



Space Exploration Review

December 2009

Foreword

This report provides advice to Ministers on the options open to the UK in the field of space exploration. It was agreed by the Minister for Science and Innovation and the Terms of Reference were approved by the Secretary of State for Innovation, Universities and Skills in May 2008.

The report builds on the advice offered to BNSC by the UK Space Exploration Working Group in September 2007 and takes account of reports from other expert bodies and discussions with international partners and other experts.

The work was carried out by a small team seconded in to BNSC. The economic analysis was carried out by London Economics who were selected by a competitive bid. The review was overseen by a Steering Committee taken from BNSC, STFC and DIUS¹, and including an independent member.

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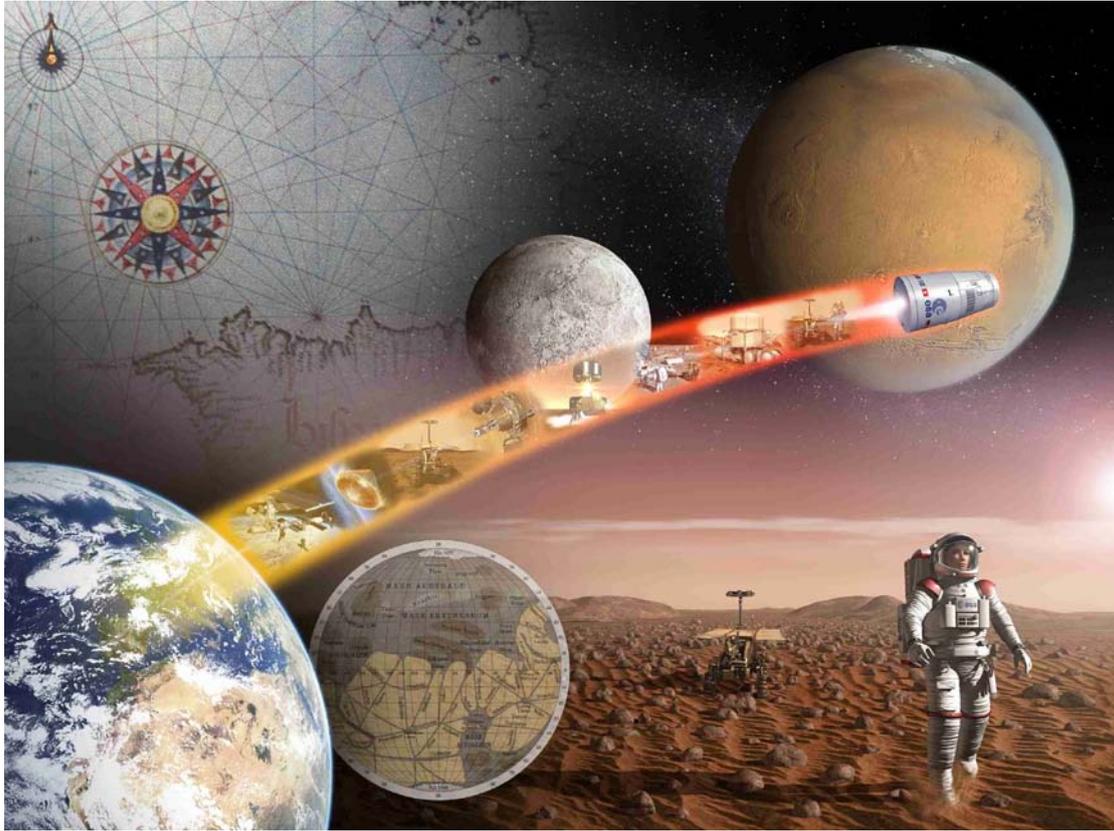


Image: ESA

1 Executive Summary

1.1 *The issue*

A number of countries have developed new plans for exploring the Moon, Mars and near-Earth objects using both robotic spacecraft and humans. These plans are coalescing into an endeavour known as the Global Exploration Strategy. As we enter the second 50 years of space exploration, this surge of activity suggests that we are truly on the verge of a second ‘space age’. This presents both an opportunity and a challenge for the UK.

The purpose of this report is to advise Ministers on options for UK involvement. It builds on previous advice from expert bodies in the UK, principally the UK Space Exploration Working Group (SEWG) which reported to BNSC in 2007. It considers both the costs and the benefits of an expanded programme of space exploration, as recommended by the SEWG. It takes into account the value for science and innovation, benefits to the economy and to a wider social agenda including education and inspiration, exploiting existing UK strengths in robotic exploration.

This chapter contains a summary of the full report. The full report follows in subsequent chapters and includes an analysis of possible commercial opportunities offered by space exploration, conducted by London Economics as part of this exercise.

1.2 *Timing*

The decision on the level of engagement in exploration has long-term strategic implications. The timing of this decision affects the range of opportunities open to the UK since international discussions on leadership roles are well underway. There are specific opportunities in which the UK could take a major role, and extract major benefit, which build on our existing strengths. To secure these, the UK would have to stake its claim before these international discussions are concluded. As other nations declare their plans, the UK will need to demonstrate its firm intention to become involved if it wishes to play a major part.

1.3 *Options*

The report analyses four options, with costs and benefits, both in terms of economics and in terms of wider impacts for society. Each option is composed of a realistic set of individual projects which taken together form a coherent space programme. These options are:

- 1) Reduced option: eliminate involvement in space exploration and restrict the UK to the mandatory ESA Science Programme only²;
- 2) Status quo: continue with the current level of investment (restricted to the ESA Science programme and robotic Mars exploration programme);
- 3) Increase investment in robotic-only exploration, focused on the Moon and asteroid exploration through national projects and bilateral activities with other space agencies;

² The ESA Science Programme covers a range of science disciplines including astronomy, the study of the Sun and planetary science, entirely using robotic missions. It excludes exploration of the Moon and Mars.

- 4) Invest in both robotic and human activities, leveraging the UK's strength in robotic technologies to secure astronaut places in the human exploration of the Moon (two versions of this option are included to illustrate the range of expected costs and benefits).

1.4 Background and rationale

The global space market is currently worth \$251bn per annum. It has been growing at 11% p.a. and is expected to expand further. The agreed UK Government Strategy (UK Civil Space Strategy, 2007) is to maintain or grow the UK share of this expanding market. This requires that the UK shall stay at the cutting edge of relevant developments in science and technology. The challenges of space exploration will be a key enabler in positioning the UK to realise its strategy, by driving forward new technologies and innovative capability. Commercial opportunities would flow from new innovations and improved competitiveness in areas such as communications, navigation and Earth observation.

There are wider 'spin out' benefits that stem from the fact that space is a challenging and demanding environment. Designing systems to cope with the extremes of the space environment in turn creates new technologies and novel approaches that can be used on Earth. New collaborations between the science and engineering disciplines needed to design the tools for exploration would result in unexpected innovation. Furthermore, the increasing number of countries engaged in exploration will create demands for services and hence new opportunities for commerce.

The public interest in both the robotic and human exploration of space inspires the next generation of scientists and engineers and would help to develop and retain the skilled workforce needed by the UK. And, while space exploration satisfies a fundamental human need to explore, the space missions themselves would deliver new knowledge to satisfy our curiosity about the origin and evolution of life and of the Solar System, and to apply to the stewardship of the Earth through studying the environments of other planets.

The Global Exploration Strategy (GES), developed by 14 space agencies in 2007, provides a framework for collaboration, shared costs and risks, and increased sustainability. It offers the UK a practical route to realising the benefits of space exploration through establishing an important 'niche' contribution to the overall effort. A commitment now to play an active role as a founder member of the GES would make the UK a key player at a time when plans for the new era of exploration are being laid out. A later commitment would be feasible, but the range of options may be more limited.

From its internationally recognised strengths in space science and technology, the UK must be smart in its choice of investments. We must select those areas that create the greatest impact in order to satisfy our goals. And we must work in collaboration with our international partners to leverage our skills and investments. One route to develop such collaboration is through the new ESA Centre being built at the Harwell Science and Innovation Campus. Part of this facility will be devoted to exploration activities.

1.5 Analysis

Four options have been analysed by combining individually costed projects to form four coherent space exploration programme scenarios – one programme scenario corresponding to each option. The projects within a scenario were time-phased in accordance with a realistic schedule and cost profile. The wider international context was factored in: the schedule of the US human lunar programme, current thinking on European

exploration projects, realistic technology readiness etc. Other combinations of projects to form different scenarios are possible. However, the four options are chosen to represent clear break-points in the range of possibilities. An assessment of the relative merits of each option is set out in the following table, which includes examples of the types of impact that each would deliver to science, innovation, commerce and society. Chapter 3 provides information on the individual projects which make up the programme scenarios.

Option	Science	Innovation	Commerce	Society
1 Reduced option	Loss of currently growing strengths in planetary science	Loss of growing strengths in rovers, life search instruments etc.	Loss of ESA contracts. Loss of spin-off opportunities (robotics, medical diagnostics etc.)	UK not involved in the search for life in our Solar System
2 Status quo	Mars robotic exploration – why did the histories of Earth and Mars diverge and did (or does) Mars support life?	Autonomous rover technology. Instruments for life detection	ESA contracts. Commercial spin-offs (use of autonomous robotics, medical diagnostics)	UK part of search for life in our Solar System. Aurora Fellowships – training the next generation of planetary scientists
3 Enhanced robotic	Interior structure and history of the Moon. Telescopes on the Moon. Asteroid science and threat to Earth	Demonstration of lunar communications infrastructure. Novel power sources for space	Novel commercial lunar drilling. Strengthened UK smallsat industry	Space robotics in education. Hands-on training for engineers on national missions
4 Human and robotic	Exploring the Moon – a record of 4 billion years of solar system history. Life sciences and diagnostics	Human deep drill project. Robot/human collaboration. New medical techniques	Commercial lunar telecommunications. In situ resource processing and use of technology on Earth	UK astronauts in schools. National role models for STEM

Key	Worst	Poorer	Status quo	Better	Best
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Table 1. Example impacts from the various scenarios

Option 3 or 4 would be a long-term, strategic choice. In either case the programme would build up slowly with reviews built into any delivery plan (the first after five years), allowing phased involvement and sufficient time to establish whether the expected benefits are being realised. Table 2 shows predicted spend profiles for the options listed above (based on 2008 exchange rates).

London Economics considered six case studies to assess the commercial returns that could potentially flow back into the UK economy as a result of Government investment in space exploration. These case studies involved extensive consultation with likely downstream sector users as well as current space industries. The specific case studies used were drawn from a wider pool. In each case potential for a strong return on investment is found, with

the range of opportunities available depending on the extent and ambition of the investment.

Public sector investment of this kind, through programmes of research and exploration, is a necessary precursor to robust commercial exploitation because of the need to compete in a strong international market: reducing risk for new technologies and accelerating their development to achieve first-to-market advantages.

However, these are inevitably risky investments given the long lead-times: while there are in some cases very large upside returns projected on public and private investment, the returns are not guaranteed. Some of the underpinning uncertainties can be mitigated through effective management, but others, such as future oil prices, will remain genuine uncertainties. Similarly, we cannot expect to recognise all the potential opportunities at this point, so future directions must remain under regular review. It is also likely that some of the activities considered would be used to trade with other nations for ‘in kind’ benefits (for example access to facilities or flights for UK astronauts) instead of contracts.

The following sections briefly explain the content, benefits and drawbacks of each of the four investment options outlined above.

1.6 Option 1 – Reduced option

Option 1 would be for the UK to reduce its involvement from the current level to the minimum required for it to remain a member of ESA, saving about £20m a year. This would retain involvement in the mandatory Science Programme (which includes some exploration of the outer Solar System), but would eliminate UK involvement in ESA’s Aurora Mars exploration programme which has been the subject of strong investment since 2005 and has established the UK as an international player. Such a withdrawal would send out a negative message at home and abroad about the importance the UK attaches to front-line science and technology as well as removing the existing benefits to industry and education.

Option 1 would save money, but damage the UK's reputation in science and innovation, reduce international influence, reduce benefits from the ESA programme and send out strongly negative signals within the UK about the prospects for careers based on STEM subjects.

Figure 1. Predicted spend profile for the proposed options

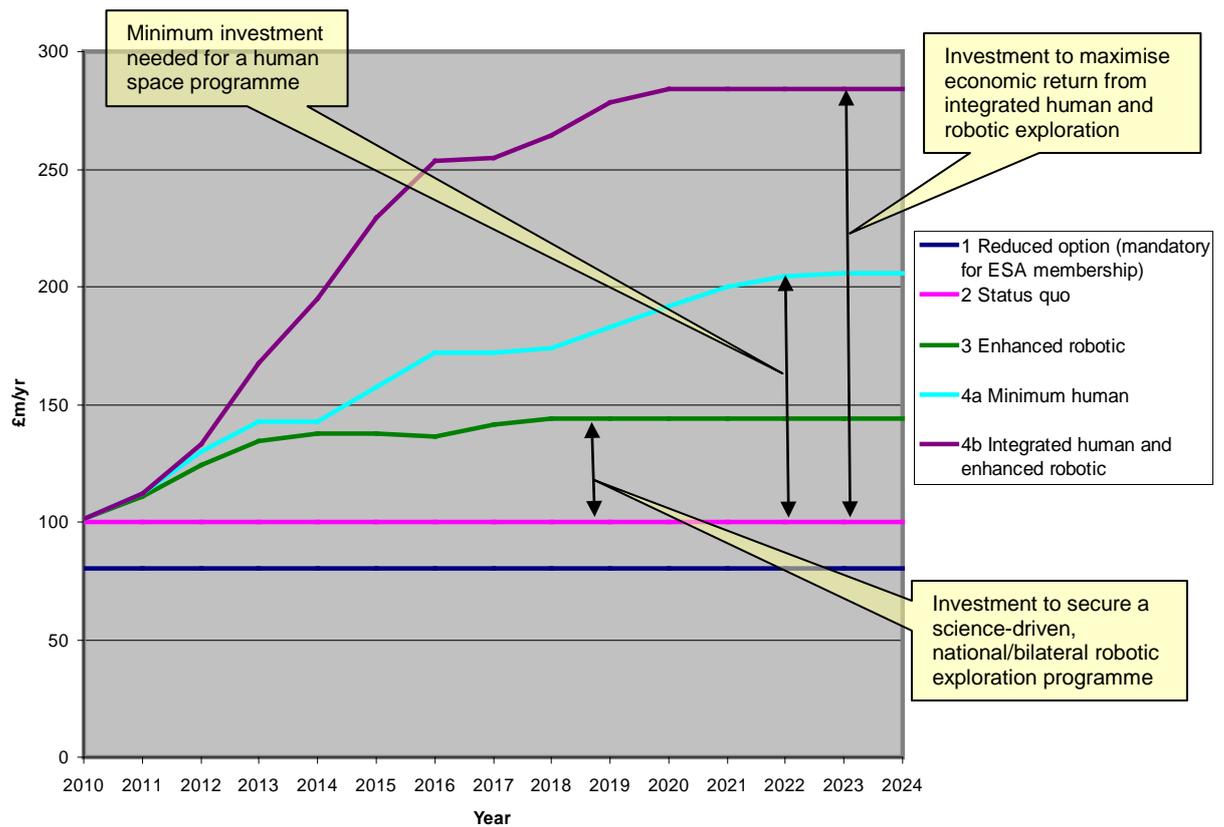


Table 2. Spend profiles in £m for first six years

Option	Year					
	2010	2011	2012	2013	2014	2015
1 Reduced option (ESA Science Programme only)	80	80	80	80	80	80
2 Status quo (ESA Science and Aurora Mars Programmes only)	100	100	100	100	100	100
3 Enhanced robotic exploration via NASA	101	111	124	135	138	138
4a Minimum human exploration	101	112	130	143	143	157
4b Integrated human and robotic exploration	101	112	133	168	195	229

1.7 Option 2 – The current position

At present the UK subscribes to the mandatory ESA Science Programme and to the optional Aurora Programme, which is focused on the robotic exploration of Mars. In addition to our science involvement, this gives opportunities for technology leadership as well as contracts for UK industry. Because of our relatively low overall investment in space in comparison with other countries (for example the UK spends less than one third the amount per capita on space compared with France, Germany and Italy), the public perception of UK strengths is at present low. Instead the UK has concentrated on areas of highest impact including life search instrumentation and the robotic rover for the first mission, ExoMars. UK involvement already includes 80 UK scientists and over 100 engineers, and demonstrable wider benefits here on Earth are being measured.

Option 2, the current programme, delivers good returns for science and innovation, but will not fully exploit the opportunities that arise from new international plans for space exploration. It will also result in a gradual loss of influence in international programmes, demonstrate a lack of ambition and exclude UK industry from involvement in new commercial ventures.

1.8 Option 3 – Enhanced robotic programme

This option would be based on existing UK strengths. It could include work on an innovative lunar science and communication mission (MoonLITE) and later a collaborative mission to understand the threats to humanity posed by the hundreds of Earth-crossing asteroids. A robotic drilling project to study the lunar crust would generate new knowledge about the Moon as well as strongly benefitting terrestrial applications in the oil and gas industry. Other innovation opportunities include the development of novel power sources through the new ESA Centre being built at the Harwell Science and Innovation Campus.

This scenario, although principally science and technology driven, would offer expanded opportunities for outreach programmes, the potential for success of which was demonstrated by the activities surrounding the Beagle 2 mission to Mars. The MoonLITE mission in particular, which is planned as a UK-led project with strong NASA involvement, offers the opportunity for the UK to be seen as an international player on the same level as India, Germany or Japan and has already generated substantial public interest. It would also drive new developments in low-cost satellite technology and help to cement the UK's reputation as the world leader in this field.

Such a programme would secure an improved balance between national space activities and larger projects carried out through ESA, enabling the UK to better exploit its investment in ESA. The analysis by London Economics of the potential benefits of applying new lunar robotic drilling technology to the terrestrial oil and gas industry shows that it could be worth a total of over £4bn pounds net to the UK economy if the UK is successful in capturing a sufficient share of this market and future oil prices are high enough to justify extraction in difficult to access terrestrial locations.

Option 3 would build on UK strengths in robotic technology, increase scientific return and technological innovation, and generate increased public interest in science and technology.

1.9 Option 4 – Integrated human and robotic programme

Option 4 is for an integrated programme of robotic and human exploration, building on our acknowledged strength in robotic space missions to leverage involvement in human exploration, thereby opening up new opportunities and benefits. The advantages of this over Option 3 include:

- a) Making the UK a central player in high-profile human activity, with the associated benefits for UK competitiveness;
- b) Creating opportunities to fly UK astronauts as members of international teams of explorers, who would then serve as role models for aspiring scientists and engineers and a direct feedback from experience of operations in a challenging and novel environment;
- c) Opening up opportunities for UK companies to be involved in the large-scale infrastructure required for human habitation on the Moon and to develop technical expertise of high relevance to life on Earth, for example in closed-cycle environments and biomedicine.

Possible goals could include a place for a UK geologist-astronaut in an international team working on the Moon's history and its relationship with life on Earth, or UK engineers demonstrating a novel telescope on the Moon of a type that could not be built here on Earth. Such activities could be undertaken in two possible ways.

In the first, the UK would join the lunar exploration elements of the ESA human spaceflight programme. As these are in a formative stage, the UK would seek to work with other member states to secure a programme which matched UK goals. This is the traditional UK approach. However, at present, ESA is focused on technologies which do not align well with UK interests and capabilities.

Alternatively, the UK could engage in a bilateral agreement with the US and directly barter for astronaut places against one or more specialised UK contributions to the international endeavour. Examples could be a lunar communications satellite system, radiation protection for astronauts, or the production of oxygen from materials on the Moon using UK know-how. This bilateral approach has been followed by Canada for many years and has secured many astronaut places, a high visibility of Canada's capability and good technological return.

Since the human return to the Moon is unlikely to occur until after 2020, such a programme would grow over a period of years as capacity is built up, irrespective of which implementation path is followed. The programme should be reviewed every 5 years to ensure that the expected benefits are being realised. The MoonLITE mission would again be an essential first step. It would demonstrate credibility and commitment, but also test technologies needed for a lunar telecommunications service, a key infrastructure element, and deliver novel world-class science.

New commercial opportunities would arise from the need for efficient and reliable services, and through wider exploitation of the novel infrastructure components that would

need to be developed (e.g. intelligent robotics to support human explorers) and there would be further opportunities through the involvement of the media in enabling public participation. The impact of a significant programme which includes high-profile British astronauts would create opportunities for inspiration, outreach and education in STEM subjects as well as helping to attract and retain science and technology talent in the UK.

Plans to land human crews on the Moon and elsewhere will drive the development of heavy-lift launch vehicles and these will in turn enable the development of more complex international scientific missions which will be designed to be supported by both humans and robots. Already, the James Webb Space Telescope, NASA's successor to Hubble, will be provided with the minimum equipment needed to allow servicing by future astronauts, even though it will be located at a deep-space orbit 1.5 million km from Earth. And as Steve Squyres of Cornell University (Principal Investigator on the Mars Exploration Rover project) has said: '...sending robots to Mars is what I do for a living, but even I feel that the best exploration, the most compelling exploration is going to be done by humans.'

In terms of costs, the scenario work has shown that the minimum cost of a viable human spaceflight programme (shown as 'Option 4a, Minimum human' on the graph on p11) requires an expenditure growing over ten years to a steady state of about £100m extra a year. This cost estimate has been generated 'bottom-up' based on the bilateral approach, but is consistent with participation in proportion to UK GDP in the existing ESA human spaceflight programme.

However, a more complete range of opportunities opens up if a larger investment is made. This is shown as 'Option 4b, Integrated human and enhanced robotic' on the graph. Using plausible assumptions, the analysis carried out by London Economics suggests that investment in technologies such as oxygen production from lunar materials could be worth in total over £400m net to the UK economy; the provision of communications and navigation services to the international lunar exploration endeavour could be worth as much as £6bn; terrestrial application of space medicine could be worth £400m and autonomous robotics techniques £2.6bn. Note, however, that these estimates are based on variables with significant uncertainties and could therefore be much higher, but in some cases could fail to materialise.

Between the lower and upper bounds of the two expenditure curves is a range of opportunity in which to optimise UK investment in robotic and human activities to yield the best balance of *economic* return against cost while simultaneously increasing the number of astronaut launch opportunities which exploit the investment for *science* and *outreach/inspiration* purposes. This combination of benefits lies outside the remit of current organisations funding UK space activities.

Option 4 would bring the greatest benefit, increasing the returns for both science and innovation, generating new opportunities for commerce and creating the maximum interest in the value of studying STEM subjects through the existence of British astronauts. It would also maximise the benefits brought through experts from different disciplines working closely together.

1.10 Conclusions

- 1) The UK is securing excellent science, technology and commercial benefits from its investment in the ESA Mars robotic programme.
- 2) A viable option exists to develop a science-driven, national/bilateral robotic exploration programme focused on the Moon and asteroids. This would strengthen and re-balance the UK's space programme which is heavily biased towards ESA at present. The proposed MoonLITE mission fits this scenario.
- 3) A human space exploration programme could be pursued through joining the nascent ESA exploration programme or through bilateral collaboration with NASA (the 'Canadian Model'). Because it prepares for a human lunar exploration programme, the MoonLITE project is consistent with this approach.
- 4) A minimum human spaceflight programme is possible. However, a properly integrated robotic and human programme comprising focused UK contributions to robotic infrastructure and technology would yield a stronger mix of technology impact and economic return while simultaneously delivering the benefits of prominent UK astronauts working on the Moon.
- 5) The analysis prepared by London Economics suggests that there is the potential for substantial direct economic return from associated commercialisation and other technology spillovers. However, these returns are highly uncertain.
- 6) The initial trajectory and level of investment is very similar for options 3, 4a and 4b, which allows a few years to fine-tune investment choices based on delivered performance.

2 Background and issues for the UK

2.1 Introduction

Over the last few years many countries have developed new plans for exploring the Moon, Mars and near-Earth objects. These plans are coalescing into a global endeavour, known as the Global Exploration Strategy. As we enter the second 50 years of space exploration this surge of activity suggests that we are truly on the verge of a second ‘space age’. This presents both an opportunity and a challenge for the UK.

The Space Exploration Working Group

The SEWG was set up by BNSC to provide independent advice on the opportunities and benefits of UK participation in space exploration and on the areas to focus on.

The twenty-three members concluded that:

- The UK should prepare for involvement in the era of global space exploration in both robotic and human aspects.
- The existing UK robotic exploration programme is a success for both science and innovation.
- Expansion to include robotic exploration of the Moon is desirable.
- The UK should seek international partnership within the frame of the Global Exploration Strategy.
- A permanent human outpost on the Moon has good science potential in the period after 2020.
- Increased cooperation between robotic and human space systems is likely.
- Commercialisation aspects are important.
- Joined up education and outreach policy is a must.

The purpose of this report is to develop evidence on options for UK involvement. It builds on previous advice from expert bodies in the UK, principally the UK Space Exploration Working Group (SEWG) which reported to BNSC in 2007³. It considers both the costs and the benefits of an expanded programme of space exploration, as recommended by the SEWG. It takes into account the value for science and innovation, benefits to the economy and to a wider social agenda including education and inspiration, exploiting existing UK strengths in robotic exploration.

Global space revenue from government and private sources reached \$257 billion in 2008⁴ (with a growth rate of 2.4% during 2007 and 11% during 2006⁵) and will expand further as space exploration activities increase. The UK share is currently £7bn.⁶ As international plans develop, exploration will become an increasingly important part of the space sector and the UK must decide whether to become involved from the early stages of this new endeavour.

There are many types of activity which may be termed ‘space exploration’.

For the purposes of this report, we follow the Global Exploration Strategy which sets out ‘a vision for globally coordinated space exploration focused on Solar System destinations

³ *Report of the UK Space Exploration Working Group*, independent report to BNSC, September 2007

⁴ *The Space Report 2009*, The Space Foundation

⁵ *The Space Report 2008*, The Space Foundation

⁶ *Case4Space Summary Report*, UK Space and EADS Space, October 2006.

*where humans will someday live and work.*⁷ For the foreseeable future, this means the Moon, Mars, certain asteroids and certain locations in deep space that have a practical utility, such as the so-called 'Lagrangian' points increasingly being used by space observatories. This definition implies (but arguably may not require) the use of humans.

A programme of space exploration can offer multiple benefits and these drive other countries to pursue such programmes.

- In science, there are outstanding questions concerning the origin and evolution of the Solar System that may be answered through study of the Moon and asteroids.
- Questions concerning the origin and distribution of life, and the conditions under which it arose, may be investigated through exploration of Mars and the Moon. Some of these questions will be best investigated by robots, but others will require humans.
- Having humans on the Moon can also enable a series of important science investigations of the cosmos and will result in new understanding of biology and physiology as astronauts learn to survive in new environments.
- Integrated robotic-human exploration requires cross-disciplinary R&D work, bringing together experts in medicine, artificial intelligence, communications and human-machine interfaces. This forces the development of novel medical interventions and preventive techniques, including techniques for assisted living, that can help support the ageing population of the Earth.
- New business opportunities are foreseen in commerce, telecoms, media, entertainment and space tourism. Designing for harsh environments can drive technologies with applications on Earth in fields such as robotics, autonomous systems, novel power sources, closed-cycle life support systems, advanced materials, medical diagnostics and tele-medicine.
- Space-faring nations throughout the world recognise the power of space exploration as a magnet to attract and retain science and technology talent and to inspire their younger citizens to study science, technology, engineering and mathematics.
- Nations also use space exploration as an instrument of 'soft power': that is, to demonstrate to citizens at home and nations abroad their ability to harness scientific, cultural, and organisational abilities to achieve peaceful goals.
- Cooperation at a global scale with new international partners can demonstrate common purpose and bring greater cultural understanding, thus enhancing global security and developing tools and techniques that may be used to tackle other global challenges

The UK is involved in space exploration through its participation in ESA's Science Programme (which includes exploration of the Solar System) and through the Aurora programme (which is mainly focused on robotic exploration of Mars). The UK is

⁷ *The Global Exploration Strategy: The Framework for Coordination*, May 2007, agreed and published by ASI, BNSC, CNES, CNSA, CSA, CSIRO, DLR, ESA, ISRO, JAXA, KARI, NASA, NSAU, and Roscosmos, http://esamultimedia.esa.int/docs/GES_Framework_final.pdf

presently not involved directly in human space exploration having chosen not to participate in the International Space Station project.

2.2 Overview of this report

This report was commissioned by the Minister for Science and Innovation and the Terms of Reference were agreed by the Secretary of State for Innovation, Universities and Skills in May 2008. It answers a commitment given in the UK Civil Space Strategy published by the Government in February 2008 to *‘undertake a study of programme options drawing on the findings of the 2007 UK Space Exploration Working Group, taking into account the scientific, technological and economic costs and benefits, and UK’s existing strengths in robotic exploration.’*⁸

This chapter provides the background to the issues. The current scale of the global space industry is surveyed, the emergence of the Global Exploration Strategy is explained, and the existing position of the UK is outlined.

Chapter 3 presents options for UK involvement in future space exploration. These options include reducing, maintaining or growing the current level of UK activity. Potential future projects are introduced in order to estimate the costs of these options and to illustrate how they might be composed. An economic analysis carried out by London Economics Ltd. for this review has investigated the scale of the economic benefits that would accrue from the various options. As it is impractical to predict the future economic benefits from technologies that have not yet been invented, this analysis restricts itself to the subset of opportunities for which data is available. A qualitative analysis of four programme options is presented in order to consider the non-economic impacts (scientific, societal, educational etc.).

Chapter 4 presents a synthesis of the findings including a comparison of the different options and overall conclusions.

⁸ *UK Civil Space Strategy 2008-2012 and beyond*, BNSC, 2008, <http://www.bnsc.gov.uk/assets/channels/about/UKCSS0812.pdf>

2.3 The wider space scene and the UK's role

Fifty years after the beginning of the space age, the use of space systems by nations worldwide has become an essential part of everyday life. While the popular image may still be of NASA and its space shuttle launches, in reality, there is a thriving 'space economy' in which countries as diverse as Japan, Nigeria, Brazil and Canada have significant roles and strengths.

Although not widely acknowledged among the general public and media, the UK has an important existing capability in space upon which to build an expanded role in space exploration. The UK is a leader in satellite manufacture (both for large satellites and smaller, low-cost ones), in using space for communications for both civilian and military purposes, and in space science (including Earth observation and exploring the universe).

UK space systems are used to forecast the weather, to monitor and speed the response to natural disasters, to understand climate change and its impacts, to provide global mobile telecommunications both for entertainment and to support our armed forces on critical security duties abroad. They are used to improve transport and distribution services, and to answer basic questions about the history of the universe and the origin and distribution of life.

Thus, the exploration and use of space is already woven both commercially and culturally into the fabric of society.



started its life as an intergovernmental body and now owns and operates one of the largest satellite communications networks in the world, comprising a fleet of eleven satellites operated out of its headquarters in London.

The government investment in the Inmarsat 1-4 satellites generated 40 times the original investment through contracts, jobs and taxation. Inmarsat has recently won a contract from ESA to develop Alphasat 1-XL, which will support a new generation of mobile technologies and communications across Europe and Africa. This was enabled through funding of around £20 million a year from the Government. The contract retains 500 technology jobs in the UK and the projected flow of revenue is £250 million.

