Science and Technology Facilities Council

Innovation Clusters | North West Space

MIDLANDS SPACE CLUSTER

Power4Space

Appendices

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

UK SPACE AGENCY

Appendix 1

Space Nuclear (RTIC) Companies – North West England and the Midlands

- Space Nuclear (RTIC) Companies – North West England and The Midlands
- AALCO Metals Limited
- Amari Precision Tubes Limited
- Amentum UK
- Americhem Europe Limited
- Ametek (Gb) Limited
- AURORIUM HOLDINGS UK LIMITED
- B.S.T. Supplies & Co Ltd
- Beckett Gas International Limited
- Belman Technologies Limited
- Bizlink Tailor-Made Cable Uk Limited
- Bluecore Heatsinks Limited
- Businesswise Solutions Ltd
- Bytronic Automation Limited
- Cerberus Nuclear
- Cloos (Uk) Limited
- Core Nuclear Solutions
- Croft Additive Manufacturing Ltd
- CVI Laser Limited
- Cyclife Uk Ltd
- DDC Electronics Limited
- Delkia
- DEVTANK LTD
- Diodes Semiconductors Gb Limited
- Direct Rail Services Limited
- Drurys Engineering Limited
- EOS Electro Optical Systems Limited
- ESR TECHNOLOGY LIMITED
- ETL SYSTEMS LIMITED
- European Thermodynamics Limited
- Filtronic Broadband Limited
- First Water Limited
- Fort Vale Nuclear Limited
- Forth Engineering (Cumbria) Ltd
- Fortum O&M (Uk) Limited
- Fylde Cnc Specialists Limited
- HI-Tech Aerospace Components Limited
- Hollygate Fabrications Limited
- Huntsman Polyurethanes (Uk) Limited
- Hutchinson Engineering Ltd
- Kepston Holdings Limited
- Kingfield Electronics Limited
- Krempel (Uk) Holdings Limited
- L.P.W. Technology Limited
- Laird Limited
- Laker Vent Engineering Limited
- Lcl Electronics Assembly Ltd
- Liberty Tube Components Limited
- Lubrizol Limited

- M & I Materials Limited
- M P Engineering (Uk) Limited
- M. & A. Packaging Services Limited
- Metal Process Services Limited
- Methode Electronics Uk Limited
- Micro Spring & Presswork Company Limited(The)
- Midland Aerospace Limited
- Midlands Components Limited
- Migatronic Welding Equipment Limited
- Moltex Energy Limited
- MOOG Controls Limited
- MST (Engineering) Ltd
- MVG Industries UK Ltd
- United Kingdom National Nuclear Laboratory Limited
- Novocomms Limited
- Oerlikon Metco Coatings Limited
- Pacific Nuclear Transport Limited
- Perpetual Atomics Ltd
- Philip James Precision Engineers Ltd
- Plus Automation Ltd
- Preci-Spark Limited
- RAF General Engineering
- RAI Co
- Rheinmetall Bae Systems Land Ltd
- Rhombi Holdings Limited
- Rolls-Royce Smr Limited
- Roxel (Uk Rocket Motors) Ltd
- Schott Uk Limited
- SGL Carbon Fibers Limited
- Shelton Machines Limited
- SMS - Smart Made Simple Ltd
- Sphera Solutions Uk Limited
- Spincraft Etg Limited
- Steel Dynamics Ltd
- Tekdata Interconnections Ltd
- Texas Instruments Limited
- Thales Dis Cpl Uk Limited
- MTC Ltd
- Thermal Issues Limited
- Trailer Engineering Limited
- TTM TECHNOLOGIES EUROPE Ltd
- Tuv Sud Nuclear TechnologiesÂ
- Tweddle Fabrications Ltd
- U W Developments Limited
- ULO Limited
- Valley Associates Ltd
- W.H.Rooke & Co.(Redditch)Ltd
- Westakes Engineering Ltd
- Westinghouse Springfields

Appendix 2

Workshops

Workshops 1a and 1b: Common Facilities/Infrastructure Requirements

Workshops 1a and 1b focused on identifying facilities, infrastructure, or skills likely required for the design, development, delivery, deployment, and decommissioning of RPSs and/or Microreactors. Consideration was also given where capabilities developed for those technologies could eventually be applied or evolved in support of Nuclear Propulsion.

