Economic Analysis to support a Study on the Options for UK Involvement in Space Exploration

Final Report

British National
Space Centre

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19th March 2009

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19th March 2009

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Acknowledgements

We would like to thank all the space specialists and terrestrial user representatives who provided their time free of charge to this study. The individual specialists who were interviewed in the first stage of the study are listed in Annex 1. The organisations that sent representatives to the six terrestrial user workshops, for the second stage of the study, are the following:

Lunar and terrestrial drilling: Logica Oil, Logica Space, KBR, Shell and Schlumberger.

Low cost launch technology**:** Reaction Engines, Bristol Spaceplanes, SSTL, Qinetiq, Virgin Galactic (VG was met separately as they could not make the workshop date).

In-situ resource utilisation: Green Metals, Professor Derek Fray, and Professor Iain Crawford (University College London).

Lunar communications and navigation: Logica, Partnerships UK, Orbit Research, Astrium, HPC Ltd, Goonhilly New Ventures, and the University of Plymouth.

Robotics: Yorkshire Forward, Astrium, SciSys, National Nuclear Laboratory, Roke, and QinetiQ

Space medicine: University College London, South Hampton University Hospitlas Trust, University of Bath, Qinetiq and the European Astronaut Centre.

We thank these representatives for their input and specialist advice. The Cost Benefit Analyses are the work of London of Economics and not that of the above organisations.

Executive Summary

This report presents the independent economic analysis of a set of business opportunities that may arise from future investments in space exploration. The analysis supports a broader study exploring the options for UK involvement in future space exploration under the direction of a Steering Group comprising representatives from BNSC, STFC, DIUS and the independent member Lord Broers.

The economic analysis employs a cost benefit analysis (CBA) in line with HM Treasury Green Book.

The CBAs assume that international space exploration efforts will include a return to the lunar surface and human habitation from 2020.

Six business opportunities are analysed across three future investment scenarios. The investment scenarios and the business opportunities are the following:

- Enhanced robotics:
  - → Tele-robotic and autonomous drilling on the Moon for scientific purposes and for oil and gas exploration on Earth.
  - → Low cost launch technology for exploration, terrestrial communications and space tourism.
- Enhanced robotics and minimum human:
  - → In-situ resource utilisation for oxygen production in extra-terrestrial environments and titanium production on Earth.
  - → Communications and navigation architecture for lunar exploration.
- Full robotic and human:
  - → Robotics technologies for human exploration and terrestrial food production processes, household/service robots and nuclear decommissioning.

→ Medical technologies for human exploration and terrestrial intensive care, acute care and elderly care.

The business opportunities were selected after an intense round of face-to-face interviews with over 30 businesses, research organisations, and specialists engaged in the space sector in the UK (and in some instances, such as lunar drilling and medical technologies, from specialists drawn from across the EU). Twenty seven business opportunities were identified in this first round.

The full set of 27 business opportunities identified in the face-to-face interviews then underwent two rounds of qualitative assessment using the following eight 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, that is, what are the linkages with terrestrial users and knowledge transfer processes
- Demand drivers, that is, 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

It was also necessary to use two feasibility criteria which assessed whether the project team could gain access to potential terrestrial users of the technology, and if the required information could be provided by these users.

The first qualitative round was a subjective analysis which ranked the opportunities against the criteria. The second qualitative round was a multi-criteria analysis which was used to determine how the set of business opportunities changes when the importance of different criteria are changed.

The outcomes from the two stage qualitative assessment were then discussed with the BNSC, and the broader steering group, before agreeing to the six opportunities listed above for inclusion in the detailed CBAs.

Each of the business opportunities were then investigated in detail in a workshop setting that brought together the space sector specialists with specialists in the terrestrial industries that may benefit from spin-out technologies from space exploration.[1] The workshops were used to collect information both on the features, costs and expected timing of future space architecture and technology, and on the features, benefits and timing of the possible terrestrial applications.

How the Cost Benefit Analyses are implemented

Due to the nature of space technology, there is uncertainty surrounding both the cost and characteristics of the technology and the benefits that may accrue to both terrestrial users and those industries supplying direct to space exploration activities. In order to ensure the CBAs contain the best information available, the project team has invested significant resources in meeting with both specialists supplying direct to the space sector and with terrestrial users who may benefit from the spin-out technologies. Further, each CBA is implemented using multiple scenarios for the main features of the business opportunity, and we identify the main drivers and risks that are important for realisation of future benefits. The detailed CBAs for each business opportunity are presented in chapters 5 to 10.

The net present values have been calculated using the total cost of the technologies to the UK.[2] We have therefore made no assumptions about whether the cost is incurred by public sources or private sources.[3]

The funding mix will also be influenced by the trading of resources between space going nations. For example, the "Canada Robotic Arm" was traded for astronaut places and opportunities for Canadian science on the International Space` Station.

Further we have included (only) the direct impacts due to the technologies. We have not included the indirect (flow-on) impacts on related sectors of the economy.

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[1] Spin-out is also referred to as synergy, this is because the relationship is two way: technologies spin-in from terrestrial applications to space and spin-out from space to terrestrial applications. This study focuses on spin-out.

[2] These costs were provided by the BNSC and by space specialists.

[3] From our discussions with space specialists and terrestrial users, the costs can be shared between private sources and public sources. There are both private, industry and public benefits that may accrue from these business opportunities, and a mix of funding should be sought.

In addition, there are two important considerations when undertaking a cost benefit analysis for projects with long-term impacts. These are the following:

- Converting the costs and benefits to present values. To do this we use a technique called discounting. Discounting allows us to compare costs and benefits that occur in different time periods. The Treasury Green Book suggests a discount rate of 3.5% for projects with expected impacts of 0 to 30 years.

- Adjusting for relative price changes. The valuation of costs and benefits need to be expressed in real terms or constant prices (i.e. at 'today's' general price level), as opposed to nominal terms or current prices. Over a long-term period, the Bank of England's annual inflation target is the measure of prices to use as a general deflator. The Bank of England's inflation target is currently 2.0%.

The cost benefit models are for the time period 2009 to 2040.

Net present values for the different investment scenarios

The detailed CBAs for each of the business opportunities are presented in chapters 5 to 10.

Due to the uncertainty in regard to both the future space technologies and the future terrestrial applications, many CBA scenarios have been implemented for each business opportunity. The purpose of implementing multiple scenarios is to illustrate the wide range of NPVs under the different assumptions about the features of the space technology and terrestrial spin-outs.

The CBAs therefore facilitate an understanding of the main drivers and risks that are important for the future realisation of the benefits for each (of the six) business opportunities under the three investment scenarios.

The future investment scenarios – the main drivers and risks for the net present values

Here we provide a comparative table which shows the main drivers of benefits for each of the business opportunities and the risks associated with these drivers and therefore the realisation of the benefits.

The cells in Table 1 are coloured such that those risks that may be controllable are 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) are coloured "red", and those which have a mix of controllable and uncontrollable drivers and therefore risks are coloured "orange".

Table 1: Business opportunities; main drivers and risks for benefit realisation

Investment scenario	**Business opportunity**	**Main drivers of the benefits**	**Risks that impact upon the drivers and thereby realisation of benefits**
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: ❑ 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) Technology can launch only small payloads to low earth orbit, then 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, • 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.
Enhanced robotics and	In-situ resource utilisation	Cost overrun and demand for oxygen on the lunar surface	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

Table 1: Business opportunities; main drivers and risks for benefit realisation

Investment scenario	Business opportunity	Main drivers of the benefits	Risks that impact upon the drivers and thereby realisation of benefits
minimum human		for propulsion and human habitation	through interaction (both for robotic and human exploration) with other space going nations and organisations.
	Communications and navigation architecture	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.
Full robotic and human	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.
	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 trail and error at the laboratory testing stage. However, 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.

The most likely net present values

After presentation of the cost benefit scenarios to space specialists at the BNSC, the following net present values for the three investment scenarios are considered to be most likely.

Full details of the cost benefit analyses for each business opportunity are presented in chapters 5 to 10.

Table 2: Future investment scenarios net present values (£ million)

Enhanced robotics			**Enhanced robotics and minimum human**			**Full robotic and human**		
Tele-robotic and autonomous drilling	Low cost launch technology	Aggregate net present value	In-situ resource utilisation	Communications and navigation	Aggregate net present value	Robotics	Space medicine	Aggregate net present value
4,219	NPV not included at request of BNSC	4,219	432	6,162	6,594	2,642	435	3,077

Note: The aggregate NPV is a summation of the individual business opportunity NPVs.

Conclusions

The detailed cost benefit analyses provide the estimated net present values of benefits that could accrue to the UK economy from future investment in space exploration. Due to the nature of the space exploration technologies, the cost benefit analyses are implemented using multiple scenarios which allow us to observe what the main drivers of the benefits and costs may be for each business opportunity, and how the estimated net present values change as the magnitudes of the main drivers change.

Each cost benefit analysis therefore presents a matrix of net present values, and we highlight where (and under what conditions) the NPVs may become negative. This has allowed us to present a comparison of the business opportunities by risk type and the possibility for risks to be managed by the UK (either private or public organisations). We have used a traffic light coding system in Table 1, presented above, which allows the reader to quickly compare across investment scenario and business opportunity and to see those which have more controllable (less controllable) risks.

The CBA scenarios have been presented and discussed with the BNSC and the most likely scenarios identified. The most likely net present value for each business opportunity and the investment scenarios is presented in Table 2 above. The largest net present value is for the enhanced robotics and minimum human scenario.

1 Introduction

London Economics in conjunction with Mr Rodney Buckland, an independent contractor, has undertaken an economic analysis in late 2008 and early 2009, of the business opportunities that may arise from future investment in space exploration.

The objective of the study is to provide detailed economic benefits that may arise under three different exploration investment scenarios.

1.1 The report structure

Chapter 2 presents the main features of each of the cost benefit analyses (CBAs), and the net present value (NPV) for each of the (three) investment scenarios. Chapter 2 can be read as a stand alone chapter, but we suggest that readers should also refer to the detailed CBAs contained in chapters 5 to 10. Chapter 3 presents details of the two stage qualitative assessment of business opportunities undertaken prior to the detailed CBAs.

The detailed CBAs (as previously mentioned) appear in the following chapters:

- Chapter 5: Lunar and terrestrial drilling
- Chapter 6: Low cost re-usable launch technology
- Chapter 7: In-situ resource utilisation (ISRU) and titanium production
- Chapter 8: Lunar communications and navigation
- Chapter 9: Robotics
- Chapter 10: Space medicine

2 Cost benefit scenarios for future space exploration investment

In this chapter the range of net present values (NPVs) from the three future investment scenarios are presented. The investment scenarios, as mentioned previously, are the following:

- Enhanced robotics
- Enhanced robotics and minimum human
- Full robotic and full human

The net present values for each of these future investment scenarios estimate the additional net benefits in today's values that could accrue to the UK economy if investment is increased above the status quo: The status quo is the ESA Science Programme and the ESA Aurora Programme.

The net present value ranges for each of the business opportunities are very large. This is because the specific features of the space technology are uncertain at this point in time, and because the potential terrestrial markets for spin-out technologies also contain uncertainty. Therefore, for each business opportunity we conduct many different scenarios. The purpose of implementing multiple scenarios is to show how the NPV may change as different variables in the CBA are changed. The full scenario testing for the business opportunities are presented in Chapters 5 to 10.

We believe that the best information available today has been used in the CBAs. The project team has spent seven months collecting information to inform the CBAs, and have spoken to over 50 space specialists in the UK and (in some instances) Europe. Further, we have conducted seven workshops, which brought together the space specialists and the terrestrial users to identify and estimate the spin-out benefits to the terrestrial economy. We believe this is the first time space specialists and terrestrial users have been brought together for this purpose. (We asked NASA if they had undertaken such an exercise and they reported that they had not).

The cost benefit analyses have been undertaken using the total cost of the technology to the UK. We make no assumptions about the mix of funding between the private and public sectors. Tables 1, 2 and 3 present the main features of the CBAs, the main drivers that determine what the realised net present values of costs and benefits will be, and the potential range of the NPVs.

Further, the space exploration sector in the UK reports figures mainly in US dollars. Through the report we use US dollars, however we do present the cost benefit analyses and the associated net present values in UK pounds(£). We use the long-run exchange rate of £1 = $1.5.

Table 3: Net present values (NPV) enhanced robotics investment scenario

Business opportunities: Lunar drilling and low cost launch technology	**NPV**
Lunar drilling costs: Three different cost scenarios are implemented, (1) a cost of US$180 million from 2013 to 2018; (2) cost of US$450million over the same time period, and (3) a scenario that doubles the cost of scenario 2, and doubles the time such that the total cost is US$1.2 billion between 2013 and 2024. ***Terrestrial spin-outs to oil and gas industry**:* The CBA models three sources of terrestrial benefit, (a) automation which provides access to inhospitable environments and thereby 'new' oil, (b) remote operations which facilitates the possibility of 'one-way wells' and thereby reduces the cost of drilling and servicing wells, (c) self-repair coatings for drill bits which reduces the cost of drill replacements. ***Magnitude for terrestrial benefits:*** From expert discussions, automation increases the potential supply of oil by opening up new oil reserves, the CBA assumes that of the total known oil reserves in the arctic (a representative inhospitable environment), either 50%, 25% or 0% of these reserves can be extracted by oil companies using automation technologies. Remote operations reduces well drilling and servicing costs either by 50% or 33%, and self repair coatings extinguishes the need to replace drill bits and thereby avoids the cost of replacing 800 drill bits per year. The price of oil is also important, and the CBA is implemented using historical oil price data at US$30, $40 and $100 per barrel. ***UK share of terrestrial benefits:*** From expert discussions, the CBA assumes that the UK has greater comparative advantage in remote operations technology, followed by automation and then self-repair coatings. This comparative advantage distribution, generates the following benefit scenarios, (1) of the total remote operations benefits 1% flows to the UK, of the automation total benefits 0.6% flows to the UK and the total benefits of self repair coatings 0.4% flows to the UK – the remainder flows to other nations who also benefit from the technologies (e.g the Netherlands, Australia); (2) 25% of benefits from remote operations to the UK, 15% for automation and 10% for self repair coatings.	***The CBA range:*** 108 different CBA scenarios are implemented for lunar drilling. The NPVs are positive and large under almost all scenarios. Negative NPVs arise when; • The price of oil is low • The terrestrial spin-out benefits from automation technology result in only a small percentage of total oil reserves in inhospitable terrestrial environments being extracted. • When only a small portion of the total benefits from the spin-out technologies - automation, remote operations and self-repair coatings - accrue to the UK.
Low cost launch technology (Re-usable launch vehicles): Low cost launch technology costs: There are four different technologies under development in the UK. Each has different specifications and therefore each can perform different functions for space exploration. "Skylon" can substitute for current expendable launch technology and therefore can launch payloads to the ISS, lunar surface and stationary orbit satellites, plus small satellites to Low Earth Orbit and public access (tourism). Spaceship2 can supply the small satlite market and public access to a	*The CBA range:* For each low cost launch technology we implement 4 different CBA scenarios. The magnitude of the benefits depend on the following: • What the technology can do.

Table 3: Net present values (NPV) enhanced robotics investment scenario

Business opportunities: Lunar drilling and low cost launch technology	**NPV**
suborbital trajectory (100km). Ascender and Spacebus is a staged approach. Ascender is small sub-orbital plane with functions limited to activities such as micro-gravity experiments. Spacebus can replicate the functions of current expendable launch technology. The costs for the development of each varies significantly due to their different specifications. The total estimated costs are Skylon, $12 billion over ten years, Space ship2 $300 million over six years, Ascender $90million over four years, Spacebus $3.5billion over seven years (the Ascender and Spacebus are sequential investments). ***Magnitude for terrestrial benefits:*** The magnitude of the benefits depends on type of technology, because the different technologies can service different markets/uses, as described above. Overall the magnitude of benefits depend on how much demand there is for low cost re-usable launchers to transport payloads to the lunar surface and stationary orbit (space services), to low earth orbit (the market for small satellites) and the demand for public access to space. ***UK share of terrestrial benefits:*** If the launch technology can carry payloads to the lunar surface and stationary orbit, then we assume that 20%, 60% or 100% of the expected savings of the new technology relative to existing launch technology is realised. For technologies that can launch small satellites we assume that UK firms could capture 50%, 60% or 100% of the potential market. For public access we assume that the UK can capture 25% or 50% of the world market at a price per person of $150,000, or 75% of the market at a price of $85,000. For micro-gravity research we assume that 60% or 100% of the potential revenues form microgravity research could be captured with either a slow take-up rate or a fast take-up.	• What the demand is for space services in stationary orbit and on the lunar surface. • Demand form the small satellite market. • Secondary drivers are demand for public access, and micro-gravity research.

Table 4: Net present values (NPV) enhanced robotics and minimum human investment scenario

Business opportunities: In-situ resource utilisation and lunar communications and navigation	**NPV**
In-situ resource utilisation on the lunar surface costs: Three different cost scenarios are implemented, (1) a cost of US$465 million; (2) US$ 697.5 million, and (3) US$930 million all over the time period 2013 to 2022. ***Terrestrial spin-outs to titanium and steel sectors:*** The CBA models the substitution of conventionally produced titanium (the Kroll process using titanium tetrachloride) with a British discovery that separates titanium from its oxide using electro-deoxidisation. The British discovery can produce, at commercial scale, FeTi, Ti-6Al-4V, pure CP, and rutile-based titanium alloy. These four titanium products substitute for alloys used in steel production, titanium used in aerospace, corrosion applications for uses such as chemical plants, and the construction of stainless steel products, respectively. Only the first three titanium products are modelled in the CBA because the fourth is totally new product and we could not source a current price for the rutile based alloy. ***Direct benefits from supply of lunar oxygen for propulsion and human habitation:*** ISRU is a substitute for transporting oxygen from Earth the Moon. The current cost of shipping 1 tonne of oxygen using expendable launch technology (the US Altair lunar lander cargo version) is between US$25million and $100million. The expected demand for propulsion on the lunar surface is between 37.6 tonnes and 56.4 tonnes per year from 2020 to 2040. The expected demand for human habitation is between 1 and 5 tonnes per year from 2020 to 2040. ***UK share of terrestrial benefits:*** The CBA assumes that 55% of revenues from FeTi flow to the UK, 65% for Ti-6Al-4V and 48% for Pure CP. ***UK share of oxygen demand on lunar surface:*** The CBA models three different scenarios UK supplies ¼ of total oxygen demand, 1/6 and 1/10.	***The CBA range:*** 72 different CBA scenarios are implemented for ISRU. The NPVs are positive and extremely large under many of the scenarios. The NPVs are so large because of the cost of transportation to the Moon. The NPVs move negative as the costs of developing the ISRU technologies increase, as the demand for oxygen on the lunar surface declines and as the UK's share of lunar oxygen supply decreases.
Lunar communications and navigation costs: Two cost scenarios are modelled in the CBA (1) £959 million, (2) £1.3 billion (both) for the period 2010 to 2030. ***Direct benefits from supply of lunar communications:*** From expert discussions, it assumed that demand for lunar to Earth communications increases from 1 mega-bite per second (Mbps) in 2010 to 325 Mbps in 2030. The price space going nations and other users (such as the media) will be willing to pay is assumed to be between £1million per year for each Mbps up to £5million per year	***The CBA range:*** 50 different CBA scenarios are modelled. The NPVs are positive in most of these scenarios. The NPVs move negative as the price users are willing to pay for communications decreases to £1 - £2 million per Mbps, as the cost of the lunar communications service increases and

Table 4: Net present values (NPV) enhanced robotics and minimum human investment scenario	
Business opportunities: In-situ resource utilisation and lunar communications and navigation	**NPV**
for each Mbps. ***UK share of direct benefits:*** The UK may not service all of the required data traffic, or the levels of demand may not be as high as predicted. Therefore, 5 different supply share scenarios are modelled in the CBA (a) UK supplies 25% of expected demand; (b) 50%; (c) 75%; (d) 100% and (e) 125% - to account for a demand 25% greater than that predicted. ***The CBA range:*** 50 different CBA scenarios are modelled. The NPVs are positive in most of these scenarios. The NPVs move negative as the price suers are willing to pay for communications decreases to £1 - £2 million per Mbps, as the cost of the lunar communications service increases and as the UK's share of communications supply decreases.	as the UK's share of communications supply decreases.

