Review of UK Life and Physical Science Research using Space Facilities

An information report to the
Microgravity Review Panel

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1 Executive summary

This report is presented by the British National Space Centre for review by the Microgravity Review Panel appointed to consider the potential benefits to the UK of setting up a national programme of research using microgravity facilities. The Terms of Reference and the membership of this panel are included in Sections 2 and 3.

The UK has previously taken a small role in microgravity activities, but funding has been spasmodic making it difficult for researchers to take a long-term interest and build up a base of expertise and infrastructure to support their work. With the International Space Station now in orbit and carrying out research and with the new ESA microgravity research programme under way, it is important for the UK to decide whether it wishes to join its international partners in this type of research or not.

The report gives details of the areas of research that might benefit from such a programme, and considers the options for how such a programme could be set up.

The whole question of whether to fund such activities is made difficult by the large range of different disciplines that could benefit (each overseen by a different funding body), and the high cost of most of the facilities involved. There are useful parallels with the decision on whether to fund the Diamond facility.

The fact that most facilities are run as part of international space programmes requires the UK to decide at a national level whether to participate.

Issues that will need to be covered will include the expected value of the science that can be done using microgravity facilities, the value of the applications that may be developed, other benefits to UK industry (whether suppliers of instrumentation or companies who wish to exploit facilities), the value of collaborations between international researchers working in related fields (since most researchers will not be solely users of microgravity facilities), and the possibility of serendipitous discoveries and unforeseen developments that could enhance technology. Other issues such as the cultural value of involvement in international collaborations and the benefits for public engagement in science and technology and the resulting encouragement of young people into technical careers should not be overlooked.

Details on many of the scientific research areas are included without comment on their relative importance and options for the UK to participate in such activities are discussed.

The options can be summarised thus:

- join the ESA programme by paying a membership subscription;
- agree a bilateral arrangement with one of the partners in the International Space Station;
- use the facilities as a purely commercial user;
- continue as at present with uncoordinated funding of research;
- cease all funding of such activities.

In each case, it is worth considering whether existing UK research funds should be supplemented by a specific allocation to help set up a coordinated national programme of some kind.

Finally, should the panel recommend that the Government set up such a programme, it will be necessary to consider possible models of funding. These include seeking contributions from relevant funding sources (such as the Research Councils), seeking a separate line from within the existing Science Vote, or seeking new money from elsewhere in Government.

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3 Terms of reference of Review Panel

The Minister for Science, Lord Sainsbury, has requested advice from BNSC on the possible value of setting up a UK programme of life and physical science research using space facilities. This is prompted largely by the start of operations of the International Space Station and the setting up of the new European programme for life and physical sciences and applications utilising the International Space Station ('ELIPS'), although such a national programme would potentially use a range of space- and ground-based facilities.

BNSC has therefore asked an independent Review Panel to consider the case and to make recommendations by the end of November 2002 jointly to the Director General of BNSC and the Director General of the Research Councils.

These recommendations should address the following questions:

- Would a national programme in life and physical sciences in space represent value for money for the UK or not?
- If so, should such a programme require membership of the ESA ELIPS programme and at what level?
- Would the UK's interests be better served by some other arrangement (such as uncoordinated funding of individual experiments)?
- What level of funding would be appropriate and who should provide it?

The Review Panel will comprise a chairman and three other members with administrative support provided by BNSC.

4 Membership of Review Panel

Prof Bill Wakeham (Chairman), Vice-Chancellor of Southampton University and Chairman of BNSC Life and Physical Sciences Network Group

Sir Richard Sykes, Rector of Imperial College

Sir Peter Williams, Chairman of Engineering and Technology Board

Dr Steve Garwood, Director of Materials, Rolls Royce plc

5 Background

5.1 'Microgravity'

The term 'microgravity' strictly refers to the weightless conditions encountered in orbit where there are small perturbations caused by on-board activities, atmospheric drag, etc. In practice it tends to be used to describe facilities available for all types of study using weightless conditions (such as drop towers and parabolic flights) and also research which uses the same facilities but which makes no use of the weightless conditions (such as radiation exposure and earth observation).

Thus, for the purposes of this report, it is intended only as a short-hand to cover all research in the life and physical sciences using the ISS as well as other weightless facilities.

5.2 The current situation

Studies of life and physical sciences in space that exploit microgravity conditions have never been a high priority in comparison with other UK space activities. A review of this topic was carried out by SERC in 1989[1] and concluded that there was no strong case at that point for the UK to join the ESA microgravity programme. Also, during the 1980s, whilst many European countries were persuaded to join the USA in the planning and construction of the International Space Station (ISS), the UK declined. This was in keeping with the UK policy of "putting space to work", i.e. needing to identify clear scientific or commercial benefits from space activities before participating. Other European countries were more prepared to be swayed by political and cultural considerations. Having joined the Space Station programme, it became imperative for those countries to maintain a community that might exploit the Station when it reached its routine operations stage. Hence, those countries that joined the programme were also strong supporters of the ESA Microgravity Research programmes.

BNSC/DTI contributed a low level of subscription to the first ESA Microgravity Research programme, EMIR-1 but decided not to contribute to EMIR-2. Subsequently BNSC/DTI decided to join, at a low level, the EMIR-2 Extension Programme with the specific objective of opening opportunities for UK researchers to enable an assessment to be made in about 2002/3 of the prospects for UK activities in this field.

Now that the ISS is nearing the end of its construction phase and is becoming available for research and commercial activities, and 2 years after joining the EMIR-2 Extension Programme it is appropriate for the UK to consider again its approach to life and physical sciences in space.

5.3 Other space research

The UK is a founder member of the European Space Agency (ESA) and conducts the vast majority of its space research through participation in the ESA programmes. These are divided into two types: mandatory and optional. The mandatory programmes are the Science Programme and the General Budget. The UK also chooses to take part in most of the optional programmes.

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[1] 'Prospects for British participation in microgravity research', Prof Sir Brian Pippard FRS. See Appendix 3 for summary and comments.

Subscriptions to mandatory programmes are calculated in proportion to the GNP of each member state. The UK's GNP share is currently 17% of the total. For optional programmes member states may choose their level of subscription, but this may not be below 25% of their GNP share[2].

A breakdown of the amounts subscribed by the UK to the various ESA programmes is given in Table 1. The figures are quoted for 2001 (the latest complete ESA fiscal year) and are thus a snapshot only, but they give a good indication of the relative amounts contributed by the UK to the total ESA budget under the various headings. (Note that in 2001 the UK's GNP share was 14%.)

Programme	**Total ESA budget (€M)**	**UK subscription (€M)**	**Proportion subscribed by UK**
LAUNCHERS	479.3	0.24	0.05%
TELECOMMUNICATIONS	134.7	8.0	5.9%
NAVIGATION	74.7	10.4	13.9%
EARTH OBSERVATION	197.6	32.3	16.4%
MANNED SPACE & MICROGRAVITY	575.1	0.5	0.08%
TECHNOLOGY	77.5	4.6	5.9%
SCIENCE	361.6	51.0	14.1%
OTHER	237.0	27.2	11.5%
TOTAL	**2137.5**	**134.2**	**6.3%**

Table 1. Total ESA budget and UK contributions for 2001 by programme.

The subscription to the Science Programme is covered by PPARC, who are also the funding authority for the UK researchers who participate in the projects. The Science Programme funds the cost of the spacecraft and the management of the missions, whilst the national funding authorities (PPARC for the UK) pay for the cost of the instruments.

The PPARC activity is in line with its remit to promote high-quality (world-class) research in astronomy and planetary science. The PPARC programme uses both ground-based and space-based techniques, the choice of technique being assessed in terms of science return for the level of investment. In practice, space-based techniques tend to be chosen when science objectives can

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[2] Strictly, it is possible to subscribe below 25% of the GNP share so long as there is unanimous support from all participating states. However, most states are unhappy about such deals and Germany has explicitly stated that it will veto them in the future.

be achieved only through in-situ measurements or observations are necessary at wavelengths that do not penetrate the Earth's atmosphere.

Earth observation uses the unique elevation and mapping characteristics of spacecraft to make observations of importance in global studies of the earth's surface and its atmosphere. In addition to the research benefits, there is again some spin off into ground-based technology resulting from improvements in instrumental techniques. The subscriptions to ESA's optional programmes in this area are shared between NERC (for science programmes) and DTI (for applications programmes).

In microgravity the UK is currently a very low level participant in the EMIR-2X programme, which is a precursor to ESA's European Life and Physical Sciences research programme (ELIPS). This enables the UK to participate in the appropriate forums, which are formulating the overall scope and content of this programme. This will terminate within the next 12 months, at which point non-ELIPS-subscribing member states will be barred from such activities and receipt of results and data, effectively isolating them from the rest of the community. In the mean time, the low level of the UK's subscription to EMIR-2X has made other member states suspicious that we may be trying to gain benefit from these programmes without appropriate commitment.

The ELIPS programme is a 5-year rolling programme which started in January 2002. Thus far 12 of the 15 ESA member states have signed up (UK, Portugal and Finland are the exceptions). As with space science and earth observation activities, a central subscription would be needed with UK experiment costs funded through the Research Councils' normal channels. The other participating member states have differing reasons for funding work in microgravity. These include strategic support for the science, interest in technical applications, industrial considerations, and a combination of cultural and philosophical reasons. (For further details of the views of other ESA Members States, see Appendix 4.)

BNSC has indicated to ESA that it expects to have a judgement regarding ELIPS membership from Lord Sainsbury around the end of 2002 following the completion of this review.

Thus the UK can only proceed on the basis of a philosophical belief that some 10 years into the future work initiated now will form the basis for solid investment and progress in many fields.

5.4 Previous reviews in the UK

The Pippard Report (1989)[3] was written by Professor Sir Brian Pippard on behalf of the SERC. This review was set up to investigate the prospects for British participation in microgravity research and concluded that such research was in its infancy and that it would be hard to justify spending significant sums of money so far in advance of the completion of the ISS. However it also concluded that there was value in measurements of physical properties (such as diffusion coefficients) and in protein crystallisation activities. In retrospect it has turned out that protein crystallisation in space has yet to achieve its anticipated success (though some very good work has been done) – but many other areas have turned out to be much more useful. Pippard dismissed the prospect of industrial manufacture of semiconductors and pharmaceuticals in space as poor. This has turned out to be a correct analysis and indeed the over-emphasis on the concept

[3] 'Prospects for British participation in microgravity research', Prof Sir Brian Pippard FRS. See Appendix 3 for summary and comments.

of a 'factory in space' in the early days has done a great deal to undermine the credibility of the ISS as a serious laboratory.

