Science and Technology Facilities Council

Innovation Clusters | North West Space

MIDLANDS SPACE CLUSTER

Power4Space

Prioritising the UKs adoption of nuclear power systems in space as a unique strategic capability, providing sustainable opportunities for long-term regional economic growth

A Pan-Regional Partnership between the North West Space Cluster and the Midlands Space Cluster, funded by the UK Space Agency

UK SPACE AGENCY

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- Midlands Aerospace Alliance
- Midlands Space Cluster
- National College for Nuclear
- United Kingdom National Nuclear Laboratory
- Nuclear Skills Delivery Group
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Executive Summary

The UK has identified specific space capabilities (Intelligence/Surveillance/Reconnaissance, Space Domain Awareness, etc)[1] as priorities to be developed due to their strategic and operational importance, however, the need for these capabilities is not unique to the United Kingdom, they will therefore operate in a highly competitive global ecosystem of near identical proficiencies being developed by other spacefaring nations, thereby limiting export value. Meanwhile, the UK also faces complex decisions around its legacy of nuclear power and the development of future systems (e.g., AMRs, SMRs, and Fusion)[2], whilst communities with established nuclear capabilities, like West Cumbria, face a decline in the legacy nuclear industries upon which they depend, with no clear replacements. Simultaneously, due to accelerating Beyond Earth activities, both institutional and commercial, including Lunar, Martian, and defence ambitions, there is increasing global demand for long life, reliable, non-solar power and/or heating systems in space[3], as provided by nuclear systems, such as Radioisotope Power Systems (RPS) and Advanced Modular Reactors (AMRs/Microreactors).

Understandably, access to radiological materials traditionally used in such systems (such as Plutonium) is severely limited and politically sensitive. Fortunately, Americium (Am241), a natural decay product within the UKs stores of civilian plutonium in Cumbria, has been demonstrated as a viable alternative fuel source for long term heat/power systems in Space. However, access to the UK stockpiles has been limited due to the scale of facilities and skills required to extract, process, and safely transport this material.

The UK therefore has the opportunity and capability to adopt the development of nuclear power systems as its national unique selling point for space. To maximise returns on existing nuclear investments, and to support new investment into the communities in which they are embedded, the North West of England and the Midlands should support the UK's adoption of space nuclear power systems as a national unique selling point (USP), utilising their unique capabilities, facilities, and skills base to develop these technologies, and engaging with national and international partners to develop and access markets.

As the UK renews its commitment to process and store legacy nuclear fuels[4], the possibility of scaled up processing of Am241 is presented. The scaled up production of UK built Am241 thermal units and power systems, and ultimately higher output AMR/'Microreactors', could support the safe, secure, and cost-effective clean-up of our legacy nuclear sites, enhancing and retaining UK nuclear skills and facilities, whilst strategically positioning the UK to provide power solutions to the emerging market in deep space activities, estimated to worth $21bn by 2045[5].

In support of this proposition, the North West of England and the Midlands formed a Power4Space pan-regional cluster partnership, enabled by funding from the UK Space Agency, to explore how both can leverage their joint strengths and unique nuclear expertise and facilities across the following sites:

- Sellafield (Cumbria)
- Springfields (Lancashire)
- Birchwood (Cheshire)
- Raynesway (Derbyshire)
- Space Park Leicester (Leicestershire)

With a focus on developing:

- Extracting Am241 at a scale of kgs/year (post-PuMA2)
- Large Scale Fuel Pelleting
- Fuel clad welding, up to and including fully sealed RPS/RHU
- Radioisotope heat source assembly /integration facility
- Mechanical qualification test facility
- RPS/RHU storage capability
- Mechanical qualification test facilities
- AMR development and production
- AMR fuel development and production

By adopting the methodology[6] used throughout the Power4Space project, both regions can enhance their capacity to identify mutually beneficial opportunities, attract investment, and support UK and European space ambitions.

To create this report, key organisations Rolls-Royce, the UK National Nuclear Laboratory, and the University of Leicester were convened by their respective regional Space Clusters to explore mutual challenges in developing space nuclear technologies, a series of workshops then engaged wider networks across both the Space and Nuclear sectors to explore possible solutions and instigate collaborations therein. In addition, Data City Innovations Ltd mapped 97 businesses in the North West of England and Midlands to contribute to a future space nuclear supply chain.

Engagement with these stakeholders identified the following mechanisms that could enhance UK space nuclear capability, and unlock significant regional economic opportunities for the Midlands and the North West Space Clusters:

1. Take a place-based approached to support existing nuclear capabilities across North West of England and the Midlands, aligning with requirements for future terrestrial energy requirements, thereby maximising the UKs return on existing investments in nuclear, ensuring the long-term success of Space Nuclear as a national endeavour, and supporting long-term economic and social stability in some of the UKs most vulnerable communities
2. To secure buy-in from businesses, research institutions, and investors, make available publicly accessible market analysis, exploring in greater detail the market opportunities[7] associated with space nuclear capabilities, such as in-orbit servicing, assembly, and manufacturing (ISAM), applications across both the Lunar and Martian economies, and deep space operations, including in situ resource utilisation (ISRU) and propulsion
3. Explore routes to enable the Nuclear Decommissioning Authority to secure access to greater quantities of Am241, aligned with the renewed commitment to process and remove the UK's legacy nuclear materials
4. Consider how alternative funding models could facilitate access to UK facilities to enable a responsive, agile, rapid approach to developing these technologies
5. Prioritise the development of cross-sector (Space and Nuclear) skills provisions
6. Work with international partners to take full advantage of access to international missions, projects, and export markets

These actions would ensure the UK can create a national USP in space, stimulate investment into economically vulnerable communities, and enhance the UK's nuclear and space capabilities.

