missions).

Courtesy: K. Ingemar Jönsson

Figure 2.2.2.3: A water bear, *Richtersius coronifer*, of the TARDIS experiment exposed to space in the ESA facility BIOPAN on the Foton M-3 mission.

The ORGANICS experiment examines the stability of selected complex organics such as PAHs, fullerenes, kerogenes and the evolution of organic matter in space in general. In the ENDO experiment the capability of endolithic organisms, such as cyanobacteria, to survive the conditions in Earth orbit is tested. OSMO will determine the potential role of carotenoid pigments in solar radiation and vacuum desiccation protection in halophilic microorganisms. In SPORES the possibilities of the chances and limits of life to be transported from one body of our solar system to another by natural processes will be explored using spores from different species. The main goal of PHOTO is to improve the knowledge of solar UV radiation-induced DNA damage within *Bacillus subtilis* spores and its biological consequences. The experiment SUBTIL experimentally tests mutational spectra of *Bacillus subtilis* spores exposed to high vacuum and solar UV radiation in space. The experiment PUR investigates the modelling of the UV photoreactions of pyrimidines in DNA by using polycrystalline uracil and investigations of bacteriophage T7 thin films. With R3D-E the actual doses of visible and UV radiation is measured in addition to the LET spectra of the cosmic ionizing radiation.

Amendments of future exobiological exposure facilities were suggested but not realised so far, for example the provision of a sun-pointing device and temperature control that maintains sub-zero temperature during sun exposure.

(v) ESA has supported the development of life-support systems including: (1) regenerative processes to recycle oxygen, water and food, with the ultimate objective of the MELiSSA loop that is designed as a closed system to recycle waste and to provide oxygen, clean water and some food supplements (plants and edible cyanobacteria); (2) early detection, control and prevention of chemical and microbial contamination. A series of spaceflight experiments of fundamental research (MESSAGE-1, MESSAGE-2, Mobilisatsia and BASE-A) were carried out during four 10-day taxi-flights (missions Odissea, Cervantes, DELTA/Soyouz flights 8S and 9S and Astrolab) and have checked the viability of various bacterial strains on Petri dishes and plexiglass biocontainers, the viable counts by successive dilutions, the production of mutants via transposition, the efficient transfer of conjugative plasmids in Gram-negative and Gram-positive bacteria, the overexpression of some proteins (proteomics) and the overexpression of genes (transcriptomics) in spaceflight. The last experiment used among other bacteria the strain *Rhodospirillum rubrum*, one of the bacteria purposed to colonise a compartment of the MELiSSA regenerative loop. Most of these experiments showed the feasibility of using microbial strains to manage their growth and to check key genetic features in spaceflight conditions. These experiments pave the way for future and more complex experiments (i.e. ARTEMIS, BIORAT etc.) leading to a progressive demonstration of safe life-support system in space.

(vi) The ESA multiuser facility Matroshka was developed to measure organ (or tissue equivalent) doses in selected critical radiosensitive organs, an important prerequisite for radiation risk assessment. Matroshka was launched in 2004 and used in a cooperation of 18 universities and space agencies from the US, Russia, Japan and Europe for the first time for measurements of the radiation distribution (experiments SORD and RADIS) inside a human phantom under EVA conditions. Sets of passive detectors are provided for mission-integrated measurements of absorbed dose, neutron dose and flux of heavy ions and their spectral composition with regard to charge, energy and linear energy transfer (LET). The active detectors measure the flux of neutrons and of charged particles and the corresponding dose rate and LET spectra separately for galactic cosmic particles and trapped particles as a function of time. In addition, a particle spectrometer (ALTEINO) measures the radiation environment close to the Matroshka facility. The studies on Matroshka will be supported by the Hamlet project selected for funding through FP7. A second objective of the Matroshka experiments is to investigate the effects of different shielding material by providing defined multilayer configurations for radiation shielding optimisation and validation in LEO. The flight testing of new soft materials in flight will be supported by ground testing and calculations, to assess shielding strategies for LEO and, in perspective, for interplanetary vehicles and habitat modules on planets.

The ALTEINO instrument was launched in 2002 and used for the ISM-1 and ISM-2 taxi-flight missions in 2002 and 2005 as part of a programme of ASI experiments. The instrument was reactivated again in Increment 12 as part of the ALTCRISS investigation and will run until increment 17. The ALTEINO instrument consists of a series of silicon detectors which permits the measurement of LET and particle spectra (including Fe spectra) and directional information on the particles. Different shielding materials have also been tested as part of the ALTCRISS project.

The ALTEA-SHIELD project consists of a series of projects, both in space and on the ground. The ground-based studies examine light flash phenomena and how this correlates with heavy ion flux on different brain regions in mice and patients undergoing heavy ion therapy. The ALTEA-Space experiment uses an active dosimeter which measures particle flux and LET spectra with six detector arrays.

(vii) ESA has supported an elaborated preflight verification and test programme for exposure experiments in the facilities EXPOSE-E and -R. This proved to be a very successful approach for the selection of suitable strains of model organisms, for the determination of the limiting physical parameters in the space experiments and for the definition of the design of the multiuser space hardware.

The ESA Topical Team, ROME (Response of Organisms to the Martian Environment) coordinated studies on the effects of low temperatures, UV radiation, low pressures and desiccation on a diversity of microorganisms using Mars simulation facilities in Europe with special emphasis on the DLR Mars Simulation Chambers, Köln, that are explicitly defined by ESA as a ground-based facility for ESA life sciences studies. This team finished its work with the publication of the ROME report (Cockell and Horneck, 2007).

(viii) The suggested field studies in regions which are suitable terrestrial analogues of extraterrestrial environments to test and validate sensitive detection devices for signs of past and present life in preparation for life detection experiments on Mars and Europa, and to train technicians and scientists involved in future planetary missions, have not so far been supported by ESA.

(ix) ESA is operating a website for astrobiology (http://www.spaceflight.esa.int/exobio) thereby providing a platform for communication, training and education in the field of astrobiology. This ESA website has hosted the web pages of the European Astrobiology Network Association (EANA), a network that currently links scientists active in astrobiology from 17 European nations.

(x) ESA and its Erasmus Centre have organised a tele-teaching-based lecture series on astrobiology (Astrobiology Lecture Course Network, ABC-Net) with experts from different European universities covering the various research fields, from the study of the overall pattern of chemical evolution of potential precursors of life, in the interstellar medium, and on the planets and small bodies of our solar system; tracing the history of life on Earth back to its roots; investigating the environments of the planets in our solar system and of their satellites, with regard to their habitability; and searching for other planetary systems in our galaxy. The first successful pilot project started in the academic year 2005/06 with lectures and an interactive question and answer period between students and teachers. At some universities exams are offered to earn credit points in the Bologna Accords for a standardised European academic education. In the academic year 2007/08 the second lecture series of the ABC-Net took place. The lectures are broadcast to the participating universities and are publicly available by video-on-demand under: http://streamiss.spaceflight.esa.int/

Implementation of ESF-ESSC previous recommendations

The working groups were also requested to identify those areas where previous recommendations for the ELIPS programme had not been met. There are four areas where potentially better results might have been achieved, but which could be the focus of the next ELIPS programme.

- There have been no coordinated field analogue studies (see point viii) above. The next ELIPS programme should consider making a greater effort to conduct astrobiology field analogue studies;
- There have been no free-flying satellites other than Foton with BIOPAN. The next ELIPS programme should work strongly toward the development of these capabilities;
- The ELIPS programme, although achieving good scientific results, has not achieved the visibility that it could for astrobiology. A stronger education programme should be developed;
- The accessibility of research publications arising from ELIPS is not as good as it could be. There should be a bibliography of publications from the previous ELIPS programme and this should be a standard procedure (collection of publications) for the next programme.

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2.2.3 Physiology

The space environment provides investigators with the ability to study biological systems under conditions of physical extremes. In particular the near weightless environment associated with microgravity provides a powerful tool with which to probe the fundamental properties of physiological systems.

As argued in the 2005 ESF report already, "the purpose of the programme is to determine the effects of gravity on animal and human physiological systems from the level of the genes to integrated systems. To understand how gravity affects physiology is fundamental for our knowledge of how animals and humans have evolved on Earth and how gravity modulates mechanisms in health and disease. To obtain this goal, experimenters must have access to acute and longterm changes in G-levels including microgravity. Therefore, spaceflight is an essential part of the programme.

There are many similarities between effects of low levels of gravity and those of ageing, diseases, and sedentary life styles. Therefore, research in microgravity adds to our knowledge of how to treat these conditions. Furthermore, research under 0-G conditions contributes to the understanding of how gravity burdens the life of diseased individuals such as those with e.g. heart failure, osteoporosis, paralysis, etc. Therefore, physiological research in space is expected to lead to new knowledge, which will have the potential of improving treatment and rehabilitation and result in improved health for the general public".

Human space operations also involve exposure to, and protection from, other physical extremes including high energy radiation fields, enriched oxygen environments, low atmospheric pressures and rapidly alternating cycles of daylight and darkness.

The protection of human crews engaged in spaceflight operations presents a unique set of problems whose solution demands an in-depth understanding of whole-body, integrated physiology and cross-disciplinary work between life scientists, engineers and technologists. From this derives the field of space physiology.

The studies however are not confined to flown experiments but include investigations in terrestrial laboratories and analogue environments. Indeed the foundations of the programme as a whole lie within comprehensive programmes of ground-based research linked to European centres of academic excellence. These in turn, while advancing our understanding of the effects of the space environment upon human physiology, advance our basic understanding of the human body and drive the development of new technology, some of which finds an application in everyday healthcare.

The list of achievements derived from these programmes of research includes but is not limited to the following (supporting references at the end of this section):

Fundamental research

- Arabidopsis experiments exploring the gravisensor properties common to all cells have shown that early reproductive development in this plant can occur normally under spaceflight conditions; they will provide the first integrated model on how cellular gravi-perception occurs in biology;
- New fundamental cognition, motor control, sensorimotor integration in both in human and in animal models;
- Demonstration of changes in muscle and neuromotor control and exploration of their implications for increased injury risk;
- Improved understanding of the effects of mechanical stress on bone remodelling;
- Demonstration of the dependence of the heart-lung interaction upon gravity.

Research in support of crew healthcare and health maintenance

- Development of improved methods for radiation monitoring during orbital operations;
- Telemedicine and tele-operated medical equipment;
- Demonstration of interference with autonomic regulation during and after short duration flights;
- Studies of circadian physiology in animal models taking advantage of rapid alterations in dark-light cycles in LEO;
- Studies of muscle and bone interactions in microgravity;
- Development of novel methods to assess bone quality for the early detection of bone remodelling disorders and osteoporosis.

Research using analogue environments and facilities

- Psychological studies of intercultural interactions in isolated/extreme environments;
- Demonstration of the importance of the nutritional state in maintaining whole-body physiology during bed rest studies;
- Demonstration of the cardiometabolic risks induced by bed rest comparable to those seen in patient groups with sedentary lifestyles;
- WISE study: 60 women in bed rest and demonstration of the efficacy of exercise countermeasures in this group;
- Development of a short-arm centrifuge facilitating the assessment of artificial gravity as an integrated countermeasure.

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2.2.4 Psychology

Psychological research focuses on achieving knowledge that has an applied value for promoting safety, productivity and health among crews operating in space as well as for ground-based personnel. Two broad categories of countermeasures for the crews in space may be defined. The first involves the accommodation of the environmental conditions to the psychological needs and capabilities of humans (e.g. habitability, design of living quarters, work-rest schedules). The second category involves an inverted approach by attempting to adapt humans as well as possible to the living conditions and work demands of spaceflight, mainly by developing strategies for in-flight support, selection and training of crew members. So far, most psychological research has addressed the latter group of countermeasures. Countermeasures need to be grounded in empirical knowledge on the psychological effects of living and working for prolonged periods in space. A concern is that long duration space missions involve chronic exposure to living and working factors that can entail detrimental effects on the behaviour and performance of crew members. These factors can broadly be divided into four categories:

- Stressors unique for the space environment; e.g. microgravity, radiation, and alterations of usual dark-light cycle;
- Stressors related to the technical constraints of a space habitat and its life-support system; e.g. confinement, restricted range of sensory stimulations, limited facilities and supplies for personal hygiene, and elevated CO_2 concentration in the ambient air;
- Stressors related to the mission-specific operational and experimental workload of astronauts; e.g. work underload and overload, sustained stress;
- Stressors arising from the psychosocial situation in a space habitat; e.g. isolation from family and friends, lack of privacy, restricted and enforced interpersonal contacts.

Most of the living and working conditions for crews in space are not unique to the space environment. Much of the present understanding about psychology in space is based on studies of groups operating in analogue environments where personnel are exposed to many of the same stresses as those experienced by astronauts in space. Such environments involve crews over-wintering on research stations in Antarctica, polar expedition teams and confinement studies performed in hyperbaric chambers designed to model aspects of human space missions. ESA has sponsored the following series of ground-based simulations of spaceflight by the use of hyperbaric chambers facilities:

- ISEMSI in 1990: Six crew male members from West European nations confined for 28 days in Bergen, Norway;

- EXEMSI in 1992-93: Four crew members (3 males and 1 female) from West European nations confined for 60 days in Cologne, Germany;
- HUBES in 1994-1995: Three Russian, male, crew members confined for 140 days;
- SFINCSS in 1999-2000: One Russian, crew was confined for 240 days, and two crews were confined for 110 days. One of the latter crews had a multinational composition and included the only female member.

HUBES and SFINCSS were conducted at the Institute of Biomedical Problems in Moscow, Russia by the Russian Space Agency. In addition, ESA activities in the psychological area include the following projects:

- HUMEX: 'A study of the survivability and adaptation of humans to long-duration interplanetary and planetary environments' (Manzey, 2003). The study evaluated the possible medical, biological and psychological risks associated with exploration missions based on specific reference scenarios for human missions to the Moon and Mars;
- REGLISSE: 'Review of European ground laboratories and infrastructures for sciences and support exploration'(Manzey, 2002). The project focused on identification of requirements for a ground-based research facility;
- A project directed toward the definition of tools for psychological support for long-duration exploration missions (Solodilova-Whiteley, 2007);
- ESA has been cooperating with the French Polar Institute and the Italian Antarctic programme on research activities at the Antarctic station Concordia. The area in which Concordia station is located is considered to be one of the most hostile places on Earth, and is regarded as a good analogue for future interplanetary missions. Psychological studies are currently being conducted, but results have not yet been published.

Together with research conducted in other isolated and confined settings, these ESA-sponsored activities have identified psychological issues that may have operational impacts during human space missions. They have also provided empirical evidence for psychological phenomena anecdotally reported from space missions. In the following sections we will present achievements in three areas: (i) Psychological health and wellbeing; (ii) Interpersonal relationships; and (iii) Cognitive and skilled performance. The associated short- and longer-term priorities are described in section 3.4 of this report.

Psychological health and wellbeing

The main findings from research regarding psychological health and wellbeing in space are the following:

- Crew members have experienced psychological reactions that have included lapses of attention, emotional lability, psychosomatic symptoms and a considerable decline in vigour and motivation;
- Some results from space simulation studies and polar expeditions suggest that adaptation may occur in stages over time and that the most serious problems are likely to occur around half-way or during the third quarter of confinement. However, empirical evidence for the existence of specific critical phases has been equivocal. Other studies suggest that individual stress responses are largely dependent on the unique characteristics of a specific analogue;
- Sleep in space is often restricted, more disturbed, structurally altered and sometimes also shallower than on Earth. This has also been found for personnel living on research stations in Antarctica;
- Studies have identified personality characteristics associated with coping in teams living and working in isolated and confined environments. Yet, the relevance of some personality characteristics seem to be 'mission-specific' and relative to team composition.

Interpersonal relationships

Studies of personnel in isolated and confined environments have identified a number of factors that have an impact on the efficiency and quality of interpersonal relationships, including crew structure and cohesion, leadership style, gender and cultural background of crew members, and inter-group relationships (Gushin et al. 1997, Kanas 1990, Kanas & Manzey 2008, Manzey 2003, Sandal 2001, 2004). While these factors are general predictors of satisfaction and efficiency in organisational settings, they also seem to be influenced by a range of specific contextual variables during space missions. The main findings from research regarding interpersonal relationships related to human space missions are the following:

- Space crews often experience greater social cohesion by virtue of undergoing a common experience along with increased 'psychological distance' to outsiders (Mission Control) and a progressive reduction of crew to ground communication;
- The authority of the assigned Commander tends to be challenged. There have been several observations of 'status levelling' characterised by the Commander assuming a more equal status to other crew members over time;
- There have been frequent observations of tension expressed between the confined crew and Mission Control;
- Interpersonal tension within the crew has been expressed through exaggeration of trivial issues, 'scapegoating' of deviating crew members, territorial behaviour, withdrawal of single crew members, and subgroup formations;
- Interpersonal tension has resulted in breakdown in

crew cohesion and communications between crews confined in connected modules during a space simulation study;
- Crew members from national/cultural minorities have express more dissatisfaction with their work environment relative to majority crew members. However, this phenomenon may be confounded with 'host-guest' relationships;
- Interpersonal tension has increased around the middle and towards the end of the confinement;
- Psychological incompatibility of crew members has been associated with demographic variables, personality characteristics, needs, values and motivation. Small sample sizes make it difficult to isolate the effects of single variables; for example from professional training and the organisational setting in which the project was conducted.

Cognitive and psychomotor performance

The main findings in this area of research are:
- Microgravity does not seem to impair basic cognitive functions (e.g. perceptual processing, memory, logical reasoning), despite some disturbances of attention and skill processes during primary adaptation;
- Most impairment observed seem to be related to workload, fatigue or other unspecific stress effects.

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2.3 Physical Sciences

The main event leading the discussions between the participants into the present evaluation is without any doubt the success of the integration of Columbus in orbit. Its activation initiates the accomplishment of ambitious programmes.

The physicists involved in microgravity research are eager to perform their measurements after long years of delay. For many research teams the future actions are already defined and the facilities to run their projects are either flying, ready to fly or in the final step of preparation. They would like to be considered a priority in the coming budget to complete their existing selected projects.

The Topical Team programme has strongly contributed to the detailed definition of the proposed experiments; these discussion forums allowed the assessment of strong scientific strategies in order to generate the highest scientific return from combined experiments performed around a given science field. This programme is bringing together scientists from different laboratories with their different approaches and experiences, and contributes to their mutual enrichment. This programme must have a recognised rating in the coming ELIPS 3 programme in order to prepare for the future.

The MAP programme is a unique way to bring industry to science teams and science teams to industry, to help scientists understand the request from industry with regard to delays in results. This is a difficult challenge in investigations using orbital platforms. An increase of the budgets dedicated to MAP was unanimously recommended.

The discussions were running in parallel within the three subgroups defined by the cornerstones of the Obernai and Evian meetings. The exchanges inside these subgroups (Fundamental Physics, Fluid Physics and Materials Science were conducted by different chairpersons; they have developed their arguments differently as reported hereafter. Each subgroup is expecting a strong and adequately funded ELIPS 3 programme. The development of a new research programme is not a single action but a global process of interrelated subprocesses. It is not just a new idea or collection of ideas, nor the development of a new facility, nor the emergence of a new research field. It is all of these things in an integrated fashion.

The division of microgravity research in the physics area into three subgroups as proposed during the Sasbachwalden meeting appeared to be not only arbitrary, but also as hampering communications inside the community and the emergence of new topics. This is in contradiction to the Topical Teams and MAP spirit. The researchers in fluid physics have the opinion that they are also doing fundamental physics; the researchers in materials science are closely linked with the study of fluid behaviour. all these projects are really interdisciplinary, balancing between applications and basic science, even if materials science is, in the present distribution, more naturally oriented towards applications. The fluids under investigation are generally high-temperature opaque metallic melts that do not allow detailed non-intrusive analysis as is possible with the transparent low-temperature liquids mostly used in the present division by fluid physics investigations.

This realisation, which was also shared by the life sciences workshop participants, led us to propose cross-disciplinary priority areas, in addition to the more classical disciplinary cornerstones and research priorities.

2.3.1 Fluid physics and combustion

Fluids are present everywhere in everyday life. They are also the fuels of the spacecraft and are widely used in satellites and life support. But it is an everyday experience that fluids are very sensitive to gravity: on Earth liquids flow downwards, gas mostly rises. Under the weightlessness conditions of space, other forces (capillary, osmotic, thermo-capillary, inertial etc.) that are usually negligible with regard to gravity forces, control fluid behaviour and can make their management hazardous. The objectives of fluid research in microgravity is twofold: (i) to investigate fluid behaviour in order to manage fluid and fluid mixtures in space; and (ii) to benefit by the absence of gravity forces in order to detect new behaviour. Both areas of research are driven by industry and fundamental science.

Fluids are present in the other scientific disciplines presented in this report and it is not surprising that the programmes on fluid research overlap those of fundamental physics and materials science. There are a number of collaborative programmes through Topical Teams, for example the one on Critical Point Phenomena in Plasma Dust. We here focus on the hydrodynamics, thermal and phase transition behaviour of fluids, either pure – and here supercritical fluids are especially interesting – or mixed up; particular examples are foams and biofluids, and of chemically reacting fluids. A particularly important point in the latter is concerned with combustion. These programmes are mostly the continuation of previous ones that are still the object of high interest from industry and from a scientific fundamental point of view.

In combustion science there is even stronger evidence for the need for microgravity research. Unlike with liquids, combustion reactions solely take place in the gas phase. This accounts for gaseous fuels as well as for liquid or solid fuels that need to be vaporised to form a flammable mixture with air. As compared to fluid science (here taken as research on the liquid state of aggregation) inertia is much smaller, diffusivity is about ten times higher and the temperature gradients driving buoyancy on Earth are extreme. During, for example. the ignition reactions that happen within nanoseconds and in extremely thin layers, temperature gradients may easily exceed 10 000 degrees per second and per millimetre. Thus combustion research demands a high quality of microgravity but in most cases only over short periods of time. However, varying the ambient parameters such as flow rates, pressure and ambient temperature, a large number of single experiments is necessary to arrogate for a long-term microgravity facility. An exception is the combustion of solid fuels (e.g. in fire safety research) where a long-term facility is required even for a single experiment.

During the three-year period after the preceding ESSC-ESF recommendations (Obernai/Evian review), and in spite of very successful sounding rockets, parabolic flights and Foton capsules, fluid sciences suffered from the absence of a long-term dedicated facility onboard the ISS. The recent successful launch of the Fluid Science Laboratory in Columbus should remedy the situation and lead in the coming years to a large number of breakthroughs. In combustion science, the Bremen drop-tower and the A300 parabolic aircraft were extensively used delivering important results and supporting industry in strengthening their direction of development. A Phase-A study for a European insert on high-pressure/high-temperature combustion to the US-Combustion Integrated Rack was successfully completed when this rack was set on hold, following the change of paradigm in the US space programme in 2004. At present there is no combustion-dedicated facility on the ISS nor is a European facility foreseen. This fact, added to the small size of the European microgravity combustion community, restricts the topics and gives rise to an intercontinental collaboration.

General highlights

The cornerstones of the previous ELIPS programme were first concerned with the increase of the number of flights and the continuation of existing programmes, including the facilities for Columbus. These recommendations were in general followed (parabolic flights, drop-tower, sounding rockets, Foton, taxi-flights to ISS), despite the severe budget restrictions. Columbus is now in orbit, which augurs well for future highlights.

Other recommendations were the need for ground-based research, looking into structural arrangements by, for example, synchrotron radiation, neutron scattering, EXAFS, etc. This recommendation was followed and a number of breakthroughs have been obtained thanks, for example, to the magnetic compensation of the gravity facility.

Two subtopics were considered priority themes to be studied: (i) high pressure ignition and combustion and transcritical fuel droplet vaporisation; and (ii) boiling and boiling crisis. For the former, experiments and numerical simulations have pushed the knowledge about the self-ignition process of fuel spray forward remarkably, enabling decisions to be made on the most promising way to reduce environmentally harmful emissions. The latter indeed led to important findings as outlined in the following.

As already mentioned, the Topical Team programme is a powerful ESA tool that supports and allows the development of new ideas, new experiments and new measurements. The output of these teams can continue to be developed in the framework of the MAP programme. The benefits of this concept can be found in the numerous scientific publications of the teams involved in this process, as can be seen in the four examples provided below.

- From the CIMEX MAP programme, two campaigns of measurements of heat transfer performances under microgravity conditions were performed on new high performance heat pipes and capillary pumped two-phase loops: the experiment HEAT in the MSG of the ISS during the DELTA taxi-flight and the TEPLO experiment during the Foton-M3 mission. They were the results of integrated efforts between university teams and industry (ASTRIUM and EHP);
- In the same CIMEX MAP programme, two sounding rocket flights (MASER 9 and MASER 10) prepared the CIMEX 1 experiment to be performed in the FSL on-board ISS;
- The experiment SCCO, in Foton-M3, measured some diffusion properties (important for oil reservoir modelling) of 12 samples of crude oils with the active participation of TOTAL and Canadian scientists supported by CSA. This was coordinated by the DSC MAP project. It is accepted that this investigation will continue with Chinese oil companies on a Chinese platform;
- The successful experiment JEREMI proposal (Japanese-European Research Experiment on Marangoni Instabilities) also results from Topical Team activities. The project aims to: study heat transfer through moving liquid/gas non-plane interfaces; the influence of the ambient conditions on the behaviour of free interfaces; and of fluid flow beneath, in cylindrical geometry of liquid bridge systems. JEREMI is foreseen on ISS in the Japanese module KIBO in 2011.

New heat and mass transfer investigations are under preparation and are proposed for the FSL Facility by the Topical Teams CBC and Boiling, and supported by the following MAPs: Encon, Saphir and Emerald. These teams are coordinated by C. Colin (IMFT, Toulouse), L. Tadrist (IUSTI, Marseille), JC Legros/O. Kabov (MRC-ULB, Brussels).

Finally, materials and fluid physics are closely related. Two areas of interdisciplinary research were defined for the future and were expected to be activated by the formation of two new topical teams:

- *Nucleation:* bridging the activities in metallic materials to more complex systems, such as proteins, semiconductors, complex macromolecules.
- *Self-organisation:* This feature is encountered in systems far from the thermodynamic equilibrium.

Fluid physics

- **Phase transition – Evaporation and boiling – Condensation**

  Heat transfer

Heat transfer coefficients were measured in ammonia under microgravity conditions (thermal loop CYRENE in plane and sounding rocket parabolic flights). The regimes were those encountered in forced convection boiling and condensation in a small (4.8mm internal diameter) aluminium pipe. The experimental results for boiling and condensation heat transfer cannot be interpreted by using the usual generally admitted correlations. Based on these results, a new method based on the coupling of the void (vapour) fraction with the interfacial shear flow rate has been developed to account for the functioning of thermal machines that cools and heat in space.