Guest Associates produced a report "The potential impact of space-based R&D on the competitiveness of the UK pharmaceutical industry" for BNSC in 1996. Its optimistic conclusions have not however been borne out by the subsequent response of that sector.

In 1999 a conference, 'Futures in UK Space Biomedical Research', was held at UCL with the support of the British National Space Centre. The aim of this conference was to evaluate the potential for the establishment of a UK-based effort in space biomedical research. The resulting strategy has led to the setting up of national and international steering groups, the creation of undergraduate and postgraduate training courses and the establishment of the Centre for Aviation, Space and Extreme environment medicine.

In August 2002 MRC and BNSC jointly organised a workshop *'Space for health or health for space?'* to look at the possible benefits to ground-based medicine in the fields of muscle, bone, cardiovascular and neurovestibular research. This was attended by UK researchers (both those with and without space experience) and by some key figures from US and European research groups. Copies of the presentations from this workshop may be examined on the web site http://www.microgravity.ac.uk/. This captured only a selection of the spectrum of disciplines related to space biomedical research.

An independent panel met to consider the presentations and found that researchers were not well connected with each other or with the broader academic community. They felt that the microgravity facilities available were probably not especially good for pathophysiology and that large amounts of money would be needed to make an impact. However they also felt that some interesting possibilities exist and they were interested in bilateral arrangements with ESA and NASA. They were also keen to see better linkage between UK researchers and their international counterparts. (A summary of their findings can be seen on the UK microgravity web site at http://www.microgravity.ac.uk/MRC Workshop/Report.pdf.) Meetings are now planned between the Chief Executive of MRC and representatives of NASA and of ESA before the end of the year to investigate the possibilities for collaboration.

5.5 Present status of activities in the UK

When the ESA EMIR-1 and -2 series of programmes were coming to an end, the UK had to consider whether to join the EMIR-2 Extension programme. The UK, mainly because of the evolution of the ISS programme towards routine operations, decided to participate in EMIR-2 Extension and also to strengthen the networking of the UK community and the potential funding organizations and to increase the flow of information to those organizations. This was done by setting up the Life and Physical Sciences Network Group, previous to which there was a noticeable lack of awareness of the possibilities within the Research Councils.

In contrast, Research Council-funded astronomy, space science and earth observation has a long and successful history in the UK. For these areas of research that use expensive orbital facilities there is no choice but to participate in international programmes. Researchers in these fields have become adept at securing selection following international Announcements of Opportunity and then bidding for national funding. In most cases this is their only route.

This is not the case for those researchers who wish to use microgravity facilities to supplement their ground-based research - for them this two-stage approach is unfamiliar. And they have the added disadvantage that they have had no reassurance that they would gain access to them since the UK has not subscribed to these programmes consistently – so even if they secured participation in one collaboration, they would have no guarantee of being able to continue with any future developments.

Despite the lack of allocated funding, UK researchers have demonstrated great interest and achieved considerable success in proposals submitted to international programmes in microgravity. Three International Announcements of Opportunity have been made in the field of microgravity so far. These have resulted in proposals from 102 UK researchers from 33 universities, 5 research institutes and 13 industrial companies (details are included in Appendix 5). The proposals cover research in fields represented by each of the Research Councils (except ESRC). Lack of national funding has prevented many of these researchers from taking a significant role in these collaborations, despite many receiving very high ratings from international peer review committees. Some five projects with UK involvement have nevertheless been funded (one with funding from BBSRC, one with DTI funding and the rest using university or private funds to match the ESA funding), but these will not continue beyond their first phase unless the UK joins the ELIPS programme.

UK researchers also play a major role in ESA's 'Topical Teams'. These teams of independent scientists are supported by ESA to assess which problems in a wide range of targeted areas of science and technology would benefit from research using microgravity techniques. They are the prime tool for setting the future direction of the ESA programme. Of 33 teams in total, there are 19 with UK membership.

5.6 What is special about space facilities?

All objects on the surface of the earth are subject to the force of gravity. For some objects, a simulation of the absence of gravity may be obtained by flotation – and indeed this is used for some types of medical experimentation – or by randomly varying the direction of the gravitational vector. However, it has become evident that the effects of gravity are more widespread than was previously realised.

For example, individual plant cells seem to be sensitive to gravity and physiological processes in humans respond to the lack of gravity in unpredicted ways. Complex fluid flow is hard to model, with many important effects masked by gravitational forces and preventing the study of processes such as crystal formation in molten metals.

Space facilities also offer features other than weightlessness. The availability of crew on the ISS will allow intelligent intervention in experiments as well as the opportunity to study human subjects; the unique radiation environment will allow the study of effects on biological samples in extreme environments.

In general, in studying any physical process, it is useful to be able to alter the parameters which influence it – such as temperature or pressure. Until recently it has not been possible to remove the effect of gravity for more than a very short period of time and so the behaviour of systems depending on fluid flow have not been fully explored.

Further details of these research issues are discussed the next section.

Of course the space environment creates special demands on experimenters. The high cost of launching hardware into space requires that instruments be small and light. The difficulty of maintenance requires that they be reliable. The cost of crew time requires them to be simple to operate. And the closed environment requires them to be safe to run and benign if they fail. This combination of factors has led to many advances in technology which are the basis of commercial spin out as well as enforcing a rigorous approach to design techniques and product assurance.

And space has always held a special fascination for the public. Anyone who has talked to school children about technical or scientific matters will confirm that the largest number of questions are asked about the space aspects of a project. The power of this work to attract children into the study of science and technology cannot be over-estimated.

5.7 Facilities available

There is now a range of facilities available to create a period of free fall and thus give the same physical effect as zero gravity. The simplest is the drop tower – an evacuated shaft sufficiently tall to give several seconds of weightlessness. Some valuable experiments can be conducted in these conditions (such as small combustion experiments). For longer periods an aircraft may be used to fly in a parabolic trajectory, giving periods of around 20 seconds of weightless conditions, alternating with periods of increased gravity. This can be used for a larger range of experiments, though of course this alternating gravity is not suitable for sensitive or longer-term experiments.

Periods of several minutes can be achieved with sounding rockets (typically up to around 10 minutes in total). The series of rocket flights supported by ESA has carried out many worthwhile experiments over many years and continues today under the EMIR-2X and ELIPS programmes.

To achieve periods of several days to weeks, it is necessary to reach orbit – using a platform such as the Russian Foton capsule or the US Shuttle. And for longer periods, an orbiting platform is required – and since the demise of MIR, the only such platform has been the ISS. Typical experiment times may be measured in months.

Of course the above facilities are on a scale of increasing cost, with the cost of a kilogramme raised to the orbit of the ISS being quoted in the region of $30k. Clearly it is vital to do thorough ground preparation and there are many ground-based facilities across Europe and elsewhere which are designed to help in this task.

It is worth noting that about 60% of ESA microgravity activities are ground based. These are studies and experimentation in processes to gain an effective understanding prior to formulation of mature proposals for flight experiments.

Not all experiments require the use of the ISS, but since the various facilities described above are generally counted as part of international space programmes, they are run and financed through space programmes and access to them generally requires membership of the relevant programmes. The ESA ELIPS programme is the source of finance for such facilities in Europe.

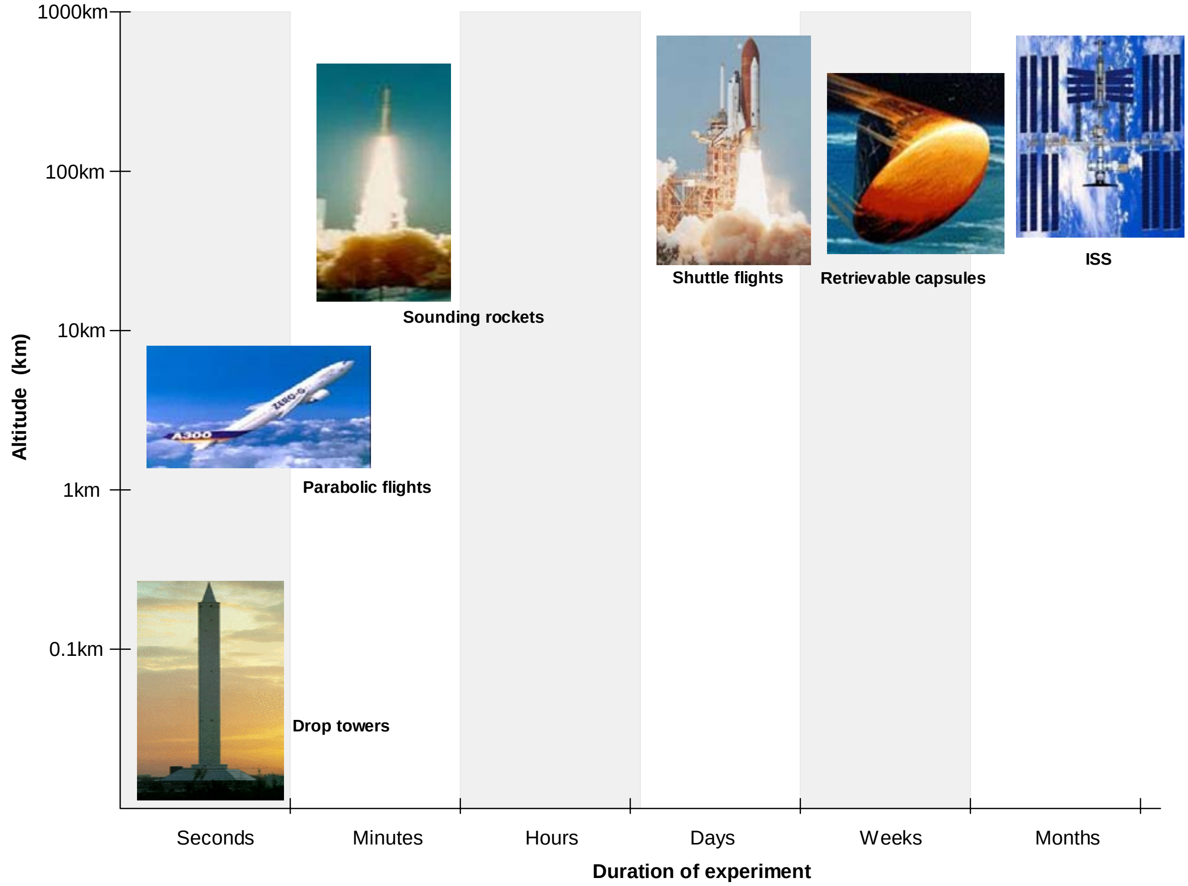

Fig. 1. Facilities available for microgravity research through the ELIPS programme

6 Scientific challenges

Microgravity facilities have the potential to help research in many unrelated areas. These can be conveniently divided into six disciplines following the categories defined in ESA's ELIPS programme.