The following organisations attended these workshops:

- UKRI-STFC
- Rolls Royce
- United Kingdom National Nuclear Laboratory
- University of Leicester
- Amentum
- Dalton Nuclear Institute (University of Manchester)
- Britain's Energy Coast Business Cluster

Key points raised

- For Rolls Royce (RR) to meet current deadline (2031/32) for lunar surface deployment of Microreactor, facilities in the USA will need to be accessed.
- RR have submitted documentation to HMG outlining what they require to meet Artemis 7 deadline.
- UK/EU facilities often exist but are not competitively priced. Often cheaper to fly entire team to US for testing.
- New funding models to facilitate access to UK facilities could enable a responsive, agile, rapid approach to developing these technologies. Programmes such as ANSIC may be considered as a potential framework
- Am241 controlled by HMG via NDA.
- From their Central Lab in Cumbria, United Kingdom National Nuclear Laboratory (UKNNL) is processing Am241 with funding from UK Space Agency. Uni of Leicester building RPS product using UKNNL extracted Am241 as fuel. Current missions (Rosalind Franklin Mars Rover, 2028, and ESA Argonaut lunar lander, 2030s). Requirements for production etc to meet those two missions are understood and in place. Addressing the wider commercial market for both Human and Robotic activities across Medium Earth/Geosynchronous Orbit, the Moon, and Mars would require investment into new facilities to extract and process Am241 at scale (minimum several kg per year)

- Considerable market for nuclear power systems in space exist beyond current institutional missions (ie, NASA, ESA, etc), but engaging HMG to discuss the true scale of opportunity (and therefore upscaling of UK investments, commitment, and activity) is complex due to the range of considerations across HMG regarding nuclear decommissioning scope, defence/proliferation responsibilities, ownership of Am-241, investments into other means of long term handling of nuclear materials etc
- Whilst Rolls Royce and Uni of Leicester/Perpetual Atomics have carried out market analysis for their propositions, publicly available data is difficult to obtain. Subsequently, as the opportunity has not been widely communicated beyond specialist interests, the wider nuclear industry has been unaware of, or reluctant to engage with, Power4Space capabilities.
- Space applications beyond Low Earth Orbit are the most immediately addressable market for these power systems, but future terrestrial applications (including SMRs and Fusion) will likely also require the skills, facilities, and supply chain support mechanisms developed for Power4Space capabilities. Therefore, by prioritising RPS and AMR development in the near term, the UK would build the foundations for a robust, diverse nuclear sector suitable for the 21st century and beyond.
- Given the relatively small scale of Power4Space compared to other UK nuclear activities, it is critical that any new facilities required be delivered around existing sites to leverage the UKs decades long experience in nuclear. These include:
    - Sellafield (Cumbria)
    - Springfields (Lancashire)
    - Birchwood (Cheshire)
    - Derby (Derbyshire)
    - Leicester (Leicestershire)

The following tables of required capabilities was compiled jointly by Roll Royce and United Kingdom National Nuclear Laboratory, with feedback from Amentum, BECBC, and the University of Manchester. Once compiled, these tables were reviewed and edited by University of Leicester/Perpetual Atomics Ltd.

CAT1: Readily available in the UK

CAT2: Potentially available in the UK, with investment or support into existing capabilities

CAT3: Not currently available in the UK, investment required to develop capability

Radioisotope Power Systems

Capability	Nuclear/ Non-Nuclear Environment	UK Capability	Notes
Large scale pellet manufacturing	Nuclear	CAT3	Assuming production of multiple RPSs, each requiring ~ 1kg
Fuel clad welding capability, up to and including sealed source	Nuclear	CAT1/2	Multiple Am-241 pellets will be inserted into rhodium-platinum alloy cladding which will then be welded shut, allowing the unit to be categorised as a sealed source. Provision of a fuel clad welding capability within a glovebox, to seal the fuel clad once assembled and to undertake weld verification. This could be in an existing glovebox or may require a new build. The current lead time for new glovebox manufacture could be up to five years.
Radioisotope heat source assembly / Integration facility	Non-Nuclear	CAT1/2	Sealed fuel clads will be combined with layers of aeroshell and casings then assembled to make a full radioisotope power source unit There are two standard heat source products that have been developed. One is a 3 W thermal RHU the second is a 200 W thermal larger heat source for RTGs and Stirling Generators

Capability	Nuclear/ Non-Nuclear Environment	UK Capability	Notes
Mechanical qualification test facility	Non-Nuclear	CAT2	Prior to export of the RPS/System, acceptance testing should be carried out. This will ensure the RPS is acceptable for integration into the launch vehicle. Carrying out these tests prior to export will ensure any issues found can be addressed in the UK manufacturing facility. Acceptance testing for an RPS typically involves the following areas: • Vibration • Mass properties • Thermal balance testing These tests may require witnessing by an appropriate representative.
Radioisotope heat source/ System storage - prior to shipping.	Non-Nuclear (assuming sealed source)	CAT1/2	Facilities would be radiological facilities for sealed source storage.