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- **Dynamic wetting phenomena, contact line, recoil force (boiling crisis)**

  Boiling crisis revealed

A new study carried out at 33K explains why certain industrial heat exchangers, including those used at power plants, melt catastrophically during a so-called ‘boiling crisis’. The crisis occurs at a critical heat flux, when the bubbles that nucleate in the liquid on a heater’s surface merge into a vapour film that inhibits further heat transfer to the liquid. The same thing happens when a water droplet hits a hot frying pan: a vapour layer insulates the drop so that it evaporates slowly. In a heat exchanger, though, the heater can rapidly overheat and even melt. Both a model for and a detailed look at the boiling crisis were provided. The model invokes vapour recoil, whereby a molecule that escapes a liquid surface pushes against that surface, analogous to the gas thrust of a rocket engine. At high enough heat flux, a growing bubble can forcefully push the liquid entirely away from the heating element. That model was upheld by experimental work performed in a ground-based facility in Grenoble where weightlessness is produced in a strong magnetic field gradient. H_2 was kept near 33K, its critical temperature, where boiling can occur very slowly. Better understand-

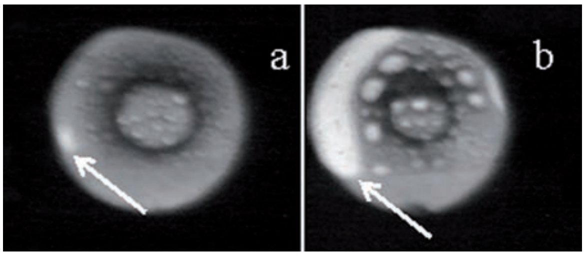

Figure 2.3.1.1: Observation of the boiling crisis under weightlessness conditions (Magnetic Ground Based facility in Grenoble) in H_2 near its critical temperature (33K). Heating is provided by the sapphire front-heating window. The arrow in (a) shows the appearance of a dry spot that rapidly expands in (b) to dry out the heater.

ing of the boiling crisis will facilitate countermeasures at industrial sites and will provide a basis for the re-ignition of the Ariane 5 Vinci engine in orbit where the boiling crisis is a serious concern.

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• Vibration as a form of artificial gravity

Gas-liquid phase transition

The transition from liquid to gas and back again is slowed down in a weightless environment. An artificial form of gravity can be created by using low amplitude (100-300µm) and moderate frequency (10-50Hz) vibration of the sample. This work has implications for work in space, where fluids do not behave the way they do on the ground.

Past studies have shown that vibrating an astronaut's legs and feet helps to prevent muscle decay or bone decalcification. The study was performed at the much more basic level of individual bubbles and droplets, and what happens to them when you add or subtract the effects of gravity.

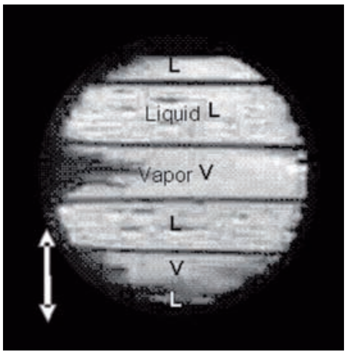

Figure 2.3.1.2: Sample of liquid CO_2 in presence of its vapour in a Maxus 5 sounding rocket when submitted to vibration of 300µm amplitude and 20Hz frequency. After a temperature change, liquid droplets and vapour bubble order in well-defined liquid and vapour phases with plane interfaces reminiscent of Earth-bound conditions.

Movement between liquid and vapour states is aided by buoyancy: bubbles rise and droplets fall. But without gravity these actions cease and liquids condense only by the haphazard and slower process of collision between droplets or bubbles. Experiment were carried out in CO_2 in a sounding rocket and in a 20mm^3 sample of liquid/gaseous hydrogen that was levitated in the strong magnetic field of a ground-based facility in Grenoble. The field grabs onto the magnetic moments of the H_2 molecules, helping to suspend them. This essentially creates an artificial weightlessness (only about 1% of Earth's gravity remains) and allows one to see how capillary forces and 'wetting' (the process by which a liquid layer builds up on a surface) are dominant in a freefall environment. Then some of the effects of gravity are artificially added back in, this time in the form of high-speed but low-amplitude vibrations.

The vibrations cause motion in the fluid, which induces effects that resemble gravity. Bubbles and droplets go 'up' and 'down' again when the vibration is turned on. As far as simulating gravity, vibrations seem to work.

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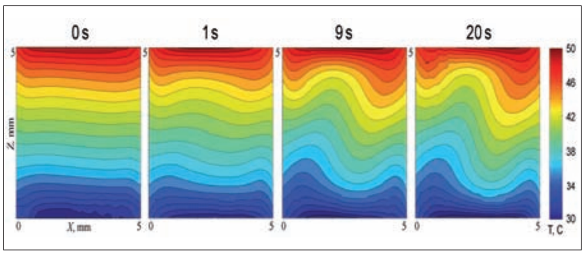
Thermo-vibrational convection

A fluid submitted to vibration can exhibit thermal instabilities similar to the one encountered on Earth, as the well-known Rayleigh-Bénard instabilities. Experimental evidence has been reported of convection caused in weightlessness by translational vibration of non–uniformly heated fluids in parabolic flights. Former data gathered in the former MIR station have also been used. Although the theory of thermo-vibrational convection in weightlessness has been well developed, direct experimental proofs of this type of motion were missing.



Courtesy: Shevtsova

Figure 2.3.1.3: The evolution of temperature field in a vibrated square sample 5mm length filled with alcohol (side view) during parabola weightlessness conditions. Vibration: 45mm amplitude, 4Hz frequency. Well-organised rolls present experimental evidence of thermal vibrational convection and verify existing theoretical studies.

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• Interfaces – Foams – Emulsions

Interaction of typical surfactants, proteins

A gas bubble (or liquid droplet) is attached to a capillary and immersed in a liquid that contains surface active molecules (surfactants, proteins etc.) that adsorb at the interface. The bubble (droplet) oscillates under the effect of imposed pressure oscillations in the capillary (typically from 0.01 to 100Hz). The amplitude and phase frequency dependence of the bubble (droplet) shape enables the surface elasticity modulus to be obtained in real-time. From this modulus the characteristics of the adsorption layer (e.g. compressibility) and its evolution can be inferred, which makes this technique (called FAST), extremely valuable to quantitatively characterise the interface properties in microgravity.

Courtesy: L. Liggieri, 2007

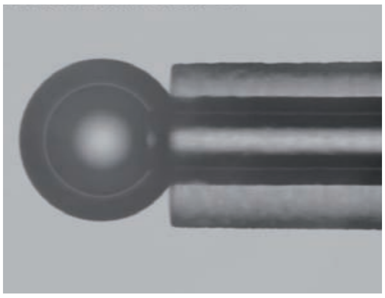


Figure 2.3.1.4: The oscillating bubble attached to the capillary.

Wet foams (imbibition)

An important result has been obtained in parabolic flights (plane and rockets) on the drainage in space of 'wet' foams; namely foams with a large percentage of liquid that are usually dried by gravity flows on Earth. Foams with liquid fraction as large as 30% are still stable and the wetting front obeys a diffusion process, a result that is also of importance for other poro-elastic materials such as plants and biological tissues.

Reference:

A. Saint-Jalmes, S. Marze, H. Ritacco, D. Langevin, S. Bail, J. Dubail, G. Roux , L. Guingot, L. Tosini, P. Sung *'Diffusive liquid propagation in porous and elastic materials: the case of foams under microgravity conditions' Phys.Rev.Lett., 98, 058303 (2007)*

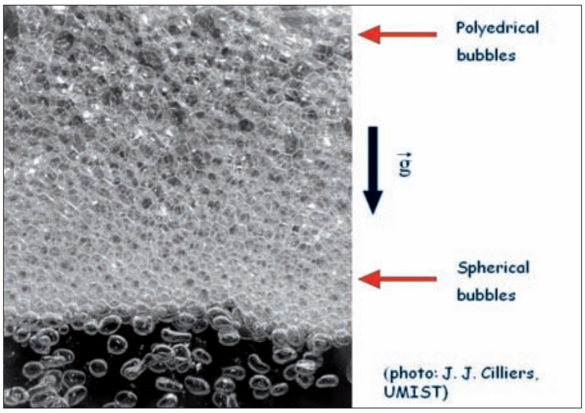


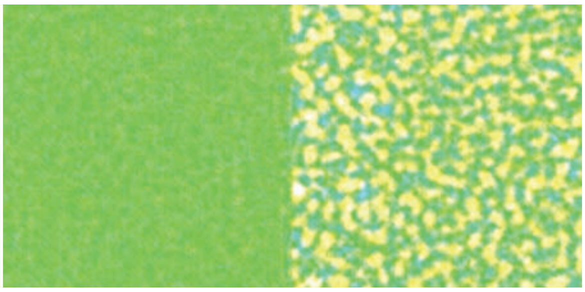
Figure 2.3.1.5: Drainage of a 'wet' foam on Earth. This process does not exist anymore in space where, instead, the wetting front obeys a diffusive process.

• Giant fluctuations at gas-liquid dissolving interface

It was discovered 10 years ago that, unexpectedly, large spatial fluctuations in concentration can take place during a free diffusion process, as the one occurring at the interface of liquids undergoing a mixing process. Fluctuations of concentration (and density) are however seen that are due to a coupling between velocity and concentration fluctuations in the non-equilibrium state. As the amplitude of the fluctuations are limited by gravity, an experiment (GRADFLEX) in the Foton-M3 mission aimed to observe the fluctuations increase ('giant' fluctuations) when gravity is not present. The experiment was performed at the interface between a liquid and its vapour above the critical point where liquid dissolves in the vapour. The observation results of such giant fluctuations will influence other types of microgravity research, such as the growth of crystals. It may even lead to some new technological spin-offs.

Reference:

A. Vailati and M. Giglio, *'Giant fluctuations in a free diffusion process', Nature 390, 262-265.*



Courtesy: ESA.

Figure 2.3.1.6: Fluid theory confirmed during a Foton flight. False colour images from the single fluid study, showing temperature fluctuations in a simple, single-component organic fluid on Earth (left) and aboard Foton-M3 (right). The fluctuations in normal gravity on Earth are barely visible.

Courtesy: Misbah

Figure 2.3.1.7: The effect of shear flow in vesicules (model of blood cells) flowing in a pipe under weightlessness.

• Biofluids: microfluidic of biological materials

Although the basic constituents of a biological fluid as, for example blood, are of the order of micrometres, gravity and its absence can deeply affect the behaviour of biofluids. The other length scales (diameter and length of the vessel) are indeed large. Investigations in weightlessness (parabolic flights) of vesicles, which are good models for blood cells, show that vesicles can undergo temporal oscillations under the influence of shear flow. These studies have also industry relevance as micron-sized particles that are very close to blood compounds (red blood cells, white blood cells) and can be separated by a hydrodynamic focusing method (the so-called 'split' technique). These experiments could allow the elimination of toxic products from blood (the haemodialysis) or the recovery of proteins from blood plasma. Microgravity is mandatory to improve the process. In particular, it was shown in parabolic flights that the non-specific transversal migration of cells that was observed, which is detrimental to separation efficiency of mixtures of different species, was because of the shear-induced hydrodynamic diffusion. Thanks to this finding, the SPLITT fractionation technique was successfully modified.

References:

M. Mader, C. Misbah, T. Podgorski, Dynamics and rheology of vesicles under a shear flow under gravity and microgravity, Microgravity sci. technol. XVIII-3/4, 200-2003 (2006).

Dorra Salhi, Mauricio Hoyos and Pascal Kurowski, Séparation de particules microniques par focalisation hydrodynamique, Mécanique & Industries 5, 589-596 (2004)

Combustion

• Auto-ignition of hydrocarbon fuels

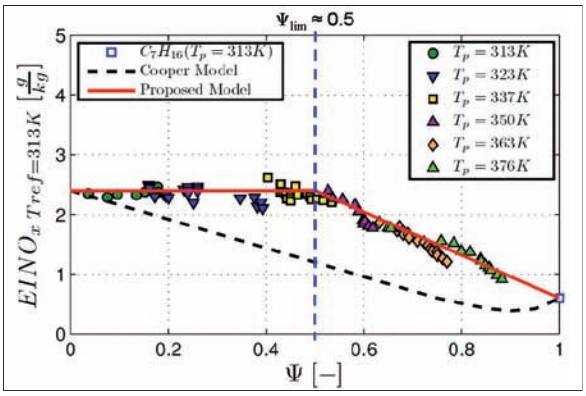
The most promising way to reduce emissions of nitric oxides from gas-turbines and diesel engines is in lean pre-mixed combustion. This requires a pre-vaporisation of the dispersed fuel and a pre-mixing of the fuel vapour with air through turbulence prior to the auto-ignition of the mixture. As the time available for this physical process is very limited in a high-pressure/high-temperature environment, experiments and simulations were investigating the auto-ignition process of fuels and the dependency of the NO-formation process on the degree for pre-vaporisation. As a result, the following image shows that dependency of the NO-emissions from the degree of pre-vaporisation for the kerosene.

As can be seen, essential NO reduction starts only beyond a degree of pre-vaporisation of 50%. A new model was developed matching the experimental results. Achieving this high degree of pre-vaporisation in technical installations is always connected to the hazard of a mixture undergoing auto-ignition in a pre-mixing duct outside the combustion chamber. This circumstance gives rise to research on the auto-ignition process of single fuel droplets and the development of a numerical model for spray auto-ignition based upon the results from microgravity research.

As a result of this research on n-heptane droplets, the numerical simulation of the ignition delay for various overall air/fuel ratios is shown in Figure 2.3.1.9 plotting the induction time over the initial droplet diameter.

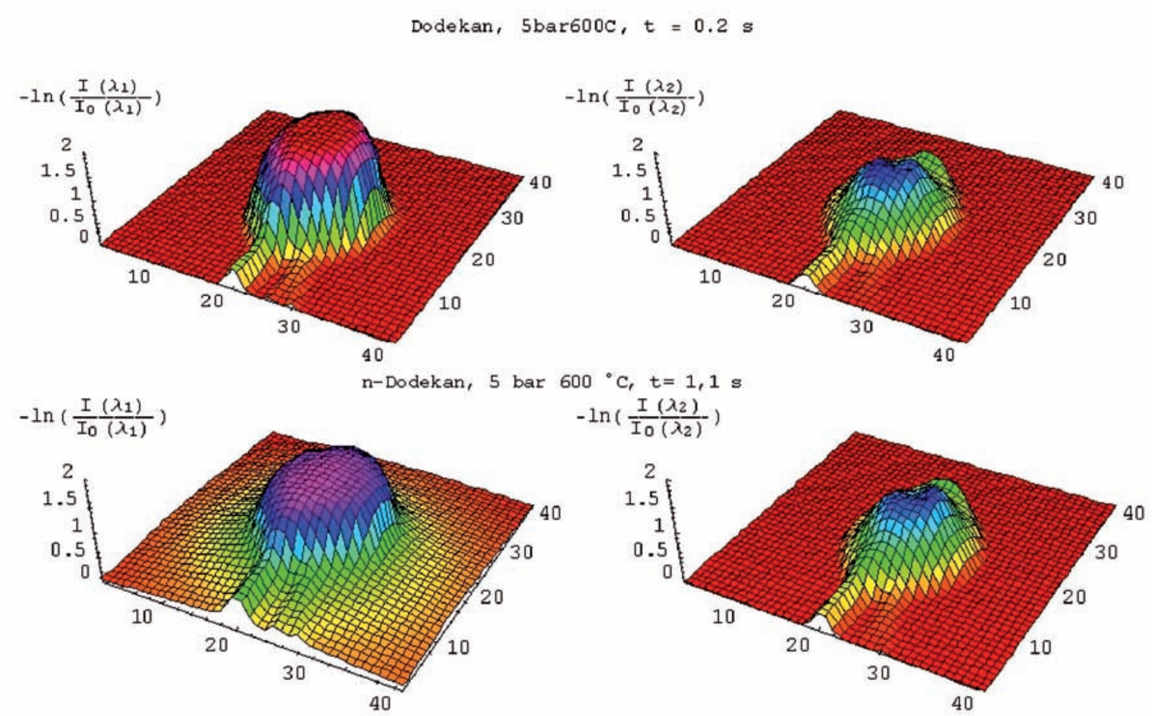
The graph shows that for all overall-mixture ratios the induction time decreases with a decreasing initial droplet diameter but increases when ignition does not happen during droplet lifetime. In other words: the induction time of homogeneous and single-phased systems (left of the lifetime line) is longer than that of heterogeneous, multiphased systems. This gets larger with richer air/fuel mixtures.

This important finding may assist in dispelling the former concerns that the available time until auto-ignition might be sufficient for pre-vaporisation but not for subsequent pre-mixing. In contrast, if pre-vaporisation could be achieved there will be an additional time given for pre-mixing. To deal with the contradiction that this extra time is given specifically for rich mixtures while low-NOx combustion is possible only in the lean regime, one could, for example. design an injector that vaporises the fuel only with a portion of the combustion air and rapidly mixes it with the rest of the air after vaporisation.



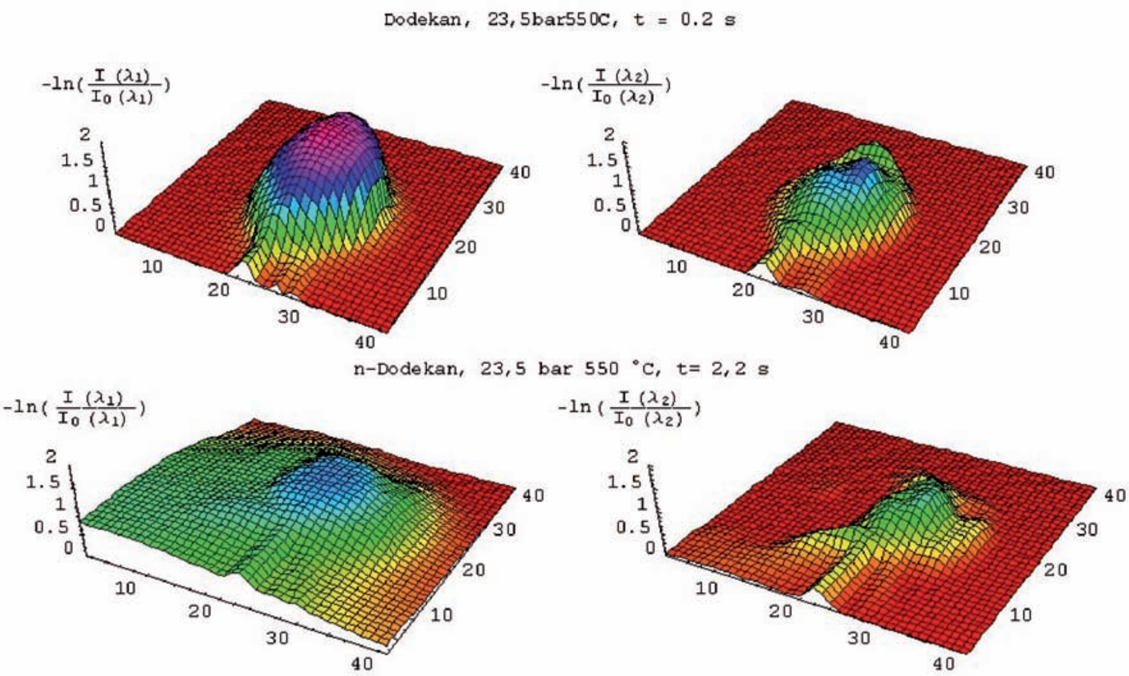
Courtesy: Moesl.

Figure 2.3.1.8: Dependency of the emission index of NO from kerosene spray combustion on the degree of pre-vaporisation. 0 = non pre-vaporised; 1 = completely pre-vaporised.



Courtesy: C. Eigenbrod

Figure 2.3.1.10: Subcritical vaporisation of an n-dodecane droplet after 0.2s (top) and after 1.1s (bottom). From the raw image (left) differentiation leads to the fuel concentration (right).



Courtesy: C. Eigenbrod

Figure 2.3.1.11: Supercritical vaporisation of an n-dodecane droplet after 0.2s (top) and after 2.2s (bottom). From the raw image (left) differentiation leads to the fuel concentration (right).

Courtesy: C. Eigenbrod

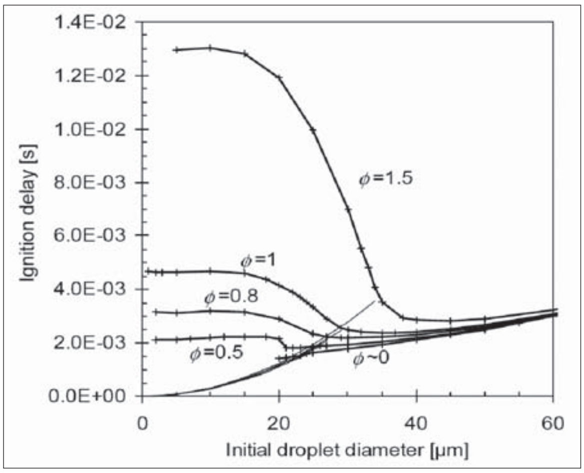


Figure 2.3.1.9: Ignition delay of n-heptane droplets over initial droplet diameter at 17bar and 400°C with the overall air/fuel ratio as parameter. The lines fixed to the diagram's origin indicate the end of droplet lifetime.

Another question related to the initial processes of spray combustion was, whether or not mixture formation is accelerated when the ambient conditions exceed the critical conditions of the fuel. Drop-tower experiments were for the first time carried out not trying to observe the droplet diameter regression rate (which is difficult as in supercritical conditions there is no clear-cut liquid/gas interface) but applying an absorption spectroscopy technology that measures the radial fuel concentration independent from its state of aggregation.

The sample images, Figures 2.3.1.10 and 2.3.1.11, show the experimental results after image processing.

Also these results show the dissipation of the liquid/gas interface and thus the reduction in surface tension. But an evaluation of the radial fuel concentration overall radius and through all 20 drop experiments did not account for the significant increase in vaporisation rate but only a slight increase of less than 5%. As at the critical point the liquid and its gas phase are in equilibrium there is no significant difference in diameter of the fuel-affected area between sub- and supercritical conditions. The expansion of the fuel vapour into the ambient air is mostly diffusion controlled and there exists no difference between sub- and supercritical conditions. This might be the reason why combustion of spray at supercritical conditions of the fuel does not show significant differences. The findings give rise to the assumption that this might be different under extremely turbulent conditions when the vortex scale is on the scale of the initial droplet diameter and thus the fuel vapour sphere is not only transported but sheared.

References:

S. Baessler, K. Moesl, T. Sattelmayer, NOx Emissions of a Premixed, Partially Vaporized Kerosene Spray Flame, Journal of Engineering for Gas Turbines and Power, Vol. 129, 2007, pp. 695-702.

O. Moriue, M. Mikami, N. Kojima, Ch. Eigenbrod, Numerical simulations of the ignition of n-heptane droplets in the transition diameter range from heterogeneous to homogeneous ignition, Proc. Combust. Inst. 30, pp. 1973-1980, 2005.

• Development of a theory-based model for solid fuel combustion (fire safety relevant)

Investigations on solid fuel combustion in microgravity are of direct relevance for the safety of human spaceflight; for example regarding the long-term planned missions to Mars or permanently manned lunar stations. It is only twenty years ago that it was claimed that terrestrial buoyancy is indispensable for a fire to be self-sustained. Later it was learned that steady state combustion is also possible in microgravity. But as microgravity fires are usually much less vigorous than those arising with the aid of natural convection it was confirmed that the fire safety regulation applied to aeronautics must be also sufficient and applicable to astronautics. This assumption was found to be misleading. Even though it is true that space fires are weaker this may also be an additional hazard, causing fires to expand over large areas without being detected. Things become worse when materials which are not flammable under terrestrial conditions may burn in microgravity. The reason for this difference is rather simple: under terrestrial conditions natural convection not only facilitates the transport of oxidiser to the flame and of exhaust gases off the flame, but also with the exhaust gases a lot of heat gets lost. A material is flammable and the flame propagates, when more heat is produced through the flame than lost through convection and radiation. In microgravity this convection is cut off. On the one hand, this means that combustion is only diffusion controlled which makes the process weaker, but on the other hand combustion heat gets lost only through heat conduction. As a result, the pyrolysis zone is smaller but hotter than under terrestrial conditions. This enables a material that would be self-extinguishing on Earth to burn self-sustained in microgravity.

The related projects and its experiments in parabolic flights, sounding rockets and in the drop-tower are of a preparatory character for long-term microgravity experiments in an unidentified host facility. However the experiments made during the last ten years showed that a theory-based approach is badly needed rather than empirical tests space qualifying materials today.

Reference:

G. Legros, A. Fuentes, B. Rollin, P. Joulain, J.P. Vantelon, J. Torero, Extinction simulation of diffusion flame established in microgravity, Journal of the Energy Institute ISSN 1743-9671, vol. 79, no 4, pp. 207-211, 2006

- **Diagnostics on particle formation from diffusion flames**

This research is directly connected to the fire safety research in space as described before and is additionally delivering insights into the mechanisms of particle formation from non pre-mixed flames as in terrestrial combustion engines (diesel engines, gas turbines, furnaces and boilers).

Drop-tower experiments were performed applying the technique of Laser-Induced Incandescence (LII) to simultaneously measure the two-dimensional distribution of soot concentrations and primary particle sizes from methane, ethane and heptane non pre-mixed flames. Additionally, temperature fields were measured to relate the particle size information to flame temperature by 2-colour emission spectroscopy. As a result it was found that the primary particle size roughly doubles in non-buoyant microgravity flames. This was found to be fuel independent. Because of lack of convective transport, as described before, the flame temperatures are reduced in microgravity. This is the main reason for larger primary particle sizes. 'Fuel–specific' is whether or not the laminar jet diffusion flames exhibit an opening of the flame tip. This is the case for ethane and heptane flames while methane flames remain showing a closed tip shape. If the flame opens, the oxidation of soot ceases, allowing for a further growth of the primary particles.

These results imply conclusions on the health aspects of soot-producing fires in microgravity: depending on which materials burn rather different aggregates may be produced when compared to terrestrial fires. The results also imply technical conclusions as the emitted particles may be of practical use; for example to generate functional coatings for sensor technologies.