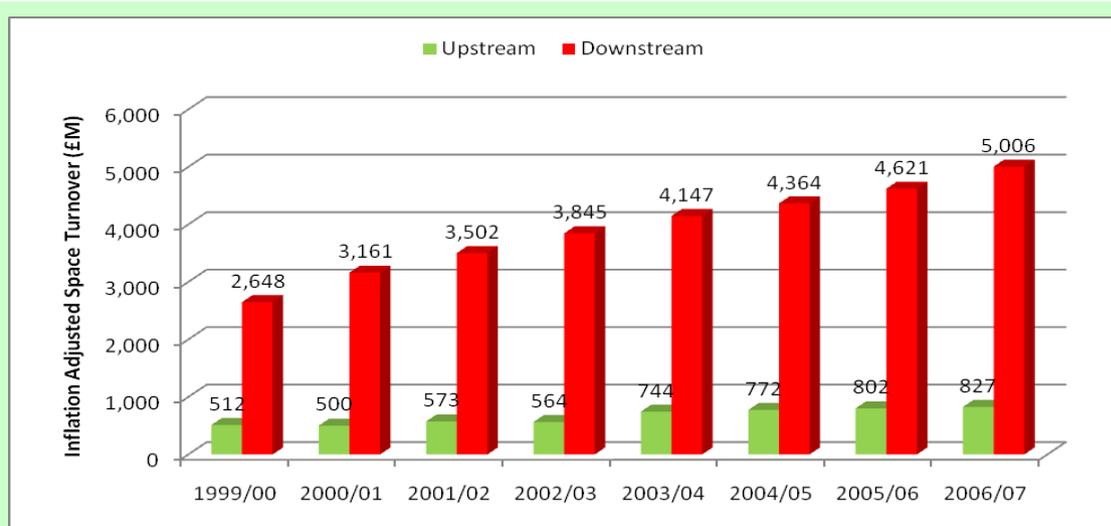


Figure 2. Trend in UK upstream and downstream space turnover⁸

The UK is strong in both the technology (upstream) and applications (downstream) areas of space. The upstream market (technology) is dominated by the space prime market (e.g.



employs almost 300 staff and has launched 32 spacecraft with 9 more in preparation. In 2000 the BNSC's MOSAIC programme funded the prototype of what became the Disaster Monitoring Constellation (DMC). This is a network of micro-satellites that is providing disaster monitoring from space, translating an initial government investment of £15m into a successful business which has so far returned over £100m to the UK economy, and established SSTL as a world leader in the emerging field of low-cost satellites. The success of DMC helped SSTL win the ESA contract to design and build the Galileo demonstrator GIOVE-A.

satellite manufacturing) while satellite broadcast services currently dominate the downstream activities (applications). The total turnover in 2006/2007 was £5.8 billion, which continues the trend for growth. The downstream sector is now 85% of the total. Growth is continuing to increase with an 8% increase between 2005/6 and 2006/7⁹ (see Figure 2), more than three times faster than the economy as a whole.

UK space supports 68,000 jobs and contributes £6.5 billion to GDP,¹⁰ and customers include the commercial sector (80% of the total), military, government and space agencies. It is predicted that space could add £150 billion to the UK economy by 2020.¹¹

The UK is currently a successful player, but to retain our position we must stay at the cutting edge of science

⁹ *Size and Health of the UK Space Industry*, BNSC, 2008)

¹⁰ *The Case for Space: The Impact of Space Derived Services and Data*, Oxford Economics, May 2009

¹¹ *Vision 2025*, UKspace, June 2007

and technology developments. A promising path to doing this is through space exploration.

Estimates of the world space economy have indicated that the underlying trend is one of major growth (see Figure 3). The market for space-enabled research worldwide is expected to grow by a factor of 10 by 2020.¹³ Each nation involved in space demonstrates a return on government investment of a factor of three or more.

Developing economies are investing heavily in space and this is changing the balance of expertise around the world. For example, both China and India already have larger space programmes than the UK and have even greater ambitions for the future.

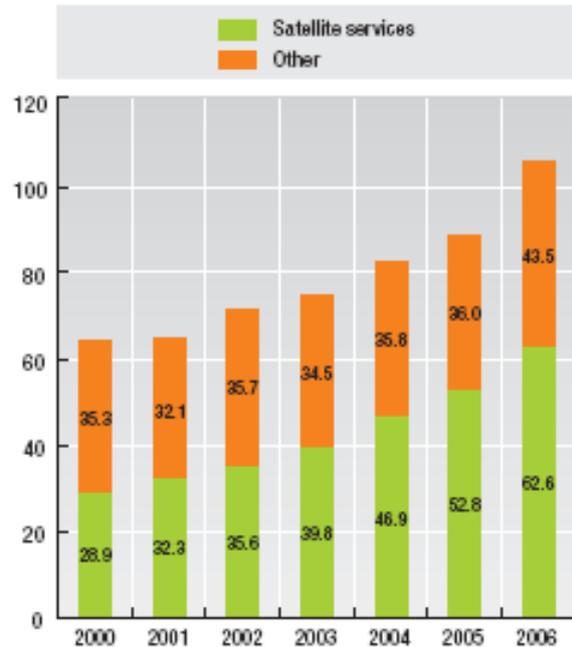


Figure 3. World satellite industry revenue (\$bn) for services and other (ground equipment, launch industry and satellite manufacturing).¹²

The UK needs to act if it wishes to maintain or increase its stake in growing international space markets and thus increase its high impact on the UK economy.

2.4 What is space exploration?

In the context of this report space exploration encompasses the region of the solar system that is accessible to human beings using currently feasible technology (or to reiterate the Global Exploration Strategy, '*Solar System destinations where humans may one day live and work*'). This includes the Moon, Mars, certain Near Earth Objects (asteroids) and particular regions of space from Low Earth Orbit (LEO) through to the various libration points in the Earth-Moon and Earth-Sun systems. These latter locations have special properties and uses (see box on p22).

Excluded from this definition of space exploration is the purely scientific exploration of the outer Solar System (since we cannot yet build space vehicles able to carry and protect astronauts on such voyages), as well as space-based observatories used to study the stars and universe beyond. Likewise unmanned satellites in Earth orbit are excluded – for

¹² *Space Economy at a Glance*, OECD, 2007

¹³ *Case4Space summary report*, UK Space and EADS Space, October 2006.

example those providing Earth observation, communications and navigation services). Both robotic and human activities are included – exploration *per se* does not favour one over the other, though in many cases a combination of both is the best approach.

Space exploration within this definition encompasses projects which may combine in varying degrees scientific, technological, cultural and economic goals. Example goals include science objectives such as the study of lunar geology to understand the history of the Earth; technology demonstrations, such as testing new communication techniques; and commercial projects such as the search for usable mineral resources on the Moon or Near Earth Objects.

In the medium term, the main focus of international space exploration efforts will be on the Moon and Mars. The Moon is of interest in its own right, since it holds a (probably unique) record of the origin and evolution of the Solar System, but it will also serve as a test-bed to demonstrate the techniques needed for more complex missions to Mars. The brief visits by the Apollo astronauts between 1969 and 1972 – a total of about 100 hours on the surface between the twelve moonwalkers – barely scratched the surface of our nearest neighbour in the Solar System. A sustained return to the Moon offers a huge range of opportunities which are now being defined by the scientific and technological communities. In the UK, the Space Exploration Working Group carried out a survey of lunar exploration opportunities as part of its report published in 2007.³

The international community is interested in Mars since it has similarities with Earth (for example an atmosphere, seasons, and the possibility that life has existed or could have existed). Robotic exploration has been underway since the primitive probes of the nineteen-sixties but has gathered pace only in the present decade thanks to the current generation of missions, notably the European Mars Express orbiter and the NASA rovers *Spirit* and *Opportunity*. A major medium-term goal is to return samples of Mars to Earth using robotic probes. This is seen as a major international mission for the decade beginning 2020 and will stretch robotic mission technology to the limit. Far more technically challenging will be human expeditions to Mars which will first require demonstration of many techniques using both terrestrial analogues and preparatory lunar missions.

Lagrange Orbits

There are several points in space where the gravitational pull from the Earth combines with that of the Sun to create stable orbits. One such point is located about 1.5 million km from the Earth in the direction towards the Sun, and a satellite located there can orbit the Sun while staying at a fixed distance and direction from Earth – a location especially useful for spacecraft observing the Sun.

A similar point exists about the same distance from Earth but on the night side – this is especially useful for sensitive astronomy missions since they avoid passing in and out of Earth's shadow and are far from its radiation. Two points in the same orbit as Earth, but 60° in front and behind it, are especially stable and could therefore make useful locations for future space stations, minimising the fuel needed to maintain orbit. An equivalent set of Lagrange points exist around the Earth and the Moon, offering further possibilities for space stations.

The benefits of space exploration can be both direct (benefits arising from the objectives of a particular mission) and indirect (arising as a by-product of the mission). Examples of each include:

- securing new knowledge;
- driving the development of new technologies;
- encouraging innovation;
- exploiting new direct commercial opportunities;
- inspiring the next generation to take an interest in science;
- maintaining that interest to help provide and retain a skilled workforce;
- promoting the UK as place to invest;
- marketing UK innovation globally.

Take as an example a possible UK involvement in a robotic Mars sample return mission, something which is already being planned. The nominal, scientific, goal is to recover a number of samples of rock, soil and atmosphere from Mars, in order to understand its history, to understand whether it could or does harbour life, and if not, why not. At a cultural level, the age-old question 'are we alone?' is likely to be answered in the present century. A Mars sample return mission and subsequent human missions will be fundamental parts of the answer. Whether or not the UK chooses to play a role in such a global scale and globally visible project, it will occur anyway.

Technologically, such a mission will require new capabilities in autonomous docking and rendezvous of space vehicles, techniques potentially relevant to other applications of space, such as the remote assembly of large communications antenna farms or the construction of solar power satellites.

Such autonomous robotics know-how clearly has many terrestrial applications in transportation and where human-robot interaction must be safe and secure.

Lunar communications infrastructure – mobile phones on the Moon?

Long term activity on the Moon (scientific, human exploration, resource exploitation, etc) will require various types of infrastructure such as navigation, communications, and habitation. The UK, with established strengths in activities such as low-cost satellites and both ground and space-based communications, can confidently look to providing infrastructure for the Global Exploration initiative such as lunar orbiting communications systems, and to develop this as a commercial offering in the same way as terrestrial satellite communications.

Tuberculosis detection – from searching for life on Mars to saving life on Earth

In common with existing space activities, present and future space exploration can be confidently expected to lead to a whole range of translational benefits, economic, technological and others.

A current example is the development, funded by the Wellcome Trust, of a portable instrument for the *in-situ* detection of Tuberculosis in sub-Saharan Africa derived from miniaturised and low-power instruments developed for use on Mars and in exploring a comet (on the Beagle 2 and Rosetta missions).

Further, in order to protect Mars from contamination by terrestrial organisms, and likewise to protect Earth from the (very unlikely) threat of contamination by Martian organisms, elaborate robotic handling of the samples from their initial acquisition on the planet all the way back to their examination in Earth-bound laboratories will be needed. Such techniques will draw on, drive forward and then spin back out techniques for securing, handling and examining hazardous nuclear or biological substances on Earth.

Thus, as the most demanding area of space activity, the techniques developed through space exploration can help to drive other areas of space endeavour (such as Earth observation, communications, navigation), and thus ensure future competitiveness. In this regard, it is notable that the Indian Space Research Organisation has given the need to advance the skills and capabilities of its space workforce as

one reason for moving beyond its established Earth observation and communications space programme into lunar exploration (India launched its first lunar probe in 2008). But beyond the space uses, the technological advancement can be employed by industries in many other sectors.

International exploration of the Moon, Mars and near-Earth objects will go ahead, delivering a range of benefits to participants. The UK must decide if it wishes to play a significant part in these activities.

2.5 International space exploration scene

Recognising their common interests, 14 of the world's space agencies, including the UK, worked together between December 2005 and May 2007 to agree a shared vision for space exploration. The resulting Global Exploration Strategy¹⁴ provides a framework for collaboration between participating nations. It sets out a new way of working by acknowledging the different goals of each nation, while seeking to enable cooperation on activities that may be mutually supportive.

The body tasked with implementing the GES is the International Space Exploration Coordination Group (ISECG). This group met for the first time in November 2007 in Berlin and 13 of the original GES signatories (including the UK) are now members. Participating agencies share interests, objectives and plans in space exploration with the goal of strengthening both individual exploration programs and the collective effort.

ISECG is working on a roadmap for future exploration and is developing standards to ensure that future missions are compatible (for example allowing mechanical elements to connect together and hence increase redundancy, efficiency and possibilities for international collaboration). It is also beginning to address questions such as the opportunities for commercial developments and

The Global Exploration Strategy

As the International Space Station neared completion, it had become clear that space-faring nations were setting their sights higher and preparing for the next destinations beyond Earth orbit – to the Moon, Mars and other destinations where it is possible that humans may reach.



The nations that created the Global Exploration Strategy did so because they understood that sustainable space exploration is a challenge that no one nation can do on its own. But they also understood that each had their own reasons for exploration and that collaboration would be more successful if these differences were acknowledged. They thus created a framework for coordination rather than a single global programme. This mechanism would strengthen the work of individual nations as well as the collective effort as a whole.

While each nation may have different objectives, the GES expresses a vision shared by all. This vision describes how exploration of the Moon, Mars and beyond will be used to derive new knowledge in science and technology, to develop a sustained human presence in space, to encourage economic expansion, to create new global partnerships and to inspire and educate people, especially the young.

¹⁴ *The Global Exploration Strategy: The Framework for Coordination*, May 2007, agreed and published by ASI, BNSC, CNES, CNSA, CSA, CSIRO, DLR, ESA, ISRO, JAXA, KARI, NASA, NSAU, and Roscosmos, http://esamultimedia.esa.int/docs/GES_Framework_final.pdf

the need for international legal frameworks.

International Space Station

The International Space Station (ISS) is a joint venture between the USA, the European Space Agency (ESA), Russia, Japan, and Canada. It is a large and complex structure orbiting about 400 km above the Earth's surface. It is composed of several modules that have gradually been bolted together, in orbit, over the last 10 years, and will be completed by the end of 2011.¹⁵ It now has a permanent crew of six astronauts and in October 2009 Belgian Frank de Winne took control as its first European commander.

ESA's Columbus laboratory was attached to the ISS in February 2008, and contains racks of biological and medical instruments, as well as experiments in fluid physics, materials science and physiology.

One of the major achievements of the ISS has been the ability to maintain astronauts in orbit for extended periods of time. This is a necessary first step for any human space exploration programme. It will also be used increasingly to demonstrate technologies needed for future exploration missions.

The UK has not contributed to ESA's optional ISS programme.



Figure 4. The ISS as it is today. (Image ESA/NASA)

The GES thus presents an opportunity for cost-effective engagement in space exploration with partners in other countries.

The UK has played a strong intellectual role in developing the framework for the GES and there is a current window of opportunity for the UK. As the International Space Station (ISS) nears completion, the ISS Partners have begun to plan the next stages in their programmes of space exploration.

China and India are starting ambitious programmes of human spaceflight, while other countries such as South Korea and the Ukraine are starting to plan their involvement. As these plans begin to crystallise, it will become increasingly difficult for other players to claim leadership in their chosen areas.

¹⁵ A timeline for construction of the ISS is available at http://esamultimedia.esa.int/multimedia/esa_iss_assembly_sequence/index_pop.html.

The Return to the Moon – a possible vision for 2025

By 2025 the Global Exploration Strategy suggests that we will have delivered significant infrastructure to the surface of the Moon. A lunar base will have been established, perhaps near the Shackleton crater at the South Pole, staffed by teams of astronauts for several months at a time. These will be international teams of scientists, engineers and technologists and maybe even writers and educationalists.

New technology will be used to supply oxygen from material on the lunar surface and electricity from nuclear and solar power sources. Manned and unmanned rovers will explore the surface with the aid of lunar GPS. Geologists will study the Moon's crust to help understand the evolution of the Solar System and astronomers will use the far side of the Moon to study the cosmos in unexplored parts of the electromagnetic spectrum.

New medical technologies will be developed to support the teams on the Moon. These will have applications to terrestrial healthcare – for example personalised medicine. The first lunar tourists will accompany some of the professional astronauts.

Education will be carried out using virtual reality technology, and access to the Moon will be provided to schools worldwide for education and entertainment.

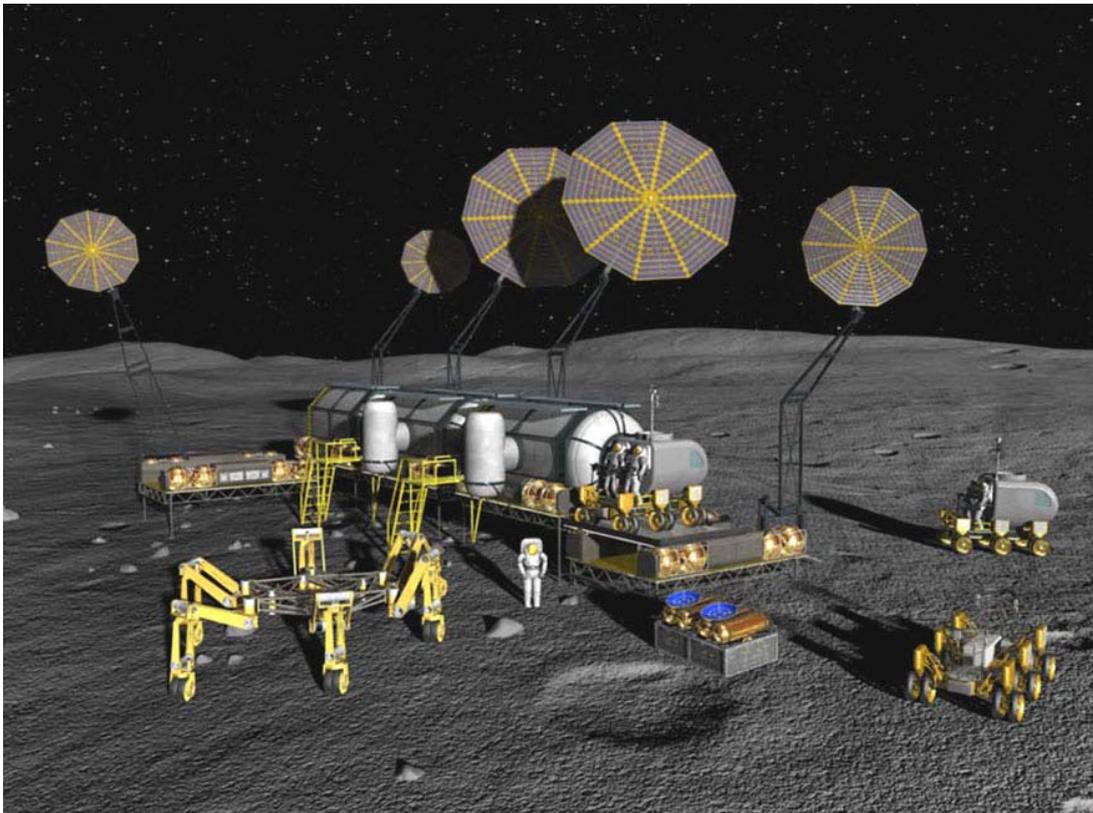
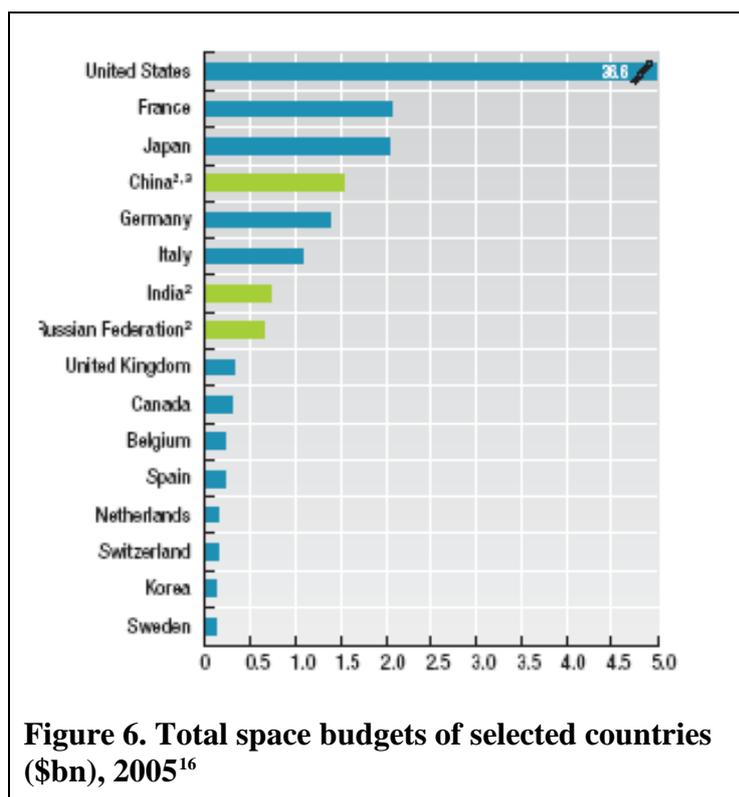


Figure 5. Artists impression of lunar base (Image NASA)

The Global Exploration Strategy provides an opportunity for cost-effective engagement in space exploration.

2.6 Plans of other nations

Space exploration is no longer confined to a small number of players, but is being carried out by an increasing number of countries. While space agencies do not all define the proportion of their budgets dedicated to exploration, an idea of the relative levels of activity can be gauged from the overall space budgets of the main players. The most recent available figures are shown in Figure 6, below, and total space budgets as a proportion of GDP are shown in Figure 7 on p30.



In **Europe**, the EU and the European Space Agency (see box on p29) agreed in 2001 a strategy to explore the Solar System, stimulate technology and inspire in young people an interest in science and technology. The result was ESA's planetary exploration programme, Aurora, to conduct robotic and human exploration of the Solar System (especially Mars) and to search for life beyond Earth. The UK is a major partner in Aurora: it is the second-largest contributor to the ExoMars mission which will search for evidence of past or present life on Mars and UK industry is leading the ExoMars rover project; it is also the largest partner in the programme to develop technology for future Mars missions.

Collaboration through ESA enables its member states to engage in exploration on a level with other international powers. In addition, the three biggest ESA members, France, Germany and Italy, also have significant national programmes to ensure that they gain the maximum value from their involvement. Each has a different focus, but all seek to maximise the gains for their nation in science, technology, innovation and economic impact. All three regard human spaceflight as an important activity, providing the most visible part of their programme to the public and generating inspiration for the next generation.

¹⁶ *Space Economy at a Glance*, OECD, 2007

The **United States** has the largest space budget of any nation (NASA received \$17bn in 2008) and thus its plans dominate the international effort. Its programme supports Earth and space science, aeronautics and construction and operation of the majority of the International Space Station. In 2004 the Vision for Space Exploration set out US plans to set up a permanent outpost on the Moon for science and exploration and to implement a sustained and affordable human and robotic exploration programme. The goal is *'to advance US scientific, security, and economic interests through a robust space exploration program.'*¹⁷ It also uses space exploration as 'a strategic tool of U.S. diplomacy to strengthen relations with allies, reduce future conflicts, and engage members of the developing world.'¹⁸

NASA received an additional \$1bn in 2009 as part of an economic stimulus package by the incoming administration and the budget request for 2010 seeks to consolidate this increase. Under this proposal NASA's annual budget for human space exploration would increase from \$4bn to \$6bn.

In early 2009, a high-level committee was appointed by President Obama to review the implementation of NASA's human spaceflight plans. The goal is 'to provide options that will ensure the nation's human space flight program remains safe, innovative and affordable in the years following the space shuttle's retirement.'¹⁹ The report was published in October 2009.



The European Space Agency (ESA) is a multi-national agency that facilitates access to space. The UK was among the founders in 1975. It now has 18 member states and cooperates with the EU (though it is separate from it).

One of the major goals of ESA is "to ensure that investment in space continues to deliver benefits to the citizens of Europe and the world." ESA's activities are divided into programmes, which are either mandatory (all member states contribute in proportion to their national Gross Domestic Product) or optional (a member state may choose to contribute, or not). The main Science Programme is mandatory, but the robotic exploration and human spaceflight programmes are optional.

The UK joined the robotic exploration programme (known as Aurora) in 2005, and is one of the nations driving this agenda; activities include the robotic exploration of Mars. In contrast, the UK is not a partner in the human spaceflight programme (set up to co-ordinate access to the International Space Station and the European astronaut corps).

ESA has over 2000 employees based at five centres. It is funded by its member states with an annual budget of around €3.6 billion (2009). A recent agreement between ESA and the UK established a centre at Harwell, the first completely new ESA centre to be opened for almost 20 years. It is anticipated that the centre will become a focus of ESA's robotic technology development and innovation in using space for many practical applications, as well as becoming Europe's leading centre of expertise in planetary protection.

¹⁷ NASA Authorization Act, 2005

¹⁸ *Advancing the Frontiers of Space Exploration*, Barack Obama, 2008

¹⁹ NASA Press Release 09-102, 7 May 2009

The US is working actively with international partners under the aegis of the Global

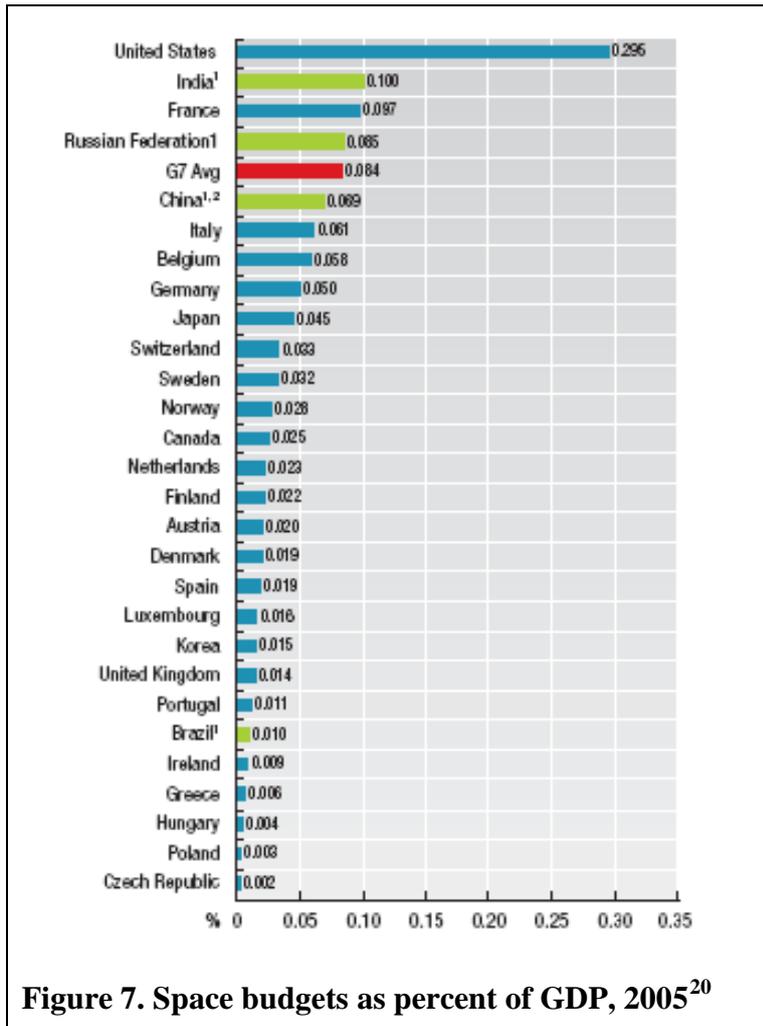


Figure 7. Space budgets as percent of GDP, 2005²⁰

Exploration Strategy and has worked closely with the UK in support of the proposed UK-led MoonLITE mission. The US also leads the International Lunar Network which is intended to create a network of science sensors across the Moon provided by missions from many different countries. The UK is a member.

Despite its much smaller GDP, **Canada** has roughly the same civil space budget as the UK. Its interest in space exploration is mainly for science and innovation, but also to demonstrate Canadian capabilities and to attract and retain talent in Canada. It has successfully built and installed robotic arms on the Shuttle and the ISS in exchange for 14 flights of its astronauts, who are trained by the USA.

Japan spends some £1.3bn a year on its space programme. Its vision for 2025 is to develop world-class launch vehicles and satellites with an aim to build a secure and prosperous society. In exploration, it is preparing for human space activities and for the utilisation of the Moon, and plans to take a leading role in a lunar base. It has a satellite in orbit around the Moon as well as one on its way back to Earth carrying a sample of material collected from an asteroid.

China has increased its space activities very rapidly over the last 15 years, partly to demonstrate its increasing international importance and partly as a driver for its industry. In 2003 it became the third nation to launch its own astronauts. It has a satellite in orbit around the Moon as well as those for Earth observation, meteorology and disaster monitoring.

Russia uses space to enhance the quality of life of its people, maintain economic growth, foster development and increase national security. Exploration of the Moon has a very high priority in its strategy and manned missions are planned for scientific, technological and economic benefit.

²⁰ *Space Economy at a Glance*, OECD, 2007

Astronaut programmes

So far the citizens of 38 countries have flown in space. The most active programmes are in the US, Russia, Europe, Canada, China and Japan. ESA currently has an Astronaut Corps of 14, including Frank de Winne who became Commander of the ISS in October 2009 and Tim Peake from the UK who joined the corps in September 2009. European astronauts work as members of international crews to install and maintain equipment and to carry out experiments.

India has also become a major player recently, with its own launch capabilities and various satellites, including Chandrayaan-1 currently orbiting the Moon and carrying a UK-built science instrument. It plans its own programme of robotic missions to the Moon and Mars, as well as human missions to Earth orbit and, in due course, to Mars. These are intended to advance the skills and capabilities of its workforce and to advance technology for use in industry.

More detail on the programmes of these countries is provided in Appendix B.

Many countries have announced significant plans for space exploration, each with its own goals and motivations.

2.7 Commercial players

There are increasing numbers of commercial players in the space industry who provide services to government and private sector users in fields such as communications and transport, while others are addressing new areas such as space tourism.

Although space exploration has been science-driven to date, and compelling science will continue to be a good reason to explore beyond Earth orbit, terrestrial exploration capability has historically jumped ahead when business drivers and commercial returns are also identified. Governments also favour injection of private sector funds to improve public sector value for money.

Commercial players can broadly be divided into companies that:

1. already have a product;
2. are developing a product;
3. purchase services (mainly flight opportunities) from government or military sources to sell to the public;
4. provide support services.

A specific company might operate in more than one of these fields. Each category of company is considered below, with specific commercial examples.

2.7.1 Companies that already have a product

Space agencies have always contracted industry to build spacecraft and associated instrumentation. From this has developed a significant global industry that has evolved beyond simply supporting government and military requirements to a non-government turnover of \$174bn or 68% of the world space market.²¹

Several companies have built spacecraft, satellites and associated technologies for remote or robotic operations (e.g. communications satellites) for government, military or commercial purposes. For example: Paradigm, a subsidiary of EADS Astrium, built and operates the three-satellite Skynet 5 network that is used for military communications by the UK Ministry of Defence and other users. Lockheed-Martin, Boeing and Northrop-Grumman are examples of huge aerospace organisations that for many years have been prime contractors to NASA in the development of spacecraft and launch vehicles.

2.7.2 Companies that are developing a product

This category includes companies that are motivated by the vision of a new generation of space exploration that is not controlled by government or military spending. Some are working to lower the cost of spaceflight so that it becomes more available to all. Products include spacecraft to enable space tourism for the public, as well as spacecraft that can operate under government contract.

For example Orbital Sciences is developing a re-usable vehicle for transporting astronauts to the International Space Station. Bigelow Aerospace is developing a space habitat capable of supporting a human crew, and currently has two prototypes in orbit (Genesis I and Genesis II). These are demonstrating the technologies necessary to construct and deploy a full-scale, crewed, commercial orbital space complex. Blue Origin is developing a vertical take-off, vertical-landing vehicle designed to take a small number of astronauts on a sub-orbital journey into space, whilst XCOR is building a horizontal take-off vehicle for a similar purpose.

Reaction Engines in the UK is developing a reusable single-stage-to-orbit space plane that can carry cargo into orbit and has secured some preliminary development funding from BNSC and ESA. Virgin Galactic aims to develop and run the world's first commercial spaceline, with a fleet of their own sub-orbital spaceships. To this end they have the exclusive rights to products from Scaled Composites, the company that won the \$10m X-prize for the first private spaceship to reach an altitude of 70 km above Earth's surface.

2.7.3 Companies that purchase services

There has been a growth in companies that purchase flight opportunities from government or military sources to sell on to the public. For example, Space Adventures buys 'spare places' on-board the Russian Soyuz rocket that re-supplies the ISS. The company also sells (for \$102,000) sub-orbital flights that give the passenger a few minutes of weightlessness. The first spaceflight price-war broke out in December 2008, with a company called Rocketship Tours offering sub-orbital spaceflights aboard XCOR's Lynx spacecraft for only \$95,000.

²¹ *The Space Report 2009*, The Space Foundation

2.7.4 Companies that provide support services

As well as companies that have commercial products to market, there is an opportunity for service industries to support such companies. A current example in the UK is Logica, the business and IT company that supports a wide range of commercial and military enterprises. The London Satellite Exchange (a subsidiary of Astrium) matches the requirements of customers to appropriate companies. Serco, more usually seen as a train-operating company, also services military and commercial aeronautical companies.

2.8 Opportunities for the UK and UK strengths

Table 3 is a (non-comprehensive) summary of some of the main companies with interests in the commercial opportunities of space exploration. Companies specifically associated with or based in the UK are marked in blue, demonstrating UK interests in three of the four identified categories. Indeed, Virgin Galactic is one of the main players in the developing space tourism industry although much of the development work associated with this company takes place outside the UK.