Introduction

Nuclear power systems are critical for space exploration, providing reliable energy and heating for spacecraft and instruments in environments where solar power is insufficient, such as deep space or shadowed planetary regions

These systems primarily include **radioisotope power systems (RPS)** and **advanced modular reactors** (Sometimes, referred to as 'Space Batteries', RPSs use heat from the natural decay of radioactive isotopes, such as plutonium-238, to protect against the deep cold of space, and to generate tens to hundreds of Watts of electricity for use by the spacecraft over years or even decades, making them highly durable and ideal for long-term missions, including deep space probes such as Voyager, and planetary rovers such as Curiosity, and Perseverance[8].

RPSs have been used in multiple deep space missions since the 1960s, and, given their traditional use of Plutonium as a heat source, have been the sole purview of nations with Human spaceflight capabilities; the United States, and the Soviet Union/Russian Federation, and more recently, China, and India.

- Advanced Modular Reactors (AMRs), known as 'Microreactors', generate electricity using the heat generated by the fission of uranium atoms, offering several hundred to several thousand Watts, and so are suitable for larger missions or habitats, such as the Artemis lunar base, an international project currently underway led by NASA and ESA. These systems ensure continuous power for critical functions like scientific instruments, communication, and thermal management, enabling exploration far beyond the reach of traditional energy sources.[9]
    - Whilst 34 fission reactors are known to have flown in space since the 1960s, their use is usually limited to demonstration prototypes, rather than active long-term missions. Similarly to RPSs, the nature of the nuclear material used to power these systems has traditionally put their deployment and operation solely in the hands of the United States and the Soviet Union/Russian Federation.
- Nuclear Propulsion, including Nuclear Electric Propulsion[10] (using nuclear to power high output electric ion thrusters), and Nuclear Thermal Propulsion[11] ('nuclear rockets'), is likely to become a requirement for deep space activities around the middle of this century, responding to a need to drastically reduce journey times for interplanetary journeys and deep space exploration.

With their decades of nuclear expertise, the **North West of England[12] and the Midlands[13] are at the heart of the UKs globally recognised nuclear capabilities**, and it is from there that a new, strategically important capability is emerging. Consequently, the UK Space Agency has funded both the North West of England and Midlands Space Clusters to collaborate in this area, and bring together relevant expert stakeholders across their regional supply chains to explore how this capability can further enhanced, and harnessed to unlock new strategic and commercial opportunities for the UK space sector.

In partnership with the University of Leicester, United Kingdom National Nuclear Laboratory, based in Cumbria, Lancashire, and Cheshire, have demonstrated that Americium-241, a natural byproduct of the storage of legacy nuclear materials at Sellafield, can be used in place of Plutonium-238 to power RPSs[14]. Whilst Am-241 powered RPSs would have 20-25% the power of a Plutonium system on an equivalent isotope mass basis, they still have considerable applications, as evidenced by the selection of one of these systems for ESA's Rosalind Franklin Rover to Mars in the late 2020s[15]. Once that mission successfully demonstrates their efficacy, ESA will deploy UK built RPSs, powered by ~1kg of Am241, on the 'Argonaut' lunar cargo landers throughout the 2030s[16].

From the decay of stored Plutonium[17], the UK has approximately 10 tonnes of potentially accessible Am241, presenting a unique opportunity to develop a new sovereign capability and position itself as a top-tier spacefaring nation through the development and deployment of Nuclear Power systems for use in Space (Power4Space). This capability is currently only held by the United States, Russia, and to an extent, China, and India.

Powering the UKs Continuous at Sea Deterrent (CASD) capability[18], Derby and its environs have several decades of experience in designing, developing, and deploying small fission systems for independent mobile platforms on remote, extended operations. The UK has invested more in Microreactor design and development than the US over the last 5 years; more than £40m, shared between UK Government and Derbyshire based Rolls Royce[19]. This gives the UK a favourable position relative to NASA's Fission Surface Power (FSP)[20] programme and enables the UK to propose that FSP becomes a UK-US collaborative programme under the Artemis Accords.

Although they differ in design, materials, technology, and power output, RPSs and AMRs are similar to CASD power systems in their long-term, low maintenance use of nuclear materials, and so building up the required skills and services for Power4Space capabilities will result in a more robust ecosystem to support emerging terrestrial nuclear technologies, such SMRs and Fusion.