Courtesy: Will

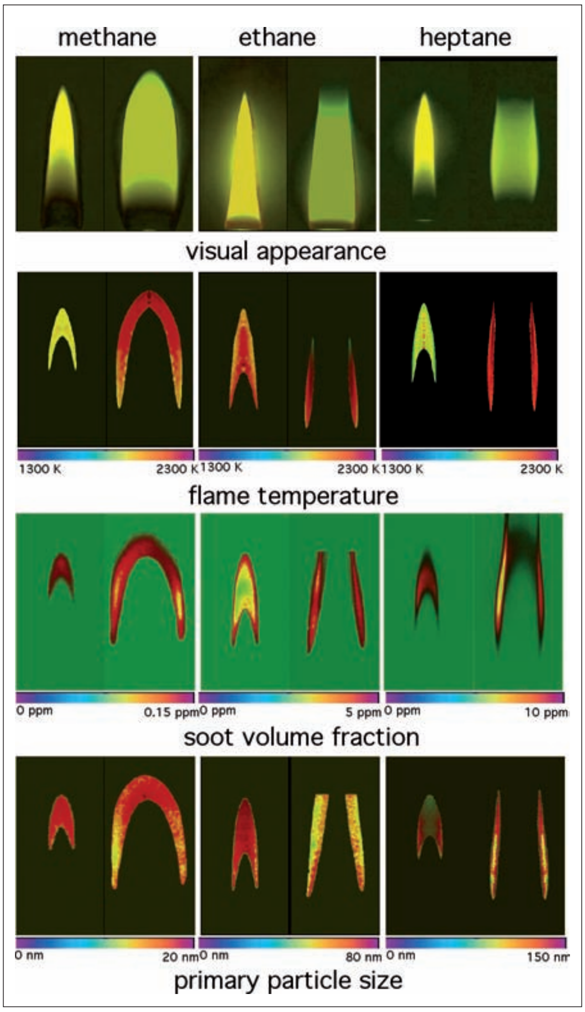


Figure 2.3.1.12: Comparison of methane, ethane and heptane laminar jet diffusion flames in microgravity.

Reference:

J. Reimann, S. Will, Optical diagnostics on sooting laminar diffusion flames in microgravity, Microgravity sci. technol. XVI-1, pp. 333-337, (2006)

2.3.2 Fundamental physics

The report considers achievements in fundamental physics research in microgravity during the past four years and covers the time frame 2004-2007. Whilst the scientific outcomes of this programmatic theme are extensive, no one achievement can be attributed only to the ELIPS programme alone, nor was funded solely by ESA. However, the opportunities afforded by ELIPS, together with funding from national agencies, (potentially provided as a result of ELIPS opportunities) have led to various important scientific outcomes. The bibliography at the end of this section lists the relevant references reporting the scientific results.

Fundamental interactions–quantum physics in space-time

The field was established in ELIPS for the first time in 2004. At that time, it had been recognised that quantum sensors have a high potential for measurements with extremely high precision and that conditions of weightlessness can optimise those sensors and experiments for gravitational physics, quantum physics, and phenomenological studies for quantum gravity.

The importance and the impressive developments in the field of long-range quantum communication and entanglement experiments, aimed at assessing the space-time structure and principles of quantum physics. The recommendations led to several projects and assessment studies for specific projects funded by ESA and the national space agencies in Austria (ASA), France (CNES), Germany (DLR), and Italy (ASI).

These are the following:

- ACES project: The already approved experiment ACES is a clock ensemble onboard ISS consisting of a caesium clock and a hydrogen maser that will substantially advance time measurement from space. ACES will perform new tests in fundamental physics (relativity and variability of fundamental constants) and new applications in Earth observation and geodesy. The ACES engineering models have all been delivered and successfully tested on the ground.
- QUANTUS project (funded by DLR): First realisation of a Bose-Einstein condensate under weightlessness with a time-of-flight of 1 second on drop-tower Bremen. The project also demonstrated the feasibility and technical maturity to process Bose-Einstein condensates in a robust and down-scaled facility.
- Assessment study and research project for the development of optical clocks in space (Space Optical Clocks). The project aims to build a prototype of an atomic optical clock for future space applications.
- Assessment study and research project for the development of the engineering model of a prototype atom interferometer in order to demonstrate technical maturity for later space flights.
- Space-QUEST project and related studies ACCOM and QUIPS: First time demonstration of the transmission of entangled photon over long distances (up to 144km on the Canary Islands). The project successfully tested and verified quantum optical transceivers on the ground as prototypes for space application.

Courtesy: QUANTUS-Collaboration

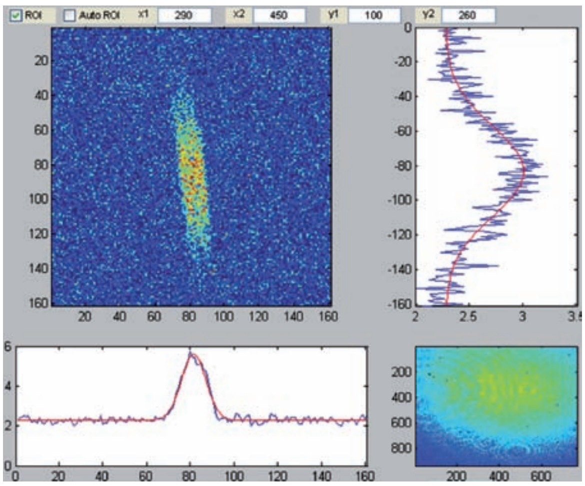


Figure 2.3.2.1: Bose-Einstein condensate (BEC) after 700ms time of flight (free evolution time) in weightlessness during an experiment in the drop-tower in Bremen. The picture demonstrates that weightlessness enables the attainment of much higher time of flights than under the influence of the terrestrial gravitational field. The experiments enable ultra-low temperatures (below the nK-regime) and much larger sizes of the BECs and allow a direct observation of the quantum matter.

Soft Matter Physics

Complex Plasma Physics

The ELIPS 2 goals have mainly been achieved. The existing facility onboard ISS is operating and experiments were carried out. Currently, the Plasma Crystal Facility PK-4 is under construction, to be finished by 2010. Among the major achievements are:

- The Phase A/B study of the PK-4 Facility to be installed on ISS between 2006 and 2008 and the start of the Phase C/D for PK-4 which should be finished by 2010;
- Parabolic flight campaigns with PK-4;
- Parabolic flight campaigns with PK-3 Plus for the test and preparation of the space experiment (operational on the ISS since January 2006);
- Six experimental runs of PK-3 Plus, each 1.5 hours of pure microgravity time, performed during the Astrolab mission with the discovery of:
  – electro-rheological plasmas
  – waves in complex plasmas

The analysis of these experiments is still ongoing.

- The initiation of a Topical Team for Critical Points in Complex Plasmas in cooperation with Japanese coworkers;
- The Phase A study for the IMPF experiment on the IMPACT facility (2004-2006).

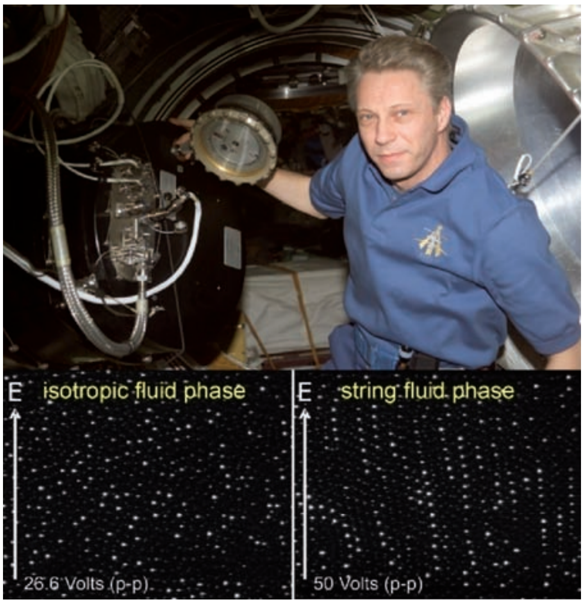


Figure 2.3.2.2: The image combines the operation of PK-3 Plus on the ISS by Thomas Reiter during the Astrolab mission and the most important result from the laboratory, so far, the transition from a homogeneous fluid to a string fluid - the first observation of electrorheological plasmas [Ivlev et al., Phys. Rev. Lett. 100 095003, 2008].

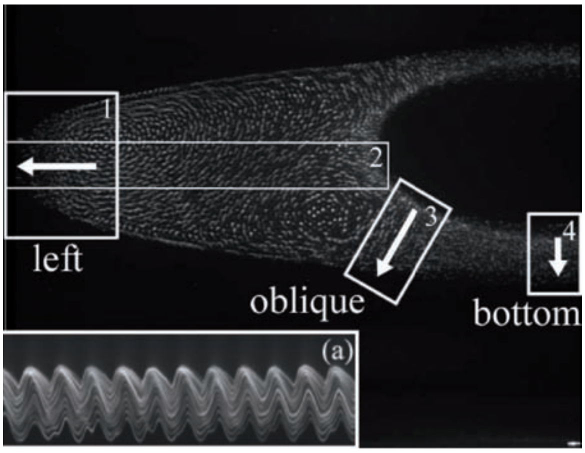


Figure 2.3.2.3: This graph shows another result from PK-3 Plus on the ISS: the combination of self-excited and excited waves in complex plasmas. The image shows an original image with an exposure time of 0.24 sec. The areas of investigation and the direction of the waves are marked. In the insert, a periodgram of a vertical slashing mode at excitation frequency of 2Hz is shown [Schwabe et al., New J. Phys. 10 033037, 2008].

In addition the following activities, mainly funded by national agencies, took place:
- The operational phase of PKE-Nefedov on the ISS had stopped in July 2005;
- More than 30 papers (14 in the ELIPS 2 time frame) in refereed journals about the research of complex plasmas under microgravity conditions had been published meanwhile;
- Experimental runs of PK-3 Plus, each 1 5 hours of pure microgravity time, on ISS with the following objectives (Figures 2.3.2.2 and 2.3.2.3):
  - basic experiments to explore the phase space of the new lab PK-3 Plus
  - first dedicated experiments relating to the critical point in complex plasmas
  - two-phase flow experiments (Rayleigh-Taylor instability)
- Start of the predevelopment phase PlasmaLab for new plasma chambers specially designed for future space experiments (IMPF/IMPACT) in November 2007.

Dust physics
Within the ELIPS programme several experiments on short-term microgravity facilities have been carried out:
- Powder aggregation experiments and computer simulations;
- Parabolic flights on low-velocity dust-aggregate collisions at ambient and low temperature;
- Parabolic flights and drop-tower experiments on photophoretic particle motion and particle trapping by photophoresis;
- Drop-tower experiments on thermophoretic particle motion, thermal creep-induced convection and particle trapping by thermophoretic dynamic balancing.

Among these experimental campaigns, the following important results had been achieved:
- Almost 20 metals were investigated in evaporation/condensation experiments, including the production of new exotic alloys. Measurements of fractal dimension by laser light-scattering techniques had been carried out and had been matched by computer simulations;
- The luminescence of silicon nanoparticles produced by laser bombardment was measured;
- Electrical conductivity of fractal aggregates was proven (a presaging relevance for superconductivity);
- Fern-like metallic fractal aggregates related to the thermodynamics of crystallisation were realised, yielding regular patterns (contrary to random patterns of spheroidal monomer aggregates);
- Cosmology models of the early universe were experimentally reproduced by patterns obtained via laser evaporation of metallic samples;
- Experiments were carried out to look for alternatives to dark matter in the universe (supporting Modified Newtonian Dynamics Theories);
- First ever measurements of random impact low-velocity collisions of dust aggregates were performed at ambient and low temperature, providing impact angle-dependent coefficients of restitution, showing efficient conversion of translational to rotational energy.

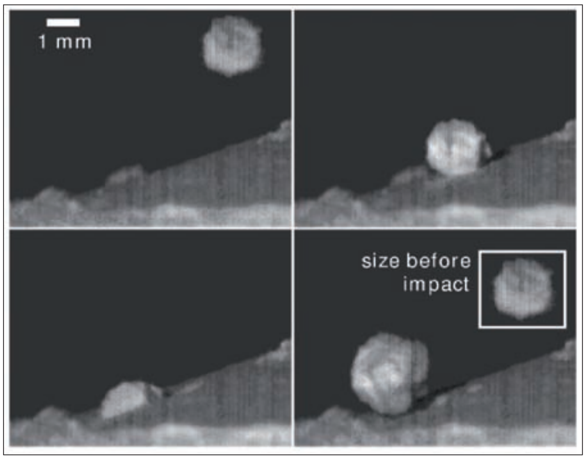


Figure 2.3.2.4: Impact of an mm-sized high-porosity dust aggregate into a macroscopic high-porosity dusty surface, performed in the Bremen drop-tower. The images (from top left to bottom right) show the approaching projectile (velocity 1.8m/s); the point of first contact between projectile and target; the point of deepest penetration; and the moment when the projectile leaves the target. The projectile's escaping velocity is so low that it would not have rebounded under normal gravity. Note that the projectile after rebound is more massive than the impinging one (see inset). Figure taken from Langkowski et al. 2008.

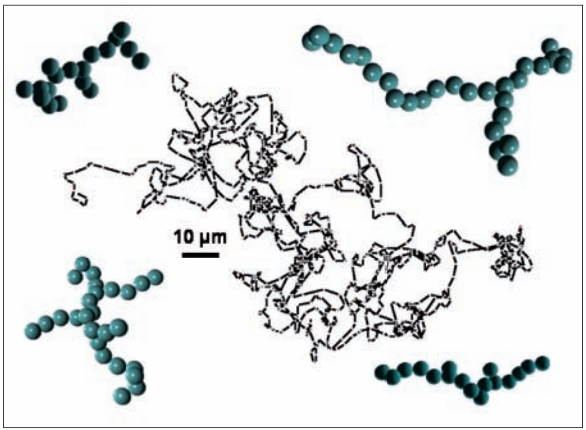


Figure 2.3.2.5: Four examples of dust aggregates grown by Brownian-motion-induced collisions in a long-duration microgravity experiment (Blum et al. 2000). The displayed dust aggregates were reconstructed from three-dimensional microscopic images in a space shuttle experiment and consist of SiO_2 spheres with 1.9µm diameter. The centre of the image shows a trajectory of a single SiO_2 sphere with 1.5µm diameter, recorded in a drop-tower experiment (Blum et al. 2006). The trajectory consists of 1024 position measurements and has a total duration of 2.2 seconds. The gas pressure in the experiment was 100Pa. Figure taken from Blum et al. 2008.

For the first time, measurements were made of impacts of mm-sized dust aggregates into cm-sized dusty objects. The astonishing result is that sticking occurs when the impact velocity exceeds a threshold velocity, while below that value, the projectiles bounce (Figure 2.3.2.4):

- First measurements world wide of random impact low velocity collisions of hyper-quenched ice particles in free-fall at around a temperature of 150K were carried out. Collisions are highly elastic with very effective conversion of translational to rotational energy;
- The photophoretic velocity of single µm-sized dust grains and aggregates thereof was measured. As predicted by theory, the photophoretic velocity in a rarefied gas is on average proportional to the particle size with considerable deviations in velocity and direction;
- Experiments to measure the solid-state greenhouse effect under low-gravity conditions were carried out;
- The first-ever measurement of the ballistic part of Brownian motion and Brownian rotation of µm-sized particles in rarefied gas was realised. The measurements exactly match the theoretical prediction by the Ornstein-Fürth theory (Figure 2.3.2.5);
- The behaviour of granular matter under reduced-gravity conditions (0.01-1g) was observed. While the static angle of repose seems to be independent of residual acceleration, the dynamic angle of repose shows a strong gravitational dependence;
- The macroscopic cloud convection induced by gas thermal creep along the non-uniformly heated walls was observed. Flow pattern and individual particle velocities matched theoretical predictions and numerical simulations;
- In the problem of negative thermophoresis, analysis showed that variation of accommodation coefficients may invert the sign of particle velocity or make it zero. Record parameters were achieved experimentally. The most conservative estimate of the upper value of thermophoretic velocity was found to be much lower than any previously reported values;
- A new type of dynamic balancing, the thermophoretic trap, was proposed.

Vibration and Granular Matter Physics

The major achievements are:

- A new method for gauge calibration and accurate measure of the restitution coefficient;
- The evidence for period ringing in a very dilute ball gas;
- The evidence for non-ergodicity for a vibrating dissipative billiard;
- The accurate measurement of the speed distribution in a low density granular gas and the evidence for a biphasic system (Figure 2.3.2.6);
- The measurement of the inhomogeneous density distribution in an intermediate dense granular gas;
- The evidence that the physics of a vibrating granular gas is non–extensive.

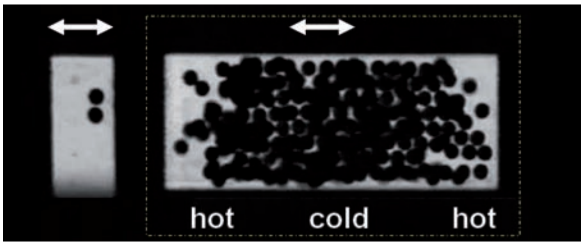


Figure 2.3.2.6: Vibrated granular gas in 0g: (left) snapshot of two grains moving at the same speed in a vibrated cell under weightless conditions; both particles collide only with the walls and make a round-trip per vibration period. Their speed is then much faster than the boundary speed and their motion remains 'coherent', that is, in phase with the vibration. (Right) many grains that collide with the walls and with each other. The grain density is higher in the middle of the cell, making their temperature colder. Double arrow: vibration amplitude 0.3mm and frequency 60Hz. Experiment from Maxus 5 rocket.

Environmental Physics

Within the parameters of using ISS for Earth observation, climate research and space science, the completion of Phase A of the Atmosphere-Space Interactions Monitor (ASIM) and the initiation of Phase B are considered a major achievement. ASIM is designed to measure the region of the atmosphere above severe thunderstorms and for related scientific goals.

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C. Lämmerzahl, H. Dittus, Fundamental Physics, Space, Missions, and Technologies, in: Lasers, Clocks, and Drag-free: Exploration of Relativistic Gravity in Space (H. Dittus, C. Lämmerzahl, S. Turyshev, Eds.), Springer Publisher, Berlin, Heidelberg, New York, p. 3 -25, 2007

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2.3.3 Materials science

Materials science is an interdisciplinary field dealing with the properties of matter and their applications to various areas of science and engineering. This science investigates the relationship between the structure of materials and their properties. It includes elements of applied physics and chemistry, as well as chemical, mechanical, civil and electrical engineering. With significant media attention on nanoscience and nanotechnology in recent years, materials science has been propelled to the forefront.

The research, from both a fundamental and an applied point of view, is concerned with the synthesis, atomic structure, chemical element distribution and various favourable properties of materials and structures. The basic understanding and optimisation of properties and structures is further supported by sophisticated computer models from the nano- to the macroscale and leads to manifold applications in industrial products. Prominent examples are found in the aerospace, automotive, biomedical, energy and microelectronics industries. For a wide range of new or better products, solidification processing of metallic alloys from the melt is a step of uttermost importance in the industrial production chain. Consequently, this field of new materials, advanced processes and products constitutes a major backbone of European industries.

The physical properties of engineering materials, such as mechanical strength, creep and wear resistance, ductility, heat transport as well as magnetic and electronic characteristics are determined by their nano- and microstructure, chemical composition and defects produced during the synthesis process; for example during solidification from the melt. Besides the atomic scale inherent in condensed matter and the intermediate scales associated with the solidification of microstructures, fluid flow driven by gravity generally occurs in the melt at the macroscopic scale of a cast product so that the relevant length scales in a casting are widespread, from the atomic size (crystalline defects such as dislocations, attachment of atoms etc.) to the metre size of the ingot (fluid flow, spacing of dendrite side branches).

On this basis, materials science is closely related to fluid physics and to some extent to fundamental physics, for example in the areas of ‘phase transformations’ and ‘soft matter’. The motivation for performing benchmark experiments in the microgravity environment is straightforward. First of all, in space it is possible to suppress the gravity-induced effects of fluid flow and more subtle sedimentation effects during solidification. Therefore, the contribution of diffusion to mass and heat transport in the melt can be investigated without the complications of buoyancy-driven thermo-solutal convection and sedimentation/flotation. As a result, fresh insights into alloy solidification/processing can be gained with the potential to produce novel microstructures.

Second, the space environment allows applying containerless processing techniques such as electromagnetic levitation. Levitated melts can be controlled effectively at temperatures more than 2000°C, which in turn enables critical liquid parameters to be measured much more accurately compared to the Earth laboratory. Therefore, it is expected that the specific environment of space and microgravity conditions over long periods of time at ISS will lead to breakthroughs in materials science by eliminating complex distorting effects. In this way, obtaining unambiguous benchmark data and processing conditions will be achieved. So far, only surface-relevant properties of liquids could be measured whereas in the future the entire range of volume-dependent thermophysical properties will be accessible on ISS.

The report considers achievements in materials science research under microgravity conditions in the time period 2005-2007, based on a number of parabolic flight programmes and sounding rocket flights. This European research is embedded in an international materials science network with active groups in Japan, China, India, Russia, Canada and USA.

A key area of microgravity research in this field is centred on metallurgy/materials processing in space. A number of subtopics have been identified in the research programme, including eutectic, peritectic, monotectic, intermetallic alloy growth and multiphase multicomponent alloy solidification. Examples for high tech systems are high-temperature superalloys (base: Ni, Ti etc.), low weight-high strength metals (aluminium, magnesium) precision casting (cast-to-shape, very thin etc.), nanomaterials, transparent model systems, semiconductors (silicon for solar cells), polycrystals, photovoltaic and functional thermoelectric materials.

Melt processing in space allows the design of new materials with better performance. Such advanced products can range from metre-sized objects to micrometre-sized powders. Examples are turbine blades for energy conversion in land-based power plants and for jet engines, low-emission energy-effective engines for cars, so-called ‘supermetals’ (amorphous metal alloys) as thin sheets for electronic components with ultimate strength, high-performance magnets, medical implants such as hip replacements, fine metallic powders to catalyse chemical reactions, to name just a few.

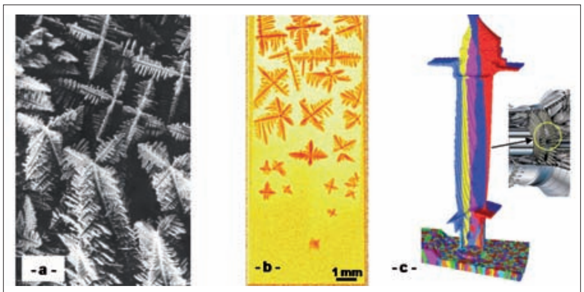
Accordingly, to produce materials that meet ever-higher specific requirements, in particular to save energy by reducing weight or for use at high temperature, the solidification processing of structural materials in metallurgy has to be controlled with ever-increasing precision, all the more as it is foreseen that materials for tomorrow will be optimised in their design and more efficiently produced.

In order to fulfil these goals a comprehensive scientific programme has been established, which is based on a joint approach by modelling and numerical simulation of fundamental physical phenomena and their interactions at the multiple length scales involved in industrial processes, and benchmark experiments on technical and selected model alloy systems.

The most prevalent solidification microstructures exhibit a dendritic morphology, either columnar (Figure 2.3.3.1a) or equiaxed (Figure 2.3.3.1b). For example columnar dendrites (Figure 2.3.3.1c) are required for aeroengine turbine blades capable of operating at ever higher temperatures with excellent creep properties and life in service.

The interactive feedback between experiments and sophisticated computer simulations developed within the last ten years that now drives the design and processing of materials is reaching levels that have never been seen in the past. Thus, two aspects are most essential for the continued improvement of materials processing with increasing requirements for composition, microstructure and service achievements, which often implies the breaking of technology barriers:

- The reliable determination of the thermophysical and related properties of metallic melts in order to understand the fundamentals of complex melts (e.g. multicomponent, intermetallics, semiconductors etc.); and
- The reliable determination of the formation and selection mechanisms at microstructure scales in order to understand the fundamentals of casting and other solidification processes (foundry, welding, microelectronic soldering etc.), and foster the development of quantitative predictive numerical simulation.



Courtesy Ch.-A. Gandin, MINES ParisTech.

Figure 2.3.3.1. (a) Columnar dendritic growth in a directionally solidified Co-Sm-Cu peritectic alloy showing primary and secondary arms. The view of the dendrite array is obtained by etching away the $Cu_{17}Sm_2$ matrix from the primary Co dendrites (courtesy R. Glardon, W. Kurz, EPFL). (b) Equiaxed grains growing in the melt during isothermal cooling down of an Al – 4wt% Cu alloy observed by synchrotron X-ray radiography at ESRF (courtesy H. Nguyen-Thi, University Paul Cezanne). (c) THERCAST® simulated 3D grain-structure in a turbine blade geometry produced by investment casting, with the selection with time of a few columnar grains visible on the outer surface, and close-up on turbine blades in a cutaway view of the Engine Alliance GP7200 engine for Airbus A380.

Thermophysical properties of fluids for advanced processes

Among many results the three most significant achievements are listed below.

- Establishment of containerless levitation technique for high-precision measurements at temperatures up to 2000°C (Fecht and Bilia 2008; Wunderlich and Fecht 2005);
- Measurement of a range of thermophysical properties (surface tension, viscosity) of metallic (Ti-, Ni-, Fe-, Cu-based alloys) and semiconducting materials (Si, Ge) as a function of temperature and composition of stable and undercooled liquids (Higuchi et al 2006; Wunderlicht et al. 2007);
- Interfacial properties of demixing systems (Egy et al. 2003; Battezeatti et al. 2006).

The high chemical reactivity of these industrial metallic alloys in the liquid phase has initiated the development of containerless processing techniques for thermophysical property measurements. In electromagnetic levitation, a specimen is exposed to a high-intensity radio frequency field. The induced current distribution interacts with the external field to create a lifting force. In addition, the generated current heats the sample. In microgravity conditions only small positional forces are required improving the processing control and experimental accuracy tremendously. In Figure 2.3.3.2, a schematic depiction of the analytical capabilities of the facility is shown.

The *ThermoLab MAP* project was conceived to provide a comprehensive data set by combining conventional thermophysical property measurements with advanced containerless processing techniques on ground and under reduced gravity conditions. Containerless processing based on electromagnetic (EML) or electrostatic (ESL) levitation has the advantage that it allows the handling of high-temperature liquid metals without contact with container walls. In addition, non-contact measurement methods needed to be developed. For surface tension, viscosity, and density measurements, these are based on high-resolution and high-speed optical recording of the sample shape as a function of time and temperature. Calorimetry, including thermal relaxation times, is based on high resolution non-contact temperature measurement and modulated induction heating. For the time being, the electromagnetic levitator (EML) provides the most versatile tool for the different types of alloys which have been processed successfully as well as the maturity of non-contact thermoanalytical measurement methods established with this device. In the EML, the specimen can be processed under high vacuum conditions as well as under a protective or reducing gas atmosphere.

In Figure 2.3.3.3 a typical temperature-time profile for a parabolic flight experiment is shown.