Table 3. Example commercial space activities

Company	Category	Offering	Purpose	Address
Astrium/ Paradigm Secure Communications	1	Skynet 5 satellite network	Commercial provider of military- grade satellite communications	http://www.paradigmsecure.com/home
SSTL	1	Commercial satellites	Develop small satellite missions from concept through to in-orbit operations	http://www.sstl.co.uk/
Astrium	2	Space plane	Space tourism	http://www.astrium.eads.net/en/families/space-plane-tourism-flight-shuttle
Bigelow	2	Genesis I, II	Next-generation of crewed space complexes	http://www.bigelowaerospace.com/
Blue Origin	2	New Shepard	Space tourism	http://public.blueorigin.com/index.html
Lockheed	1, 2	Orion	Design and production of spacecraft and instrumentation	http://www.lockheedmartin.com/capabilities/sst/index.html
Logica	4	Logistics	Operations support	http://www.logica.com/space/132007
Orbital Sciences Inc	1, 2	Orion	Satellites and launch vehicles; CEV	http://www.orbital.com/
Reaction Engines	2	Skylon	Provide inexpensive and reliable access to space	http://www.reactionengines.co.uk/index.html
Scaled Composites	2	Tier One Project	World's first privately funded manned space program, including SpaceShipTwo and its carrier aircraft White Knight	http://www.scaled.com/
Space Adventures	3	Space travel	Open spaceflight and the space frontier to private citizens	http://www.spaceadventures.com/index.cfm
SpaceX	2	Dragon	Transport of cargo or crew into orbit	http://www.spacex.com/dragon.php
Virgin Galactic	2	SpaceShip2	Commercial spaceline for space tourism	http://www.virgingalactic.com/

Company	Category	Offering	Purpose	Address
XCOR	1, 2	Lynx	Develops rocket-propelled vehicles, rocket propulsion systems, and propulsion components to customer order	http://www.xcor.com/index.html
London Satellite Exchange	4	Networks	Operations support	http://www.satellite-exchange.com/

Commercial companies are playing an increasing role in space exploration and exploitation, and the UK is home to some of the key players.

2.9 Use of space for skills and education

One of the major impacts of active space programmes is in inspiring students of all ages. With a continuing need to encourage more students to take up careers in science and engineering, it is important to analyse the effect that an extended programme of space exploration could have on education outcomes.

The problem in the UK is well-documented. Whilst the number of young people taking physics A level has increased over the last two years to 24,703 (having dropped from 53,365 in 1983),²² the Government recognises that much more still needs to be done to increase this further and meet its ambitious target of 35,000 entries by 2014. It has also substantially increased its 2014 target for numbers of young people studying mathematics A level to 80,000 (57,618 young people took mathematics at A level in 2008).²³

The Government is fully aware that 'employers continue to be concerned about the supply and quality of graduates in STEM subjects' and points out that, 'Although the **supply** of STEM graduates has increased, it hasn't increased as fast as for non-STEM graduates (over the period 2002/03 to 2006/07 STEM qualifiers grew by 11% compared to 15% for non-STEM) and employers tell us anecdotally that **demand** for STEM graduates outstrips this.'²⁴

The Government is doing much to increase the number of young people studying STEM subjects in school and beyond. It has allocated £140m (over the period 2008-11) to support its strategy to educate the next generation of scientists and mathematicians. This aims to make learning more engaging, relevant and exciting for pupils of all ages, to make young people aware of the range of interesting careers and opportunities open to those who study STEM subjects, and to increase the number of specialist science and mathematics teachers and ensure they have access to good quality continuing professional development that leads to better quality teaching and higher achievement.²³

²² *The Demand for Science, Technology, Engineering and Mathematics (STEM) Skills*, DIUS, January 2009

²³ Department for Children, Schools and Families, 2009

²⁴ *Higher Education at Work – High Skills: High Value*, DIUS, April 2008

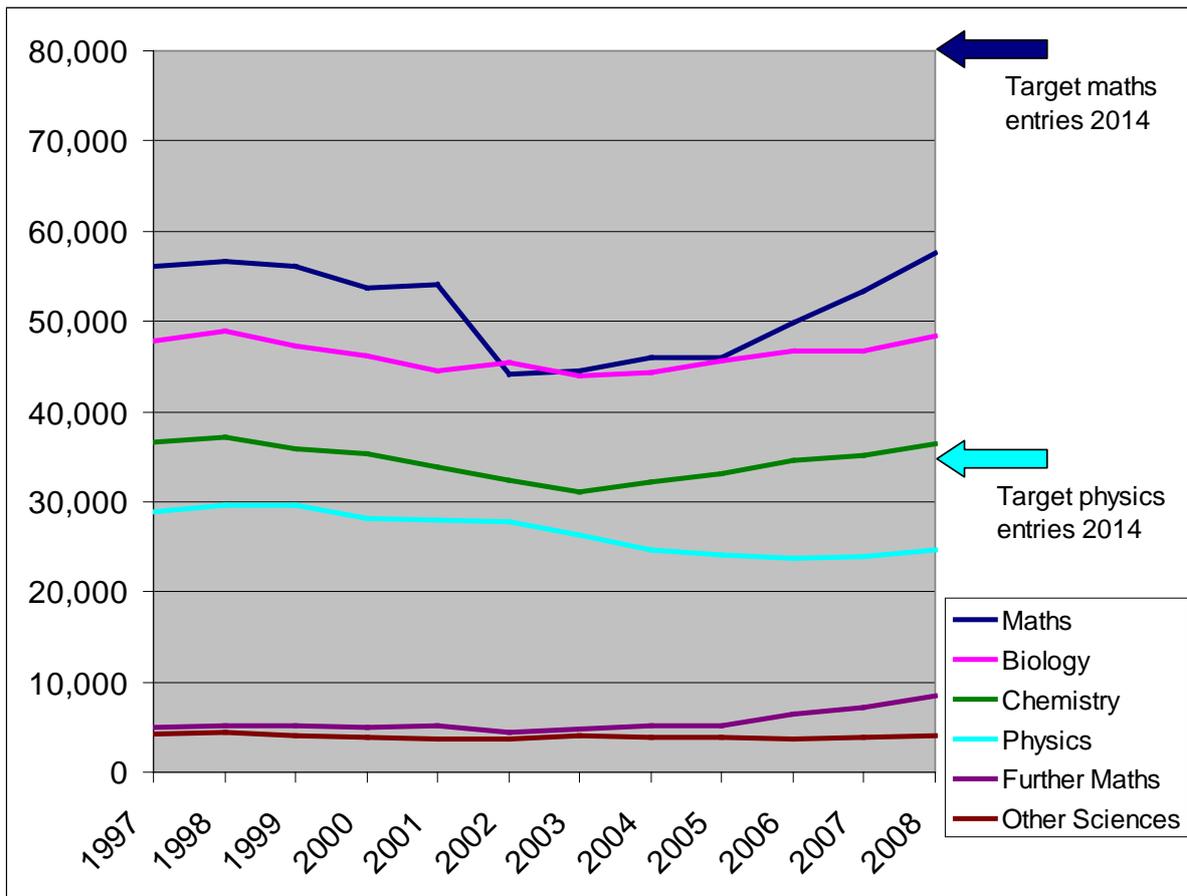


Figure 8. Total A-level entries at schools and colleges in the UK²³

While numerical evidence on the value of space in education is rather limited and hard to establish, many studies have provided anecdotal evidence. For example the Barstow report²⁵ stated that *'The accumulated evidence base demonstrates that space and astronomy topics are of major importance in stimulating young people to enjoy science and to encourage more participation in science subjects.'* Many space topics are well suited to education aims, with activities illustrating topics in physics, chemistry, mathematics and engineering, as well as in geography, citizenship and (for human missions) biology. The sense of adventure implicit in the *exploration* of space gives additional impact, especially when astronauts are involved who can relate their experiences directly.

"Our survey found that space has a direct, positive effect on educational and career decisions and on participation and achievement in physical sciences at GCSE, A-level and in Higher Education. It also improves motivation and behaviour. Substantial anecdotal evidence and limited but persuasive quantified evidence [...] support these assertions.

²⁵ Barstow, M., *Bringing Space into School Science*, report commissioned by BNSC, 2005, <http://www.stfc.ac.uk/Resources/PDF/barstow.pdf>

"Respondents feel that space appeals to boys and girls across ages, abilities and cultures; it connects to unanswered questions, large scale resources and innovative technologies. Beyond science, it has global, environmental, ethical, humanitarian and enterprise dimensions. No other theme is suggested with as much opportunity to interest, motivate and influence young people."

The Education and Skills Case for Space²⁶

Current UK education activities related to space include the Scottish Space School which has reached a very large number of students in the age range 5 to 18 (22,000 in 2005/6), the new Space Academy (funded by the East Midlands Development Agency and involving the National Space Centre, the Science Learning Centres, STEMNET and two universities), the Leading Space Education Project (a joint project between STFC and the Specialist Schools and Academies Trust) and the new European Space Education Resource Office (ESERO-UK, funded by ESA and DCSF and run by the National Science Learning Centre). BNSC HQ is actively collaborating with DCSF and with the skills arm of BIS. Any future programme should capitalise on these initiatives to ensure the widespread take-up of the opportunities that would arise.

It is clear that the key to ensuring greatest impact for education is to ensure that it is embedded into every new space programme from the start. The linkage between space exploration programmes and education should be strategic, explicit and with measurable educational outcomes for learners and educators.²⁷

Space exploration can play an important role in the vital task of increasing STEM uptake in the UK.

²⁶ Spencer, P. and Hulbert, G., *The Education and Skills Case for Space*, survey for BNSC, EADS Astrium, PPARC and Yorkshire Forward, 2006

²⁷ Ojha, A. (Director of Education, National Space Centre), private communication

2.10 Current UK space policy and opportunities

Since 1986, when work began on the ISS, the UK has chosen not to invest in any programmes of human spaceflight. However it is the fourth largest investor in ESA, but judged by investment in space as a fraction of GDP, it is some way down the list of European nations (see Figure 7 on p30). Instead the UK has targeted areas that were considered to be particularly advantageous to the UK's future prospects. As a result, this has meant that the UK has not been seen as one of the large space powers and has had to develop a strategy of selective investment in which it aims to be at the cutting edge of its chosen areas, making the most of its investments through strategic international collaborations.

Through these investments the UK can claim some degree of international leadership in satellite manufacture (both for large and small satellites), low-cost small satellites, mobile communications, rovers, autonomy and space science. This selective approach is reflected in the support of ESA programmes and in bilateral ventures outside ESA.

As a result the UK is now well-positioned in the discussions that are taking place under the auspices of the Global Exploration Strategy for the definition and future direction of this major world-wide exploration undertaking. This is because the UK has quite specific and identifiable areas of expertise where it could lead in this global venture.

The funding structure currently in place in the UK is based on the 'user pays' approach, whereby funding for space activities is tensioned against related activities. For example the cost of monitoring the environment from space can be compared with the cost of collecting the same data on the ground by the scientists best able to judge.

This has worked well in most cases where a single user can be identified, but has caused considerable problems where there is more than one user department each with a different level of interest. This effect is compounded in the case of space exploration since there could be equal benefits for many areas – including science, innovation, commerce, education and society. Some of the objectives of space exploration – such as innovation and inspiration – might well be achieved by other means, but only space exploration combines these with expansion of the boundaries of human knowledge and presence beyond Earth. However, the individual beneficiaries of such a programme would not have the mandate or the competence to judge the wider benefits outside their own areas and thus there would be barriers to seeking agreement among them on the best path to follow.

The UK has focused its resources on a few key space activities which could form the basis for a strong participation in international space exploration, but agreement on a path to follow will require cross-departmental agreement and strong political leadership.

2.11 Choices for the UK

The UK has taken a conservative approach to investment in space over the last few decades. As a result, and despite its great capabilities and achievements in space, it is a 'sleeping giant' compared with its international competitors. It is now clear that an expanded international programme of space exploration will happen, and at an increasing pace (with some short term slow-down due to the worldwide recession perhaps), whether the UK participates or not. It is now necessary to decide where the UK's future lies in this endeavour and to act resolutely in securing the path to achieving it.

There are some major decisions for the UK if it wishes to play a significant role in the new space exploration initiative for the next 3 decades. The international community is beginning to define the infrastructure that will be used on the Moon and elsewhere for the next 20 to 30 years. Decisions taken in the coming few years will thus affect the role that the UK does or does not play in this initiative for years to come.

The UK must decide on its level of ambition to join its international partners in space exploration, and must decide if it makes sense to choose to opt out of human-related activities.

2.12 Summary Points

1. Space exploration means the systematic exploration by robotic and human means of destinations upon which humans will one day live and work.
2. It is no longer confined to a small number of players but involves many countries plus emerging commercial organisations.
3. Space exploration combines scientific, technological, societal and political goals.
4. The completion of the International Space Station in 2010 coupled with the development of the Global Exploration Strategy, which sets new goals for the international community, has created a decision point to define its future direction in space exploration.
5. The UK has a strong foundation in its scientific and technological capability in space, but as the rest of the world moves forward, the window for decision-making will become more limited.
6. The options for the UK's engagement include working with a range of partners in a multi-lateral way: thus a key issue is to select an approach which plays to the UK's strengths and maximises the benefits.

Chapter 3 presents a detailed analysis of several options for UK involvement in space exploration including analysis of the status quo and options for increasing investment in robotic and human exploration. The costs and benefits are analysed and example activities are detailed.

The overall findings are summarised in Chapter 4.

3 Options for UK investment in space exploration

The previous chapter set out the background to the current global resurgence of interest in space exploration and explained that the UK is now at a critical point in deciding its way ahead. There are very many different possible paths, but to enable a reasoned debate on the choices, several clear levels of involvement can be distinguished, each delivering different benefits and representing different levels of ambition.

Four options have been considered to illustrate these different levels of future UK investment. Three of these correspond to those identified by the Space Exploration Working Group and listed in the Terms of Reference of this Review (see Appendix A). For completeness and in accordance with standard government practice, an additional 'reduced option' has been included which provides a baseline against which the others can be compared.

In order of increasing cost, these options are:

- 1) **Reduced option:** eliminate involvement in space exploration and restrict the UK to the mandatory ESA Science Programme only.²⁸ This is the minimum level that could be conceived without taking the drastic step of leaving ESA altogether.
- 2) **Status quo:** continue with the current level of investment (restrict to ESA Science programme and the robotic Mars exploration programme). This option would see the UK taking no serious role in the GES and the new opportunities that it provides.
- 3) **Increase investment in robotic-only exploration,** focused on Moon and asteroid exploration through national projects and bilateral activities with other space agencies. This would build on current UK strengths in robotic space activities and provide opportunities for innovation and commercial development, but would (as now) exclude activities involving humans in space.
- 4) **Invest in both robotic and human activities,** building on the UK's strength in robotic technologies to secure astronaut places in the human exploration of the Moon. Two versions of this option are included to illustrate the range of expected costs and benefits:
 - a) The minimum investment required to secure the involvement of UK citizens in human spaceflight. This would include investment in one key niche area to provide a service which could be traded for astronaut flights, but would exclude all other technological developments assumed in Option 3.
 - b) A modest, but integrated, programme including both robotic and human activities. This would combine the main elements of Option 3 and Option 4a in order to deliver maximum impact across the full range of benefits, including innovation, science, commerce and education.

²⁸ The ESA Science Programme covers a range of science disciplines including astronomy, the study of the Sun and planetary science, entirely using robotic missions. There are no missions planned for exploration of the Moon and Mars for the foreseeable future within this programme.

3.1 Implementation of options

Each option may be implemented through a combination of specific projects or 'programme elements'. A programme element might mean a specific space mission, such as the proposed MoonLITE lunar mission, a technology development programme for novel space power systems, or a supporting space education and outreach initiative. These programme elements each have their own schedules and cost profiles which have then been combined to define the overall budget envelope for each option and also to suggest the points at which major reviews should be held to judge progress and revise priorities.

To varying degrees, each of these programme elements creates opportunities for science, innovation, commercial endeavour and education. The benefits of these elements have been analysed and summarised in the following sections. In particular – and in order to illustrate the potential economic impact of each of the options – several programme elements with *commercial* potential have been selected for more detailed analysis: we have called this subset our 'opportunities', and the analysis approach used is discussed further below.

3.1.1 Programme elements for each option

The programme elements were selected in discussion with industry experts at a dedicated workshop. Each element was chosen for its relevance to UK skills and goals and a nominal cost profile was agreed. Some elements could be implemented by the UK acting alone, but most would be best tackled in collaboration with one or more international partners. This is reflected in the relevant cost profiles.

Each high level programme option could then be built up out of combinations of these elements, together with a few over-arching activities such as management and outreach/education. The wider international context was factored in, for example: the schedule of the US human lunar programme, current thinking on European exploration projects, and realistic timescales to achieve the necessary level of technology readiness.

The programme elements are briefly introduced in the following sections on each option. However, the complete list of elements and their detailed spend profiles are presented more fully in Appendix C.

Note that the programme elements included in each option are only intended to *illustrate* what could be achieved at different levels of investment. While each combination is self-consistent, other combinations could well be imagined. The first job of a body entrusted with executing an extended programme of space exploration would be to re-examine the mix of activities in the light of changing circumstances, goals, opportunities and costs.

3.1.2 Commercial opportunities enabled by each option

One of the key tasks of this review has been to provide an analysis of the potential economic impact of additional UK investment in space exploration. As part of the overall project a dedicated study was therefore commissioned from London Economics and overseen by BNSC to provide independent economic assessment. The full report of this work is available separately.²⁹

²⁹ *Economic Analysis to support a Study on the Options for UK Involvement in Space Exploration*, London Economics, 19 March 2009

It is clearly not feasible to predict with any confidence the economic impact of every programme element – partly because of the number and variety of activities included and partly because it would require a level of prediction that simply does not exist for innovative activities based on new technologies. Picking winners in the commercialisation of science and technology is notoriously difficult. Yet winners do emerge from sustained public sector investments. Examples include microelectronics (partly a by-product of the drive for miniaturisation in the early years of space exploration), MRI medical scanners from basic physics research, and the use of communications and navigation spacecraft in every day life as a by-product of the original ‘space race’ of the Cold War era..

Instead of a broad-brush qualitative approach it was agreed that a set of six case studies of specific commercial 'opportunities' should be analysed in a quantitative way. These opportunities represent new programme elements that could be implemented in an expanded programme of space exploration: i.e. they will not be carried out unless the UK chooses to invest in them. These examples serve to illustrate the possibilities for increased economic impact, while at the same time acknowledging that any one of them may in the end fail to deliver the hoped-for benefits, and, indeed, that the greatest impacts may come from innovations that have yet to be conceived. The purpose of these case studies is to show how the unique combination of engineering skills and challenges presented by space exploration can be harnessed to generate wealth using *existing* UK skills and *known* opportunities. By definition, the economic returns from *new* skills and *unknown* opportunities cannot be predicted.

Some of these opportunities are already sufficiently concrete to be worth pursuing now, but a directed programme of knowledge exchange will also be required to ensure that future innovations are fostered and shared with industries outside the space sector and thus generate the largest possible impact for the UK.

A range of candidate opportunities was examined by London Economics through extensive contacts with the UK space sector (including face-to-face interviews and a series of workshops with experts from inside and outside the space sector). This demonstrated an exciting range of commercial possibilities with benefits in different sectors, each enabled by investment in one or more of the four options considered. It was from this longer list of some 45 opportunities that the six case studies were chosen based on criteria such as the availability of commercial information and the likely size of the impact.

In each case, potential for a strong return on investment is found, with the range of opportunities available depending, not surprisingly, on the extent and ambition of the investment. Public sector investment can be required to stimulate commercial exploitation for several reasons. These may include: the need to compete in an international market conditioned by the behaviour of other governments (especially the US); the need to reduce risk on new technologies with uncertain return and to accelerate their development to achieve first-to-market advantages; or because the full range of benefits do not accrue solely to the original investor, but instead more widely to society or commerce. The timescales of the returns are typically too long-term for private investment alone to secure capital.

Thus, these are risky investments where the public sector can help realise benefits that would otherwise not be secured. Of course, while there are in some cases very large upside returns on public and private investment, these returns are not guaranteed. The analysis identified the main drivers and risks that are important for the realisation of future

benefits. As with any endeavour, some of these risks can be mitigated through effective management, while others will remain outside UK control.

Since these case studies are provided as illustrations of the commercial opportunities that may be expected from a coherent programme of exploration, it is not directly possible to extrapolate from these a realistic return on the complete programme options. Rather, these should be used as examples of economic impacts that may be generated by careful management. In each case the key parameters which drive the calculated net present values should be used as a guide to the effective planning of such projects in order to realise the maximum gains from them.

Factors for later planning and selection include: secondary effects such as additional market opportunities arising as a consequence of these primary initiatives; the reaction of market forces to reduce some benefits such as cost reductions; and the balance of selecting between a small number of UK owned flagship 'brand products' and a larger number of joint initiatives with reduced UK leadership of individual projects, but which diversify the UK's investment risks.

In the following sections, we elaborate the programme options and the programme elements that each is assembled from, and discuss the benefits that each may give rise to. The list of opportunities and a summary of the method of analysis is included in Appendix D.

3.2 Option 1: Reduced option

Eliminate involvement in space exploration and restrict the UK to the mandatory ESA Science Programme only.

3.2.1 Description

In considering the options for the UK, it is important to consider the value of the current activities. This may be envisaged by considering the 'reduced option', by which we mean reducing the existing programme to the minimum level. This would involve concentrating our efforts on the mandatory part of the ESA programme (since withdrawing from this programme would also imply withdrawing from ESA itself).

The mandatory Science Programme includes both astronomy missions and missions to explore the Solar System: for example the BepiColombo Mission to Mercury and the Rosetta Mission to land on a comet. However missions to the Moon and Mars are excluded from this programme.

Under this scenario, the UK would thus focus its efforts on robotic missions to the further destinations within the Solar System. These present many excellent opportunities for UK scientists and industry, but where there are activities which are common to exploration of both the outer and inner planets UK players would find themselves at a disadvantage. Further, these destinations do not give rise to any direct commercial opportunities, although indirect (i.e. spin-off) opportunities can and do arise.

3.2.2 Costs

The UK's involvement in the ESA Science Programme costs roughly £80m p.a., a figure fixed in proportion to the UK's GDP. In this scenario we would save the cost of participating in the Aurora programme, which is about £20m p.a. (including support for related national activities). These sums are allocated by the Science and Technology Facilities Council (STFC). The subscription to Aurora is tensioned by STFC against other UK science goals.

3.2.3 Benefits for science

No new areas of science would be enabled – we would have the opportunity to maintain our involvement in, and influence over, ESA's science programme, and would develop the capabilities and science community required to take part in the planned space missions included within it. Missions relevant to the exploration agenda are in the planning stage, and include a large-scale mission to Jupiter and a smaller-scale mission to return a sample from an asteroid. Both of these missions will produce excellent science, and UK scientists are heavily involved in each project. However, withdrawing from the Aurora programme would reduce the areas of science in which we are already involved, precluding us from taking part in missions to Mars and to the Moon.

Forthcoming missions in the mandatory science programme include the study of a near-Earth asteroid and return of a sample from it to Earth. This would enable the modelling of asteroid dynamics as well as analysis of its surface and curation of samples on Earth.

3.2.4 Benefits for innovation

In accordance with ESA's geo-return rules, the majority of the value of the UK's subscription is returned in the form of contracts to UK companies. These contracts

encourage the UK space sector to develop new technologies for use in other types of space mission, such as communications, navigation and Earth observation. They also encourage innovations for use in terrestrial applications. UK work in support of the ESA Science Programme has resulted in many valuable innovations (such as the TB detector which was developed from instruments on the Rosetta and Mars Express missions – see p244), but new opportunities being pursued through the Aurora programme would be curtailed.

3.2.5 Benefits for commerce

ESA contracts help to ensure that the UK space sector maintains its competitive edge in international markets for space components. Thus, pulling out of Aurora would make it harder for UK companies to make competitive bids and gain full benefit from the ESA Science Programme. There is also a risk that the UK's capabilities will be drained away as companies – particularly large multi-nationals such as EADS-Astrium – make commercial decisions to focus their investments on countries with a more favourable space policy.

3.2.6 Benefits for society

At the political level, for the UK to reduce its involvement in exploration at a time when other nations are just building up would seem perverse. The UK would become a weak partner for international collaboration.

There would be less opportunity to inspire students into the physical sciences and engineering and to use space exploration for education purposes. The perception would be reinforced that the most interesting space engineering feats are occurring elsewhere in the world.

Option 1 would save money, but damage the UK's reputation in science and innovation, reduce international influence, reduce benefits from the ESA programme and send out strongly negative signals within the UK about the prospects for careers based on STEM subjects.

3.3 Option 2: Current baseline option

Continue with the current level of investment (confine to ESA Science programme and the robotic Mars exploration programme).

3.3.1 Description

In addition to playing a full and successful role in ESA's Science Programme, the UK is a major partner in the robotic elements of ESA's optional Aurora programme. It is currently the second-largest contributor to the ExoMars mission (due for launch in 2015/16) and the largest partner in the Mars Robotic Exploration Preparatory Programme, which will develop technology required for future missions. The UK currently subscribes €14m per year.

Within the Aurora programme, the UK's biggest involvement is the provision of the ExoMars rover. This is being carried out by Astrium, supported by various subcontractors.

The structure of the ESA programme is such that it is possible to remain involved in robotic exploration while staying out of the human activities.

It is not yet clear how much lunar exploration will be included in the programme, since many European countries have aspirations to conduct their own national lunar missions, however much preparatory work is underway to define possible European elements of future lunar exploration architecture such as a robotic logistics lander for supporting crew on the Moon.

In this scenario, the UK would continue its involvement in the ESA programmes at the current level. It would neither engage the other GES countries, such as the US or China, in further bilateral collaborations, nor increase its investment in UK activities in support of the ESA programmes.

3.3.2 Costs

The cost of the UK's participation in the ESA Science and Aurora programmes is roughly £100m p.a. (including the necessary supporting national activities).

3.3.3 Benefits for science

Despite recent exciting discoveries of possible niches for life elsewhere in the Solar System, such as on Europa (Jupiter's satellite) and Enceladus (Saturn's satellite), Mars is probably the best location beyond Earth to seek extinct (or even extant) life. Mars is known to have significant quantities of water, albeit locked up in the form of ice. But there is now tantalising evidence that water might have flowed in very recent years³⁰, supporting the possibility of life having existed (or even existing still). Since the surface is bombarded with biologically damaging ultraviolet and ionizing radiation, ExoMars will, for the first time, drill significantly below the surface of Mars, up to two metres, to attempt

³⁰ Balme et al., "Orientation and distribution of recent gullies in the southern hemisphere of Mars: observations from High Resolution Stereo Camera/Mars Express (HRSC/MEX) and Mars Orbiter Camera/Mars Global Surveyor (MOC/MGS) data," *Journal of Geophysical Research* 111 (2006), p. E05001.

to find evidence. ExoMars will be arguably the most sophisticated tool yet deployed in the search for past or present life.

The UK has leading or significant involvement in several instruments either directly attempting to detect life or to characterise the environment in which life might exist, including:

- Urey Mass Spectrometer – for the measurement of biologically significant atoms and molecules and their isotopes
- Life Marker Chip – for the detection of biologically significant molecules ('biomarkers')
- Raman Spectrometer – for the analysis of inorganic and organic molecules
- Ultraviolet/Visible Spectrometer – for the characterisation of the biologically damaging ultraviolet radiation
- Advanced Environmental Package – for the measurement of meteorological and other environmental factors

3.3.4 Benefits for innovation

The prominent role of UK industry in some of the key elements of the ExoMars mission and other activities in the Aurora programme is helping to develop new techniques, products and services within the space sector and with applications in other sectors. These range from robotic buggies that can be used at airports by those with mobility difficulties and guidance systems for areas where there is no GPS signal (e.g. underground) to cleaner cheaper solvents to replace the hazardous solvents currently used. Other possibilities include new battery technology, dextrous manipulators and thermal protection systems.

3.3.5 Benefits for commerce

In addition to the economic benefits from the ESA Science Programme mentioned in the previous chapter, strong economic benefits have been identified from technology developments arising from ExoMars. A patent is pending for technology development on the instrument payload and markets estimated at €72m have been identified for new products arising from ExoMars industrial contracts in the UK.

Analysis by STFC's Economic Impact Team in March 2008 has shown some preliminary results for the effects on the UK economy due to work on ExoMars. A survey of industry showed that there would be an additional 146-182 people employed directly, and a further 73 indirect staff being employed. Their report identified that:

“A significant effect will also be felt through an improvement in the companies’ knowledge base. They will be able to recruit quality staff, improve skills and training, increase technical knowledge, build critical masses of expertise in given areas and transfer knowledge gained on the mission to other parts of their business.”

And:

“The majority of the 13 companies involved in ExoMars believed that involvement in the mission would allow them to leverage additional funding and that it would enhance their chances of being involved in future space missions.”³¹

The main economic benefits arise from technology spin-out and the IP generated from involvement in ExoMars: 75% of the companies involved stated that they expected IP to be generated from the mission. The potential for technology transfer from this work is significant. Some companies have already started generating IP from work on the mission which is being leveraged into other parts of their business. From the 13 companies involved in ExoMars so far, 12 reported potential technology transfer to other areas within their own companies, both inside and outside their particular sectors.

Companies reported technology transfer benefit to other sectors including military and defence, civil transportation, aviation and the oil/gas industries. Applications included autonomous operations in hazardous environments. One company reported that:

“...the real growth will be in the push to terrestrial spin-out projects where we would expect work in robotics to secure significant opportunities in defence and transport systems and so a further 5-10 [contracts] can be easily foreseen and potentially a complete new line of business.”³¹

3.3.6 Benefits for society

The Aurora programme aims are threefold – to explore the Solar System, to stimulate new technology, and to inspire the young people of Europe to take a greater interest in science and technology. It is not simply about the science, or industrial capability, but the added value of a holistic approach that includes a coordinated programme of public outreach and education. An example is the public interest in the Mars Rover developed by Astrium UK (named Bradley). ‘Bradley’ and its predecessor ‘Bridget’ are in huge demand for public appearances and have toured Europe, inspiring young and old alike.

The UK has an extensive and varied range of organisations that promote space education. These organisations often work independently of each other and, although they have a positive contribution to make to the promotion of space as a context for the teaching of science, technology, engineering and mathematics (STEM), the lack of coordination reduces the impact of their work. Work is therefore underway with ESA in setting up a European Space Education Resource Office in the UK.

This will add value by being a conduit of information and facilitator of links between all stakeholders, including the space community (ESA, BNSC Partners, the UK space industry) and educators. To ensure that it is effective and properly linked into the education system it will be run by the National STEM Centre, which is part of the National Science Learning Centre.

Currently there are active programmes funded by STFC to support education – for example the Leading Space Education Programme which is a collaboration with the Specialist Schools and Academies Trust. So far 30 schools are involved and a further 20 will be added in 2009/10. The aim is to embed the use of space in secondary school teaching and learning of STEM subjects using beacon schools to share activities with local

³¹ Paper presented to STFC Council, September 2008

secondary and primary schools and with many of the Trust's 1,200 STEM specialism schools.

Although the UK has achieved considerable success in its space exploration activities through the ESA programmes, against the background of the rapidly evolving space exploration policy globally, maintenance of the current level of UK investment might be seen as an effective retreat as other countries expand their investment. As well as the loss of commercial and industrial opportunities, this would greatly reduce the UK ability to influence future international space science programmes. It would also limit the possibilities to further public interest and understanding of science.

Option 2, the current programme, delivers good returns for science and innovation, but will not fully exploit the opportunities that arise from new international plans for space exploration. It will also result in a gradual loss of influence in international programmes, demonstrate a lack of ambition and exclude UK industry from involvement in new commercial ventures.

3.4 Option 3: Enhanced robotic option

Increase investment in robotic-only exploration, focused on the Moon and asteroid exploration through national projects and bilateral activities with other space agencies.

3.4.1 Description

In this scenario, the UK would continue its current involvement in the ESA Science and Aurora Programmes, and would invest additionally in selected areas of robotic activity in which it has a strong track record in order to deliver new science and drive innovation. This would be done mainly through nationally-run programmes and through collaboration with other nations (with the US as the most likely first partner). This is in line with one of the recommendations of the Space Exploration Working Group which proposed that the UK should initiate a targeted robotic lunar programme as part of a preparation for a more extended human spaceflight programme.