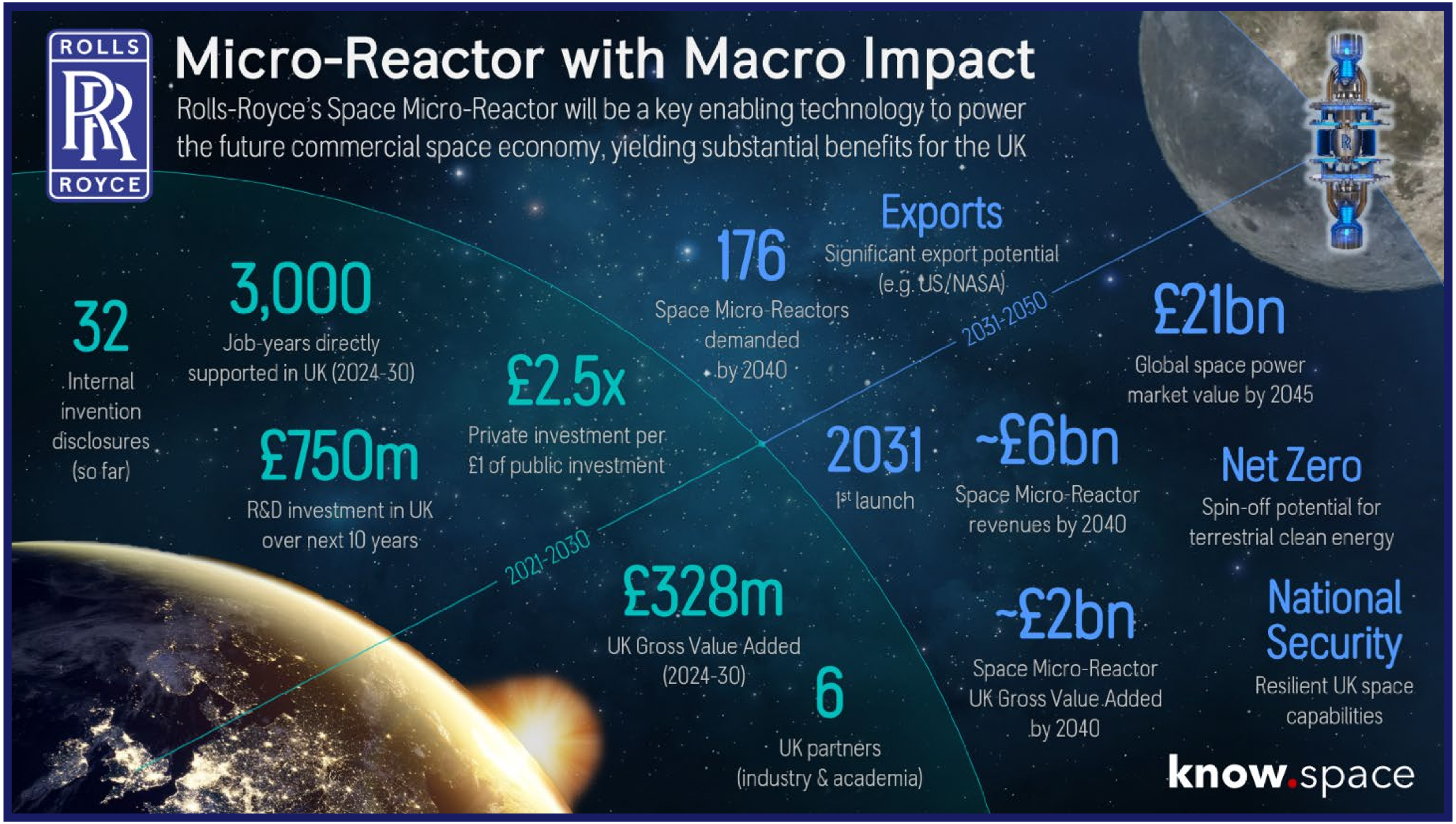
By the middle of this century, having acquired the skills and capabilities to design, develop, deliver, and deploy RPSs and Microreactors, the UK would be well positioned to evolve its position as a market leader in Power4Space technologies by addressing the Nuclear Propulsion demand for deep space operations.

Detailed independent market analysis of the future growth opportunity for RPSs, Microreactors, and future Nuclear Propulsion has not been made publicly available, but consensus achieved via this project between UKNNL, Rolls Royce, and University of Leicester/Perpetual Atomics is that there is potential for thousands of new jobs and £10'sBn in the nearer term, and £100'sBn towards the late 2040s when considering the wider scope of institutional and commercial Space missions, long with potential terrestrial applications.

The image below summarises the potential market for AMRs, as reported by Know.Space. For RPS/RHU, given the lower power and more mobile nature of their applications, a market size of several hundred units might be assumed by the mid-2040s.

Figure 1: Micro-Reactor with Macro Impact: Know.Space and Rolls Royce

Rolls-Royce's Space Micro-Reactor will be a key enabling technology to power the future commercial space economy, yielding substantial benefits for the UK: **32** Internal invention disclosures (so far), **3,000** Job-years directly supported in UK (2024–30), **£750m** R&D investment in UK over next 10 years, **£2.5x** Private investment per £1 of public investment, **£328m** UK Gross Value Added (2024–30), **6** UK partners (industry & academia), **176** Space Micro-Reactors demanded by 2040, Significant export potential (e.g. US/NASA), **2031** 1st launch, **~£6bn** Space Micro-Reactor revenues by 2040, **~£2bn** Space Micro-Reactor UK Gross Value Added by 2040, **£21bn** Global space power market value by 2045, **Net Zero** Spin-off potential for terrestrial clean energy, **National Security** Resilient UK space capabilities.



Approach and Process of the Development of this Report

This report is delivered as part of the 'Power4Space Pan-Regional Partnership' between the North West Space Cluster and the Midlands Space Cluster, funded by the UK Space Agency's 2023 'Cross Cluster Partnership Fund'.

The geographically adjacent clusters of the North West Space Cluster, and the Midlands Space Cluster are home to the two technologies emerging as the UKs only Nuclear Power in Space propositions:

- Am-241 powered Radioisotope Power Systems (RPSs, commonly known as 'Nuclear Batteries') and Radioisotope Heating Units (RHUs)
- Fission based Advanced Modular Reactors (AMRs, commonly known as 'Microreactors')

The design, development, delivery, and deployment of these technologies aligns with growth priorities established by the Midlands, and North West England concerning both Nuclear and Advanced Manufacturing, specifically:

Midlands Engine – Review of Nuclear & Related Industries in the Midlands (Jan 2023)[21]

Proposed Actions and Recommendations:

- Item 1 – Support bids for nuclear manufacturing sites
- Item 7 – Support creation of nuclear test, validation, and R&D facilities

Cumbria Nuclear Prospectus – (August 2020)[22]

- Advanced Nuclear Technologies
- Advanced Fuel Development
- Future Fuels Manufacturing Facility
- Pioneering Nuclear Research and Innovation
- UKNNL Am-241 RTG featured case study
- UK Reactor Research

Lancashire FDI Action Plan – (2022)[23]

Energy

Key investment strength

- Investment into 'Clean Energy Tech Park' (Springfields Westinghouse Nuclear site)

Opportunities

- Establish sites to enable new technologies to be developed, demonstrated, and commercialised
- Working with the Nuclear Industry across the UK

Advanced Engineering Manufacturing (AEM)

Key investment strength

- 2nd highest concentration of AEM in the UK

Opportunities

- Market seeking – the strong manufacturing base creates a market for new technologies and presents an opportunity for supply chain companies to be close to their customers

Tessellating the above regional priorities with the capabilities outlined in the 'National Space Strategy In Action'[24] report, the Power4Space Pan-Regional Cluster Development project focused on strengthening collaboration across the geographically adjacent Space Clusters of the North West of England, and the Midlands. To achieve this, and in additional alignment with the UK Space Agency's 'Space Exploration: Technology Road Map'[25], the two Clusters cooperated to support the delivery of the above mentioned emerging, potentially internationally strategic technologies, by:

- Identifying challenges to developing these nuclear power systems
- Initial mapping of potentially relevant UK supply chains and capabilities
- Delivering a programme of pan-regional events to:
  - ideate practical solutions to these challenges
  - convene consortia to explore those solutions beyond the duration of this project
- Producing this public report to highlight the opportunities for investment into UK capabilities and supply chains underpinning the successful roll out of UK built nuclear power systems for space.
- Producing a final report that scopes a framework for a sustained partnership across the two regions based upon the outcomes and 'lessons learnt' from the completed programme of work

Led by UKRI-STFC, the organisation delivering the North West Space Cluster, the Power4Space partners were:

- North West England
  - UKRI-STFC
  - North West Aerospace Alliance
- Midlands
  - University of Leicester
  - Midlands Aerospace Alliance

The project partners convened key UK organisations involved in the development of P4S technologies:

- United Kingdom National Nuclear Laboratory
- Rolls Royce
- University of Leicester

In addition, the following stakeholders attended all associated workshops, providing input and insight:

- Amentum
- Dalton Nuclear Institute (University of Manchester)

Following initial discussions with Rolls Royce and the United Kingdom National Nuclear Laboratory to determine their requirements and expectations, seven workshops were delivered, convening the key organisations above, alongside a range of additional UK organisations as appropriate for the theme of each workshop, as described on the following spread.

Project Activities

Convening Key Organisations

The North West Space Cluster, and the Midlands Space Cluster used their positions as trusted partners to convene the relevant key organisations:

- North West England
  - United Kingdom National Nuclear Laboratory
- Midlands
  - University of Leicester
  - Rolls Royce

To protect commercial interests, separate discussions with each organisation were carried out by their respective regional space cluster managers to ascertain the challenges faced. The two cluster managers then convened to compare the outputs of these discussions to identify challenges or concerns common to all parties. Only the common challenges were taken forward to form the themes of the resulting workshops.

In addition, building upon these discussions and using publicly available sources of information, such as Fit For Nuclear[26], and European Cooperation for Space Standardisation (ECSS)[27], a scan of the North West England and the Midlands was commissioned to identify a potential industrial base that might support the development of Power4Space technologies.

A Scan of the Relevant UK Industrial Base

The Data City Ltd (TDC) were tasked with mapping the potential Space Nuclear supply chain, producing a preliminary database of companies operating in the sector along with key information on the sector size, location and trends.

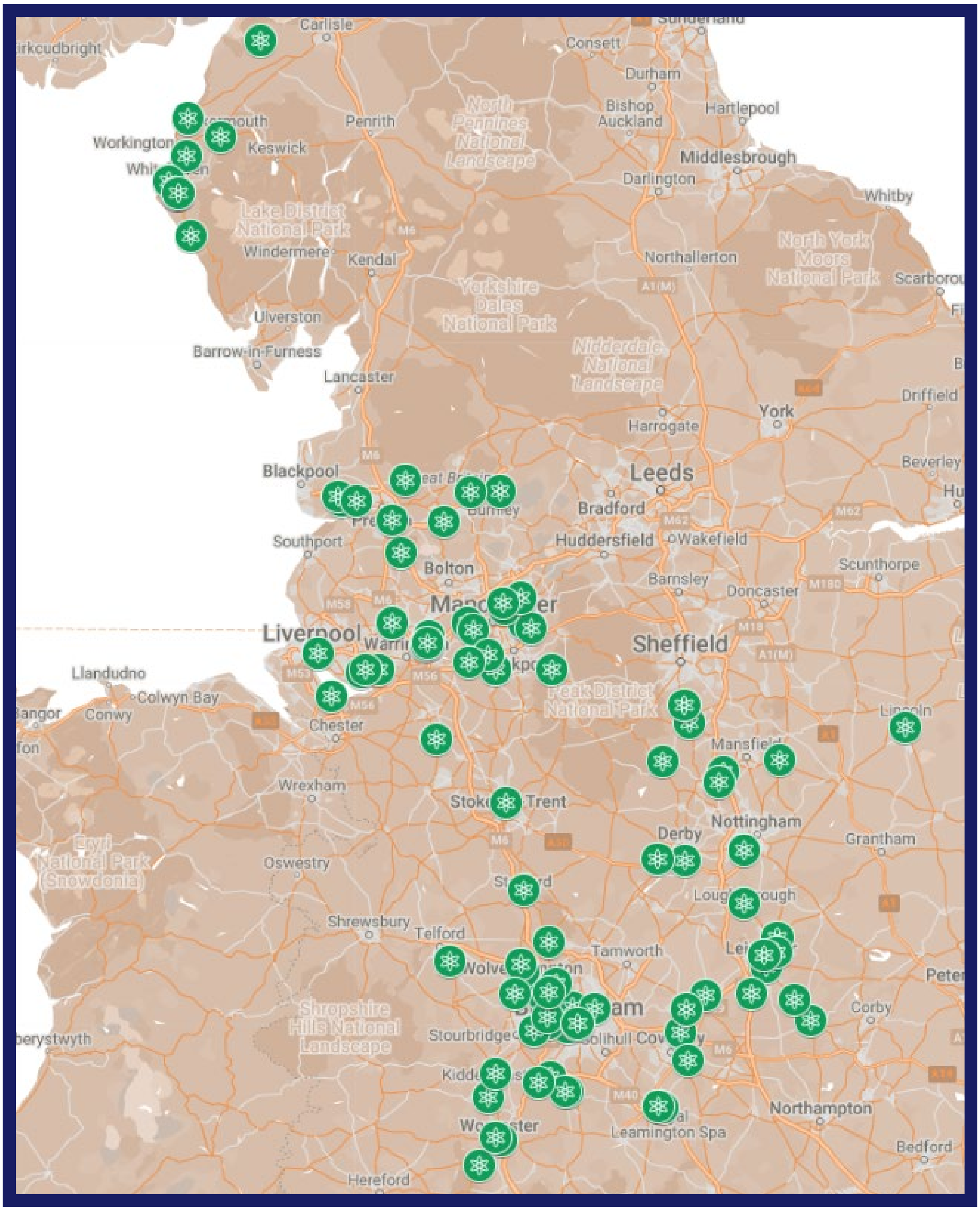
Real-Time Industrial Classifications, or RTICs, are datasets that represent the emergent economy. They are built with TDC's machine learning and website scraping technology in the Data Explorer platform. In short, RTICs group companies that describe their activity similarly in their website text, allowing the user to make custom sectoral lists.