Table 5: Net present values (NPV) full robotics and human investment scenario

Business opportunities: robotics and space medicine	**NPV**
Autonomous robotics costs: We were unable to source costs for the robotics and therefore we use as a proxy the expected costs to the UK of a pressurised exploration rover which will use autonomous robots to support a human crew. This cost is £333 million. We also double and quadruple the costs for the sensitivity analysis. *Terrestrial spin-out benefits*: (1) The UK's share of the household and service robotics market may increase: Three market share increases are modelled in the CBA. (2) Cost savings to the UK food processing sector as robots support and substitute for human labour: Four cost savings scenarios have been modelled (10%, 5%, 1% and 0.5%). (3) Servicing and decommissioning nuclear power stations in the UK: Three cost scenarios have been modelled and we assume the cost savings due to the robotics technology is 0.5%.	The CBA range: We modelled 27 different CBA scenarios. The food processing spin-outs were the most well defined benefits, and when the more uncertain benefits of household robotics and nuclear decommissioning were added the CBA does not change very much. The net present values are positive in almost all circumstances.
Space medicine costs: The CBA models space medicine using example UK technologies. These are, non or minimally invasive telemetry and the identification of molecular targets and whole body physiology research. Five cost scenarios are modelled in total for this CBA. *Terrestrial spin-out benefits:* Benefits accrue to the NHS in terms of reduced number of people in intensive care and staying for shorter period of time. Improved patient referral process for acute care. Reduction in the number of hip fractures for the elderly (due to improved knowledge of bone and muscle wasting).	The CBA range: We model 15 different CBA scenarios. The net present values are positive in al ost all circumstances.

3 Qualitative assessment of the business opportunities

This chapter details the two stage qualitative assessment of business opportunities. The qualitative assessment, as previously stated, was undertaken prior to selection of the business opportunities for inclusion in the CBAs.

3.1 Survey of organisations engaged in the space industry to identify business opportunities

The first step in the identification of business opportunities involved a survey of organisations engaged in the space industry. An initial list of such organisations was provided by the BNSC, and this list was complemented by Mr Rodney Buckland.

The survey was implemented in the following way: Structured interviews were conducted with representatives from each organisation by Mr Rodney Buckland and Dr Charlotte Duke (LE) in August to November 2008. All interviews were conducted face to face, unless otherwise requested by the representative, and each interview lasted for at least two hours.

The list of surveyed organisations, the representatives from each organisation and the business opportunities identified by each, are presented in Table 40 in the Annex 1 .

3.2 Mapping business opportunities to programme investment options

Each potential business opportunity was then mapped to a strategic investment option. The investment scenarios used for the qualitative analysis were those presented to London Economic by the BNSC in the "Tentative UK Space Exploration Roadmap to 2030". The investment scenarios were subsequently re-defined at a BNSC workshop in November 2008, such that the scenarios are not tied to specific future missions, but rather they are defined by the extent of robotic and human investments. Further, we had hoped to initially undertake 15 business opportunity CBAs, but this became impossible as the information about each of the business opportunities was very difficult to gather.

3.3 First round qualitative assessment

The business opportunities were then assessed qualitatively by London Economics, with supporting input by Rodney Buckland, against the criteria requested by the BNSC, and complemented by additional criteria suggested by London Economics. The criteria are the following:

- ❑ Position of the space product or service in the space exploration value chain
- ❑ Position of the "new " product or service in the terrestrial recipient sector
- ❑ Timescale of the expected spillover/spin-out
- ❑ Risk to market, which is broken down into,
    - Innovation environment, that is, what are the linkages with terrestrial users and the knowledge transfer process
    - Demand drivers, that is, why may terrestrial users want the product
- ❑ Who are the potential customers for the new product or service
- ❑ Significance of the new product based on the size of the spillover/spin-out

Two feasibility criteria where included, as these assess the possibility of undertaking more in depth analysis of each business opportunity for Task 2, the cost benefit analysis. These two feasibility criterion are:

- ❑ Information available for estimating the cost of the space product from the space industry
- ❑ Access to potential terrestrial users of the space technology to inform the expected demand drivers and significance of the business opportunities

The first round qualitative assessment was presented to BNSC at the interim project meeting, 23rd of September 2008. Further input was provided by BNSC at this meeting, and this input was then incorporated into the first round qualitative assessment. The first round qualitative assessment is presented in Annex 2

3.4 Second round qualitative assessment

The information from the first round qualitative assessment was then used in a Multi-criteria analysis. The purpose of the MCA was to identify the 7 most promising business opportunities from the full set of opportunities identified. And, to then, distribute the 7 business opportunities across strategic programme investment options to ensure that the business opportunities carried forward for further investigation in the cost benefit analysis represent a mix across each strategic programme option. The MCA is presented in chapter 4.

4 Multi-criteria analysis of business opportunities

In order to identify the most promising business opportunities to carry forward to the cost benefit analyses, this section first undertakes a (preliminary) multi-criteria analysis (MCA) of the different options. Although many techniques would be widely acknowledged as methods of multi-criteria analysis, they cover a wide range of quite distinct approaches (in contrast to cost benefit analyses, which is a more unified body of techniques). A general explanation of MCA is presented in Annex 3.

In this study we use the MACBETH multi-criteria analysis model to assess the attractiveness of the different business opportunities. As with all MCA approaches, the MACBETH model makes the options and the contribution of the different criteria against which they are assessed explicit, and requires the exercise of some degree of judgment.

The first step in the MCA is to define the options and the criteria, and to decide how each option is assessed under each criterion. In this study, the options are the range of possible business opportunities which are being examined (as identified in the structured interviews, section 3.1). The criteria of the model comprise of a range of qualitative characteristics, which take one of a discrete set of qualitative values for each option (see Box 1 below). These criteria are the same as those used in the first round qualitative assessment (section 3.3).

The multi-criteria analysis was undertaken with the first set of strategic investment programme options. As stated in chapter 3, the investment scenarios were subsequently re-defined so that they are not tied to any specific future mission but instead are framed in terms of increasing robotic and human options. Further, we had hoped to undertake 15 business opportunities, but this became impossible due to the difficulty in gaining information about the space technologies and their potential terrestrial spin-outs.

Box 1: Criteria used in the MCA

Criterion 1: Position in the space exploration value/supply chain;

Upstream or downstream: upstream is preferable because in this case the effects of the spillover will be felt more widely as the benefits 'flow' down the chain.

Criterion 2: Position of the "new" product in the value chain of the recipient sector;

Upstream/Downstream: upstream is preferable because in this case the effects of the spillover will be felt more widely as the benefits 'flow' down the chain.

Criterion 3: Timescale of the expected spillover;

Short term (2/3 years), medium term (4 to 6 years), long term (7 to 10 years), very long term (>10 years): shorter timescales are preferred.

Criterion 4: Innovation environment, that is, what are the linkages with terrestrial users and knowledge transfer processes;

High, medium or low: highly innovative environments are preferred to medium which are preferable to low.

Criterion 5: Demand drivers, that is, why may terrestrial users want the product;

Strong, medium or weak: strong demand drivers are preferred medium, which are preferable to weak.

Criterion 6: Potential customers for the new product (industry, government departments, health, households, etc);

Industry, government or households or any combination of the three: a combination of all three is most preferable, followed by 'industry and government', then 'industry and households' and then industry alone. Options where industry is not a customer are less preferable, with 'government and households' preferable to government alone which is in turn preferable to households alone.

Criterion 7: Significance of the new product based on the size of the potential spillover;

Large, medium or small: large sized spillovers are preferable medium which are preferable to small.

Criterion 8: Information availability for estimating the space costs of the new product;

High, medium or low probability of getting the information: high probabilities are preferable to low.

Criterion 9: Access to potential users;

High, medium or low probability of getting access to potential users: high probabilities are preferable to low.

Criterion 10: Potential for further study;

Definite, possible or unlikely: definite further study is preferred to possible which is preferred to unlikely.

As outlined in box 1, the qualitative values taken by each criterion, for each option, have a specified order of preference. For the purposes of the preliminary MCA, we first assume equal increments across the range of preference levels for each criterion, with the most preferred qualitative value indexed at 100 and the least preferred indexed at zero.

The MCA model allows different weights to be given to each criterion. This allows some criteria to be treated as more important than others in the decision making process. In the first case, we attached equal weights to every criterion, i.e. we assume that each of the criteria is equally important. One of the virtues of the MCA model is that this assumption can be altered in accordance with new information and expert judgement. This is demonstrated in two alternative MCAs which are presented later.

The output of the MCA is an 'overall score' for each option, calculated as the weighted average of each option's score over all the criteria. The MCA assesses a total of twenty-four different business opportunities, or options, which fall into the five different strategic programmes.

The overall scores given by the initial MCA are generally quite evenly spread (Table 6). Among all the options assessed three (Titanium produced from Rootile, Lunar communications technology and Robotics: dexterous hands) achieved the joint top overall score of 95 (of a maximum 100), followed by a small gap to the fourth placed option (Drilling on lunar surface) which scored 91.7. Between the top five options, four of the five strategic programmes are represented.

According to these results, assuming a total of fifteen options are taken forward to the cost benefit analysis stage, this includes all the shaded options in Table 6, and two of the next four in the table.

Table 6: MCA overall scores: equal criteria weights.

Option (strategic programme in parentheses)	Score
ISRU i.e. Titanium produced from Rootile (Lunar robots)	95.0
Lunar communications technology (Lunar robots)	95.0
Robotics: dexterous hands (Mars robots)	95.0
Drilling on lunar surface (Billenium Archive)	91.7
Remote sample analysis (2): Remote analysis of samples (Mars robots)	88.3
Wireless bio- telemetry (Lunar base)	88.3
Geology technology: Designer solvents for tar sand oil extraction (Mars robots)	86.7
Data acquisition and data handling linked to bio-telemetry (Lunar base)	85.0
Postgraduate and industrial training (ESA Programme)	80.0
Human decision aides (Lunar base)	78.3
Psychology of humans (Lunar base)	78.3
ISRU - Nuclear power generation (Lunar base)	75.0
Robotic Navigation: 3D imaging of terrain for navigation of rovers (Mars robots)	75.0
Disease control technology: Backward Planetary protection ofr orbiter (Mars robots)	71.7
Disease control technology: Forward Planetary Protection for lander and rover (Mars robots)	71.7
Remote sample handling: Sample acquisition, transfer and encapsulation on lander and rover (Mars robots)	71.7
Robotic Navigation: Speckle velocimetry (laser navigation similar to a computer mouse) (Mars robots)	71.7
Detection: Laser Illumination for detection and ranging (LIDAR) (ESA Programme)	70.0
ISRU e.g. generation of oxygen in Lunar environment (Lunar base)	63.3
ISRU - Solar power generation and storage (Lunar robots)	61.7
Robotics: Autonomous robots (Mars robots)	55.0
Robotics: autonomous robots (2) (Mars robots)	51.7
Sample receiving facility (Mars robots)	45.0
Space planes (Lunar robots)	25.0

In the cost benefit analysis it is necessary to examine a balance of business opportunities across the different strategic programmes. Hence, in Table 7 we present the overall scores by strategic programme. This shows that at least one option from each strategic programme is included in the fifteen highest scoring options (again shaded), so it is possible to take forward to the cost benefit analysis the most desirable options, according to the MCA, and have representation from each of the strategic programmes.

Table 7: MCA overall scores by strategic programme: equal criteria weights.

Option by investment scenario	Score
Billenium Archive	
Drilling on lunar surface	91.7
ESA Programme	
Postgraduate and industrial training	80.0
Detection: Laser Illumination for detection and ranging (LIDAR)	70.0
Lunar base	
Wireless bio- telemetry	88.3
Data acqusition and data handling linked to bio-telemetry	85.0
Human decision aides	78.3
Psychology of humans	78.3
ISRU - Nuclear power generation	75.0
ISRU e.g. generation of oxygen in Lunar environment	63.3
Lunar robots	
ISRU i.e Titanium produced from Rootile	95.0
Lunar communications technology	95.0
ISRU - Solar power generation and storage	61.7
Space planes	25.0
Mars robots	
Robotics: dexterous hands	95.0
Remote sample analysis (2): Remote analysis of samples	88.3
Geology technology: Designer solvents for tar sand oil extraction	86.7
Robotic Navigation: 3D imaging of terrain for navigation of rovers	75.0
Disease control technology: Backward Planetary protection ofr orbiter	71.7
Disease control technology: Forward Planetary Protection for lander and rover	71.7
Remote sample handling: Sample acqusition, transfer and encapsulation on lander and rover	71.7
Robotic Navigation: Speckle velocimetry (laser navigation similar to a computer mouse)	71.7
Robotics: Autonomous robots	55.0
Robotics: autonomous robots (2)	51.7
Sample receiving facility	45.0

Uneven criteria weights

The MCA presented above gives equal importance, or weight, to each criterion. Here we allow the weights given to the criteria to differ, by carrying out two alternative versions of the original MCA.

The first gives greater importance to three criteria:

> Criterion 4: Innovation environment, that is, what are the linkages with terrestrial users and knowledge transfer processes
>
> Criterion 5: Demand drivers, that is, why may terrestrial users want the product

> Criterion 7: Significance of the new product based or the size of the potential spillover;

In the MACBETH model the criteria weights always sum to one hundred. For the first of our two alternative MCAs, the weights given to the three criteria above are equal, but twice the size of the weights given to the other seven criteria (i.e. the weights are 15.39, for the more heavily weighted criteria, and 7.69 for each of the remaining seven criteria).

When these weights are applied, the MCA unambiguously identifies the fifteen most attractive options (shaded in Table 8). Unsurprisingly the options with the highest overall ratings in the previous MCA remain in the top fifteen, with only a few changes in the ordering.

The main differences occur at the margin, where options are on the verge of being included in the highest scoring fifteen in both this MCA and the last. Three options, *Disease control technology: Backward Planetary protection for orbiter*, *Disease control technology: Forward Planetary Protection for lander and rover* and *Remote sample handling: Sample acqusition, transfer and encapsulation on lander and rover*, were candidates for the cost benefit analysis from the previous MCA, but are not according to the alternative MCA.

On the other hand, the option *Robotic Navigation: Speckle velocimetry (laser navigation similar to a computer mouse)* is confirmed as part of the top fifteen, and *Detection: Laser Illumination for detection and ranging (LIDAR)* is included in the cost benefit analysis where it was not before.

Table 8: MCA overall scores: Criteria 4, 5 and 7 weighted heavily.

Option	Score
ISRU i.e Titanium produced from Rootile	96.2
Lunar communications technology	96.2
Robotics: dexterous hands	96.2
Drilling on lunar surface	93.6
Remote sample analysis (2): Remote analysis of samples	91.0
Wireless bio- telemetry	91.0
Geology technology: Designer solvents for tar sand oil extraction	89.8
Data acqusition and data handling linked to bio-telemetry	88.5
Psychology of humans	83.3
Postgraduate and industrial training	80.8
Human decision aides	79.5
Robotic Navigation: Speckle velocimetry (laser navigation similar to a computer mouse)	78.2
Detection: Laser Illumination for detection and ranging (LIDAR)	73.1
ISRU - Nuclear power generation	73.1
Robotic Navigation: 3D imaging of terrain for navigation of rovers	73.1
Disease control technology: Backward Planetary protection ofr orbiter	70.5
Disease control technology: Forward Planetary Protection for lander and rover	70.5
Remote sample handling: Sample acqusition, transfer and encapsulation on lander and rover	70.5
Robotics: Autonomous robots	65.4
ISRU e.g. generation of oxygen in Lunar environment	64.1
ISRU - Solar power generation and storage	59.0
Sample receiving facility	50.0
Robotics: autonomous robots (2)	43.6
Space planes	26.9

Breaking the overall scores down by the different strategic programmes we see, again, that there is at least one option from each strategic programme in the set to go forward to the cost benefit analysis (shaded options in Table 9). The main difference to the results of the previous MCA (comparing these results with those in Table 7) is that both of the options in the ESA programme are included in the cost benefit analysis.

Table 9: MCA overall scores by strategic programme: Criteria 4, 5 and 7 weighted heavily.

Option by strategic programme	Score
Billenium Archive	
Drilling on lunar surface	93.6
ESA Programme	
Postgraduate and industrial training	80.8
Detection: Laser Illumination for detection and ranging (LIDAR)	73.1
Lunar base	
Wireless bio- telemetry	91.0
Data acqusition and data handling linked to bio-telemetry	88.5
Psychology of humans	83.3
Human decision aides	79.5
ISRU - Nuclear power generation	73.1
ISRU e.g. generation of oxygen in Lunar environment	64.1
Lunar robots	
ISRU i.e Titanium produced from Rootile	96.2
Lunar communications technology	96.2
ISRU - Solar power generation and storage	59.0
Space planes	26.9
Mars robots	
Robotics: dexterous hands	96.2
Remote sample analysis (2): Remote analysis of samples	91.0
Geology technology: Designer solvents for tar sand oil extraction	89.8
Robotic Navigation: Speckle velocimetry (laser navigation similar to a computer mouse)	78.2
Robotic Navigation: 3D imaging of terrain for navigation of rovers	73.1
Disease control technology: Backward Planetary protection ofr orbiter	70.5
Disease control technology: Forward Planetary Protection for lander and rover	70.5
Remote sample handling: Sample acqusition, transfer and encapsulation on lander and rover	70.5
Robotics: Autonomous robots	65.4
Sample receiving facility	50.0
Robotics: autonomous robots (2)	43.6

For the second alternative MCA we give greater weight to two criteria:

> Criterion 1: Position in the space exploration value/supply chain;
>
> Criterion 2: Position of the "new" product in the value chain of the recipient sector;

For this alternative MCA, the weights given to these two criteria are equal, but twice the size of the weights given to the other eight criteria (i.e. the weights are 16.67 and 8.33).

The results of this MCA identify twelve options for the cost benefit analysis (shaded in Table 10), with any three of the next four making up the remainder. Again, unsurprisingly the options with the highest overall scores in the original MCA remain in the top fifteen.