Microreactor/Advanced Modular Reactor

Capability	Nuclear/ Non-Nuclear Environment	UK Capability	Notes
Mechanical testing	Non-Nuclear	CAT1	Not applicable
Thermal testing	Non-Nuclear	CAT1	Not applicable
Vacuum testing	Non-Nuclear	CAT1	Not applicable
Vibration testing	Non-Nuclear	CAT1	Not applicable
Dust & gas testing	Non-Nuclear	CAT1	Not applicable
Functional testing	Non-Nuclear	CAT1	Not applicable

Capability	Nuclear/ Non-Nuclear Environment	UK Capability	Notes
Electrical testing	Non-Nuclear	CAT1	Not applicable
Instrumentation testing	Non-Nuclear	CAT1	Not applicable
Controls testing	Non-Nuclear	CAT1	Not applicable
Materials radiation	Nuclear	CAT1/2	Not applicable
Neutron scattering	Nuclear	CAT1/2	Not applicable
Gamma irradiation	Nuclear	CAT1/2	Not applicable

Capability	Nuclear/ Non-Nuclear Environment	UK Capability	Notes
Post irradiation examination	Nuclear	CAT1/2	Not applicable
Remote monitoring	Both	CAT1/2	For many applications, microreactors will be autonomous or run by a small team monitoring single or multiple microreactor sites from one remote location. While this may be a "nice to have" for terrestrial applications, for space and some defence use-cases, autonomous control and remote operations will be key to meeting mission requirements around safety, reliability and operational lifespan. A UK microreactor testbed could trial autonomous operation and control technologies for unattended and reliable operations to support future safety cases for microreactor and other reactor types (e.g. AMR).
Launch load/ impact testing	Non-Nuclear	CAT2/3	Not applicable

Capability	Nuclear/ Non-Nuclear Environment	UK Capability	Notes
In-core Nuclear testing	Nuclear	CAT2/3	Not applicable
Mechanical testing	Nuclear	CAT2/3	Repeat of non-nuclear test
Thermal testing	Nuclear	CAT2/3	Repeat of non-nuclear test
Vacuum testing	Nuclear	CAT2/3	Repeat of non-nuclear test
Fuel form development -	Nuclear	CAT2/3	To develop experimental fuel forms and understanding the effects of poisons on safety cases relevant to the specialist needs of microreactors and the potential to supply small quantities of “boutique” fuels.
Reactor physics modelling	Non-Nuclear	CAT2/3	Skills requirement a key area where UK capability requires support. Microreactor designs require versatile and robust neutron transport solvers.

Capability	Nuclear/ Non-Nuclear Environment	UK Capability	Notes
Fuel behaviour modelling	Non-Nuclear	CAT2/3	Skills requirement– will be crucial to ensuring the reliability, efficiency and safety of microreactors. By accurately simulating the performance of nuclear fuel under extreme conditions (such as low gravity) modelling helps optimise reactor designs capable of enduring prolonged missions and delivering robust power outputs. This is particularly important for applications in remote locations and space fission power systems.
Fuel cycle modelling –	Non-Nuclear	CAT2/3	Skills Requirement - activities would build on long-term UKNNL investment via the Security and Non-Proliferation Focus Area, and under UKNNL's New Build business, for example, using the ORION code to model microreactor systems.
Zero-power ground nuclear testing	Not applicable	CAT3	Not applicable
Electrically heated system test	Not applicable	CAT3	Not applicable

Capability	Nuclear/ Non-Nuclear Environment	UK Capability	Notes
Zero-gravity testing	Non-Nuclear	CAT3	Not applicable
Vibration testing	Nuclear	CAT3	Repeat of non-nuclear test
Launch load/ impact testing	Nuclear	CAT3	Repeat of non-nuclear test
Zero-gravity testing	Nuclear	CAT3	Repeat of non-nuclear test
Dust & gas testing	Nuclear	CAT3	Repeat of non-nuclear test
Functional testing	Nuclear	CAT3	Repeat of non-nuclear test

Capability	Nuclear/ Non-Nuclear Environment	UK Capability	Notes
Electrical testing	Nuclear	CAT3	Repeat of non-nuclear test
Instrumentation testing	Nuclear	CAT3	Repeat of non-nuclear test
Controls testing	Nuclear	CAT3	Repeat of non-nuclear test

Nuclear Propulsion

Piggybacking on the terrestrial applications for nuclear power, in particular those supporting terrestrial decarbonisation, utilise existing UK facilities and host on non-licenced sites where possible to minimise costs.