Note that details of many of the UK proposals for work in these areas are given on the microgravity web site, http://www.microgravity.org.uk/.

6.1 Fundamental physics

6.1.1 Complex and dusty plasmas

Complex plasmas are important because they are expected to give an insight into the fundamental physics of condensed matter – including homogeneous, inhomogeneous and anisotropic systems.

The phenomenon of 'plasma condensation' was discovered in 1994. This term refers to strongly-coupled complex plasmas which adopt a liquid or crystalline state. A strongly-coupled plasma is one in which the Coulomb potential between neighbouring particles is much greater than their thermal energy. Complex plasmas are normal electron-ion plasmas to which have been added micron-sized particles. These particles have masses some 10^{11} times that of the plasma ions and they attract several thousand electron charges. This slows their movement down by a factor of some 10^5 and increases the separation of the particles to around 0.1 mm, making their behaviour easy to study using conventional microscopy.

Thus complex plasmas exhibit many of the same properties as solids and liquids, but on a scale large enough to study the molecular behaviour which gives rise to these properties.

In the ground-based laboratory the microparticles have to be supported electrostatically. The force required has a profound effect on the liquid flow properties and crystal structures (limiting crystals to around 20 layers). However in microgravity conditions it is possible to create three-dimensional systems free of bulk forces.

The International Microgravity Plasma Facility is being developed in Europe to fly on the ISS in order to study a range of fundamental properties of matter. These include:

- Plasma physics at the kinetic level
- Phase transitions
- Waves, shocks and global modes
- Surface physics at the kinetic level
- Interfaces, shear, friction
- Transitions from atoms to solids

6.1.2 Cold atoms and quantum fluids

Cold atom clocks in space can attain accuracy levels unreachable on earth. This could lead to huge improvements in navigation and GPS systems.

In 1925 Einstein predicted that a gas made up of identical particles, cooled to a low temperature and at sufficient density, would condense into its lowest energy state with zero velocity. Atoms in these so-called ‘Bose-Einstein condensates’ all occupy the same quantum state and have very peculiar quantum properties that are being investigated by some 50 groups in the world. For example, the coherence of the atoms is analogous to that of a laser beam and has allowed the creation of the ‘atom laser’. The problem is that as soon as such particles are released from the magnetic trap in which they are contained, they are accelerated by gravity from their typical speed of around 30 μm/s to 1 m/s in a tenth of a second. This makes it difficult to study their behaviour over any significant period. Experiments in microgravity will investigate these phenomena and may be able to test quantum theories of gravitation in an attempt to resolve the apparent conflict between general relativity and quantum mechanics.

By slowing atoms down in atomic clocks it is possible to increase the accuracy of measurement of time by a large amount. The stability of the atomic clock under development in Europe for flight on the ISS will be some three orders of magnitude better than those currently flying on GPS satellites. In addition to improving the accuracy of the time standard, this will allow more accurate tests of fundamental physical parameters such as the gravitational red-shift and possible drift in the fine structure constant.

6.2 Fluid and combustion physics

6.2.1 Structure and dynamics of fluids and multi-phase systems

The key reason for studying fluid physics in microgravity conditions is to investigate surface effects. On earth, fluids are generally bound by solid surfaces or dominated by the body force. As a result, many surface effects are not properly understood and the equations used to describe them have not been tested. This includes ‘Marangoni convection’ which can drive fluid flow by surface tension effects along the interface between two immiscible fluids, but is generally neglected on earth as it is too difficult to quantify.

When liquids and vapours are forced to circulate together in a pipe, the resulting two-phase flow can adopt a wide range of complex regimes. The different densities of the two phases means that gravity will have a large influence on the regime and hence on the flow rate. The physics of multi-phase flows is not well understood and the removal of the effect of gravity will allow a greater understanding of some of these complex properties. Such an understanding is crucial to the design of heat exchangers, chemical reactors, distillation columns and oil and gas pipelines.

The critical point of a substance is the temperature at which all distinction between the liquid and gas phases disappears (for example 375°C and 225 bar for water, 33 K and 13 bar for hydrogen). At this point the fluid will become infinitely compressible and thus gravity will cause the fluid to compress under its own weight causing the fluid to stratify. Thus any ground-based study will measure properties averaged over different conditions rather than those at the critical point. Microgravity research will help to provide a fundamental understanding of behaviour at the critical point where conductivity and heat capacity are infinite, large-scale density fluctuations occur and the fluid becomes opalescent. Such an understanding will also be of benefit to applications in the food, waste management and energy industries.

The effects of capillary forces in fluids are generally masked on the ground by bulk forces, except in systems with very small dimensions. In the absence of gravity the surface effects dominate and so the structure of bubbles, droplets and foams is determined entirely by surface tension and boundary conditions. This allows the study of those effects and should lead to a better understanding of the behaviour of foams and emulsions.

6.2.2 Combustion

The buoyancy caused by changes in density as fuel is burnt in flames will clearly be missing in weightless conditions. Thus microgravity experiments allow the measurement of true flammability limits for fuel/air mixtures which on earth are found to vary with the direction of the gravity vector. The processes controlling the behaviour of diffusion flames (in which the fuel and oxidiser are unmixed) are poorly understood. Microgravity provides an environment in which these processes can be observed without the disturbing effect of convection and hence should help to improve the accuracy of simulations which currently depend on semi-empirical methods.

Microgravity is also a valuable tool for investigating the behaviour of the combustion of droplets and particulates – another area lacking good data due to the difficulty of observing the ignition of fuel particles in a spray.

Since most combustion processes are relatively rapid, many experiments can be conducted using drop towers rather than space platforms.

6.3 Material sciences

6.3.1 Thermophysical properties

Molten metals tend to react with their containers, so the best measurements of thermophysical properties are achieved using containerless levitation techniques. Unfortunately the magnetic fields required to resist the force of gravity have a considerable influence on the accuracy of the results. Similar techniques used in space offer the promise of much greater accuracy due to the smaller forces required. Many key properties of steels and other alloys are only known to little better than a factor of two, reducing the value of the theoretical simulation of smelting and casting processes.

6.3.2 New materials and processes

By eliminating gravity-induced effects, information about new materials and processes can be gained from experiments in space. For example our understanding of crystal growth and solidification of metals, inorganic and organic materials, and biological macromolecules would benefit from microgravity-based research.

For example, the formation of columnar dendritic and equiaxed grain structures in casting processes on the ground is disrupted by sedimentation. Experiments in microgravity should improve the fundamental understanding of this process.

By undercooling molten metals it is possible to create amorphous or ‘glassy’ structures. These can have roughly double the strength of the conventional crystalline versions – more akin to the strength of a ceramic, but without the problem of brittleness. Microgravity conditions allow the temperature of the melt to be controlled more accurately and the effect of convection can be removed, giving a greatly improved facility for studying the parameters controlling the formation of these new materials.

The processes involved in the production of other new materials such as metal foams, can be studied more easily in microgravity since gravity causes such foams to drain, preventing control over the liquid fraction (or ‘wetness’), bubble size and uniformity over the sample.

6.4 Biology

6.4.1 Biotechnology

The use of microencapsulation is widespread in industry. This technique is used to immobilise various biocatalysts in a thin polymer shell – for example in continuous fermentation processes. Drugs may be encapsulated, allowing staged delivery of doses as the encapsulation breaks down in the body. One of the most exciting new developments is the encapsulation of endocrine cells for the treatment of diabetes. In this case the cells are encapsulated to protect them from rejection whilst allowing the transport of chemicals through the encapsulating membrane.

In order to manufacture these microcapsules it is necessary to stir the suspension to avoid sedimentation. This makes it impossible to observe the microcapsules during their formation and the convection produced is also known to have a strong effect on the resulting structures. Microgravity conditions will allow the various parameters controlling the process to be separated and hence improve the techniques for manufacture on the ground. The ESA Topical Team charged with considering the needs for research in this area is led by the UK.[4]

Cell differentiation also seems to be strongly affected by gravitational effects, and sedimentation makes it hard to culture three-dimensional tissues on the ground. NASA has achieved considerable success, however, in the culture of cartilage and tumour cells in rotating-wall vessels developed to mimic microgravity conditions. However, this is not well-suited to the growth of more complex tissues for which microgravity is expected to be a better environment, allowing the study of the metabolic control of growth and differentiation in order to improve the growth of artificial organs on the earth.

6.4.2 Plant physiology and cell biology

Despite over a century of research into the mechanisms by which plants respond to gravity, some important details remain uncertain. For example, the cells of root tips contain tiny organelles (called statoliths) that sediment under the influence of gravity and have been generally accepted as the site of gravity perception in roots. However, tests have shown that it is not necessary for the statoliths to move in order for the plant to respond to gravity, suggesting that there may be other mechanisms at work. Microgravity offers an opportunity to investigate this controversy.

However, of possibly greater significance is the opportunity to ‘switch’ gravity on and off and hence to study the mechanism of signalling pathways in plant cells. This is of fundamental significance to an understanding of plant physiology as there are no other signals that can be removed completely in this way. Such studies should also shed light on the role of genes in the perception of gravity and the transduction of signals in plants.

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[4] Prof Tony Whateley, Strathclyde University.

6.5 Physiology

6.5.1 Bone and muscle

Since gravitational loading is one of the principle stimuli governing the structure and function of both bone and muscle, its absence allows researchers to observe unique properties of these systems.

The effect of gravitational unloading on the musculoskeletal system, observed both during space flight and in bed rest studies, has parallels with terrestrial disease processes. This has enabled researchers to investigate elements of the poorly understood cell signal transduction pathways that underpin diseases responsible for significant morbidity and mortality in the general community, such as osteoporosis.

Microgravity appears to influence the structure and function of bone and muscle at the molecular level. Genetic influences in the response of these systems to exercise are already under investigation. Microgravity and bed rest studies, available through the space programme, allow the behaviour of bone and muscle to be studied from the opposite end of the spectrum, under conditions of inactivity, providing valuable new data which may help to elucidate the role of genetics in the remodelling of these tissues. These studies should contribute to a greater understanding of the fundamental mechanisms underlying bone and muscle physiology as well as yielding new therapeutic techniques.

6.5.2 Neurovestibular

Sensorimotor integration at the level of neurovestibular function is a gravity-dependent function. The uncoupling of gravity from this system has improved our understanding and has led to the revision of existing theories.