The most striking difference when greater weights are applied to criteria 1 and 2 is that the option *Postgraduate and industrial training* is no longer in the group for cost benefit analysis, whereas from the original MCA it was well inside the top fifteen at number nine. This is because it is downstream in the space exploration supply chain, which is undesirable, and this characteristic is given greater importance in this MCA.

Table 10: MCA overall scores: Criteria 1 and 2 weighted heavily.

Option	**Score**
ISRU i.e Titanium produced from Rootile	95.8
Lunar communications technology	95.8
Robotics: dexterous hands	95.8
Drilling on lunar surface	93.1
Remote sample analysis (2): Remote analysis of samples	90.3
Geology technology: Designer solvents for tar sand oil extraction	88.9
Human decision aides	81.9
Psychology of humans	81.9
Wireless bio- telemetry	81.9
Data acqusition and data handling linked to bio-telemetry	79.2
ISRU - Nuclear power generation	79.2
Robotic Navigation: 3D imaging of terrain for navigation of rovers	79.2
Disease control technology: Backward Planetary protection ofr orbiter	76.4
Disease control technology: Forward Planetary Protection for lander and rover	76.4
Remote sample handling: Sample acqusition, transfer and encapsulation on lander and rover	76.4
Robotic Navigation: Speckle velocimetry (laser navigation similar to a computer mouse)	76.4
Postgraduate and industrial training	75.0
ISRU - Solar power generation and storage	68.1
Robotics: Autonomous robots	62.5
ISRU e.g. generation of oxygen in Lunar environment	61.1
Robotics: autonomous robots (2)	59.7
Detection: Laser Illumination for detection and ranging (LIDAR)	58.3
Sample receiving facility	37.5
Space planes	20.8

When we break down the scores by the different strategic programmes it shows the importance of no longer taking *Postgraduate and industrial training* forward to the cost benefit analysis. In this case, none of the options from the ESA programme are included.

Table 11: MCA overall scores by strategic programme: Criteria 1 and 2 weighted heavily.

Option by strategic programme	Score
Billenium Archive	
Drilling on lunar surface	93.1
ESA Programme	
Postgraduate and industrial training	75.0
Detection: Laser Illumination for detection and ranging (LIDAR)	58.3
Lunar base	
Human decision aides	81.9
Psychology of humans	81.9
Wireless bio- telemetry	81.9
Data acqusition and data handling linked to bio-telemetry	79.2
ISRU - Nuclear power generation	79.2
ISRU e.g. generation of oxygen in Lunar environment	61.1
Lunar robots	
ISRU i.e Titanium produced from Rootile	95.8
Lunar communications technology	95.8
ISRU - Solar power generation and storage	68.1
Space planes	20.8
Mars robots	
Robotics: dexterous hands	95.8
Remote sample analysis (2): Remote analysis of samples	90.3
Geology technology: Designer solvents for tar sand oil extraction	88.9
Robotic Navigation: 3D imaging of terrain for navigation of rovers	79.2
Disease control technology: Backward Planetary protection ofr orbiter	76.4
Disease control technology: Forward Planetary Protection for lander and rover	76.4
Remote sample handling: Sample acqusition, transfer and encapsulation on lander and rover	76.4
Robotic Navigation: Speckle velocimetry (laser navigation similar to a computer mouse)	76.4
Robotics: Autonomous robots	62.5
Robotics: autonomous robots (2)	59.7
Sample receiving facility	37.5

As mentioned previously, one of the benefits of MCA is that it transparently illustrates how the weighting of the different criteria, and value of the qualitative chraceristics within each criteria, can impact upon the set of business opportunities to be taken forward. The weights and the qualitative values can be adjusted through further discussion and expert judgement.

5 Lunar and terrestrial drilling

In this chapter we present a case study for spin-out technologies from Lunar drilling to terrestrial drilling. We focus on the benefits that may flow to the oil and gas industry both internationally and in the UK.

The information presented in this chapter has been provided by participants at the Lunar and Terrestrial Drilling Workshop conducted by BNSC and London Economics in December 2008. Representatives at the workshop were from Shell, Schlumberger, Baker Hughes, the Open University and Logica.

The information provided by workshop participants has been complemented with publicly available information from referenced sources, which are identified throughout this chapter where they are used.

5.1 Mapping the benefits and costs of lunar and terrestrial drilling

In this section we discuss the costs and benefits from lunar drilling as used in this report. The costs for lunar drilling are taken from estimates provided by specialists in lunar drilling technology.[4]

5.1.1 Costs of lunar drilling

We model three different cost scenarios for the cost of lunar drilling. These scenarios are the following (in current prices):

Scenario 1:	The 'low cost scenario' uses a total cost of US$180 million over a six year period beginning in 2013 (including lander, drill and earth operations)
Scenario 2:	The 'high cost scenario' uses a total cost for lunar drilling of US$450 million over a six year period (again) beginning in 2013 (including lander, drill and earth operations)
Scenario 3:	The 'very high cost scenario' doubles the costs from the high cost scenario (Scenario 2) and assumes that the costs are sustained, at their maximum level, for twice as

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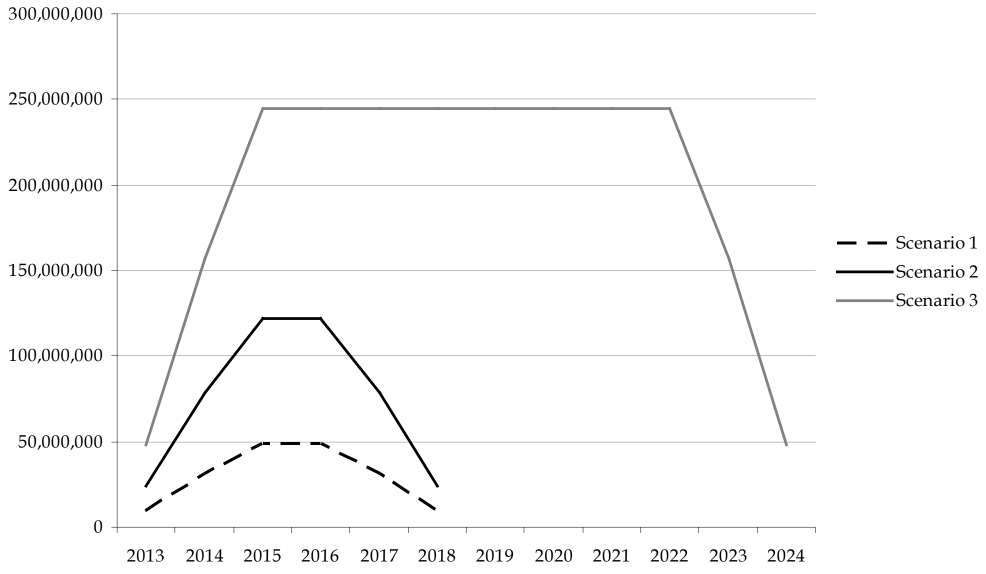
[4] The total costs for scenarios one and two were provided to London Economic by a private firm engaged in lunar drilling technology and by the BNSC respectively. The assumed distribution of these costs across the years 2013 to 2024 was taken from scenario estimates provided to London Economics by BNSC. This distribution is 5% of total cost in year 1, 17% in year 2, 27 % in years 3 and 4, 17% in year 5 and 5% in year 6.

long. This gives an estimated total cost of nearly US$ 1.2 billion between 2013 and 2024.

Figure 1 charts these four cost scenarios across the time period 2013 to 2024.

Figure 1: Cost scenarios for lunar drilling



5.1.2 Technical and non-technical benefits to terrestrial drilling

A number of areas of technical benefit were identified at the workshop, these were:

- Automation
- Remote operations
- Robotics
- High data rate transmission systems
- Lightweight material and (self repair) coatings

Non-technical benefits were also identified by specialists at the workshop, and these were:

- There is a shortage of skilled graduates that choose to work in the oil industry. This is often because oil drilling is considered "low tech". Drilling on the moon could illustrate that drilling can be high tech and exciting, and thereby encourage more skilled graduates, such as engineers, to enter the oil industry.

- Encouraging good graduates to be astronauts. The question was explored; what would be the public relations value of a "Shell', "Schlumberger" or "Baker Hughes" astronaut?

5.2 Cost benefit analysis

The cost benefit analysis (CBA) focuses on three potential sources of technical benefits for the UK: automation, remote operations and self-repair coatings. The analysis focuses on these particular aspects because the necessary figures are currently available in order to estimate the size of the benefits.

5.2.1 Automation

Automation allows the extraction of previously unreachable oil reserves under, for example, the Arctic. The potential benefits to the UK come from the revenues that could be derived from the exploitation of these reserves. The level of the benefits depends on the size of the oil reserves under the Arctic, the percentage of the total oil reserves which can be extracted, and the future price of oil. Each of these factors is considered in turn below:

Oil reserves

The available oil reserves under the Arctic are assumed to be equivalent to the reserves currently available in the North Sea.[5] The US Government Energy Information Administration quotes the proven oil reserves in the North Sea Region in January 2006 at 13.4 billion barrels,[6] and this figure is used in the CBA.

Extraction rates

It is unlikely that all of the reserves will be extractable, so three possible scenarios are modelled in the CBA. Two of the scenarios assume that half of the reserves can be extracted or, alternatively, just one quarter of the reserves can be extracted, whilst the third (extreme) scenario assumes that in reality none of the oil is retrieved.

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[5] Estimate provided by specialists at the workshop.

[6] The Energy Information Administration drew this estimate from the Oil and Gas Journal.

Oil prices

Data from Trend Forecaster at InflationData.com is used in the CBA to inform our assumptions regarding the price of oil. This data provides the price per barrel of crude oil averaged over the year for every year since 1946. In constant 1997 prices, the minimum price since the turn of the century was just under US$30 per barrel, whilst in 2008 the price went well above US$100. Hence, we the use US$30 and US$100 per barrel in constant prices as upper and lower estimates for the price of oil in calculating future benefits. The mean price per barrel since 2000 is around US$40, and this is used as a middle estimate in the CBA.

Timing of benefits

The net present value of the costs and benefits to the UK is also influenced by the expected timings of the benefits. For the purposes of the CBA the benefits are assumed to start to accrue to the UK from 2020, when exploitation of the arctic oil reserves is expected to begin, and continue until 2040. It is also assumed that benefits are distributed uniformly over this 20 year period.

5.2.2 Remote operations

Remote operations allow cost savings to be made because it could be possible, to drill one-way wells. This reduces the time to drill, evaluate and trip out (withdraw from the well). The potential benefits to the UK come from increased productivity in drilling and servicing of wells, and thereby savings to UK firms engaged in oil exploration and production. The level of the benefits depends on the number of wells that need to be drilled and serviced each year, the number of days required to drill and service each well and the cost per day to carry this out. Further, the benefits also depend on the number of days the new technology is expected to save.

Many of the figures used to populate this section of the CBA were provided by experts from the oil industry during the workshop. To guard against any misjudgement by the experts, the sensitivity of the results to dramatic changes in some key variables is tested in the sensitivity analysis.

Present cost of servicing wells

For the purpose of this analysis we assume that 100 wells are serviced each year. Further, following the specialists' advice we assume that, at present, it requires 40 days to service a well. Finally, a realistic figure for the cost per day of servicing each well is US$ 40,000, giving a total yearly cost of US$160 million.

Expected savings from remote operations technology

Starting from the assumption that to service one well requires 40 days, two alternative assumptions are made in the CBA regarding the number of days that can be saved per servicing, based on consultations with specialists at the workshop. The upper estimate is that the new technology can save half of the previous time required (20 days), while the lower estimate is that one third of the time can be saved (13 days).

Timing of benefits and the share of the UK

Again, it is necessary to consider the expected timings of the benefits and the percentage of the total benefits that are expected to accrue to the UK. We assume that the benefits will begin to accrue to the UK from 2010 onwards, and to continue uniformly until the end of the analysis period in 2040.

5.2.3 Self repair coatings

Self repair coatings potentially mean drill bits do not need to be replaced. The potential benefits to the UK come from savings to UK oil firms in not having to trip-out and replace the drill bits in wells.

The level of the benefits depends on the number of drill bits that require changing each year, as well as the cost of each drill bit and the cost to change them. Again, figures used to populate this section of the CBA were provided by experts during the workshop with representatives from the oil industry.

Number of drill bits changed per year

Using estimates provided by industry specialists present at the workshop, we assume that 100 wells are provided with new drill bits each year. There are eight bits per well, so in total 800 bits are changed per year.

Cost per change

A price of US$ 50,000 per drill bit is used in the CBA, following advice from industry representatives. Further, following the same advice, the cost to make the change is assumed to be US$ 150,000, giving a total cost of US$ 400,000 per drill bit.

Timing of benefits

As in the previous two sections, the timings of the benefits and the percentage of the total benefits expected to accrue to the UK are relevant in the CBA. We assume that the benefits will begin to accrue to the UK from 2010 onwards, and to continue uniformly until the end of the analysis period in 2040.

5.2.4 UK share of the total benefits

It is important to consider whether all of the potential benefits are likely to flow to the UK, and if not what percentage of the total the UK is likely to receive.

The UK is not expected to capture all of the revenues from the exploitation of the Arctic Oil reserves. It is likely that more than one multinational company will be involved in extracting the oil, and therefore the proceeds will spread around the globe. In addition, the UK cannot expect to receive the entire benefits derived from the cost savings which result from the remote operations technology and self repair coatings. Hence, the CBA models a number of benefit scenarios.

Each of the sources of benefits analysed in the CBA (automation, remote operations and self repair coatings) are assigned weights to reflect the strength of the UK in these different technologies. The UK is assumed to have greater strength in remote operations, followed by automation and then self-repair coatings. The CBA models three different benefit scenarios whilst respecting these weights.[7] Scenario 1 represents a situation where very small proportions of the total benefits flow to the UK. Namely, 0.6% of the total benefit from automation flows to the UK, 1% of total benefits flow to the UK in remote operations and 0.4% for self repair coatings. Scenario 2 represents a situation where large proportions of the benefits accrue to the UK; 15% from automation, 25% from remote operations and 10% from self repair coatings. [8]

Percentage of total benefits accruing to the UK:

	Scenario 1	Scenario 2
Automation	0.6%	15%
Remote operations	1%	25%
Self repair coatings	0.4%	10%

---

[7] The weights which reflect the UK's strength in these different technologies are 1 for remote operations, because the UK is assumed to have the greatest strength in autonomous systems, 0.6 for automation and 0.4 for self-repair coatings.

[8] We also modelled two intermediate situations. Intermediate situation (a), assumed that the UK accrues 3% of the total benefits from automation, 5% from remote operations and 2% from self-repair coatings. Intermediate situation (b), assumed that 6% of the benefits from automation flowed to the UK, 10% from remote operations and 4% from self-repair coatings.

5.3 Net present values

Tables 7, 8 and 9 present the net present values in US dollars for the different scenarios tested.

In the low cost scenario for lunar drilling (Table 7), net present values become negative in the situation where no arctic oil can be extracted (in total), and when only a small percentage of benefits accrue to the UK from the automation, remote operations and self-repair coatings. In all other situations, for the low cost drilling scenario, the net present values are positive.

Table 8, presents the high cost lunar drilling scenario, and in this case we observe that net present values can be negative in situations where 25% of the oil in the arctic is extracted, and the percentage of benefits that accrue to the UK are low.

Table 9, presents the very high cost (with cost over run) lunar drilling scenario. In this case, we can observe net present value becoming negative irrespective of the percentage of oil that can be extracted from the arctic, and the benefits that accrue to the UK from automation, remote operations and self repair coatings are low.

Table 12: Net present values lunar drilling low cost scenario (£m)

Price of oil	**US$30 per barrel (£20)**		**US$40 per barrel (£26.7)**		**US$100 per barrel (£66.7)**	
Benefits scenario – percentage of benefits that flow to the UK	**Scenario 1**	**Scenario 2**	**Scenario 1**	**Scenario 2**	**Scenario 1**	**Scenario 2**
Low cost scenario = US$180 million (£120 million) between 2013 and 2018						
S:1,A: 50% arctic oil extraction in total and 50% cost savings per day from remote operations	183	6,474	266	8,549	764	21,004
S:2,A: 25% arctic oil extraction in total and 50% cost savings per day from remote operations	58	3,360	100	4,398	349	10,625
S:3,A: 0% arctic oil extraction in total and 50% cost savings per day from remote operations	-66	246	-66	246	-66	246
S:1,B: 50% arctic oil extraction in total and 33% cost savings per day from remote operations	181	6,413	264	8,489	762	20,944
S:2,B: 25% arctic oil extraction in total and 33% cost savings per day from remote operations	56	3,300	98	4,338	347	10,565
S:3,B: 0% arctic oil extraction in total and 33% cost savings per day from remote operations	-69	186	-69	186	-69	186

Table 13: Net present values lunar drilling high cost scenario (£m)

Price of oil	**US$30 per barrel (£20)**		**US$40 per barrel (£26.7)**		**US$100 per barrel (£66.7)**	
Benefits scenario – percentage of benefits that flow to the UK	**Scenario 1**	**Scenario 2**	**Scenario 1**	**Scenario 2**	**Scenario 1**	**Scenario 2**
High costs scenario = US$450 million (£300 million) between 2013 and 2018						
S:1,A: 50% arctic oil extraction in total and 50% cost savings per day from remote operations	64	6355	147	8431	645	20886
S:2,A: 25% arctic oil extraction in total and 50% cost savings per day from remote operations	-60	3241	-19	4279	230	10506
S:3,A: 0% arctic oil extraction in total and 50% cost savings per day from remote operations	-185	127	-185	127	-185	127
S:1,B: 50% arctic oil extraction in total and 33% cost savings per day from remote operations	62	6295	145	8370	643	20825
S:2,B: 25% arctic oil extraction in total and 33% cost savings per day from remote operations	-63	3181	-21	**4219**	228	10446
S:3,B: 0% arctic oil extraction in total and 33% cost savings per day from remote operations	-187	67	-187	67	-187	67

Note: The value in bold is the "most" likely NPV given discussion with space specialists.

Table 14: Net present values lunar drilling very high cost scenario (£m)

Price of oil	**US$30 per barrel (£20)**		**US$40 per barrel (£26.7)**		**US$100 per barrel (£66.7)**	
Benefits scenario – percentage of benefits that flow to the UK	**Scenario 1**	**Scenario 2**	**Scenario 1**	**Scenario 2**	**Scenario 1**	**Scenario 2**
Very high costs scenario = US$1.2 billion (£0.8 billion) between 2013 and 2024						
S:1,A: 50% arctic oil extraction in total and 50% cost savings per day from remote operations	-627	5663	-544	7739	-46	20194
S:2,A: 25% arctic oil extraction in total and 50% cost savings per day from remote operations	-752	2550	-710	3588	-461	9815
S:3,A: 0% arctic oil extraction in total and 50% cost savings per day from remote operations	-876	-564	-876	-564	-876	-564
S:1,B: 50% arctic oil extraction in total and 33% cost savings per day from remote operations	-630	5603	-546	7679	-48	20134
S:2,B: 25% arctic oil extraction in total and 33% cost savings per day from remote operations	-754	2490	-713	3527	-463	9755
S:3,B: 0% arctic oil extraction in total and 33% cost savings per day from remote operations	-879	-624	-879	-624	-879	-624

6 UK low cost launch technology programmes

The analysis in this chapter uses evidence from three examples of low cost launch technology development programmes currently being undertaken by UK organisations. These are the Skylon project by Reaction Engines Ltd., SpaceShip2 by Virgin Galactic and the Ascender/Spacebus staged development project by Bristol Spaceplanes Ltd. In each case, the technology being developed can be referred to as 'spaceplanes'. We first provide a brief overview of each programme, illustrating the past and (intended) future developments of the technology.