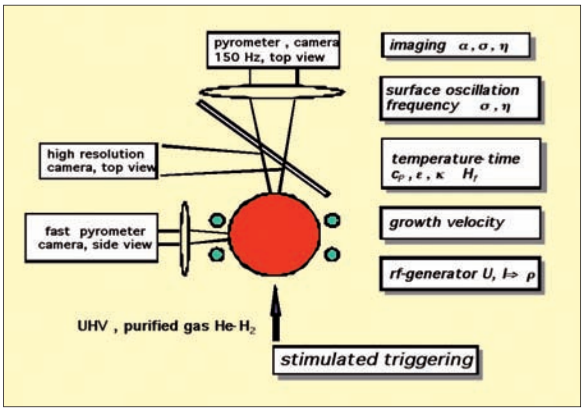


Figure 2.3.3.2. Schematic depiction of the electromagnetic levitation device with its analytical capabilities.

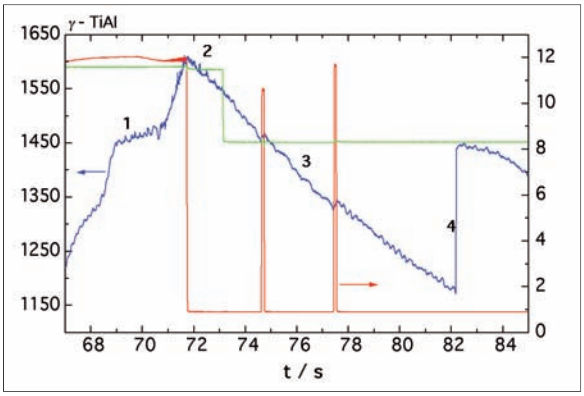


Figure 2.3.3.3. Temperature-time profile of processing a γ-TiAl alloy on a parabolic flight. Temperature is shown on the left hand ordinate, rf-heater (red) and positioner (green) voltages on the right hand ordinate; 1: heating and melting; 2: nearly force-free cooling with the heater turned off; 3: application of heater pulses for the excitation of surface oscillations; 4: further undercooling and recalescence.

Using the Electromagnetic Levitator, surface oscillations of the hot liquid drop with a diameter of 8mm can for instance be introduced by an electromagnetic pulse and the resulting shape variations analysed by a high-speed high-resolution video camera. Among the results, the surface tension has been studied as a function of temperature in the range 1050-1450°C of liquid Ni – 75 at% Al processed under low gravity in four parabolic flights with 10 seconds of processing time each.

New materials, products and processes

One of the ultimate goals of materials science is the quantitative and predictive multiscale modelling of solidification phenomena. Apart from the knowledge of thermophysical properties discussed above, this also requires an understanding of fundamental mechanisms. Using microgravity, considerable progress has been achieved in this regard through the interplay between benchmark experiments in µg and 3D computer modelling. Prominent examples are the prediction and observation of the columnar-equiaxed transition (CET) and the equiaxed single grain growth from an undercooled alloy. Within the IMPRESS project, first fractal-like aggregates of catalytic Ni could be produced, and a new, castable, intermetallic Al-Ti alloy was developed. There is a general trend now to move away from simple systems to multicomponent, multiphase alloys, including stable and metastable monotectics, leading eventually to in situ functional materials. A major achievement was also the development of in situ, real-time diagnostics tools, such as time resolved x-ray radiography. Among many results the three most significant achievements are listed below:

- First fractal-like agglomeration of Ni-nanoparticles for fuel cell applications (Gunter 2008; Gunter private communication 2008);
- Single grain growth in levitated undercooled drop (Fe-C-Mn)/experimental observation and 3D modelling (Volkman et al. 2007; Gandin et al.2008);
- Advanced Intermetallics (TiAl, NiAl) and quantitative prediction of structures (CET, dendrite morphology) (see http://www.spaceflight.esaint/impress) (Sturz et al. 2007).

Several series of ground and Texus/Maxus sounding rocket experiments were carried out within the MICAST and CETSOL MAPs and IMPRESS project to pave the way for the use of the Low Gradient Facility and Solidification and Quenching Facility in MSL. Unexpectedly, it was found that fluid flow, either driven by gravity or forced by a magnetic field, was enhancing dendrite arm coarsening despite the fact that tip radius was not affected. Benchmarking of the columnar-to-equiaxed transition has begun on Al – 7 wt% Si alloys with Maxus7, suggesting that the presence/absence of CET should be linked to the effectiveness of melt inoculation by dendrite-arm fragmentation. For the sake of comparison, development of phase-field modelling is pursued to reach quantitative numerical prediction from the scale of the dendrite tip to the scale of cooperative array growth.

The IMPRESS Integrated Project comprises about 40 industrial and academic research groups from 15 countries in Europe. The project aims to elucidate the relationship between the processing, structure and final properties of new intermetallic alloys, such as TiAl and NiAl. Indeed, these intermetallic alloys, due to their crystal structures and strong chemical bonds, have many attractive mechanical, physical and chemical properties that make them valuable for various applications. For instance, a new castable intermetallic Al-Ti alloy was developed for investment casting of lightweight high-strength turbine blades with 40cm length for next-generation aeroengines, which will contribute to reducing fuel consumption. Also, first fractal-like aggregates of catalytic Ni, of potential relevance for high-performance fuel cell applications, were produced in low-gravity where self-gravity collapse is suppressed.

In addition to these two cornerstones, achievements in the subtopic ‘crystal growth’ are discussed below.

Crystal growth as a subtopic

Protein crystallisation

The ESA project, Influence of Mass Transport and Surface Growth Processes on Protein Perfection, identifies the microgravity-relevant processes influencing crystal growth from solution. These processes are largely independent of the material (protein), which was chosen on the basis of its scientific interest, its suitability as a model system for crystal growth and the previous experience of the teams involved. Central to the study of the microgravity-relevant aspects of crystal growth is the recognition of the processes that could plausibly explain a different growth behaviour or crystal quality in reduced gravity environments. All intermolecular interactions are about 32 orders of magnitude stronger than those related to gravity. Therefore, only the macroscopic mass transport of solute molecules to the growing crystal surface and interrelation of this transport with the solute incorporation processes at the crystal interface may explain any observed differences in growth behaviour or in crystal quality. The study of the processes by which mass transport at the supramolecular scale could control crystal quality is the key subject of the project.

Further main objectives have been established:

- Assessment of the effect of Protein Depletion Zone (PDZ) and low supersaturation growth;
- Assessment of the effect of Impurity Depletion Zone (IDZ) and diffusive purification;
- Nucleation of crystals has been addressed even more rarely than crystal growth either in ground or in microgravity experiments. In the latter case, it is commonly assumed that no gravity effects could be expected because the interactions involved in nucleation should be exclusively of molecular origin, but several other effects of convective/diffusive mass transport on nucleation from solution must be taken into account.

Single crystal growth

Growth of Cd-Zn-Te, a promising material for X-ray detectors, for example in medical applications, is one of the key topics. It was grown under microgravity conditions with the Travelling Heater Method (THM), and the conditions for de-wetting were determined which makes this method, at least partially, also containerless. The three main achievements are:

- De-wetting phenomena and application to semiconductor crystal growth

- Development of a new protein crystal growth facility (GCF)
- Hierarchical porous materials for chemical and medical applications.

Zeolites

Synthetic zeolites are porous silicate-based materials that are invaluable materials in a sustainable industrialised world. For example, zeolite adsorbents and catalysts are highly important for petroleum refining operations and natural gas purification. Applications extend into a wealth of new areas including environmental protection and the production of chemicals serving as pharmaceuticals, nutriceuticals, fragrances, flavours, agrochemicals, as well as sensors, electro-optical devices etc.

Cross-cutting through these disciplines, the development of new theoretical and experimental techniques as well as in situ diagnostic tools, such as the X-ray facility XRMON, was considered as a major achievement with spin-off potential for terrestrial applications.

General achievements, common to all disciplines, are also the establishment of a European Materials Science Network, and the successful joining of microgravity benchmark experiments with advanced three-dimensional multiscale simulations.

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3. Life sciences

3.1 Biology

3.1.1 Rationale

Two factors, one pragmatic and the other more academic, drive research in space biology. The pragmatic factor is a need to know more about the long-term effects of the space environment, including both microgravity and radiation, on organisms/cells as well as how those organisms/cells adapt to that environment. This information is essential for assuring the safety of humans exposed to the space environment for extended periods, as will occur in travel to and from the Moon or Mars. The other driving force for biological research in space is a desire to understand the fundamental ways that cells, tissues and organisms sense and respond to gravity and/or space radiation. Here we essentially study the influence of gravity on life by examining the responses of living materials when gravity is altered or removed with a long-term view to understanding the biological system by modelling and simulation.

Both the applied and the pure driving forces for space research are seen by us as equally important and need to be addressed in tandem.

The specific aim of gravitational and radiation biology as part of the ELIPS 3 programme is to analyse and understand the specific impact of altered gravity (this includes weightlessness, reduced gravity as on the Moon and Mars and hypergravity) as well as radiation on life in its broadest form. Hence, the mandate includes examination of single cells, tissues and organisms representing a range of plants, animals, bacteria and others.

The effects studied cover everything from genetics, development and behaviour of whole organisms to the complex interactions of animals, plants, bacteria etc. in enclosed habitats. The understanding of these impacts is crucial for the successful exploration of space and other planets and may also be exploited to foster industrial and medical development on Earth. While the main purpose of these studies aims at an understanding of basic phenomena, potential applications include subminiaturised analytical technology for fast and reliable diagnosis of diseases and infections, countermeasures for radiation impact or contaminated ecosystems.

European research in gravitational and radiation biology is certainly world-leading at the moment especially as the closest competitor in this field, the USA, has cut its basic biology programme nearly down to nothing due to a shift of the general focus. Europe should therefore seize the opportunity to invest in the future and secure the short-, mid-, and long-term possibilities not only for gaining basic knowledge, but also for inventing innovative applications.

3.1.2 Implementation priorities

Recommendations of the Biology group

The Biology working group has defined new cornerstones. The previous definitions based on science areas (cell and molecular biology, plant biology and developmental biology) were often confusing or misleading because of the vastly overlapping research topics. The new cornerstones focus instead on the underlying basic scientific questions which are common independently of the specific issues addressed. In addition to these cornerstones, the following general recommendations are made:

- The selection of model organisms has to be science-driven. We deliberately do not recommend particular model organisms and/or cell culture systems. In a diverse field such as biology it is necessary to choose the best system for the best science.
- However, wherever and whenever possible, sample-sharing should be encouraged, preferably in the context of multilab experiments. This, of course, enforces the use of ‘common sense’ model systems, but ‘uncommon’ model systems must not be discouraged.
- Preflight hardware has to be provided in sufficient quality and number early enough to allow the PIs/USOCs to perform ground tests in order to prepare for possibly necessary countermeasures. Ground-based studies are needed in support and an optimisation of experiment collection and assembly of different experiments during an increment on ISS should be enforced.
- Furthermore, for the use of transgenic organisms, ESA should develop rules based on national and European laws.
- Other recommendations focus on communication (ESA-scientist, scientist-scientist in an interdisciplinary context) which should be improved, the implementation of the ESF/ESSC recommendations (ESA should inform ESSC of implementations on a yearly basis), programme coordination (regarding an improvement of funding by national agencies/EU programmes in the context of multinational experiments) and technological restrictions (development of hardware, design of alternatives to be used after the era of ISS).

Cornerstones

The Biology working group feels that the existing concept of cornerstones should be modified. Instead of definitions focusing on science areas (e.g. plant biology, cellular and molecular biology and developmental biology), an approach is proposed that focuses on three science questions (see below). In addition, an indication of the development of the field is included hereafter in terms of percentage increments. Care should be taken not to misunderstand these indications as being a priority list, but instead as a way to grade how much we know about a specific question.

The rating adopted here uses 'percent (%)' to roughly indicate (not to exactly describe) the state-of-the-art of how thoroughly a particular scientific question has been answered. Deliberately, the ranking runs from 0% (an issue with no clear evidence available) in incremental steps of 20% each up to 100% (issue resolved). Please be aware that the percentage increments in reality do not correlate with the necessary effort to gain a next step. It will be, for example, much easier to perform a step from 0% to 20% in comparison with a 20% increment reaching from 80% to 100%.

A. The perception of gravity, the effect of radiation and the respective adaptation processes at the cellular level

How is the weak force of gravity detected by single cells?	0%-20%
How are single cells adapting to weightlessness?	40%-60%
How are cells affected by cosmic radiation (emphasis on High-Z particles)?	20%
How are ageing, gravity and radiation connected?	0%
How and why can 'non-professional gravisensing' cells sense gravity?	0%

B. Relation of single cells to extracellular matrices, other cells, tissues, organs and the whole organism

Cellular and systemic integration	40%
Adaptation of systems to altered gravity	40%
Life cycle from embryonic development to senescence	20%
Hormonal and neural regulation	40%
Plant cell and cell wall interaction	20%

C. How is gravity shaping organisms (plants and animals)?

Musculo-skeletal development	40%
Molecular basis of axis development	20%
Plant architecture	20%
Organ development	40%

Model organisms

While the exclusive use of a limited number of model organisms certainly has advantages with regard to hardware development and scientific gain, the Biology working group clearly states that the selection of model organisms must be purely science-driven. In order to achieve results that can be generalised and allow a substantial progress in the understanding of the impact of gravity and radiation on living systems, the best system must be selected for the best scientific question. However, regarding sample sharing or multilab projects (see below) the use of (if possible sequenced) model organisms might be inevitable to speed up scientific progress and could be encouraged by specific AOs or the implementation of dedicated Topical Teams.

Sample sharing

The Biology working group identified sample sharing as a valid and promising possibility for increasing the return value of the scarce flight opportunities. Sharing process should be organised by the responsible agency. ESA is advised to extend existing databases by experiment descriptions for approved flight experiments while clearly indicating the experimental set-up, fixation and unused sample material. This database should be mandatorily referenced in flight proposals. Consequently, flight experiments should be open for new scientific teams to facilitate unused sample material. In this regard, sample material is not only defined as biological material, but includes also digital information; for example DNA-array results. However, to account for the efforts of the conducting laboratories such information should be restricted for exclusive use for one year after successful completion of the experiment. Such experiments should be planned and developed well in advance to provide ample time for colleague scientists to participate in the experiment protocol and sample-sharing process, although the initial science group remains responsible for the actual experiment protocol used. Sharing scientists should include the initial team members in their publications. A start to looking into the possibilities of opening up flight-related data to the user community in order to facilitate future data sharing has been made via the EU-ESA FP7 project ULISSE (Cal ID FP7-SPACE-2007-1).

Multilab experiments

With regard to the development and funding of large interdisciplinary projects the Biology working group favours projects facilitating, for example, controlled environmental systems (CES). Life-support systems are specifically designed for the support of humans, removal of waste and for food production. They are built of separated units each constructed for specific task such as oxygen production or nitrogen removal. In contrast, CES are used to study complex interactions between animals, plants and bacteria under different conditions, for example weightlessness. So, the former is a support unit while the latter is a research unit. However, in a CES, food production is also possible, depending on its size. In addition, such a system can have a positive psychological effect for crews on long term missions.

Such systems have flown successfully in the past (C.E.B.A.S. minimodule, Aquacells, OMEGAHAB). They allowed the involvement of many laboratories addressing scientific questions relevant for plant sciences, cell and molecular biology, microbiology, zoology and developmental biology. CES are also of great relevance for astro/exobiology and can improve collaboration between both fields. The establishment of a dedicated Topical Team is required for the implementation of such system(s). In addition, a strong interest exists in the Chinese space programme in such systems which might help promote cooperation on new flight opportunities. Besides CES, also other multilab experiments using, for example, the Zetos bone explants research facility or the ERISTO modules might be used for this purpose.

Preflight requirements

ESA is asked to provide access to flight hardware (including infrastructure) sufficiently early prior to flight in order to allow experimenters/USOCs to make tests and eventually propose improvements preflight. It is mandatory to ground-test hardware identical with flight hardware beforehand. In many biological experiments, an especially great effort is devoted to hardware development once an experiment is selected for a flight, however, little effort is made for experiments selected only for flight. ESA must fully cover all necessary costs for development and testing of hardware by laboratories involved. The actual science activities should be funded by the scientists´ own means.

As an absolute minimum, ESA should imperatively act upon the space industry and provide the related infrastructure in order to make it possible that: (i) the hardware is being delivered early enough prior to flight for experiment sequence tests (ESTs) at the various USOCs/FRCs; (ii) the hardware must be provided as necessary for these tests (e.g. experimental containers, ECs, must be to hand in a sufficient number; if possible, the hardware should be virtually identical to the flight hardware).

In the case (first point) of the hardware not being delivered early enough, USOCs/FRCs cannot guarantee that possible failures/anomalies found in the course of, for example, ESTs can be readily identified and put right well in advance of the actual flight experiment. In the case (second point) where the test hardware is not provided as necessary regarding, for example, the number of ECs (or, e.g. the test-ECs differ significantly from the flight hardware), the USOCs/FRCs cannot perform, for example, full ESTs and thus, possible failures cannot be identified prior to carrying out the actual flight experiment.

Ground-based studies

Flight proposals should include a programme comprising appropriate ground-based studies. All results clearly indicate that ground studies with random positioning machines, 2D and 3D clinostats or centrifuges (hypergravity, or ground-based radiation research for human space exploration) typically yield some indications of possible effects of microgravity on the system studied. However, the Biology working group acknowledges that, depending on the system, no effect may be observed in ground-based studies. Nevertheless, such experiments must be mandatory before the actual flight experiment can be approved and should be enforced (continuously open research programme of ESA: Access to ground-based facilities: http://www.spaceflight.esa.int/users).

Optimisation of experiment collection and assembly of different experiments during an increment on ISS

Improve the use of the BioLab facility. Biological experiments have to be implemented that use in an optimised manner the typical 6-month period of one mission increment. In principle, there are three types of experimental approaches or scientific areas that have to be considered for BioLab even if the construction of new hardware is necessary. These experiments include: (i) the frequent repetition of experiments using uni- and multicellular organisms that can stay either in a kind of resting stage and can easily be activated at any time or can survive longer periods unattended without problems; (ii) multigeneration experiments to study aspects of heredity under space conditions, using, for example, *Caenorhabditis elegans, Drosophila sp., Danio rerio, Oreochromis mossambicus, Xenopus laevis* – the latter vertebrate species currently cannot be implemented for multigeneration experiments because of the lack of hardware. However, it remains a most important issue whether vertebrates can complete a full life cycle under space conditions (in this regard, please consult ISLSWG 1999 Woods Hole recommendations - Moody and Golden (2000), which are still effective) and the required hardware should be developed; and (iii) the analysis of space environment on the biological clock in animals that allows automated observations of several physiological parameters (model animal: scorpions; experience collected during the experiment SCORPI-T on Foton-M2).

Transgenic organisms

In several member states of the ELIPS 3 programme legal regulations for the use and transport of transgenic organisms exist. However, in the context of flight experiments no clear rules regarding the use of transgenic organisms are effective. ESA is asked to negotiate and implement such rules.

Communication

The Biology working group advises ESA to improve the flow of information to scientists and to facilitate communication among PIs. This includes the implementation of a 'one point of contact' concept regarding flight experiments. The recent changes in ESA organisation as well as the enforcement of user support centres (USOCs) especially require information to circulate to ESA from the scientists and from ESA to the scientists in a more efficient way.

Interdisciplinary communication

There is a strong consensus that communication between the scientific communities working on human physiology, astro/exobiology and biology or even physical sciences should be drastically improved. The European Low Gravity Research Association (ELGRA) as the scientific platform for space and (micro-) gravity-related sciences covers both life and physical sciences. This existing platform should be made use of to foster improved communications between various disciplines.

Implementation of the ESF/ESSC recommendations

ESA should inform ESSC on a yearly basis of the current state of the implementation of the recommendations.

Programme coordination

International collaboration in space experiments is much encouraged. However, even if a project is approved by ESA, the national agencies are responsible for the required funding. When only certain collaborative efforts are funded the whole experiment is jeopardised. ESA is asked to negotiate with the national agency and/or EU programmes to coordinate this process more efficiently. This applies to less elaborate collaborative proposals.

Technological restrictions

Hardware development is seriously delayed, namely the development of advanced microscopy systems. This is severely hampering progress in biology. In this context it should be stated that technological restrictions should not be allowed to define the experimental set-ups. However, financial restrictions obviously apply. ESA is asked to increase the hardware development process based on the urgent needs of the scientists.

Since the ISS life-time for research is limited, and since alternative programme developments take time, such developments should be taken up early with the aim to have a reliable long-term research option for ESA, that can be largely independent.

Also, a more frequent use of unmanned rocket flights lasting two or three weeks (such as Foton) is strongly desired by the Biology working group. BioLab is already almost fully booked, which makes it difficult for European scientists to have their future experiments flown on the ISS.

However, numerous experiments can be flown effectively without the need of crew. Since the Shuttle is no longer used as a platform for European late access biological experiments, activities have been shifted to Soyuz. The facilities at the Soyuz launch base have improved significantly over the last years, but serious limitations to performing the best possible science remain. ESA is requested to forcefully explore the possibility of using the current European launch capabilities of Soyuz rockets in Kourou. Using the launch capabilities at Kourou might solve problems of customs, logistics and laboratory infrastructure. Regarding the need for experiments, ESA might even consider the development of a European platform (satellite) for experiments in biology. Moreover, it has to be considered if Chinese Shenzou-based platforms could be used as another alternative.

3.1.3 Mid-term priorities

A. The perception of gravity, the effect of radiation and the respective adaptation processes at cellular level

• How is the weak force of gravity detected by (single) cells?	0%-20%
• How and why are cells adapting to weightlessness?	40%-60%

As has been stated in the section 2 on achievements, gravitational biologists have hitherto gathered much information regarding the adaptation of individual cells towards altered gravity. Altered gravitational conditions affect single ('solitary') cells as can be found in multicellular organisms such as lymphocytes and single cells artificially removed from the intact organ (e.g. cultured endothelial or bone cells).

The adaptation of unicellular organisms also has to be taken into account here. There is, however, an apparent lack in understanding the underlying signal transduction chains. We have clear ideas (which remain, however, far away from being called a resolved issue), how unicellular organisms such as Paramecium and Euglena detect the weak force of gravity. We also do have some hints on how non-professionally gravisensing cells of multicellular organisms (such as the lymphocytes and endothelial cells mentioned) may detect gravity. There is, however, no clue, why such cells (regarding evolutionary traits as well as functional parameters) can sense gravity, what the underlying signalling chains are, and if possible similarities are shared by the great variety of cells encountered.

Even chemicals have been found to control gravity-mediated signalling in plants. Moreover important knowledge has been obtained in the plant model *Arabidopsis thaliana* on major elements of the gravity-signalling pathways enabling future integrated systems approaches. Future experiments need to be directed towards applying quantitative systems biology approaches to understand gravity and signalling.

• How are cells affected by cosmic radiation (emphasis on High-Z particles)?	20%
• How are ageing, gravity and radiation connected?	0%

It is clear that cosmic radiation (especially High-Z particles) affect cellular function. During phylogenetic development, cosmic radiation was shielded from Earthly life. Nevertheless, radiation may lead to a cellular adaptation, not exclusively to a loss in function or even cellular death.

Regarding research under space conditions, weightlessness and radiation have both to be taken into account regarding an investigation of the corresponding effects on cells (regardless of the cell - be it a unicellular organism, a blood cell or a body cell of an astronaut).

Also, little is known about the mechanisms of cellular (and thus organism) ageing.

Finally, we know almost nothing about a possible interconnection between ageing, radiation and gravity.

Specific objectives

The Biology working group has identified the following objectives, which should be tackled in the future in order to reach the goal of cornerstone A.:

- Clarification of the mechanisms of perception of the gravitational signal, particularly concerning an identification of gravity-specific signalling chains (i.e., the mechanism of signal transduction – gravity is a very weak force – including the role of the cytoskeleton and of mechanical stimuli) and underlying gravity-related genes.
- Investigating adaptive phenomena and underlying mechanisms of cellular adaptation and an adaptation of the cell cycle and cell proliferation to space conditions.
- Clarification of radiation damage (including a radiation-dependent gene expression, DNA damage and repair) and the issue of (premature) ageing under microgravity conditions.
- Investigation of oxidative stress and organelle turnover. Recent studies revealed a crucial role of reactive oxygen species (ROS) as versatile molecules mediating a variety of cellular responses in plant and animal cells, including programmed cell death (PCD), development, gravitropism, gravity-mediated signalling and hormone signalling. A picture showing how ROS function in signal transduction networks has started to emerge as the result of recent studies providing genetic, cell biological and physiological evidence describing roles for ROS in gravity signalling. However, further efforts are necessary to characterise the targets and molecular functions of ROS in microgravity as well as the complex interplay of ROS-generating and ROS-scavenging mechanisms. Moreover, the interactions of nitric oxide with other ROS species in hormone signalling is a subject of interest. How are ROS asymmetrically generated in tissues and organs such as roots by gravistimulation to regions of reduced growth are questions of major importance for space biology.
- Involvement of cell mechanics in disease/treatment. Increasingly more information has been gathered in the past years that, for example, transformed cells, such as cancer cells, do not only display an altered cellular metabolism but also show changed cellular mechanics. This mechanical signature, in concert with other biochemical, biological and genetic pathways, offers unique new perspectives through which human health and disease at the molecular and cellular levels could be better understood. For example, an important step in cancer metastasis involves the penetration of epithelial cells through the endothelial layer, which critically depends on mechanical characteristics such as cell elasticity and deformability. Gravity related research has shown that cells do change their shape at altered gravity conditions. A better understanding of (micro-) gravity-related processes could contribute to a better understanding of some diseases.

B. Relation of single cells to extracellular matrix, other cells, tissue, organs and organism/cellular and systemic integration

• Cellular and systemic integration	40%

Organisms are composed of cells; communication between cells is a key element of the body's integrity. Thus, organisms offer the chance to study the impact of altered gravity on individual cells embedded in their natural cellular environment taking appropriate ex vivo tissue culture systems or animal and plant models. As to its level of advancement *Arabidopsis thaliana* will be prone to systems biology approaches aiming at a complete description of the influence of gravity on this biological system by employing knock-down procedures, high-throughput transcriptome and proteome analysis as well as mathematical modelling. The observations of these studies can be compared to the results obtained from isolated cells, grown in cultures as well as supracellular signalling processes in tissues and organs and elucidate how complex tissues and organs respond to gravity. This will ultimately lead to an understanding of the logic and design principles of the complex regulatory networks that operate at the levels of combinatorial signalling input, transduction and nuclear signal integration. Unravelling the molecular nature, organisation and logic of complex decision-making systems will be a major scientific success and create industrial spin-offs.