The concept of neuroplasticity is central to the understanding of rehabilitation following neurological injury. The most significant clinical examples of this are the recovery of motor and sensory function following stroke and spinal cord injury. In addition neurovestibular dysfunction plays a central role in the aetiology of falls in the elderly. This, combined with osteoporosis, is a leading risk factor for hip fracture in the elderly population, from which the overall mortality is around 50% within one year.

Thus the control of balance is of central interest to investigators both in the UK and internationally and has many clinical implications. Microgravity is the only environment in which investigators can uncouple gravitational influences from the neurovestibular system and observe the results of this perturbation. At present, although teams in the UK are researching the mechanisms underlying the control of balance, there are no microgravity related efforts in this field. The UK community's understanding of microgravity research in this field must be developed further before its potential can be appropriately assessed.

6.5.3 Cardiovascular

Autonomic function, the system of automatic control governing the heart and blood vessels, is a complex physiological phenomenon that is at present poorly understood. Observations of the post-flight response of the cardiovascular system have yielded new insight and led to the refinement of existing models.

Autonomic dysfunction is a significant cause of morbidity and mortality in the general community. Disturbances of this system can lead to a variety of medical consequences ranging from faints and falls in the elderly to fatal cardiac arrhythmias in young people.

Space flight is associated with significant disturbances of cardiovascular and autonomic function and studies of this phenomenon have generated new hypotheses. This has led to a refinement of existing models of cardiovascular function with specific reference to the 'gold standard' Guyton Model of Cardiovascular Physiology. This has had a fundamental impact on our understanding of the heart in both health and disease.

In addition, techniques developed to assist in the investigation of cardiovascular phenomena and rhythm disturbance in space flight have proved useful in the terrestrial setting. These new techniques in near patient monitoring have been developed for use in everyday healthcare and are currently the subject of a commercial development project.

6.6 Astro/exobiology and planetary exploration

6.6.1 Origin, evolution and distribution of life

In order to consider the possibility that life originated outside the earth, it is important to gauge the ability of organisms to survive under the extreme conditions that exist in space, and in simulated planetary environments. It is important to understand whether any organisms are capable of surviving such factors as extreme temperatures and large doses of radiation that are present in certain environments outside earth's atmosphere. These environments can be investigated by the use of samples mounted on the outside of space vehicles, especially during long periods in orbit and during re-entry.

This is a significant area of research in the UK and a well-connected community exists. A report on UK interests is available.[5]

6.6.2 Preparation for human planetary exploration

As manned expeditions to other planets become possible, it will be necessary to quantify the effects of radiation doses and investigate the impact of isolation in a high-stress environment on humans. In addition, developing the scientific knowledge base for identification and utilisation of in-situ resources as well as developing life support systems will be crucial if plans for interplanetary travel are to be realised. Note however that these areas are not considered to be a high priority in the UK.

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[5] 'Astrobiology in the UK' (1999). See Appendix 1.

7 Other opportunities

7.1 Industrial opportunities

There are four main types of opportunity open to industry. These can be summarised thus:

1. Factories in space. A concept much-heralded in the early days, but that is unlikely to be an option for the foreseeable future due to the high costs of access to space.

2. Spin-offs. This covers the improvement of industrial processes and the development of commercial products as a result of work done to support activities in space. For example the Danish heart monitor developed for space and now marketed for use in European hospitals.

3. Applications. This covers industrial activities developed or improved by the use of research carried out in space for the purpose. This would include, for example, drugs developed using knowledge gained from protein crystallisation in space.

4. Direct contracts. Money contributed in subscriptions to ESA programmes is spent largely in European industry. The rules for the ELIPS programme would result in 2/3 of any UK subscription being spent on contracts with UK firms.

The initial concept for the Space Station included projected support from commercial users. This has not materialised due to the high costs involved and the significant period of time (of the order of more than 5 years), which must elapse before results could show any commercial return.

Two relevant activities have been commissioned by Space Agencies in recent times.

1. '*Commerce and the International Space Station'* - a report to NASA and Congress conducted by KPMG.

2. Three '*Strategic Marketing Study*' reports commissioned by ESA (presented at a meeting at Noordwijk in May 2000) and carried out by:

   a) Battelle ITM

   b) Cranfield Management Institute

   c) ACCESS-MATRIX

The common overall conclusion from these independently-conducted studies is that the tangible commercial returns in the field of microgravity are far from becoming mature. They forecast that the need over the next 5 –10 years is for state-sponsored basic research to establish a background from which a partnership between industry and government can proceed to demonstrate potential, and then for a similar further period before genuine commercially-sponsored R & D will be attainable. That is of course a general overview and there is hope that exceptions arise to pioneer an earlier way.

To stimulate this, NASA and ESA have both announced the objective of reserving 30% of their respective share of the Station's capacity for commercial interests. ESA have gone further and offered funding assistance to suitable applications, with NASA additionally exploring state/private profit-sharing approaches.

Rules are in place to protect the commercial IPR of any company conducting work on the ISS, so it is altogether possible that successful work would not become visible to the public until a safe point of market interest has been reached.

Although much is claimed regarding industrial support for current research programmes an investigation shows that this is mainly at a token level, or at best an "in-kind" level which can be contained by a company within its general laboratory work.

However some work with potential commercial application is known to have been conducted or is in preparation:

- Interferon separation
- Cast iron solidification parameters
- Manufacture of precision micro-spheres
- Liver cell function
- Protein crystallisation
- Not specifically a user of the ISS for micro-gravity purposes, a €100M external facility RAPID-EYE is to be mounted externally on the Columbus module to provide a quick-reaction commercial Earth observation service.

Over the past decade the capability of French, German, Italian and Spanish industries has seen expansion in the design and production of orbital modules and systems together with advanced instrumentation. In this period UK industrial interests have been limited by lack of government support in European programmes. Two examples of work where its expertise has been sought (Brunel University with its design of glove box, flown on the Shuttle, but where further development has now been passed to the Netherlands and Germany and a €10M 2.5 ton cryo-magnet being developed at Culham on a Swiss sub-contract, which caused protests from committed European contributing sources). Neither will progress in the UK in the future without government commitment.

With the opportunities for the design and construction of major facilities now securely tied to the major players, if the UK chose to enter the ELIPS programme, realistic ambitions for industry will probably be limited to contracts (based on *juste retour* of the UK subscription) involving SMEs. Specifically ESA advise that they see the best opportunity for the UK to be with those SMEs who demonstrate links to scientific interests, notably those where university spin-out companies are involved. This however could well be the prime source for future industrial stimulation as ideas are carried forward.

7.2 Public engagement in science

The falling number of students choosing to study science and technology subjects at university is a matter of widespread and growing concern in UK industry. Subjects which involve space research are effective at generating interest in young people. An interesting comparison can be made with astronomy – many universities have added astrophysics to their physics courses as they find this increases the number of applicants (and of course the majority of these do not necessarily go on to become astrophysicists, but instead add to the number of educated scientists available to industry and commerce). Likewise, one incidental advantage of a UK microgravity research programme would be the opportunity to generate more interest in science and technology generally and among the young in particular.

Indeed there is now a growing programme of undergraduate modules available at UCL in space biomedicine (the intake for 2002 is 36 students, attracting a high academic standard). This is expanding into a research programme and there are plans for a post-graduate course. A Centre for Aviation, Space and Extreme Environment Medicine has been set up under the guidance of the Space Biomedical Advisory Group with the involvement of Kings College, Imperial College and UCL to coordinate the teaching and research activities of these three centres.

Additionally, two self-motivated and self-supported university student groups have followed up their 2001 ESA parabolic flight experiment experiences and successfully proposed experiments to fly on the Russian Foton 15-day flight in October 2002. The York team are to fly some 120 small samples of a range of saturated protein solutions in a crystallisation experiment, and a similar team from Edinburgh are to fly a microbacterial solution to study proto-planetary atmosphere creation.

7.3 Culture

Although impossible to assign a monetary value, it is worth considering the cultural value of participation in microgravity programmes. On the world stage there is some surprise that the UK has remained out of such programmes since many countries are involved for largely cultural reasons. As with other areas of pure science, the value of curiosity-driven research cannot be quantified except in retrospect since it is impossible to predict what discoveries may be made or what impact they will have.

8 Options for the UK

The high cost of most space activities means that few nations can afford to work alone. The UK has been a member of ESA since its formation and carries out most of its space research through collaboration in ESA programmes, though it does also have some bilateral arrangements with other nations such as Japan and the USA.

If the UK were to set up a national programme supporting research in microgravity, the most obvious route would therefore be to join the ESA programme.

However there are various alternatives to consider: collaboration with NASA instead of ESA; collaboration with one of the other ISS partners (Russia, Canada or Japan); use of facilities on an *ad hoc* commercial basis (either through ESA or through a commercial company). These options are summarised below and further detail is given in Appendix 7.

Note that some options are dependent on membership of the ESA programme and others are not. It would therefore be possible to select more than one - however, the under-developed state of UK research in this area would make it hard to justify at this stage.

8.1 Join ESA programme (ELIPS)

Summary – Join programme for remainder of the first five-year phase (started January 2002) and at minimum permissible level.

Benefits – Access for UK researchers to European collaborations and all facilities (both European and other), influence in content, management and strategy of ESA programme, return of 2/3 of subscription in contracts to UK industry.

Costs – €13.8M over remaining 4 years, plus UK research costs funded by RCs out of existing budgets and in competition with other peer-reviewed funding requests.

Problems – Cost, late joining reduces influence of UK in defining programme.

8.2 Collaborate with NASA

This is only an option if we are already member of the ESA programme since the US does not wish to enter into bilateral agreements outside the Intergovernmental Agreement on the ISS. If we were to join ELIPS, collaboration with the US would be possible without recourse to further agreements.

8.3 Collaborate with other US organisations (e.g. NSBRI)

Summary – It would be possible for individual UK institutes to make their own arrangements with other US organisations.

Benefits – No need to join ELIPS or form international agreements, UK could select specific areas of research, no need for central funding.

Costs – Unknown.

Problems – No strategic overview of UK microgravity interests for planning or synergy, no influence in planning of international research or facilities, no sight of planning processes, flight opportunities limited to collaborations with organisations keen to involve UK researchers, no automatic right of access to facilities or results (other ISS members may veto UK participation or receipt of results).

8.4 Collaborate with other ISS Partner nations (e.g. Canada, Russia)

Summary – Negotiate bilateral agreement with Canada, Russia or Japan.

Benefits – Possibility of negotiating different deal; may be more selective than joining ELIPS (only pay for topics of interest).

Costs – Unknown, but likely to be similar to that with US.