The Data City worked with UKRI-STFC/North West Space Cluster to define the sector and publish this as an RTIC in the Data City platform.

UKRI-STFC/North West Space Cluster convened and managed stakeholders to work with the Data City on the taxonomy definition, RTIC development and quality assurance. Then, using their own proprietary processes, The Data City designed the sector taxonomy, mapped the sector using their machine learning platform, and published sector database as an RTIC.

Using that RTIC, a baseline of 96 businesses across the North West of England and the Midlands have been identified that could form a supply chain for space nuclear technologies. A map of these companies is included below, and a full list can be found in Appendix 1.

Figure 2 - A map of organisations identified as being potential supply chain



Workshop Outputs and Key Findings

Complete write-ups of each workshop can be found in Appendix 2.

Across all workshops and activities, it was agreed that the UK has a clear opportunity to leverage its existing expertise and investments in the terrestrial nuclear sector to create a new national capability in 'Space Nuclear' (non-fission power and heating systems, fission power systems, and nuclear propulsion), with non-fission systems (such as Radioisotope Power Systems) enabling some legacy nuclear materials to be put 'beyond reach', but not 'beyond use'. This is an opportunity to develop a strategic unique-selling-point on the world stage, one that could support the safe, secure, and cost-effective clean-up of the nation's legacy nuclear sites, would create new opportunities for job creation and economic growth in some of our most economic vulnerable communities, and would create a vibrant new export market. In addition, through the careful alignment of skills provisions and investment in facilities, the development new terrestrial nuclear capabilities, such as SMRs and Fusion, could also be supported.

To maximise the UKs return on investment into terrestrial nuclear capabilities, and to leverage long established expertise, any new facilities and programmes should be centred on established centres of nuclear capabilities, which are primarily located across the North West of England and the Midlands. As well as ensuring cost-efficiency, there will be positive economic and social impacts on communities dependent on legacy nuclear programmes, many of which currently face decades of decline through the loss of dedicate infrastructure and highly skilled jobs[28].

Skills provisions must be made that support both the nuclear sector and the space sector in the long-term, encouraging where appropriate shared practices and standards, thereby enabling skilled workers to service both sectors throughout their careers. A more detailed consideration of this cross-sector skills provision can be found in Annex 2: "Workshops 2a and 2b: Developing and Delivering Skills".

The UK, with its well-established nuclear industry and a robust position in the international space ecosystem, including through its membership in ESA, is therefore well-positioned to become a leader in nuclear power systems for use in Space, supplying this enabling technology for a wide range of deep space activities and industries.

The following considerations are therefore presented:

Address Technological Gaps

RPSs traditionally utilise Pu-238 as a power source. Due to demand for these materials, there exists a significant gap in the availability of suitable radioisotope fuel for RPS. The UK should seize the opportunity to address this gap by scaling up its production of Am-241 as part of the processing stage of the long-term geological storage of its source material, legacy stores of civilian Plutonium. The United Kingdom National Nuclear Laboratory (UKNNL) has already demonstrated the ability to extract several grams of Am-241 per year and, with investment from the UK Space Agency, is increasing production to up to 1kg per year by the end of this decade via the PuMA2 facility. Meeting this goal would position the UK as a major global supplier of radioisotope fuel for RPSs for institutional missions, such as ESA's Argonaut missions, planned to resupply the Human and Robotic lunar presence beginning in the 2030s. However, to address the expected future market for long-term, deep space power and heating systems, the UK should consider the market demand for scaling up Am-241 production to provide tens of kilos per year.

The key to making any of the options for power in space work over long periods is automation. This implies that software systems will be required and, because of the very nature of the systems involved, they will need to be very highly assured systems. Therefore, while there remain a number of key challenges to the deployment of nuclear power in space, if the software that controls and automates processes around them cannot be easily and quickly developed such that it can be certified, then the whole endeavour is unlikely to be flown. Such high assurance techniques exist within the UK and a report has recently been written for the Controls and Instrumentation Nuclear Industry Forum (and the Office for Nuclear Regulation). The IET recently held a webinar on 'Accessible Formal Methods for Nuclear Engineering' which presented the work and it can be accessed here: tv.theiet.org/?videoid=18012

Launch Certification

The UK is actively working with the UN to define the safe use of nuclear applications in space. The UK should leverage this expertise to become a leader in developing international standards for the launch certification of spacecraft with nuclear power sources. This capability would be valuable to other space agencies looking to launch RPS missions and could help to facilitate international collaboration.

Invest in Emerging Technologies

Radioisotope Power Systems

The UK should priorities investments into RTGs, Radioisotope Heating Units (RHUs), and Stirling generators for space exploration missions, particularly into scaling up the extraction of Am241 from its source material (supporting UK commitments to the processing and removal of legacy nuclear fuels), and into improving the power output and efficiency of these systems. This would further enhance the UK's position in the RPS field, uniquely enabling the UK to meet the growing demand for more powerful and capable RPS for missions to the Moon, Mars, and beyond, thus creating a unique-selling-point for the UK in space.

Advanced Modular Reactors/'Micro Reactors'

As the international community gears up for a return to The Moon[29] and to establish a Human presence on Mars[30], the UK should prioritise opportunities to adapt its existing expertise in nuclear reactor technology to the development of AMRs for space applications, delivering kW to mW levels of continuous, long-term power beyond Earth. This should involve collaborating with international partners, such as NASA and ESA, leveraging advances in terrestrial technologies to develop systems suitable for powering Lunar and Martian infrastructure[31,] and eventually supporting In-Space Resource Utilisation activities[32].