• Adaptation of systems to altered gravity 40%

Knowledge about the adaptation to the spatial environment is insufficient. So far, there is no comprehensive analysis about the kinetics of the adaptive processes. The main reason is that in both human and animals it is difficult to measure physiological parameters such as muscle activity, heart activity and respiration with a sufficient high resolution. Thus, it is still open whether adaptation follows an asymptotic or swinging kinetic, and to which extent the stable condition of physiological parameters, after having completed adaptation, differs from that in Earth environment. Techniques have to be developed and proper animal models such as invertebrate animals (e.g. scorpions, crickets, crustaceans, snails), aquatic vertebrates (e.g. cichlid fish *Oreochromis mossambicus*) or mammals (e.g. rats, mice) have to be used to fill this lack of knowledge because adaptation studies contribute to the development of countermeasures. It should be emphasised in this regard that not only spaceflight but also hypergravity studies could be instrumental in solving some of these questions.

• Life cycle from embryonic development to senescence 20%

Multigeneration experiments to study aspects of heredity under space conditions are sorely needed. Especially, it has to be clarified (ISLSWG 1999 Woods Hole recommendations – Moody and Golden (2000), still being effective), whether vertebrates can complete a full life cycle under space conditions. Aquatic organisms such as fish are suitable candidates, because: (i) numerous species of fish have a short time-span from one to the next generation (F1); and (ii) fish have been shown to be able to reproduce and develop normally under weightlessness conditions (particular adaptations, especially regarding the vestibular organ and neuronal parameters of the vestibular system excluded). However, other models systems such as Drosophila, *C. elegans* or Arabidopsis could also be applied to address the issues at stake.

• Hormonal and neural regulation 40%

Complex animal systems are both under hormonal and neural control, with these regulatory systems strongly interfering with each other. Secretin, for example, a classical hormone, is involved both in neural and neuroendocrine pathways, but the neuroactivity and neural regulation of its release are yet to be elucidated as well as numerous issues regarding the interaction of its pleiotropic functions. Especially little is known about the effect of microgravity on the hormonal and neural interdependent pathways that mediate particular hormone-induced actions.

• Plant cell and cell wall interaction 20%

There exists a strong interaction between the cell wall and the plasma membrane. This interaction is largely mediated by integrin-like proteins (e.g. in *Zea mays*). In, for example, Zea, the cell wall and/or cell wall-plasma membrane interaction plays important roles in the perception of osmotic stress. Accordingly, altered gravity and thus increased or decreased mechanical load may well interfere with this interaction and effect an altered downstream signalling. This issue remains to be clarified.

Specific objectives

Studies on mechanotransduction should be addressed at the system 'extracellular matrix-membrane integrins-cytoskeleton' (until now the studies mainly consider cytoskeleton) with a focus on (molecular) mechanosensing. This will also contribute to an understanding of complex cell interactions and tissue organisation, on which much information is lacking.

- 3D aggregation of single cells/microbial biofilms
- Apoptosis/programmed cell death
- Cosmic radiation-induced cancer?
- Epigenetic regulation of cell-cell and cell-matrix interactions
- The translation of cell reactions in a time frame

C. How is gravity shaping organisms (plants and animals)?

• Molecular basis of axis development 20%

Gradients of growth factors are responsible for the establishment of both the anterior-posterior and the dorso-ventral body axes. Left-right (i) symmetry also is accomplished by such factors. The beating of cilia in early stages of animal development seems to play a crucial factor in growth factor distribution. Several findings indicate that the change from a directed movement of growth factors on Earth to a diffusion-determined spread in microgravity causes modifications of the shape of the body. In fact plants provide excellent examples for studying the role of asymmetrically distributed growth factors and rapid, gravity-mediated redistribution of cellular constituents such as proteins of the PIN family. Such studies will enable important insights into how gravity affects cell polarity, axis formation and hence organ development in plants. In vertebrates, the wnt-chain strongly affects the body axis. A knock-down of specific factors from this wnt-pathway leads to an upward bending of the shape of body axis; a similar upward bending of the body was observed in *Xenopus* tadpoles after several spaceflights. Ground-based as well as flight studies can significantly increase knowledge on the impact of gravity on the gradients of growth factors in organisms and, therefore, on axis formation.

• Organ (e.g. musculo-skeletal) development 40%

The early development of invertebrates seems to be only slightly affected by the space environment, whereas the further development in a series of animals is rather strongly affected. The contrary seems to apply for some vertebrates. Investigations to clarify these differences will much contribute to the understanding of invertebrate versus vertebrate development.

Regarding humans, it is well known that spaceflight affects almost all organs/physiological systems. Zayzafoon and colleagues have stated in their review (Immunol. Rev. 208, 267-280, 2005) that the systems affected which are of key importance to human space exploration are the musculoskeletal, neurovestibular, and cardiovascular systems. Alterations in the immune and endocrine functions have also been described. Bone loss has been shown to be site specific, predominantly in the 'weight-bearing' regions of the legs and lumbar spine. This phenomenon has been attributed to a reduction in bone formation resulting from a decrease in osteoblastic function and an increase in osteoclastic resorption.

The underlying molecular mechanisms are, however, still far from being clarified. Also, the effect of spaceflight on the interdependent functionality of organ systems is not fully understood. In order to elucidate the organ and systemic mechanisms involving (micro-)gravity adaptations, more effort has to be dedicated to hypergravity animal research (van Loon et al., 2005a).

• Development of plant organs 0%-20%

Plants develop organs post-embryonically *de novo*. Recent investigations of workshop participants provide the basis for analysing the interaction between *de novo* formation of plant organs in response to gravity and mechanical strain. In Arabidopsis, for example, lateral root establishment coincides with a waving pattern in the growing root with lateral roots always emerging on the convex side of a wave confirming that gravity-induced root bending and lateral root initiation are correlated. *De novo* lateral root positioning is consistent in relation to root shape and in response to gravitropic response.

• Effects of mechanical perturbation 20%

The effect of mechanical perturbations on plant and animal growth has been reported in many studies. Efforts need to be made to elucidate the physiology of primary steps of mechanosensing. The identifcation and quantification of the mechanical stimulus and of the dose-responses have seldom been studied and the relative contributions of the different tissues to mechanosensing and the way local sensing is integrated within the whole organism to produce a response are still unclear. Important examples for studies in this important topic are the plant cell wall; the activation of signals from mechanical perturbations and the subsequent signalling chains that elicit responses are not yet explored. What types of mechanosensory channels are activated by mechanical perturbation effects on the plant cell wall, the integrins and other cell wall proteins? How is altered gravity and thus increased or decreased mechanical load interfering and affecting down-stream signalling? Such issues need to be resolved.

• Plant architecture 20%

Plant architecture is, to a large extent, determined by the environment. Mechanical perturbations, such as changes in turgor, are sensed and translated into developmental responses, including changes in growth rate and the initiation of new organs. An overwhelming majority of higher plants are immobile and rely on the mechanical support an extensive root system provides. Lateral roots, formed by post-embryonic initiation and development, determine the shape of a plants root system, and develop in response to specific environmental cues such as mechanical stimuli and in response to gravity.

Specific objectives

- Molecular and evolutionary aspects of gravisensing need to be elucidated in plants and animals. What is the molecular nature of gravisensors, what are their targets and mechanisms of action? How are gravity sensors within and across phylogenetic trees related? What is the role of mechanoreceptors and true statocysts, what is their common evolutionary origin (are they mono- or polyphyletic?) and what are their molecular mechanisms of action? Knowledge in the molecular

mechanisms of action of mechanosensors in plants and animals will provide important knowledge of the important physiological consequences that weightlessness has on body physiology.
- Changes induced by altered gravity in animal cells not directly associated (apparently) with mechanic stimuli (not belonging to tissues with antigravitational functions, such as bone, exoskeleton, and muscle, in animals, or with specific responses to the gravity vector, such as plant root columella, containing statocytes) need to be understood. This means promotion of the study of basic essential functions of cells in conditions of altered gravity, in order to know whether or not altered gravity is a stress condition for cells, and, if so, to what extent. Quantitative studies should be encouraged in order to resolve these important issues.
- The response of connective tissue to altered gravitational conditions has to be clarified (also to be seen with regard to organ development under altered gravity conditions). In this context, also an understanding of a gravity-dependent switch from two- to three-dimensional cell growth is of importance.

Development of technology to measure the effect of gravity and radiation on the cellular level

In nature, cellular systems are exposed to multiple environmental stimuli. Cells recognise molecular cues, translate them into intracellular 'commands', and 'react' precisely and dynamically regulating their behaviour. Molecular hints, however, are not the only instructive signals that cells receive. Cells are subjected to stress, particularly mechanical stress, which influences multiple cellular activities ranging from cell adhesion, to proliferation and apoptosis. The study of the effects of physical forces on cell behaviour has improved significantly over the last years. However, methods to deliver mechanical inputs into cells and simultaneously monitor their biological responses at the subcelullar level with enough resolution in vivo are not available. Thus, to date, no rigorous analysis of mechanosensation or mechanotransduction at the organism level has been possible. Even less is known about how they induce changes at the organisms´ global level and how they adapt their phenotype to environmental conditions. The field of signalling science has changed markedly over the past years as more and more signalling pathways were discovered in plants and animals and these pathways have become increasingly complex over the years. The draft sequences of the many genomes suggest that more than 20% of the genes code for signalling proteins. This impressive number supports the notion that signalling molecules play an essential role for many life processes affected by gravity and weightlessness. This emphases that models depicting signalling pathways as linear input-output cascades are an oversimplification. Instead, signals seem to be processed in the cell through networks with multiple feedback and crosstalk nodes. Furthermore, signal initiation, amplification, transport, localisation and termination are highly dynamic processes requiring new techniques and approaches. Systems biology is one approach that aims at a complete description of a biological system by employing knock-down procedures, high-throughput transcriptome and proteome analysis as well as mathematical modelling.

While the very first space biology experiments were quite basic and from the exploratory 'look-and-see' type, experimental facilities for gravitational biological studies have been improved over the years. However, current facilities and modules for spaceflight in vitro cell biology studies are still limited to simple 'rinse-and-fix' type studies. Cells are cultured for some time, maybe some media changes are performed and finally stopped with some chemical fixation. The nature of these experiments limits the assays mostly to mechano-transduction and mechano-adaptation but is less capable for studies on mechano-perception. Studying mechanosensing or gravisensing in 'professional' and 'non-professional' cells calls for investment in more sophisticated facilities capable of real-time measurements such as confocal and near scanning field microscopes, atomic force microscopes or optical tweezers. Such research facilities provided as general tools for cell biological research on the ISS or free-flyer systems would increase our knowledge and understanding significantly.

Important technical advances need to be made to understand the control mechanisms of cell behaviour and cell differentiation. This calls for the development of an *automated and controlled cell cultivation system including an optical inspection* to understand in depth the molecular mechanisms of individual processes and generate accurate descriptions of the interactions among already hugely complicated pathways. Ultimately, this will result, at a quantitative level, in the understanding of the relationships between genotype and phenotype. Therefore enabling technologies are needed for *quantitative image data capture, spatial information and analysis of time courses (4D)* on a variety of biomolecules to define gene and protein functions. Detailed knowledge of the spatio-temporal distribution of all proteins expressed in a given cell type is the ultimate goal on the way to understanding how the different cell types behave and to start building computational models that simulate cell behaviour. Acquiring this information for even a single cell type is daunting with today's technology. Collecting it for all cell types of an organ regardless of developmental, environmental or disease states seems beyond reach. Powerful new instruments and assays are now needed to monitor pathway components on a time scale (4D) and identify their functional specificity in the physiological context of living cells. Imaging at high-throughput is still extremely challenging because of the lack of robust instrumentation, assay technologies and especially the lack of automatic computer-based quantitative analysis methods.

The following techniques would be of particular help in reaching the goal:
- Automatic bioreactors and microscopy to monitor molecular dynamics in cells in situ with high time resolution
- Visualisation of molecular dynamics in individual cells in vivo
- Lab-on-a-chip
- Genomics and proteomics
- Mass spectrometry

Specific objectives

Novel technological platforms need to be established to enable space scientists to access new types of information of unmatched quality and will have a major impact on how systems biology and analysis of signalling interactions are performed in future space research. This includes visionary and powerful new systems for timely and spatially resolved modulation of signalling agents in micro-confinements to control the quantities and reaction dynamics of signalling cascades. Automated screening platforms currently under industrial construction such as Autoscreen (Agilent) will make it possible to run such experiments on signalling cascades within minutes rather than weeks as it is the case for experiments involving cell cultures today. Implementation of such groundbreaking new instruments into space research will combine spatially (3D) and temporally (1D) resolved imaging with automatic and intelligent image analysis algorithms in order to study complex cellular systems in natural environments. This will yield statistically analysed quantitative data sets of signalling events in cells and whole organisms and will allow the identification of gene and protein functions and of interactions of a wide range of molecular networks within space-relevant model organisms.
- Although not a mid-term priority (this has to be implemented as soon as possible) and not a question of technology in the direct sense, experimental hardware of sufficient quality and extent must be provided to USOCs sufficiently early for ground-based tests to identify and correct possible problems prior to flight.
- An increased use of ground-based research and corresponding funding is necessary. Such research typically yields indications of possible effects of altered gravity (and, particularly microgravity) on the system studied. In order to use flight opportunities (and the related resources) as effectively as possible, the Biology working group points out that it is mandatory to include the results of ground-based studies in applications of flight proposals. Therefore, such ground-based studies should be enforced (and financed) by ESA/national space agencies and/or the European Union.
- Measure molecular dynamics in single cells to produce time-resolved 3D data sets
- Improved fixation and storage facilities
- Improved visualisation methodology in space and in ground-based facilities
- Facilitation of genomic and proteomic approaches
- The development of tissue array systems as in vivo diagnostic systems
- HCS (high content cells)screening as an effective method of studying biological material and its reactions during space travel and residence in microgravity

Cooperation: in what fields would interdisciplinary cooperation be valuable?
- Materials science, mathematics, physical sciences (e.g. for modelling biological hypotheses/biological entities such as bone/fluid dynamics, for description of pathways and networks). A better understanding of the intra- and extracellular mechanical environment (mechanomics) or other physical parameters involving the cell biology (physicomics) is required if we want to pinpoint the role of gravity on single cells. Such studies involve a close collaboration between (bio-)physicists, material (soft matter) sciences experts, mathematicians, bio-engineers and biologists. There is, for example, a critical need to develop more detailed computational simulations of cell and molecular gravitational mechanics that accurately capture interactions and cytoskeletal dynamics as the cytoskeletal network is altered by gravity. Model studies could be initiated or coordinated by ESA in order to start developing this avenue.
- Education. Educational programmes could also be very valuable and beneficial to foster and improve the interdisciplinary cooperation within the ELIPS programme.

Technology: what are the critical technological needs and developments (including infrastructures)?
- Innovative (state-of-the-art) imaging techniques (high-end microscopes, image processing capabilities etc.) are needed to show the dynamics of molecules/cellular components and tools to measure membrane potential, for life imaging and manipulation;
- Non-temperature dependent (i.e. independent from ambient temperature) storage capability should be developed and implemented;
- Nanotechnology (e.g. as radiation protector) should be introduced/applied;
- Neurophysiological recording techniques for both channel and system analyses in the context of adaptation of organisms/cells to the space environment (microgravity/radiation) should be available.

Constraints: The major constraint is budgetary since most of the technologies required for the proposed studies have been developed and are currently used in regular ground-based research.

3.1.4 Spin-off and applications potential

What are the main potential spin-off applications of current research?

Biological research in general and biological research using space as an environment in particular is primarily fundamental research. Thus, it provides the basis for astro/exobiology and human physiology research.

Several spin-off applications came recently into being. Related publications are provided in the section 2 on achievements. A number of spin-off companies have also been founded.

A spin-off company (using a spin-off image analysis software) founded in the context of space experiments (Real Time Computer, Möhrendorf, Germany) develops a custom-made image analysis software which allows the identification and track objects in images. Based on this system, a water quality bio-assay was developed that determines potential hazardous water contamination within minutes.

The activities of Zero-g LifeTec GmbH are closely related to the activities of the Space Biology Group of the ETH Zurich, Switzerland. *Zero-g LifeTec GmbH* offers essentially four kinds of services: (i) the consultation in space life sciences with space agencies, aerospace companies, universities and biotec companies; (ii) the development of sophisticated instrumentation such as incubators, bioreactors, cell- and tissue-culture devices; (iii) support for ground-based simulations using instruments such as clinostats, which allow a random exposure of the biological objects to the gravity vector. Other instruments, such as the hyperfuge or the free-fall machine, allow further experimentation devices for gravitational biology; and (iv) promotion and training of space life sciences up until university level.

What are the main potential spin-off applications of future (short- and long-term) research?

- Advanced microscopy and fluorescence markers for diagnostic purposes
- Lab-on-a-chip
- Biological radiation detection systems
- Radiation countermeasure
- Anti-ageing measures

What are the main impacts of Microgravity Application Programmes? What would you recommend for the future?

1. List of current MAP activities with regard to biology

- Eristo-Osteoporosis
- Vascular Endothelial Cells in Microgravity: Gene Expression, Cellular Energy Metabolism and Differentation
- Ballistic and Holographic 3D High-Resolution Imaging of Bone
- 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 Microgravity Environment
- Bone Metabolic Studies in a Combined Perfusion and Loading Chamber

MAP proved to be a successful tool for stimulating research and exchange of technology between the science community and industry. Thus, this programme should be continued. The currently running MAP should be carefully evaluated before renewal. New MAP should be established based on the indicated priorities.

2. Main impacts of MAP

- Basic knowledge on gravity perception in plants and plant cells
- Quantification of bone turnover and influence of mechanical forces on bone cell gene expression, osteoblast and osteoclast activity
- Formation of tissue/organ equivalents under different mechano-stimulatory environments, e.g. bone, liver, vascular endothelia
- Development of bioreactors for different cell types and tissues
- New approach for measuring blood clotting (platelet activity)
- Knowledge on (artificial) bacterial ecosystems
- Monitoring pathogenic bacteria

How to raise awareness for the public? What are the ‘exciting’ subjects and discoveries that should be communicated to the public?

ESA has to improve on-line information on current experiments (including provision of results/outcome) such as:

- Better access and increased number of on-line and downloadable pictures and video sequences as well as better search capabilities within the ESA domain should be provided. Search lists also should carry ‘microgravity’ as an item (instead of only ‘ISS’ or ‘manned spaceflight’).

- Experimenters should actively contact the media (namely press and TV) to communicate experiments/ results.
- Without doubt, animals in space are exciting subjects. Tadpoles and larval fish, for example, perform somersaults at weightlessness. Although this (until now not fully understood) behaviour has been observed for decades and its phenomenology is well-known by those scientists who are using aquatic vertebrates as model organisms, the general public always is fascinated when seeing space-footage with little animals tumbling around. Experiments using arthropods such as scorpions (these are usually being referred to as quite 'nasty beasts' in the eye of the non-scientific observer) inevitably create excitement by the ingenuous watcher.

Such experiments are extremely well suited to catch the interest of the tax-payer.

Of course, it is mandatory that the lay person should be well informed by the PI about the scientific importance of the experiment. Eye-catchers must not be stand-alone experiments ('nice-to-see'), but they have to carry a message which can be understood by everybody and thus is worthwhile for the media to communicate.

What would you recommend when considering Education and Training?

- Initiate the establishment of an international curriculum for space-biology and space-technology training programmes including bachelor, master and PhD programmes (e.g. Marie-Curie networks).

  In this context (or also standing alone), summer schools or workshops on space biology and/or space technology should be initiated/continued. ESA should reach an agreement about ECTS credits in these classes in collaboration with interested universities. By this means students could use that class to earn credits with regard to soft skills (included in bachelor courses). Thus, students could become involved in space sciences early in their career.
- Such a platform should also include an international exchange programme on the level of students, young scientists (including post-docs) and teachers.
- ESA should make an inventory and coordinate educational outreach (for example the 'school-lab' concept (e.g. as established by DLR)). ESA should learn from similar activities in member states and other space agencies and should avoid reinventing the wheel. All parties involved should set up collaborations in educational programmes in order to bring this important issue to a higher level. There are educational programmes not only in agencies but also in individual schools (lower and higher level education) that might be used more widely.
- Really focus on education and keep the PR content to the absolute minimum. Distinguish PR clearly from educational content.
- Strengthen ground-based research for preparation of spaceflight (also, in order not to jeopardise diploma and/or PhD theses in case of budget cuts or mission failure) but also as regular education, training and research in gravity-related phenomena.

  As has been outlined as a recommendation by the Biology working group, such ground-based studies should be mandatorily carried out in support of a flight proposal.

3.1.5 Interfaces and synergies with other ESA programmes

Biology is the mother science of all other disciplines of life sciences. Biological research provides the basics to understand the mechanisms underlying the function of cells, organs/tissues and intact multicellular organisms including humans. Biological research therefore is closely and synergistically interconnected with all scientific disciplines investigating environmental effects on biological processes. Phenomena addressed by, for example, the Human Physiology and the Astrobiology working groups can be elucidated only on the basis of the insights drawn by biologists. There are also clear interfaces of biology with exploration efforts.

In this context, it has to be defined what 'exobiology' actually deals with and how exobiology has to be discriminated from 'astrobiology' as a biological discipline. According to common sense, astrobiology (or exobiology) is the interdisciplinary study of life in the universe, combining aspects of astronomy, biology and geology. It is focused primarily on the study of the origin, distribution and evolution of life.

According to the denominations themselves, 'astro'- or 'exo'-biology cannot deal with Earthly organisms. However, since organisms other than those from Earth are not available, astro/exobiology has resorted to investigating Earthly organisms in extreme environments. Thus, astro/exobiology is particularily interfaced with mainstream biology.

- **Altered gravity research (Astro/Exobiology, Human Physiology, Exploration)**

All scientific disciplines dealing with the effect on spaceflight on cellular, organ-specific and organism organisation are closely interconnected regarding the investigation of altered gravity affecting biological processes.

- **Radiation (Astro/Exobiology, Human Physiology, Exploration)**

As has been outlined by the Biology working group, the effect of (space) radiation on cells and organisms is a major issue of scientific interest. Since radiation affects single cells, cells in the context of an organ and cells as the basic element of multicellular organisms including humans, there are clear interfaces between biology, astro/exobiology (i.e. radiation) and human physiology (in as much as radiation issues are of interest here).

A fine example to demonstrate these interconnectivities is the facility Matroshka. It was developed to measure organ/tissue equivalent doses in selected critical radiosensitive organs, which is an important prerequisite for radiation risk assessment.

Certainly, exploratory efforts also will have to take into account findings by Earth-based biologists and exobiologists.

- **Life-support systems (Exploration, Human Physiology, Astro/Exobiology)**

Bioregenerative life-support systems such as MELiSSA are primarily concerned with human support in space (thus, they are strongly interconnected with human physiology) and are as such especially interconnected with issues regarding, for example, nutrition and pharmacological aspects, whereas astro/exobiology is concerned with the survival and growth of organisms in space which are included within such systems.

Bioregeneretaive life-support systems using aquatic vertebrates and further unicellular and multicellular organisms (e.g. plants) to be efficiently used for multispecies multilab experiments are especially suited to provide synergies between the various communities working on life sciences research.

- **Microbial safety in closed environments, including biofilms (Astro/Exobiology)**

- **Neuroscience (Human Physiology)**

Numerous neuroscience issues can be clarified in depth only using animal model systems. Investigations on such model systems have brought about insights into the basics of neural adaptation to an altered gravitational environment, especially by the use of arthropods. Aquatic vertebrates (tadpoles and fish) have shown the effect of altered gravity on the development of, for example, the vestibular organ, and critical periods for vestibular development were found. Behavioural studies on aquatic vertebrates clearly support the ‘otolith asymmetry hypothesis’ to explain (and possibly allow the discovery of countermeasures for) human space sickness.

How can your research field benefit from these programmes?

- Geophysical information needed regarding life-support systems on the Moon or Mars.

How can these programmes benefit from your research field?

- Knowledge on the effect of altered gravity/radiation (including possible synergies of altered gravity and radiation) on biological systems.

Merging Aurora and ELIPS 3 programmes

We would like to see a better coordination and interconnection of both programmes. Until a roadmap as well as a clear definition of the role of the different parts of the programmes are available no final statement can be made.

3.2 Astrobiology

3.2.1 General recommendations

General recommendation No. 1

ESA’s Life Sciences Programmes have been the historical home of astrobiology (previously termed exobiology) for more than 30 years (Bjurstedt 1979). This highly evolving multidisciplinary area of space life sciences shall remain an active part of ESA’s ELIPS programme.

General recommendation No. 2

The Astrobiology working group expressed concern about the impact on the coordination of astrobiology science in ESA as a result of the movement of ExoMars and MSR from HME to Science and Robotic Exploration. To maintain and foster the high international scientific reputation of European astrobiology research, a strong coordination between the two directorates is mandatory.

General recommendation No. 3

The Astrobiology working group saw clear scientific and technological synergies between ELIPS and the Aurora Core programme, but it does not have sufficient knowledge to make a statement on the value of a merger and its consequences. The group strongly recommends that an in-depth discussion should occur with the European astrobiology community prior to any decision being made.

General recommendation No. 4

The Astrobiology working group recommended that ESA prepare an Astrobiology ‘roadmap’ clearly identifying required synergies between programmes, identifying flight opportunities (Earth orbit and planetary missions), ground-based studies and field studies. The roadmap should clearly state where astrobiology should drive future missions. We recommend the organisation of a workshop to define the roadmap at the earliest opportunity (in coordination with existing organisations, e.g. EANA, ESF).

General recommendation No. 5
The Astrobiology working group recognise that there are many synergies between different disciplines within ELIPS. Examples of these possible synergies include the study of organism response to space conditions which is applicable to problems in astrobiology and in human physiology (e.g. bacterial and human cell response to microgravity). Common scientific questions can be addressed by common technical approaches (e.g. cell bioreactors). The working group felt strongly that the ELIPS programme should seek to foster cross-disciplinary activities between astrobiology, biology and human biology. This might be achieved by common ELIPS workshops in science and technology to look at cross-cutting science and technology problems.

3.2.2 Implementation priorities: the next 10 years

The Astrobiology working group identified several areas of research priority for the ELIPS programme. These were split into areas associated with the International Space Station, space missions not involving the ISS and other 'general' areas of space science activity.

International Space Station (ISS)
1. The study of prebiotic chemistry and how the first building blocks of life were formed and the environment in which they formed remains a key astrobiology question. Specific areas of interest include:
- Response of prebiotic building blocks (e.g. amino acids, sugars, nucleic components) to space conditions
- Polymerisation, stability and replication studies under microgravity
- Organic compounds and mineral interactions in microgravity.

Technology Development. Passive experiments are well developed. In addition, there is a need for facilities for studying chemical reactions in microgravity.
Cooperation. Cooperation can be envisaged with astronomers and materials scientists.
Competence. There is a high level of competence to continue this work within Europe, based on previous work carried out in the BIOPAN and EXPOSE programmes.
Needs. There is a need for continued flight opportunities; namely the continuation of BIOPAN and EXPOSE and the development of new facilities.
Why fund? There is an outstanding heritage which must be developed using new flight facilities.