Problems – Cuts across UK policy of working with Europe, would require UK to handle management aspects provided through ESA programme, likely to encounter same reluctance to by-pass international subscription as found with NASA and therefore be denied this option.

8.5 Use facilities on commercial basis

Summary – Individual research groups are free to make use of the ISS by paying for their usage directly, either through one of the ISS Partners or one of their commercial agents. Similarly, most of the other microgravity facilities could be hired commercially from their operators.

Benefits – No need to join ELIPS, judge merits of each project separately and only pay for topics of interest.

Costs – Unknown (depends on level of support from funding authorities).

Problems – No strategic overview, no opportunity of working in collaborations (as most collaborating researchers belong to member states and will avoid the complexity of working with a non-member using different route), no return of fees to UK industry.

8.6 Do nothing

Summary – If no central funds are allocated to international subscriptions, researchers may still attempt to raise funding for commercial use of microgravity facilities if they are able to. Thus this is much the same as the previous option.

Benefit – Lowest cost option.

Cost – Zero.

Problem – No involvement in research or industrial collaborations, no access to results, poor political impression of UK as world-class player.

8.7 Summary

The possible combinations of options for the UK are shown in the following table:

ELIPS	NASA	Other US	Non-US	Commercial
Member	√	√	√	√
Non-member	X	√	?	√

8.8 National programme

If the UK were to decide to subscribe to an international programme, it should also consider the question of funding for UK researchers. This would be to ensure that it received the maximum benefit from its investment in the programme.

The obvious arrangement would be to consider joining the ESA ELIPS programme and then let researchers bid for funding for their experiments from the relevant Research Council or other suitable body. This may be the best arrangement, but it should be considered whether the fledgling interest in such types of research in the UK would be well served in this case. There is no history of funding such research in the UK and (possibly as a result) there are few groups who have built up expertise in the use of microgravity facilities and little awareness of what they could offer.

Other European countries (notably Germany – see Appendix 4) have seen fit to allocate specific funding for microgravity activities in the early stages. As with most areas of new endeavour, the initial results were poor and microgravity acquired a bad reputation as a result. However, most European states involved in the ESA programmes now find that their microgravity research is on the same standing as that of other areas of research.

An additional factor, unique to the UK, is that the large range of different areas of research that could make use of microgravity means that funding such work would not fall to any single Research Council, and so there is little opportunity for a strategic approach to such questions. A moderate sum (perhaps half that of the ESA subscription) could be set aside for a period of several years until the value or otherwise of such activities could be demonstrated in normal competition with other non-space activities.

Such a national programme would also be a valuable way to involve UK researchers who could provide inputs to influence the future direction of European research.

9 Possible sources of funding

Microgravity can be looked upon as a tool to help researchers, much the same as any large and expensive facility such as a neutron source or a telescope. Decisions on the possible funding of such facilities are generally left to the funding authority for the area of research that would benefit. Hence the decision on the funding of a telescope would be left to PPARC and a neutron source to EPSRC. This is eminently sensible for facilities with a clear user group, but becomes a problem for facilities that would benefit a large range of different disciplines. If the UK were to decide to join an international programme such as ELIPS, the cost of membership would have to be met by some means.

Several possibilities may be considered:

9.1 Share costs pro-rata among the Research Councils

For the UK to take a joined-up, strategic approach, it is necessary to add together the benefits of such a facility for each area. In principle it would be possible to seek contributions from each interested party – however the mechanics of such negotiations would be protracted and could result in each downplaying their interest to reduce their relative contribution to the total. A panel trying to allocate financial shares among the Research Councils would have a hopeless task.

9.2 Central funding through BNSC

Most other European states avoid this problem by providing central funding – usually through their national space agency. This would go against the trend for the UK where it is felt that decisions are best left to the user groups. For example, BNSC has recently announced that it is transferring money for earth observation to NERC so that spending decisions can be made against user requirements.

9.3 Central funding through another body

Given the disparate nature of the users of such facilities, it would be wise to have a single body charged with the responsibility of representing the needs of the users and representing their interests to Government and to the international community (be it ESA, NASA or others). Without this the UK's activities would be fragmented and lacking in direction.

The obvious source of funding would be through OST, with the option of top-slicing a sum from the Research Councils or of providing a line of new money. An alternative would be to seek DTI funding on the basis that any research would benefit the Government's innovation agenda.

Control of the programme could then be provided either through BNSC and its advisory bodies, through one of the Research Councils acting on behalf of the others (CCLRC might be the obvious example, but in principle any could perform this function) and under the guidance of a steering panel with representatives from all of the users groups.

In addition it should be considered whether a central sum of money should be set aside for a national programme in support of the international subscription. The obvious approach would be to allow researchers to apply in the normal way to Research Councils. This would have the advantage that proposals would be subject to the normal peer review process but does not remove the need to convince both the international peer review committee and that of the relevant Research Council.

Clearly it is important that if the UK should decide to join the ESA programme, it should ensure that there is a single organisation responsible for handling the interface between UK interests and ESA. This would enable there to be a coherent UK strategy, and ensure that there would be an organisation responsible for making researchers aware of the possibilities for the use of microgravity facilities funded by the UK. Following the examples of space science and earth observation, such an organisation would have to work in partnership with BNSC to make the most of links with other aspects of UK space policy.

For comparison it may be helpful to mention briefly the arrangements in other areas with similar problems. Space science is funded entirely by PPARC, and from 2003 PPARC will become responsible for the whole of the UK subscription to the ESA Science Programme. As a mandatory programme, PPARC has no direct control over the sums involved (though it has been largely through strong negotiation by PPARC staff that the level of the budget has been reduced to a level acceptable to the UK). PPARC is also responsible for a proportion of the mandatory ESA General Budget. As a partner in BNSC, PPARC ensures that there is a co-ordinated approach to UK policy.

The subscription for the ESA Earth Observation Programmes is similarly due to be handled by NERC. This has until recently been met by DTI, but in the review of BNSC completed in September 2002, it was agreed that it was more appropriate for the finance to be transferred to NERC. As with PPARC, co-ordination with other areas of space policy is assured by NERC's membership of BNSC.

The UK subscription to CERN and to ESO is met by PPARC, and again in each case the relevant facilities fall entirely within the remit of PPARC.

The case for the Diamond synchrotron facility was more complicated with a mixture of users from a variety of disciplines supported by different Research Councils (mainly EPSRC and MRC). Funding was provided by OST and the Wellcome Trust and overall management of the facility is in the hands of a limited company under the control of CCLRC, with a Board of Directors including members of the funding partners, the Research Councils, industry and the universities.

Funding for fusion research has recently been transferred from UKAEA to EPSRC. The funds are ring-fenced for the next year, but not after that. It remains to be seen whether this area of research will succeed in competition with other activities in EPSRC's portfolio.

Appendix 1: Referenced documents

1. 'ELIPS: Life and Physical Sciences in Space, Executive Summary', ESA (2001)

2. 'Recommendations for ESA's Future Programme in Life and Physical Sciences in Space', European Science Foundation (2000)

3. 'Prospects for British participation in microgravity research', Prof Sir Brian Pippard FRS (1989)

4. 'The Potential Impact of Space-based R&D on the Competitiveness of the UK Pharmaceutical Industry', Guest Associates report for DTI (1996)

5. Swiss evaluation: 'The Microgravity Programmes of the European Space Agency and Switzerland – An Evaluation' (Feb 2001)

6. Dutch evaluation: 'Microgravity Research in the Netherlands: Past Performance and Future Perspectives' (Jan 2001), plus 'Future Prospects of Microgravity Research in the Netherlands' (Sept 2000)

7. 'Space Scientific Research in Belgium, Volume 1: Microgravity 1994-2000', Belgian Federal Office for Scientific, Technical and Cultural Affairs (2001)

8. '10 Years Space Biomedical Research in Austria', ed. H G Hinghofer-Szalkay (2001)

9. 'Astrobiology in the UK', Community report to BNSC (1999)

Appendix 2: Notes on UCL Conference 'Futures in UK Space Biomedical Research'

In the United Kingdom there exists a working infrastructure capable of supporting a programme in space life science research. This has been achieved through the implementation of the strategy proposed in 1999 at the *'Futures in UK Space Biomedical Research'* conference held at UCL with the support of the British National Space Centre. The aim of this conference was to evaluate the potential for the establishment of a UK-based effort in space biomedical research. The resultant strategy led to the adoption of a bottom-up approach comprising a dynamic evaluation of the potential opportunities offered by the international space programme, alongside the establishment of a basic infrastructure capable of supporting a nascent programme.

This project has achieved the following:

- The establishment of a national steering group for space biomedicine supported by BNSC.
- The establishment of an international steering group for space biomedicine supported by ESA and NASA.
- The development of undergraduate education programmes supported by NASA and ESA.
- The development of postgraduate education programmes supported by NASA and ESA.
- The establishment of the Centre for Aviation, Space and Extreme Environment Medicine.
- The creation of first class postgraduate training opportunities for UK students.
- The creation of first class opportunities in research for UK life and medical science researchers.
- The development of ongoing research collaborations with international laboratories.

The business plan supporting this model relies upon regular income from undergraduate and postgraduate taught courses, administrative support from University College London, teaching support from extramural UK speakers, teaching support from international space agency staff and formal research grant awards.

This strategy in combination with the Centre for Aviation, Space and Extreme Environment Medicine represents a platform through which a more comprehensive, strategic review could be undertaken and a formal, multi-centre, UK programme could be established.

Appendix 3: Comments on the Pippard Report

The Pippard Report is referenced in Appendix 1. This appendix gives comments (with the benefit of hindsight) on the main recommendations made in the report (quoted in italics).

I have pleasure in submitting my report on the prospects for British participation in microgravity research. If it is not as clear as you wish, or if there are matters you would like me to deal with more fully, I shall be happy to do what I can to help.

I see no strong case for becoming seriously involved - a worrying conclusion in view of the support given by the other European countries, not to mention USA, USSR, Japan and China. But if their scientists had ever been faced with the prospect of contributing to that support at the expense of their own budgets for research we might not find ourselves so much out of line.

This remains true, now with only the UK, Finland and Portugal among European nations to remain outside of the ESA activity. Most of the committed nations have supported the microgravity initiative for industrial or philosophical reasons and have matched their investment with ring-fenced research money.

The relevant arguments summarized below do not imply that participation is unjustified, but hedge it around with such conditions as could only be met by strenuous lobbying, followed by a hard recruitment exercise to overcome the dearth of interest that is the harvest of years of neglect.

Again this remains true, but a hard recruitment and lobbying exercise implies a national directive which has never existed.