Alignment with Terrestrial Future Nuclear capabilities

Critically, investments into the above capabilities should be carefully aligned to support the UKs ability to deliver future nuclear applications here on Earth. This includes Small Modular Reactors (SMRs), terrestrial AMRs (for example, for temporary deployment in disaster response), and Fusion.

Given their smaller scale, and more immediate use cases (such as Rosalind Franklin, and Artemis), Power4Space capabilities provide a unique opportunity for the UK to deliver the expanded skills, facilities, and practices it will require to deliver its own sustainable, secure, sovereign energy supply throughout the 21st century and beyond.

Nuclear Propulsion

Whilst not an immediate opportunity, the potential benefits of nuclear propulsion for future human missions to Mars and beyond should be noted. The UK should consider investing in research and development of nuclear propulsion technologies, such as Nuclear Electric Propulsion (NEP), and Nuclear Thermal Propulsion (NTP). This may require long term investment and skills development, but earlier investments into RPSs and AMRs could be aligned to support such future development. This would further position the UK at the forefront of a potentially transformative technology for deep space activities.

Place Based Strengths and Opportunities

The key capabilities required to maximise the UKs strategic prioritisation of Power4Space technologies, including skills, facilities, and potential supply chains, whether public, private, or academic, are concentrated in communities across North West England and the Midlands. Many of these communities are economically dependent on the traditional nuclear industry and are considered economically vulnerable due to this dependency. For example, in West Cumbria, one of the most economically deprived areas in England[33], the Sellafield site is one of the largest employers, with approximately 70% of jobs directly tied to the nuclear sector and many more supported indirectly through the supply chain and associated services. Sellafield is also in a long decommissioning phase, with consistent reduction in work force predicted over the coming decades and no obvious candidate to replace those opportunities. Fortunately, the site is also home to the UKs Am-241. Therefore, the diversification of UKs nuclear industry to include the production of RPSs, in direct support of national commitments to the processing and removal of legacy nuclear fuels, would be of long-term significance to some of the UKs most vulnerable communities. Similarly, the development of AMRs will provide long-term opportunities across Derby and the east Midlands. By prioritising these sites for the development of RPSs and AMRs and their associated facilities, programmes, and skills, the UK will be leveraging existing commitments, maximising the national return on investment into nuclear, and ensuring long-term regional growth and social stability via the development, delivery, and deployment of a key strategic capability.

Foster International Collaboration

The importance of international collaboration for advancing space nuclear power and propulsion technologies cannot be underestimated. By prioritising the development of these technologies as a unique proposition, the UK has the opportunity to elevate its position as a top-tier space power, taking a leading role in fostering collaboration by sharing its expertise, resources, and technologies with other space agencies.

In this regard, the UK should continue to leverage its existing relationships with international partners, such as through its involvement with ESA, to build new partnerships and collaborative projects[34].

Enhance Public Perception

The UK should prioritise the importance of improving communication about the safety elements of radioisotope and AMR systems to stakeholders, including the public. Addressing public concerns[35] and ensuring transparency in the development and deployment of space nuclear technologies beyond low Earth orbit (LEO) will be crucial for gaining public acceptance and support. The UK should commit to public engagement initiatives to educate the public about the benefits and safety of space nuclear power, addressing any misconceptions or fears with positive messaging:

- Reduction in the UKs overall spent fuels in storage via an innovative, practical application of decay products that is truly 'beyond reach'
- Establishment of a national USP in a strategically important international arena
- Creation of long-term economic opportunities for economically vulnerable communities, such as West Cumbria, and Derby.

Policy Advocacy

The UK should take a lead role advocating for policies that support the peaceful development and utilisation of space nuclear power both domestically and internationally. This could include supporting funding for research and development, streamlining regulatory processes, and promoting international cooperation.

By taking a proactive and strategic approach, the UK has the opportunity to become a global leader in the field of space nuclear power and propulsion, contributing significantly to future space endeavours, reducing its nuclear stockpiles, and powering local growth.

Following the Workshops, a number of attendees identified specific opportunities they believe could be addressed in the short term to advance the UKs development of these technologies. The Workshop organisers have made the appropriate introductions to foster potential commercial opportunities resulting from the Power4Space project.

Building the Future

It was agreed across all workshops that the UK has the choice of three possible futures:

Future 1 - Business as usual

The UK fulfils its RPS commitments to currently scoped institutional missions, such as the Rosalind Franklin Rover, and the Argonaut missions:

- Following previous investments, such as PuMA2, the UK supplies approx. x1 RPS system for 6 individual ESA missions
    - x 1 Rosalind Franklin Rover – approx. 2029
    - x 5 Argonaut – beginning approx. 2031

- No new facilities required
- No new jobs created
- No significant utilisation of Am241 stockpiles
- No new export market created

Future 2 - The UK as an active partner in Humanity's activities beyond Earth

In addition to Scenario 1, the UK delivers Microreactors for in-space deployment, for example, under the Artemis Programme.

- Investments made into and by Rolls Royce and its supply chain, and wider UK industrial base to secure Surface Fission Power (FSP) selection
- Dedicated international partnerships secured to enable access to non-UK capabilities where required
- Critical experience gained and skills developed in building & operating small scale civil nuclear reactors, thereby supporting national priorities for SMRs and future nuclear
- Jobs and contracts created across Midlands and North West England, with further positive impacts across UK-wide supply chains

Future 3 - Maximising Power4Space technologies as both a strategic capability and an export opportunity

In addition to Scenario 2, the UK also becomes an exporter of unique space power systems for both international partnerships, and the commercial space sector.