6.1 UK launch technologies

Skylon

The Skylon spaceplane was originally conceived as a direct replacement for expendable launch systems.

The intention is that the decrease in cost and increase in capability, availability and reliability will allow Skylon to provide an improved service to the 'conventional' launch market. Hence, Skylon is expected to be capable of replicating all of the functions currently performed by existing technologies, including launching satellites and supplying the International Space Station.

In addition to the conventional market, Reaction Engines have also developed a configuration for the payload bay which facilitates the integration of passengers to serve demand for public access to space.

In summary, the scope of Skylon's potential capability is very broad. However, completion of the work is expected to take around ten years.

SpaceShip2

Virgin Galatic is developing SpaceShip2, capable of lifting six passengers and two crew on a suborbital trajectory to altitudes in excess of 100km. The launch is performed over two stages: SpaceShip2 is initially carried to an altitude of 15.5km (50,000 feet) by a mother-ship, before being released and making the journey to space at a maximum altitude of 110km (360,000 feet).

Modifications to SpaceShip2 should enable it to place small payloads into useful orbits. Discussions between Virgin Galactic and Surry Satellite Technology Ltd (SSTL) concluded that satellites of mass between 10 to 100kg

(50kg on average) could be placed into orbits of 97° inclination (sun synchronous) at altitudes of between 400 and 800km.

Work on the design and construction of SpaceShip2 is well advanced. SpaceShip2 and WhiteKnight2, the mother-ship, will be unveiled in 2008, with 12-18 months of test flights before Virgin Galactic commence commercial flights.

Ascender/Spacebus

Bristol Spaceplanes' Ascender and Spacebus provides a 'staged' approach to developing reusable, low cost launch technology. The early stages of the programme developed the Ascender, a small sub-orbital spaceplane with two seats and capabilities limited to functions such as microgravity experiments, high altitude photography and meteorology. One purpose of the early stages is to generate early revenue streams before the full programme is completed.

The latter stages build on the earlier work to develop the SpaceBus which has greater and more wide ranging capabilities. Like Skylon, the Spacebus is expected to be able to replicate all of the functions currently performed existing rocket technologies.

6.2 Cost benefit analysis

The analysis draws on data relating to the three programmes outlined above to populate the CBA. Additional information was provided by a number of specialists in the field of spaceplanes and launch technologies, who took part in a workshop lead by London Economics and overseen by the BNSC. The specialists present at the workshop represent organisations involved in the development of the technology, and organisations involved in the industries that are expected to benefit from the technology in the future.

The costs included in the CBA arise from the investment needed to develop low cost launch technologies. The programmes currently being pursued in the UK put the UK in a leading position globally in the development of this type of technology. However, the investment required to complete the work is considerable.

The potential benefits to the UK arise from the ability to launch spacecraft at significantly lower cost than can currently be achieved, providing relatively inexpensive access to space for international governments, private companies and the public. Demand for these launch services is likely to come from a number of sources around the world, including the public and private sectors.

Demand for launch services already exists from some sectors, most significantly from governments and private companies that require satellites for communications and observation purposes and for space research. Other sources of demand are expected to grow alongside the development of the technology, as low cost access to space becomes a reality.

6.2.1 Costs

Our analysis of the cost of developing low cost launch technology is based on the three programmes currently being undertaken by UK organisations. The costs associated with each of these were estimated by leading participants closely involved in the programmes. The total estimated costs are:

- SpaceShip2: $300 million over six years (2009 to 2014)
- Skylon: $12 billion over ten years (2009 to 2018)
- Ascender/Spacebus: $90 million (Ascender) over four years (2009 to 2012), rising to $3.5 billion over seven years (2009 to 2015) (Spacebus)

Clearly these estimates vary considerably. Although the principal of the technology is the same in each case (to reduce the cost of access to space), the actual specifications of the projects are very different, which in turn determine what the space plane can do (as discussed in section 6.2), and these differences in specification lie behind the large variation in the cost estimates.

6.2.2 Benefits

Potential benefits arise from the opportunity to provide launch services to a number of industries and institutions, at significantly lower cost than current rocket technologies. The CBA focuses on a selection of important applications for low cost launch technology where information is available on the size of the benefits that could be achieved. In particular, the analysis focuses on:

- Potential revenues from space tourism (or public access):

  > The space tourism market refers to members of the general public who desire to visit space. Demand is expected to come from those wishing to visit space for pleasure, and those wishing to undertake work and research in space (e.g. university academics and students).

- Savings generated in the area of space services:

  > The availability of low cost options for launching spacecraft is likely to save space going nations significant costs from the civil space exploration budget, and to UK industries launching (large) satellites.

- Potential revenues from launching small-satellites:

According to research by Virgin Galactic and SSTL, the market for launching small-satellites (less than 500kg) shows an upward trend over recent years. This is attributed to the realisation that small, low-cost spacecraft can perform useful functions and be relied upon for operational missions. It is expected that the market will grow further as low cost launch options become more widely available.

- Potential revenues from micro-gravity manufacturing/research

  If the cost of access to space can be reduced sufficiently, then the prospective market for manufacturing and science research in a micro-gravity environment could be very large. Demand for this type of facility is likely to come from a number of industries, for example pharmaceuticals industry. However, in reality, it is very difficult to accurately estimate the actual size of the market.

Each of these sources of benefits are discussed in turn below.

Potential revenues from space tourism

The analysis of the potential revenue streams from space tourism uses evidence on the estimated global demand for space tourism at a range of ticket prices, as provided by a specialist participating in the workshop. At a ticket price of around $480 thousand annual demand is just 100 passengers, whereas if the price can be reduced to $27 thousand the market is about ten thousand passengers per year (Table 15 and Figure 2).

Estimates from experts involved in developing the launch technology indicate that a realistic ticket price that could be achieved is around $100 thousand. Hence, the CBA is carried out using two alternative ticket prices either side of this value: $150 thousand and $85 thousand per ticket. The corresponding levels of demands are 10,000 tickets or 100,000 tickets per year respectively, equivalent to annual market sizes of $1.5 billion or $8.5 billion.

Investment in low cost launch technology is likely to place the UK in a leading position in the future space tourism industry, as British companies and organisations utilise their first mover advantage in the market. However, the UK will still only capture a percentage of the revenues. Hence, in the CBA we vary our assumption about the proportion of the market that is served by UK providers as part of the sensitivity analysis, examining the outcomes when this value is taken to be 25%, 59% and 75%.

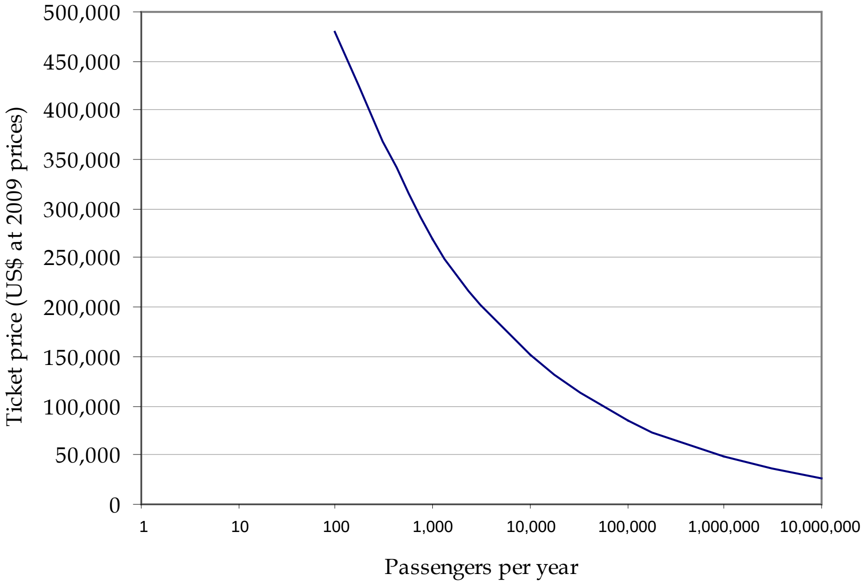
All of the current UK launch technology research programmes (described above) are expected to deliver technology capable of serving the public access market, so the potential revenues from space tourism are included in the CBA for each technology.

Table 15: Space tourism annual market size

Passengers per year	Ticket price (2009 $)	Market size (2009 $m)
100	478,801	48
1,000	269,250	269
10,000	151,410	1,514
100,000	85,144	8,514
1,000,000	47,880	47,880
10,000,000	26,925	269,250

Source: London Economics and BNSC low cost launch technology workshop January 2009.

Figure 2: Space tourism demand and ticket prices.



Source: London Economics and BNSC low cost launch technology workshop January 2009.

Savings generated in the area of space services

Reducing the cost of launching spacecraft is likely to save space going nations millions of dollars from future civil space exploration budgets. In addition, UK industry stands to save even greater sums as a result of cheaper space services, such as cheaper launch costs of communications satellites. Estimates provided by specialists present at the workshop indicate that the overall spend on space activities would drop by two thirds. For the civil space programme this represents a saving of $150 million, whilst the estimated potential savings for UK industry are around $800 million.

In practice, the savings that can be achieved depend on the specifications and capabilities of the technology that is developed, and these factors vary between the three launch technology programmes discussed above.

On the one hand, Skylon and SpaceBus are anticipated to have wide ranging capabilities and are assumed to be able to serve the needs of the civil space exploration agenda and the requirements of UK industry. Hence, the CBA assumes that the savings described above are achieved in these cases, at rates of 20%, 60% and 100% in order to test the sensitivity of the results to this aspect.

On the other hand, representatives from the SpaceShip2 and Ascender programmes indicated that civil space exploration and large scale industrial functions are not target applications for these technologies. Hence, although in practice a small percentage of these benefits may be realised, they are omitted from the CBA for these cases.

Potential revenues from launching small-satellites

The market for launch vehicles for small satellites has been evaluated by Virgin Galactic and SSTL. The research examined the potential customer base for launching satellites of mass around 100kg at a price of $5,000/kg. The investigation concluded that the market comprises around 15 spacecraft per year of average weight 100kg, plus around 85 spacecraft per year of average weight 1-5kg. Thus, the CBA assumes an overall market size of $8.6million per year.[9]

Each of the three current UK programmes is expected to develop technology capable of serving this market. Hence, the potential revenues are included in the CBA for each of the programmes, at rates of 50%, 75% and 100% in order to test the sensitivity of the results to this benefit.

Potential revenues from micro-gravity manufacturing/research

All of the experts consulted for this analysis agreed that the prospective market for manufacturing and science research in a micro-gravity environment is potentially very large if the cost of access to space can be reduced sufficiently. However, it was also noted that it is very difficult to accurately estimate the potential size of this market in reality.

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[9] 5000x((100x15)+(2.5x85)) = 8,562,500.

Estimates from one specialist placed the size of the market at $300-600 million, and in the CBA we use the midpoint of this range ($450 million) as a starting point. However, due to the highly speculative nature of these estimates, the sensitivity analysis examines a wide range of outcomes where the size of the market captured by the UK is assumed to take a range of alternative values.

Two import sources of uncertainty to consider are:

- First, the value of the market and the proportion of the market captured by the UK may differ from value estimated by the expert;

- Second, not all of the technologies under development are capable of serving the entire market.

To account for the first, we make three alternative assumptions in which the UK captures 20, 60 and 100 percent of the market. Further, because of the high degree of uncertainty, we examine a fourth scenario where none of these benefits are realised by the UK.

To account for the second source of uncertainty, we make different assumptions about the size of the market which can be served by the four different technologies. We assume that Skylon and SpaceBus can serve the whole ($450 million) market, as these technologies have the most wide ranging technical capabilities. We assume that SpaceShip2 and Ascender can serve only serve markets worth $100 million and $45 million respectively. These figures are based on information provided by representatives from Virgin Galactic and BSS.

Finally, given the size of the market and the UK's involvement, there is still uncertainty over how quickly the market will expand after low cost access to space becomes available. Two scenarios are considered in the CBA. The first scenario assumes the up-take of micro-gravity manufacturing and research by industry is 'quick', growing from zero to the maximum, steady level over just four years following completion of the technology. The second scenario assumes that the up-take by industry is 'gradual' and this period is more prolonged, taking ten years in all.

6.3 Net present values

Due the large differences in the technical specifications, costs and potential applications, the results are presented separately for each of the four technological developments considered in the CBA (Skylon, SpaceShip2, Ascender and Spacebus). For each case, we present the time-discounted present values of the costs and the benefits. Further, we also present and the net present value of developing each technology under four scenarios: the worst-case, pessimistic, optimistic and best-case scenarios. These scenarios are defined by the following assumptions about the benefits:

Worst-case scenario: The realised benefits correspond to *25%* of the space tourism market at a ticket price of *$150 thousand*; *20%* of the total potential savings to the civil space programme and space services to British industry; *50%* of the market for launching space satellites; and *zero* revenues from micro-gravity manufacturing and research.

Pessimistic scenario: The realised benefits correspond to *25%* of the space tourism market at a ticket price of *$150 thousand*; *20%* of the total potential savings to the civil space programme and space services to British industry; *50%* of the market for launching space satellites; and *20%* of the total potential revenues from micro-gravity manufacturing and research, under the assumption of *gradual up-take* by industry.

Optimistic scenario: The realised benefits correspond to *50%* of the space tourism market at a ticket price of *$150 thousand*; *60%* of the total potential savings to the civil space programme and space services to British industry; *75%* of the market for launching space satellites; and *60%* of the total potential revenues from micro-gravity manufacturing and research, under the assumption of *gradual up-take* by industry.

Best-case scenario: The realised benefits correspond to *75%* of the space tourism market at a ticket price of *$85 thousand*; *100%* of the total potential savings to the civil space programme and space services to British industry; *100%* of the market for launching space satellites; and *100%* of the total potential revenues from micro-gravity manufacturing and research, under the assumption of *quick up-take* by industry.

6.3.1 Skylon

Costs

Present value of the development costs: £6,851m

Benefits

Table 16: Potential revenues from space tourism (public access) (£m)

	Percentage of global public access market captured by the UK		
Ticket Price	**25%**	**50%**	**75%**
$150,000	2,743	5,487	8,230
$85,000	15,427	30,853	46,280

Note: All figures are present values (discounted at the Green Book recommended rate of 3.5%).

Table 17: Savings generated in the areas of the civil space programme and space services used by British industry (£m)

Source of cost saving	**Percentage saving achieved**		
	20%	**60%**	**100%**
Civil space programme	217	652	1,087
British industry space services	1,160	3,479	5,798
Total	1,377	4,131	6,885

Note: All figures are present values (discounted at the Green Book recommended rate of 3.5%).

Table 18: Potential revenues from launching small-satellites (£m)

	Percentage of global market captured by the UK		
Total market size	**50%**	**75%**	**100%**
$8.6 million /yr	31	47	62

Note: All figures are present values (discounted at the Green Book recommended rate of 3.5%).

Table 19: Potential revenues from micro-gravity manufacturing/research (£m)

Up-takes of micro-gravity services	Percentage of potential revenues realised (total = $450m)		
	20%	60%	100%
Quick up-take	566	1,697	2,828
Gradual up-take	480	1,439	2,399

Note: All figures are present values (discounted at the Green Book recommended rate of 3.5%). A fourth scenario assumes that none of these revenues are realised

Net Present Value

Table 20: Net Present Value of costs and benefits for Skylon (£m)

Scenario	Cost	Benefit	Net Present Value
Worst-case	6,851	4,151	-2,699
Pessimistic	6,851	4,631	-2,220
Optimistic	6,851	11,104	4,253
Best-case	6,851	56,055	49,204

6.3.2 SpaceShip2

Costs

Present value of the development costs: £183m

Benefits

Table 21: Potential revenues from space tourism (public access) (£m)

	Percentage of global market captured by the UK		
Ticket Price	25%	50%	75%
$150,000	2,743	5,487	8,230
$85,000	15,427	30,853	46,280

Note: All figures are present values (discounted at the Green Book recommended rate of 3.5%).

Savings generated in the areas of the civil space programme and space services used by British industry: No savings (as discussed above the specifications for SpaceShip2 do not allow the space craft to provide these services).

Table 22: Potential revenues from launching small-satellites (£m)

Total market size	Percentage of global market captured by the UK		
	50%	**75%**	**100%**
$8.6 million /yr	31	47	62

Note: All figures are present values (discounted at the Green Book recommended rate of 3.5%).

Table 23: Potential revenues from micro-gravity manufacturing/research (£m)

Up-takes of micro-gravity services	Percentage of potential revenues realised (total = $100m)		
	20%	**60%**	**100%**
Quick up-take	164	491	818
Gradual up-take	142	425	708

Note: All figures are present values (discounted at the Green Book recommended rate of 3.5%). A fourth scenario assumes that none of these revenues are realised

Net Present Value

Table 24: Net Present Value of costs and benefits for SpaceShip2 (£m)

Scenario	Cost	Benefit	Net Present Value
Worst-case	183	2,774	2,591
Pessimistic	183	2,916	2,733
Optimistic	183	5,958	5,775
Best-case	183	47,160	46,977

Note: All figures are present values (discounted at the Green Book recommended rate of 3.5%).

6.3.3 Ascender

Costs

Present value of the development costs: £57m

Benefits

Potential revenues from space tourism (public access): No revenues, specifications to not allow the technology to provide this service.

Savings generated in the areas of the civil space programme and space services used by British industry: No savings, as above specifications to not allow the technology to provide this service.

Table 25: Potential revenues from launching small-satellites (£m)

	Percentage of global market captured by the UK		
Total market size	**50%**	**75%**	**100%**
$8.6 million /yr	31	47	62

Note: All figures are present values (discounted at the Green Book recommended rate of 3.5%).

Table 26: Potential revenues from micro-gravity manufacturing/research (£m)

Up-takes of micro-gravity services	**Percentage of potential revenues realised (total = $45m)**		
	20%	**60%**	**100%**
Quick up-take	83	249	415
Gradual up-take	72	217	362

Note: All figures are present values (discounted at the Green Book recommended rate of 3.5%). A fourth scenario assumes that none of these revenues are realised

Net Present Value

Table 27: Net Present Value of costs and benefits for Ascender (£m)

Scenario	**Cost**	**Benefit**	**Net Present Value**
Worst-case	57	31	-26

Table 27: Net Present Value of costs and benefits for Ascender (£m)

Scenario	Cost	Benefit	Net Present Value
Pessimistic	57	104	47
Optimistic	57	264	207
Best-case	57	478	421

Note: All figures are present values (discounted at the Green Book recommended rate of 3.5%).