These selected areas include the demonstration of lunar communications and navigation, based on UK strengths in designing and building small satellites. The MoonLITE mission is now undergoing initial design studies and would be a UK-led mission, with support from the US and possibly other partners. This mission would carry out science investigations on the Moon, through the deployment of innovative penetrators carrying instruments. Early models were successfully tested in the UK in 2008.

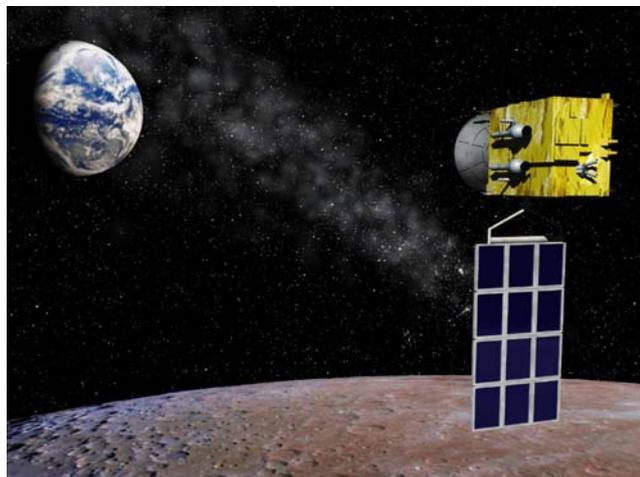


Figure 9. The proposed MoonLITE mission (Image UCL)

Other activities might include involvement in ESA programmes to develop lunar rovers (building on UK expertise developed on the ExoMars rover), and involvement in a possible asteroid mission to carry out science and evaluate threats to Earth (building on capabilities developed on the Cassini and Rosetta missions).

Technology developments could include harnessing UK skills in drilling for investigating the deeper layers of the lunar crust using robotic techniques.

Novel power sources will also be needed, such as efficient and reliable nuclear power plants to maintain lunar bases. One route to develop such technologies would be through the new ESA Centre on the Harwell Science and Innovation Campus. Part of this facility will be devoted to exploration activities.

A significant part of such a programme would be a formal mechanism to track new innovations and encourage uptake in terrestrial applications. It would also be vital to embed a strong programme of educational activities to make full use of the inspirational value of such advanced robotic techniques.

3.4.2 Costs

In order to determine the cost of this option for robotic exploration, the following elements have been included in addition to the current activities listed under Option 2: a lunar communications and navigation demonstrator mission, a share of a lunar rover, a share in a robotic lunar drilling mission for science, development of space nuclear power systems, a share in an asteroid mission, various science instruments to study the Moon and suitable education and technology transfer initiatives. To carry out a programme such as this would increase the cost from the current level of about £100m per year to around £144m a year (rising in steps from the current level to reach steady state at around 2018).

The following table and figure show the possible spend profile during the early years of a UK programme of robotic exploration.

Table 4. Spend profile for Option 3: Enhanced robotic programme								
Year	2010	2012	2014	2016	2018	2020	2022	2024
Spend £m/yr	101	124	138	136	144	144	144	144

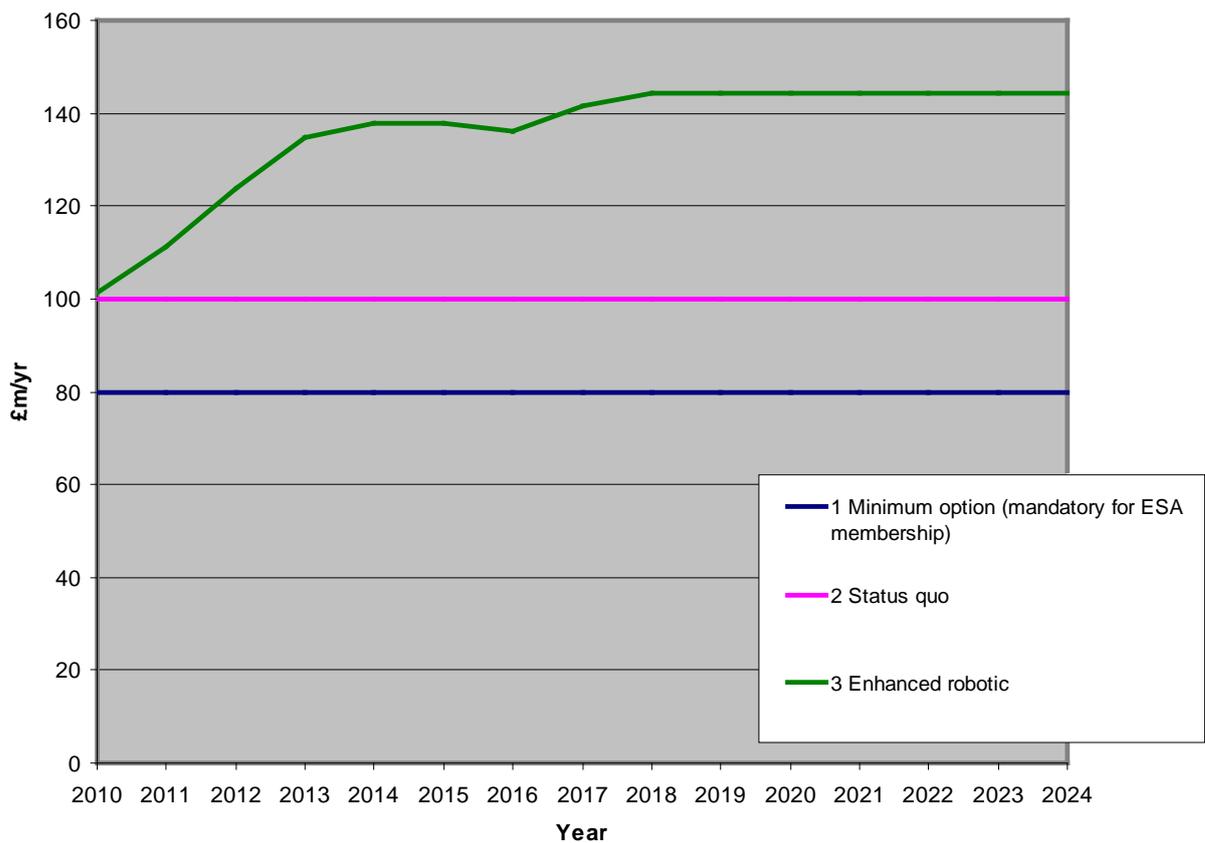


Figure 10. Spend profile for Option 3: enhanced robotic programme (compared with Options 1 and 2)

Further detail on the breakdown of these costs is included in Appendix C.

3.4.3 Benefits for science

Despite significant progress in recent years in our understanding of the Moon, particularly its origin and evolution, there are still major gaps in our knowledge. For example: is there a core, how much heat is flowing from within the Moon, and what are the origins of the 'moon quakes' detected by instruments left by Apollo astronauts? Measurements made by the astronauts and the instruments they deployed were crucially important, but were limited by being close to the equator and on the near side. For the same reasons the samples collected and returned are unlikely to be representative of the whole Moon and the relatively close spacing of the seismometers only allowed shallow 'moonquakes' to be measured and so the deep interior was not sampled by this technique. Making measurements over a wide range of locations will enormously extend our understanding and knowledge of the Moon, in terms of structure, origin, evolution and 'how the Moon works.'

Furthermore, there has been considerable development in our understanding of the role of the Moon as a museum of the Solar System. Because volcanic activity ceased relatively early in the Moon's history, scientists believe that a record of the early history of the Solar System may have been preserved on or below the inert surface of the Moon. This may include samples of the solar wind, which may in turn reveal the behaviour of the early Sun as well as the radiation conditions experienced when life began on Earth. And, just as meteorites originating from Mars have been found on Earth, it is likely that pristine samples of rocks from Earth are preserved on the Moon, maybe containing chemical evidence of conditions pertaining on Earth at the time life began, but which has been irretrievably lost by the destructive geological processes operating on our world.

The prospect of involvement in a mission to sample an asteroid also offers exciting scientific opportunities. It is thought that the planets were formed from the dust and other debris which once surrounded the Sun. The violent processes involved in the formation of the planets some 4.6 billion years ago have obscured the evidence of their origins, but the remains of this debris is still contained in comets and asteroids, so measuring their chemical constituents will help to reveal the origins of the planets.

Additional possibilities exist for robotic exploration of other bodies (though only Mars and asteroids are considered to be within the scope of this report).

The return of samples to Earth will require a curation facility for the preliminary analysis, distribution and storage of material. Such a facility could be combined with the new ESA Centre at Harwell, providing a new focus for planetary research in the UK.

3.4.4 Benefits for innovation

The extension of activities to include robotic exploration of the Moon will result in a new range of challenges which will inevitably generate new technologies and other innovations to cope with the unique environment. For example, the need to drill remotely on the Moon to extract samples from deep below the surface will require the development of drills which can operate for long periods without lubricants or replacement. They will need self-lining drill holes since the uncompacted upper layers will be dry and liable to collapse. The need to operate without human involvement will require improved automation and reliability.

Likewise the increasing capability of robotic missions to the Moon and elsewhere will require improvements in battery technology (in which UK industry has a strong record) and the even greater demands of human outposts will require the development of new

power sources and techniques to improve energy efficiency, all with obvious applications on Earth. Nuclear technology is expected to be a key area of expertise at the new ESA Centre at Harwell.

Further advances can be expected through work on lunar rovers and the impact probes that will be deployed from the MoonLITE mission in order to embed scientific sensors in the lunar surface. This mission will also help to demonstrate the use of UK-developed low-cost small satellites for exploration beyond Earth orbit and so extend our commercial leadership in this business.

In order to ensure that the maximum advantage is gained from such a programme, it is important that the innovation process is actively stimulated rather than being left to chance. The recommendations of the ABOTTS Report, which preceded the UK's subscription to the Aurora programme, are just as relevant to this extended programme. Thus the first goal should be to "improve UK competitiveness through enhanced technology readiness levels in strategically selected technologies."³³

It will also be necessary to provide brokering support to encourage a broader network of companies to provide services to the programme (much as has been done by the Science and Technology Facilities Council to encourage new UK suppliers to CERN, the European particle accelerator).

In order to maximise 'spin-in' and 'spin-out' between space and the other sectors it will be necessary to promote cross-links in supply and demand for space technologies. This may be done through a combination of existing and new mechanisms, including Faraday Partnerships, related Knowledge Transfer Networks and cluster organisations. Such actions are included in the cost of this option.

3.4.5 Benefits for commerce

Each of the areas of potential innovation mentioned above will create opportunities for UK businesses, both in the space sector and in others (e.g. oil and gas, energy, robotics). These will in turn provide benefits for the UK economy by increasing the range of products and scale of operation of existing enterprises and by creating new ones. The increasing demand for launch services will provide added incentive for new developments in launcher technology. The UK has several novel technologies which could make it a significant player in this market – and, while this is not limited to exploration missions,

'The insights generated by fundamental scientific research are important in long-term innovation performance. They produce generic technologies that create new industries, from the physics behind the computer chip to genetic treatments for disease. Many of the UK's most successful businesses build directly on scientific discovery.'

'That is why it is so important to continue to invest in science and accelerate the flow of research into society and to challenge scientists to work more creatively and entrepreneurially with one another and with business.'

Innovation Nation³²

³² Innovation Nation, Department for Innovation, Universities and Skills, March 2008

³³ ABOTTS Knowledge Transfer from Space Exploration: Prospects and Challenges for the UK, report by Qi3 for BNSC, April 2005

cheaper access to orbit would both enable more complex missions and create completely new business opportunities (such as tourism, and commercial cargo and crew transportation services).

An additional, unquantifiable, benefit comes from the high-profile nature of space exploration activities. This gives a platform for hi tech companies to demonstrate the reliability of products which originate from operations in space and for the UK to showcase its capabilities more effectively and thus improve access to a range of global markets. And as the space market expands, an active UK programme would help to ensure that British companies maintain or increase their international share.

In analysing the impact on the economy of such a programme, it is not possible to make concrete predictions based on an expected pay-back for a given level of investment since there are so many variables which affect the outcome. Previous examples of Government investment are worth noting however: UK contributions to ESA's telecommunications technology programme (ARTES) produced returns on investment of 7:1 and investment in the UK-led Disaster Monitoring Constellation produced returns of 9:1.³⁴

In order to demonstrate what may be achieved through future investments, examples of new commercial opportunities that would be enabled by increased involvement in robotic exploration have been chosen for more detailed analysis. These examples are intended to illustrate what may be possible in such a programme rather than as a firm prediction of return on investment.

Among these possibilities, two specific technologies that could fit in this scenario have been analysed in detail. These are lunar drilling and low-cost launch technology. Each analysis takes account of a range of

Case study 1: Lunar drilling

Many of the objectives of lunar exploration will require the ability to drill into the surface of the Moon. This will require new techniques – especially in remote control, autonomy, and new materials for drill bits. These will all have applications in terrestrial drilling for oil and gas.

This report considers the benefits in the oil and gas sector for the UK from three technical advances: automation, remote operations and self-repair coatings. There may be other valuable terrestrial applications in this and other sectors, and as with all new technologies it is not certain that all of these benefits can be realised.

Improved automation will allow the extraction of previously unreachable oil reserves – for example under the Arctic. New techniques in remote operations will increase productivity in drilling and servicing wells. And the challenge of drilling remotely in the airless conditions on the Moon will require new drill bit technologies such as self-repairing coatings (to avoid the replacement of drill-bits).

On the assumptions given in Appendix D, the net benefit to the UK could be over £4bn. Each assumption can be challenged, but so long as the UK can claim at least a 1% share of the global benefits, the Net Present Value remains positive.

Such a programme would also help to address the chronic lack of suitable graduates joining the industry. It is not hard to envisage a recruitment campaign for an oil company using the slogan, 'Join us and explore the Moon.'

³⁴ *Case4Space Summary Report, 2006*

plausible assumptions which influence the expected return on investment – resulting in a large range in the net present value (NPV) for each.

Case Study 2: Low cost launch technology

The cost of all space missions is strongly dependent on the cost of launchers. Several UK companies have novel solutions with the potential to drastically reduce these costs.

Virgin Galactic has demonstrated the use of its carbon composite carrier and has paid-up customers ready to take their sub-orbital flights. Reaction Engines has designed a revolutionary air-breathing engine for their Skylon spaceplane. A £6m programme to demonstrate a key technology has been funded through private investors and a €1m contract from ESA. Bristol Spaceplanes plans to demonstrate its low-cost reusable 'Ascender' spaceplane, to be followed by a larger model called 'Spacebus'. (Details in Appendix D.)



Figure 11. Skylon (Reaction Engines)

The first case considers the benefits to the UK terrestrial oil drilling industry through the development of tele-robotic and autonomous techniques needed on the Moon (see box on p54). In most scenarios the NPV is very large and positive (although in some it can be negative). The crucial factor in achieving a large benefit is to ensure that the UK gains a sizeable share of the market for such technology on Earth. Given this proviso, a benefit to the UK economy of over £4bn could be expected over the period to 2040.

Likewise for low cost launch technology (see box on this page), all of the predictions for the NPVs are large (in the region of several billion pounds depending on which technology and operating conditions are assumed).

Although this could be a key enabling technology for space exploration, it should not be considered primarily an exploration-related activity as it could potentially transform the means of access to orbit for all space missions. In addition the level of investment needed would be larger than the sum of all the other elements in the proposed scenario,

so *no provision* for this activity has been included in the costings. However the number of options and the variations between the results suggest that it would be wise to conduct a dedicated study on this technology as a separate exercise from this Review.

3.4.6 Benefits for society

Involvement in a dedicated asteroid mission would have the obvious public benefit of increasing understanding of such bodies and the threat they pose to Earth, thus helping to devise mitigation strategies and reduce public alarm.

Increased funding would enable discussions with other space-faring nations on possible joint activities and help to grasp the opportunity presented by the UK's early role in agreeing the Global Exploration Strategy and to take an influential role in its implementation.

The exciting science return and the involvement of the UK in lunar robotic exploration would in turn inspire a greater interest among the general public (as experienced during the Beagle-2 campaign on Mars). The proposed MoonLITE mission, as part of this, is already provoking huge interest in the media and inspiring children and adults alike.

By embedding education activities as part of an increased programme it should be possible to increase the impact on educational outcomes at all levels and across the country. This could be done through a combination of resource packs for schools and colleges, champions in each region to promote and develop new resources, and with an educationalist to lead and work with scientists and engineers carrying out the programme.

Goals should be set for education, with

outcomes being measured for both learners and educators. The new European Space Education Resource Office, run by the National STEM Centre, would provide a valuable resource for identifying needs for new resources relevant to the curriculum and for marketing and distributing them to educators (not just across the English regions, but also within the Devolved Administrations).³⁶ Appropriate costs for a programme of action in education and outreach are included in this option.

“The greatest contribution that NASA makes in educating the next generation is by providing worthy endeavors for which students will be inspired to study difficult subjects like math, science and engineering because they too share the dream of exploring the cosmos.”

Mike Griffin, NASA Administrator
(2005 to 2008)³⁵

Option 3 would build on UK strengths in robotic technology, increase scientific return and technological innovation, and generate increased public interest in science and technology.

³⁵ Quoted by Winterton, J. and Currier, P., *Using Data and Analyses to Assess NASA Education Programs and Guide Programmatic Decision-Making*, IAC, 2008

³⁶ *European Space Education Resource Office for the United Kingdom (ESERO-UK), Final Report*, National Science Learning Centre, January 2009

3.5 Option 4: Human and robotic option

Invest in both robotic and human activities, leveraging the UK's strength in robotic technologies to secure astronaut places in the human exploration of the Moon and beyond.

3.5.1 Description

In this scenario, UK strengths in robotic technology and planetary landers would be harnessed deliberately to create a modest programme of human-related activities, supported by a small precursor programme with UK astronauts. This would enable the UK to integrate its activities with the programmes of its international partners as they extend their influence across the Solar System in order to deliver new areas of science, spur innovation, create opportunities for commerce, and inspire greater interest in science and technology.

This option encompasses a large range of possible activities from the absolute minimum level of involvement to a major programme of human spaceflight. In order to evaluate the costs and benefits to the UK of such a programme, two possibilities have been considered. The first, Option 4a, represents the minimum investment required for the UK to secure a viable involvement in human spaceflight. The second, Option 4b, represents a more balanced and integrated approach in order to secure the strongest possible economic return.

In the minimum alternative represented by **Option 4a**, the UK could – for example – offer a service of broadband lunar communications and a lunar navigation service to other space-faring nations in return for the involvement of UK scientists in the early human expeditions to the Moon in the early 2020s. This would

require a demonstration of the technology through the MoonLITE mission (mentioned in Section 3.4.1) and lead to the possibility of a UK citizen walking on the surface of the Moon in the following decade. This approach is similar to that of Canada, which has created its own corps of astronauts in return for technology supplied for the Shuttle and ISS programmes.

Other activities included in this option would be similar to those in Option 3 (enhanced robotic), but to minimise the overall cost, several other interesting technology developments would be excluded, for example in nuclear power, robotic lunar drilling, lunar rovers and asteroid threat missions.

In **Option 4b**, these technology developments would be included, together with new activities such as a share in the development of ESA's planned small lander and its large cargo lander.

Why send humans into space?

“Humans have unique decision-making capabilities that allow them to respond to new situations based on previous experience and knowledge. Sending humans to live and work in space takes full advantage of the intellectual capital and real-time reasoning that only they can provide. A human can quickly find and tighten a loose bolt on a core-sample drilling rig, whereas it might take hours to programme a robot to do so, even if it had the means to sense the problem. We are a long way from having robots that can match humans, even in the lab.”

The Global Exploration Strategy³⁷

³⁷ *The Global Exploration Strategy: The Framework for Coordination*, agreed and published by 14 agencies, including BNSC, May 2007

Additional technology developments could include a mission to demonstrate the conversion of lunar regolith (i.e. minerals) to produce oxygen, which will be needed by any future human missions. In this case, the UK could offer to supply oxygen to other nations involved in lunar exploration in return for involvement of UK engineers in human-assisted drilling operations or the construction of novel types of astronomical telescope on the far side of the Moon and thus provide an alternative route to secure the participation of UK astronauts.

While it is widely accepted that space provides an inspirational platform on which to build education activities, the involvement of UK astronauts through either version of Option 4 would provide a far greater impact. The increased range of activities would also help to carry messages about the excitement of science and technology into many different areas, and the publicity that would be generated would provide opportunities for wider appreciation of the strength of UK talents. Option 4 could be undertaken either through our membership of ESA or in collaboration with another international partner.

“...sending robots to Mars is what I do for a living, but even I feel that the best exploration, the most compelling exploration is going to be done by humans.”

Steve Squyres of Cornell University
(Principal Investigator on the Mars Rover project)³⁸

In the first case, the UK would join the lunar exploration elements of the ESA human spaceflight programme. As these are in a formative stage, the UK would seek to work with other Member States to secure a programme which matched UK goals. This is the traditional UK approach. However, at present, ESA is focused on technologies for human spaceflight which do not align well with UK interests and capabilities.

Alternatively, the UK could engage in a bilateral agreement with the US and directly barter for astronaut places against one or more specialised UK contributions to the international endeavour (e.g. a lunar communications satellite system, radiation protection for astronauts, or the production of oxygen from materials on the Moon using UK know-how). This bilateral approach has been followed by Canada for many years and has secured many astronaut places, a high visibility of Canada’s capability and good technological return.

Since the human return to the Moon is unlikely to occur until after 2020, such a programme would grow over a period of years as capacity is built up, irrespective of which implementation path is followed. The programme should be reviewed every five years to ensure that the expected benefits are being realised.

Option 4 includes the cost of a significant programme to stimulate the innovation process and ensure that there is effective knowledge exchange between academe and industry. Likewise a dedicated education and outreach programme is included to harness the inspirational benefits of UK astronauts. These aspects are much the same as discussed for Option 3 (see Section 3.4.4 and Section 3.4.6).

³⁸ CNN interview, 4 January 2005, transcript at <http://edition.cnn.com/TRANSCRIPTS/0501/04/ldt.01.html>

3.5.2 Costs

The overall programme would rise in cost from the current level of £100m per year to a peak of around £206m by 2023 in the case of Option 4a, and £284m by 2020 for Option 4b.

The following table and figure show the possible composition of costs during the early years of a programme based on Option 4a – allowing a minimum level of human exploration – and also of the integrated programme of human and robotic exploration implied by Option 4b.

Table 5. Spend profile for Option 4: Human and robotic programme									
Year		2010	2012	2014	2016	2018	2020	2022	2024
Spend £m/yr	4a Minimum human	101	130	143	172	174	192	205	206
	4b Integrated human and enhanced robotic	101	133	195	254	264	284	284	284

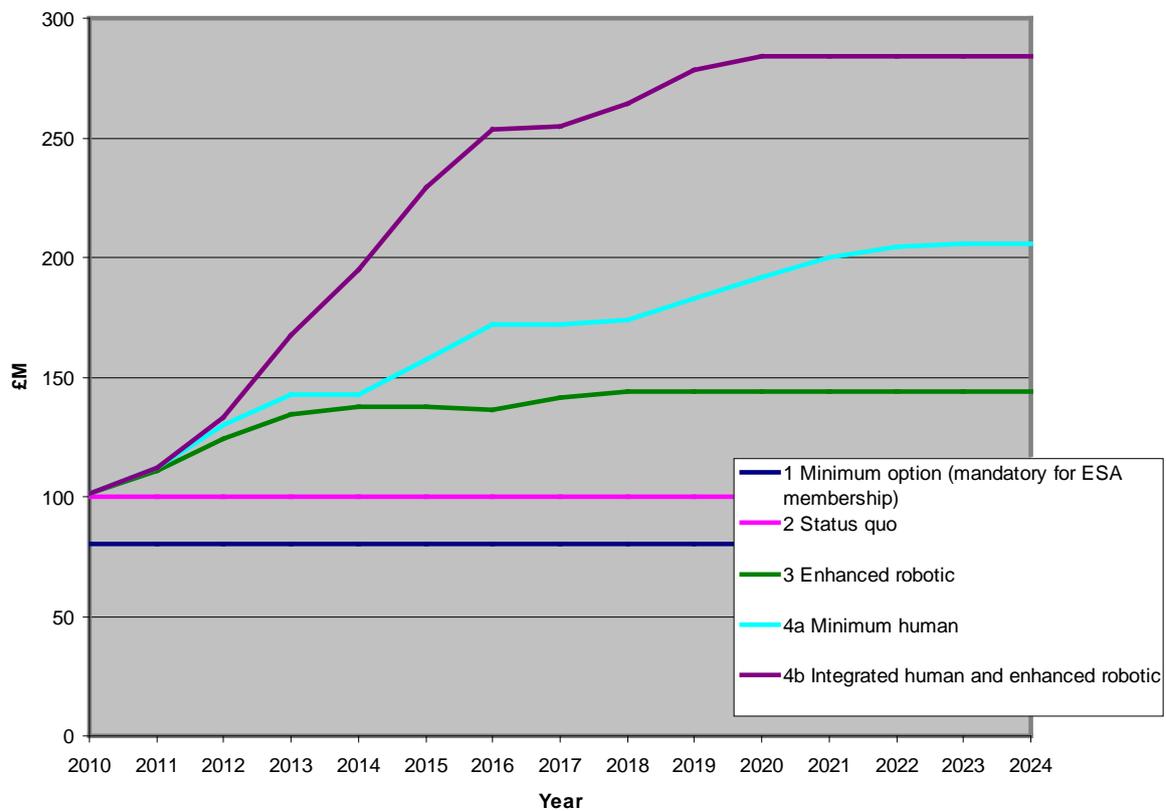


Figure 12. Spend profile for Option 4: Human and robotic programme, compared with Options 1 to 3

Further detail on the breakdown of these costs is included in Appendix C.

3.5.3 **Benefits for science**

The biggest impact for science of human involvement in space exploration may well come from the increased capacity of launchers needed to carry astronauts and their supplies. This will enable a range of larger and more capable scientific instruments to be flown. And the availability of astronauts to assemble, adjust, repair and augment science instruments in space and on the Moon will make it unnecessary to limit designs to those which can operate entirely autonomously. Already, the James Webb Space Telescope, NASA's successor to Hubble, will be provided with the minimum equipment needed to allow servicing by future astronauts, even though it will be located in a deep-space orbit 1.5 million km from Earth.

The involvement of humans would also open up access to a range of new scientific possibilities – including a raft of life-sciences, especially medicine. New science areas that would be enabled by participation in human space flight include:

- **Medical science:** living in the space environment causes changes to organisms that are analogous to the changes that occur on Earth as a result of the ageing process. Thus the space environment is a laboratory in which the ageing process can be studied, along with the effects of degenerative disease on bones, tissues and organs.
- **Microgravity sciences** (see box).
- **Lunar science:** acquisition of a greater range of lunar samples for investigation; greater facility for surface and sub-surface exploration and sample recovery.
- **Other science areas:** servicing and replacement of instrumentation used for astronomy and fundamental physics experiments.

Microgravity

The conditions in space where objects are effectively in 'free fall' are usually called 'microgravity'. Such conditions cannot be replicated on Earth for more than a few seconds, so orbiting spacecraft provide unique facilities for research. Since gravity drives fundamental behaviours such as convection, sedimentation and buoyancy, it can dominate processes in areas such as fluid mechanics, crystallisation, geology and physiology. Thus experiments in microgravity are beginning to shed light on these and other processes, including important ones driven by surface tension which are too small to measure in the presence of gravity – for example in cell behaviour and microencapsulation.

The UK Microgravity Review in 2003³⁹ concluded that the benefits would justify participation in such research, but funding was not available at the time. BNSC agreed to keep the prospect of involvement under review. The simplest route to participation would be through ESA's ELIPS programme of life and physical science research, as recommended by the UK Space Exploration Working Group.⁴⁰

³⁹ Wakeham, B., Sykes, R., Williams, P., Garwood, S., *Recommendations of the Microgravity Review Panel*, (2003), and Ministerial statement, <http://www.microgravity.org.uk/review.htm>

⁴⁰ *Report of the UK Space Exploration Working Group*, independent report to BNSC, September 2007, Recommendation 9.

“There is no question that humans ‘on site’, even with limited mobility and suit-limited dexterity (i.e., Apollo), are orders of magnitude more efficient samplers of planetary materials than machines...”

“... As an example, the ongoing field exploration activities of the Mars Exploration Rovers typically require multiple days to access and interrogate one sample. It is well-known that an appropriately-suited human explorer could conduct a similar sample acquisition and inspection in a matter of minutes, even with an Apollo-class space-suit. [...] human field explorers are one to two orders of magnitude more effective and efficient at collecting samples than robots, while also providing for a higher mass gathering capability relative to machines...”

Jim Garvin, NASA Chief Scientist (2004) and Chief Scientist for Mars Exploration (2000-2004)⁴¹

3.5.4 Benefits for innovation

The requirement to design safe and robust systems to support humans and cope with hostile environments far from Earth will force the development of innovative and highly reliable systems with benefits for patients on Earth as well as developments in closed-cycle systems for use in space habitats, with benefits for terrestrial recycling and other environmental applications.

As with Option 3, it would be vital to manage the development of innovation to create the maximum impact for the UK, especially to capitalise on the new collaborations between experts in many different disciplines who would work together on such missions. These could be expected to result in innovations in the design of robots which have to interact with people, new techniques in patient care (for example novel systems to monitor astronaut health remotely and reliably), as well as provision of innovative services such as lunar broadband communication and navigation, consumables such as oxygen, or new activities such as tourism or media.

In Option 4a, the main innovations would come from cross-working between different disciplines linked to human and robotic activities respectively that have not previously been brought together in the UK, and from the challenges of providing broadband communications and navigation services to users on the surface of the Moon and in orbit around it.

The expanded Option 4b includes a robotic mission to demonstrate the conversion of lunar regolith to produce oxygen which would capitalise on novel UK technology which would also be used to radically advance the production of titanium on Earth. The terrestrial application on Earth would reduce energy use and cost, reduce emissions of greenhouse gases, produce new low-cost alloys and possibly create innovations in other related areas such as aluminium production. Further activities included in Option 4b relate to nuclear power, robotic lunar drilling, lunar rovers and asteroid threat missions and would bring the benefits for innovation already described for Option 3

⁴¹ Jim Garvin, NASA Chief Scientist (2004), *Earth, Moon, and Planets* (2005) 94: 221–232

A novel technology with applications for both human exploration and existing unmanned spacecraft would be the development of advanced radiation protection systems using plasma shields.

This may sound like science fiction, but it is an area with a significant UK lead and with an application of fundamental importance, since radiation may prove to be the biggest threat to astronauts venturing beyond Earth's own protective plasma shield (the magnetosphere). Although it would be enabled by Option 4, this activity has not been included in the cost estimates since it is currently at too early a state of development to allow accurate analysis.

3.5.5 Benefits for commerce

As with Option 3, the technical innovations mentioned above create opportunities inside and outside the space sector. These will help to maintain advantage for UK businesses at the top of global value chains and hence support the economy. Likewise the high visibility of human space missions will further increase the opportunities to market UK expertise.

Involvement in human activities will create opportunities to serve new markets that are currently inaccessible to UK companies. These include ground-based activities such as medical assessments, training of astronauts, and information management systems for health. New space-based activities might include communications and oxygen-production services mentioned above, as well as advanced robotics and radiation protection.

Case Study 3: Lunar communications and navigation

Future lunar exploration will require communications data relay services in order to allow the poles and the far side to be safely reached by both robotic and human means. Data to be transmitted will include basic command and monitoring of spacecraft, safety of life critical data for astronauts, scientific data, and high definition TV data for media and – eventually – entertainment such as gaming.

The UK is a leading supplier and operator of communications satellites, it has the world-leading builder of small low-cost satellites, and it has led the world in funding major projects through Public-Private Partnerships.

Thus the UK could combine these capabilities to provide a lunar communications service for multiple agencies – achieving both economies of scale and opportunities for collaboration with each. Such a system could be demonstrated by the proposed MoonLITE programme, which is ready to begin its Phase A study. Discussions have begun with NASA on how such a system might operate.

Extrapolating from the cost of existing communications services on Earth and the predicted need for lunar communications, such a service might theoretically achieve an NPV of over £6bn - though such a programme would most likely be seen as a UK contribution to the international programme resulting in benefits in kind rather than in cash. Once in operation, however, this could also be extended to provide a commercial service to other organisations, such as TV and internet companies, to enable students and the public to follow and participate actively in future exploration missions.