- Enhanced clean up of legacy UK nuclear sites via upscaled extraction, processing, and beyond Earth utilisation of Am-241
- High skilled jobs created across North West England and the Midlands, including in some the UKs most economically vulnerable communities, as well as across UK-wide supply chains
- Enhanced UK nuclear sector resilience and diversification, with significant export opportunities
- UK becomes global market leader with a unique strategic capability, leveraged to secure itself as a top-tier spacefaring nation

There was consensus across the workshops that **Future 3 is the preferred scenario.** In that respect, the following recommendations are presented:

Recommendations

Prioritising the development of Power4Space capabilities will not only create a unique-selling-point for the UK, unlocking its potential as a top-tier spacefaring nation, but it will provide much needed long-term economic opportunities for those communities currently dependent on legacy nuclear, such as West Cumbria, and on nuclear manufacturing, such as Derby.

To fully seize unique this opportunity, the UK should:

Carry out publicly available market analysis to determine the potential market size. This will unlock the involvement of UK business and research institutions across a range of relevant sectors and capabilities.

Policy Change

Enact policy change, empowering the Nuclear Decommissioning Authority to enable secure access to greater quantities of Am241. This can be delivered as part of the UKs renewed commitment to process and remove legacy nuclear materials.

Place-Based Approach

Take a place-based approached, investing in the established capabilities across North West England and the Midlands, thereby leveraging the UKs world renowned nuclear expertise and maximising the national return on existing investments in the sector whilst supporting long-term economic and social stability in some of the UKs most vulnerable communities.

Cross-Cluster Skills Development

Prioritise the development of cross-cluster (Space and Nuclear) skills provisions, as detailed in the 'Workshops 2a and 2b: Developing and Delivering Skills' section of this report:

- Establish a Nuclear for Space overall programme level Joint Task Force
- Workforce and Skills Modelling and Forecasting of Workforce and Skills needs
- Establish the Nuclear for Space Skills programme
- Space and Nuclear Skills Collaboration to share and learn from good practices
- Create new Skills Delivery JV for the Space Sector

International Partners

Work with international partners to open secure export markets for RPS and, eventually, AMR, enabling economic diversification of UK industry to the Moon, Mars, and beyond.

New Funding Models

Establish new funding models to facilitate access to UK facilities to enable a responsive, agile, rapid approach to developing the following technologies. Programmes such as ANSIC may be considered as a potential framework.

For the development of RPSs: support the development of new or expanded sovereign capabilities, including:

- Large Scale Fuel Pelleting
- Fuel clad welding, up to and including fully sealed RPS/RHU
- Radioisotope heat source assembly /Integration facility
- Mechanical qualification test facility
- RPS/RHU storage capability

For AMRs: Encourage R&D, or international cooperation, around the following capabilities:

- Materials radiation
- Neutron scattering
- Gamma irradiation
- Post irradiation examination
- Remote monitoring
- Launch load/impact testing
- In-core Nuclear testing
- Mechanical testing
- Thermal testing
- Vacuum testing
- Fuel form development -
- Reactor physics modelling
- Fuel behaviour modelling
- Fuel cycle modelling
- Zero-power ground nuclear testing
- Electrically heated system test
- Zero-gravity testing
- Vibration testing
- Launch load/impact testing
- Zero-gravity testing
- Dust & gas testing
- Functional testing
- Electrical testing
- Instrumentation testing
- Controls testing

Pan-Regional Collaboration

To maximise the UKs return on investment into existing terrestrial nuclear capabilities, and to ensure their own retention of the associated value chains, the North West of England and the Midlands should publicly commit to supporting the UKs adoption of Power4Space technologies as a key national unique-selling-point.

These regions should therefore prioritise supporting national space agencies, such as the UK Space Agency, the European Space Agency, and other international partners, to develop and promote these technologies.

With a clear signal of support for prioritising Power4Space from central government, the two regions can jointly leverage their existing nuclear capabilities across the following sites:

- Sellafield (Cumbria)
- Springfields (Lancashire)
- Birchwood (Cheshire)
- Raynesway (Derbyshire)
- Space Park Leicester (Leicestershire)

with a focus on developing the following capabilities:

- Post-PuMA2: Extracting Am241 at a scale of kgs/year
- Large Scale Fuel Pelleting
- Fuel clad welding, up to and including fully sealed RPS/RHU
- Radioisotope heat source assembly /integration facility
- Mechanical qualification test facility
- RPS/RHU storage capability
- Mechanical qualification test facilities

Established economic mechanisms, such as Freeports and Investment Zones, should be leveraged or expanded to attract investment, whilst public-private partnerships should be developed at the relevant sites across both regions to enable closer cooperation between institutions, investors, customers, and end-users, with a focus on shared R&D resources and business support.

Furthermore, the North West of England and the Midlands should entrench collaboration by expanding the Midlands Space Cluster's 'Pivot Into Space' programme across both regions, thereby supporting the diversification of existing supply chains, including Nuclear, into the space sector. Additional mechanisms for space-terrestrial technology transfer could also be explored.

In addition, as demonstrated in the University of Manchester Case Study commissioned as part of the Power4Space Pan-Regional Partnership, research institutions across the North West of England and the Midlands should engage with key stakeholders, such as Perpetual Atomics and Rolls Royce, to identify how existing capabilities can support R&D into the following:

- Materials radiation
- Neutron scattering
- Gamma irradiation
- Post irradiation examination
- Remote monitoring
- Launch load/impact testing
- In-core Nuclear testing
- Mechanical testing
- Thermal testing
- Vacuum testing
- Fuel form development -
- Reactor physics modelling
- Fuel behaviour modelling
- Fuel cycle modelling
- Zero-power ground nuclear testing
- Electrically heated system test
- Zero-gravity testing
- Vibration testing
- Launch load/impact testing
- Zero-gravity testing
- Dust & gas testing
- Electrical testing
- Instrumentation testing
- Controls testing

Pan-Regional Collaboration beyond the Power4Space project will be addressed in a separate report to the UK Space Agency, delivered jointly by the North West Space Cluster and the Midlands Space Cluster.