(1) *From the purely scientific viewpoint the only area that promises significant extension of fundamental knowledge, and could be usefully pursued over a prolonged period, is the crystallization and X-ray analysis of proteins. In the absence, until very recently, of striking successes the British molecular biologists have regarded microgravity coolly, holding that the money would be better spent on the ground. The latest (unpublished) reports from NASA may, however, force them to reconsider their position. See § (11).*

Over the ensuing period this area has been subjected to much debate with early experimentation not being shown to be conclusive. Even so, current experiments by UK scientists as members of consortia are seeking and achieving flight. This activity will be terminated at the end of 2002 should the UK not contribute to the ELIPS programme.

Recently the US has flown a late generation crystallisation facility on the ISS. Reports of the returned crystals are eagerly awaited.

(2) *In molecular biology, as in all other applications, microgravity offers an extra technical facility, not a substitute. Without adequate ground support money spent in space is wasted.*

ESA has gained experience that supports this. In fact some 60% of the ESA funds in this area are directed to ground based investigations in all areas of technology.

(3) *Much other microgravity research is self-limiting. New phenomena have been, and will be, discovered but, once revealed, they are often better investigated further on the ground.*

This is now an accepted tenet. However, many phenomena will require long periods of microgravity conditions to investigate fully.

(4) *The prospects for manufacture in space, whether of semiconductor crystals or pharmaceuticals, are poor.*

The fundamental economics of space-based activities preclude manufacture in orbit for profit. Knowledge gained may improve ground-based processing to the point where an economy results. But frequently the disciplined preparation for a space experiment reveals ground-based improvements without recourse to a space flight. This is a criticism of ground-based preparation rather than a criticism of space-based work.

Work has shown the superiority of space based processing (for example the production of Interferon and microelectronic crystal materials), but the current costs of such processing would not be justified by the market as it stands. This may change as flight costs reduce, but it is still a long way off.

(5) *Measurements of physical properties (e.g. diffusion constants) of liquids at high temperatures, and of water around the critical state, are extremely difficult under any conditions, but should be helped by eliminating gravity. Such measurements are of limited scientific interest; the real case for undertaking them is the large rewards they might bring (though with no guarantee) in new or improved industrial processes. They could form the staple occupation of a centre of expertise in microgravity.*

This is the reason for the focus on application-oriented research within the ESA programme. At the ESA Council of Ministers in Edinburgh in 2001, the Executive was given a clear guide to give more emphasis to research that could be applied to industry, and the ELIPS programme has been adapted as a result.

An additional element of the ELIPS programme is the creation of a series of User Support and Operations Centres (USOCs) across Europe. Each one is charged with supporting users from across Europe in a given discipline – so for example the USOC in Cologne is responsible for helping users of the Biolab facility, whilst the USOC in Naples does the same for the Fluid Sciences Laboratory.

(6) *It is to be expected that ideas for experiments, perhaps more limited in scope but still imaginatively stimulating, would be generated once the centre was running. Without such a centre, the practical difficulties of organizing exploratory experiments would stifle them at birth; in particular, university participation in microgravity could not thrive.*

The concept of such a UK centre was never a possibility given the size and disparity of the potential community. However the European Space Agency has formed such centres (see (5) above) and has formed a number of Topical Teams which draw together the expertise of member countries' scientists in order to recommend the future needs of each research area.

Some central support would be needed in the UK, but following the model of countries such as the Netherlands and Belgium, it would be possible for the bulk of the organisation to be handled by ESA. This would be largely a question of the level of influence desired by the UK – a greater influence in ESA programmes would require a stronger team to coordinate UK activities and interests. This could be achieved through BNSC's usual Partnership model which would require close involvement of the relevant user groups (Research Councils, industry, universities, etc.).

(7) *The cost of maintaining a useful presence in microgravity is unlikely to be less than £8 million a year. To spend this sum annually, during the ten years before Columbus provides adequate access to space, would outrage the scientific community in its presently perceived straitened circumstances. And after ten years the intellectual reward from Columbus is unlikely to reconcile it for missed opportunities.*

Aiming only for an interactive scientific level membership of ELIPS and leaving actual experimentation to grant applications and judgement from the Research Councils, the cost to the UK is about €3M per year. An additional sum will be required to contribute towards flight costs and supervision of UK subscriptions. Now that Columbus is largely built and the ISS is in orbit, it is not a question of paying to build the hardware, but of whether (and how) to exploit the facilities.

With the launch of Columbus not due until 2004 and limited resources to support facilities now in orbit, there will not be very many flight opportunities for a while, but UK researchers are already in the queue and will lose their place if the UK does not join the ESA programme.

(8) *For the scientists the only acceptable way to pay for membership of ESA and for the centre of expertise would be to follow the example of the rest of the world, and guarantee the costs out of a separate, extra, allocation.*

This remains true. The example of other countries such as Germany (see Appendix 4) indicates that it may be necessary to ring-fence costs for a period to allow researchers to develop the necessary expertise to compete in the normal way with other peer-reviewed research.

(9) *Even if this were to be arranged, there are so few interested scientists in the country that only a very determined Director could recruit staff for the centre of such quality as to justify the outlay.*

There are more UK scientists interested in the work than are shown in Research Council records, simply since many hoped for ESA funding and declined to use their time to make grant applications into a system which was likely to be unsupportive. The ESA activity has replaced the concept of a UK centre (see (5) and (6) above).

(9) *I have concentrated on the intellectual and commercial opportunities of micro gravity research, and have taken no account of the engineering and instrument-making firms and consultants who are interested in developing equipment for use in spacecraft. Generally speaking, such firms have small need to conduct experiments in space during the development, and their concern is whether, without a British presence, they will continue to win contracts. Apart from shortage of time, I lack the commercial experience to study this question.*

Without a significant UK support in Europe for this UK firms have had no opportunity to exploit *juste retour* from the ESA programmes. One indeed has seen its design work on glove box facilities pass to Holland and Germany as a result.

Other members of consortia are prevented from designing and building experiments for the same reasons.

Subscription to the ESA programme would guarantee a return of 2/3 of the subscription to UK industry in the form of contracts. This could be directed principally towards new spin-out companies working closely with scientific researchers on instrumentation for space experiments and other high-technology applications – giving rise to opportunities for spin-out into ground-based applications.

(11)Finally, to revert to § § (1) and (2), I am principally anxious lest we lose the eminent position we hold in protein crystallography. I suspect that, so long as their laboratory work remained at the highest level, our leading researchers would be able to team up with colleagues abroad if that were the only way to participate in space growth of crystals. But they must keep at the highest level, and I wish to draw attention to the suggestion made at the end of Appendix l(d).

We should note the increasing animosity expressed by our neighbours about the UK intransigence in joining the European joint activities. Certainly they intend to bar any collaboration from the UK which bypasses membership of ELIPS.

The comments relating to crystallography remain true, even if the progress in this field has been less than meteoric, however there are other fields to consider in which UK scientists are active. They include microencapsulation (UK leads a topical team here), medical effects (osteoporosis, muscle wastage), metallurgy (solidification processes and thermophysical properties), biology – (plant graviresponse), and radiation effects upon DNA. See Appendix 5 for more details.

Appendix 4: Views of other ESA Member States

Of the 15 ESA Member States, only Finland, Portugal and the UK have so far declined to join the ELIPS programme. It is useful to consider the reasons that the others choose to be part of this programme. The following comments have been gathered from the national delegations to the ESA Programme Board for Human Spaceflight, Research and Applications (which is responsible for overseeing the ELIPS programme).

Austria

Austria set up an active programme in the early 1990s. Most of the work was done jointly with Russia in the life sciences (and included an astronaut). This work was believed to be world class, but to demonstrate this it was decided to join the ESA programme (ELIPS) for the first period of five years and then evaluate the results gained by Austrian scientists in a more rigorous scientific selection process (the Russian criteria tend to be more dominated by finance).

Denmark

Denmark is pleased with the good scientific return from its involvement in microgravity research. It also has good connections with industry who are keen to exploit the opportunities offered.

One key example they quote is a heart and lung measurement device developed as part of the microgravity programme. The constraints of the space environment required a simple, compact, light, non-invasive device – and the resulting portable device has been patented and is shortly to be used in European hospitals.

Germany

The following notes were made by Jeremy Curtis during a meeting between Prof Bill Wakeham and Prof Ivan Egry (Head of the German Space Agency's ZEUS Centre) on 4 September 2002.

The main reasons for Germany helping to build the ISS were political and in order to support German industry.

Prof Egry mentioned that the German Physical Society had been very critical of manned spaceflight in the late 1970s and that there had been improbable promises made about factories in space. This position has now changed with German research concentrating on fundamental studies of such things as fluid behaviour.

German microgravity activities have been subjected to three reviews in the last two years. First the European Science Foundation reviewed the ESA programme and was very positive about the materials sciences. Then the German Ministry of Research (BMBF) asked the Fraunhofer Gesellschaft to review German activities. A set of expert panels were set up (including non-space experts) who found a good publication record and with microgravity researchers found to be doing as worthwhile science as anyone else. Finally the Helmholtz Gesellschaft, which coordinates all government-funded research centres, did a further evaluation as part of its competition for funding between them. The result of this evaluation was an increase in funding (for both life and physical sciences) based on the quality of the science being carried out.

Prof Egry drew attention to some of the features of microgravity research that made it hard to support initially. As with most new areas of research, the initial experiments were often unsuccessful, and so presentations at conferences were dominated by the methods used rather than the results achieved. Unlike many other areas, a second chance to get results can take many years.

He also reported that Germany had had problems persuading industry to participate. The main problem was that German industry expects most materials research to be carried out with public funds. If they are to fund it, they require that their rivals are excluded and that their choice of materials is tested – so government-funded research focuses on generic alloys. There is interest from one company who would like to study the viscosity of alloys on the ISS, but they first want to see a demonstration that existing arrangements will suit an industrial partner.

DLR now think that there is a case for transferring funding to the German Science Foundation (DFG) who would normally fund materials research, but who won't fund space-related costs. They are now negotiating with DFG to set up a joint review process.

Prof Egry felt that this was still very early days to be able to predict what impact microgravity research will have, but he mentioned that whilst the theory of fluid flow (e.g. differential equations) is 100 years old, much of it has not been properly tested as it is just too difficult. For example, the Marangoni effect has been known about for a long time, but it was not appreciated what effect it would have on crystal growth until microgravity research began. He felt also that microgravity research would be more a matter of incremental improvement to knowledge rather than the stuff of Nobel prizes.

Finally he mentioned that Germany views the participation of UK researchers as vital to Europe. He thought that the existing communities of researchers would be destroyed if the UK stayed out of ELIPS and these would be hard to recreate.