Further details may be found in Appendix D.

As with Option 3, it is not possible to present a simple figure for return on investment for a given size of programme due to the large range of the variables involved. Instead, four more case studies are presented each of which is enabled by a programme based on Option 4. As before, the range of net present values in each case is large, but mostly positive.

Option 4a provides for the development of a communications and navigation service (see box on p62) to one or more nations wishing to communicate with astronauts or instruments on the lunar surface.

There is a convenient analogue in terms of the communications and navigation satellites currently encircling the Earth, but there is great uncertainty in the perceived price of such communications on the Moon. The analysis predicts a positive net present value in all cases except where the price is very low or the UK takes a very small share of such service provision.

Given a timely and well-ordered programme, an NPV of over £6bn seems reasonable. The intention would then be to use this figure to inform negotiations with other nations in return for participation of UK astronauts in exploration of the Moon and elsewhere.

Option 4b creates further possibilities. For in-situ resource utilisation, the goal on the Moon would be to generate oxygen for use in rocket engines and for breathing. The value comes in providing oxygen supplies to customers on the Moon (initially expected to be mainly government agencies) and in the development of an improved process for producing titanium on Earth (both in terms of price and pollution). A plausible NPV would be in the region of £400m up to 2040.

Case Study 4: Oxygen production on the Moon

Supplies of oxygen both for astronauts and for rocket propellant will be vital for long-term human exploration, but will be expensive to transport from Earth. A British company has developed and patented a novel and efficient process to separate oxygen from titanium ores found on the Moon.

This process produces titanium alloys as a by-product (with possible use in future lunar construction projects) and is also expected to work with other ores found on the Moon, including those based on iron and calcium.

The technology could also be applied in the titanium industry to reduce both costs and pollution (especially carbon dioxide).

Combining the expected costs of delivering cargo to the Moon with the number and scale of missions currently being planned, we have estimated the potential market for commercial production on the Moon. Applying the technology to the production of titanium on Earth could gain competitive margin in existing world markets and enable production of a cheap new titanium-based alloy with the potential to displace stainless steel in many applications.

Even if we ignore this last application (since it is not possible to analyse the market for a material that does not yet exist), we find significant economic benefit with the NPV likely to be over £400m over the period to 2040. Further details may be found in Appendix D.

The analysis of the value of robotics to the economy has focused on the benefits that come from designing robots to work with and in support of humans as will be required for future human exploration of space. Three economic impacts have been considered: maintaining the competitiveness of the UK food processing industry through robotics, decommissioning nuclear reactors, and developing robots for the household market. Of these the dominant effect is in the labour-intensive food industry where even a small saving could result in an NPV of around £2.6bn.

In the case of medical applications from space, there are various opportunities to consider. These include the direct understanding of physiological effects such as muscle and bone wastage, which are rapid in space and apparently similar to ageing effects on the ground. New understanding from this accelerated process could help reduce the number and seriousness of hip fractures in the elderly.

Techniques required for the remote and continuous monitoring of astronaut health could have significant impacts on the treatment of patients in intensive care and in acute care. While the main result may be improved outcomes for patients, the NPV due to savings in the cost of treatment could amount to over £400m.

Finally, a further case study on astronaut protection (mentioned in the previous section) has been considered, but not analysed for this report since the technology is still at a very early stage and the data on expected costs is therefore not yet available. This UK-led innovation based on fusion reactor technology should be able to protect astronauts in the same way that the Earth's magnetic field shields the Earth from damaging space radiation.

Laboratory tests have demonstrated that a powerful magnetic field can be used to maintain a plasma shield around a spacecraft, diverting charged particles from the solar wind.

Case Study 5: Autonomous robots

The new generation of space robots designed to assist astronauts will need increased dexterity, built-in intelligence, reliability, tolerance to harsh conditions and safety of operation. These will benefit many ground-based applications, for example in the food industry, in the household robot market and in decommissioning nuclear reactors. The UK is already a leading player in the development of robotics for space.

In the food industry robots can increase efficiency (needed for the UK to compete on world markets) and improve food hygiene, as well as reducing injury from causes such as repetitive strain and back problems from production lines. Depending on the savings in labour achieved, NPVs of between £250m and £2.6bn are possible, but again a risk is involved.

The impact of space in developing new robots and marketing them for use in the home could increase UK market share and increase the NPV by about £75m.

Robots designed for use in the harsh conditions on the Moon and Mars could also be applied to the decommissioning of nuclear power stations, saving money, increasing capability and reliability, and removing the current need for umbilical cords. With UK decommissioning costs predicted to be over £60bn the NPV could be over £22m.

There could also be impacts from many other applications. Already work for the ExoMars rover is being applied to robotic buggies to transport elderly people at airports and elsewhere (a market estimated at over €40m).

Further detail is provided in Appendix D.

While this is not expected to provide complete protection from space radiation, it could provide the first line of defence for long-duration missions to the Moon and may solve the biggest problem expected in the longer-term aim of a human mission to Mars.

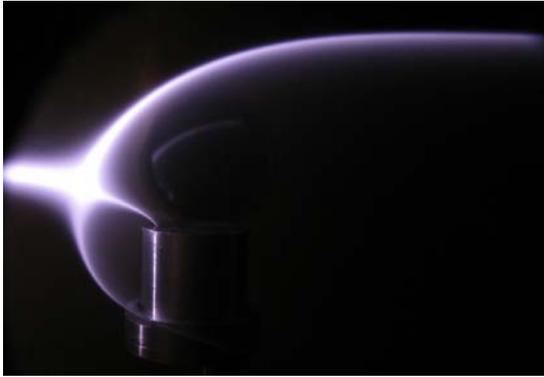


Figure 13. Laboratory demonstration of plasma shield (STFC)

In addition to the impact this could have on the ability of humans to live for long periods in space, there may be a much larger economic impact if such devices could be used to protect commercial communications spacecraft, increasing their lifetimes and reducing the cost of insurance. Due to the uncertainties in the costs and potential markets, no attempt has been made to analyse the NPV, but it is worth noting that communications satellites generate annual revenues in excess of £25bn p.a. and that it would not be unreasonable to suppose that this technology could increase the lifetime of each satellite by 10%.

All of the economic benefits discussed in this section depend on assumptions about key variables. The numbers given are best estimates of the most realistic outcomes. However, there are some conditions that would result in negative returns. In addition, in many cases the NPV would remain a notional figure and would be seen as a UK contribution to the programme. In these cases there would be a need for Government funding.

3.5.6 Benefits for society

Involvement in human space exploration would send a powerful signal that the UK intended to be a serious player in the space field, adding credibility to the country's efforts across the sector, and encouraging inward investment. By working with other countries in the context of the Global Exploration Strategy, the UK could enjoy many of the benefits

Case Study 6: Medical applications

The need to maintain the health of astronauts working in space will require improvements in real-time monitoring as well as greater understanding of the physiological changes known to affect astronauts. The UK is a leader in complex data handling techniques and adaptations for astronaut health monitoring could be applied to the care of terrestrial patients. Likewise the need to develop lightweight, robust medical equipment is likely to help patients on Earth. One example of a TB sensor developed as part of UK space exploration activities is already undergoing trials (see p24).

It is expected that countermeasures needed to help astronauts avoid physiological changes such as muscle and bone deterioration, as well as disorientation, will have similar benefits for the elderly, who are prone to falls (caused partly by muscle deterioration and balance problems) and which can result in fractures (made worse by bone loss).

From the economic point of view, savings from the reduced number and severity of hip fractures and in critical and acute healthcare could result in an NPV of £300m to £400m. Commercial exploitation of new technologies may add to these figures.

In addition, non-economic benefits include improved health and wellbeing as well as better healthcare, especially for the elderly.

Further details may be found in Appendix D.

of involvement in human exploration without incurring the costs associated with developing the large infrastructure needed.

A role in human spaceflight opens up major new opportunities for technology translation to life and medical sciences and biotechnology with benefits for health and wellbeing (especially for the elderly). It also creates new capacity and opportunities for research and technology spin-outs creating new products and services, as well as possibilities for space tourism and virtual involvement by ordinary citizens in space exploration. It would also serve as a platform for new international partnerships, which in turn opens up new markets. The UK would be in a good position to influence and provide leadership in the Global Exploration Strategy.

The greatest impact of all may be in education. This would come through capitalising on the impact that astronauts can generate through relating their experiences directly. It is worth noting that it is NASA policy for their astronauts to spend a considerable amount of their time talking to schools.

'When I stand in front of students, it is totally demoralizing if I say, "Become an aerospace engineer so you can build a plane that's 20 percent more fuel efficient than the one your parents flew." Of course that has no hope of exciting them. But if I say, "Become an aerospace engineer so you can design the first piloted craft in the rarefied atmosphere of Mars," the effect is totally different. [...] With that kind of vision, all I have to do is point my students toward it, flames of ambition get lit, and a new generation of innovators rises up.'

Dr Neil deGrasse Tyson, Member, Commission on the Future of the US Aerospace Industry⁴²

The National Space Centre and Scottish Space School already use human spaceflight as a way to engage children. It is the best platform for public engagement. These efforts would be an order of magnitude more effective if the UK had its own astronauts. This would contrast with the current perception by the general public of the UK focus on satellites and communication as 'worthy but dull'.⁴³ This option takes us beyond that in a very distinct and positive way. The UK would be involved in high profile engineering feats, which would be a source of pride in engineering, and an incentive for engineers, which is lacking currently in the UK. Students would no longer have to look to NASA for inspiration in space technologies and science.

As with Option 3 (see Section 3.4.6 on p55), by embedding education activities as part of an increased programme it should be possible to increase the impact on educational outcomes at all levels and across the country. As before, this could be done through a combination of resource packs for schools, champions in each region to promote and develop new resources, and an educationalist to lead and work with scientists and engineers carrying out the programme. A UK astronaut corps would provide a strong

⁴² *The Case for Space Exploration*, The Space Foundation, March 2006

⁴³ *Report of the UK Space Exploration Working Group*, independent report to BNSC, September 2007, Section 8.3.1

focal point for such a programme, generating interest through public appearances both in the media and in visits to schools, science centres and events.

With the increased range of topics that would be relevant to the curriculum, it would make sense to involve, at both a strategic and an operational level, government organisations such as the Qualifications and Curriculum Authority, the Department for Children, Schools and Families and the skills part of BIS.⁴⁵

“Neil Armstrong ... was the first person from Earth to step onto another celestial body. ... He demonstrated to people everywhere that no dream was too big and, thereby, dared them to dream as well.”

Joan Johnson-Freese, US Naval War College⁴⁴

Option 4 would bring the greatest benefit, increasing the returns for both science and innovation, generating new opportunities for commerce and creating the maximum interest in the value of studying STEM subjects through the existence of British astronauts. It would also maximise the benefits brought through experts from different disciplines working closely together.

⁴⁴ *The Case for Space Exploration*, The Space Foundation, March 2006

⁴⁵ Ojha, A. (Director of Education, National Space Centre), private communication, 10/2/09

4 Summary

4.1 Options considered

Chapter 3 has described the details of each of the options analysed, setting out the elements that might be included in each, along with the costs and the benefits to be expected.

Each of the options we have considered requires a different level of investment and would result in a different range of benefits. To summarise, the key aspects of these options are:

1. Reduce the existing level of support for space exploration (to include only those aspects which form part of the mandatory ESA Science Programme). This could save the UK some £20m p.a. compared with the current level. It would cause considerable damage to the UK's reputation in science and innovation, reduce international influence, reduce benefits from the ESA programme and send out strongly negative signals within the UK about the prospects for careers based on STEM subjects.
2. Continue with the current level of investment (including funding for ESA's Mars robotic exploration programme and limited national technology funding) at a total cost of around £100m p.a. This would continue to deliver good returns for science and innovation, but does not exploit the new opportunities that arise from international plans for space exploration.
3. Increase investment in robotic exploration (building on the previous option by investing in a programme of robotic exploration in collaboration with other partners). This option would require a relatively slow increase in investment, reaching around £35m p.a. extra by 2013 and a steady state of around £45m by 2018. It would build on UK strengths in robotic technology, increase scientific return and technological innovation, and generate increased public interest in science and technology. As the divide between robotic and human missions becomes increasingly blurred, this option will begin to limit the opportunities for UK involvement.
4. Invest in both robotic and human activities. This could leverage the UK's strength in robotic technologies to secure astronaut places in the human exploration of the Moon. Two versions of this option are considered:
 - a. The minimum version of this option to allow the involvement of UK astronauts in exploration would require a slowly rising investment, reaching around £40m p.a. by 2013 and rising to a steady state of just over £100m p.a. by 2022. This option would bring some of the benefits of innovation in limited areas of endeavour as well as enabling one or more significant commercial opportunities with a potentially large impact on the economy. Although these economic benefits may not be optimal, this option would have a positive impact on education and other societal outcomes due to the high-profile involvement of astronauts.
 - b. Option 4b integrates both human and robotic activities and would require a substantially larger investment starting in line with the previous version, but rising to an extra £68m p.a. by 2013 and reaching a steady state of around £180m p.a. on top of current levels by 2020. This option could bring

significant benefit, increasing the returns for both science and innovation, generating many new opportunities for commerce and creating the maximum interest in the value of studying STEM subjects through the existence of British astronauts. This level of investment would put the UK on a par with other major countries in Europe.

These options may be considered as example points on a much larger range of options – in principle any mix of these may be considered, but these represent clear break-points in the field of possibilities.

The activities included in these options may be seen as milestones on a UK exploration roadmap. A diagram of such a roadmap is shown in Figure 11, below.

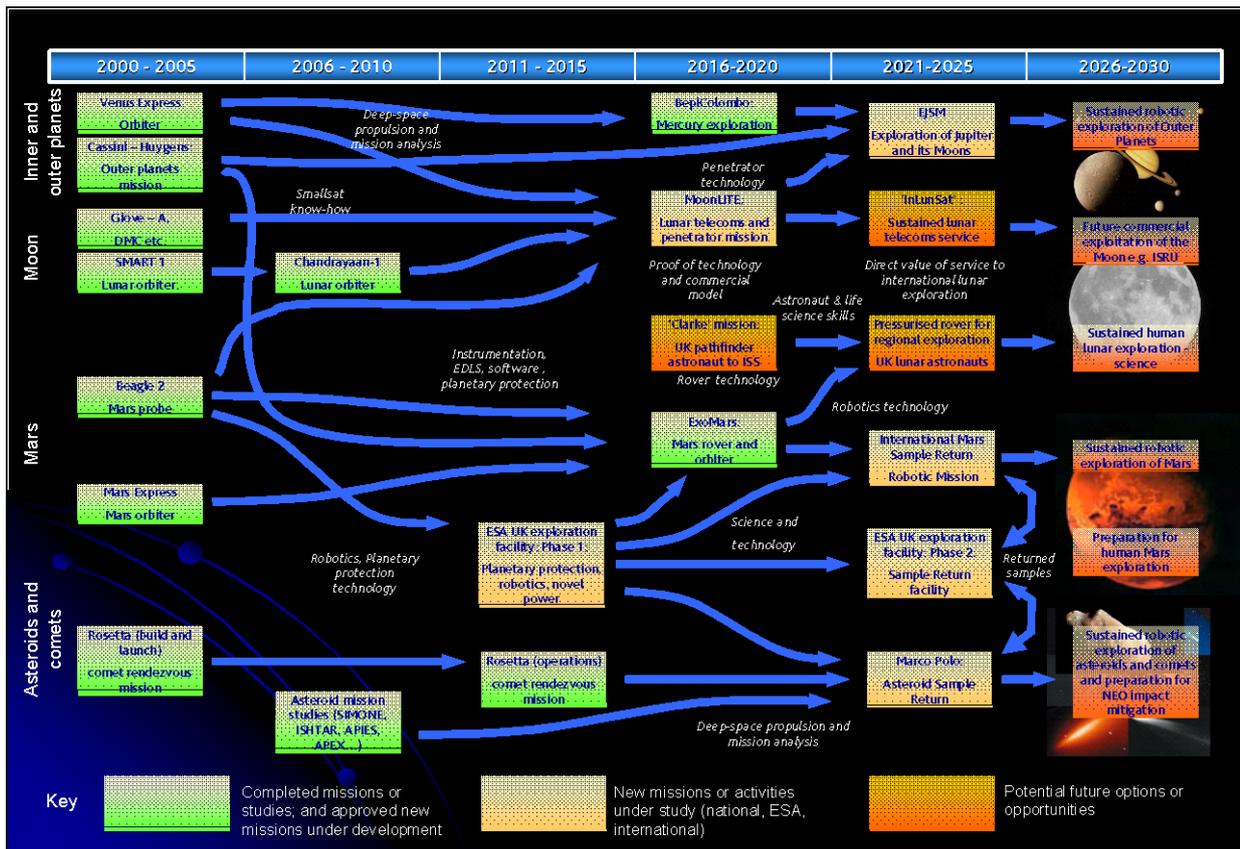


Figure 14. Tentative UK exploration roadmap

While lack of space has prevented the inclusion of all of the activities described in this report, the diagram shows how the knowledge gained on one activity can support several further activities and how, taken together, they can deliver the goals for sustained exploration shown on the right of the diagram.

4.2 Synthesis of benefits

The UK gains great benefit in **science** from its current investment in exploration through the ESA Science and Aurora programmes.

These include leading roles in the search for life on Mars and in missions to explore the outer Solar System. Much of this would be prejudiced by a reduced involvement in these programmes. New opportunities are being presented for science as other nations begin more detailed exploration of the Moon. An increased involvement in robotic activities through option 3 would give the UK

access to new areas of science, especially in exploring the history of the Solar System that is recorded on the surface of the Moon.

However, there is a danger that the UK will begin to be left behind as future missions increasingly use a combination of human and robotic techniques. In due course it will become much harder to limit involvement to those missions which have no human component. And the presence of humans on the surface of the Moon and Mars will enable a whole new range of science, due both to the increased size and capability of possible science payloads, taking advantage of the heavy lift infrastructure needed to support a human presence, and the ability of astronauts to install, adjust and maintain complex new instruments. This could include the use of the stable surface of the Moon as a location to build a new generation of sensitive astronomical telescopes.

The challenge of designing missions to work successfully in the harsh conditions of space has always led to high levels of **innovation**.

Examples currently under development include adaptation of novel sensors from planetary and cometary missions for use in compact, lightweight TB detectors, and instruments developed for detection of terahertz signals in space adapted to detect concealed weapons at airports. Examples of future innovations stemming from UK involvement in the Aurora programme include developments of rover technology, instruments for detecting biologically significant molecules and sample handling techniques. These developments would be lost if the current programme were to be reduced.

In contrast, an enhanced robotic programme would bring a range of new opportunities including improved drilling technologies, novel power sources, additional rover technologies, and new applications for small satellites. It could also foster new developments in communications and navigation technologies as well as opportunities in robot-human collaboration and medical techniques.

The integrated human and robotic option would create innovations in such areas as titanium processing, autonomous robots to support humans and medical applications. Crucially however, it would considerably enhance the conditions for serendipitous innovations brought about by close collaborations between scientists and engineers from widely differing fields.

The UK gains good **commercial** returns from its involvement in the ESA programme.

UK companies win contracts from ESA which help to maintain the competitive edge of the space sector in international markets, while spin-offs from this work create new commercial opportunities in other sectors. An enhanced robotic programme would offer new opportunities in areas targeted at UK strengths such as small satellites, drilling for oil and gas, and rovers.

Involvement in human exploration at a minimum level would also offer opportunities to develop the UK strength in small satellites while taking an early lead in the provision of lunar communications and navigation services, much as Inmarsat has done for terrestrial communications. The integrated human and robotic option would give more influence in setting the international approach to commercialising space exploration to benefit industry in the UK.

UK strategy for economic recovery

"...the Government also has to do more to help equip high potential British firms. We need to take a range of actions. We must improve the skills of our people and adapt them to the specialist demands of a modern economy; strengthen our capabilities in research and development; innovate further in science and technology, and industrialise this innovation in commercially successful ways. These actions are the bridges to our economic future."⁴⁶

It would also give first-to-market benefits in several additional areas of UK strength such as the supply of oxygen from lunar materials, autonomous robots in support of humans, medical applications and lander technologies – all of which will have spillover opportunities on Earth. Many of these opportunities have the potential for very large economic impact, although large uncertainties are involved. These would help to support the new Government approach to target interventions that ensure Britain continues to retain and develop strengths in high-value areas of global growth or rapid and fundamental technological change.

Space exploration has a range of impacts on **society**.

New initiatives are helping to increase the impact of the current programme on education by providing materials for teachers and learners of all ages, but much more needs to be done to capitalise on these opportunities. A reduction of investment would narrow the range of activities, especially in some of the most stimulating fields of endeavour such as the exploration of new planets and the search for life. This would send out negative messages to young people about the importance of STEM subjects in the UK. In contrast, an enhanced programme of robotic exploration could include education outcomes as a key deliverable, inspiring new interests in STEM subjects.

A programme with human involvement could be expected to have a far larger impact due to the ability of astronauts to relate their experiences directly and to act as inspirational role models. It would capture the imaginations of young people, challenging them and inspiring them to study the harder subjects and drawing them into careers in science and technology. The inspiration provided by UK astronauts would also encourage wider interest in science and technology among the public. Such a programme would help to retain skilled workers and

⁴⁶ *New Industry, New Jobs*, Department for Business, Enterprise and Regulatory Reform, April 2009, Section 1.12

demonstrate the significance of the UK in high-profile international activities and increase its influence in preparing for humanity's expansion beyond Earth.

At the political level, nations use space exploration as an instrument of 'soft power': that is, to demonstrate to citizens at home and nations abroad their ability to harness scientific, cultural, and organisational abilities to achieve peaceful goals. In essence it advertises the UK as an attractive place in which to invest. Cooperation at a global scale with new international partners can demonstrate common purpose and bring greater cultural understanding, thus enhancing global security and developing tools and techniques that may be used to tackle other global challenges

An assessment of the relative merits of each option is shown in the following tables, which include examples of the types of opportunity that could offer benefits to science, innovation, commerce and society.

Table 6. Example impacts from the four scenarios compared with the status quo

Option	Impacts for science
1 Reduced option	Loss of currently growing strengths in planetary science
2 Status quo	Mars robotic exploration – investigations into why the histories of Earth and Mars diverged and whether Mars supports (or supported) life
3 Enhanced robotic	Mars robotic exploration Significant role for UK in lunar science Interior structure and history of the Moon Asteroid science and threat to Earth
4a Minimum human	Mars robotic exploration Life sciences and diagnostics Medical research related to ageing Astronomy using telescopes on the Moon Increased role for UK in lunar science Microgravity science
4b Human and robotic	Mars robotic exploration Life sciences and diagnostics Medical research related to ageing Exploring the Moon – a record of 4 billion years of solar system history Astronomy using telescopes on the Moon Asteroid science and threat to Earth Prominent role for UK in lunar science Microgravity science

Key	Worst	Poorer	Status quo	Better	Best
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Option	Impacts for innovation
1 Reduced option	<p>Negative perception of UK technology</p> <p>Loss of growing strengths in rovers, life search instruments etc.</p>
2 Status quo	<p>Diminishing perception of UK technology</p> <p>Autonomous rover technology</p> <p>Instruments for life detection</p> <p>Innovations in terrestrial technology:</p> <p style="padding-left: 40px;">Medical diagnostics</p>
3 Enhanced robotic	<p>Improved perception of UK technology</p> <p>Demonstration of lunar communications infrastructure</p> <p>New applications for smallsats</p> <p>Development of new rover technology</p> <p>Novel power sources for space</p> <p>Innovations in terrestrial technology:</p> <p style="padding-left: 40px;">Drilling techniques (new oil reserves, improved drill bits)</p> <p style="padding-left: 40px;">Medical diagnostics</p> <p style="padding-left: 40px;">Nuclear power</p>
4a Minimum human	<p>Robot/human collaboration</p> <p>New medical techniques</p> <p>Innovative operational lunar communications infrastructure</p> <p>Innovations in terrestrial technology:</p> <p style="padding-left: 40px;">Medical diagnostics</p> <p style="padding-left: 40px;">Terrestrial communications and navigation techniques</p>
4b Human and robotic	<p>Innovations expected from interdisciplinary work</p> <p>Innovative operational lunar communications infrastructure</p> <p>Human deep drill project</p> <p>Development of rover technology</p> <p>Innovations in terrestrial technology:</p> <p style="padding-left: 40px;">Titanium processing</p> <p style="padding-left: 40px;">Medical applications (instruments, data handling, diagnostics)</p> <p style="padding-left: 40px;">Robotics (food handling, nuclear decommissioning, household)</p> <p style="padding-left: 40px;">Terrestrial communications and navigation techniques</p> <p style="padding-left: 40px;">Nuclear power</p>

Option	Impacts for commerce
1 Reduced option	<p>Loss of ESA contracts</p> <p>Loss of spin-off opportunities (robotics, medical diagnostics etc.)</p> <p>Misses opportunity to choose role(s) in exploration; hard to choose role later to suit UK aims</p> <p>Reduced economic impact</p>
2 Status quo	<p>ESA contracts continue at current level</p> <p>Commercial spin-offs (use of autonomous robotics, medical diagnostics)</p> <p>Misses opportunity to choose role(s) in exploration; hard to choose role later to suit UK aims</p> <p>Economic impact continues at current level</p>
3 Enhanced robotic	<p>Some influence in future commercial exploitation</p> <p>Benefits of being first to market in chosen fields</p> <p>Become early exploiter of a few commercial opportunities, e.g. lunar drilling</p> <p>Somewhat strengthened UK smallsat industry</p> <p>Increased economic impact</p>
4a Minimum human	<p>Considerable influence in future commercial exploitation</p> <p>Benefits of being first to market in chosen fields</p> <p>Become early exploiter of a few commercial opportunities, e.g. lunar communications and navigation</p> <p>Strengthened UK smallsat industry</p> <p>Increased economic impact</p>
4b Human and robotic	<p>Considerable influence in future commercial exploitation</p> <p>Benefits of being first to market in chosen fields</p> <p>Become early exploiter of UK's preferred commercial opportunities, e.g.</p> <ul style="list-style-type: none"> Lunar communications and navigation service In situ resource processing for oxygen production Autonomous robots in support of humans Medical applications Lander technologies <p>Strengthened UK smallsat industry</p> <p>Large economic impact</p>

Option	Impacts for society
1 Reduced option	<p>UK not involved in the search for life in our Solar System</p> <p>UK no longer considered credible partner in space science and excluded from exploration</p> <p>Increase in skilled workers moving abroad</p>
2 Status quo	<p>UK part of search for life in our Solar System</p> <p>Aurora Fellowships – training the next generation of planetary scientists</p> <p>UK maintains minor (though reducing) influence in space science and exploration</p> <p>Danger of skilled workers moving abroad to satisfy ambitions</p>
3 Enhanced robotic	<p>Space robotics in education</p> <p>Hands-on training for engineers on national missions</p> <p>Some increase in inspiration for STEM take-up</p> <p>Worthwhile programme helps to retain skilled workforce</p> <p>Increased influence in international space exploration strategy</p> <p>Improved understanding of asteroid threat</p>
4a Minimum human	<p>Education programme using UK astronauts in schools</p> <p>National role models for STEM, inspires take-up of STEM subjects</p> <p>Inspiration for society of having UK astronaut on Moon</p> <p>Exciting programme helps to retain skilled workforce</p> <p>Increased influence in international space exploration strategy</p>
4b Human and robotic	<p>Education programme using UK astronauts and space robotics in schools</p> <p>National role models for STEM, inspires take-up of STEM subjects</p> <p>Inspiration for society of having UK astronaut on Moon</p> <p>Hands-on training for engineers on national missions</p> <p>Exciting programme helps to retain skilled workforce</p> <p>UK significant player in international space exploration strategy</p> <p>Improved understanding of asteroid threat</p>

4.3 Meeting Government aims

The Government has identified **five key trends and challenges** that it will have to confront in the period to 2017 if it is to make further progress against its goals of sustainable growth and employment, fairness and opportunity, a secure and fair world, and modern and effective public services. These are:

1. Demographic and socio-economic change (with rapid increases in the old age dependency ratio on the horizon, and rising consumer expectations of public services);
2. Intensification of cross-border economic competition (with new opportunities for growth, as the balance of international economic activity shifts toward emerging markets such as China and India);
3. The rapid pace of innovation and technological diffusion (which will continue to transform the way people live and open up new ways of delivering public services);
4. Continued global uncertainty (with ongoing threats of international terrorism and global conflict, and the continued imperative to tackle global poverty); and
5. Increasing pressures on our natural resources and global climate (requiring action by governments, businesses, and individuals to maintain prosperity and improve environmental care).

These challenges will have far-reaching implications for the UK, demanding innovative cross-government policy responses and early, coordinated action across departmental and organisational boundaries.⁴⁷ A well-founded space exploration programme would require a similar level of coordination across government.

The UK's current space exploration activities contribute mainly to the second and third of the five challenges through innovations developed for space and their impact on the UK economy. An increased exploration programme would have additional benefits for the fifth challenge as new energy-efficient power generation and storage techniques are developed for space, but with applications on Earth. A human spaceflight programme would help to tackle the first challenge through medical advances of benefit to the elderly. New sensor technologies developed for space are likely to be of service in tackling the fourth and fifth challenges through remote monitoring techniques (just as sensors designed for astronomy are now being used for remote sensing of the environment and for detecting explosives at airports). The enhanced options would offer increased impacts on STEM take-up in education, needed to maintain the UK's competitive position implied in the second challenge.

The 2007 Comprehensive Spending Review set out the Government's key priority outcomes in the form of 30 **Public Service Agreements** (PSAs) for the spending period 2008 – 2011.⁴⁸ A list of the PSAs is given in Appendix E. These are grouped under four themes: (i) sustainable growth and prosperity; (ii) fairness and opportunity for all; (iii) stronger communities and a better quality of life; and (iv) a more secure, fair and

⁴⁷ *Long-term opportunities and challenges for the UK: analysis for the 2007 CSR*, HM Treasury, November 2006

⁴⁸ *Public Service Agreements 2008-2011*, HM Treasury,

environmentally sustainable world. A UK space exploration programme can address some of these PSAs directly: for example, PSA 4 is a commitment to "promote world class science and innovation in the UK." Current missions are already returning high quality data that are being used by UK scientists to infer the evolutionary history of water (and potential for life) on Mars, while autonomous rover technology (developed in the UK for future space missions) is being trialled at airports for transport of customers with reduced mobility.

A space exploration programme could also contribute to the PSAs aimed at increasing the health, employment prospects and social conditions of UK citizens, or alleviating global problems such as conflict and climate change. For example, technological advances in instrumentation developed for remote detection of chemicals on the surface of Mars can be deployed at airports or other public places to detect chemicals associated with bomb-making, supporting PSA 26 to "reduce the risk to the UK and its interests overseas from international terrorism."

A space exploration programme addresses many of the PSAs through enhanced business opportunities leading to increased employment. The associated education activities enabled by UK involvement in advanced robotic exploration and especially by the involvement of UK astronauts would contribute to the PSAs concerned with education standards. These, in turn, enable a wealthier and more technologically-aware UK society. Appendix E gives further examples of how a UK space exploration programme works towards specific PSA goals and hence achievement of the Government's priority targets.

In tackling the current economic crisis, the Government has set out its plans in *New Industry, New Jobs*: "There are four immediate priority areas for action and reform in Britain: **innovation, skills, finance and infrastructure**. We must also continue to ensure that British businesses are able to **access growing global markets**."⁴⁹

Chapter 3 has set out the impact of each option on innovation and skills, while involvement in international exploration efforts would help to ensure access to this global market which, as described in Chapter 2, is growing faster than the economy as a whole.

The benefits for skills and innovation go hand-in-hand with each other, as explained in the Government's White Paper, *Innovation Nation*:

"The effects of innovative people are self-reinforcing: innovative businesses are attracted to highly skilled and creative workforces and, in turn, innovative people are drawn towards exciting and challenging career opportunities. Furthermore, innovative people generate new ideas that require skilled people to implement and exploit them."⁵⁰

This observation has particular relevance here, given the innovative and inspirational nature of space exploration.