Capability	Nuclear/ Non-Nuclear Environment	UK Capability	Notes
Critical technology - hot hydrogen flow test rig	Both	CAT2	Small scale lab testing (synergies with the UKAEA high temperature induction test facility) - Aim to derisk potential showstoppers such as thermomechanical durability and erosion resistance of candidate fuel and radiation shield materials. Costs could be minimised if this was hosted at a non nuclear licenced site such as a University but hosting at the UKNNL would also be a possibility.
Critical technology- radiation shield materials	Nuclear	CAT2	Small scale lab (synergies with Dalton Cumbria Facility) testing to derisk potential showstoppers - Aim to derisk potential showstoppers such as thermomechanical durability and erosion resistance of candidate fuel and radiation shield materials.
Critical technology - fuel architectures	Both	CAT2	Small scale lab testing (synergies with the UKAEA high temperature induction test facility) testing to derisk potential showstoppers such as thermomechanical durability and erosion resistance of candidate fuel and radiation shield materials.

Workshops 2a and 2b: Developing and Delivering Skills

Given the specific nature of skills provision in a highly technical sector, Scotby Consulting Ltd were commissioned to design and deliver Workshops 2a and 2b. The following was curated and compiled by Scotby Consulting Ltd as a separate report, as an output of those workshops.

Detailed independent market analysis of the future growth opportunity for Microreactors and RPS has not been made publicly available, but consensus between key organisations is that the potential may be for 1000's jobs and £10'sBn in the nearer term, and £100'sBn in the longer term when considering the wider scope of institutional and commercial Space missions, along with future terrestrial applications.

Consequently, workforce and skills demand to deliver this growth potential will also be significant. Timing of the growth in skills demand, including replacement demand from retirements of an ageing workforce will need early action to build the competent workforce needed to support future delivery.

This section describes a collaborative process in which Employers, Regional Clusters, and Training and Education providers across the North West and the Midlands have worked together across two workshops to identify skills solutions that will enable the future competent workforce to be built to support Power4Space.

A key theme is "getting organised" to deliver a Workforce and Skills Programme supported by both Public and Private sectors in which a formal programme structure, funded and resourced, would coordinate and deliver a series of related Workforce and Skills Projects. This programme can also be aligned to the existing Nuclear Skills Delivery Group and a future Space Strategic Skills Body to encourage collaboration between the Space and Nuclear sectors in developing cross skilled competent people for the future Nuclear for Space workforce.

Current skills gaps are already affecting progress; Electrical and Instrument Engineers, Whole System Engineers, Design Engineers, Scientific, Safety Case, Operations and growing Space knowledge and experience of exiting staff are current priorities identified through the workshop process. Given the "lead time to competence", which can be up to 10 years from recruit to competence, the Skills thread is of the highest priority for action.

The need will be to develop people into "thousands" of new jobs as part of an Operational Nuclear for Space eco-system which acts as a bridge between the Space and Nuclear sectors, enabling collaboration and the joint development of skills and career pathways; an integrated Programme linking up the strategic skills bodies for both sectors.

To develop the roadmap and path forward to scale up this new market is a critical enabler of the many actions needed. To carry out such a roadmap study alongside future market and workforce and skills analysis would provide greater clarity on what should be done, when, how, the scale of the opportunity and the benefits that can be delivered regionally and nationally. Creating the delivery system to support scale up of the market opportunity across manufacturing, testing, facilities, commissioning, and operations to realise full potential is a significant multi agency and supply chain response, developing "Nuclear for Space and terrestrial remote applications".

However, some key issues require greater clarity to realise this full market potential. Those issues are not developed further here but will require in depth agreement across Government on a way forward, for example:

- The necessary Regulatory and Licensing standards and processes for the technologies, launch and operations have not yet been defined
- Uncertainty of support for developing a broader commercial market beyond the initial institutional missions and,
- Re-use of existing nuclear materials to support development of this market has not been agreed beyond the initial missions.