2. Beyond prebiotic chemistry, astrobiology is concerned with how organisms survive in space. This work encompasses the question of whether life can be transferred between planets and the conditions for organisms on other planets and on early Earth. Responses of organisms includes primarily microbial, including viruses, but also multicellular organisms, communities and biofilms to fully exposed and controlled space conditions and ISS flight conditions. Specific objectives within this question include the study of:
- Gene regulation (genomics) and proteomics in response to physical and chemical stressors associated with space (e.g. variation of gravity, radiation, space vacuum)
- Genome and proteome evolution of non-pathogenic and pathogenic organisms in response to spaceflight conditions, particularly for life-support systems
- Influence of space conditions on organism and cellular life-span
- Gene transfer in space conditions (life-support systems and behaviour of communities such as biofilms)
- Survival and adaptation of extremophiles to space conditions and simulated planetary (Mars) conditions
- Response of biosensors to space conditions.

Technology Development. Although there have been many experiments looking at 'passive' desiccated organisms (e.g. BIOPAN and EXPOSE), there has been very development in looking at active organisms. The Columbus module offers a huge potential for growth of these studies.
Cooperation. Cooperation with physiologists and biologists is needed to define technology needs.
Competence. Need for capacity building and partnerships. Good possibilities for transfer of technology into astrobiology and this should be a focus of cooperation.
Needs. Need for bioinformatics and technology transfer expertise. New flight opportunities are required; for example, advanced EXPOSE and other exposure facilities.
Why fund? Europe has a strong existing capacity in this area which needs to be developed. Need for new flight facilities through budget to develop high potential.

3. Although bioregenerative life-support systems are primarily concerned with human support in space, astrobiology is concerned with the survival and growth of organisms in space which are included within such

systems. As many of the organisms within life-support systems could also potentially contaminate planetary surfaces and other experiments their potential survival in space is also covered by astrobiology. Specific research areas within this field to be studied include:
- Effects of space conditions on bioreactors
- Optimisation of integration of biota with technology for robustness, optimum weight, etc.
- Genetic stability of closed-life-support systems

Technology Development. There is a strong heritage with existing MELiSSA studies (Lobo and Lasseur 2003) and laboratory studies. There is a good potential for growth.
Cooperation. Cooperation with engineers. Develop existing cooperation (e.g. Canada).
Competence. Very high competence has been developed.
Needs. Integration of life-support systems elements is required and expertise to do this must be further developed.
Why fund? To take this to the next level (a fully integrated test life-support system) requires new funding.

Specific Recommendation No. 1

The availability of the Columbus module at the ISS is an important milestone for future astrobiology research in Low Earth Orbit (LEO). ESA should provide further long-term experimentation opportunities on board the ISS with advanced external exposure facilities (e.g. sun-pointing, low temperature, in situ analysis) as well as bioreactors with sophisticated analysis devices inside the Columbus module.

Non-ISS missions

Many non-ISS missions offer opportunities for addressing key scientific questions in astrobiology. The major priority areas we see for non-ISS missions are the following:

1. Short-term and repeated studies of the responses of organisms (primarily microbial, including viruses, but also multicellular), communities and biofilms to controlled or fully exposed space conditions. Their advantage is: (i) to provide statistically significant data from repeated experiments; and (ii) to define experimentation conditions in preparation of long-term experiments on board the ISS. Specific objectives within this area are:
- Gene regulation (genomics) and proteomics in response to physical and chemical stressors associated with space (e.g. gravity, radiation);
- Genome and proteome evolution of non-pathogenic and pathogenic organisms in response to space conditions, particularly for life-support systems;
- Influence of space conditions on organism and cellular life-span;
- Gene transfer in space conditions (life-support systems and behaviour of communities such as biofilms);
- Survival and adaptation of extremophiles to space conditions;
- Response of biosensors to space conditions.

Technology Development. The state of development is good. The BIOPAN and Biobox have been a good achievement of the last ELIPS programme, and a continuation of the programme as well as new opportunities are needed.
Cooperation. Cooperation could be developed with physiologists and biologists and engineers to define technology needs.
Competence. There is a good level of competence developed using BIOPAN.
Needs. Need for bioinformatics and technology transfer expertise. Flight opportunities required; for example BIOPAN, Biobox or similar facilities on board free-flying satellites.
Why fund? Europe has a strong existing capacity in this area which needs to be developed. Need for new flight facilities through budget to develop high potential.

Specific Recommendation No. 2

ESA should continue to provide frequent short-term missions in LEO for astrobiology experiments using free-flying satellites. Such experiments are required for: (i) increasing the statistical significance of the results by repetition of the experiments; (ii) defining experimentation conditions in the preparation of long-term experiments on board the ISS; and (iii) testing astrobiology space hardware in the preparation of astrobiology experiments on board the ISS or on planetary missions.

2. Europe is taking a stronger lead in the study of astrobiology on Mars, primarily through ExoMars and Mars Sample Return. Specific areas of study should include:
- Instrument development and deployment for life detection
- Selection of landing and sampling sites for ExoMars/MSR
- Studies of organic and biological contamination on spacecraft
- Biological containment (surface receiving facility and science) for MSR

Technology Development. State of development is strong and there is a huge potential for development (both technically and in community).
Cooperation. There are strong international scientific links, but ELIPS might work to develop new links with additional agencies (e.g. China, India). The technology collaboration is strongly driven by the export situation

outside ELIPS, particularly from and to the US.
Competence. Still some areas where Europe is not autonomous (e.g. power sources). There is a need for ELIPS to investigate requirements and technical shortfalls of achieving autonomy in Mars exploration.
Needs. Concern about ExoMars mission organisation and timeline arising from multiple factors (e.g. political and financial).
Why fund? Unprecedented expertise in astrobiology payload and mission planning (ExoMars) must be taken to implementation of mission.

Specific Recommendation No. 3

ESA should foster astrobiology activities with regard to the exploration of Mars, with emphasis on the timely realisation of the astrobiology missions ExoMars and Mars Sample Return. Mars is one of the prime targets meeting the overarching scientific goal 'Emergence and co-evolution of life with its planetary environments', as defined by ESSC-ESF position paper Science-Driven Scenario for Space Exploration (ESF, 2008).

3. New opportunities are emerging in space missions beyond Mars. There may emerge opportunities for astrobiology under ELIPS for possible future missions to Europa, NEOs and elsewhere. Specific areas of study should include:

- Instrumentation for astrobiology on icy and carbonaceous bodies
- Site selection and potential habitats in preparation for possible landers.

Technology Development. These areas of investigation are at a very early stage (e.g. challenges of radiation environment). Large potential if missions become available.
Cooperation. Cooperation with NASA and many other institutions may be possible.
Competence. At present expertise is at an early stage. However, expertise from many areas of astrobiology can be brought to bear upon these opportunities if they become available.
Needs. Need for capacity building for astrobiology studies of icy moons and technical requirements.
Why fund? Possibility for Europe to play a leading role in outer solar system exploration. Preparatory technical and scientific capability should be developed.

Specific Recommendation No. 4

Several moons of the giant planets (e.g. Europa, Titan, Enceladus) carry huge potential for astrobiology research. Whereas missions to these bodies are probably located within the new ESA science and robotic exploration programme, preparatory laboratory and field studies to determine the habitability of those bodies should remain part of the ESA-ELIPS programme.

4. Lunar orbital and surface facilities. At the moment, opportunities in this direction are limited, but within the life-time of the next ELIPS programme these opportunities may develop. Specific areas of investigation would include:

- Search for organics and exobiologically relevant geochemistry on the Moon
- Same types of investigations as on ISS (cross-comparison experiments)
- Life support development.

Technology Development. Very good existing lunar scientific expertise. Large potential for development if facilities become available.
Cooperation. Strong European expertise in flying astrobiology experiments could be applied to lunar astrobiology.
Competence. Expertise in orbital astrobiology experiments provides high competence for lunar possibilities if they emerge.
Needs. Specific lunar operations expertise and science implementation.
Why fund? Lunar exploration opportunities are developing. The ability to take advantage of these requires extra funding as it should not detract from orbital science in which Europe has a leading role.

Specific Recommendation No. 5

If Europe becomes further involved in robotic or human missions to the Moon, several areas of astrobiology may benefit from such missions. Provision of relevant astrobiology facilities should be included in the ELIPS programme.

General activities

1. Study of limits of life and extreme environments to support all areas of ELIPS. Astrobiology requires ground validation of hypotheses concerning the limits of life in extreme environments. ELIPS should support the development of studies of life in extreme environments, specifically:

- Use of planetary analogue field sites for science and instrument development
- Studies of response of exobiologically important organics and organisms using ground-based lab and simulation facilities
- Experiments on artificial adaptation/evolution of organisms to selected planetary/space conditions
- Continued scientific investigations on panspermia
- Studies on the evolution and adaptation of organisms and their communities in human habitats and extreme environments

- Cross-comparisons between ground-based work and space (ISS and non-ISS)
- Ground-based studies in preparation of astrobiology flight experiments on ISS and non-ISS missions (e.g. Experiment Verification Tests, Experiment Sequence Tests)
- Studies on novel types of biochemistry, genetics and life.

Technology Development. Strong autonomous expertise in Europe and potential for development.
Cooperation. Strong existing cooperation with the USA and other countries on the scientific level. New European initiatives such as the FP7 CAREX programme.
Competence. Strong astrobiology community to support this work. Many useful extreme environments in Europe that could be used in ELIPS studies.
Needs. Stronger cooperation in developing science and integrated studies. Need for greater focus on using analogue field sites.
Why fund? Europe has outstanding expertise. Level funding will allow this to continue, but the development of new investigations, better and larger coordination and the development of new facilities will allow Europe to take a better lead.

Specific Recommendation No. 6
ESA should set a certain budget aside for an astrobiology laboratory and field studies. The experience gained from such studies is vital for the success of astrobiology studies in LEO, on Mars and on other bodies of the solar system relevant to astrobiology.

2. Planetary protection. The protection of the environments of other planets from contamination continues to be a concern of COSPAR and should remain and important area of research within ELIPS. Specific areas of study include:
- Studies of microbial diversity of spacecraft and cleanrooms
- Investigation of methods for sterilisation
- Development of faster and more efficient methods for bioburden detection.

Technology Development. Very good heritage and growing influence in planetary protection studies that might be developed.
Cooperation. Cooperation already through COSPAR with many other countries.
Competence. High level of competence in technical ability and policy implementation.
Needs. Wider expertise and technical facilities for assessing bioburden and carrying out sterilisation.
Why fund? Europe is developing an increasing international presence in planetary protection and recognised expertise. To capitalise on this expertise requires support to build this position.

Specific Recommendation No. 7
As already stated in the 2005 evaluation of the ELIPS programme (ESF, 2005) ESA should continue to foster its planetary protection activities. These activities include the development of its own planetary protection programme (e.g. an ESA handbook for planetary protection measures, training of space engineers involved in planetary missions, and development of sample receiving and curation facilities).

3.2.3 Possible activities beyond 10 years

The Astrobiology working group considered areas of research that might be priority areas beyond the next ten-year timeframe. Changing political situations and priories within the world's space programmes make reliable predictions difficult. However, the following possible areas of activity were identified.

Studies in extreme environments and simulated planetary conditions
Studies of the origin of life continue to develop and will be further developed using ISS and non-ISS space platforms within the next ELIPS programme. Beyond ten years we might consider that the first steps will be taken to constraining the steps that led to the first self-replicating organisms.

Further exobiological exploration of Mars
The implementation of ExoMars and follow-up missions including Mars Sample Return offers new opportunities for the exobiological exploration of Mars. After ten years it is possible that a complex astrobiology programme will become possible on Mars involving the study and beginning of the characterisation of organics and life.

Development of a Europa/Saturn mission
Interest in Europa and the Saturn system (e.g. Enceladus) will lead to new possibilities in astrobiology in the outer solar system.

Lunar astrobiology in situ
If current plans to return humans to the Moon are implemented, new opportunities in lunar surface astrobiology will become much more likely. However, the suite of robotic missions also planned to reach the Moon will at the same time multiply the possibility of surface lunar experiments on the survival of organisms under lunar conditions.

Using the Moon to develop human astrobiology science/instrumentation for Mars
In addition to experiments to study the Moon, the lunar surface might also be used to test equipment for Martian exploration and astrobiology.

Fully integrated and functional life-support system
Beyond the 10-year horizon the creation of a fully functioning and integrated life-support system (e.g. MELiSSA) seems a realistic possibility. This objective may be realised even before the 10-year horizon. However, beyond 10 years the deployment and optimisation of such a system in extreme environments (e.g. Concordia, Antarctica) is a realistic possibility.

Further development and refinement of instrumentation
This will widen the environments that can be studied on the Earth and in space. The development of technology that can be used in extreme environments continues to be an important objective of astrobiology; beyond the 10-year horizon we see this as being a vital area of continued activity.

3.2.4 Spin-off and application potential

The ELIPS programme could give focus to numerous areas that have potential spin-off applications. Some of the spin-off possibilities identified by the Astrobiology working group included:

- Response of organisms to space conditions could be used to select organisms with possible industrial use (e.g. antibiotics), with space conditions used to provide a selection environment.
- Miniaturisation of genomics technologies, e.g. lab-on-a-chip. Many of the technologies required for astrobiology, particularly life detection, require miniaturisation, for example for deployment on robotic craft. These miniaturisation approaches could be applied in many other environments. Examples of potential instrumentation include XRD, XRF, Raman, LIBS, lab-on-a-chip (cf. ExoMars).
- Life-support systems offer a large number of possibilities for industrial applications. These include technology for the recycling of water and waste (sustainable development).
- Scientific experiments conducted in Earth orbit on organism response to space conditions will generate knowledge that can be applied to many other environments, for example on microbial diversity/genetic behaviour (e.g. mobile genetic elements).
- Studies on life-support systems could be used to produce applied information for the production of viable microbial fuel cells in energy production.
- Methods for radiation dosimetry in space conditions, such as, for example, on ISS and BIOPAN can be used to assess radiation exposure in many other environments such as civil aircraft. This spin-off has already occurred, but might be developed further. Theoretical modelling of radiation and standardisation of radiation measurement approaches could be further developed for civil application.
- The study of life in extreme environments can provide well-known opportunities for industrial applications including enzymes and other biomolecules with industrial applications (thermal stability etc.). Microorganisms from extreme environments could also be useful in biomining/bioremediation.

3.2.5 Education and training

The Astrobiology working group felt that education and training possibilities had not been developed to their full potential in the previous ELIPS programme. It was felt that a larger education component and budget should be a major objective of the next ELIPS programme. A larger education budget would allow the ELIPS programme to achieve several objectives in astrobiology training, outreach and education. The best way to achieve this would be to pay for dedicated educators at ESA who could work in a dedicated way on ELIPS. Tasks for these individuals should include:

- Change perception of astrobiology. Astrobiology is still an area not fully understood by a wider audience. Funding might be used to support existing or new outreach programmes in astrobiology.
- Develop a Virtual Institute of Astrobiology (development from ABC-Net). The ABC-Net activity (see section 2 on achievements) has advanced astrobiology education. However, one objective of ELIPS could be the development of a Virtual Institute of Astrobiology.
- Astrobiology has an ‘epic’ dimension in that it covers life on other planets. ELIPS might use astrobiology to inspire entry into science. Astrobiology has an interdisciplinarity that can effectively draw people into science. This would involve the better availability of ELIPS research output for educational material on the ESA website and its presentation in a style accessible to educators.
- ELIPS should seek to enhance student involvement in astrobiology by a number of methods including offering summer schools to university and PhD students.
- All of the above objectives should be met by improving the accessibility and visibility of ELIPS achievements on the ESA website. It was felt that currently web access to this information was poor.

- Better ESA links could be created between scientists to the increase visibility of research. Continued ESA support for the European Astrobiology Network Association (EANA) should be one such priority.

Specific Recommendation No. 8
ESA should foster the establishment of a Virtual Institute of Astrobiology with a strong education programme in order to teach students and scientists interested in the multidisciplinary field of astrobiology and to augment public perception of astrobiology. The Astrobiology Lecture Course Network ABC-Net is an example of a successful achievement in this direction. ABC-Net should be institionalised within the Virtual Institute of Astrobiology.

3.2.6 Potential interface with other ESA programmes

The Astrobiology working group recognised several areas of potential cooperation with other ESA programmes including:

- Strong coordination between ELIPS and science and robotic exploration is mandatory, specifically coordination with the Aurora programme;
- Science (Space Science Programme). Astrobiology allows focused synergies with all areas of planetary and space sciences. Astrobiology provides strong reasons for exploring other bodies. Other science informs astrobiology;
- Technology (Link with Robotic Exploration Programme). Instrument development for ExoMars and human exploration programme has already been a success for ESA. ELIPS can further astrobiology applications of this technology by pursuing collaboration with other ESA programmes. Technology development allows for improved astrobiology investigations and characterisation of life. Knowledge of astrobiology (organisms' response, habitability etc.) informs instrument development (e.g. by allowing an improvement in sensitivity);
- Education (Aurora education programme). Education is a vital tool to improve visibility of astrobiology. Visibility and education in astrobiology assists other ESA programmes (such as instrument development in the robotics programme). Also see above for comments on education.
- The ISS Exploitation Programme provides a platform for astrobiology experiments (e.g. effects of gravity). Spin-off from ECLSS (life-support systems) improves operation of ISS.

3.3 Physiology

3.3.1 Future research priorities in physiology

The Physiology working group recommended that future research strategy should build upon the themes highlighted in the previous 2005 ESF report. Special attention should be given to the following areas:

Integrated Investigative Approach

The European Space Agency brings together scientists from many disciplines, crossing the boundaries between life and physical science, as well as those between science, technological innovation and engineering. In addition the nature of space physiology research demands a holistic approach to studies, considering the interactions between whole organ systems as well as neurobehavioural factors.

Microgravity physiology remains one of the few areas of research, outside terrestrial medicine, in which whole-body, integrated physiology is central. This too is something upon which ESA should capitalise since it is one of the few remaining agencies which might preserve the expertise of investigators working in the field of whole body physiology. It is this potential for an integrated approach to research that is the greatest strength of the current ESA programme. However, to date, ESA has not taken full advantage of this asset. Resources should be committed to more fully exploiting the potential for integrated, cross-disciplinary physiology research programmes.

Translational Research

It is clear that much of the research undertaken in support of human spaceflight operations has relevance to terrestrial applications. Further resource should be committed to translating space physiology research, where possible, for application in multiple fields of human activities on Earth. This includes the development of new, advanced diagnostic techniques, therapeutic and rehabilitation techniques, learning and training methodologies as well as non-invasive and minimally invasive biotelemetry.

For this to succeed small, well focused multidisciplinary teams should be assembled and tasked with specific solutions. From this it is likely that novel solutions might arise that would not otherwise have been possible.

Data Sets, Data Mining and Data Acquisition

The nature of whole body physiological research leads to the generation of large, complex data sets. Advances in genomic techniques in particular, allow many data points to be created from small numbers of study subjects. This, coupled with the long-term nature of studies of human physiology, demand a new approach to data analysis and processing. Specifically, resources should be committed to exploring how data mining techniques might be employed in these complex data sets such that the maximum benefit can be obtained.

It follows also that secure, high integrity data archiving techniques should exist, which allow anonymised records to be held in perpetuity and accessed by future research teams or for the purposes of longitudinal health monitoring.

Finally there should be better communication between the operational aspects of human space flight and the science side such that medical data with potential scientific value do not remain hidden indefinitely. This is a question of trust between crew members and medical operations teams and of communication between scientists and medical operations.

Artificial Gravity and Partial Gravity

Since the future plans of the international space agencies include planetary exploration on the surface of both the Moon and later Mars a better understanding of partial gravity environments/artificial gravity should be obtained. This should not be pursued in preference to or to the exclusion of other countermeasure techniques. It remains possible that single system countermeasures, alone or in combination, may not be sufficient to fully protect human physiology during long duration deployments. However, the study of physiology under conditions of microgravity provides a unique tool with which to probe the physiological system, yielding new data which could not have otherwise been obtained. This provides a sufficient case for continuing the parallel pursuit of both discrete and multisystem countermeasures.

ESA has an advantage in this area having inherited earlier, and now abandoned efforts, by the United States. This, coupled with the multidisciplinary approach highlighted above, provides a new and unique opportunity.

A comprehensive evaluation of artificial gravity as a multi-system countermeasure should be undertaken. With appropriate focus this is an area in which ESA could lead the international space community. To facilitate such efforts further investment in short and long centrifuge facilities is recommended. Short radius devices are necessary for the investigation of intermittent hyper-G exposure. Long radius centrifuges, with radii of the order of tens of metres, are required for the investigation of artificial gravity environments and vehicle designs which provide continuous gravito-inertial loading. Short radius facilities currently exist but further development of an infrastructure to support long radius facilities is required. From a physiological standpoint it is probable that astronaut crews cannot be optimally protected in the absence of artificial gravity countermeasures. This is an area in which ESA has the potential to lead the international space community and one which has the potential to fundamentally alter the existing paradigm of human space exploration. For these reasons it is worthy of further investment.

Exploitation of the Columbus module

Clearly the newly launched facilities aboard Columbus should be prioritised if maximum advantage is to be gained from this module.

3.3.2 Spin-Off Potential

The Physiology working group felt strongly that spin-off applications should not be required to justify the prosecution of programmes of fundamental science. The group did however acknowledge that there were many areas in which space physiology research might give rise to new discoveries of fundamental importance and new therapeutic and diagnostic technology and techniques. These include but are not limited to the following:

- Rehabilitation techniques
- Phenotypic shifts in haemopoetic stem cells
- Development of new 3D analysis tools for bone
- Use of space/bed rest as a metabolic model for sedentary lifestyles
- Postural control and hip fracture
- Improved longitudinal study technniques
- New tools in psychological assessment of small groups
- Small blood volume, analysis techniques in immunology for neonatal care
- The use of astronaut-screening techniques for orthostatic intolerance in general medicine
- Bed rest and space flight as parallel processes in the investigation of the physiology of ageing
- Non and minimally invasive biotelemetry.

3.3.3 Interface and Synergies with other ESA Scientific Programmes

The Physiology working group discussed the potential for interface and synergy with other ESA scientific programmes. Liaison between ELIPS and Aurora programmes currently occurs predominantly at working level with varying levels of effectiveness. Reorganisation between these two programmes with transfer of some personnel from core programmes to the Directorate of Human Space Flight will alter this relationship. The overall impression, however, is one of limited integration between programmes at present. The working group specifically recommends that ESA should have a more specific strategy for coordination between programmes.

In addition to this, the group discussed the apparently poor linkage between the mission operations directorate and programmes of scientific research. If the operational significance of basic scientific research is to be maximised then better integration between these programme elements is required.

3.3.4 Streamlining Research Activities

The Physiology working group recommends that physiology research programmes should be based upon three principle pillars:
- **Fundamental science**
- **Applied science**
- **Exploration-driven science**

The working group further recommended that the following themes should be superimposed upon this foundation:
- **Radiation**
- **Human performance**
- **Microbial safety**
- **Systems homeostasis and adaptation**
- **Life-support systems**
- **Countermeasures.**

The Physiology working group defined these areas as suitable subtitles under which programmes of research might be focused and directed.

There was broad agreement that the Topical Team format already employed by ESA is a highly effective mechanism and should be preserved in any future research programme. It recommended the formation of Topical Teams within the broad categories listed above.

Facilitation of Multidisciplinary Work

Multidisciplinary work, which brings together scientists, engineers and technologists from diverse backgrounds, is one of the greatest strengths of space exploration research programmes. In order to capitalise upon this the creation of formal infrastructure to facilitate cross-disciplinary collaborations is strongly recommended. This might include focused announcements of opportunity, working groups, workshops and dedicated funding streams for such activity.

Implementation Priorities

The Physiology working group recommended that highest priority should be allocated to implementation of mechanisms that would facilitate an integrated approach to research and translational research.

It further highlighted the importance of programmes of education and public engagement. It is clear that the future supply of scientists and engineers of sufficient quality is essential to Europe's economic growth and to the future of the European Space Agency's strategy.

Space science and human space exploration in particular are excellent tools with which future generations of scientists and engineers might be inspired. Significant resources should be allocated to enhancing ESA's programmes of education and public engagement. The group noted that this point had been made on multiple occasions at previous meetings, including the preceding ESF reviews of the ESA life science programme, but that to date little had been done to act upon past recommendations.

3.4 Psychology

Section 2.2.4 presented the achievements in three areas of psychological research: Psychological health and wellbeing, Interpersonal relationships, and Cognitive and skilled performance.

The associated short- and longer-term priorities are presented below.

3.4.1 Short-term priorities

Psychological health and wellbeing

- Investigate the characteristics and underlying determinants of altered sleep-quantity and sleep-structure in space;
- Identify the time course of psychological adaptation during long duration isolation and confinement;
- Develop efficient assessment methods for the identification of individual proneness to psychological problems and psychiatric disorders in long duration missions;
- Establish sensitive measures for monitoring the 'emotional state'" of crew members in space.

Interpersonal relationships

- Determinants of interpersonal compatibility and team performance during long duration to be used for crew composition and training;
- Investigate changes in interpersonal interactions, crew structure and culture (norms and values) in isolated and autonomous crews over prolonged periods in isolated and confined environments;
- The impact of national, professional and organisational cultures on performance of crews and surrounding ground-based personnel;

It is difficult to draw conclusions from previous simulation studies because of differences in composition, (small) crew size, training background and duration.
- Future studies should thus involve repeated ground-based simulations of a minimum duration of 3-4 months

and sample size of at least 20-30, using facilities that are functionally equivalent; an overall experimental design and a core set of measures for these simulations should be defined.

Cognitive and psychomotor performance

- Focus on the adaptive/compensatory nature of human response to stress and workload, rather than assuming passive models of human performance;
- Make better use of new developments in cognitive testing, rather than rely on general test batteries, or use batteries that are designed to be sensitive to the demands of extreme work environments;
- Explore the use of highly relevant simulation tools to study close-to-real work tasks rather than rely entirely on generalised low-validity tests – though it is essential to ensure adequate training for such complex tasks. Simpler tasks, designed to measure changes in underlying cognitive or skilled components, will be useful where their relation to target performance can be demonstrated, and also where only limited training time is available;
- Study the impact on performance in direct relation to associated effects on physiology and subjective state – allowing the assessment of the costs of adaptive control;
- Need to study optimal methods of training of the complex tasks and stress management essential for mission success.

3.4.2 Long-term Research Priorities and Emerging Fields

Limitations of previous research have been the intractable problems of small sample sizes as well as a lack of methodological consistency. Comparison of data collected from space with those from simulation studies will be essential to assess the value of the information with regard to different aspects of space missions beyond the characteristics of the physical environment. Any attempt to transfer experiences across settings requires a thorough evaluation of the variables of crew member characteristics, crew size, crew tasks and overall mission objectives.