⁴⁹ *New Industry, New Jobs*, Department for Business, Enterprise and Regulatory Reform, April 2009, Section 3.3

⁵⁰ *Innovation Nation*, Department for Innovation, Universities and Skills, March 2008

4.4 Resources required

A commitment to a future programme of space exploration would be a long-term strategic one. Spend would build up slowly with reviews built into any delivery plan, the first coming after five years, allowing phased involvement and sufficient time to establish whether the expected benefits are being realised, without committing resources in the long-term.

The table and graph, below, show predicted spend profiles for the four options listed above.

Note that, even with the most ambitious of the proposed spend profiles, the UK's space expenditure would still be well below that of the other big countries in Europe.

Table 7. Spend profiles for first six years (£m)						
Option	Year					
	2010	2011	2012	2013	2014	2015
1 Reduced option (ESA Science Programme only)	80	80	80	80	80	80
2 Status quo (ESA Science and Aurora Mars Programmes only)	100	100	100	100	100	100
3 Enhanced robotic exploration via NASA	101	111	124	135	138	138
4a Minimum human	101	112	130	143	143	157
4b Integrated human and enhanced robotic	101	112	133	168	195	229

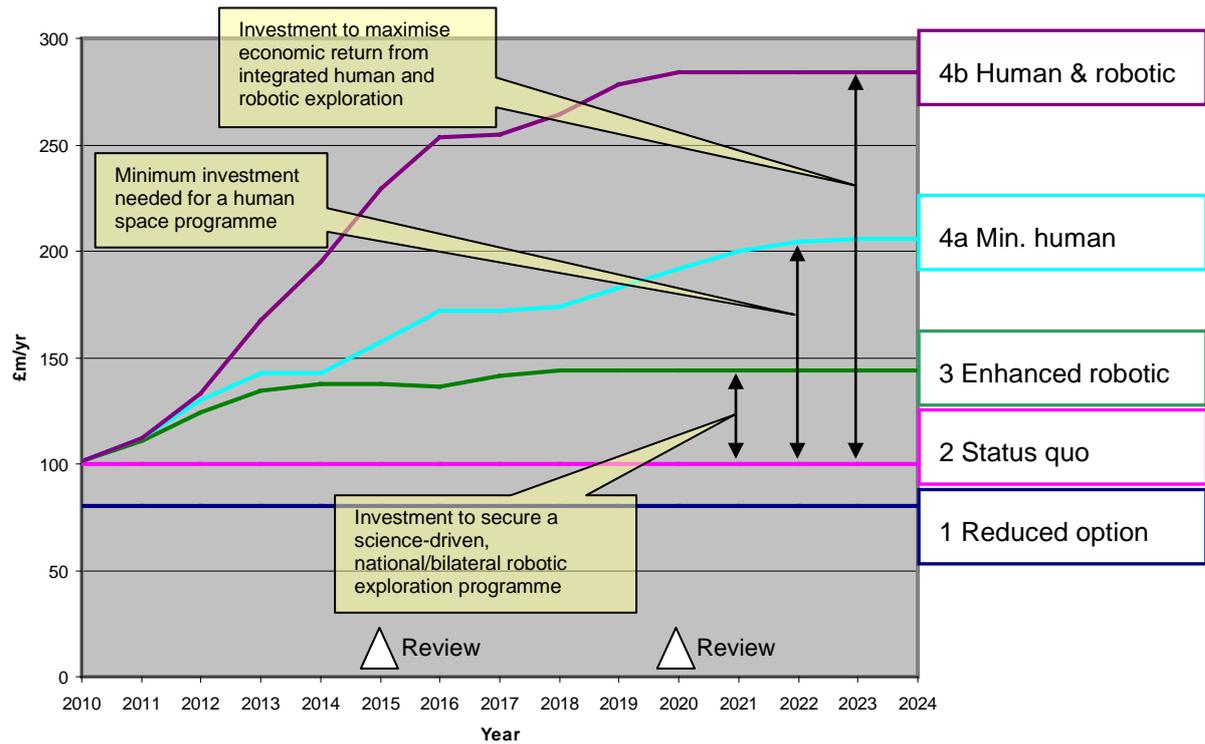


Figure 15. Spend profiles for each option

This report does not attempt to discuss the appropriate source of possible funding for an increased programme, other than to make two observations:

1. The beneficiaries of such an extended programme would be in many different areas whose interests are currently served by different lines of funding. With benefits for science, innovation, commerce, education, skills, health, and society in general it is unlikely that simultaneous agreement could be reached among all relevant Government Departments with present mechanisms.
2. It should be noted that the proposed programmes are only partly science-led. While science may set the direction and motivation for many of the exploration activities proposed in this report, it would be a mistake to label such a programme as a science programme. In this case it would certainly fail to deliver since the scientific peer review system has neither the mandate nor the competence to consider the wider benefits to society.⁵¹

⁵¹ Ian Crawford, A&G • February 2009 • Vol. 50

4.5 Delivery

The cross-disciplinary nature of activity and wide range of benefits to different end users would require well-structured management to ensure that the different aspects are properly linked to deliver all benefits. If the UK were to embark on an extended programme of space exploration, it would be necessary to consider the suitability and effectiveness of existing structures to oversee and manage such a wide-ranging but coherent programme. The outcome of such a review may be to recommend changes to the structure of BNSC or even the creation of a new organisation with executive and funding powers of its own.

A crucial aspect of the extended options (Options 3 and 4) is to deliver improvements to education and skills as well as knowledge exchange. It will be vital to ensure that these aspects are properly bedded into any programme from the beginning.

The recent creation of an ESA Centre at Harwell, which includes space exploration as a major focus, creates additional opportunities for synergy between European operators, UK industry and academic groups as well as with relevant specialist groups and facilities already on the Harwell campus.

The selection of a UK national to the ESA astronaut corps presents a further opportunity for the UK to become more involved in human spaceflight activities and may further increase the range of opportunities available under Option 4, as well as providing a natural focus and a public face for such activities in the UK.

In setting up such a programme it will be important to ensure that the legal framework is not a barrier. This could affect the provision of high value added activities such as space tourism and low-cost reusable launchers⁵² as well as long-term issues such as the exploitation of minerals on the Moon and elsewhere. These will require international agreement – something that will be easier for the UK to influence as a participant than as an outsider.

4.6 Timing

The decision on the level of engagement in exploration has long-term strategic implications. The timing of this decision affects the range of opportunities open to the UK since international discussions on leadership roles are underway.

In 2009/10 crucial decisions on the proposed MoonLITE mission will be needed since it is expected to be carried out in collaboration with the US and must be dovetailed with their plans. Decisions will also be needed within the UK to inform any necessary bids into the next Government Spending Review.

The Augustine Review of the US human space programme reported in October 2009 and is expected to set the future direction of US strategy. The outcome of this process is not yet known, but it is likely to include increased emphasis on international collaboration.

ESA and the EU are in the process of defining a European strategy for space exploration through a series of high-level meetings in 2009 and 2010 in which the UK is playing an active role.

The International Space Exploration Coordination Group is currently bringing the plans of agencies together to agree the shape of future developments on the Moon – from defining

⁵² Recommendation 12, *Report of the UK Space Exploration Working Group*, September 2007

the types of mission to agreeing the hardware needed and how it will work together. Those with the clearest plans have most influence in setting the pace and direction of these developments. A global reference architecture for human lunar exploration will be agreed by July 2010.

To secure the opportunities presented, the UK would have to stake its claim before these international discussions are concluded. As other nations declare their plans, the UK will need to demonstrate its firm intentions to become involved if it wishes to play a major part. Already in 2009, the opportunities are narrowing.

4.7 Partners

If the UK chooses to adopt either of the options to increase its role in exploration, it will be necessary to agree how best this may be achieved.

Space exploration is too large an endeavour for any country to pursue alone, and the UK would have to choose its partners carefully. There are many options including working with our traditional partners in the US and Western Europe as well as options to widen existing relationships with Russia or Japan or to begin a completely new level of cooperation in space with China or India. While there may be valuable opportunities to consider in these latter examples, for the purposes of this report we shall limit ourselves to the first two, since these can be analysed with the greatest degree of confidence.

In the case of Europe, there is an existing mechanism whereby we could increase our contribution to ESA through subscription to the relevant programmes. These would include Aurora for robotic activities, balanced by suitable national investment to ensure that the wider benefits are exploited. For human activities the ESA route is less clear. It is now too late to play a meaningful part in the ISS programmes and ESA's human-related programmes for exploration are at a very early stage. Thus it is hard to be definitive, but the UK could be influential in setting the direction. The UK could do this by making its intentions clear well before the ESA Ministerial Conference expected in 2011 – as well as by beginning investment in relevant human-related activities in the UK. Given the roughly constant level of funding available within Europe, we can estimate that the size of the human exploration programme will be similar to that of the ISS programme which it will in due course replace. An early entry-point could be studies and a preparatory human space flight programme to gain experience through the involvement of the newly-selected UK astronaut in the ESA corps (involving flights to the ISS as well as to the Moon in due course).

The obvious alternative is to negotiate participation in future human space exploration missions in return for provision of key services or hardware. This route has been followed by Canada, which has flown its astronauts through its provision of robotic arms for the Shuttle and ISS programmes. The same approach was taken by Italy, which agreed to supply three logistics modules to the ISS in return for six flights of Italian astronauts, together with a share of the science exploitation.

While no direct comparison may be made, it is useful to consider the trades that were made in these two cases. The first robotic arm for the Shuttle cost the Canadian government C\$100m, but the subsequent sale of further robotic arms gave a 6:1 return on the initial investment. Continuation of the programme gave Canada 14 flights (with 9 astronauts) to the ISS as well as access for Canadian scientists. Italy spent around €600m

(at today's prices including maintenance costs) on the three Multi-Purpose Logistics Modules, in return for six flights (three short-duration and three long-duration).

The expenditure proposed in the previous section allows for the development of several elements that could form part of a negotiation for involvement in the human exploration programme of the US (or indeed of other nations). It is likely that the 'exchange rate' would be considerably different for lunar missions, but it is clear that provision of a communications and navigation service, or a facility to generate oxygen from lunar regolith, would buy a substantial role in future human missions – maybe a small number of UK astronauts carrying out scientific and technical activities on the Moon.

4.8 Conclusions

Space exploration is too expensive for any single country to embark on alone, so the world's space-faring nations, including the UK, have come together to agree the Global Exploration Strategy. This provides the opportunity for each nation to play a role that suits their level of ambition and their specific national interests. The UK must decide what role it wants in this new endeavour.

There are many different motivations for space exploration. As with most new space activities and most types of terrestrial exploration, the first motivation is generally for science.

However, this new international activity creates opportunities for both technological innovation and commercial endeavour. The inclusion of astronauts will have several further effects: increasing the flexibility of science missions as intelligent humans are on hand to assemble, adjust and maintain instruments; while the extra lift capacity needed to carry them creates opportunities for larger and more complex instruments. Humans still make better explorers than robots, being able to spot the unusual and serendipitous to make new discoveries and choose the most valuable samples. The need for engineers and scientists from the wide range of disciplines working together on human spaceflight will inevitably produce new understandings and innovations.

Some of these can be predicted, and analysis has shown that there are opportunities for big economic impact in some of them. But it is the ones that cannot yet be predicted that may have the biggest impact – just as the impact of miniaturisation of electronics for space or the widespread reliance on satellites for communication and navigation were not predicted when astronauts first visited the Moon and scientists first experimented with radio communications in space. Whether predicted or not, history shows that the benefits of these opportunities will fall to those who are geared up to exploit them.

And finally we should not under-estimate the value brought by the involvement of astronauts in generating interest in science and technology. For many people, science is seen as dry and impersonal, but the impact of a living breathing astronaut to humanise science and relate their personal experiences of carrying out science and engineering in space has been shown to be inspirational.

For these reasons it does not make sense to categorise space exploration as 'science', 'innovation', 'commerce', or even 'education'. Rather it should be seen as an opportunity to weave these themes together, each in support of the other:

- Science giving direction to the work of astronauts and challenging engineers to innovate;
- Innovations arising from coping with the harsh environment of space and cross-working between disciplines giving rise to new commercial possibilities and to improvements in healthcare and energy production;
- New enterprises making exploration more sustainable and harnessing innovations to benefit the economy;
- Astronauts from the UK working on international missions, enabling new science and providing inspiration for STEM education;
- Each of these aspects demonstrating aspirational careers, and thus developing and retaining technical skills in the workforce.

All of these things taken together will help to generate new knowledge, develop new technologies, raise the level of skills in the workforce and create opportunities for innovative business in the UK. This will help to re-build the economy and improve the wellbeing of people in the UK.

In summary:

1. The UK is securing excellent science, technology and commercial benefits from its investment in the ESA Mars robotic programme.
2. Viable options exist to develop a science-driven, national/bilateral robotic exploration programme focused on the Moon and asteroids. This would strengthen and re-balance the UK's space programme which is heavily biased towards ESA at present. The proposed MoonLITE mission fits this scenario.
3. A human space exploration programme could be pursued through joining the nascent ESA exploration programme or through bilateral collaboration with NASA (the 'Canadian Model'). The difficulties of maintaining focus on UK interests within a larger 'club' favours the latter approach. Because it prepares for a human lunar exploration programme, the MoonLITE project is consistent with this approach.
4. A minimum human spaceflight programme is possible. However, an integrated robotic and human programme comprising focused UK contributions to robotic infrastructure and technology would potentially yield a stronger mix of technology impact and economic return while simultaneously delivering the benefits of prominent UK astronauts working on the Moon.
5. The analysis prepared by London Economics suggests that there is the potential for substantial economic return from associated commercialisation and other technology spillovers. However, these returns are inevitably uncertain given the long lead time.
6. The initial trajectory and level of investment is very similar for options 3, 4a and 4b, which allows a few years to fine-tune investment choices based on delivered performance.

“The exploration of space will go ahead, whether we join in it or not, and it is one of the great adventures of all time, and no nation which expects to be the leader of other nations can expect to stay behind in the race for space... We set sail on this new sea because there is new knowledge to be gained ... and used for the progress of all people.”

John F. Kennedy, quoted by Barack Obama⁵³

⁵³ Obama Space Policy, 2008

Appendix A Terms of Reference

A.1 Summary

The objective of this study is to provide advice to Ministers on the future programme options for UK involvement in space exploration, taking into account the scientific, technological and economic benefits, and the UK's existing strengths in robotic exploration.

It is a specific action identified in the Government's new space strategy, released on 14 February 2008. This noted that the publication of the Global Exploration Strategy⁵⁴ presented a suitable point to review the role of the UK in space exploration. The work will take into account the recommendations in the report of the independent UK Space Exploration Working Group.⁵⁵

For the purposes of this study, the definition of 'space exploration' may be taken as *'The systematic exploration by robotic and human means of Solar System destinations upon which in the foreseeable future humans will live and work.'*⁵⁴ Therefore this work will not address space applications such as terrestrial communications and navigation, or Earth observation.

It is expected that the report will be made public after consideration by the Government.

A.2 Purpose

The study will assess the benefits of investment in the Space Exploration programme and the potential for such investment to add value to:

The Economy: Space already contributes about £7bn annually to the UK economy and the UK has world-leading capability in this sector. The world market in Space and related activities is projected to grow by a factor of ten by 2020. To maintain or increase its market share, and attract inward investment, the UK will need to pioneer novel and disruptive technologies, and ensure that it then capitalises on these technologies for commercial advantage. To what extent can the exploration programme drive this development through setting cutting-edge challenges?

Skills: To realise the economic benefits of space, the UK will require a ready supply of trained engineers, scientists and technicians, skilled in the complete life cycle of spacecraft and instrument development and in extracting the full benefit from these programmes. The advanced skills needed for space can act to pull through the high tech skill base of the UK more generally. How should the UK invest in order to develop the next cadre of experts in these areas?

Science: Access to the Moon and other solar system objects with large-scale infrastructure will revolutionise the science of the solar system, including study of its history and formation, and the development of life. How can the UK maintain its world-leading position in these fundamental science areas? How can the UK capture the wider scientific

⁵⁴ 'The Global Exploration Strategy: The Framework for Coordination', May 2007, agreed and published by ASI, BNSC, CNES, CNSA, CSA, CSIRO, DLR, ESA, ISRO, JAXA, KARI, NASA, NSAU, and Roscosmos

⁵⁵ 'Report of the UK Space Exploration Working Group,' September 2007, BNSC

benefits stimulated by the inherently cross-disciplinary nature of the exploration programme (e.g. in medicine, energy, autonomous systems etc)?

Inspiration: The exploration of the Solar System is the sort of grand challenge that can act as a beacon to attract the next generation of young scientists and inspire the population at large to take an interest in science in its wider sense. How should the UK position itself so as to realise these benefits?

A.3 Background

There is a renewed interest among many nations in the exploration of the solar system using both human and robotic means. This was set out clearly in the Global Exploration Strategy⁵⁴, signed up to by 14 nations including the UK in 2007.

This provides a long-term roadmap for nations that wish to become involved in this global endeavour and hence it is important that the UK decides whether to take a leading role through early involvement or if it wishes to remain outside such activities; playing ‘catch-up’ at a later date is likely to be much more difficult. Moreover a significant delay in UK decision-making will certainly reduce or eliminate the range of opportunities which currently exist. This is why the current study is felt to be timely.

Other nations have their own reasons for taking part in space exploration, but the UK must make its own decisions on whether being involved would serve the national interest and whether the benefits would justify the costs.

The Space Exploration Working Group was set up by the UK Space Board to consider what, if any, involvement would be appropriate for the UK. It made a series of recommendations supporting the need to build on the UK’s strengths in robotic technology to extend its involvement in wider aspects of space exploration. This would deliver benefits in a range of areas from commercial opportunities to technology development, innovation and skills both within and outside the space sector.

The Space Exploration Working Group was an ad hoc group of experts in many different fields and as such it was not able to provide the necessary detailed economic analysis, nor the negotiations with the UK’s international partners that would need to be conducted at government-to-government level. This study is therefore intended to give the UK Government the information necessary to consider the recommendations and hence decide on the level of funding appropriate for a UK programme of space exploration.

A.4 Global context

To put the present opportunities in context, it is important to recognise the plans of other nations. The US has published the most comprehensive plans so far. In addition to NASA’s continuing programme of robotic science missions, these plans include the building of a new generation of launchers and a Crew Exploration Vehicle to replace the Shuttle. Their intention is to return to the Moon no later than 2020 and to implement a sustained human and robotic programme extending across the solar system with supporting innovative technologies, knowledge and infrastructure. The US have, crucially, stated in the Vision for Space Exploration (2004) that they wish to promote international and commercial participation and have listed a range of technologies in which they would welcome international cooperation – hence creating opportunities for other nations, such as the UK.

In this context, the US is working with the UK to define joint lunar exploration projects, including the proposed UK-led MoonLITE science and technology mission. In addition,

they have invited the UK to participate in their new International Lunar Network programme which will see further opportunities for joint science and technology developments.

The current focus of the European Space Agency's €100M/year Aurora exploration programme which started in 2005 is the scientific exploration of Mars, with a first robotic rover mission planned for launch in 2013. This will prepare Europe to subsequently partner NASA in a robotic mission to return samples from Mars around 2020. This is widely acknowledged as a very important scientific goal requiring international collaboration. The UK is the second largest player in Aurora. The UK also contributes to the €400M/yr space science programme of ESA, which undertakes basic research in physics and astronomy.

The UK does not participate in ESA's €500M/year human spaceflight programme. Led by Germany, France and Italy, this has seen the development of the successful ATV robotic space freighter, the Columbus life-science laboratory – now attached to the International Space Station (ISS) – and a continuing programme launching European astronauts to build and operate the ISS.

ESA and its main contributors now propose to build on the robotic and human spaceflight expertise built up in Europe to prepare for an involvement in combined robotic and human planetary exploration. Thus the UK must shortly consider whether it will wish to participate in combined missions once they begin or whether it will relinquish its leading role in planetary exploration. Despite its active role in Aurora, the UK is only 12th (out of 17) among the member states in its per capita contribution to ESA.

Other nations have also published ambitious plans. Within Europe, Germany is planning a national lunar mission, France is focused on enabling technologies especially for Mars exploration, Italy is planning a Mars Telecoms Orbiter and development of orbital and planetary robotics. All three countries are contributing to the Russian Crew Space Transportation System which will provide a means of launching and recovering European and Russian astronauts to replace the 30-year old Soyuz vehicle.

Canada has played a relatively small but central role in the international human spaceflight programme by contributing its skill in building robotic equipment in return for both commercial contracts and flights for Canadian astronauts – in total 14 flights by 8 astronauts so far. This successful programme has been identified as one possible model for UK developments in exploration.

Japan has built a large laboratory module for the International Space Station, flown several astronauts and has launched missions to the Moon and to an asteroid. It is now planning follow-on missions and is preparing for human lunar exploration starting in a decade's time. Russia plans a Moon lander mission and a sample return mission to Phobos (one of the moons of Mars). It plans a human mission to the Moon in 2025 and to Mars after 2035. China has flown three astronauts and has plans for a range of lunar missions with one already successfully in orbit around the Moon. India's Chandrayaan-1 mission will carry a UK-built instrument to the Moon this year, while future plans include further lunar missions and its own programme of human spaceflight.

In total 38 countries now have an astronaut programme, the most recent additions being Malaysia in 2007 and South Korea in 2008.⁵⁶

Another factor in the international scene is the emergence of both a sub-orbital and orbital space tourism market which is driving innovation in technology and business models, and will ultimately reduce the cost of access to space. There are several companies already in the market and the European aerospace giant EADS is projecting a global market of 15,000+ space tourists per year by 2020.

Clearly it will be important for the study to investigate these plans to establish what opportunities they may provide to the UK both in terms of collaboration with other nations, and the provision of services to them through commercial arrangements. This will help us to judge whether investment in exploration can emulate previous successful investments in space by the UK (such as in small low-cost satellites, and in communication and navigation satellites – now both fully commercial) which have resulted in the current annual contribution to the UK's GDP of £7bn.⁵⁷ The total size of the global space market is now estimated at \$251bn and grew at a rate of 11% during 2006.⁵⁸

A.5 Timing

The aim is to report towards the end of 2008/9 financial year.

A.6 Objectives

1. To set out the range of programmatic options open to the UK for future involvement in both robotic and human exploration within ESA and through known bilateral opportunities.
2. To provide an economic evaluation (including quantification and assessment of direct and indirect impact, as well as spill-over benefits) of
 - science opportunities
 - new technological opportunities (e.g. robotics)
 - emerging economic opportunities (e.g. telecoms services, spin out technology)
 - skills
3. To assess other impacts on wider agendas such as science and society, culture and education

These assessments are each to be carried out on the basis of three different options:

- A. continuation at current levels of investment (including current levels of funding for ESA's Aurora programme and limited national technology funding);
- B. increased investment in robotic technologies (building on Option A by investing in a programme of robotic lunar exploration in collaboration with other partners);
- C. investment in robotic and human activities (building on Option B through a preparatory programme of human spaceflight in collaboration with other partners).

⁵⁶ The Space Economy at a Glance, OECD, 2007, ISBN 978-92-64-03109-8.

⁵⁷ 'Case4Space Report,' UKspace, October 2006.

⁵⁸ 'The Space Report 2008,' The Space Foundation, April 2008.

Investment in human spaceflight may be facilitated by UK contributions in the area of robotic technology following the Canadian model.

For the purposes of this study, the following definition of ‘economic impact’ may be used: “A policy action has an economic impact when it affects the welfare of consumers, the profits of firms or the revenue of government. Economic impacts range from those that are readily quantifiable, in terms of greater wealth, cheaper prices and more revenue, to those less easily quantifiable, such as effects on the environment, public health and quality of life.”⁵⁹

A.7 Methodology

The work will be led by a Project Manager from BNSC and carried out by a Study Group composed mainly of STFC staff, though others may be co-opted as necessary.

The study will be overseen by a small Steering Committee including members from BNSC, STFC, DIUS (economist, Innovation Group).

The Steering Committee will report to the UK Space Board and the Study Group will keep the Minister for Science and Innovation briefed through a short monthly meeting to ensure that the report meets Government needs.

To ensure independence, an economic review will be carried out by an external consultancy who will report to the Project Manager and whose work will be guided by the Steering Committee.

The work will be organised into five workpackages:

1 Review of existing information.

For example the *Report of the Space Exploration Working Group*⁵⁵ and the existing UK industrial *Case4Space*⁵⁷ study on spin-out and economic benefit. The purpose will be to select those opportunities that show the most promise for the UK and to identify gaps in understanding in order to inform the remaining work packages.

2 UK consultation

This will seek the views of industry, academia, other Research Councils (MRC, NERC, EPSRC, BBSRC) and other government departments, especially on education.

It will establish the level of potential benefit across Government and industry. A range of techniques may be used to collect this information from written submissions to interviews with key players and workshops with groups of experts from outside the space field.

3 International consultation

This will comprise discussions with key international collaborators (e.g. USA, ESA, Canada, India) to investigate opportunities and to benefit from lessons learned elsewhere. In particular the study will look at the focused and selective Canadian approach to robotics in support of human activities that has enabled involvement of Canadian astronauts at low cost.

4 Economic analysis

⁵⁹ ‘Measuring economic impacts of investment in the research base and innovation – a new framework for measurement,’ DTI, 2007.

Employing a recognised economic analysis group, the report shall capture as quantitatively as possible the expected future economic benefits in the widest sense: commercial opportunities, access to markets, benefits to the science base (which embraces fields as diverse as medicine and cosmology), to education and skills and to society. It should look ahead at least to 2025. This work will be overseen on a day-to-day basis by the Project Manager, with oversight provided by the Steering Committee. The DTI definition of economic impact should be used (see above under ‘Objectives’).

5 Compilation of report

Compilation into a single coherent report for Ministers setting out programme options with associated costs, expected benefits and risks. The report shall include a review of mechanisms to ensure that the technological benefits of proposed programmes are fully exploited.

1/5/08

Appendix B Plans of other nations

This appendix sets out in more detail the plans and motivations of the key international players in space exploration.

B.1 Europe

Europe's strategy for space, endorsed by the European Union Council of Research and the European Space Agency (ESA) Council in 2001, calls for Europe to:

- explore the Solar System and the Universe
- stimulate new technology
- inspire the young people of Europe to take a greater interest in science and technology

As a result of this challenge, in 2002 ESA set up the Aurora Programme. The primary objective of Aurora is to create, and then implement, a European long-term plan for the robotic and human exploration of the solar system, with human exploration of Mars being a long-term target. A second objective of Aurora is to search for life beyond the Earth.

Before attempting a human mission to Mars, the planet's environment needs to be characterised and potential hazards to humans identified. This will be achieved through a series of robotic missions to Mars starting with ExoMars (to be launched in 2016) leading to a Mars sample return mission. In addition the necessary technologies and capabilities for long-duration human spaceflight have to be developed and tested. Human space technologies will be demonstrated on the International Space Station and a programme of human exploration of the Moon will build on this to prove technologies required for Mars exploration. Each phase of exploration on the way to the human exploration of Mars will require increasingly complex technology. In some cases existing technology can be further developed or adapted, but in many cases European industry will be asked to come up with new innovative technology to make future exploration missions possible.

Europe recognizes that exploration will be a truly international endeavour and ESA enables European states to participate in exploration as an equal partner with other major powers. ESA has identified a number of different scenarios for European engagement in the international exploration programme. Studies have been commissioned on different lunar elements that Europe could provide – these include pressurised rovers, habitats and communications infrastructure. In discussion with the member states ESA will decide which of these elements will be taken forward.

The UK is a major partner in the robotic elements of the Aurora programme, being the second-largest contributor to ExoMars and the largest partner in the Mars Robotic Exploration Preparatory Programme, which will develop technology required for future missions. The UK currently subscribes €14M per year.

Within Europe, the major players in space exploration are Italy, France and Germany.

B.2 France

France is in the process of agreeing its national priorities for space. It is no longer motivated by prestige (as perhaps was the case some twenty or so years ago); instead current priorities are:

1. Access to space (launchers, space transportation);
2. General applications for the benefit of citizens (e.g. telecoms and navigation);
3. Protection of the environment (mainly Earth observation);
4. Science and technology (which covers big science issues, innovation and competitiveness – this includes the exploration programme);
5. Security and defence.

However, it also takes the view that human space exploration is not simply a matter of science, but it is important for the French public and at the political level, while also having technological and economic benefits.

B.3 Germany

Germany is focusing most of its exploration efforts on making full use of the ISS and on lunar exploration. It presently spends about €200m a year on human spaceflight activities. It has plans for a Lunar Exploration Orbiter and is studying ideas for a lunar lander. DLR is funding national research in exploration technologies such as reversible fuel cells, life support systems and in-situ resource utilisation. It is also a major stakeholder in ESA's Automated Return Vehicle, a first stage in developing a European human space vehicle.

B.4 Italy

Italy is also in the process of agreeing a new National Aerospace Plan for the period 2009-2011 (though ASI intends to extend this to plan for the next 15 years). It has three main themes to guide its programme:

1. Space activities for citizens;
2. The society of knowledge;
3. A dream for the new generation.

The last of these is intended to use space to engage young people in science, technical and engineering careers.

The Plan proposes a national lunar mission to optimise Italy's industrial and technological expertise and its scientific skills.

B.5 United States

NASA's plans for extensive exploration of the Moon are intended principally as a stepping stone to 'expand human and robotic presence into the solar system.'⁶⁰ NASA's 2008 budget is \$17bn, which amounts to 0.6% of the US Federal Budget and is by far the

⁶⁰ NASA Authorization Act 2008

largest budget of any civilian space agency (US military space expenditures are larger). The main goal of the programme is to construct a permanently occupied outpost on the Moon to conduct science and exploration. This will also act as a staging post and demonstrate techniques needed for a human mission to Mars. NASA is working on several lunar missions and has initiated the International Lunar Network. This collaboration will create a distributed network of sensors across the Moon using multiple lunar missions from different countries. If funding can be found, the first node could be the UK's proposed MoonLITE mission.

A new space transportation system, Ares, the successor to the Shuttle, is currently under development, together with a crew vehicle, Orion. NASA has also set up an innovative programme to reward companies able to demonstrate novel launchers which may reduce the cost of access to space. NASA continues to launch a robotic Mars mission on a two yearly cycle, gradually accumulating knowledge on the red planet. At present, three satellites are in orbit around Mars and two rovers are operational on the ground. In 2011, it will launch a much larger nuclear-powered rover, and further orbiters and landers are planned for the next decade. Increased collaboration is planned with ESA, exactly in the spirit of the GES.

The key elements of NASA's exploration programme are:

- Complete the International Space Station
- Safely fly the Space Shuttle until 2010
- Develop and fly the Crew Exploration Vehicle no later than 2015
- Return to the Moon no later than 2020
- Extend human presence across the solar system and beyond
- Implement a sustained and affordable human and robotic program
- Promote international and commercial participation in Exploration

According to the plans of the new US President, 'Space exploration must be a global effort. Barack Obama will use space as a strategic tool of U.S. diplomacy to strengthen relations with allies, reduce future conflicts, and engage members of the developing world.'⁶¹ NASA received an additional \$1bn in 2009 as part of an economic stimulus package by the incoming administration. The NASA budget request for 2010 seeks to consolidate this additional sum by increasing the total to \$18.7bn p.a. The proposal (which has yet to be agreed by Congress) would increase the total spent on human space exploration from \$4bn to \$6bn p.a. A review of the implementation of NASA's human spaceflight plans has been announced. The goal is "to provide options that will ensure the nation's human space flight program remains safe, innovative and affordable in the years following the space shuttle's retirement."⁶² The review will report by August 2009.

The Committee carried out a review of options for a US human space flight architecture to:

- Expedite a new US capability to support utilization of ISS

⁶¹ 'Advancing the Frontiers of Space Exploration', Barack Obama, 2008

⁶² NASA Press Release 09-102, 7 May 2009

- Support missions to the Moon and other destinations beyond LEO
- Stimulate commercial space flight capability
- Fit within the current budget profile for NASA Human Space Flight activities

In addition to the objectives described above, the review was asked to:

- Determine the appropriate amount of R&D and complementary robotic activities needed to make human space-flight activities most productive and affordable over the long term
- Determine appropriate opportunities for international collaboration
- Evaluate what capabilities would be enabled by each of the potential architectures considered
- Evaluate options for extending ISS operations beyond 2016
- Potential for inspiring the nation, and motivating young people to pursue careers in STEM subjects

The Committee received input from Congress, the White House, the public, industry, and international partners.⁶³

B.6 Canada

Canada has been very successful in making use of its niche role in providing robotic arms to the US Shuttle and ISS programmes. The first robotic arm for the Shuttle cost the Canadian government C\$100m, but the subsequent sale of further robotic arms gave a 6:1 return on the initial investment. Continuation of the programme gave Canada 14 flights (with 9 astronauts) to the ISS as well as access for Canadian scientists. Canada intends to continue this successful exploitation of its technology in space exploration by providing rovers for use on the Moon and later Mars. As part of a stimulus package, the Canadian Space Agency has received C\$110m for this purpose in early 2009.