Workforce and Skills – Purpose

To generate meaningful industrial engagement with the technologies covered in the Power4Space project, delivering a programme that convenes relevant organisations from both the Space and Nuclear sectors to ideate collaborative solutions to the common challenges facing the development, delivery, deployment, or decommissioning of UK built space-bound advanced power systems beyond the established institutional missions (Rosalind Franklin – 2028, Argonaut – 2031, proposed Artemis missions – beyond 2031).

The Workforce and Skills milestone has generated a programme of engagement across the Space and Nuclear sectors to examine opportunities for collaboration and identify potentially investable solutions in support of those opportunities, engage relevant parties, and promote the formation of future partnerships.

Our purpose across both collaborative workshops was to;

- Understand the common Technical, Workforce and Skills development and deployment challenges of UKNNL Space Batteries and RR Microreactors
- Identify the potential Workforce and Skills solutions that could be delivered across the NW and the Midlands Space Clusters to support development, deployment and operations
- Consider how Employers and Education and Training providers can work together to support delivery.

Approach and Process

Two joint workshops have been delivered with follow up discussion between both workshops to develop the thinking and present ideas for implementation. The approach has been collaborative, geographically in both the NW and the Midlands, and engaged Employers and Providers as follows:

Workshop 2a – 4 October, Nuclear Skills Academy, Derby

- A small group discussion of the opportunity and challenges faced by employers, their workforce and skills demands, and the strategic issues facing growth
- Rolls Royce, UKNNL, Amentum, NW and the Midlands Space Cluster Managers.

Workshop 2b – 24 October, Energus, Workington, Cumbria

- A wider group of employers and training and education providers to identify the potential collaborative solutions that could support workforce growth and skills development
- University of Central Lancashire, University of Cumbria, National College for Nuclear, Lakes College, Britain's Energy Coast Business Cluster, Rolls Royce, UKNNL, Amentum, NW and the Midlands Space Cluster Managers
- This workshop also involved a presentation delivered remotely by the Nuclear Skills Plan team, the UK Space Agency and the Satellite Applications Catapult.

Although the Universities of Manchester and Leicester were invited, they were unable to attend, but both have been consulted in the sharing of the drafts of this paper. Both workshops above were independently facilitated and a record made from each. This paper summarises the proposed way forward.

Workforce and Skills Challenges

Across both workshops, Employers and Educators discussed the challenge of creating an Operational workforce and delivery culture, whilst recognising the opportunity is subject to both competition and policy uncertainty. This also recognised the "lead time to competence" for new recruits can vary from up to 10 years for a new apprentice, to a few months for qualified people pivoting in from other companies or sectors.

Policy uncertainty related to access to nuclear materials currently the responsibility of the Nuclear Decommissioning Authority, and to uncertainty of support for developing a broader commercial market beyond the initial institutional missions. Both of those will require cross Government departmental agreement.

However, in reviewing the plans of both technology projects in some detail a broad picture of the scale of demand was discussed as follows:

- The current Nuclear sector is planning for workforce growth from its current 80k to 100k people by 2030, which is recruitment of 40k when retirement replacements are included – their plan for Growth is the National Nuclear Strategic Plan for Skills
- The Space sector will also grow steadily from its current 45k and is at an advanced stage in development of its Workforce and Skills Action Plan – both sectors share many common skills gaps
- Nuclear for Space will add to the joint people demand above and could be significant if market development is successful
- Rolls Royce and UKNNL identified a broad growth in demand by 100's of people in the near term and a potential workforce of 1000's in the longer term
- UKNNL's PUMA2 plant will enhance the current laboratory scale facility to a production line of up to 200 people before 2027 and future commercial capacity would require additional lines and staffing
- Rolls Royce current design team will need to grow x4 in the next 2 years to 100's people with future additional growth as the project reaches manufacturing and delivery for the first unit alone
- Current skills gaps were already affecting progress; Electrical and Instrument Engineers, Whole System Engineers, Design Engineers, Scientific, Safety Case, Operations and growing the Space knowledge and experience of exiting staff were identified as current priorities
- The future Nuclear for Space Market for both Microreactors and RPS combined was identified as up to £10'sBn in the near term and up to £100'sBn by 2040 although this was a high level estimate
- Given the "lead time to competence" and the competitiveness of recruitment of a scarce group of skills needs then early action to organise and step up workforce and skills delivery arrangements to match demand would be essential
- Also any new skills arrangements developed to deliver Nuclear for Space would also support the wider growth of both Space and Nuclear allowing for an early "no regrets" opportunity to invest in skills.