A mission to Mars will add a new dimension to the history of human expeditions with regard to the distance and duration of travel. Such missions might not be comparable to any other undertaking humans have ever attempted because of the long distance of travel, the duration of permanent living dependent on automated life-support systems, the degree of isolation and confinement, and the lack of short-term rescue possibilities in case of emergencies. Current knowledge about human adaptation under these conditions is very limited, although predictions about the emergence of certain psychological issues might be extrapolated from Earth-based analogues and studies and previous spaceflights. Specifically, more research in the following areas is needed:

- Research on and development of effective training tools in order to prepare crews for exploratory missions. Specifically, problems of maintaining critical skills on very long (Mars) missions requires a major focus on training resistance to skill loss;
- Research on and development of effective support tools in order to provide the best possible psychological inflight support of crews during exploratory missions;
  a. Establish countermeasures for monitoring and dealing with social problems and individual stress reactions;
  b. Establish countermeasures for reducing the impact of boredom and monotony on performance and psychological health;
- Research on safety management in space organisations.

4. Physical sciences

4.1 Fluid physics and combustion

4.1.1 Current and upcoming research priorities

It should be first noted that several programmes are running that need to be continued. We will thus begin with such current activities.

Fluid sciences current activities

Convection and interfacial heat- and mass-exchange, phase transition, boiling

This domain of research is particularly important as it is concerned with thermal exchanges by evaporation or boiling and condensation. The ambition is to develop high yield thermal processes for management of fluids in space: cooling devices, life-support systems. A dedicated study is concerned with the Vinci engine of Ariane 5 rocket to be reignited in orbit, and then to be cooled down at the liquid hydrogen and oxygen temperature with high efficiency.

For this purpose the underlying mechanisms of liquid-gas phase transition have to be well documented for the weightlessness environment. Fundamental studies need then to be pursued. Surface temperature gradients on the liquid-gas interface provoke intensive flows (Marangoni convection) and drastically change the heat transfer. The vicinity of the gas-liquid critical point is particularly interesting as, in addition to the particular sensitivity to accelerations that the fluid acquires in this region and the use of industrial fluids in space in their supercritical state, it permits the results to be put under universal, scaling laws, valid for all fluids.

Fluid management under dynamic conditions (e.g. vibrations)

Vibrations do exist in spacecraft and satellites and their effect on fluids is very little documented. Depending on their frequency and amplitude, vibration can induce thermal effects and can modify phase transition (evaporation, boiling and condensation) in a manner similar to Earth's gravity. Micrometre, moderate frequency vibration can thus create a kind of artificial gravity. Here too, supercritical fluids appear to be very sensitive to this mechanical excitation. This field of research should be developed as times longer than those provided by parabolic flights (planes and sounding rockets) are needed to determine the final equilibrium state after gas-liquid phase transition.

Foam drainage, foam structure and rheology, emulsion, droplets

The study of foams in weightlessness has just started and many questions remain unanswered, concerning, for example, their long-time dynamics, draining, bubble breakup and stability. Foam is widely used for cleaning and stopping combustion and the result of these studies are important issues for life support and fire safety in satellites and spacecrafts.

A related field is concerned with sprays, sprays that are used for immediate and powerful cooling devices; the study addresses the formation of droplets and the spray breakup.

All the above studies imply the use of surface active species (surfactant). Further measurements of adsorption kinetics and the study of the capillary management of liquids by such surface active species and particles are thus considered necessary.

Bio- and micro-fluid dynamics

The study of biological fluids that are essentially made of deformable micro-particles (blood cells) has just started. The behaviour of such fluids, at the boarder between life and physical science, is gravity-dependent and the high interest in their study is obvious. It indeed gives an understanding from a physical point of view of the modifications in space of the complex biofluid flows. It also permits the improvement of the functioning on Earth of devices using micro- and biofluidics.

Combustion current activities

Combustion Properties of Partially-Premixed Spray Systems

Within this third phase of the Microgravity Application Promotion project, experiments and numerical simulations will be carried out to investigate the auto-ignition behaviour of second generation biofuel. The focus is on GTL (gas-to-liquid) kerosene that is synthesised through the Fischer-Tropsch process from either biomass or coal. This fuel is becoming increasingly important in technical applications. The investigations compare those fuels to fossil-based kerosene and will develop appropriate model fuels to allow a numerical simulation of spray auto-ignition including detailed chemical reaction mechanisms. Potential technological approaches to future low-NOx combustion can be anticipated as a result of this research.

In 2009 a sounding rocket flight will be carried out (Texus 46) in cooperation with the Japanese JAXA on NOx- emissions from partially pre-vaporised droplet array combustion.

Fluid Physics upcoming activities

General: research between 1g and 0g with exploration background

The development of the exploration programme needs a number of fluid behaviours to be investigated at Moon gravity (g/6) and Mars gravity (g/3) and more generally at different gravity levels. Such weak but finite acceleration can be provided by centrifuges in weightlessness – but centrifuges add a Coriolis force – and by plane parabolic flights. An artificial variable gravity can also be provided with magnetic fields in Earthbound laboratories. The development of these possibilities has to be supported.

Nanoparticles and nanostructures at liquid interfaces and in liquid films, self-arrangement of nanostructured materials

The development of the micro- and nanofluidic systems in electronics, computers, health devices raise questions regarding their functioning and whether they remain efficient or at least innocuous in space. Objects are small but cooperative and boundary effects make them g-sensitive. In particular, biofluids, a field of research already under development, should increase their activity in relation to life science programmes.

Capillary and thermocapillary effects in microfluidics

Capillary effects are essential when fluids are under weightlessness and are widely used for heat pipes. The functioning of the devices in the micrometre range is thus of great interest, not only for space relevance but also because such devices are now being used on Earth.

Chemo-Hydrodynamic Pattern Formation at Interfaces

Hydrodynamically unstable chemical fronts or interfaces influenced by chemical reactions underlie many industrial applications. The coupling of chemical reactions and hydrodynamics can occur in several ways. The two most common cases are nonlinear volume reactions that create their own interface (chemical fronts) and chemical reactions at liquid-liquid interfaces (chemically driven interfacial convection). The objective is a quantitative study of pattern formation due to the coupling between chemical reactions at interfaces and hydrodynamical instabilities. These studies should also lead to quantification of their consequences, namely the changes in heat/mass transfer or mixing rates.

Chemical Physics in supercritical fluids (with exploration)

Supercritical fluids, namely fluids at pressures and temperatures larger than the critical point pressure and temperature, correspond to gases with the density of liquids. Then they acquire very strange properties, for example CO_2 at room temperature and pressure above 72 bar becomes a very efficient (and harmless) solvent of organic materials. At higher temperatures (400°C) and pressures (450 bar), in supercritical water, chemical reactions become very fast and very efficient. These properties are already used in industry to extract oils or to clean contaminated areas (CO_2) or to oxidize in H_20 and CO_2 by this a cold combustion some dangerous wastes like ammunitions or radioactive materials. There are no data yet concerning the behaviour of these supercritical fluids in space, what is known is only the strange thermal behaviour under weightlessness of the fluids near the critical point. In addition to the interest in discovering new supercritical properties in space, investigating supercritical chemical reactions will support the exploration programme and the associated life-support devices where recycling is requested.

Combustion upcoming activities

Combustion synthesis of functional metal-oxide nanoparticles

In continuation of the former soot formation investigations and the fire safety research this project will focus not on the health aspects but on the technological aspects of particle formation through laminar jet diffusion flames. The goal of this project is to explore combustion synthesis of tin-oxide nanoparticles for gas sensor applications.

A unique focus of this effort would be the development of new, ultra-sensitive sensors with very thin functional layers that can be processed at the short residence times available under microgravity conditions. A dedicated reactor will be built for FSP (Flame Spray Pyrolysis), a highly versatile process for manufacture of nanoparticles with superior catalytic, mechanical and electrochemical properties. Organo-metallic precursors for tin oxide and dopant metals will be evaluated and selected for synthesis of nanostructured sensors with the appropriate morphology and optimal characteristics. Sensor particles and film properties will be characterised systematically by a range of state-of-the-art techniques. Microgravity is anticipated to influence stagnation layer thickness and deposition dynamics. Additional effects on flame temperature profile may influence particle agglomeration and sensor film morphology.

Fire safety in space

The investigations on flammability and flame spread of materials for space application will be continued. In this phase, particular new diagnostic techniques shall be developed to perform:

- flame visualisation (direct emission, CH, OH emission)

- particle image velocimetry
- temperature measurement through pyrometry
- measurement of heat fluxes
- light extinction diagnostics and soot collection
- diagnostics of the oxygen depletion in the combustion zone.

Further, a theory-based model describing the flame spreading over solid combustible materials will be developed.

4.1.2 Implementation priorities

In order to make the fluid physics and combustion research activities more efficient, we propose that ESA considers the following commentaries.

Foster an interdisciplinary research with life science teams, e.g. in the Exploration programme. Two examples can be cited: the case of micro-biofluidics and the recycling of wastes by cold combustion in supercritical water waste, in connection with the life support MELiSSA project.

It is suggested that there be an increase in collaboration with non-ESA countries and agencies, such as CSA, NASA, or the Russian, Japanese and Chinese agencies. These collaborations already exist, for example through some International Topical Teams. This development gives at least the possibility of increasing the access to space and to facilities, which is difficult at the present time. There is a particular necessity for a cooperative utilisation of combustion research-dedicated facilities with NASA and JAXA, as the European combustion community is small but it should not abandon its research activities. This is especially important because long-term manned space missions will remain particularly risky as long as no theoretical model for flame spread over combustible solid materials is available.

Space-dedicated EU research programmes offer a possibility to seek additional funding for laboratories.

A better harmonisation is needed between ESA and national agencies in supporting the laboratories. This problem is recurrent; the research programmes selected by an ESA peer review have also to be reviewed independently by national space agencies. Everybody has in mind these European collaborative researches that stopped because one or more laboratories had to withdraw for lack of national support.

A significant hiatus exists in Europe between funding of space experiments by ESA and the funding of researchers, ground-based work, data exploitation etc, at national or EU level. It is recommended to find a way to harmonise the approval cycles and funding processes of ESA and national agencies.

In the decision to give access to space, it could be envisaged to give more weight to the re-utilisation of already existing facilities.

It is therefore recommended that ESA aims at re-utilising or re-designing existing facilities rather than spending budget for new facilities in fluid physics and combustion.

The ground support to space research laboratories is supplied by national space agencies, in addition to the regular funding process where these laboratories compete against less expensive research. At least three selection processes thus have to be followed; one at European level with ESA, and two at national level with the space agencies. Finding a way to unify and harmonise these selection processes is a priority.

ESA should support ground-based experimental and simulation activities and aim at a better consolidation between 1g and 0g research. Together with national agencies and the EU, ESA should seek for more harmonised selection processes.

In most cases, microgravity research is fundamental research in the sense that the data obtained are not directly applicable to technical terrestrial problems. Therefore in order to deal with this existing hiatus a way would be to include in the space research portfolio one or several steps of adoption of technical problems, namely numerical simulation-based research.

An example taken from the field of droplet ignition or droplet combustion: microgravity experiments are performed on millimetre-sized droplets in quiescent ambiance. Even when delivering quantitative data, the gained data have only qualitative value to industry. In order to support a better utilisation of the data one must take those microgravity data to validate numerical simulations for identical situations, then numerically scale it down to micrometre-sized droplets and numerically implement droplet-droplet and droplet-gas interactions. These steps should be done in addition to microgravity research within the space segment.

Numerical simulation-based research based upon microgravity data must therefore be funded by space agencies. Common calls and selection processes must be established jointly between space agencies and agencies supporting ground-based research.
Finally it is stressed again that the Topical Team programme is a powerful ESA tool which supports and allows developing new ideas, new experiments and

new measurements. The outputs from the work of these teams can continue to be developed in the framework of the MAP programmes.

4.1.3 Application potential

As already stressed above, the science of fluids and combustion in space aims to investigate the behaviour of fluids and chemically reacting fluids in a reduced gravity environment: weightlessness of the open space, weak acceleration in a spacecraft, Moon and Mars gravity. Some objectives are then already application-oriented. A list is given below:

- More efficient cooling/heating systems
  The study of thermal exchange by evaporation/boiling and condensation aims to improve the yield of heating cooling devices.
- Better understanding of emulsion flows, especially drainage and phase separation in microchannels with application to microfluidic machinery
  The application is twofold: it makes the microdevices work in weightlessness and uses microgravity to identify difficulties encountered on Earth (e.g. the hydrodynamic sorting of proteins).
- Waste treatment
  The research on waste recycling (by e.g. supercritical water oxidation) is important for exploration missions and promises to be also beneficial for new terrestrial applications.
- Biofluidics for health and life science
  Human exploration needs the behaviour of the biofluids to be investigated in depth.
- Better understanding of flame propagation on solid walls, methods of fire suppression
  New standards on the definition of material flammability based on fundamental knowledge rather than on empirical data gained from 1g-experiments
- New functional materials (e.g. sensors, catalysts etc) through thin-film deposition of combustion synthesised nanoparticles

4.1.4 Cross-cutting issues

A number of interdisciplinary fields of research have been identified throughout the workshop. We list and comment them below. It is anticipated that interdisciplinary Topical Teams could be created on these topics.

Interdisciplinary work between materials science and life sciences

- Phase transition, link with materials science
  Gas-liquid phase transition proceeds from the same general processes of nucleation and growth of a new phase. Joint research on the fundamental bases of solidification and crystallisation should be considered with materials sciences where a liquid phase with the same thermal and capillary instabilities (Rayleigh vibrational, Marangoni) also exists.
- Welding, link with materials science
  Welding in microgravity is essentially thermocapillary (Marangoni) convection. A natural synergy exists with the Materials Sciences Group in this area.
- Biofluids, links with life science
  The study of model biofluids should be linked with the study of real biological fluids as investigated in life sciences.

Research related to the Exploration programme

In the course of this report, direct links with the Exploration programme have been noticed:

- Research between 1g and 0g
  This concerns studies aiming at investigating fluid and combustion behaviour at Moon and Mars gravity. Strong emphasis was put on studies at intermediate gravity levels (Moon, Mars). The utilisation of a centrifuge for drop-tower experiments, parabolic flights with 1/3 g and 1/6 g, or experiments using magnetic fields on the ground, were envisaged.
- Life support and waste treatment (MELiSSA project)
  Some research, such as that on supercritical water oxidation, could be led in collaboration with the life support study in the exploration programme. (Contacts have been already made and a joint meeting was held).
- Fire safety research will become more important
- Energy production using Moon and Martian resources
  This is a quite general goal where combustion and fluid sciences could give their expertise.

4.2 Fundamental physics

Experiments of increasing precision are essential to learn about the microscopic and macroscopic structure of our universe and the underlying physics. Increasing precision and sensitivity will lead to new results which could bring us to a new understanding of our world picture. Space is an ideal laboratory enabling completely new fundamental and much more precise experiments than on Earth. One field of interest is in quantum physics. Because of an enormous progress in the manipulation of quantum systems it is possible with state-of-the-art experimental techniques to prepare macroscopic quantum systems (e.g. Bose-Einstein condensates). Those quantum systems enable interference experiments, but have lifetimes of a fraction of a second on Earth only, because the quantum systems are influenced by gravity. Simply said, on Earth, the ensembles of cold atoms fall out of the interferometer which limits the experimental time. Only a weightlessness environment guarantees a very long free evolution time and enables us to attain the extremely low temperature regime which is essential to improve the experimental accuracy by orders of magnitude.

Dust physics plays an important role in the formation of planets, on planetary surfaces, and in planetary atmospheres. Basic knowledge about fundamental interactions, such as aggregation physics, energy transport in particulate systems, or radiative forcing, is still lacking. Because of gravity-induced size segregation and rapid sedimentation in an Earth-based laboratory, measurements of these effects in particle-gas systems is possible only under long-duration weightlessness conditions.

The ELIPS programme for research in space has proved to play an important part in fundamental research. High precision experiments of increasing sensitivity and accuracy offer innovative chances to investigate microscopic and macroscopic structures. Physics faces new challenges for research dedicated to a much better understanding of our picture of the world.

It has become clear that space is an ideal laboratory and unique environment enabling new fundamental experiments, orders of magnitude more precise than on Earth. Fundamental physics stimulates research with regard to the universal laws and basic theories of physics which have to be questioned as it is not possible to unify them along the lines given by conventional quantum theory.

All theoretical approaches and conceptions to investigate this fundamental inconsistency predict violations of the underlying assumptions and hypotheses of the basic theories. It is of interest to improve experimental precision using, in particular, space as laboratory. It is obvious that the search for New Physics is the key issue for finding new methods which, inevitably, will lead to new concepts for technological application. Challenging space experiments set the goals. The development of new technology for those experiments is useful and promising, anyway for our future. Fundamental physics research objectives can be summarised as follows:

- **Fundamental research for understanding the systems under study**
- **Transfer of know-how into other fundamental and applied research areas**
- **Transfer of know-how for industrial application**

In this context, the Topical Teams established within ESA's ELIPS programme play an important role and act as multipliers of science and resources and are mandatory for the preparation of new research fields. It is recognised that the process of discussion in Topical Teams intensified the desire to utilise the International Space Station for innovative research fields. The report concentrates on those research activities for fundamental physics (already established, under preparation, or planned to be carried out within the up-coming decade) under conditions of weightlessness.

In contrary to the ELIPS 1 and 2 programmes, it seems to be of advantage to distinguish three major fields of interest:

- **Fundamental interactions/quantum physics in space-time**
- **Soft matter physics (covering the fields of complex plasma physics, dust physics, and vibration and granular matter physics)**
- **Environmental physics (covering mainly the research activities with regard to the atmosphere-space interaction monitor to be mounted on ISS)**

It is important to state that the quickly developing techniques in many fields of research will probably enable completely new experiments already in the near future which seem to be beyond experimental reach from today's perspective (e.g. search for dark matter in the solar system or investigations of modified Newtonian dynamics etc.). Some areas studied today (e.g. quantum optics) would not have been seen as part of the Fundamental Physics microgravity programme only a few years back. It is therefore important to enable new proposals at any time and keep the programme outline flexible enough for innovative developments.

4.2.1 Research Priorities and Emerging Fields

Science Goals and Instruments

The recent launch and the start of the regular operation of the European Columbus module for the ISS is the start of a new era for microgravity research in Europe and offers unique opportunities for innovative research.

The existing and planned facilities should be used (or brought into use) as quickly as possible to gain the maximum scientific return. New research subjects must be implemented without further delay. In order to continuously improve European excellence in microgravity research, ESA must emphasise that space experiments must be embedded in strong basic science.

It is recognised with much regret that, at the same time, NASA stopped its Fundamental Physics programme, which complicates cooperation and joint technological developments.

The recommendations in the area of fundamental physics focus in particular on the future of facilities to be installed onboard the ISS. There are many science goals in the areas of quantum physics, cold atom physics, general relativity, and soft matter physics which can be achieved only under conditions of weightlessness (e.g. operation of extremely precise atomic clocks for gravitational physics experiments and metrology, large expansion and long time-of-flights of macroscopic quantum matter, e.g. Bose-Einstein condensates, highly precise matter wave atom interferometers and atom lasers). In addition, ISS should be used as a permanent platform for large-scale experiments and observation (e.g. quantum entanglement experiments between Earth and space, time transfer between ACES and Earth-based laboratories, Earth monitoring with ASIM).

It is also recommended to establish the new and emerging field of matter wave interferometry with supermassive particles. Although the quantum superposition principle is well established in the microscopic domain, there is at present no indication of whether it still holds in the macro-world. A viable way to test this experimentally is to bring increasingly massive particles into a macroscopically distinct superposition state, as is done in matter wave interferometry.

Such a demonstration would be a striking manifestation of quantum mechanics with particles conventionally seen as classical. Microgravity conditions are required, because one cannot practically work with de Broglie wave lengths much below 1pm. Particle beams with even larger masses would have to be so slow that the gravitational acceleration precludes their interference in terrestrial experiments. It will allow testing unconventional theories of the quantum-classical transition, such as spontaneous collapse models, and it would venture into parameter regimes where effects of quantum gravity might become observable.

The list of priority projects in Soft Matter Physics contains many cross-links to materials and/or fluid science (e.g. complex fluids, foams, aerogel etc). It is expected that the specific research interests will lead to many synergetic results. Synergies within the soft matter physics are already visible in the fields of dust physics and granular matter physics, where strong overlap exists; for example planetary regolith and planetary ring dynamics.

The following implementation plan for Fundamental Physics is recommended:

- Completion of the Phase C/D and final implementation of the ACES atomic fountain clock until 2013;
- Strong support of cold atom physics research under weightlessness with emphasis on Phase A/B studies and pre-developments of space hardware, in particular the developments of:
  a. Space Atom Interferometer
  b. Facility to process Bose-Einstein condensates and atom lasers
  c. Space Optical Clock
  d. Space Optical Frequency Comb
  e. Space-QUEST (for quantum entanglement experiments).
- Support of the emerging field of supermassive particle interferometry;
- Continuation and completion of the Phase C/D development of the PK(Plasma Crystal)-4 facility;
- Start of the Phase C/D for the IPE-Facility;
- Start of the Phase C/D for the VIPGran-Facility for granular physics;
- Strong support of the Phase A/B development for the double rack facility IMPACT consisting of the IMPF-Facility for Complex Plasma Research and the ICAPS-Facility for research on dust agglomeration;
- Strong support of the Phase C/D activities for the development of the ASIM observation platform.

Critical Technology/Requirements

The fundamental physics science programme of ELIPS needs various new technologies and experimental techniques so far not, or not sufficiently, qualified for space application. Therefore, the Fundamental Physics working group worked out a list of urgent technology developments to support the ambitious science programme appropriately. In particular, the following technologies should be available:

- Space-qualified laser diodes
- Space-qualified fibre optics
- Optical and RF links (e.g. for efficient time transfer); this desire is shared with the ESA-Science Programme)
- Techniques to clean optics in a dusty environment (important even for the ESA Exploration programme)
- Space-qualified power lasers
- Real-time telescience and diagnostics capabilities
- High data rate telecommunication
- Space-qualified nonlinear optical crystals
- g-jitter isolation/free-flying platforms
- Centrifuge for radial accelerations between 1mm/s^2 to 20m/s^2
- Fast compression video systems with a high compression ratio.

It is recommended to set up a generic technology development programme.

4.2.2 Potential Spin-off Applications and Societal Importance

The implementation of the various science goals within the ELIPS programme needs broad political and financial support. Therefore, it is seen with concern, that the upcoming ELIPS 3 programme contains more and more contributions for the ESA Exploration programme. ESA´s microgravity research should be rather driven by laboratory research and fundamental science interests, than by political plans and industrial interests to explore the Moon or Mars. ESA´s Exploration programme and the ISS utilisation for space exploration should be based on its own resources.

Nevertheless, various technology fields have been identified which are of benefit for general application and in particular for adaptation in ESA´s Exploration and Aurora programme. These are:

- New inertial sensors and precise clocks for spacecraft navigation resulting from cold atom physics;
- Impacts to communication technology and cryptography as a result of time transfer and quantum entanglement experiments and technology development;
- Applications for radio science from precise ranging and time transfer;
- Technology for communication via optical links;
- Space-time precision metrology;
- Technologies for grain manipulation, transport, disagglomeration, breaking etc.;
- Technologies to prevent dust contamination;
- Observation of the solid state greenhouse effect on Mars;
- Learning about crater formation and impacts on planetary and moon surfaces;
- Technologies for landing and locomotion on regolith;
- Solar cell development from complex plasma research;
- Plasma medicine;
- Plasma vapour deposition;
- Development of ‘exotic’ alloys.

In addition, some interesting impacts from the planned Exploration programme for fundamental research are expected. In particular, for gravitational physics, the possibility of precise deep space ranging to satellites and planets as well as Very Long Baseline Interferometry (VLBI) will be of great benefit in order to be able to carry out various tests for special and general relativity (e.g. experiments to measure the Shapiro time delay).

It is worth mentioning that even ESA´s Science Programme will benefit from fundamental physics research under weightlessness which no doubt will contribute much to cosmology, astrophysics, star formation, solar system physics as well as astrobiology.

It has also been recognised that fundamental physics research on ISS, because of its basic science goals, helps to promote international cooperation with various countries and societies (e.g. USA, Russia, Canada, Japan and China). This point had been identified as having a high societal importance.

4.2.3 Commonalities

Some fields of fundamental physics, in particular in soft matter physics, have coinciding or similar goals to materials science. The recommended research topic ’soft matter’ covers all states ranging from solids (e.g. foams, granular solids, polymers) to liquids (e.g. emulsions, colloidal suspensions – so called ‘complex fluids’) and plasmas (so-called ‘complex plasmas’). These states of soft matter closely resemble the states of ordinary matter, with the exception that they are ‘supramolecular’, with the supramolecular (particle) component being highly variable in both physical and chemical properties. In fact, a number of biological systems (e.g. blood, membranes) would also be classified as soft matter.

Accordingly, the commonalities with regard to fluid and material physics are substantial – the division is more along the lines of fundamental physics research against application-oriented research. Fundamental research topics of common interest (albeit pursued at different levels of temporal/spatial resolution) are for instance phase transitions, critical point studies, non-Hamiltonian and non-Newtonian fluid behaviour, tribology, origin of turbulence at the kinetic (individual particle) level, two-stream flows, wave propagation, solitons, kinetically resolved shocks, etc. In fact all fundamental problems associated with stability, flows, self-organisation and structure formation, thermodynamic equilibrium and non-equilibrium phenomena.

The discussion has even shown that dust and granular physics contribute intensively to the science goals of the ELIPS 3 programme. There are strong commonalities between dust and granular-matter physics. Besides the fundamental question below; namely which particle size interactions are dominated by interparticle forces in a given physical scenario, natural systems with such a wide spectrum size exist that both adhesive collisions and granular-matter behaviour occur simultaneously. Examples of such systems are regolith-covered surfaces of small solar system bodies and Saturn’s main rings. Joint investigations in this direction are desirable.

4.3 Materials science

Fresh insights into the fundamentals of metallic alloy solidification can be gained with the potential of producing novel microstructures. In parallel, the space environment allows levitated melts to be controlled effectively at temperatures up to 2000°C, which in turn enables critical liquid physicochemical parameters to be measured much more accurately compared to the Earth laboratory. These cornerstone research activities cooperatively lead to improved validation of numerical models of solidification processing from the melt as mentioned earlier.

In what follows, most of the topics addressed are structured according to the cornerstones of materials science, as defined in the previous exercise in Obernai, namely:

- Thermophysical properties of fluids for advanced processes
- New materials, products and processes.