It is recommended that North West England and the Midlands respond individually to the Power4Space opportunity as follows:

North West England

The region's extensive nuclear infrastructure, from research through manufacturing to management and decommissioning, along with adjacent capabilities in advanced engineering manufacturing for the defence sector, makes it an ideal location for developing and testing technologies for space-based applications, with key nuclear hubs including:

- Sellafield (Cumbria)
- Springfields (Lancashire)
- Birchwood (Cheshire)

The North West of England should focus on the development of fuels and associated technologies, capitalising on its existing stores of decay products, on the resulting knowledge of those materials, and on its experience operating remotely in extreme environments, exploring new ways to use these capabilities for space missions.

North West Nuclear Arc and Britain's Energy Coast Business Cluster (BECBC) should be engaged to accelerate the innovation and development of technologies, expertise, and infrastructure required for space based nuclear power and propulsion. These regional networks should commit to exploring how existing manufacturing and digital capabilities can integrate into the supply chains for space-based nuclear power and, eventually, propulsion.

Establish as a leader in developing cooperative skills provisions, servicing both Nuclear and Space, as outlined in "Annex 2: Workshops 2a and 2b: Developing and Delivering Skills" of this report. Relevant institutions include, but are not limited to;

- National College for Nuclear
- Lakes College
- Energus
- University of Lancashire
- University of Cumbria
- Lancaster University (Nuclear Lancaster)
- University of Manchester

With established capabilities in robotics and AI for extreme environments, the North West of England can develop technologies to support the use of space based nuclear systems, for example for remote operations, or materials handling. This would align with local priorities to develop existing expertise in AI, digital technologies, and robotics, especially in software and software development, and in cyber security, which can be used for the development of the secure autonomous systems and remote operations required for space-based nuclear technologies.

Relevant capabilities that may be leveraged include:

- Centre for Robotic Autonomy in Demanding and Long Lasting Environments (CRADLE) – University of Manchester/Amentum
- Dalton Cumbrian Facility – University of Manchester
- Nuclear Lancaster – Lancaster University
- Robotics and AI Collaboration (RAICo) - UKAEA, NDA, Sellafield Ltd, University of Manchester

In this respect, to demonstrate how research institutions across the region might utilise existing capabilities and expertise in support of Power4Space ambitions, the University of Manchester's Dalton Nuclear Institute was commissioned to carry out the following:

1. A review of the effects of ionising radiation on shielding and active materials, on a journey from earth to either the moon or mars,
2. As 1, but for 20 years' residence on either the moon or mars,
3. As 2, focussing on the lunar south pole,
4. An analysis of the UK's capability to support associated materials testing in the relevant radiation environments.

An excerpt from the report from University of Manchester Dalton Nuclear Institute can be found in Annex 3.

Midlands:

The Midlands should capitalise on its strong base in nuclear manufacturing, with companies like Rolls-Royce already focused on the development of space-based nuclear systems.

The region has a network of companies, large and small, with significant roles in the nuclear sector, and national commitment to nuclear energy in space is likely to generate opportunities for both small and large businesses with a need to develop supply chains and skills.

Interventions such as the Midland's Aerospace Alliance (MAA) 'Pivot into Space' have demonstrated significant impact in assisting established businesses to expand into the space sector. Such a programme could provide the basis of a specialised programme, kick-starting the development a Space Nuclear supply chain.

With a focus on supporting the pioneering work at the University of Leicester, the Midlands can build on its existing R&D facilities, such as the to support the development of space-related nuclear technologies.

- Energy Research Accelerator (ERA) - University of Birmingham or the National Nuclear User Facility (NNUF),

The region's established advanced manufacturing base should be supported to develop new components, systems, and technologies for space-based nuclear reactors, and perhaps eventually propulsion systems.

With the STEP fusion plant being built in the Midlands, the knowledge, skills, and facilities developed for Space Nuclear technologies should be carefully aligned to support the STEP project, which in turn could eventually be applied to space-based propulsion. The region would therefore be positioned as a leader in developing both advanced power and propulsion systems throughout this century.

As described in PART 4 of this report, Universities and colleges in the Midlands should build upon their existing nuclear training programmes to develop cross-sector mechanisms to train a workforce capable of designing, building, and operating space-based nuclear systems, as well as future terrestrial nuclear systems.

Conclusion

The authors would like to thank the parties who have taken part in regional workshops and discussions of the nuclear power in space opportunity. This includes several organisations and individuals who have taken significant time out of their schedules and travelled considerable distances.

It was agreed across all workshops and activities that nuclear power systems will likely be an enabling technology for many of the UKs identified critical space capabilities, such as SDA and ISAM, as well as the nascent Lunar economy, and the wider Deep-Space economy that will emerge over the coming decades. Early adopters of these high-powered capabilities will not only have greater options on mission destinations, durations, and operations, but they will likely also become service providers for their non-nuclear competitors, enabling them to extend their own operational distances and mission durations.

Given the UKs established expertise, supply chains, and skills base in the nuclear sector, the development of nuclear power capabilities for space should be a priority for the UK, maximising existing investments into nuclear by taking a place-based approached centred across the network of established sites, such as Cumbria, Lancashire, Cheshire, Derbyshire, and Leicestershire.

Crucially, where possible, the UK must commit to utilising its own nuclear materials, such as Am-241, to power these technologies. In this respect, assurances are sought from HMG, including NDA and UKSA, that the potential for nuclear for space has been fully considered in relation to committing to a Plutonium strategy that may impact access to these materials if not deliberately aligned. Empowering scaled access to Americium in the processing stage of Plutonium disposal and storage will not only support our nation's commitment to the clean-up of the UK's earliest nuclear sites safely, securely and cost effectively, but it will sustain and create jobs and opportunities across some of the UKs most deprived communities. It will unlock new avenues for academic and commercial innovation, and it will further secure the UKs strategic position as a top-tier spacefaring nation.

Furthermore, by carefully aligning with requirements for future terrestrial energy ambitions, the UK can increase productivity across both the Space and Nuclear industries, with investments and advancements in each sector supporting and strengthening the other.

It is clear however that this can only be achieved with significant Government and Industry leadership to gain alignment of Strategy and Policy towards this goal.

The North West and Midlands Space Clusters confirm their continued support for that process and seek to work closely with UKSA and other stakeholders on how alignment can be achieved.

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