6.3.4 SpaceBus

Costs

Present value of the development costs: £2,102m

Benefits

Table 28: Potential revenues from space tourism (public access) (£m)

	Percentage of global market captured by the UK		
Ticket Price	**25%**	**50%**	**75%**
$150,000	2,743	5,487	8,230
$85,000	15,427	30,853	46,280

Note: All figures are present values (discounted at the Green Book recommended rate of 3.5%).

Table 29: Savings generated in the areas of the civil space programme and space services used by British industry (£m)

	Percentage saving achieved		
Source of cost saving	**20%**	**60%**	**100%**
Civil space programme	217	652	1,087
British industry space services	1,160	3,479	5,798
Total	1,377	4,131	6,885

Note: All figures are present values (discounted at the Green Book recommended rate of 3.5%).

Table 30: Potential revenues from launching small-satellites (£m)			
	Percentage of global market captured by the UK		
Total market size	**50%**	**75%**	**100%**
$8.6 million /yr	31	47	62

Note: All figures are present values (discounted at the Green Book recommended rate of 3.5%).

Table 31: Potential revenues from micro-gravity manufacturing/research (£m)			
Up-takes of micro-gravity services	**Percentage of potential revenues realised (total = $450m)**		
	20%	**60%**	**100%**
Quick up-take	566	1,697	2,828
Gradual up-take	480	1,439	2,399

Note: All figures are present values (discounted at the Green Book recommended rate of 3.5%). A fourth scenario assumes that none of these revenues are realised

Net Present Value

Table 32: Net Present Value of costs and benefits for SpaceBus (£m)			
Scenario	**Cost**	**Benefit**	**Net Present Value**
Worst-case	2,102	4,151	2,049
Pessimistic	2,102	4,631	2,529
Optimistic	2,102	11,104	9,001
Best-case	2,102	56,055	53,953

Note: All figures are present values (discounted at the Green Book recommended rate of 3.5%).

7 In-situ resource utilisation (ISRU) and titanium production

In this chapter we present a case study for the FFC-Cambridge Lunar ISRU process. The FFC process was discovered by a Cambridge University team. The FFC process separates titanium from its oxide using electro-deoxidisation. The main innovation is the FFC "inert anode" which facilitates the electro-deoxidisation process.

The innovation is patented by a UK firm called Green Metals/British Titanium.[10]

7.1 Mapping the benefits and costs of ISRU and titanium

The fundamental FFC process can potentially be used to produce oxygen from Lunar and Martian regolith for rocket propulsion and human outposts on the Moon and Mars.[11]

Significant by-products of the FFC ISRU process include metal alloys arising from the regolith. In the case of the lunar equator, where ilmenite is abundant, a form of ferro-titanium would be produced which could potentially provide structural materials for building in extra-terrestrial environments and thereby further facilitate future exploration of the solar system. The ability to make simple metal objects offers an important safety feature to lunar inhabitants. We do not consider the supply of structural alloys on the moon in this report.

The potential benefits and costs to the UK economy of early investment in the FFC process for oxygen generation on the moon are investigated. The potential benefits of titanium production on earth are also explored.

7.2 The FFC ISRU process

The FFC ISRU process for oxygen generation on the moon is currently at TRL 2 to 3.[12] The following activities have already been undertaken:

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[10] There is currently a legal process underway to determine the patent ownership. We do not make any comment on this legal process.

[11] The recent discovery of water ice on Mars should allow simple electolysis of water to generate oxygen.

- The inert anode has been identified and run for extended periods of time without degradation.
- A design for a lunar furnace (within which the electro-deoxidisation of lunar regolith can take place) has been prepared
- The chemistry process using lunar regolith containing Fe and/or Mg, and called JCS1[13], has been thoroughly researched and oxygen generation efficiencies have been illustrated and peer reviewed

7.3 Potential benefits and costs from ISRU oxygen generation on the Moon

There are two main steps to develop the FFC ISRU process for lunar use. These are the following:

- ☐ An ISRU characterisation stage which can develop the technology to from TRL 2/3 to TRL 5;[14] and,
- ☐ A demonstration mission taking the technology from TRL 5 to TRL 7

7.3.1 ISRU Characterisation

Table 33 maps the ISRU characterisation stage. It is important to map each step of characterisation in order to identify the flow of costs and benefits. The characterisation steps were identified for the purpose of this study at an ISRU Focus Group held on the 19th November 2008,[15] a follow-up discussion on the 21st November and written information provided by the FFC ISRU team (Green Metals Ltd and Cambridge University).

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[12] TRL is Technology Readiness Level, a technology management tool that underpins technology road mapping by providing a tangible indication of the maturity of interdependent technologies.

[13] This is lunar stimulant containing lunar ilmenite and was provided by NASA to the FFC team.

[14] TRL is Technology Readiness Level. The TRLs are reproduced in the appendix to this report.

[15] Participants at the ISRU focus group were, Professor Derek Fray of Cambridge University, Iain Crawford of University College London, Rodney Buckland, Jeremy Curtis BNSC, James Hamilton Green Metals Limited and Charlotte Duke London Economics.

Table 33: FFC ISRU Characterisation

Characterisation stage	Benefits	Benefits timing	Costs	Costs timing	Uncertainties
Phase 1 (duration 12 months): Experimental scale					
Full review of existing technologies and relevant literature. Development of project through study of existing technologies and comparisons with other projects using Ilmenite feedstock Test FFC process using anorthositic feedstock Identification of optimal materials for construction to ensure space qualification. Design small scale FFC reactors for laboratory experimentation. Procure materials and systems for construction. Construct reactors Test durability of components, analyses of oxygen for purity using anorthositic feedstock	Results to be published in international forum. Benefits derived include: ☐ UK Knowledge, world class innovation published in international forum ☐ World class research lead by UK institution ☐ UK knowledge generation about space qualified construction materials which is then transferred to other nations ☐ Engagement of early career researchers (early post-docs) in innovative research in the UK ☐ Encourage inflow of world class skills from other nations to the UK ☐ ISRU technology at TRL 2/3 - TRL 4	Year 1 Indirect benefits of increased skill base in the UK, development of world class research in UK institutions and inflow of skilled labour is accrued over an unlimited time period	Year 1 cost estimate £1 million	Year 1	Has been peer reviewed and accepted for publication – no uncertainty. Using ilmenite the FFC process (at experimentation scale) is world class Does the process work at sufficient efficiencies with minerals that have no Fe and/or Mg? See box 1 below for further explanation. How long will identification of optimal materials through literature review and experimentation take? Can the optimal construction material for space qualification be identified? Can durability be achieved i.e. anode current life-span is 5 months? Is oxygen purity sufficient for human consumption and/or rocket propulsion?

Table 33: FFC ISRU Characterisation

Characterisation stage	**Benefits**	**Benefits timing**	**Costs**	**Costs timing**	**Uncertainties**
Phase II (36 months): Upscale process and validation in a space relative environment					
Study of operating conditions to which a life size prototype will need to adhere Numerical development for computer aided design and simulation of FFC reactor Materials selection for internal components at space qualification levels Life size reactor design Determine automation and process control, design and implementation of complex control systems Construction of prototype Experimentation and, data collection and process optimisation	❑ World class knowledge and skills developed in the UK ❑ Inflow of world class knowledge and skills to the UK ❑ Training of next generation world class scientists in the UK ❑ Cross-collaborations between ISRU reactor designers and UK firms that can produce automated control process ❑ Publication of knowledge in international peer reviewed forums Technology at TRL 5	Years 2 and 2 Indirect benefits of increased skill base in the UK, development of world class research in UK institutions and inflow of skilled labour is accrued over an unlimited time period	Year 2 , 3 and 4 cost estimate £4 million, £ 4 million and £1 million respectively	Year 2 and 3	High uncertainties but no greater than other cutting edge research. Uncertainties include, Sustained operation can be illustrated in severe conditions re-created in the NASA Lunar Chamber. Automated process control model can be developed and constructed Automated process can be integrated with reactor and operate under lunar conditions.

Box1: Anorthite

The FFC ISRU process has been demonstrated to work in a small scale terrestrial laboratory setting using JSC1, a lunar regolith stimulant supplied by NASA that contains ilmenite (Ilmenite can contain the following compounds on earth $(Fe,Mg,Mn,Ti)O_3$*).*

If lunar landing zones are in the lunar sea areas, then lunar ilmenite can be used as a feedstock for the FFC ISRU process because the regolith in the lunar sea areas contains Fe and Mg minerals.

However, future lunar outposts will most likely be located at the south pole highlands, and ilmenite (and/or Fe/Mg minerals) are not present in highland regolith, instead regolith at the poles contains anorthositic minerals $(CaAl_2Si_2O_8)$*. Therefore, it is important that any lunar ISRU process can also use anorthositic regolith which predominately contains anorthite.*

Professor Fray has explained that FFC electro-deoxidation is remarkably tolerant to input and that anorthosites can be processed into an alloy of calcium, aluminium and silicon metals with the liberation of oxygen. Such an alloy is brittle and has no commercial application in everyday terrestial use however in a lunar environment different considerations apply.

(Information provided by Iain Crawford of University College London).

7.3.2 ISRU Demonstration

If the FFC ISRU process can be developed to TRL 5 in the short run, say by 2010 to 2013, then it will be possible to move to TRL 7 where the related systems can also be tested, such as autonomous rovers for collection of regolith and transport of regolith to the FFC reactor under lunar conditions. The technology could then be included in a demonstration mission. If a demonstration mission can be successfully completed, at an estimated total cost of £300 million over seven years starting in 2015 (if solely funded by the UK), then the following benefits may accrue to the UK economy in the future.[16]

Rocket propulsion on the moon

If oxygen can be generated in-situ, then the weight of rockets could be reduced because oxygen would not need to be carried from the earth to the moon for the return journey. The amount of oxygen that must be carried to

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[16] Professor Fray's team is confident it can demonstrate the FFC ISRU process within such a timeframe. The team received a contract from NASA for such work and completely removed the oxygen from JSC1, receiving a letter at the end of the first year's work saying it had "exceeded expectations".

the moon for the return trip is 9.4 tonnes using the Altair lunar lander (cargo version).[17]

The estimated cost of transporting 1 tonne of oxygen to the moon is between US$25 million[18] and $ 100 million[19].

The oxygen cost of one return trip is therefore between US $ 235 million and $ 940 million.

It is estimated that there may be between four and six return trips per year to the moon from 2020.[20] Therefore, ISRU requirements for rocket propulsion will be between 37.6 tonnes and 56.4 tonnes per year.[21]

If the transportation of oxygen for return journeys can be eliminated through the development of an ISRU process then the cost of each trip to the moon can potentially be reduced by the following amounts:

- ☐ If four trips are made then between US$ 940 million to $ 3,760 million
- ☐ If six trips are made then between US$ 1,410 million to $ 5,760 million

These ranges provide an estimate of the upper value of oxygen on the lunar surface for rocket propulsion. These estimates can therefore be (very loosely) used as an estimate of space nations' maximum willingness to pay for oxygen on the lunar surface.

It is unlikely that all revenue from oxygen production on the lunar surface will accrue to the UK. Other nations will probably receive a portion of these revenues because, for example, the integrated systems including autonomous rovers for collection of regolith and transport of regolith to the FFC reactor under lunar conditions, will in part be supplied by other space nations. In order to account for this sharing of revenues we decrease the expected UK revenue from oxygen supply by 50%.

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[17] Estimate from Bob Parkinson's model and provided by Rodney Buckland.

[18] Estimate from Bob Parkinson's model and provided by Rodney Buckland.

[19] Estimate provided at the ISRU focus group meeting.

[20] Estimates from Bob Parkinson's model,

[21] From, (9.4t*4 = 37.6) and (9.4t*6 = 56.4)

Human outpost on the moon

If it is assumed that to support a four person permanent outpost on the moon one to five tonnes of oxygen per year is required.[22]

It is likely, however, that assuming human boots land on the moon in 2020, then human stays on the moon will initially be of short duration, 14 – 30 days, and according to NASA enough oxygen can be taken to the moon for these short visits. For tractability we assume that from 2020 there will be demand of one to five tonnes of oxygen on the moon for a human outpost from ISRU processing.

The possible upper value range of ISRU oxygen for human support is therefore between US $ 25 million to $ 100 million if one tonne per year is required, to US $ 125 million to $500 million if five tonnes is required. We again reduce this revenue estimate by 50% for the reasons outlined above.

Benefits of ISRU oxygen production for exploration on the moon and beyond

If oxygen can be generated in a lunar environment, then opportunities for robotic and human scientific exploration of the moon will be expanded. The value of increased knowledge generated by exploration is difficult to value and could potentially have unlimited benefits. Further, the use of ISRU oxygen could facilitate robotic and human exploration beyond the moon to Mars and other parts of the solar system, again this is very difficult to value and could be unlimited (e.g. discovery of life). The ability to generate oxygen on the moon is an economic advantage in planetary exploration. Because of the moon's lesser gravitational pull it makes financial sense to use the moon as a staging post for journeys to Mars and elsewhere as smaller rockets can be deployed.

7.4 Risks of ISRU production

The main risk of ISRU oxygen production on the moon is if there is water in ice at the lunar south pole in commercially meaningful quantities. If there is water at the lunar south pole then there may be cheaper ways of providing oxygen as compared to an electro-deoxidisation process. Currently NASA does not know if there is water under the moon's surface.[23] However, for exploration beyond the polar region ISRU may be the preferred choice as it

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[22] Note, this is required to support a only portion of the human requirements. The estimate is taken from an operating assumption for a NASA model run by Chris Colvert of NASA; we have not been told what the assumed proportion is but NASA has promised to report their assumptions to Jeremy Curtis. We have no know time line of if or when NASA will report back.

[23] Point raised by Iain Crawford at the ISRU Focus Group.

could be difficult to transport water or oxygen from the poles to other locations on the lunar surface.

The next main risk is the efficiency of oxygen production using anorthite. As discussed above in Box 1, anorthite is the material at the lunar south pole and therefore will be the most likely feedstock as opposed to ilmenite. The electro-deoxidation of the anorthite mineral can be readily demonstrated at laboratory scale.

7.5 Potential benefits and cost from titanium production on earth

The fundamental FFC process can be used to produce titanium. Titanium is a substitute for steel. The current processes for producing titanium is the Kroll process and is higher in cost as compared with the estimated cost of producing titanium by the FFC process. A main factor in production cost is that while Kroll titanium is made from expensive titanium tetrachloride, the FFC process runs on cheaper precursors.

There are significant benefits to the environment as well: Kroll is a pollutive process; steel, stainless steel and aluminium are all generators of greenhouse gases on a scale well in excess of 1 billion tonnes per annum. FFC, in contrast, emits oxygen when fitted with the novel anode invented by Drs Fray and Doughty and patented by Green Metals. There are secondary benefits to widespread titanium use for such applications as transport: vehicles made from titanium would be significantly lighter than those made from steel, and would use smaller engines and be less pollutive.

The following estimates for the costs and benefits of titanium production using the FFC process have been supplied by Green Metals. These figures are commercially confidential and must not be reported outside of the project steering group.

The FFC process removes oxygen from metal oxides and holds the following Unique Selling Points:

- Cheaper feedstock such as natural rutile (a mineral found on beaches)
- The product does not contain impurties (Kroll titanium contains magnesium chloride)
- Fewer processing steps are needed to produce finished goods
- Non-melt process for alloy production.

London Economics has been shown estimates of Profit and Loss for a commercial scale FFC smelter. This estimate provides for the production of four different titanium products.. These are:

1. FeTi. The easiest alloy to process, used as a grain refiner in steel production. Oxygen levels are not critical
2. Ti-6Al-4V. This is the workhorse alloy of the titanium industry providing outstanding strength to weight rations and is widely used in aerospace.
3. Pure CP. Pure titanium that is used for its high resistance to corrosion in applications such as chemical plants.
4. Rutile-based titaniu alloy. A novel alloy designed to compete in price with stainless steel that will find many applications in use such as vehicle parts, armour for fighting vehicles and for the construction of naval vessels. Also in domestic applications such as kitchens, pots and pans etc.

These are all substitutes for existing titanium products (which in turn are substitutes for steel

Price of titanium

FeTi has a current spot price of US$ 8,800 per tonne. The FFC process can potentially produce FeTi at US $8,818 per tonne. Therefore, the FFC process can produce FeTi at the same price as current methods; if we assume that the spot price is a good proxy for the cost of production.

Ti6Al4V has a current spot price of US$ 34,100 per tonne. The FFC process can potentially produce Ti6Al4V at $ 22,046 per tonne. Therefore, the FFC process can potentially produce this alloy at 35% less per tonne; assuming the spot price is a good proxy for the cost of production

Pure CP has a current spot price of $ 11,340 per tonne. The FFC process can potentially produce CP at $ 9,921 per tonne. Therefore, the FFC process can potentially produce this anti-corrosive substance at 13% less per tonne; again assuming the spot price is a good proxy for the cost of production.[24]

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[24] The following information has been provided by Green Metals on the price of titanium: Metal prices in general have fallen sharply in price since the credit crisis; the paralysis in world trade will continue to distort supply and demand. Titanium is no exception. Titanium is unusual amongst metals markets as it exhibits two distinguishing features: it is extremely price inelastic, and metal is separated into two categories. One is metal with established provenance used for aerospace and is sold to the likes of Rolls-Royce under long term contract. Then there is a spot market where no provenance exists and where the metal is used from non-critical applications such as golf clubs or bicycle frames. Until recently there were only 8 titanium producers worldwide and contract details and production costs have been guarded closely. This contrasts to the mature metals like copper traded on the terminal

The rutile alloy is a new substance and therefore there is no current spot price. For now we leave this new alloy out of our analysis.

Potential market size for titanium

The estimated world consumption for FeTi, Ti6Al4V and Pure CP are as follows:

- FeTi has a current world consumption of 50,000 tonnes
- World consumption of Ti6Al4V is 40,000 tonnes
- Pure CP has a world consumption of 60,000 tonnes

World industry revenue

The potential world industry revenue is as follows:

- FeTi using both current technology and the FFC process at current spot price has a potential world industry revenue of approximately $ 440,000,000 if 50,000 tonnes is consumed.
- Ti6Al4V using current technology has a potential world industry revenue of $1,364,000,000, and using the FFC process it is $881,849,049 if 40,000 tonnes is consumed and we assume that world demand does not increase as price decreases.
- Pure CP using current technology has a potential world industry revenue of $ 680 400 000, and using FFC process it is $ 595,248,108; again assuming world demand is constant as prices change.

UK industry revenue

If it is assumed that UK industries using the FFC process capture 10% of world demand then UK industry revenue could potentially be the following:

- FeTi at $44,000,000

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markets.

Titanium prices are probably 30% plus lower than levels pre-crunch. While no cancellations have been made by airlines for the new generation of airliners, aerospace demand accounting for half the total titanium demand may survive better than other metals. Demand for industrial applications may benefit from a backlog of oil industry orders for a while. However the rapid expansions of Chinese Kroll production is a negative factor and spot prices are likely to fall towards marginal cost.

- Ti6Al4V at $88,184,905
- Pure CP at $ 59,524,811

These three estimates assume that demand remains constant as prices change.