Space exploration and human spaceflight are closely integrated into the overall programme of Canadian space activities which it considers to be strategic for its national interest. Its particular interest in space exploration is mainly to derive scientific knowledge and to drive innovation, but it also regards it as important in maintaining and raising awareness of Canadian technical capabilities as well as in attracting and retaining talent in Canada. Canada has close working relationships with NASA and with ESA (of which it is an associate member).

B.7 Japan

The vision for 2025 of the Japan Aerospace Exploration Agency (JAXA) is to develop world-class, high reliability launch vehicles and satellites with an aim to build a secure and prosperous society. The satellites will include those that manage natural disasters and safety issues (e.g. tsunamis, earthquakes). These will provide timely warnings directly to individual portable terminals.

They aim to take a leading position in the world of space science and begin preparations for Japan's own human space activities and for the utilization of the Moon. They plan to take a leading role in a lunar base and will aim to realise a 'Deep Space Harbour' to allow

⁶³ Presentation to ISECG by John Olson of NASA's Exploration Systems Missions Directorate, 20 May 2009

extended periods of stay for human activity. This could either be at a Lagrange point or on the Moon. Exploration of galaxies, black holes, the Sun, the Moon, Venus and Mercury are high on their agenda. JAXA will evaluate a prototype hypersonic aircraft that can fly at the speed of Mach 5, allowing a journey across the Pacific in only 2 hours.

Japan's Kaguya satellite is currently in orbit around the Moon and has returned spectacular video imagery of the Moon's surface as well as valuable scientific data. Kaguya's HDTV cameras were included on the spacecraft as a means of outreach — to share Kaguya's view with Japanese citizens. Near real-time transmissions broadcast on Japanese public television are reportedly very popular. The Hayabusa spacecraft collected a small sample from the surface of asteroid Itokawa in 2005 and is due to return to Earth in 2010.

The 'Space Basic Law' was enacted in May 2008 and has three pillars: diplomacy on space, industrial development, and security. The Prime Minister is expected to approve the 'Space Basic Plan' in May 2009 and the budget 2009 is ¥192.5bn (about £1.3bn), with an additional ¥47.7bn (£300m) for services.

B.8 China

Starting from a relatively low base, the Chinese space programme has seen an enormous expansion over the last 15 years. Very significant developments have taken place in the areas of human spaceflight, space applications and space science amongst others. Space activity now plays a major role in Chinese national strategy and was one of the major planks of the country's most recent five-year plan announced in 2008. Space clearly is seen as playing several roles in China – including being a beacon for China's increasing importance in the international context, as a driver for China's burgeoning high-tech industrial and commercial sector and for geostrategic reasons.

The most visible exemplar of China's space activity is its human spaceflight programme. In 2003 China became only the third nation in the world to demonstrate its capability to put its own astronauts into space with the launch of Shenzhou V. In 2008, 2 'taikonauts' were orbited and a highly symbolic spacewalk was carried out. Another very high profile activity is the Chang'E lunar programme which has seen the successful launch of China's first lunar orbiter, Chang'E 1, which is currently taking scientific measurements in orbit around the Moon. The Chang'E and Shenzhou programmes are given enormous prominence in China (and externally) and are seen as significant symbols of China's national confidence, capability and pride.

There has been comparable progress in the area of space applications, including launchers, Earth observation, meteorology, surveillance and disaster monitoring and mitigation. China has also made significant progress in launching satellites for other nations, either purely as a launch agency (in the case of Nigeria and Venezuela) or as part of a joint programme (in the case of Brazil). As an indication of China's level of space activity in this area, in a period of 23 days in December 2008, China launched three applications spacecraft from three different launch sites in mainland China, namely Yaogan IV (EO and Disaster Monitoring), Yaogan V (EO, Disaster Monitoring and Space Science) and Fengyun-2-06 (Geostationary Weather satellite). It launched a total of 11 satellites in 2008.⁶⁴

⁶⁴ *The Space Report 2009*, The Space Foundation

Although China has made enormous strides in all aspects of space activity, it proclaims that it is actively seeking international collaboration on a partnership basis. China has signed governmental space cooperation agreements with at least 11 space-faring nations. Some joint projects with the UK have already taken place, but the scale of activity is low, mainly limited on the UK side by financial constraints.

B.9 Russia

Russia aims to concentrate on four strategic goals: enhancement of people's life quality, maintaining high rates for stable economic growth, creating potential for further development and increasing the level of national security⁶⁵. Exploration of the Moon and other space objects has the highest priority. Environmental monitoring of the Earth, satellite communication and broadcasting, accomplishment of space projects to study the solar system and universe, maintaining equal rights involvement in the ISS and future manned projects, carrying out manned missions for economic, scientific, and application benefit, and applied research enhancement and validation of new space technologies are all high on the Russian agenda. Roscosmos, the Russian space agency, has recently announced plans to develop a heavy-lift launcher suitable for human lunar missions.⁶⁶

B.10 India

India has its own launch capability so its space programme can operate autonomously. Recently, due to a strong interest within the Indian scientific community, the Indian Space Research Organisation (ISRO) has been launching dedicated science missions. In October 2008 it launched Chandrayaan-1, the first in a series of orbiters focused on the Moon. Chandrayaan-1 is a complex spacecraft with 11 instruments including instruments from Europe (ESA), United States (NASA) and Bulgaria. The ESA instrument, an X-ray spectrometer, was built in the UK and has been successfully returning data on the geochemical make-up of the lunar surface since December 2008.

India intends to follow this with a robotic mission to the Moon which is already planned and funded (Chandrayaan-2). Future plans include a robotic mission to Mars, a human mission in low Earth orbit and a long term aspiration is a human mission to Mars.

The motivation quoted by ISRO for moving beyond its established earth observation and communications space programme into lunar exploration is the need to enhance the skills and capabilities of its space workforce and to advance technology for use by industries in many other sectors.

⁶⁵ Federal Space Program of the Russian Federation

⁶⁶ <http://news.bbc.co.uk/1/hi/sci/tech/7946689.stm>

Appendix C Details of options and costs

Chapter 2 sets out the overall aims and benefits of each option. It also describes in general terms what is included in each. This appendix provides a more detailed breakdown of the proposed programmes within each option and shows how the overall spend figures were derived.

C.1 Options for UK investment in space exploration

Four options have been considered to illustrate these different levels of future UK investment. These are described in Chapter 3 and repeated here.

In order of increasing cost, these options are:

- 1) **Reduced option:** eliminate involvement in space exploration and restrict the UK to the mandatory ESA Science Programme only. This is the minimum level that could be conceived without taking the drastic step of leaving ESA altogether.
- 2) **Status quo:** continue with the current level of investment (restrict to ESA Science programme and the robotic Mars exploration programme). This option would see the UK taking no serious role in the GES and the new opportunities that it provides.
- 3) **Increase investment in robotic-only exploration,** focused on Moon and asteroid exploration through national projects and bilateral activities with other space agencies. This would capitalise on the UK strengths in robotic space activities and provide opportunities for innovation and commercial development, but would (as now) exclude activities involving humans in space.
- 4) **Invest in both robotic and human activities,** leveraging the UK's strength in robotic technologies to secure astronaut places in the human exploration of the Moon (two versions of this option are included to illustrate the range of expected costs and benefits).
 - a) The minimum investment required to secure the involvement of UK citizens in human spaceflight. This would include investment in one key niche area to provide a service which could be traded for astronaut flights, but would exclude all other technological developments assumed in Option 3.
 - b) A modest, but integrated, programme including both robotic and human activities. This would combine the main elements of Option 3 and Option 4a in order to deliver maximum impact across the full range of benefits, including innovation, science, commerce and education.

C.2 Component elements of each option

In order to analyse the different options, a set of example activities were selected at a workshop held in October 2008 with a group of industry experts. Each activity was chosen for its relevance to UK skills and goals and a nominal cost profile was agreed. Some activities could be carried out entirely by the UK, while most would be best tackled in collaboration with one or more international partners – and this is reflected in the relevant cost profiles. Each option could then be built out of combinations of these activities, together with a few over-arching activities such as management and outreach/education.

These activities are only intended to illustrate what could be achieved at different levels of investment: a more detailed review of priorities and costs would be needed before any programme is implemented.

Table 6 lists the example activities agreed at the 2008 workshop and aims to show how it is possible to create a worthwhile, integrated set of activities that the UK could realistically carry out for each option. These elements are used in the cost profiles given later in this Appendix.

Table 8. Activities used to illustrate each option

Elements	Option 1	Option 2	Option 3	Option 4a	Option 4b
ESA Science Programme	■	■	■	■	■
ESA Aurora (Mars Exploration) Programme		■	■	■	■
Programme management and support			■	■	■
Education and outreach programme			■	■	■
Technology transfer programme			■	■	■
MoonLITE			■	■	■
Modular robotic lunar rover			■		■
Space nuclear power programme			■		■
Asteroid science/threat mission			■		■
Robotic lunar drilling for science			■		■
Science instrumentation – of the Moon			■	■	■
Science instrumentation – from the Moon				■	■
Science Instrumentation – on the Moon				■	■
Communications and navigation service (orbital)				■	■
Human precursor programme				■	■
Lunar astronaut programme (corps of 2)				■	■
Lunar astronaut support equipment				■	■
ESA Small Lander					■
ESA Large Cargo Lander					■
In situ resource utilisation (ground-based)					■
In situ resource utilisation demonstration mission					■

Several further worthwhile activities were examined, but would only be feasible under a larger investment option than has been considered here or in place of some of the activities included in the examples above.

These additional activities are:

- Pressurised lunar rover
- Lunar surface installations in support of a communications and navigation service
- Human deep drill project
- Sample handling and acquisition equipment
- Mini-magnetospheres for astronaut protection
- Lunar science laboratory

Table 9. Descriptions of programme elements

Element	Description
ESA Science Programme	Mandatory programme for space science encompassing astronomy, solar physics and planetary science
ESA Aurora (Mars Exploration) Programme	Optional programme for robotic exploration of Mars
Programme management and support	Set at 15% of each programme (except for ESA-managed activities, for which management costs are included in the subscription)
Education and outreach programme	Regional and national activities to ensure take-up of education opportunities for STEM
Technology transfer programme	Industry support to improve technology readiness levels and brokering services between space and non-space sectors
MoonLITE	Small UK-led lunar orbiter to demonstrate lunar communications and to carry out science using penetrators
Modular robotic lunar rover (1/3 UK share)	Collaborative project with international partners to develop lunar rover for science and/or support of lunar astronauts
Space nuclear power programme	Development of nuclear power sources for robotic and human missions to Moon, Mars and elsewhere, using new ESA Harwell Centre
Asteroid science/threat mission (20% UK share)	Collaborative mission to near-Earth asteroid for science and to investigate mitigation strategies to avoid Earth impact
Robotic lunar drilling for science (20% UK share)	Mission to drill samples from beneath lunar surface and demonstrate necessary robotic technologies
Science instrumentation – of the Moon	Instruments to study the Moon (seismometers, magnetometers, geochemical instruments, etc.)
Science instrumentation – from the Moon (20% UK share)	Instruments using Moon as platform for observing cosmos (e.g. low frequency radio telescopes to probe early universe, optical and infrared interferometers to detect Earth-sized planets and active galactic nuclei)
Science Instrumentation – on the Moon	Investigations of effects of lunar environment (e.g. low gravity, radiation, dust, micrometeorites) on equipment and humans for application to long-term habitation and missions to Mars

Communications and navigation service (orbital)	Operational service provided by UK to other nations, funded through PFI (c.f. Paradigm Skynet-5, military communications service to UK MOD), but using 4 small spacecraft for coverage and redundancy in lunar orbit linking spacecraft, surface instruments, habitations, rovers, etc.
Human precursor programme (including science/tech.)	National precursor human missions to ISS using taxi-flights, including training for 2 astronauts and back-ups, science experiments, and capacity-building in universities and outreach to schools
Lunar astronaut programme	Permanent corps of two people to participate in lunar exploration
Lunar astronaut support equipment	Equipment needed to support human lunar programme (incl. data handling etc.)
ESA Small Lander (20% UK share of €800m)	Participation in proposed ESA plans for a small lunar lander for science and technology demonstration
ESA Large Cargo Lander (20% UK share of £2bn)	Participation in proposed ESA plans for a large lunar cargo lander to provide logistic support to NASA lunar exploration
In situ resource utilisation (ground-based characterisation programme)	Demonstration of operation of process to generate oxygen from ores similar to lunar regolith
In situ resource utilisation demonstration mission (50%UK share)	Mission to demonstrate oxygen production on Moon with view to commercial operation or opportunity for astronaut flights
Pressurised lunar rover (1/3 share)	Programme to develop pressurised lunar rover to allow astronauts to travel long distances, using UK skills from ExoMars rover and aircraft design (excludes transport to Moon)
Lunar surface installations in support of a communications and navigation service	Transceivers on surface of Moon (not needed until humans on surface)
Human deep drill project (20% share)	International mission to drill core samples below 100m (not likely before 2025)
Sample handling and acquisition equipment (50% share)	Equipment on planet (to collect samples and deliver to orbiter) and on spacecraft (to capture and return samples to Earth)
Mini-magnetospheres for astronaut protection	Demonstration of plasma shields on ground, in space and then on Moon to protect humans from ionised radiation
Lunar science laboratory (25% share)	BAS-like facility on Moon

C.3 Detailed cost figures

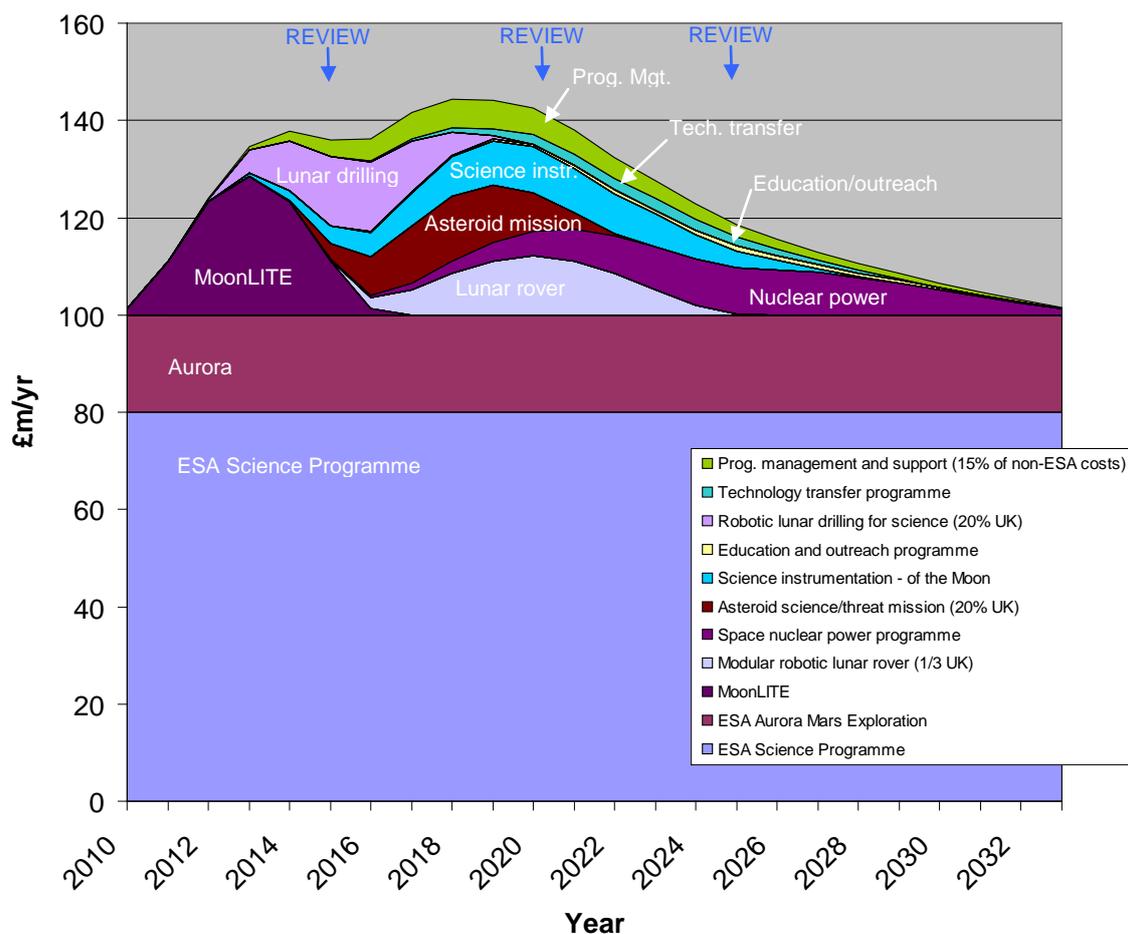
The elements listed in the previous appendix have been used as the basis for a set of nominal spend profiles to illustrate each option. The total spend figures by year for each option are given below.

Table 10. Breakdown of spend for each option (£m/yr)

	2010	2012	2014	2016	2018	2020	2022	2024
1 Reduced option	80	80	80	80	80	80	80	80
2 Status quo	100	100	100	100	100	100	100	100
3 Enhanced robotic	101	124	138	136	144	144	144	144
4a Minimum human	101	130	143	172	174	192	205	206
4b Integrated human and enhanced robotic	101	133	195	254	264	284	284	284

The breakdown of these figures can be seen in the following profiles.

Figure 16. Spend profile for Option 3: Enhanced robotic programme



Of course, assuming that such a programme produced the expected benefits, as these proposed projects come to an end they would be replaced by new ones, with spending reaching a steady state around the peak of the curve. This is the basis for the profile presented in Section 3.4.2. The figures are given in Table 9, below.

Table 11. Details of annual spend for Option 3: Enhanced robotic programme (£m/yr)

Activity	2010	2012	2014	2016	2018	2020	2022	2024
ESA Science Programme	80	80	80	80	80	80	80	80
ESA Aurora Mars Exploration	20	20	20	20	20	20	20	20
MoonLITE	1	23	23	1	0	0	0	0
Modular robotic lunar rover	0	0	0	2	9	12	9	2
Space nuclear power programme	0	0	0	0	2	5	8	9
Asteroid science/threat mission	0	0	0	8	13	8	0	0
Science instrumentation – of the Moon	0	0	2	5	8	9	8	5
Education and outreach programme	0	0	0	0	0	1	1	1
Robotic lunar drilling for science	0	1	10	14	5	0	0	0
Technology transfer programme	0	0	0	0	1	2	2	2
Prog. management and support	0	0	2	5	6	6	4	3
Total	101	124	138	136	144	143	132	123
Increase compared with current spend	1	24	38	36	44	43	32	23

Figure 17. Spend profile for Option 4a: Minimum human programme

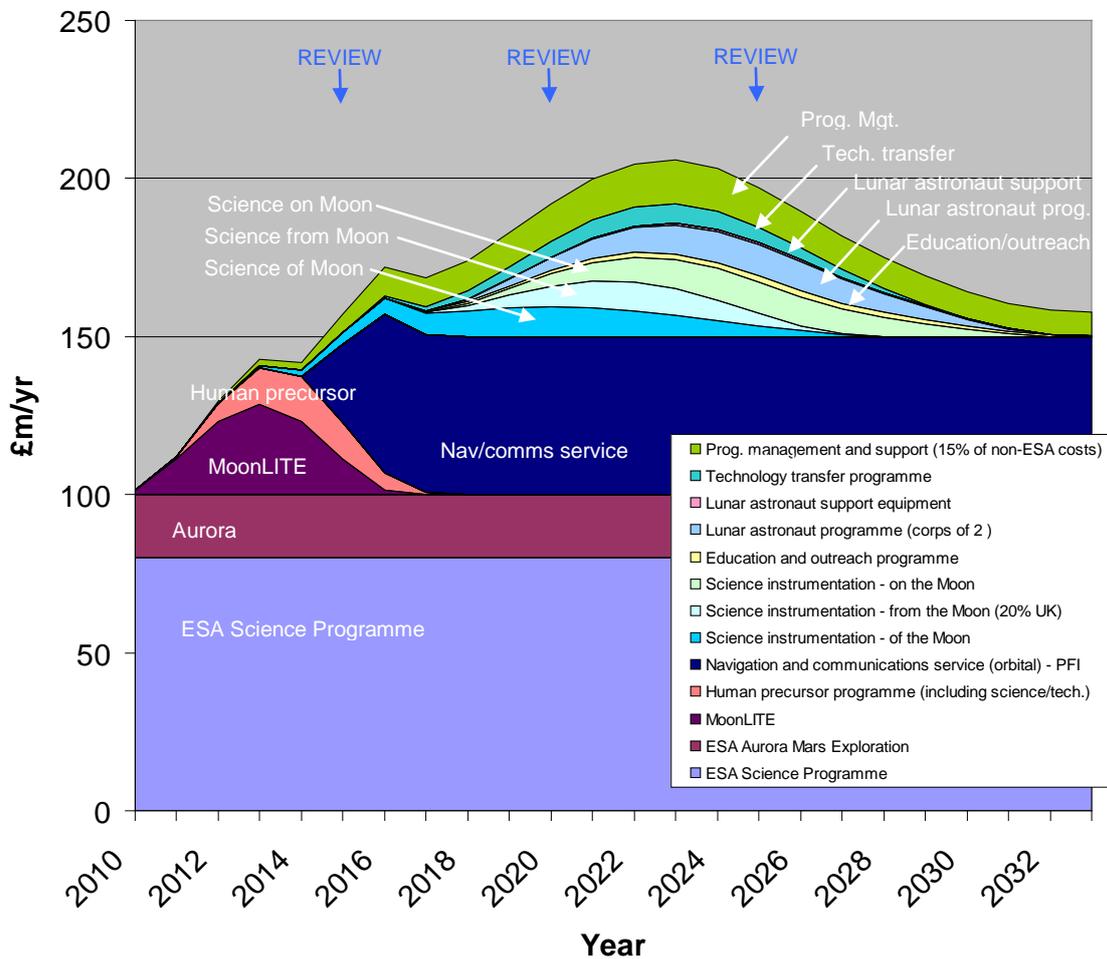
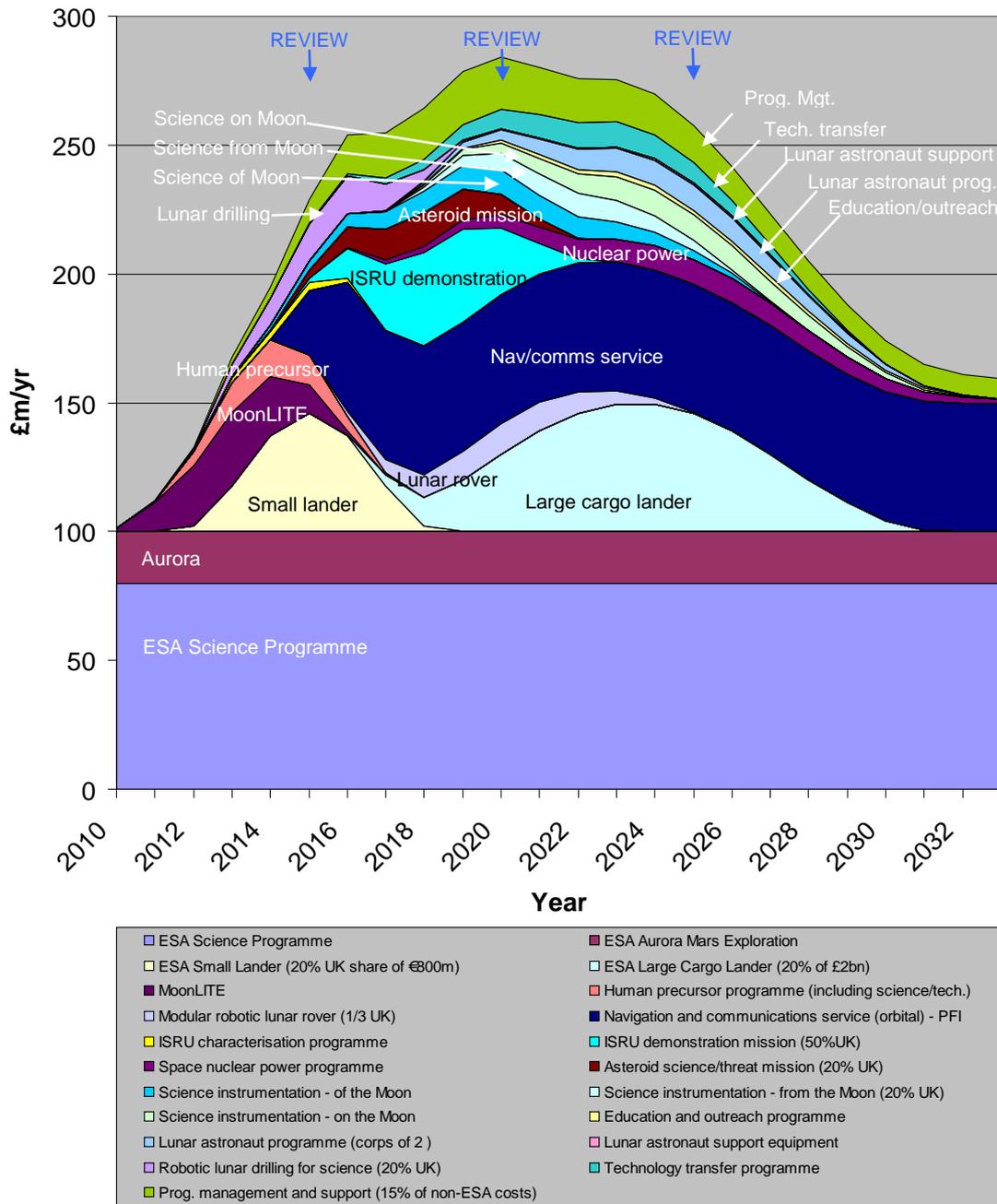


Table 12. Details of annual spend for Option 4a: Minimum human programme (£m/yr)

Activity	2010	2012	2014	2016	2018	2020	2022	2024
ESA Science Programme	80	80	80	80	80	80	80	80
ESA Aurora Mars Exploration	20	20	20	20	20	20	20	20
MoonLITE	1	23	23	1	0	0	0	0
Human precursor programme	0	6	14	6	0	0	0	0
Navigation and comms service (orbital)	0	0	0	50	50	50	50	50
Science instrumentation – of the Moon	0	0	2	5	8	9	8	5
Science instrumentation – from the Moon	0	0	0	0	2	6	9	6
Science instrumentation – on the Moon	0	0	0	0	1	4	8	10
Education and outreach programme	0	0	0	0	0	1	2	2
Lunar astronaut programme	0	0	0	0	1	4	8	10
Lunar astronaut support equipment	0	0	0	0	0	0	0	1
Technology transfer programme	0	0	0	1	3	5	6	6
Prog. management and support	0	1	2	9	10	12	14	13
Total	101	130	142	172	174	192	205	203
Increase compared with current spend	1	30	42	72	74	92	105	103

Figure 18. Spend profile for Option 4b: Integrated human and enhanced robotic programme



As with Option 3, assuming that such a programme produced the expected benefits, as these proposed projects come to an end they would be replaced by new ones, with spending reaching a steady state around the peak of the curve. This is the basis for the profiles presented in Section 3.5.2.

Table 13. Details of annual spend for Option 4b: Integrated human and enhanced robotic programme (£m/yr)

Activity	2010	2012	2014	2016	2018	2020	2022	2024
ESA Science Programme	80	80	80	80	80	80	80	80
ESA Aurora Mars Exploration	20	20	20	20	20	20	20	20
ESA Small Lander	0	2	37	37	2	0	0	0
ESA Large Cargo Lander	0	0	0	0	11	30	46	50
MoonLITE	1	23	23	1	0	0	0	0
Human precursor programme	0	6	14	6	0	0	0	0
Modular robotic lunar rover	0	0	0	2	9	12	9	2
Navigation and comms service (orbital)	0	0	0	50	50	50	50	50
ISRU characterisation programme	0	0	3	2	0	0	0	0
ISRU demonstration mission	0	0	0	12	36	26	1	0
Space nuclear power programme	0	0	0	0	2	5	8	9
Asteroid science/threat mission	0	0	0	8	13	8	0	0
Science instrumentation – of the Moon	0	0	2	5	8	9	8	5
Science instrumentation – from the Moon	0	0	0	0	2	6	9	6
Science instrumentation – on the Moon	0	0	0	0	1	4	8	10
Education and outreach programme	0	0	0	0	0	1	2	2
Lunar astronaut programme	0	0	0	0	1	4	8	10
Lunar astronaut support equipment	0	0	0	0	0	0	0	1
Robotic lunar drilling for science	0	1	10	14	5	0	0	0
Technology transfer programme	0	0	0	1	4	8	10	9
Prog. management and support	0	1	5	15	20	20	17	16
Total	101	133	195	254	264	284	276	270
Increase compared with current spend	1	33	95	154	164	184	176	170

Appendix D Economic analysis

D.1 Business opportunities enabled by each option

The Terms of Reference of this review (included in Appendix A) require that an analysis is carried out of the potential economic impact of additional UK investment in space exploration. This was carried out on behalf of BNSC by London Economics and their report is available separately.⁶⁷

The economic analysis uses a cost benefit analysis in line with HM Treasury Green Book.⁶⁸

London Economics used face-to-face interviews and a series of workshops with experts to draw up a list of commercial possibilities with benefits in different sectors, each enabled by investment in one or more of the four options considered. An initial list of 27 opportunities was supplemented by further inputs from experts.

These were then assessed against a series of criteria:

- Position in the space exploration value/supply chain
- Position of the 'new' product in the value chain of the recipient sector
- Timescale of the expected spillover
- Innovation environment (what are the linkages with terrestrial users and knowledge transfer processes?)
- Demand drivers (why may terrestrial users want the product?)
- Potential customers for the new product (industry, government departments, households)
- Significance of the new product based on the size of the potential spillover
- Information availability for estimating the space costs of the new product

A multi-criteria analysis was used to rank the opportunities. The robustness of this approach was tested by varying the importance of each of these criteria and used to choose six opportunities for more detailed study.

Table 14 shows the initial list of opportunities considered, together with the programme option that would enable each. The six case studies examined in more detail are shown in bold.

⁶⁷ *Economic Analysis to support a Study on the Options for UK Involvement in Space Exploration*, London Economics, 19 March 2009

⁶⁸ http://www.hm-treasury.gov.uk/data_greenbook_index.htm

Table 14. Initial list of business opportunities considered						
	Option	1	2	3	4a	4b
Fuel quality monitoring using x-ray instrumentation		■	■	■	■	■
Laser Imaging		■	■	■	■	■
Synchrotron radiation facility detectors		■	■	■	■	■
Aerothermal dynamics			■	■	■	■
Integrated diagnostics (e.g. life marker chip)			■	■	■	■
Autonomous navigation – speckle velocimetry and 3D imaging			■	■	■	■
Autonomous vehicles			■	■	■	■
Battery technology			■	■	■	■
Designer solvents for tar sand oil extraction			■	■	■	■
Dextrous manipulator technology			■	■	■	■
Planetary protection			■	■	■	■
Remote sample analysis			■	■	■	■
Sample receiving facility			■	■	■	■
Thermal protection systems			■	■	■	■
Lunar probes				■		■
Organics extraction				■		■
Spectral imaging				■		■
Asteroid impact mitigation				■		■
Commercial lunar drilling				■		■
Energy – generation, storage, use and scavenging				■		■
Lunar Drilling – Case Study 1				■		■
Magnetic image processing (vision for autonomous vehicles)				■		■
Nuclear power (radio isotope sources)				■		■
Software for autonomous vehicles				■		■
Solar power				■		■
Composite materials				■	■	■
Data transfer – data compression algorithms				■	■	■
Low cost launch technology – Case Study 2				■	■	■
Low cost satellites				■	■	■
Systems of systems engineering (training)				■	■	■
Astronaut training					■	■
Lunar communications and navigation – Case Study 3					■	■
Science experiments in microgravity					■	■
Oxygen production on the Moon – Case Study 4						■
Autonomous robots in support of humans – Case Study 5						■
Medical applications (instrumentation) – Case Study 6						■
Human decision aides						■
Human life support and monitoring systems						■
Information management systems for health						■
Mini magnetospheres for radiation protection						■
Networked sensors and wireless bio-telemetry						■
Psychology of humans						■
Space tourism						■
Specialised fire fighting						■
Titanium alloy production on the Moon						■

These six cases are used to illustrate the possible returns on investment in each of the extended options (Options 3 and 4) mentioned in the previous section.