The analysis above is not underpinned by Market analysis of the future growth opportunity for Microreactors and RPS, which might include systems for Space and for wider terrestrial applications. If the full market potential has been independently considered and quantified, to the knowledge of the authors of this report it has not been made publicly available, and therefore the scale of the opportunity cannot be fully understood.

Consequently, future Workforce and Skills demands to deliver the growth potential above have not been fully modelled in line with the analysis and therefore timing, growth, demand, and replacement demand from retirements have not yet been quantified in detail.

Both Market and consequent Workforce and Skills analyses studies would be an important place to start for Nuclear for Space development.

The workshops also considered how this Programme can have a lasting impact in regional communities through diversification, economic growth and social value. The group emphasised the importance of a regional approach, engaging with innovative SME's, 3rd sector groups and clusters to create pathways for young people sometimes from hard to reach groups to enter the Space and Nuclear sectors.

This requires an approach that creates access for young people starting out with lower level qualifications, but by providing access routes can engage with Apprenticeships and Technician roles as a pathway to higher qualifications. With a focus on Equality, Diversity and Inclusion throughout, with local community engagement and the creation of jobs in regional supply chains, the aim would be to create a lasting legacy.

The National Nuclear Strategic Plan for Skills

The Nuclear sector has in the previous 12 months established the National Nuclear Strategic Programme for Skills following a joint, government supported, sector wide Task Force. The Director for the delivery of the resulting Nuclear Skills Plan has been engaged in a principal level discussion and remotely presented to workshop 2.

The Plan is structured to support three thematic "legs" of the Nuclear sector; Defence, Remediation and Generation. In each of the three legs a government body acts as the anchor customer which sets the challenge and the deliverables for the sector. Those are the Submarine Delivery Agency, the Nuclear Decommissioning Authority, and Great British Nuclear.

The Nuclear Skills Plan has established a clear Programme structure from Strategic Leadership of the sector to a coordinated delivery network of Regional Hubs and Provider networks.

A clear theme from the Power4Space skills workshops has been to propose a bridge to link together strategic skills delivery arrangements to enable a cross sector joint approach to Nuclear for Space in which Space understanding is matched with Nuclear equipment development, manufacturing and operations. As an example, Nuclear Operational training for operations by astronauts of lunar based Microreactors is just one cross over point.

Space, or Nuclear for Space, could become the 4th thematic leg of the Nuclear Skills Plan but would equally be linked in the same manner to the Space Skills System with the programme bridging between the Space Strategic Skills body and the Nuclear Skills Delivery Group. In this way Nuclear for Space can enable a joint approach.

This can also facilitate a two-way flow of learning and sharing which will benefit both sectors. More information on the Nuclear Skills Plan can be found at nuclearskillsdeliverygroup.com.

In September, the Space Skills Alliance published their proposed Space Skills Roadmap which includes a range of interventions that are similar in approach to the Nuclear Skills Plan; although the language and context may be different, the crossover thematically is strong. The roadmap states the need for a Strategic Skills Body for Space to be recognised or established, which is a proposal strongly supported by the authors of this paper.

The Space Skills Roadmap can be found at spaceskills.org/space-skills-roadmap-2030#summary.

Solutions – Getting Organised, a Programme Approach

As described previously, new skills arrangements developed to deliver Nuclear for Space would also support the wider growth of both Space and Nuclear allowing for an early "no regrets" opportunity to invest in skills.

A Programme approach is proposed as a means of "getting organised" to deliver and to raise the profile of Nuclear for Space as an opportunity and a joint application of new nuclear technology.

Linking together two distinct sectors through common needs and activities is an innovative approach that would make best use of existing and future investments in skills by Government and industry. The opportunity for learning and fast track development is clear.

A proposed Programme structure is shown in figure 1 and describes the Nuclear for Space workforce and skills themes and initial proposed projects.