Italy

Italy intends in the future to concentrate on medical and biotechnology projects.

Netherlands

The reason for joining the programme in the first placed was largely political, but having invested in the ISS, it was necessary to exploit it. Hence a microgravity programme was set up and the resulting research carried out by Dutch researchers was reviewed in 2001. This resulted in a decision to join the ELIPS programme. The evaluation report is referenced in Appendix 1 and is available to the Review Panel.

Spain

Spain participates for both scientific and industrial reasons. Spanish industry receives useful contracts due to the geographical return system and its scientists have been increasingly active in both space and ground-based microgravity research.

However, it does not regard microgravity as a top priority and only contributes 2% of the budget (its GNP share would be 6.9%). For political reasons Spain aims to participate in all ESA programmes.

Sweden

The main reason for Sweden's involvement is its commitment to the sounding rocket programme operated from Esrange (in Kiruna). However, it values its scientific research carried out in the ESA programmes and would participate, albeit at a low level, even in the absence of Esrange.

Switzerland

Switzerland bases its involvement on its scientific interest and on applications to non-space activities. The question of whether to subscribe to the ELIPS programme was put to a review committee in 2001 and the report is included as a referenced document (see Appendix 1).

Appendix 5: List of UK researchers

This table includes all UK researchers who have responded to the International Announcements of Opportunity in Life and Physical Sciences (1998 to 2000). It is intended to give an overview of UK researchers who are interested in using microgravity, with the areas of research in which they are active, a suggestion as to the Research Councils most appropriate to their work and the ESA 'cornerstones' as defined in the European Research Plan for Life and Physical Sciences and Applications in Space.

RC	Discipline	ESA 'Cornerstone'	Research proposals	UK groups involved
PPARC, NERC	Fundamental physics	Complex plasmas and dust particles	Yukawa clusters	Bingham (RAL)
			Interactions of small bodies in plasmas	Allen (Oxford), Bingham (RAL)
			Atmospheric particles affecting earth radiation budget and stratospheric ozone	MacKenzie (Lancaster)
			Application-oriented plasma research	Allen (Oxford)
			Processes governing the self-ordering of strongly coupled plasmas	Bingham (RAL), Allen (Oxford)
		Cold atoms and quantum fluids	Atom optics and interferometry in space	Burnett (Oxford), Foot (Oxford), Summy (Oxford)
			Fundamental physics on the ISS	Lockerbie (Strathclyde), Kent (RAL), Sumner (ICSTM)
			Universal constant of gravity	Roxburgh (London)
EPSRC	Fluid and combustion physics	Structure and dynamics of fluids and multi-phase systems	Magnetohydrodynamics of levitated drops	Pericleous (Greenwich)
			Large scale structures and their phase behaviour formed from colloidal particles	Pusey (Edinburgh)
			Measurement of diffusion coefficients	Robinson (East Anglia)
			Mass transport in liquids (self-diffusion, interdiffusion, thermodiffusion, electromigration, etc)	Alboussiere (Cambridge)
			Study of an imposed electrostatic field on pool boiling heat transfer and fluids management	Kenning (Oxford)

			Simulation of geophysical fluid flow under microgravity	Hollerbach (Glasgow)
			Convection and interfacial mass exchange	Mendes-Tatsis (ICSTM)
			Gas liquid transfer and liquid mixing in bioreactors	Mendes-Tatsis (ICSTM)
		Combustion	Flame vortex interaction in the fields of turbulent gaseous and heterogeneous combustion	Taylor (ICSTM)
			Low-temp. reaction paths of aliphatic hydrocarbons	Griffiths (Leeds)
			Instabilities in lean gas phase combustion	Emerson (Daresbury Lab)
	Materials sciences	Thermophysical properties	Solidification of refractory metals and alloys	Greer (Cambridge)
			Solidification along a eutectic path in ternary alloys	Brown (Wales), Spittle (Wales), British Steel
			Solidification morphologies of monotectic alloys	Wheeler (Soton)
			Study and modelling of nucleation and phase selection phenomena in undercooled melts: application to magnetic and refractory alloys of industrial relevance	Mullis (Leeds)
			Microstructure formation in casting of technical alloys under diffusive and magnetically controlled convective conditions	Jones (Sheffield), ALCAN, British Steel
			Columnar-equiaxed transition in solidification processing	Hunt (Oxford), Wheeler (Soton), Alcan, British Steel
			Thermal transport phenomena in magnetic fluids under microgravity conditions	Chantrell (Bangor), O'Grady (York), Liquids Research Ltd.
			Dendrite and crystal growth in industrial alloys	Greer (Cambridge), Cochrane (Leeds), Mullis (Leeds), ALCAN, British Steel, Rolls-Royce Univ. Tech. Centre

			Thermophysical properties of liquids: modelling and non-metallic materials	Mills (ICSTM), Greaves (Aberystwyth)
			High-precision thermophysical property data of liquid metals for modelling of industrial solidification processes	Mills (ICSTM), Quested (NPL), Sandvik Steel, British Steel, Osprey Metals
		New materials and processes	Metastable solidification of composites: novel peritectic structures and in-situ composites	British Steel
			Crystallisation of CdTe and related compounds	GEC-Marconi
			Crystal growth of II-VI compound semiconductors	Brinkman (Durham)
			Crystal growth from vapour	Brinkman (Durham)
			Interfacial studies of emulsions used in industrial microencapsulation	Whateley (Strathclyde), Coakley (Cardiff), Alpar (London), Glaxo SmithKline
			Microencapsulation (cells to drugs)	Whateley (Strathclyde), Zhang (Birmingham)
			Diffusive transport - crystallisation of fibrous proteins	Chayen (ICSTM)
BBSRC	Biology	Biotechnology	Preservation of fixed and non-fixed biological samples during space experimentation	Franks (BioUpdate Foundation)
		Plant physiology	Perception of gravity, signal transduction and graviresponse in higher plants by innovative genomic technologies	Bennett (Nottingham)
BBSRC/ MRC		Cell and developmental biology	Controlled tissue development in bioreactor for pharmaceutical high throughput screening based on engineered skin, central nervous system, and liver tissues	Handa-Corrigan (Surrey)
			Ultrasonic Particle and Cell Manipulation in Microgravity	Briarty, Böhm, Davey, Power, Lowe (Nottingham), Coakley, Hawkes (Cardiff)

			Biomonitoring systems (especially systems that respond to the gravity stress, to confinement, and/or to an increased level of radiation)	Barrow (Wales), Turner (Cranfield)
MRC	Human physiology	Integrated physiology	The effect of change in gravity on the dynamic of prehension and the kinematics of the upper limb	Wing (Birmingham)
			Nutrition (relationship between nutrition and muscular changes linked to ageing, to hydration problems, and to long-term exposure to space conditions)	Elia (Dunn Nutrition Centre)
			Respiratory, circular, muscular, and bone consequences of inactivity and rehabilitation in humans	Jones (Birmingham), Sargent (Manchester Met.)
		Muscle and bone physiology	Resistance training using fly-wheel technology for crew stationed in space	Narici (Manchester Met.), Rutherford (King's College, London),
			Bone metabolic studies in a combined perfusion/loading chamber	CytoScience
			Short-duration bed-rest study	Rennie (Dundee)
			The astronaut microgravity model for the assessment of deep muscle fibre atrophy in the aetiology of low back pain	Morrissey (East London)
		Neuroscience	Neurophysiological, vestibular, and psychological consequences of prolonged bed rest	Harrison (DERA), Abram (DERA), Arendt (Surrey), Dickson (DERA), Dijk (Surrey), Elshaw (DERA), Llewellyn (DERA), Stone (DERA), Stott (DERA)
PPARC, NERC, MRC	Astrobiology and planetary exploration	Origin, evolution and distribution of life	Screening of ultra-violet radiation in endolithic and microalgal communities from Antarctica	Wynn-Williams (BAS), Edwards (Bradford)
			Artificial meteorites of sedimentary origin	Edwards (Bradford), Miller (OU)
			Laser raman spectroscopy for detecting biomarkers in Antarctica and on Mars	Wynn-Williams (BAS), Edwards (Bradford), Sims (Leicester)

			Mars immunoassay life detection instrument	Wynn-Williams (BAS), Steele (Portsmouth), Toporski (Portsmouth)
			The search for extraterrestrial homochirality	MacDermott (Cambridge), Barron (Glasgow), Drake (King's), Emery (RAL), Glazer (Oxford), Tranter (ICSTM & Glaxo Wellcome), Woolstencroft (Edinburgh), Sandford (RAL), Hyde (Cambridge), Moorbath (Oxford), Russell (Cambridge), Sandars (Oxford), Zarnecki (OU), Sims (Leicester)
			Radiation climate on Mars as relevant to exobiology	Zarnecki (OU)
		Preparation for human planetary exploration	A biosensor to monitor radiation-induced DNA damage on the International Space Station	Walmsley (UMIST), Goddard (DIAS UMIST Ventures Ltd), Fielden (DIAS UMIST Ventures Ltd), Gentronix Ltd.
			Electromagnetic techniques for in-situ planets resource prospection	Meju (Leicester)
			Upper boundary of the biosphere	Cockell (BAS)
			Physico-chemistry of ices in space	Price (UCL), Williams (UCL)

Appendix 6: Current subscriptions to the ELIPS programme

The total envelope budget is €320M. The total subscribed so far is €171.44M. Figures are current as of September 2002.

The table indicates the actual sums subscribed by each state, the percentage of the total figure so far subscribed, the percentage of the envelope budget, and the percentage that would be expected if each country bid according to its GNP (as of 2003/4).

PARTICIPANT	Subscribed (€M)	% of subscribed total (€171.44M)	% of total envelope €320M	Theoretical GNP share (%)
Austria	2.50	1.46	0.78	2.3
Belgium	22.40	13.07	7.00	2.88
Denmark	4.90	2.86	1.53	1.85
Finland	0.00	0.00	0.00	1.4
France	40.00	23.33	12.50	15.9
Germany	36.00	21.00	11.25	23.82
Ireland	0.64	0.37	0.20	0.96
Italy	32.00	18.67	10.00	13.1
Netherlands	6.40	3.73	2.00	4.61
Norway	1.00	0.58	0.31	1.73
Portugal	0.00	0.00	0.00	1.23
Spain	6.4	3.73	2.00	6.99
Sweden	10.00	5.83	3.13	2.66
Switzerland	9.20	5.37	2.88	3.45
UK	0.00	0.00	0.00	17.22
Covered	171.44	100.00	53.58	
Uncovered	148.56		46.43	
Total	320.00	100.00	100.00	100.00

Table 2. Subscriptions to the ELIPS programme.