The cost benefit analysis of these case studies was informed by a dedicated workshop on each topic, involving both space specialists and potential terrestrial users of spin-out technologies.

In each case, the net present values have been calculated on the basis of the full cost to the UK with no distinction between public and private sources of funding. These figures only take account of direct impacts due to the technologies developed, not the wider flow-on impacts in related sectors. The costs and benefits are those expected over the period to 2040 and have been discounted to present values and adjusted for inflation according to Treasury Green Book guidelines.

The analysis therefore does not account for the cost of investment financing, or for the high discount rates used by the private sector for high risk ventures.

To take account of uncertainty in the development of future technologies and their uptake in terrestrial applications, many different scenarios have been considered. These demonstrate a wide range of net present values and reveal the main drivers of benefits and the risks associated with them.

Table 16 lists the main drivers and risks for each case, with those risks that may be controllable coloured in green (for example project management risks to mitigate cost or time overruns), those which are uncontrollable (because they depend on price fluctuations in international markets, for example oil prices) coloured red, and those which have a mix of controllable and uncontrollable drivers and therefore risks coloured orange.

Those risks which are uncontrollable would require careful monitoring and those which are controllable would require effective management in order to realise the maximum gains from any programme.

Since these case studies are provided as illustrations of the opportunities that may be expected from a coherent programme of exploration, it is not directly possible to extrapolate from these to calculate a return on the complete programme. However, the most likely net present values have been considered and these are summarised in Table 15. (Note that the net present value of the low cost launch case technology has not been included since this is not specific to space exploration.)

Enhanced robotics			Enhanced robotics and minimum human		Integrated human and enhanced robotic			
Tele-robotic and autonomous drilling	Low cost launch technology	Aggregate net present value	Comms and navigation	Aggregate net present value	In-situ resource utilisation	Robotics	Space medicine	Aggregate net present value
4,219	NPV not included	4,219	6,162	6,162	432	2,642	435	3,509

Table 16: Business opportunities, main drivers and risks for benefit realisation

Option	Business opportunity	Main drivers of the benefits	Risks that impact upon the drivers and thereby realisation of benefits
3 Enhanced robotics	Tele-robotic and autonomous drilling	Oil price and access to new supplies of oil which are not accessible given current drilling technology	Oil price is low, and new oil reserves are not available to the UK. These are (in the most part) uncontrollable risks to UK government because they depend on international oil prices and international property rights for exploration in inhospitable environments
	Low cost re-usable launch technology	Technology specification and the space markets the different launch technologies can supply: <ul style="list-style-type: none"> • Space services market for payloads to the International Space Station and lunar surface, and launch of large communications satellites to stationary orbit. • Small satellite launch to Low Earth Orbit. • Public access (tourism) 	(a) If Technology can launch to ISS, lunar surface and large payloads to stationary orbit, then risk is percentage of the space service market captured by UK launch firms. (b) If technology can launch only small payloads to low earth orbit, risk depends on small satellite market size and percentage of the market captured by UK firms. (c) Technology can carry public/tourist, then risk depends on the total demand for public access. These risks can be managed to some extent by the UK. For example, <ul style="list-style-type: none"> • By ensuring that investments in launch technology (either private or public) can be made early enough such that UK firms can reasonably engage in the international efforts for re-usable lower cost launches. • By ensuring the mechanisms (such as legal frameworks) are in place to facilitate international satellite firms to demand UK launchers. • The public access market depends on consumer demand and how much private individuals value space travel. This cannot be influenced by UK regulators or government.
4a Enhanced robotic and minimum human	Lunar comms and navigation service	Demand for communications and navigation services from the lunar surface, and the price users pay for the service.	UK can have some influence over the demand for future communications services on the lunar surface, but it is predominately driven by those countries such as the USA which are the leaders in scoping the future demand for communications. This can also be influenced by UK engagement with ESA programmes.
4b Integrated human and enhanced robotic	In-situ resource utilisation (oxygen on Moon)	Cost overrun and demand for oxygen on the lunar surface for propulsion and human habitation	Cost overrun can be managed by the UK through good project management. Demand for oxygen on the lunar surface can be influenced to some extent by the UK through interaction (both for robotic and human exploration) with other space going nations and organisations.
	Robotics technologies	Cost savings realised from spin-out technologies to the terrestrial food processing sector.	While there is demand for new technologies to replace human labour in the processing sector, as reported by specialists from the UK food processing sector, it is difficult to influence how and when new technologies would be taken up by processors.
	Medical applications (Bio-telemetry and data acquisition)	Cost savings to the National Health Service in intensive and acute care, and in elderly care.	How technologies developed for space may spin-out to terrestrial uses is uncertain as medical research is often a process of trial and error at the laboratory testing stage. However, as the benefits (cost savings) are expected to accrue to the public health service and therefore through established linkages between UK space efforts and the UK public health system, the probability of these spin-outs can be influenced to some extent.

D.2 Case studies

A summary of each of the case studies is included below. Full details of the analysis and the range of net present values calculated if provided in the report by London Economics.⁶⁷

Case study 1: Lunar drilling

Many of the objectives of lunar exploration will require the ability to drill into the surface of the Moon. New techniques will be needed to do this – especially in remote control, autonomy, and new materials for drill bits. These will all have applications in terrestrial drilling for oil and gas, and indeed would be developed in collaboration with companies in this sector.

The analysis in this report considers the example of benefits in the oil and gas sector that the UK could gain from three technical advances: automation, remote operations and self-repair coatings. Of course there may be other valuable terrestrial applications in this and other sectors, and as with all new technologies it is not certain that all of these benefits can be realised.

Improved automation will allow the extraction of previously unreachable oil reserves – for example under the Arctic. For the analysis we assume that such processes will enable us to reach a quarter of the untapped reserves under the Arctic, that these amount to a similar quantity to that under the North Sea, and that the average price of oil will stay roughly at the recent average of \$40 a barrel. The UK has considerable strength in automation, so we assume 15% of the benefits coming to the UK (the rest going to other international players).

New techniques in remote operations will increase productivity in drilling and servicing wells. We assume a yearly cost of \$160m to service 100 wells and that new technology could save one third of the 40 days needed per well. We assume that 25% of the benefit accrues to the UK, reflecting our strength in these techniques.

The challenge of drilling remotely in the airless conditions on the Moon will require new drill bit technologies such as self-repairing coatings. We have estimated that this technology could save the replacement of 800 drill-bits each year at a cost of \$200k each.

A lunar drilling programme would be expensive – we have modelled three scenarios for the cost and assume the middle value of £300m to develop a lunar lander, drill and operations on Earth.

On these assumptions, the net benefit to the UK would be over £4bn. Each of the above assumptions can be challenged, but so long as the UK can claim at least a 1% share of the benefits, the Net Present Value remains positive.

In addition, such a programme would help to address the chronic lack of suitable graduates interested in joining the industry. It is not hard to envisage a recruitment campaign for an oil company using the slogan, ‘Join us and explore the Moon.’

Case Study 2: Low-cost launch technology

A huge proportion of the cost of any space mission is the cost of the launch itself. This in turn has driven up insurance costs and hence the need for spacecraft to be highly reliable, in turn pushing up the cost of manufacture and hence the cost of spacecraft. The current launch market relies on essentially the same means of propulsion as the rockets which launched Yuri Gagarin and Alan Shepard in 1961. These are very large and, for the most part, not reusable.

The opportunities are huge for any company that could drastically reduce the cost of access to space. Several in the US are competing to do so with a range of offerings, but most are still based on the same limited range of propellants, and hence physics will limit the impact they can make compared with current launchers.

Low-cost access to space could both enable new exploration activities (such as the involvement of the public through tourism) and lower the cost of planned activities (for example shipping cargo into orbit in readiness for lunar expeditions). The market is clearly much wider than just space exploration – with potential for big impacts on all users of launchers. Low-cost launches would also enable the use of lower-cost technology and lower insurance premiums.

The UK is home to several companies with novel approaches which could unlock the market for low-cost launches. We have considered three of them: Skylon (an air-breathing spaceplane designed by Reaction Engines); SpaceShip2 (a sub-orbital passenger craft being developed by Virgin Galactic); and Spacebus (to follow on from the initial Ascender sub-orbital spaceplane designed by Bristol Spaceplanes).

They have in common the concept of reusable launchers and all hope to be able to provide flights for both science experiments and human passengers. Customers are expected to include government, private companies and the public. Economic impact would come through revenues from space tourism, savings on existing launch costs, revenues from launching small satellites and revenues from flying microgravity experiments.

Many assumptions have to be made in the economic analysis. It is assumed that a ticket price of \$150,000 will generate a market of 10,000 people a year worldwide for sub-orbital flights, while 100,000 people might pay for flight tickets costing \$85,000. Over the period to 2040, savings due to lower launch costs could be \$150m for UK government-funded activities and \$800m for industry. If launch costs could be reduced to \$5000/kg (a factor of about four below current costs), the market for small satellites around 100 kg might rise to 15 a year and those around 1-5 kg could increase to 85 a year.

To take account of the different capabilities of these launchers, it is assumed that Skylon and Spacebus can each access the whole of the market for commercial microgravity flights, estimated at \$450m a year, but that SpaceShip2 and Ascender could only serve markets of \$100m and \$45m respectively.

Finally a series of different scenarios have been modelled which assume different levels of access to the space tourism market (from 25% to 75%), different proportions of the cost saving from cheaper launchers (from 20% to 100%), different proportions of the estimated market for small satellites (from 50% to 100%) and different levels of take-up of flights for microgravity (from zero to 100%, and both gradual and fast rates of take-up).

The impact of all of these assumptions on Net Present Value is as follows. Skylon, with development costs of £7bn, achieves a large NPV (over £4bn) for the two optimistic

scenarios, but a negative value (bigger than -£2bn) for the two pessimistic scenarios. SpaceShip2, with development costs of £180m, reaches over £2bn for all assumptions, and nearing £6bn for the optimistic scenario. Ascender, with development costs of £60m, reaches only small values (-£26m for the most pessimistic scenario, but £50m and over for the others), while its derivative SpaceBus, with costs of £2bn, reaches an NPV of over £2bn in all cases and \$9bn for the optimistic scenario.

Given this enormous range of different NPVs and the uncertainty of the estimates of market size and since this technology is not specific to space exploration, the costs of creating a programme of low-cost launcher development have not been included in any of the Options covered in this report. Instead it would make sense to treat this technology as a completely separate programme, the value of which should be considered in more detail by a separate review.

Case Study 3: Lunar communications and navigation

Each lunar mission requires a communications link with Earth, and some will also require communications between different locations on the Moon itself. Some of these links may be made direct from the lunar surface, but small low-power missions and activities on the far side of the Moon will require some kind of relay from satellites in lunar orbit.

The UK has several key offerings which make a very attractive package: it is a leading supplier and operator of communications satellites (through Astrium and Inmarsat respectively); it has the world-leading builder of small low-cost satellites (SSTL); and it has led the world in funding major projects through Private Finance Initiatives (such as the Paradigm Consortium which supplies communications to MOD through its Skynet-5 constellation). By combining these capabilities together the UK could build and operate lunar communications for multiple agencies – achieving both economies of scale and opportunities for collaboration with each. An important first step would be the MoonLITE programme, currently about to begin a Phase A study, which would demonstrate the feasibility of the technology and help refine the cost estimates for a full operational service.

This case study is rather different from the others considered, since most of the economic benefit is based on the presumed value of supplying services to other space agencies (whereas most of the other case studies consider spin-out activities on Earth). Since it is unlikely that other agencies will choose to purchase such services directly as a commercial arrangement, it is more likely that the benefit will be best realised by some form of barter. For example the UK might supply communications services to other nations in return for inclusion of UK astronauts in international lunar exploration teams.

However, in order to consider the prospects of such a barter, it is necessary to estimate the expected value of a lunar communications service. We have assumed that the UK would build five lunar communications satellites by 2027 (with the first launched in 2015), each costing around £300m, together with six transceivers on the lunar surface (at £10m each) and one ground station in the UK. Estimating the charge for such a service is more difficult, since there is no existing example to analyse, but assuming a charge 20 times the amount charged for existing services for users on Earth, we have based our calculation on £4m per year per Mbps of capacity. We have further assumed that we might provide 75% of NASA's expected required capacity. On this basis, we estimate the Net Present Value to the UK as being over £6bn.

This figure is not affected greatly by the cost of each satellite, though it is of course reduced if the charge rate per Mbps is lower or if the UK fails to reach this level of supply. However it only becomes negative if the charge rate drops below £1m/Mbps and the UK supplies only 25% of NASA's needs. It could be expected that once a service has been demonstrated, the UK could additionally supply the needs of other nations, increasing the NPV still more.

In addition, once a commercial lunar communications service begins operation, it will be possible to provide services for other organisations, such as TV and internet companies who will need high bandwidth TV signals to enable viewers at home and students in schools to follow and participate actively in future exploration missions.

Case Study 4: Oxygen production on the Moon

One of the limiting factors in extending exploration plans will be the availability of oxygen needed for breathing by astronauts, for drinking water and to fuel rocket engines. Current exploration plans assume that oxygen will initially be brought from Earth, but if the oxygen locked up in the regolith forming the surface of the Moon could be released, the cost of both human and robotic missions to the Moon and beyond could be drastically reduced.

A British company has developed and patented a novel process to separate oxygen from ilmenite, one of the common constituents of the lunar surface. This low-energy process could (in due course) even produce titanium alloys as a by-product which could be used in lunar construction projects. It is also expected that the process will work with other ores found on the Moon, including those based on iron and calcium.

The main innovation is the use of a novel material as an inert anode to separate the oxide into pure oxygen and titanium (current processes for titanium production use carbon anodes, generating greenhouse gases and requiring constant replacement). This new technology would provide a compact, energy-efficient oxygen-generation process for the Moon and would have obvious applications for the titanium industry where it could reduce both costs and pollution (especially carbon dioxide).

We have estimated that a mission to demonstrate the technology on the lunar surface would cost some £300m, but have conservatively used twice this figure in the economic analysis. We have analysed the direct returns that could be expected if a commercial operation were to supply oxygen for use in rocket propulsion and for breathing by astronauts. We have assumed that six trips to the Moon per year from 2020 would require oxygen to burn fuel and that each trip would use around 9.4t of oxygen on the return leg. We have further assumed for a low predicted oxygen demand for astronauts of 1t per year from 2020 and a low estimate of transportation costs to the Moon at \$25m per tonne using conventional rocket flights. We have assumed that half of any revenue generated would go to a partner outside the UK and that such a venture would only capture 25% of the international market.

For application on the ground, this process has several advantages over existing industrial processes: it uses cheaper feedstock and fewer processing steps; the feedstock does not need to be melted (saving energy); and the product is much purer. We assume that the UK-registered firms could gain 10% of the world market by supplying a better product at a lower price. Possibly the biggest impact could come from the production of

rutile-based titanium alloys which could be produced at a price competitive with stainless steel, a market 300 times the size for titanium, and thus generate a new market for lightweight, corrosion-resistant materials in a very wide spread of applications including kitchenware (currently 70% of the stainless steel market in India for example), naval components and other applications currently using steel and aluminium. We have not included this last application in our analysis as it is too speculative to set a value on a new material with no existing market. In addition to the economic impact, this green technology could help reduce emitted carbon dioxide and other pollutants.

On the assumptions listed above, the net present value for the UK's leadership of the cost-affordable titanium industry has the potential to be over £400m. There is also the likelihood that the stringent requirements for such a process on the Moon would result in new techniques that could be applied in other related terrestrial applications.

Case Study 5: Autonomous robots

Any programme of space exploration will be heavily dependent on robotic technology and the UK is already a leading player in such developments for space. This case study considers specifically the new techniques that will be required by the use of robotics in supporting the activities of astronauts. This allows us to consider three spin-off areas which require close working between robots and humans which give access to new markets for the UK.

While it is not possible to predict the specific technologies that may have the greatest impacts, there are some qualities that the new generation of space robotic assistants will need. These include increased dexterity, built-in intelligence, reliability, tolerance to harsh conditions and safety of operation. These qualities will have obvious advantages in many ground-based applications.

We have considered use of such technology in the food industry, in the household robot market and in decommissioning nuclear reactors. Of these the most promising area may be the food industry which needs to improve its efficiency if it is to compete on international markets. Currently the UK uses half the number of robots as a proportion of its workforce compared with France and Spain and a quarter of those used in Germany. In addition to increasing efficiency, robots can improve food hygiene, as well as reducing injury from causes such as repetitive strain and back problems from production lines. For this analysis we have doubled the expected cost (£333m) of a relevant programme of robotic lunar research. If the application of new robotic techniques developed in space can reduce labour costs by 1%, the net present value of such an investment would be around £250m. If we could extract savings of 5%, the NPV would increase to over £2.6bn.

The impact of space developments on the household robot market is harder to estimate as it depends on both new techniques and on the effect of the link with space on the marketing of products. We have therefore been cautious in our estimates, and on assumptions that new space technologies would increase the UK market share by up to 0.3% of a market expected to reach £10bn by 2025, these activities would increase the NPV by about £75m.

Robotics designed for use in the harsh radiation and temperature conditions on the Moon and Mars should also find application in the decommissioning of nuclear power stations, by saving money, increasing capability and reliability, and removing the current need for umbilical cords. If space technology could reduce the costs of decommissioning (predicted to be over £60bn between 2009 and 2029) by 0.5%, the NPV would increase by about £22m.

There are of course many other applications that might benefit from space robotic techniques such as bomb disposal, fire inspection, and investigation of chemical, biological, radiological and nuclear threats. Indeed, UK funded technology work for the ExoMars rover is already helping the design of robotic buggies that could be used at events, airports etc. to transport frail or elderly people. The estimated market for such buggies at airports is over €40m.

Case Study 6: Medical applications

The need to monitor and maintain the health of astronauts working in space presents a wealth of opportunities for applications for terrestrial patient care. The need to combine and process large amounts of data in real time from sensors is a challenge for those in charge of astronaut health. The UK is a leader in such complex data handling (for instance through its space and particle physics programmes) and solutions to these problems could be applied also to care of patients with acute illnesses and those in intensive care. Likewise the need to develop non-invasive telemetry and lightweight, robust diagnostic and therapeutic equipment is likely to help diagnosis of intensive care patients. Indeed one example of a TB sensor developed as part of UK space exploration activities is already undergoing trials (see p24).

In addition, the low gravity experienced by astronauts causes physiological changes such as muscle and bone deterioration, as well as disorientation. It is expected that countermeasures needed to help astronauts will have similar benefits for the elderly, who are prone to falls (caused partly by muscle deterioration and balance problems) and which can result in fractures (made worse by bone loss).

There may be many other applications of space medicine that will in due course help patients on the ground, but if we assume that such interventions could reduce by 2% the annual cost to the UK of hip fractures (estimated at nearly £900m), a saving of over £17m per year could be achieved. And if a research programme costing some £150m per year were to result in a spin-off for terrestrial medicine after, say, six years which resulted in a saving of 0.5% of the cost of intensive care in the UK and 0.1% of acute care costs, then such a programme could have a net present value of over £400m.

The NPV is still over £300m if the programme is twice as expensive or if it takes 10 years to develop such spin-outs.

In addition, there may be commercial opportunities to sell such technologies abroad while there are non-economic benefits through improved health and wellbeing as well as through better healthcare, especially for the elderly.

Case Study 7: Mini magnetospheres for radiation protection

In addition to the six case studies described above that were included in the economic analysis, a further case study was considered, but as insufficient supporting data could be gathered at this stage it has not been subjected to analysis. However, the key points are included below.

The Apollo astronauts were lucky to survive the radiation conditions during their expeditions to the Moon. If humans are to extend their reach with permanent outposts on the Moon or with crewed expeditions to Mars, one of the biggest problems will be protecting them from space radiation.

A novel technology, developed in the UK from techniques used in containing plasmas in fusion reactors, may be a major part of the solution. A cloud of plasma, held in place by a magnetic field, deflects damaging charged particles from the sun before they can reach the astronauts. This would create a miniature version of the magnetosphere that surrounds the Earth and protects us from the radiation that would have killed off all life.

While this technology may prove vital for longer human expeditions in space, it may have a larger impact on commercial spacecraft such as those for communications and navigation. Many are built and operated in the UK and such techniques could reduce the requirement for expensive radiation-tolerant components or increase the lifetime of these expensive satellites.

A consortium led by scientists from the Rutherford Appleton Laboratory including the European EFDA/JET project, UKAEA Fusion, Cranfield University and Oxford Instruments currently lead the field (and have applied for a patent), but lack funds to develop the concept beyond the current laboratory proof-of-principle stage into viable space technology.

We have not included an economic analysis of this technology since much of the information needed to analyse the benefits is confidential to the satellite insurance industry. However, commercial revenue from satellite services exceeds \$25 billion per year, so new techniques to extend spacecraft life against radiation failures may yield direct benefits of a similar scale. The potential mitigation technology is a radical new approach, which is at such an early stage that the costs are too hard to estimate. Nevertheless a qualitative assessment suggests that the benefits should far outweigh the costs on a purely economic basis – while the wider implications of the UK providing protection to the astronauts and spacecraft of other nations would be an inspiring prospect and create a strong offering with which to barter for involvement in other space activities. Although it will be some years before this technology is needed for astronaut protection, other nations will soon catch up if we do not exploit our current lead.

Appendix E Meeting the Government's Public Service Agreements

Table 17 lists the 30 Government Public Service Agreements (PSA) as formulated in the 2007 Comprehensive Spending Review (CSR). The PSAs are the key priority outcomes that the Government wishes to achieve in the spending period 2008 – 2011, and are grouped under four themes: (i) sustainable growth and prosperity; (ii) fairness and opportunity for all; (iii) stronger communities and a better quality of life and (iv) a more secure, fair and environmentally sustainable world. The PSAs are published on the Treasury web site.⁶⁹

There are benefits from a UK space exploration programme that address specific PSA priorities and could provide a direct route to many of the PSA goals. These relevant PSAs are highlighted in blue in the table below. A space exploration programme could also contribute indirectly to the PSAs aimed towards increasing the health, employment prospects and social conditions of UK citizens, or alleviating global problems such as conflict and climate change. These PSAs (almost 50% of the total number) are shaded pale green in the table. In general, a vigorous UK space exploration programme will undoubtedly enhance business opportunities, leading to increased employment and downstream technological advances. These will, in turn, enable a wealthier and more technologically-aware UK society, an important step towards achievement of the Government's goals, and the green-shaded PSAs.

PSA No.	Description
	<i>Sustainable growth and prosperity</i>
PSA 1:	Raise the productivity of the UK economy
PSA 2:	Improve the skills of the population, on the way to ensuring a world-class skills base by 2020
PSA 3:	Ensure controlled, fair migration that protects the public and contributes to economic growth
PSA 4:	Promote world class science and innovation in the UK
PSA 5:	Deliver reliable and efficient transport networks that support economic growth
PSA 6:	Deliver the conditions for business success in the UK
PSA 7:	Improve the economic performance of all English regions and reduce the gap in economic growth rates between regions
	<i>Fairness and opportunity for all</i>
PSA 8:	Maximise employment opportunity for all
PSA 9:	Halve the number of children in poverty by 2010-11, on the way to eradicating child poverty by 2020

⁶⁹ http://www.hm-treasury.gov.uk/pbr_csr07_psaindex.htm; accessed 5 April 2009

PSA 10:	Raise the educational achievement of all children and young people
PSA 11:	Narrow the gap in educational achievement between children from low income and disadvantaged backgrounds and their peers
PSA 12:	Improve the health and wellbeing of children and young people
PSA 13:	Improve children and young people's safety
PSA 14:	Increase the number of children and young people on the path to success
PSA 15:	Address the disadvantage that individuals experience because of their gender, race, disability, age, sexual orientation, religion or belief
PSA 16:	Increase the proportion of socially excluded adults in settled accommodation and employment, education or training
PSA 17:	Tackle poverty and promote greater independence and wellbeing in later life
	<i>Stronger communities and a better quality of life</i>
PSA 18:	Promote better health and wellbeing for all
PSA 19:	Ensure better care for all
PSA 20:	Increase long term housing supply and affordability
PSA 21:	Build more cohesive, empowered and active communities
PSA 22:	Deliver a successful Olympic Games and Paralympic Games with a sustainable legacy and get more children and young people taking part in high quality PE and sport
PSA 23:	Make communities safer
PSA 24:	Deliver a more effective, transparent and responsive Criminal Justice System for victims and the public
PSA 25:	Reduce the harm caused by Alcohol and Drugs
PSA 26:	Reduce the risk to the UK and its interests overseas from international terrorism
	<i>A more secure, fair and environmentally sustainable world</i>
PSA 27:	Lead the global effort to avoid dangerous climate change
PSA 28:	Secure a healthy natural environment for today and the future
PSA 29:	Reduce poverty in poorer countries through quicker progress towards the Millennium Development Goals
PSA 30:	Reduce the impact of conflict through enhanced UK and international efforts

Table 18 takes the PSAs that were identified as being able to benefit specifically from an enhanced space exploration programme (shaded blue), and matches them to what some of those specific benefits might be. The benefits are those identified in Chapter 3, and are considered under four separate headings (science, innovation, commerce and society), each one of which has been assessed in terms of the four different possible space

exploration programme development scenarios (reduced option, status quo, enhanced robotic and robotic and human).

Table 18. Match between specific PSAs and benefits from space exploration							
	PSA 1:	PSA 2:	PSA 4:	PSA 5:	PSA 6:	PSA 7:	PSA 8:
	Raise the productivity of the UK economy	Improve the skills of the population	Promote world class science and innovation in the UK	Deliver reliable and efficient transport networks that support economic growth	Deliver the conditions for business success in the UK	Improve the economic performance of all English regions and reduce the gap in economic growth rates between regions	Maximise employment opportunity for all
Scenario 1: Zero Option							
Science	√	√	√√				
Innovation	√	√	√√				
Commerce	√	√	√√				
Society	√	√	√√				
Scenario 2: Status Quo							
Science	√	√	√√	√	√	√	√
Innovation	√	√√	√√	√√	√	√	√
Commerce	√√	√√	√√	√	√	√	√
Society	√	√√	√√				
Scenario 3: Enhanced robotic							
Science	√	√	√√	√	√	√	√
Innovation	√	√√	√√	√√	√	√	√
Commerce	√√	√√	√√	√√	√√	√√	√√
Society	√	√√	√√				
Scenario 4: Robotic & human							
Science	√	√√	√√	√	√√	√	√√
Innovation	√√	√√	√√	√√	√√	√√	√√
Commerce	√√	√√	√√	√√	√√	√√	√√
Society	√	√√	√√				

There are many examples that could be selected to illustrate specific inputs to achievement of the PSAs in Table 17. A few are given in the following paragraphs, arranged by scenario. An increasing number of PSAs are addressed as the complexity (and cost) of the proposed space exploration programme increases. Some of the potential benefits are marked in Table 18 with a single tick. This is to indicate that the potential benefits are downstream from inception of a particular project or product, and may not show a benefit (or profit) for several years. Entries marked with a double tick indicate that potential benefits should ensue on a more immediate timescale.

Scenario 1: Reduced Option. Table 18 shows quite clearly that although the reduced option assists with delivery of **PSA 4** (the UK is one of the leaders on the international stage in lunar and martian science), and has the potential to deliver on several of the other PSAs [**PSA 1, 2**], it is not an option from which the Government would benefit strongly in the short term. Indeed, although it is not drawn out in the table, pursuing the reduced option would be detrimental for the Government's targets, because it does not capitalise on many of the advances already made (using Government funding delivered through the Research Councils), and reduces the opportunities that UK industry has for winning ESA contracts.

Scenario 2: Status Quo:

Science: Robotic exploration of Mars is returning high quality data used by UK scientists to infer the evolutionary history of water (and potential for life) on the planet. [**PSA 4**]

Innovation: Current development of autonomous rover technology is being trialled at airports for transport of customers with reduced mobility. [**PSA 4, 5**]. Instruments for life detection on Mars are being developed for use as a medical diagnostic tool. [**PSA 2, 4**]

Commerce: UK industry and HEIs bid for (and win) ESA contracts; commercial spin-offs (use of autonomous robotics, medical diagnostics) are already being seen from this activity. [**PSA 1, 2, 4**]

Society: The UK is playing its part in the search for life in the Solar System, a subject of many TV broadcasts. The provision of Aurora Fellowships, specifically for young scientists working in space exploration, provides training for the next generation of planetary scientists. [**PSA 2, 4**]

Scenario 3: Enhanced robotic:

Science: Robotic exploration of the Moon will allow us to place telescopes on the lunar surface, free from interference from Earth's atmosphere; enhanced exploration of asteroids, including return of a sample to Earth, will lead to a much greater understanding of the potential threat to Earth from asteroid collision and how to mitigate the threat. [**PSA 4**]

Innovation: Development of novel power sources for space have direct application in terrestrial situations where power supplies are limited or disrupted (e.g. in emergencies such as earthquakes). [**PSA 2, 4, 5**]

Commerce: Novel techniques developed for lunar drilling would spin out into terrestrial drilling projects (e.g. oil and gas exploration in hazardous and remote areas); an enhanced space exploration programme would also increase the number of launches required to deploy, service and maintain space infrastructure, strengthening the UK small-satellite industry. [**PSA 1, 2, 4-8**]

Society: Space robotics in education; hands-on training for engineers on national missions. [PSA 2, 4]

Scenario 4: Robotic and human:

Science: The lunar surface acts as a receiver for fragments of asteroids and comets, and so preserves a unique record of 4 billion years of Solar System history. This history can only be accessed by specialist and detailed examination of a wide range of material collected from the Moon. [PSA 2, 4]

Innovation: The desire for robot-human collaboration in domestic, service and manufacturing situations is likely to increase, leading to increased requirement for development and provision of suitable systems (e.g. in food-processing and preparation); development of closed-cycle environments for living and working in space or on the lunar surface will also be applicable for working in hazardous environments on earth (e.g. servicing and decommissioning of nuclear power plants). [PSA 1, 2, 4-8]

Commerce: Novel techniques developed for in situ resource processing on the lunar surface would spin out into terrestrial industries allowing use of the technologies on Earth (e.g. ore-refining for metal production). There will be commercial opportunities around provision and maintenance of lunar telecommunications. [PSA 1, 2, 4-8]

Society: UK astronauts would be national role models for STEM, both when broadcasting from the lunar surface and when visiting schools. [PSA 2, 4]

By using the metric of the PSAs that all Government Departments are required to address, it is clear that an expanded space exploration programme would help the Government (across a range of Departments) work towards achieving its priority targets.

Appendix F Abbreviations

ASI	Agenzia Spatiale Italiana (Italian Space Agency)
BAS	British Antarctic Survey
BERR	Department for Business, Enterprise and Regulatory Reform BIS Department for Business, Innovation and Skills
BNSC	British National Space Centre
CNES	Centre Nationale d'Études Spatiales (French Space Agency)
CNSA	China National Space Agency
CSA	Canadian Space Agency
CSIRO	Commonwealth Scientific and Industrial Research Organisation (Australian government body responsible for space matters)
CSR	Comprehensive Spending Review
DCSF	Department for Children, Schools and Families
DIUS	Department for Innovation Universities and Skills (now superseded by BIS, Department for Business, Innovation and Skills)
DLR	Deutsches Zentrum für Luft- und Raumfahrt (German Space Agency)
ESA	European Space Agency
GDP	Gross Domestic Product
GES	Global Exploration Strategy
IAC	International Astronautics Conference
IP	intellectual property
ISECG	International Space Exploration Coordination Group
ISRO	Indian Space Research Organisation (Indian Space Agency)
ISRU	in-situ resource utilisation
JAXA	Japan Aerospace Exploration Agency
KARI	Korea Aerospace Research Institute
MOD	Ministry of Defence
NASA	National Aeronautics and Space Administration
NPV	net present value
NSAU	National Space Agency of Ukraine
PSA	Public Service Agreement
Roscosmos	Russian Space Agency
SEWG	Space Exploration Working Group
SSTL	Surrey Satellite Technology Limited
STEM	Science Technology Engineering and Maths
STFC	Science and Technology Facilities Council
TB	tuberculosis

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