There is a general trend within ESA to focus the utilisation of the ISS more on application-oriented, or even industry-driven, research. Whereas the materials science community wants to stress that basic research is a prerequisite for applied research it is also true that materials sciences is, by definition, application-oriented. This is manifested, for example, through the active participation of more than 40 industrial companies in related ESA-MAP research programmes.

4.3.1 Upcoming research priorities

By considering the upcoming research priorities for the next 10 years, namely up to 2018, it is clear that this era will be characterised by the full use of the ISS. Currently, only a few experiments and scientists are able to use the ISS. With the successful docking of Europe's Columbus module, and the start of operation of the different materials science-related payloads, such as the MSL, FSL or EDR, a qualitatively different utilisation scenario will take place, allowing harvesting the investments made in recent years. It should be noted however, that NASA's Space Shuttle may no longer be available after 2011, reducing the up- and download capabilities of specimens considerably, until a replacement for the Shuttle becomes operational (circa after 2014).

As a result of extensive discussions a consolidated list of the following topics could be achieved. On this basis, melt processing in space will sustain the design of new and improved materials with better performance.

Thermophysical properties of fluids for advanced processes

- High-temperature alloys (nickel-based superalloys, potentially including Ta, Nb, Mo, Pt, Hf, as alloying elements, Cu- and Fe-based alloys) for energy conversion, power generation, heat management systems, fluid management;
- New light-weight, high-strength structural materials (Ti-, Mg-alloys, Al-, Ca-based Bulk Metallic Glasses) as support to space exploration;
- Diffusion coefficients (in conjunction with measurements of other thermophysical properties).

New materials, products and processes

- Complex metallic alloys (intermetallics, multicomponent alloys, nanostructures etc.) and high temperature alloys
- Energetic pyrotechnic metals (nano-Al, Mg, Fe)
- Fuel cell catalysts (Ni, PGMs)
- Bulk metallic glasses/foams (Ca-, Mg-, Ti-based)
- Shape memory alloys (Ni-Ti)
- Metal matrix composites with CNTs
- Nanoporous de-alloyed metals (various)
- Metal composites with inert nano-oxides (Mg, Al)
- Hollow sphere metal foams (Ti, Al)
- Control of grain structure in solidification processing coupled to quantitative predictive 3D modelling
- Heat exchangers/Heat sinks (Al, Cu, Na, nano-Au)
- Atomisation and spray forming
- X-ray imaging for liquid processing
- Power ultrasound processing of liquid metals (various)
- Structural modifications by deep undercooling
- Joining of interfaces (electron beam and laser welding).

Crystal growth

- Containerless and solution growth (intermetallics, THM growth of CZT, SiGe)
- Impact of convection on nucleation and self-organisation (also valid for New Materials, see above)

As mentioned before, the measurement of self- and interdiffusion coefficients in liquid alloys will become a new priority within the next 10 years. In contrast to previous experiments which concentrated on the temperature dependence of the diffusion coefficient in simple systems, the emphasis will now shift to studies of the concentration dependence in binary and multicomponent systems.

In the area of materials, products and processes the emphasis will also shift to complex alloys, con-

sidering in particular intermetallics, multicomponent alloys and in situ composites.

The control of grain structure, micro- and nanostructure in solidification processing, including deep undercooling down to the glass transition, will be a major task within the next 10 years.

In addition, more attention will be paid to interfacial phenomena and their applications in the field of joining and welding.

In crystal growth, alternative growth techniques, such as containerless and solution growth, may become an important topic for growing macromolecular hierarchical systems and to study the influence of convection on nucleation, aggregation and self-organisation.

Furthermore 'soft matter' will become a major topic for the materials science community within the next 10 years. This includes fractal aggregates, aerosols, aerogel, foams, proteins, colloids, and granular material that closely relate to many other areas in ELIPS.

4.3.2 Future priorities

It is very difficult to make predictions over long time scales. Nevertheless, some trends about the future of materials sciences under microgravity after 2018 can be identified.

In this regard, it is relevant to quote the long-term vision of the international metal casting industry for their R&D:

By 2020, the combination of average melting and mould yield for each metalcasting alloy/process family will increase significantly so that, in aggregate, the metalcasting industry yields will increase by 20 percent from current levels. Rejected casting rates will be cut by 40 percent from current industry averages. On time/complete delivery performance for the full spectrum of order/release quantities will be sustained above 95 percent across the metalcasting industry while the combination of in-process and finished inventory in metalcasting will be slashed 50 percent. (Metalcasting Industry Technology Roadmap: Pathway for 2002 and beyond, Cast Metal Coalition, October 2003).

The development of nanotechnology for space applications is a further long-term goal up to 2020 and beyond. Nanotechnology refers to a field of applied science and technology whose theme is the control of matter on the atomic and molecular scale, generally 100 nanometres or smaller, and the fabrication of new devices and materials that lie within that size range. Nanotechnology is a new and highly multidisciplinary research area, drawing from different fields such as applied physics, materials science, interface and colloid sciences, device physics, supramolecular chemistry, self-replicating machines, robotics as well as chemical, electrical, mechanical and biological engineering. The applications range from materials synthesis, advanced computing, chemical and biological analysis/detection, drug delivery/discovery, tissue engineering, to energy conversion and storage. New advanced systems with integrated nanometre-scale structures and functions present therefore a multidisciplinary challenge (Fecht and Werner *Nano-micro-interface NaMIx*. Wiley-VCH, 2004).

It is generally believed that ISS utilisation will contribute to achieving these ambitious goals. Its potential will not be exhausted by then, and the continuation of ISS use beyond 2018 is desirable also with regard to the considerable financial resources invested so far. Of course, further investments will have to be made for a new generation of payloads for the ISS. Some of the new scientific requirements may be satisfied by new inserts into existing facilities, such as a diffusion furnace and a float zone furnace with an optical imaging system for the MSL. Others may require an entirely new facility (or a substantially upgraded facility) like the proposed Physico-Chemical Laboratory (PCL), which would allow the study of interfacial, capillary and adsorption phenomena at moderate to high temperatures, or the XRMON facility dedicated to the in situ monitoring of materials processing.

On the other hand, preparatory steps have to be taken for the post-ISS era by looking into alternative payload carriers, and also by considering a redirection of materials science in space.

Assuming that the Human Exploration programme of ESA (Aurora) will have a substantial volume by then, materials science could serve this programme by developing the required materials for lunar or interplanetary missions. Within the Aurora programme, the in situ utilisation of resources may become an attractive research field for Materials Sciences. This would however require a shift in capabilities of the materials sciences community towards geophysics and related disciplines.

In summary, the following list of future priorities could be identified:

- Continued use of ISS
- New generation payloads
- Materials Science for Human Exploration (Aurora Core programme)

4.3.3 Programmatic aspects

Programmatic priorities, their implementation, and the possible synergies with other ESA programmes are discussed in this section.

There is a general consensus that ESA's major role is to provide flight opportunities, including instrumentation; that is, payloads. Funding and support for the scientific teams is primarily the responsibility of the national agencies. However, as has been pointed out before, complex scientific problems can be successfully addressed only by building teams of European dimension.

Therefore, the initiative taken by ESA to call for and to support Topical Teams as well as MAP (Microgravity Application Promotion) projects has been unanimously and enthusiastically backed by the scientists. The Topical Teams are considered as being very successful incubators for emerging topics, and to lay the ground for a network of European scientists working for the ELIPS programme. The MAP projects are considered to be a unique platform to perform in-depth research on complex phenomena, which requires the teaming of European experts.

Considering the MAP programme, ESA has announced that in the planned new call for proposals a stronger involvement of industry is required in this type of projects. In doing so, the different time scales and different levels of involvement in industrial R&D need to be considered. Long-term strategic technology development takes place on time scales of about 5 years, whereas product development has a cycle of about 2-3 years. For long-term developments, industry is considering its role as an observer in basically scientific projects. At this pre-competitive stage, companies are willing to join large projects, even jointly with their potential competitors. On the other hand, companies are willing to invest their own money in small dedicated teams in order to help to solve production-related daily problems.

As a consequence, the present form of the MAP projects should be continued, meaning that these projects would have application-oriented, but not solely industry-driven, strategic long-term objectives. As Promotion is no longer an issue, the programme should be renamed; one suggestion being Microgravity Assisted Research (MAR) or Microgravity Assisted Research and Engineering (MARE).

For some of the present MAP projects there is furthermore a definite potential to develop into the next stage where industry would play a much more prominent role, becoming direct users of the results obtained under microgravity. An excellent example is IMPRESS, an Integrated Project in the EU's 7th Framework Programme, managed by ESA. In this project, there are no competitive companies involved. Instead, for each step in the value chain, an industrial partner has a leading role. It should be noted that industry participation is based on 50% funding from the European Union.

Concerning synergies with other parts of the ELIPS programme it should be stressed that the division into fundamental physics, fluid physics and materials sciences is somewhat artificial, leading to considerable overlap between these subdisciplines. Furthermore, even the distinction between life sciences and physical sciences is not as sharp as one might think. This is very obvious in the field of protein crystal growth. Accepting the currently existing categories, the materials science community realises the existence of an overlap with fundamental physics in the area of 'soft matter'. This community has identified 'supramolecular physics' as one of its emerging fields, quoting the physics of dust and complex plasmas as typical examples. Here, a close link exists to, for example granular matter and possible synergies can be expected.

As materials science under microgravity is mainly devoted to the study of the effects on fluid flow on matter, heat transport and solidification phenomena, the relation to fluid physics is obvious. The interplay between fluid flow and phase transformations is the common denominator for both fields; the main difference between them is the material under study: aqueous solutions or low temperature liquids in one case; and high-temperature – mainly metallic – melts in the other case.

The relation of the materials sciences to the Human Exploration programme Aurora is not so clear at present. As has been pointed out before, Materials Science is a prerequisite for space exploration by providing the materials which are required for, for example, propulsion technology. Also the envisaged in situ use of resources in the framework of lunar or Martian missions will require expertise in materials science, albeit in subdisciplines currently not represented in ELIPS; for example mineralogy. This kind of research can also be considered as application oriented, with ESA becoming the customer through its Aurora programme.

4.3.4 Recommendations

Top-level recommendations have been made by the materials science community.

Definition of Cornerstones

There is no need for a redefinition of the cornerstones as defined earlier in Obernai and Evian. On the contrary, it is felt that the cornerstones need to remain fairly general, in order to allow for the integration of emerging fields. This is in line with ESA's user-driven bottom-up approach.

Courtesy: EADS Astrium, Germany.

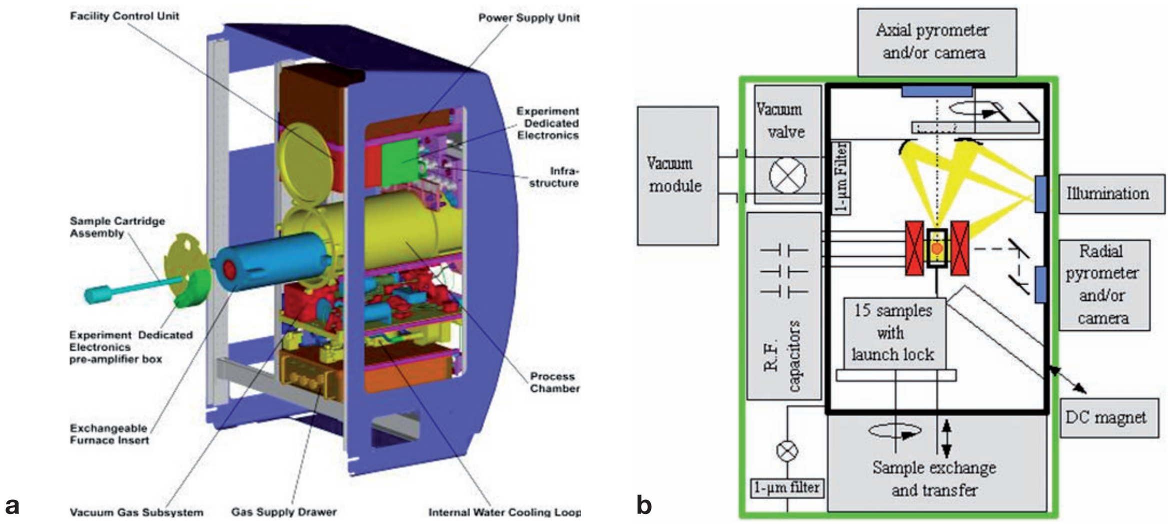

Figure 4.3.4.1. Schematic presentation of (a) the Materials Science Laboratory (MSL) and (b) the Electromagnetic Levitator (EML) reaching temperatures up to 2000°C.

ELIPS 3

With regard to the upcoming and exciting possibilities of materials research in the Columbus module full utilisation of ISS is demanded. The participants consider the ELIPS programme as essential for their research and fully support ESA in proposing the ELIPS 3 programme at the next Ministerial Council.

Funding level should be increased considerably

With the availability of Columbus, the research capabilities will increase dramatically compared with previous years. Drawbacks for fund shortage in ELIPS 2 are well known and documented (work packages cancelled, MAPs delayed or on hold etc.) with negative impact on return of investment. Hence, full utilisation of the available resources on ISS requires a proportional increase in the envisaged budget for setting up a sensible research programme with corresponding manpower in order to achieve the ambitious scientific and programmatic goals.

Topical Teams as incubators should be continued

Topical Teams are considered essential to help to explore emerging research topics and to bring them up to a level of maturity required for a flight experiment or for an application-oriented project. The Topical Team activities should be based on international and global cooperation.

The microgravity application-related programme (formerly MAP) has to be continued

Whereas the Topical Teams generate ideas, it is the role of the MAP projects to implement and execute the resulting Flight Experiments. Consequently, they should be renamed Microgravity Assisted Research (or Microgravity Assisted Research and Engineering) projects. To this end, these projects need to be based on interdisciplinary teams, covering all aspects of the planned experiment. In addition, a new class of projects should be created, which are more focused on specific needs of industry. As the availability of Columbus and the ISS constitute an order of magnitude increase in use, this has also to be reflected in the envisaged budget for the corresponding projects.

Microgravity support to human exploration is essential and needs additional funding

Microgravity assisted materials science can substantially contribute to the Aurora programme by supporting the required materials development for future human space missions. This activity may become one of the future priorities of the present programme.

It is considered as a service to the Aurora programme and would consequently require funding from there. Critical topics in this regard are reliability/lifetime issues under space conditions and the design and development of new materials, such as:

• light-weight and high-strength structural materials

(crystalline, nanocrystalline, quasicrystalline, non-crystalline)
- energy-related materials (for heat exchangers, catalysts, liquid metal coolants, heat pipes)
- radiation resistant materials
- sensor materials.

Several options should be considered to achieve these tasks, for example, setting-up a Creative Materials Centre at ESA.

Critical technologies

One of the key ISS facilities under development is the Electromagnetic Levitation device (EML): The EML permits containerless melting and solidification of alloys and semiconductor samples, either in ultra-high vacuum or high-purity gaseous atmospheres. Furthermore, the EML is equipped with highly advanced diagnostic tools which permit accurate measurements of thermophysical properties, as well as direct observation of the experiment during flight by high-speed videography (see Figure 4.3.4.1). Its completion is critical for a number of top-priority materials science projects.

Another ISS facility in the field of materials research is the Materials Science Laboratory (MSL). The furnace inserts allow both directional and isothermal solidification experiments to be performed under microgravity conditions, without and with the application of a Rotating Magnetic Field (RMF) to induce fluid flow. Additional multiuser inserts, such as a diffusion furnace, should be developed. In addition the existing furnaces should be upgraded with regard to their maximum operating temperatures.

5. Commonalities and synergies

5.1 Commonalities

Reaping the investments on ISS and Columbus

ESA's ELIPS programme was started in 2002, following plans drawn up in response to scientific developments and after backward-, as well as forward-looking evaluations by the ESF in 2000 and 2004. ESA is to be commended for its support of user-driven research in space and the opportunities that have been given to European scientists and their international partners to achieve important goals in the disciplines of life sciences and physical sciences.

Over the years Europe has secured a position of excellence in these areas. In some areas Europe is even the only place where certain ISS-related research can be carried out.

Europe can now receive a substantial return on its investments in the International Space Station, and the era that began in February 2008 with the attachment of the Columbus orbital laboratory to the ISS, and then the successful docking of the ATV Jules Verne to the ISS, must significantly increase this return on investment.

Continuation of ELIPS

The ESSC-ESF thus considers that the ELIPS programme is essential for European research in life and physical sciences in space and fully supports ESA in proposing the ELIPS 3 programme at the next Ministerial Council.

The ELIPS programme must be continued through its Phase 3 at the funding level mandated by the fact that science utilisation and return will sharply increase, starting in 2008 with the Columbus laboratory attached to the ISS and in full operation. Optimum usage of Columbus within the ELIPS programme is mandatory. In order to achieve maximum output and return on investment the funding level has therefore to be raised accordingly.

It is believed that the full potential of ISS utilisation will not be exhausted by 2018, and the continuation of utilisation beyond that date would deliver a good return on investment. Specific investments will have to be made for a new generation of payloads (or new inserts into existing facilities) for the ISS.

On the other hand, preparatory steps have to be taken for the post-ISS era by looking into alternative payload carriers, ballistic flights and free-flying orbiters. Creative use of the ATV in this context is encouraged.

MAP projects

The initiative taken by ESA to call for, and to support, Topical Teams as well as MAP (Microgravity Application Promotion) projects is unanimously and enthusiastically backed by the scientific community. Topical Teams are considered to be very successful incubators for emerging and interdisciplinary topics, and to lay the ground for a network of European scientists working for the ELIPS programme. They are considered essential to help these emerging research topics reach a level of maturity required for a flight experiment or for an application-oriented project. The MAP projects are thus considered as a unique platform to perform in-depth research on complex phenomena, which requires the teaming of European experts.

The present form of the MAP projects should therefore be continued, meaning that these projects would have application-oriented, yet not solely industry-driven, strategic long-term objectives. As promotion is no longer an issue, the programme should be renamed, one suggestion being Microgravity Assisted Research (MAR).

Furthermore, Topical Teams as incubators for future research topics should be continued.

Coordination in ESA

The ELIPS programme has demonstrated its high scientific value and relevance to European research ambitions and its balance must be preserved.

Hence new programmes on solar system exploration should not be established at the expense of ISS utilisation and ELIPS.

Concern was expressed about the impact on the coordination of astrobiology science in ESA as a result of the movement of ExoMars and Mars Sample Return from the HME/HSF Directorate to the SCI/SRE Directorate. Liaison between ELIPS and Exploration programmes currently occurs predominantly at working level with varying levels of effectiveness, although clear scientific and technological synergies exist between ELIPS and the Exploration Core programme. The reorganisation between these two programmes, including transfer of key personnel, can alter this relationship.

The overall impression is one of limited integration between programmes at present. We thus specifically recommend that ESA should have a more specific strategy for coordination between programmes and stress the importance of seriously assessing the consequences of this transfer of programme components.

To maintain and foster the high international scientific reputation of the European astrobiology research, a strong coordination between these two directorates on ELIPS and the robotic exploration programme is thereby mandatory.

Education and outreach

ESA has contributed to the success of the ELIPS programme by fostering networking between interdisciplinary Topical Teams and by communicating the scientific results of research in space, for example through the Erasmus Experiment Archive, and through ESA's own website. However, although the recent years have seen some improvement in ESA's public relations activities, education and outreach are clearly areas where major efforts must be undertaken.

The workshop participants felt that education and training possibilities had not been developed to their full potential in the previous ELIPS programme. It was felt that a larger education component and budget should be a major objective of the next ELIPS programme. It is clear that the future supply of scientists and engineers of sufficient quality is essential to Europe's economic growth and to the future of ESA's strategy. A larger education budget would allow the ELIPS programme to achieve several objectives in training, outreach and education. The best way to achieve this would be to pay for dedicated educators at ESA who could work with the ELIPS programme.

Summer schools or workshops on various research topics covered by ELIPS could be initiated. ESA should reach an agreement about ECTS credits in these classes in collaboration with interested universities. By this means students could use that class to earn credits in regard to soft skills included in bachelor courses. Thus, students could become involved in space sciences early in their career.

Such a platform should also include an international exchange programme on the level of students, young scientists (including post-docs) and teachers.

It is also recommended to substantially develop Internet resources and particularly the website of ESA. A model in that domain remains NASA's numerous websites that offer dedicated resources tuned to various audiences, from specialist to school pupils. ESA's website should become a reference in Europe, also offering real-time coverage of Europe-specific space events through an 'ESA TV' accessible through internet.

5.2 Synergies

It is evident that many synergies exist between the various disciplines of the ELIPS programme. During and after the Sasbachwalden workshops several potential interdisciplinary areas were identified that cut across the traditional division of research and are of interest to two, three or four of these disciplines; for instance:

- Soft matter physics
- Cell bioreactors
- Fluid flow and phase transitions
- Radiation
- Biofluids
- Organism response to space environment.

These areas could help define a set of Orthogonal Cornerstones and provide an innovative approach to the structuring of the ELIPS Phase 3. Such interdisciplinary orthogonal cornerstones are displayed in Table 5.1.

Common scientific questions can be addressed by common technical approaches.

It is therefore recommended that the ELIPS programme should seek to foster cross-disciplinary activities in these domains. This might be achieved by common ELIPS workshops in science and technology to look at corresponding cross-cutting science and technology problems. Another way of dealing with these activities would be to set up Topical Teams in these areas.

Table 5.1: Orthogonal cornerstones

	Fundam. physics	Fluid physics	Materials science	Biology	Astrobiology	Physiology	Psychology
Soft matter							
Cell bioreactors							
Fluid flow, welding and phase transition							
Radiation							
Biofluids							
Organism response to space conditions							

6. Appendices

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* Note: As indicated in section 1.1, only a few experts in this domain attended the Sasbachwalden life sciences workshop and it was therefore deemed necessary to implement an additional consultation after the workshop to ensure that the community's viewpoints were adequately represented. That part was the work of Gro Mjeldheim Sandal, Bob Hockey and Dietrich Manzey, who also considered additional input from Gabriel de la Torre and Berna van Baarsen.

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6.4 List of acronyms

ACES	Atomic Clock Ensemble in Space
AFM	Atomic Force Microscope
ALTCRISS	Alteino Long Term Monitoring of Cosmic Rays on the ISS
ALTEA-SHIELD	Anomalous Long Term Efects in Atronauts' Central Nervous Systems
ALTEINO	precursor of the ALTEA project
AOs	Announcements of Opportunity
ARTEMIS	Antimatter Research Through the Earth Moon Ion Spectrometer
ASIM	Atmospheric Space Interactions Monitor
BASE-A	BioArray Software Environment
Biobox	facility enabling biological specimens to be cultivated in microgravity and preserved for postflight analysis
Biopack	complement to biobox
BIOPAN	space exposure platform
CAREX	FP7 Coordination Action - Research Activities on Life in Extreme Environments
CIMEX	Connective Interfacial Mass Experiment
CNT	Carbon nanotubes
COSPAR	Committee for Space Research
CZT	Cadmium Zinc Telluride
DELTA	Dutch Expedition for Life sciences, Technology and Atmospheric Research
DESC	Dutch USOC in Amsterdam
DFG	Deutsche Forschungsgemeinschaft, German Research Foundation
D-HSF	Directorate of Human Space Flight (ESA) (as of June 2008)
DLR	Deutsches Luft und Raumfahrt, Germany's space agency
D-SRE	Directorate of Science and Robotic Exploration (ESA) (as of June 2008)
DOBIES	Dosimetry for Biological Experiments In Space
DOSIS	Dosimetry activities in the Columbus module onboard the ISS
DOSTEL	Dosimetry telescope
EANA	European Exo/Astrobiology Network Association
ECTS	Educational Credit Transfer System
ELIPS	European Research in Life and Physical Sciences in Space
EMRC	European Medical Research Councils, ESF Standing Committee
EPB	European Polar Board, ESF Expert Committee
ERISTO	European Research in Space and Terrestrial Osteoporosis
ESA	European Space Agency

6. Appendices

ESF	European Science Foundation
ESSC	European Space Sciences Committee
EuTEF	European Technology Exposure Facility
EVA	Extra-Vehicular Activity
EXEMSI	Experimental campaign for the European Manned Space Infrastructure
EXPOSE	ESA's third facility dedicated to exobiology
FLOW	bone call response to mechanical stress conditions experiment
FLOWSPACE	bone cell response to mechanical stress conditions experiment
FRC	Facility Responsible Centre
Hamlet	project for integrated distance learning
HME	Human spaceflight, Microgravity and Exploration, ESA's Directorate (prior to June 2008)
HUBES	ground-based simulation of 135-day manned spaceflight
HUMEX	survivability/adaptation of humans to long-duration exploratory missions
IAA	International Academy of Astronautics
ICAPS	Interactions in Cosmic and Atmospheric Particle Systems
IMPACT	International Multiusers Plasma, Atmospheric and Cosmic Dust Laboratory
IMPF	International Microgravity Plasma Facility
IMPRESS	Intermetallic Material Processing in Relation to Earth & Space Solidification
ISEMSI	Isolation Study for the European Manned Space Infrastructure
ISLSWG	International Space Life Sciences Working Group
ISM	Instrument Service Module
ISS	International Space Station
KUBIK	transportable incubator for biology experiment processing
LEO	Low Earth Orbit
LESC	Life, Earth and Environmental Sciences, ESF Standing Committee
MAMBA	Motorised Ampoule Breaker Assembly
MAP	Microgravity Application Promotion
Matroshka	Measures radiation load on astronauts in long duration spaceflight
MB	Marine Board, ESF Expert Committee
MELiSSA	Micro-Ecological Life Support System Alternative
MESSAGE	Microbial Experiments in the Space Station About Gene Expression
MSR	Mars Sample Return mission
Mobilisatsia	Bacterial plasmid transfer under spaceflight conditions
MULTIGEN	Molecumar and plant physiological analyses of the microgravity effects on MultiGenerational studies of Arabidoposis thalania
NASA	National Aeronautics and Space Administration (US)
NEOs	Near-Earth Objects
NIZEMI	Slow rotating centrifuge microscope
PAHs	Polynuclear aromatic hydrocarbons
PESC	Physical and Engineering Sciences, ESF Standing Committee
PGM	Platinum Group Metals
PI	Principal Investigator
PKE	Plasma Krystall Experiment (also PKE-Nefedov, PK-3, PK-4)
PR	Public relations
RADIS	Radiation Distribution
RPM	Random Positioning Machines
SFINCSS	Simulated Flight of International Crew on a Space station
SORD	Systems & Operations Requirements Document
SPLITT	split-flow thin fractionation
STS	Space Transportation System (US Space Shuttle)
THM	Travelling Heater Method
USOC	Users Support & Operations Centre
WAICO	experiment to investigate the effect of gravity on plant root growth
ZARM	Zentrum für angewandte Raumfahrt technologie und Mikrogravitation

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