Benefits to the UK economy

It is very unlikely that production of titanium using the FFC process will happen in the UK. The FFC smelters are more likely to be built overseas. Given the smelters will be located abroad, the following categories of benefits could accrue to the UK:

- Wages to UK workers for head office administration
- Profits to UK registered companies from production abroad
- Tax receipts to UK government on UK registered companies' profits
- Revenues to downstream UK firms providing high tech inputs to the FFC process (assuming the anode production is located in the UK)

Environmental benefits

The FFC process has carbon emissions of zero per tonne of titanium produced; the process only emits oxygen. Steel has an estimated carbon emission of 1.5 tonnes per tonne of steel produced. If it assumed that world steel production is 1.4 billion tonnes per year (Green Metal's estimate), and if the price of a tonne of carbon is $20 in the permit market, then the carbon cost per year of steel production is $42 billion.

If it is assumed that the FFC process for titanium substitutes for 2% of the steel market, then the carbon savings for the world can be valued at $ 840 million. This saving cannot be claimed, however, by the UK economy as the smelters will most likely be located outside of the UK. This benefit is therefore not included in the cost benefit analysis.

Other benefits from FFC titanium production

The FFC titianium production process is not anticipated to be commercial until 2023. Between 2009 and 2023 there is a "gestation" period. This period will involve further research, and this research can generate the following categories of benefits for the UK:

- Increased prestige of British science
- Increased sponsorship to British universities
- Increased stock of human capital in the sciences in the UK
- Knowledge transfer to UK companies
- Employment during the research stage

Further flow-on benefits

If titianium can be produced at a lower cost using the FFC process then possible new uses for the titanium include:

- British armed forces could possibly have access to lower cost titanium which could provide stronger combat vehicles.
- Medical instruments could be constructed with the titanium, and they may be more hard wearing and lighter.

7.6 Cost benefit analysis

The above information is analysed using the HM Treasury Green Book approach to appraisal. In this appraisal we incorporate the benefits and costs that can be valued in monetary terms. The non-monetary benefits such as increased prestige of British science and increase stock of human capital in the UK is not included as these benefits are extremely difficult to value, and instead should be considered in a qualitative way as above (sections 7.3 and 7.5).

7.6.1 Incorporating the benefits into the cost benefit the model

To incorporate the benefits of ISRU oxygen on the moon we do the following:

- Propulsion: We take the two estimated costs of transporting one tonne of oxygen from the earth to the moon. As stated above, the estimated costs are $25 million and $100 million per tonne. We then use the assumption that there will be either four or six return trips to the moon per year from 2020. In order for a rocket to launch from the moon and return to earth, it needs 9.4 tonnes. Therefore, the value of demand in today’s dollars for oxygen on the moon for propulsion is between US$940 million – US$ 3,760 million or US$ 1,410 million -

US$ 5,760 million. We then make the assumption that the UK may supply either one quarter, one sixth or one tenth of the demand for oxygen for propulsion.

- Human outpost: We again take the two estimated costs of transporting oxygen to the moon, and we assume that from 2020 either 1 or 4 tonnes of oxygen will be required per year. Therefore, the value of demand in today's dollars is between US$25 million - $100 million or US$125 million and $500million. As for propulsion, we assume that the UK supplies either one quarter, one sixth or one tenth of the demand for oxygen for human habitation.

To incorporate the benefits of titanium production on earth we do the following:

- We use the values provided by Green Metals/British Titanium. We take the price of titanium using Green Metal's technology and we multiply this price by the world demand for titanium. We then assume that UK registered firms supply 10% of the world demand and this provides an estimate of the revenue share for UK registered firms. However, not all of this revenue will accrue to the UK economy. This is because the titanium smelters are likely to be established outside the UK. If the smelters are located outside the UK then a portion of the revenue, for UK registered firms, will flow to the host economies. Therefore, using information provided by Green Metals we make the following assumptions about the share of revenue that may flow to the UK economy:
  - 0.3% of revenue goes to UK workers because we assume that the UK registered firms have their head office in the UK.
  - 20% of revenue is paid as company tax to the exchequer by the UK registered firms
  - A portion of revenue accrues to the shareholders of the UK registered firms as net profit (after tax). These net profit estimates were provided by Green Metal and are 42% for FeTi, 13% for Ti-6Al-4V and 37.5% for pure CP (see section 7.5 for a discussion of the thee titanium products).
  - 1.4% of revenue goes to UK suppliers who are assumed to produce the inert anode, a crucial input to the titanium process.

  The effect of these assumptions is that the portion of revenue that flows into the UK economy is the following:
    - FeTi, 55% of revenue flows into the UK economy

- Ti-6Ai-4V, 65% of revenue flows into the UK economy
- Pure CP, 48% of revenue flows into the UK economy

It is important to note that we have accounted for the direct impact of ISRU and titanium. In other words, we have not included the multiplier impacts of an increase in revenue accruing to UK firms which then stimulates additional expenditure and growth in other sectors of the economy.

7.7 Cost benefit values

In the table below we present the net present values for ISRU and titanium. We present a number of different scenarios to show how the net present values may change. These scenarios are the following:

- ❑ The UK may supply either one quarter, one sixth or one tenth of the total yearly oxygen demand on the moon
- ❑ Four oxygen demand scenarios are included for both the low cost estimate ($25 million) and the high cost estimate of transportation ($100 million). These demand scenarios are listed in the table below.
- ❑ Three different cost scenarios are included. These are the reported costs, reported costs +50% and reported costs + 100%

The net present value for ISRU and titanium is positive in most cases. In fact it is very large, in the billions of US dollars, for the high cost scenario for oxygen transportation. This is because the benefit of producing oxygen on the lunar surface is very high if transportation costs to the moon are high.

The net present value becomes negative as the benefit of producing oxygen on the moon decreases (as the cost of transportation decreases), as the reported costs increase and as the UK’s supply share of lunar oxygen decreases. This can be seen in the darker shaded cells in the table below.

ISRU for oxygen on the moon could therefore be a very lucrative investment for the UK. The UK has the technology which is world class, and the linkages with world class institutions such as NASA, the US Department of Defence and ESA. If the UK’s technology can contribute to the supply of oxygen on the moon then the UK could potentially benefit, and those benefits could be very large.

Table 34: Net Present values ISRU (£m)

Benefits	**Costs (UK supplies 1/4 of lunar oxygen requirements)**			**Costs (UK supplies 1/6 of lunar oxygen requirements)**			**Costs (UK supplies 1/10 of lunar oxygen requirements)**		
	Reported costs	**Reported costs + 50%**	**Reported costs +100%**	**Reported costs**	**Reported costs + 50%**	**Reported costs +100%**	**Reported costs**	**Reported costs + 50%**	**Reported costs +100%**
Low oxygen carry cost ($25millon/tonne)									
▪ 4 return trips per year and 1 tonne of oxygen for human habitation	686	299	-77	337	-49	-426	58	-329	-705
▪ 4 return trips per year and 5 tonnes of oxygen for human habitation	795	408	31	410	23	-354	102	-285	-662
▪ 6 return trips per year and 1 tonne of oxygen for human habitation	1,196	809	**432**	677	290	-86	262	-125	-501
▪ 6 return trips per year and 5 tones of oxygen for human habitation	1,304	917	541	749	363	-14	306	-81	-458
High oxygen carry cost ($100 million/tonne)									
▪ 4 return trips per year and 1 tonne of oxygen for human habitation	3,826	3,439	3,062	2,430	2,043	1,667	1,314	927	551
▪ 4 return trips per year and 5 tonnes of oxygen for human habitation	4,259	3,872	3,496	2,900	2,513	2,137	1,488	1,101	724
▪ 6 return trips per year and 1 tonne of oxygen for human habitation	5,864	5,477	5,101	3,789	3,403	3,026	2,130	1,743	1,366
▪ 6 return trips per year and 5 tones of oxygen for human habitation	6,298	5,911	5,534	4,259	3,872	3,496	2,303	1,916	1,540

Note: The above assumes a long term discount rate of 3.5% and a general inflation rate of 2.0%. Figure in bold is the most likely NPV from discussions with space specialists.

8 Lunar Communications and Navigation

8.1 Cost-benefit analysis

Potential benefits to the UK arise from involvement in the development of lunar communications architecture and the provision of communication services for future lunar exploration. The international vision for lunar exploration begins with unmanned 'landers' and robotic science during the next decade, and culminates in a permanently manned outpost in the mid-2020's to 2030. There is potential for UK involvement in the development and provision of the essential lunar communications at each stage of the exploration programme.

The cost-benefit analysis (CBA) considers among the costs the investment required to design, build and launch lunar communications infrastructure and equipment. Following this investment in the communications technology, future benefit streams arise from the provision of communication services for manned and unmanned missions to the moon and future lunar outposts.

Many of the figures used to populate the CBA were provided by experts from the space technology and communications industries during a forum lead by London Economics and overseen by the BNSC.[25] Although any predictions about the future of lunar communications are inherently uncertain for obvious reasons, the estimates used in this analysis are the most informed opinions available. Further, a sensitivity analysis is used to test the robustness of the results to dramatic changes in some key variables.

8.2 Future lunar exploration and communications

The CBA is based on the following vision of lunar exploration and communication requirements, as presented by specialists from the space industry who participated in the forum:

> Ground stations on Earth: An international network of ground stations will be required to communicate with transceivers on the lunar surface, with one station based in the UK.
>
> Transceivers on the lunar surface: Unmanned landers carrying instruments will be placed on the moon by member countries of the International Lunar Network[26] (ILN), requiring six transceivers on the lunar surface by 2015.

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[25] The forum involved representatives from EADS Astrium, Qinetiq, Orbit Research, Goonehilly New Ventures, The University of Plymouth, HPD Ltd, The Open University and Logica.

[26] Current ILN members are USA, Canada, UK, Germany, France, Italy, Japan, India and Korea. China and Russia are

Lunar communications relay satellites: An initial relay satellite for communication between Earth and the lunar infrastructure will be launched in 2015. Subsequently, the number of relay satellites required will increase to as many as five by 2027, in parallel with development of lunar science missions and manned outposts. For the purposes of the CBA, we assume that the number will increase steadily with one additional relay satellite each year until 2027.

8.3 Costs

Each of the elements described above carry their own costs and potential benefits. Here we address the costs associated with each in turn.

Ground stations

An important element of the UK's possible involvement in future lunar communications is the potential to host one of an international network of ground stations for communications with the lunar infrastructure. According to specialists currently involved in operating similar facilities who were present at the forum, such a ground station would require an initial investment in the region of £55 million in today's prices, including £5 million to convert the receiver and £50 million in the general investment in the facility. For the purposes of the CBA this investment is assumed to be evenly spread over the period from 2010 to 2015.

Following the initial investment, the facility would require £5 million each year in running costs, including around 40 technical staff paid an average salary £50 thousand per year.

Transceivers on the lunar surface

The production cost of each transceiver is cautiously estimated by industry experts at around £10 million, though the actual figure could be half this amount. The CBA assumes that these costs are spread evenly over a three year period. As mentioned above, it is predicted that six transceivers will be on the lunar surface in 2015. Following the launch of each transceiver, they will require up-keep and maintenance at a cost of £1 million per year per transceiver. Further, the transceivers have a lifespan of five years at which time they must be 'renewed' at the same cost as the initial production (£10million in today's prices).

Lunar communications relay satellites

According to the predicted future lunar exploration activities that form the basis of the CBA, the first relay satellite will be launched in 2015. The design, build and launch

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not participating.

costs of each relay satellite were estimated to be around £200-300 million in today's prices at the forum of industry specialists, depending on whether low cost launch technologies are successfully developed.

This is the most costly element of the communications architecture. For this reason the CBA calculates the net present value of the programme using a low cost estimate (£200 million per relay satellite) and, separately, a high cost estimate (£300 million per relay satellite). These two alternative cost estimates form part of the sensitivity analysis for the CBA.

8.4 Benefits

The potential benefits accruing to the UK from the investments presented above come from the provision of communications services using the ground station and the relay satellites. For each of these assets the underlying assumptions and potential revenue streams are described below, as are several sensitivity analyses to test the robustness of the results to key variables.

The average traffic of data from the lunar infrastructure to Earth and between the lunar surface and relay satellites is predicted by NASA to reach 325 mega-bits per second (Mbps) when the lunar outpost is established. For purposes of the CBA we make the conservative assumption that this will be achieved by 2030. Prior to this, the average traffic required is predicted to be 15Mbps at the lunar human return phase in 2018 and we assume that the traffic will increase uniformly until it reaches the lunar outpost level. Finally, we assume that the average traffic rises uniformly from 2010 until 2018, with a demand of 1Mbps in 2010.

Ground stations

According to the estimates of experts participating in the forum who are currently involved in running similar operations, the ground station will generate revenues of £10 million per year in today's prices during the early phases of lunar exploration before manned missions to the moon. Once manned missions have commenced and safety becomes a high priority the revenues are predicted to double. For the CBA we assume that manned missions will commence after 2020.

Lunar communications relay satellites

The potential revenues generated for the UK from the satellite relays depend on the rate that can be charged for transferring data. Industry representatives involved in the forum stated that Earth orbiting satellites charge around £200,000 per year for each Mbps of capacity. Due to the vastly increased distances involved. We use an assumption provided by the same specialists that, due to the vastly increased distances involved, the charge rate between Earth and the lunar infrastructure will be twenty times the rate for Earth orbiting satellites, or £4 million per year for each Mbps of capacity.

However, in order to test the sensitivity of the results of the CBA to the charge rate for satellite relays we include five alternative rates in the sensitivity analysis: £1, 2, 3, 4 and 5 million per year for each Mbps of capacity.

Although it is well placed to play a leading role, the UK may not service all of the required data traffic, or the levels of data traffic demanded may not be as high as those predicted. Hence, the sensitivity analysis also tests the sensitivity of the CBA results to a range of different demand level for average data traffic. Using the demand levels described above as a starting point, these are multiplied by 0.25, 0.5 and 0.75 to simulate below expected demand from UK providers, and multiplied by 1.25 to simulate above expected demand.

8.5 Net present value

The expected costs and benefits from investment in lunar communications technology over the period 2010 to 2040 generate the net present values shown in Table 35 under the range of alternative scenarios in the sensitivity analysis:

Table 35: Net present values: Sensitivity analysis (£m)					
Cost estimates and charge rates	**UK provision of communication services: Percentage NASA's estimated total requirement**				
	25%	**50%**	**75%**	**100%**	**25% over estimate**
Low cost estimate - £200m design, build and launch per relay					
£1m/Mbps	-191	418	1,027	1,636	2,246
£2m/Mbps	418	1,636	2,855	4,073	5,292
£3m/Mbps	1,027	2,855	4,683	6,510	8,338
£4m/Mbps	1,636	4,073	6,510	8,947	11,384
£5m/Mbps	2,246	5,292	8,338	11,384	14,082
High cost estimate - £300m design, build and launch per relay					
£1m/Mbps	-540	69	678	1,288	1,897
£2m/Mbps	69	1,288	2,506	3,725	4,943
£3m/Mbps	678	2,506	4,334	6,162	7,989
£4m/Mbps	1,288	3,725	**6,162**	8,599	11,036
£5m/Mbps	1,897	4,943	7,989	11,036	14,082

Note: The figure in bold is the "most likely" NPV from discussions with space specialists.

The net present value for almost all scenarios tested is positive. Net present values become negative when the portion of communication requirements supplied by the UK is lower, and the charge rate per Mbps is low. These scenarios are highlighted in grey in Table 35.

9 Autonomous robots

The development of autonomous robot technology could potentially lead to benefits in a very broad range of areas as the new technology feeds into many aspects of people's everyday lives and the economy.

At a high level, three *areas* where it is possible that autonomous robots will play an important future role are in manufacturing, as robots have the potential to cut costs and make UK industry significantly more competitive, directly in our everyday lives, as personal and service robots become more common in our homes, and in the supply of utilities such as water and power. However, identifying all the potential uses for robots and estimating the likely extent of their usage is an extensive and challenging exercise. Hence, for this CBA we focus on a narrower set of likely uses for autonomous robots. These are, firstly, the role of robots in manufacturing in the food processing sector, secondly, the market for personal and service robots and, thirdly, the use of robots in decommissioning and clean-up of the UK's nuclear power plants.

9.1 Benefits of the robotics technology

The benefits we consider in the CBA are food manufacturing, personal and service robots and decommissioning of the UK's nuclear power plants. These benefit areas were identified by specialists at the Robotics Workshop conducted for this project in January 2009.

9.2 Market for household robots

Current published figures indicate that the size of the world wide market is estimated to be £4.34 billion in terms of sales in 2009, and is expected to grow to £5.27 billion in 2010. By 2025 the value of the industry is predicted to be worth £10.67 billion.[27] The expected benefit to the UK from research into autonomous robots, as part of the space exploration programme, is that the knowledge developed will lead to technology transfer into the terrestrial economy, allowing the UK to increase its share of this global market. We examine three scenarios, where the increase in the UK's share of the personal and service robots market, stemming from the research programme, follows three different paths over time:

Scenario 1: The UK share of the world market for personal robots is 0.005% in 2022, and increases to 0.075% by 2028, and is assumed to remain at this level up to 2040.

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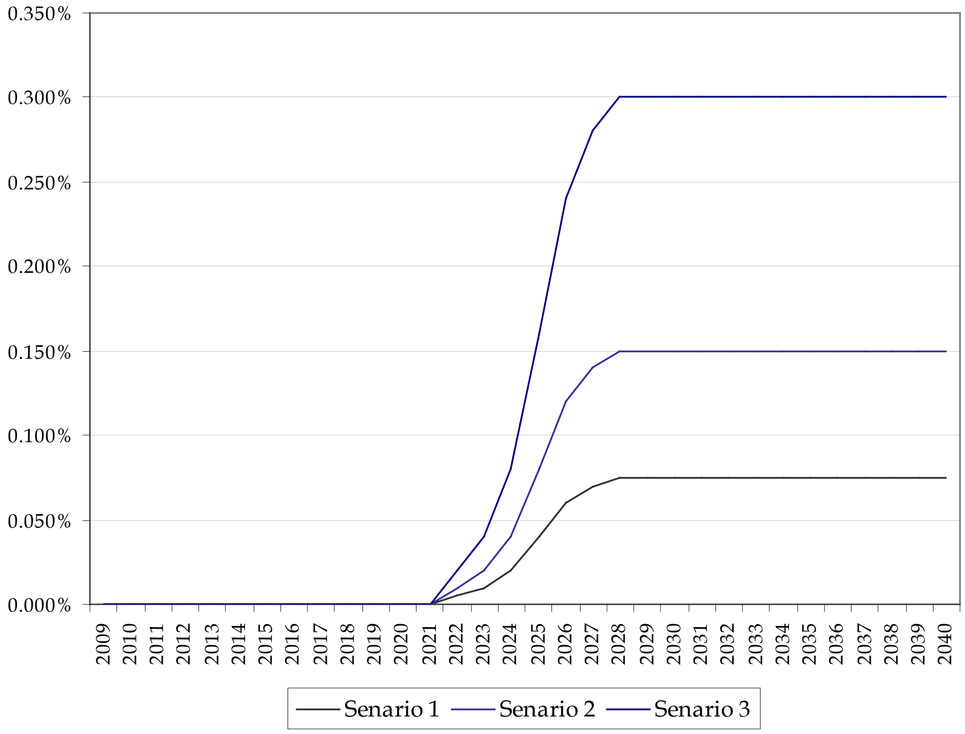
[27] This data was published by "Robotics Trends", an integrated media firm serving the personal, service and mobile robotics market place. They provide publishing, conferences and market analysis. http://www.roboticstrends.com/about/ . The data is reported in US dollars, we use the exchange rate of £ = $1.5.