The minimum level for an optional programme is 25% of GNP. At that level the UK contribution would be €320M x 17.22% x 25% = €13.78 M. If the UK were to enter the programme in 2003 then this would be spread over 4 years at €3.44 M per year.

Appendix 7: Background notes on UK options

7.1 Membership of the ESA ELIPS programme.

Over a decade ago the UK chose not to participate in the ESA programmes set up to build and use facilities for the ISS, but it is now invited to join the current programme which makes use of this and other microgravity facilities. The new programme is called ELIPS (European Programme for Life and Physical Sciences utilising the ISS) and is an optional programme that began in January 2002 for the initial 5 years term. The programme received €171M in subscriptions from 12 out of 15 of the ESA member states at the Edinburgh Ministerial Council meeting in November 2001 (Portugal and Finland were the other non subscribers). Details of the levels of subscriptions are given in Appendix 6.

As an optional programme, countries may subscribe or not as they wish, but the ESA convention stipulates that the minimum level of subscription must be at least 25% of their GNP share of the total budget.

The UK's GNP share is 17.22% and so the minimum subscription would be €13.78M spread over the remaining 4 years of this first phase.

Thus the UK is faced with two clear alternatives: to join or not to join the ELIPS Programme.

Joining the programme

Join the ELIPS programme at a minimum level (€3.44M p.a.). This benefits the UK scientists directly since they could interact with their counterparts in all aspects of the microgravity programmes and it would allow some participation in flight experiments, but for significant hardware participation additional national support (Research Councils or industry) would be needed. Flight costs are covered, but if operational use is made of the ISS then a contribution for share of the relative utilisation costs would be needed.

Note: The ESA rules on geographical return mean that two-thirds of the subscription would be returned to the UK in the form of industrial contracts. Although the bulk of the large contracts have now been let, there would be many opportunities for the UK to encourage new SMEs to bid for work on smaller facilities in collaboration with university groups. These contracts could be in a large range of disciplines, complementary to the UK's research interests.

It might be worth trying to negotiate with ESA member states the concept of joining the ELIPS programme on the basis of no additional charges for ISS flight costs during the first period of ELIPS (until the end of 2006). Costs for use of facilities other than on the ISS are included in the ELIPS programme.

Staying out of the programme

Decide not to participate in ELIPS. This effectively would debar UK scientists from any further participation in the European microgravity programmes (and make links with the programmes of the US, Japan and Canada very difficult). Membership of the ESA programme would give access to all microgravity facilities controlled by ESA directly and to those it can access through the Inter-Governmental Agreement on the use of the ISS.

Present rules for UK access to the European facilities on the ISS

ESA Member States participating in the ISS Exploitation Programme agreed in 2001 that some of the European capacity for Space Station Exploitation will be allocated to earn revenue from non-participants such as the UK and commercial users, and also agreed rules for such access. As a result of those rules, the UK would have to pay the full exploitation costs for their experiments or share in an experiment, thereby matching the payments made by programme participants through their subscription to the ISS Exploitation Programme. The access rules include the provision that charging of non-participating States may be waived, partially or in full if participating States decide that this is in the interest of science enhancement or international relations policy. Use of the ISS as a non-participant would give neither industrial return rights, nor representation on ESA advisory groups. If through such ad-hoc arrangements the UK secured more than 4% of the European capacity it would be in the interests of the UK to join the programme to secure the guaranteed industrial return and representation on advisory groups. Based on earlier responses to calls for proposals, ESA estimates in 2001 suggested that in unrestricted competition, and with sufficient national resources available, the UK might secure 10% of the European capacity.

7.2 Collaboration with NASA

The UK has long had strong collaborative links with US programmes (NASA and others) so it is wise to consider the possibilities afforded by collaborating with the US on microgravity activities.

The possibilities were discussed with senior staff at NASA's Johnson Space Centre in June 2002. During these meetings it became clear that NASA did not intend to set up bilateral arrangements with other national agencies outside the Inter-Governmental Agreement on the ISS. Thus it would be impossible to arrange such an agreement unless we were already a paid-up member (through ESA). There was no theoretical objection to individual institutions making their own agreements, but this would be without the benefit of any overall strategy in such research.

7.3 Other bilaterals

The ISS Partners are USA, ESA, Canada, Japan and Russia. Possibilities for collaboration with ESA and NASA have been set out above. It might be possible to make a bilateral arrangement with one of the others, but this seems unlikely in view of the Inter-Governmental Agreement.

These options have not been followed up for two reasons:

1. Bilateral agreements with non-ESA states would cut across the UK policy of working with ESA. Other ESA member states have for some time been suspicious of UK intentions with regard to the ISS. They are concerned that, having decided not to participate in the building of the ISS, we may now be attempting to profit by using it without any corresponding commitment. If the UK were to choose to set up an agreement with another nation rather than to join the ESA programme, this could cause considerable negative reaction to the UK among other ESA delegations.

2. In order to join international teams collaborating on research using orbital facilities we would need to be a paid-up member of the ESA programme or a full partner in our own right. As has been found with NASA, there is no route available for involvement on the back of an existing partner.

7.4 Participation as a commercial user

Now that the ISS is built, the Partners (USA, ESA, Russia, Canada and Japan) are keen to welcome paying customers. These customers may be commercial companies from participating states or from non-participating states, or they may be any other body (such as a government agency or research institute) from any state.

Thus the UK could choose to use facilities on the ISS as a paying customer. Rates for such use have now been published and there is no intention to penalise countries that are members of ESA, but not participants in the ISS (as is the case with the UK). Such commercial use could be arranged through ESA, or for a higher fee and with greater support, through the new joint-venture company, BEOS. This company is a collaboration between Astrium, OHB and ZARM, and is able to procure flights on a range of vehicles. It is the sole European agent for SpaceHab (who market the US commercial usage of the ISS).

It is likely that the Russian Space Agency would be happy to accept paying customers and have indeed carried many of them (including well-publicised amateur astronauts). Such flights for commercial research are available through BEOS or could be negotiated directly.

If the UK were to decide that it had a few clearly-defined projects that it wished to conduct on the ISS, this could be a good route to follow. The cost of the experiment would then include flight, operations, astronaut time, etc. A clear judgement could then be made on each proposal about its value for money.

However, the main drawback of the commercial route (as opposed to joining the ELIPS programme) would be that UK researchers would not be able to participate in collaborations with their international colleagues. This is because they would be barred from all ESA-funded activities, both ground-based and on the ISS. In addition, the UK would not be able to influence the future direction of the ELIPS programme, and so its relevance to UK research interests would reduce.

7.5 Do nothing

The simplest decision would be to do nothing. In this case our membership of the EMIR-2X programme would continue until it ends and no further ESA-funded activities would be accessible to UK researchers. This would eliminate UK participation in experiments in space (e.g. ISS, Shuttle) and on the ground (including sounding rockets, parabolic flights and ground-based preparatory work).

However, the commercial route would still be available to researchers with sufficient funding, so this option is actually almost the same as the commercial option described above.

Appendix 8: Status of the ISS

The International Space Station (ISS) is a modular, maintainable design following on from the general principles and experience of the MIR space station. The ISS modules (with the exception of the European Columbus module) are launched by Shuttle or Proton only partially outfitted. Further launches are necessary to carry up equipment and astronauts to complete fitting out and commissioning. Therefore there are physical limits dictated by the Shuttle payload bay, the Proton outer diameter and importantly the module and equipment air-lock dimensions.

The on-orbit activity is laborious and inevitably is not totally trouble-free in a situation where equipment is mated, and jointly operated, for the first time. This results in much maintenance and software commissioning and keeps the crew busy.

Although the “final” design state of the ISS projects a 400 ton 125 kW facility some 100 metres in length with 7 crew capability when untended by visiting manned spacecraft, its current state of assembly is about at the 50% level but capable of sustaining 3 crew on a permanent basis.

The size of crew is limited by the presence of an attached “permanent” (actually replaced at 4-6 month intervals on rotation) Soyuz 3-person spacecraft in lifeboat mode. Habitation volume is currently only at an acceptable level for this size of crew.

Re-supply and crew rotation missions are flown by Shuttle and Soyuz missions, which temporarily increase crew size. At such times the entire crew is busy with stores and equipment exchanges plus some external increment/repair work to the complex.

Current resident crew activities are dominated by installation and commissioning of equipment. Little time is available for sustained man-related science activities; clearly semi-robotic experiments (installed and initiated by an astronaut) with either data telemetry or sample return features are to be favoured.

Many science programmes are on hold until the ISS facility can be grown to support a full crew.

Further to the ISS Modules, provided and to be provided by Russia and the US, are Modules from Japan and ESA. Significant robotic arm capability is being furnished by Canada, and Italy has provided pressurised equipment transfer modules which can be shipped in the Shuttle and attached to the ISS to speed up re-supply activities.

Also into the future the Ariane V is to be fitted with an upper stage to manoeuvre payloads and dock with the ISS. This will supplement the autonomous Russian Progress missions which are currently used.

Several of the participating agencies are experiencing budgetary problems. Technical and cost reviews against international commitments are in progress but have the current effect of limiting the crew size to 3 (the crew capacity of the Soyuz “lifeboat” which is permanently present at the station.

ESA seems to have managed its programmes much better than the other agencies and is currently in good shape.

Appendix 9: Glossary of abbreviations

BMBF	German Ministry of Research
BNSC	British National Space Centre
CCLRC	Council for the Central Laboratory of the Research Councils
CERN	European Centre for Nuclear Research
CSA	Canadian Space Agency
DFG	German Science Foundation
DTI	Department of Trade and Industry
ELIPS	European programme for Life and Physical Sciences utilising the International Space Station
EMIR	European Microgravity Research Programme (divided into EMIR-1, EMIR-2 and EMIR-2X [extended] – UK is a member of 1 and 2X but not 2)
EPSRC	Engineering and Physical Sciences Research Council
ESA	European Space Agency
ESO	European Southern Observatory
GNP	Gross National Product
GPS	Global Positioning System
IPR	Intellectual Property Rights
ISS	International Space Station
MAP	Microgravity Applications Programme
MRC	Medical Research Council
NASA	National Aeronautics and Space Administration
NERC	Natural Environment Research Council
NSBRI	National Space Biomedical Research Institute (USA)
OST	Office of Science and Technology
PPARC	Particle Physics and Astronomy Research Council
RKA	Rosaviakosmos (Russian Space Agency)
SERC	Science and Engineering Research Council
SME	Small or Medium-sized Enterprise
UCL	University College London
UKAEA	United Kingdom Atomic Energy Authority
USOC	User Support and Operations Centre