Scenario 2: The UK market share is 0.01% in 2022, and increases to 0.1% by 2028, before remaining at this level.

Scenario 3: The UK share increases by 0.02% in 2022, and is 0.3% by 2028, before remaining at this level.

Note that the increase in the UK share of the global market in Scenario 1 is half that in Scenario 2, which is half that of Scenario 3.

Figure 3: Alternative CBA assumptions: Increase in the UK global market share of service and personal robotics



9.3 Cost savings for the UK food processing sector

Mr Wilson, Chairman of the British Automation and Robotics Association, emphasised the growing overseas competition, rising energy costs and labour shortages the UK food industry is now facing. He said: “UK manufacturing is in decline and unless the food sector invests in new technology it will go the same way”.

Robot density (the number of robots installed per 10,000 production workers employed in manufacturing industry) in the UK is just 44 compared to Germany at 171, France 84 and Spain at 89.[28]

Robotic solutions offer significant advantages over manually operated processes within the industry and can protect employees from the hazards of extreme temperatures, repetitive strain, and back injuries.

The size of the UK food and drink industry is estimated to be £64 billion in turnover per year, providing an ex-factory cost of £48 billion.[29] Labour costs are 15% of the ex-factory cost and it is assumed that autonomous robots can induce labour savings, in relation to ex-factory costs, of the following:

Scenario a: 10% cost saving

Scenario b: 5% cost saving

Scenario c: 1% cost saving

Scenario d: 0.5% cost saving

9.4 Servicing and decommissioning nuclear power stations

Robots can play a role in the servicing and decommissioning of nuclear power stations in the UK. Remote intervention in high radiation areas can reduce the time it takes to undertake service and thereby reduce shut-down periods. Further, robotics can extend the life of existing assets and promote new more efficient designs as the power stations can be built for remote repairs and maintenance. Simple advantages such as the removal of the need to shield electronics from radiation away from the remote device, and the removal of the need for umbilical cords for control which in-turn can reduce the time, contamination and waste associated with general maintenance. The use of micro-electronics designed for robotic exploration is adaptable to the extreme environments within nuclear power stations.

We use three scenarios for the cost of decommissioning:

Scenario i: £90.75 billion between 2009 and 2029 in nominal prices

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[28] Reported at the Robotics Workshop, London, January 2009.

[29] Estimate provided by specialists at the workshop, January, 2009.

Scenario ii: £63.5 billion (reported by the Nuclear Decommissioning Authority, NDA), again in nominal prices between 2009 and 2029.

Scenario iii: The NDA also reports a present value cost which is £49.822 billion discounted at 2.2% (Note: we use a discount rate of 3.5% in the cost benefit analysis following the HM Treasury Green Book guidelines).

We assume that robots can decrease these costs by 0.5%.

9.5 Costs of the robotics research programme

The costs of the robotics technology is uncertain at this time. Therefore we use a proxy for these costs which is taken from a BNSC workshop conducted late in 2008. The estimated cost for the research programme is £333 million from 2016 to 2024.[30] We then double these costs and quadruple these costs (over the same time period) in order to observe how the net present values change as costs increase.

9.6 Net present values

Using the benefit scenarios outlined above for household robots, UK food processing and the decommissioning of nuclear power stations we observed that the main driver of the change in net present values for robotics is labour cost savings to the UK food sector, and the cost of the robotics research programme. We therefore present the net present values for the food sector on its own, and then we add the benefits for household robots using scenario 2, and then (separately) the benefits for nuclear decommissioning using scenario ii. We only include one scenario for the household robots and nuclear decommissioning because these benefits were assessed as less well known as compared to the food sector benefits. We elected to use scenario 2 and ii, as they are the middle estimate for the benefits, and therefore are not over or under optimistic.

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[30] The proxy is the cost of a pressurised exploration rover (1/3 contribution by the UK).

Table 36: Net present values UK Food Processing Industry (£ millions)

	Cost scenario 1 £333million (nominal value) **Or, £171.4million present value**	**Cost scenario 2 £333million*2 = £666million (nominal value)** **Or, £442.8 million present value**	**Cost scenario 3 £333 million*4 = 1.3billion (nominal value)** **Or, £685.7 million present value**
Labour saving at 10%	5,799	5,628	5,285
Labour saving at 5%	2,814	**2,642**	2,299
Labour saving at 1%	425	254	- 88

Therefore, as the costs of the robotics programme increases and as the labour savings that accrue to the UK food sector decrease the net present values decline.

Table 37: Net present value UK Food Sector plus Household/Service Robots (£ millions)			
	Cost scenario 1 £333million (nominal value) **Or, £171.4million present value**	**Cost scenario 2 £333million*2 = £666million (nominal value)** **Or, £442.8 million present value**	**Cost scenario 3 £333 million*4 = 1.3billion (nominal value)** **Or, £685.7 million present value**
Labour saving at 10%, and UK market share of worldwide service robot market 0.01% in 2022 increasing to 0.15% in 2028	5,874	5,703	5,360
Labour saving at 5%, and UK market share of worldwide service robot market 0.01% in 2022 increasing to 0.15% in 2028	2,889	2,717	2,374
Labour saving at 1%, and UK market share of worldwide service robot market 0.01% in 2022 increasing to 0.15% in 2028	500	329	-13.5

When the benefit from the household/service robotics market is included we do not see a large change in the NPVs as compared to the food industry alone.

Table 38: Net present value UK Food Sector plus Nuclear Decommissioning (£ million)

	Cost scenario 1 £333million (nominal value) **Or, £171.4million present value**	**Cost scenario 2 £333million*2 = £666million (nominal value)** **Or, £442.8 million present value**	**Cost scenario 3 £333 million*4 = 1.3billion (nominal value)** **Or, £685.7 million present value**
Labour saving at 10%, decommissioning costs at £63.5 billion and a 0.5% saving.	5,821	5,650	5,307
Labour saving at 5%, decommissioning costs at £63.5 billion and a 0.5% saving	2,836	2,664	2,322
Labour saving at 1%, decommissioning costs at £63.5 billion and a 0.5% saving	448	276	- 66

When we include nuclear decommissioning we do not see a large change in the net present values.

10 Space Medicine

The economic model of the benefits of space related medical research for standard, terrestrial healthcare is based upon the idea that similar technology drivers exist for space medicine as for intensive care and acute care in terrestrial medicine. If the technology developed for space medicine could reduce the time that patients need to remain in intensive care, or avoid intensive care unit admission altogether then this will led to significant cost savings for the health service.

In addition, another area where significant cost savings could arise from space medicine technologies is in the expenditure on caring for hip fracture patients among the elderly. The physiology of space flight parallels that of ageing in terms of muscle, bone and cardiovascular deteriorations and all of these contribute to falls in the elderly. Hence, discovering measures to limit or prevent these aging processes will significantly reduce the incidence of hip fractures.

Thus the CBA models the benefits accruing to the UK from space related medical research as cost savings on certain activities undertaken by the NHS. The areas where cost savings are expected to arise, modelled in the CBA, are intensive care, acute care and hip fractures amongst the elderly. These are addressed in turn in the following subsections.

Many of the figures used to populate the CBA were provided by experts in space and terrestrial medical research who participated in a workshop lead by London Economics and overseen by the BNSC. These experts were able to provide informed opinions as well as some data relevant to the CBA. Finally, a sensitivity analysis is used to test the robustness of the results to changes in key variables.

10.1 Savings on the economic cost of hip fractures

The economic cost to the UK of hip fractures among the elderly is estimated by researchers at the University of York (Parrot, 2000) to be approximately £865m per year.[31] In addition, according to Parrot around 21 thousand hip fracture patients return home each year. Using a conservative estimate given by Parrot, we assume that 5% of those that return home following hip fractures then require full time care from a relative. This indicates that just over a thousand members of the UK population give up employment to care for hip fracture victims. Multiplying this figure by the average annual wage (£24,900) provides an estimated cost to the UK economy from lost

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[31] Parrot.S., 2000, *The economic cost of hip fractures in the UK*, The University of York for The Department of Trade and Industry.

productivity equal to almost £27m per year.[32] Thus, the total cost the UK of hip fractures among the elderly is around £891m.

Spin-off technologies from medical research as part of the space exploration programme are likely to lead to savings in the cost of hip fractures because the research aims to find solutions to maintaining muscle and bone mass in zero gravity environments. According to experts present at the workshop, the techniques discovered during the research could then be applied in terrestrial medicine to prevent muscle and bone loss in the elderly, which are primary causes of hip fractures (because weak muscles lead to falls and frail bones are prone to breakages).

Techniques for maintaining muscle and bone mass are expected to be a direct outcome of the space medical research programme, so the CBA models the potential savings in this area as quite high (relative to the savings which might be achieved in other areas). However, to avoid overstating the potential benefits the CBA still uses a conservative estimate, assuming that savings of 2% of the total cost (£891m) could be made as a result of the research. This equates to savings of just over £17.2m per year.

10.2 NHS savings on intensive care

In most intensive care patients, illness has resulted in severe dysfunction or failure of one or more vital organs but these are often treatable and potentially reversible. Intensive care medicine provides the technology to support the failing organs and the time and means to treat the underlying illness. It is high technology, life-saving care that interacts with all areas of a hospital.

The cost per intensive care bed per day is £2,000, and the average stay in intensive care is 11 days.[33] The Journal of the Intensive Care Society places annual admissions to intensive care at 71,000. Hence, the total cost of intensive care in the UK is estimated at around £1.4bn per year.

Spin-off technology from medical research as part of the space exploration programme is likely to lead to NHS savings in intensive care on account of its applicability in a wide variety of aspects of intensive care. For example, non or minimally invasive telemetry technology and lightweight, robust diagnostic and therapeutic equipment are likely to assist significantly in the diagnostic process.

Based on information provided by experts present at the workshop, the CBA models the impact of the spin off technologies resulting from the space medical research as a cost saving of 0.5% of the total expenditure on intensive care.

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[32] The average annual wage is taken from data reported by the Office of National Statistics.

[33] This is corroborated by evidence from Bennett Bion (1999), who estimate the cost per bed day to be up to £1,800 in 1999, equal to just over £2,000 in today's prices (Bennett D, Bion J. ABC of intensive care: organisation of intensive care. British Medical Journal, 1999; 318:1468-70)

10.3 NHS savings on acute care

Acute illnesses refer to diseases with an abrupt onset and usually a short course. Some acute illnesses, such as those caused by viruses, require no medical attention, while others can be cured by antibiotics or other medical treatment. At present, around 20% of the NHS budget is spent on acute care, or around £18bn annually.

Parallels exist between the technology drivers for space medicine and terrestrial acute care medicine. Specifically, improved diagnostic techniques developed for space medicine could be applied in terrestrial acute illness diagnosis to improve the procedure of referral to doctors.

However, as acute care is a much broader area of activity than either hip fractures or intensive care, the likely technology spin-offs of space medicine are expected to be less focused on the specific problems within acute care. Hence, following the guidance of the experts present at the workshop, the CBA models the cost savings to the NHS in the area acute care as 0.1% of the current total spend, or £18m annually.

10.4 Costs

The CBA models the cost of space medicine research as using example technologies presented by experts at the workshop. One area of research on which the costs are based is non or minimally invasive telemetry, whilst the other is the development of techniques to limit or prevent of muscle, bone and cardiovascular deterioration.

For non/minimally invasive telemetry the cost to develop and produce a neurological platform to flight level is $3m. Following this, in the region of a further $20m would be required to adapt the space neurological platform for use at primary health care level and as a general-purpose medical device. The additional costs cover those for highly developed software algorithms, or 'artificial intelligent' aspects, and clinical trials to develop, prove and refine these algorithms. In the CBA, these costs are converted to sterling using an exchange rate of 1.5 US$ to the pound, giving a total cost of £15.3m.

Additional costs will be incurred by the management and engineers at NASA or ESA, but there is little evidence on the size of these costs (probably in the region of $2m) and most have already been covered by NASA. Hence, they are not included in this CBA.

For the development of techniques to limit or prevent muscle, bone and cardiovascular deterioration the experts at the workshop indicated that the total cost can be broken down into three elements: 1) identifying the molecular target, 2) whole body physiology research and 3) developing the technology of terrestrial medical applications.

The experts stated that by far the greatest cost is incurred in the first step (identifying the molecular target), which is expected to cost around £12.5m. The costs for the other two steps take 10% of this value in the CBA.

10.4.1 CBA cost scenarios

The figures presented above suggest that a suitable base line cost for the research is around £30.3m.

However, it is unlikely that all research projects in the field will yield spin-off technologies which are applicable in terrestrial medicine. Multiple projects may be undertaken until spin-off technologies are discovered, meaning that the overall cost will multiply. Hence, we apply a rigorous sensitivity analysis on the cost of the research.

Specifically, we include the following five cost scenarios in the CBA, with different durations and total final costs:

- Scenario 1: Base line cost (£30.3m), spread over 4yrs
- Scenario 2: Base line cost multiplied by 2, spread over 4yrs
- Scenario 3: Base line cost multiplied by 5, spread over 10yrs
- Scenario 4: Base line cost multiplied by 10, spread over 10yrs
- Scenario 5: Base line cost multiplied by 20, spread over 20yrs

10.5 Timing of spin-offs

According to the experts participating at the workshop, the terrestrial spin-off technologies are likely to occur well in advance of the completion the space research programme. The experts agreed that a reasonable period before any spin-offs could be expected is 20% of the time required for the full research programme.

To remain consistent with the five cost scenarios of the CBA, the research programmes are modelled as lasting (alternatively) four, ten or twenty years, and the spin-offs (and the corresponding benefits) are modelled as occurring after 20%, 60% and 100% of these times.

10.6 Net present values

The Net Present Values corresponding to the various scenarios analysed in the space medicine CBA are presented in Table 39 below.

Table 39: Net Present Value (£m)			
	Proportion of research undertaken before spin-off occurs		
Cost scenario	**20%**	**60%**	**100%**
Scenario 1	725	684	608
Scenario 2	696	656	580
Scenario 3	583	**435**	307
Scenario 4	453	306	177
Scenario 5	199	-58	-251

Annex 1 Surveyed organisations

Table 40 presents the list of organisations interviewed as of the end of November 2008.

We have interviewed 24 different organisations and 32 different space specialists.

Table 40: Stakeholder interviews

Organisation	**Interviewees**	**Space product or service**
Astrium	Matthew Stuttard Ralph Cordey	systems of systems engineering (human capital) Autonomous navigation - speckle velocimetry and 3D imaging Radio isotope thermal generators (Nuclear power) Asteroid impact mitigation
Logica	David Iron Phil Bustin	Consumption products (DNA on moon) Lunar Drilling
Qi3	Nathan Hill	Energy - generation, storage, use and scavenging Autonomous transport Network sensors
Imperial	Mark Sephton	Designer solvents for tar sand oil extraction
SEA	Chris Chaloner	Planetary protection Laser Imaging Human decision aides Networked sensors
SciSys	Chris Lee	Software for autonomous vehicles
U of Leicester	Mark Sims	Autonomous vehicles Spectral Imaging Organics extraction Radio-isotope power sources Primary Partnerships Space - encouraging STEM in primary school students Data transfer - data compression algorithms Integrated diagnostics
Virgin Galactic	Will Whitehorn	Composite materials Science experiments in microgravity Astronaut training Specialised fire fighting
SSTL	Martin Sweeting Adam Baker	low cost satellites Lunar communications (broadband)
UCL	Kevin Fong	Human life support and monitoring systems Information management systems
Bristol Spaceplanes	David Ashford	Low cost Human and Robotic access to space, re-usable flight vehicles
	Bob Parkinson	Solar power

Table 40: Stakeholder interviews

Organisation	Interviewees	Space product or service
		Nuclear power Systems of systems engineering Magnetic image processing (vision for autonomous vehicles)
MSSL at UCL	Alan Smith Peter Muller	Systems of systems engineering Lunar probes Laser Imaging (LIDAR)
Shadow Robot Co.	Michael Pollitt	Dexterous manipulator technology
British Titanium/Green Metals	James Hamilton	Generation of oxygen in a lunar environment Titanium
RUR Robotics	Geoff Pegman	Advanced robotics
Fluid Gravity	James Beck	aerothermal dynamics thermal protection systems
OU	Andrew Holland	Fuel quality monitoring using x-ray instrumentation Synchrotron radiation facility detectors Bio-medical instrumentation
ABSL	Rob Spurrett	Battery technology
Clyde Space	Craig Clark	Battery technology
Excalibur Almaz	Chris Stott	Earth orbit tourism
Qinetiq	Rob Scott	MOD research (can't get access)
Space adventures		Space tourism
Open University	Vice Chancellor John Zarnecki Simeon Barber Andrew Holland	GCSM technology for tuberculosis
STFC	Ruth Bamford	Mini magnetospheres

Annex 2 First round qualitative assessment

Business opportunities shaded Green, have been assessed in the first round qualitative assessment as definite or most promising candidates for further investigation. Opportunities shaded orange have been assessed as possible. Opportunities shaded red have been assessed as unlikely for further study.

Programme investment assumptions	Strategic Programme options	Product/service	Position in space supply chain	Position in (terrestrial) recipient sector supply chain	Timing for Spillover	Risk to market		Potential (terrestrial) customers	Information availability for estimating space costs of product Y, N	Access to potential users (final and suppliers) Y, N	Size/significance in terrestrial economy	Potential for further study
		Space product/service	Upstream input Downstream final product	Upstream input Downstream final product	From now, Short-term = 2 - 3years, Medium term = 4 - 6 years, Long-term = 7 - 10 years, Very Long-term 11+ yrs	Innovation environment - linkages with terrestrial users and knowledge transfer processes high, medium, low	Demand drivers - why may terrestrial users want the product strong, medium, weak	Industry, Government, households	Information from Space industry suppliers	Users outside space industry - both final product users and suppliers to terrestrial industries	High, Medium, Low	proposed given stakeholder consultation to date
Status quo programme investment	Exploitation of UK's involvement in robotic missions of the ESA Mandatory Scientific Programme	Postgraduate and industrial training	Downstream - human capital transfer from space specialists	Upstream - training of human capital for use in terrestrial applications	Short-term	high	Potentially strong - transfer of skills to terrestrial industrial organisations	Industry	Y - MSSL	Y -list provided by MSSL for contacts	Medium	Definite
Programme investment assumptions	Strategic Programme options	Product/service	Position in space supply chain	Position in (terrestrial) recipient sector supply chain	Timing for Spillover	Risk to market		Potential (terrestrial) customers	Information availability for estimating space costs of product Y, N	Access to potential users (final and suppliers) Y, N	Size/significance in terrestrial economy	Potential for further study

		Space product/service	Upstream input Downstream final product	Upstream input Downstream final product	From now, Short-term = 2 - 3years, Medium term = 4 - 6 years, Long-term = 7 - 10 years, Very Long-term 11+ yrs	Innovation environment - linkages with terrestrial users and knowledge transfer processes high, medium, low	Demand drivers - why may terrestrial users want the product strong, medium, weak	Industry, Government, households	Information from Space industry suppliers	Users outside space industry - both final product users and suppliers to terrestrial industries	High, Medium, Low	proposed given stakeholder consultation to date
	ESA Mandatory Scientific Programme	fuel quality monitoring (NDA signed with user),	unknown	unknown	medium-term	High	Unknown	unknown	N (NDA agreement signed)	N	Unknown	Unlikely (NDA signed)
		synchrotron radiation facility detectors	unknown	unknown	short-term	High	Unknown	unknown	unknown	unknown	Unknown	Unlikely, we have limited information at this time
		Detection: Laser Illumination for detection and ranging (LIDAR)	Downstream - remote life detection system	Downstream – remote detection system	Medium-term	Medium	Strong - science monitoring on earth and potentially oil industry (i.e. identifying oil slicks as source of oil) and international property rights determination in arctic	Industry and Government	Yes – MSSL	Yes -via MSSL	High	Strong Candidate
Programme investment assumptions	Strategic Programme options	Product/service	Position in space supply chain	Position in (terrestrial) recipient sector supply chain	Timing for Spillover	Risk to market		Potential (terrestrial) customers	Information availability for estimating space costs of product Y, N	Access to potential users (final and suppliers) Y, N	Size/significance in terrestrial economy	Potential for further study

		Space product/service	Upstream input Downstream final product	Upstream input Downstream final product	From now, Short-term = 2 - 3years, Medium term = 4 - 6 years, Long-term = 7 - 10 years, Very Long-term 11+ yrs	Innovation environment - linkages with terrestrial users and knowledge transfer processes high, medium, low	Demand drivers - why may terrestrial users want the product strong, medium, weak	Industry, Government, households	Information from Space industry suppliers	Users outside space industry - both final product users and suppliers to terrestrial industries	large, medium, small	proposed given stakeholder consultation to date
Status quo programme investment	Robotic exploration of Mars	**Robotics:** Autonomous robots	Final product - integration of all technology required for an autonomous vehicle	Final product - integration of technology required for an autonomous vehicles	Long-term	high	strong -search and rescue	Government	Possible - if MOD willing to reveal costs	Possible - MOD	Potentially large - substitute for human driven search and rescue vehicles	Low - confidentiality issues may arise from MOD
		Robotics: dexterous hands	Upstream - component of an autonomous vehicle	Upstream - autonomous vehicles i.e. bomb management/explosion and management of nuclear energy generators	Medium term	high	Potentially strong - i.e. MOD, also nuclear energy generators	Industry and government (MOD)	Yes - Shadow Robotics	Yes - via Shadow Robotics	Potentially large - substitute for human bomb diffusion and nuclear power station management	Definite
Programme investment assumptions	Strategic Programme options	Product/service	Position in space supply chain	Position in (terrestrial) recipient sector supply chain	Timing for Spillover	Risk to market		Potential (terrestrial) customers	Information availability for estimating space costs of product Y, N	Access to potential users (final and suppliers) Y, N	Size/significance in terrestrial economy	Potential for further study

		Space product/service	Upstream input Downstream final product	Upstream input Downstream final product	From now, Short-term = 2 - 3years, Medium term = 4 - 6 years, Long-term = 7 - 10 years, Very Long-term 11+ yrs	Innovation environment - linkages with terrestrial users and knowledge transfer processes high, medium, low	Demand drivers - why may terrestrial users want the product strong, medium, weak	Industry, Government, households	Information from Space industry suppliers	Users outside space industry - both final product users and suppliers to terrestrial industries	large, medium, Low	proposed given stakeholder consultation to date
	Robotic exploration of Mars	**Robotic Navigation**: Speckle velocimetry (laser navigation similar to a computer mouse)	Upstream - input to autonomous navigation of rover	Upstream – input to terrestrial autonomous machines for navigation of vehicles	Long-term	high	Potentially strong for navigation of military aircraft	Industry and Government	Yes - Astrium	Possible - MOD	Potentially large	Low - confidentiality issues may arise from MOD
		Robotic Navigation: 3D imaging of terrain for navigation of rovers	Upstream - input to autonomous navigation of rover	Upstream – input to traffic flow management	Long-term	high	Potentially strong as UK population grows	Government	Y - Astrium	Yes – e.g. Transport for London, Bristol traffic management authority	Medium improves existing traffic flow technology	Strong candidate
		Geology technology: Designer solvents for tar sand oil extraction	Input - to extract organics from rock	Input - facilitates extraction of heavy oil	Medium-term	high	Potentially strong from oil industry	Industry	Y - Imperial	Y - oil companies	Potentially large heavy oil	Possible
Programme investment assumptions	Strategic Programme options	Product/service	Position in space supply chain	Position in (terrestrial) recipient sector supply chain	Timing for Spillover	Risk to market		Potential (terrestrial) customers	Information availability for estimating space costs of product Y, N	Access to potential users (final and suppliers) Y, N	Size/significance in terrestrial economy	Potential for further study

		Space product/service	Upstream input Downstream final product	Upstream input Downstream final product	From now, Short-term = 2 - 3years, Medium term = 4 - 6 years, Long-term = 7 - 10 years, Very Long-term 11+ yrs	Innovation environment - linkages with terrestrial users and knowledge transfer processes high, medium, low	Demand drivers - why may terrestrial users want the product strong, medium, weak	Industry, Government, households	Information from Space industry suppliers	Users outside space industry - both final product users and suppliers to terrestrial industries	Large, Medium, small	proposed given stakeholder consultation to date
	Robotic exploration of Mars	Disease control technology: Backward Planetary protection ofr orbiter	Upstream. Input - to facilitate safe return of Mars samples	Upstream: Input to BSLs	Long-term	Potentially high	Medium if it can reduce the risks associated with BSLs	Government and Industry	Y - SEA and University of Leicester	Potentially - e.g. Health and Safety executive that which regulates BSLs in the UK	Medium	Possible
		Disease control technology: Forward Planetary Protection for lander and rover	Upstream. Input - to facilitate safe return of Mars samples	Upstream: Input to BSLs	Long-term	Potentially high	Medium if it can reduce the risks associated with BSLs	Government and Industry	Y - SEA and University of Leicester	Potentially - e.g. Health and Safety executive that which regulates BSLs in the UK	Medium	Possible
		Remote sample: acquisition, transfer, encapsulation on lander and rover	Upstream: Input - to facilitate safe return of Mars Samples	Upstream - input to BSLs	Long-term	Potentially high if it can reduce the risks associated with BSLs	Unknown	Industry and Government	Y - University of Leicester	Potentially - e.g. Health and Safety executive that which regulates BSLs in UK	Unknown	Possible
Programme investment assumptions	Strategic Programme options	Product/service	Position in space supply chain	Position in (terrestrial) recipient sector supply chain	Timing for Spillover	Risk to market		Potential (terrestrial) customers	Information availability for estimating space costs of product Y, N	Access to potential users (final and suppliers) Y, N	Size/signi fcance in terrestrial economy	Potential for further study

		Space product/service	Upstream input Downstream final product	Upstream input Downstream final product	From now, Short-term = 2 - 3years, Medium term = 4 - 6 years, Long-term = 7 - 10 years, Very Long-term 11+ yrs	Innovation environment - linkages with terrestrial users and knowledge transfer processes High, medium, weak	Demand drivers - why may terrestrial users want the product strong, medium, weak	Industry, Government, households	Information from Space industry suppliers	Users outside space industry - both final product users and suppliers to terrestrial industries	High, Medium, Low	proposed given stakeholder consultation to date
	Robotic exploration of Mars	**Robotics:** autonomous robots (2)	Upstream. Input to sample return technology - i.e. sample processing on Mars surface	Input to production lines on earth	Medium term	Medium	Medium	Industry	Y	Potentially - e.g Marks and Spencers has expressed some interest	Medium	Unlikely
		Remote sample analysis (2): Remote analysis of samples	Upstream - component of an autonomous vehicle	Upstream -input into autonomous drilling technology for oil exploration	Long-term	high	strong - oil exploration companies	Industry	Y - Logica	Y - Logica	High	Definite
Programme investment assumptions	Strategic Programme options	Product/service	Position in space supply chain	Position in (terrestrial) recipient sector supply chain	Timing for Spillover	Risk to market		Potential (terrestrial) customers	Information availability for estimating space costs of product Y, N	Access to potential users (final and suppliers) Y, N	Size/significance in terrestrial economy	Potential for further study

		Space product/service	Upstream input Downstream final product	Upstream input Downstream final product	From now, Short-term = 2 - 3years, Medium term = 4 - 6 years, Long-term = 7 - 10 years, Very Long-term 11+ yrs	Innovation environment - linkages with terrestrial users and knowledge transfer processes high, medium, low	Demand drivers - why may terrestrial users want the product strong, medium, weak	Industry, Government, households	Information from Space industry suppliers	Users outside space industry - both final product users and suppliers to terrestrial industries	High, Medium, Low	proposed given stakeholder consultation to date
	Robotic exploration of Mars	Faster mobility system for Rover	Upstream input to Rover	Spillovers not clear, direct benefit via UK companies supplying space industry	Unknown	Unknown	Unknown	Unknown	Y - University of Leicester	Unknown	Unknown	Low – limited information
		Sample receiving facility	Downstream - terrestrial receiving facility	Downstream - the facility will demand support services (i.e. regional growth)	Long-term	Medium - SEDA interested	Medium - SEDA	Government and industry	Y	Y – e.g. SEDA	Potentially high	Possible
Programme investment assumptions	Strategic Programme options	Product/service	Position in space supply chain	Position in (terrestrial) recipient sector supply chain	Timing for Spillover	Risk to market		Potential (terrestrial) customers	Information availability for estimating space costs of product Y, N	Access to potential users (final and suppliers) Y, N	Size/significance in terrestrial economy	Potential for further study

		Space product/service	Upstream input Downstream final product	Upstream input Downstream final product	From now, Short-term = 2 - 3years, Medium term = 4 - 6 years, Long-term = 7 - 10 years, Very Long-term 11+ yrs	Innovation environment - linkages with terrestrial users and knowledge transfer processes high, medium, low	Demand drivers - why may terrestrial users want the product strong, medium, weak	Industry, Government, households	Information from Space industry suppliers	Users outside space industry - both final product users and suppliers to terrestrial industries	High, Medium, Low	proposed given stakeholder consultation to date
increase in robotic investment	Lunar exploration using robotics	Lunar communications technology	Downstream - satellite	Potential use in autonomous oil exploration, but greatest benefit will arise from UK supplying other space nations for lunar exploration purpose	Medium term	high	Potentially high if UK is the supplier to other space countries	Industry and Government	Y - SSTL	Y - SSTL and Logica for drilling	H - via direct supply to space industry	Definite
		ISRU - Solar power generation and storage	Upstream - energy for rovers and other instruments	Downstream - energy generation in remote locations and in low light environments in northern hemisphere	Short-term	medium	medium	Industry and households	Y - Astrium	N	Unknown	Low
Programme investment assumptions	Strategic Programme options	Product/service	Position in space supply chain	Position in (terrestrial) recipient sector supply chain	Timing for Spillover	Risk to market		Potential (terrestrial) customers	Information availability for estimating space costs of product Y, N	Access to potential users (final and suppliers) Y, N	Size/significance in terrestrial economy	Potential for further study

		Space product/service	Upstream input Downstream final product	Upstream input Downstream final product	From now, Short-term = 2 - 3years, Medium term = 4 - 6 years, Long-term = 7 - 10 years, Very Long-term 11+ yrs	Innovation environment - linkages with terrestrial users and knowledge transfer processes high, medium, low	Demand drivers - why may terrestrial users want the product strong, medium, weak	Industry, Government, households	Information from Space industry suppliers	Users outside space industry - both final product users and suppliers to terrestrial industries	large, Medium, small	proposed given stakeholder consultation to date
	Lunar exploration using robotics	ISRU i.e Titanium produced from Rootile	Upstream - input to construction, insulation and conductor of energy on lunar surface	Upstream - input to construction, insulation and conductor of energy on Earth	short-term	High	strong	Industry	Y - British Titanium/Green Metals and Cambridge Material Science	Y - via British Titanium	Potentially large - titanium for aviation and cars plus low environmental impact in its production as compared to current terrestrial titanium	Definite
		Space planes	Downstream substitute for rocket or shuttle for payloads and humans	Downstream: - potential for sub-orbital flight	Very long-term, but long-term for concept to be developed and illustrated	Medium	medium	Industry	Y- Bristol Space Planes	N	Medium	Low
Programme investment assumptions	Strategic Programme options	Product/service	Position in space supply chain	Position in (terrestrial) recipient sector supply chain	Timing for Spillover	Risk to market		Potential (terrestrial) customers	Information availability for estimating space costs of product Y, N	Access to potential users (final and suppliers) Y, N	Size/significance in terrestrial economy	Potential for further study

		Space product/service	Upstream input Downstream final product	Upstream input Downstream final product	From now, Short-term = 2 - 3years, Medium term = 4 - 6 years, Long-term = 7 - 10 years, Very Long-term 11+ yrs	Innovation environment - linkages with terrestrial users and knowledge transfer processes high, medium, low	Demand drivers - why may terrestrial users want the product strong, medium, weak	Industry, Government, households	Information from Space industry suppliers	Users outside space industry - both final product users and suppliers to terrestrial industries	large, Medium, small	proposed given stakeholder consultation to date
	Lunar base for Humans	Wireless bio-telemetry	Upstream - Input to human flight support	Downstream - monitoring of ICU patients	Short-term	Potentially high	Potentially strong	Industry and Government i.e. NHS	Y	Y	large	Definite
		Data acquisition and data handling linked to bio-telemetry	Upstream - Input to human flight support	Downstream - monitoring of ICU patients and co-ordination between hospitals and within hospitals	medium term	Potentially high	Potentially strong	Industry and Government	Y	Y	large	Definite
		ISRU e.g. generation of oxygen in Lunar environment	Upstream - supply of oxygen (i.e. similar to petrol stations on earth)	Upstream – most benefits will flow from supply to other space nations	Very long-term	High	Potentially strong if UK is the supplier to other space countries	Government and Industry	Y	Y – space industry	Potentially large f UK supplies to other nations	Definite
		Human decision aides	Upstream - input to manned vehicles	Upstream - input to trains or planes	Short-term	High	Potentially strong	Industry and Government	Y	Maybe - if MOD willing to participate	Medium	Possible
Programme investment assumptions	Strategic Programme options	Product/service	Position in space supply chain	Position in (terrestrial) recipient sector supply chain	Timing for Spillover	Risk to market		Potential (terrestrial) customers	Information availability for estimating space costs of product Y, N	Access to potential users (final and suppliers) Y, N	Size/significance in terrestrial economy	Potential for further study

a		Space product/service	Upstream input Downstream final product	Upstream input Downstream final product	From now, Short-term = 2 - 3years, Medium term = 4 - 6 years, Long-term = 7 - 10 years, Very Long-term 11+ yrs	Innovation environment - linkages with terrestrial users and knowledge transfer processes high medium, low	Demand drivers - why may terrestrial users want the product strong, medium, weak	Industry, Government, households	Information from Space industry suppliers	Users outside space industry - both final product users and suppliers to terrestrial industries	large, Medium, small	proposed given stakeholder consultation to date
	Lunar base for humans	Psychology of humans	Upstream - knowledge and training for humans on long space flights and confined conditions in lunar base	Upstream - better understanding of human psychology in extreme situations	Long-term	high	Potentially strong – MOD, Antarctic exploration	Industry, Government and Households	Y	Potentially Y	Medium	Possible
		ISRU - Nuclear power generation	Upstream - generation of rover and other instruments	Upstream - energy source	Long-term	potentially high	Medium - i.e. micro-generation of power	Industry, households	Y	Potentially Y	Medium	Possible
	Billenium Archive	Drilling on lunar surface	Upstream - drill technology	Upstream - drilling technology for under ice drilling and other remote locations	Medium term	potentially high	Potentially high - oil exploration	Industry	Y-Logica	Y-Logica	Large	Definite

Annex 3 A note on multi-criteria analysis

Although many techniques would be widely acknowledged as methods of multi-criteria analysis, they cover a wide range of quite distinct approaches (in contrast to cost benefit analyses, which is a more unified body of techniques).

All MCA approaches make the options and the contribution of the different criteria explicit, and all require the exercise of some degree of judgment. They differ however in how they combine the data. Formal MCA techniques usually provide an explicit relative weighting system for the different criteria included in the analysis.

MCA techniques can be used to identify a single most preferred option, to rank options, to short-list a limited number of options for subsequent detailed appraisal, or simply to distinguish acceptable from unacceptable possibilities.

The 'Multi-criteria analysis manual' (available at the Communities and Local Government website (www.communities.gov.uk) describes some of the key features that are common among different types of MCA. The eight steps involved in a MCA (as described by the manual) are listed below.

1. Establish the decision context. What are the aims of the MCA, and who are the decision makers and other key players?
2. Identify the options.
3. Identify the objectives and criteria that reflect the value associated with the consequences of each option.
4. Describe the expected performance of each option against the criteria. (If the analysis is to include steps 5 and 6, also 'score' the options, i.e. assess the value associated with the consequences of each option).
5. 'Weighting'. Assign weights for each of the criteria to reflect their relative importance to the decision.
6. Combine the weights and scores for each of the options to derive and overall value
7. Examine the results.
8. Conduct a sensitivity analysis of the results to changes in scores or weights.

The manual describes two of the key features common to different types of MCA. The first is a performance matrix, which is described as follows:

"A performance matrix, or consequence table, in which each row describes an option and each column describes the performance of the options against each criterion. The individual performance assessments are often numerical, but may also be expressed as 'bullet point' scores"…

"In a basic form of MCA this performance matrix may be the final product of the analysis. The decision makers are then left with the task of assessing the extent to which their objectives are met by the entries in the matrix. Such intuitive processing of the data can be speedy and effective, but it may also lead to the use of unjustified assumptions, causing incorrect ranking of options"…

"In analytically more sophisticated MCA techniques the information in the basic matrix is usually converted into consistent numerical values".

The second is a scoring and weighting procedure:

"MCA techniques commonly apply numerical analysis to a performance matrix in two stages:

1. Scoring: the expected consequences of each option are assigned a numerical score on a 'strength of preference' scale for each option for each criterion. More preferred options score higher on the scale, and less preferred options score lower. In practice, scales extending from 0 to 100 are often used, where 0 represents a real or hypothetical least preferred option, and 100 is associated with a real or hypothetical most preferred option.

2. Weighting: numerical weights are assigned to define, for each criterion, the relative valuations of a shift between the top and bottom of the chosen scale. Mathematical routines combine these two components to give an overall assessment of each option being appraised. These approaches are often referred to as compensatory MCA techniques, since low scores on one criterion may be compensated by high scores on another.

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