Nuclear for Space Workforce & Skills

- Projects within a single Programme framework
- Workforce & Skills, a subset of Nuclear for Space Programme
- Bridging across Space and Nuclear Skills Systems

Proposed projects

- At Nuclear for Space overall Programme level
- Joint Task Force, Government, Industry, Education, SMEs and 3rd sector groups
- Cross sector Space and Nuclear group to clarify Policy and Strategy and enable growth

Workforce & Skills Demand

- Market Analysis of future scale and growth
- Modelling and forecast of workforce and skills need
- Linking together Space and Nuclear skills needs

Proposed projects

- Project specific consortium
- Independent Market Analysis study and scenarios
- Consequent Workforce and Skills Model development
- Forecasting/Foresighting of Workforce growth and skills needs
- Linking Space and Nuclear skills to share and learn

Supply Collaboration

- Cross-region skills system collaboration
- Effective delivery vehicles existing and new
- Cross skilling between Space and Nuclear
- Cross sector learning
- International collaboration for skills where appropriate

Proposed projects

- Focus level 5 to level 7 Technician level growth
- Top up of Degree and Masters modules
- Apprenticeships level 5/6
- With Access at level 2/3
- With sector pivot levels 5-7
- Specific skills bootcamps
- Work readiness through behaviours development
- Collaboration across FE/HE via network of institutions
- *Enabling JV adopting NCfN model in Space and linked to nuclear

Skills Facilities

- Investment in best use of existing facilities
- Access regionally, repurposing and enhancing
- Targeted new equipment e.g. simulators, rigs, bespoke equipment

Proposed projects

- *Enabling JV/NCfN model
- Establishing network of regional education delivery partners
- Sharing of curriculum across the network
- Synergy of academic and vocational development
- Collaborative access to existing facilities and branding

Building Capability

- Train the Trainer/Educator
- Growing career pathways into and between Space and Nuclear

Proposed projects

- *Enabling JV/NCfN model
- Development of teaching staff across levels 5 to 7
- Curriculum development coordinated centrally, delivered locally
- Education that grows pathways into Jobs
- Cross sector movement of people Space and Nuclear
- Nuclear Graduates and equivalent for Space

Impact in Regions

- Local Economic growth and growth in jobs
- Working with SMEs and local communities
- Pathways for young people into new careers
- Hard to reach groups
- Equality, Diversity and Inclusion

Proposed projects

- Regional delivery of Education and Training encouraging access to Jobs
- Level 2/3 Access training feeding Apprenticeship and Technician roles
- Working with "Destination Nuclear" and equivalent for Space
- Deployed in regional communities

*Enabling JV/NCfN mentioned above is the same JV in each example.
One enabling central JV using a franchise model to develop curriculum once and deliver in local regions.
JV would be employer led with selected education partners.

Figure 1 Proposed Programme Approach

Solutions – Initial Projects

The projects outlined are those initial projects that would define and initiate the approach, although those will evolve over time as demand dictates. These are described below.

1. Nuclear for Space overall Programme level Joint Task Force

A Strategic Leadership group to develop and drive forward the whole Nuclear for Space environment. This would engage senior leadership in Government, Industry, Education (HE and FE), innovative SMEs, 3rd sector and community cluster input as a cross-sector Nuclear for Space coordinating group.

This group would lead in ensuring the articulation of the market opportunity, alignment of Policy, Strategy and relevant bodies to establish the overall strategic goal and development of a delivery Programme. They would establish direction, alignment to the goal and delivery mechanisms. Skills would be an element of their scope.

They would establish a multi-agency and sector response to map the path towards a Nuclear for Space economy that moves the sector from an R&D development focus towards an Operational delivery focused culture and supply chain employing 1000's of people.

2. Independent Market Analysis

A Project specific consortium to undertake an independent Market Analysis study based on a credible series of future development scenarios. This would cover:

- Direct Space applications and use cases
- Future space applications e.g. propulsion
- And non Space terrestrial applications of the technology.

This supply chain consortium would likely comprise of a small number of organisations with experience across Space and Nuclear to engage with key stakeholders and draw on specialist knowledge to form future scenarios and quantify the range of opportunities. Possible future scenarios:

- Baseline, the current planned institutional missions
- Lower confidence, higher value, full scope commercial use cases
- Whilst forecasting values, risks, probabilities and dependencies, etc
- And the key enabling political, social and industrial considerations.

3. Workforce and Skills Modelling and Forecasting of Workforce and Skills needs

Development and implementation of Workforce and Skills demand modelling for Nuclear for Space based on the outcomes of Market Analysis. This study could either be undertaken as an extension of project 2. above, or could be a follow on study separately defined and managed.

This would review best practice across industry in this type of future demand forecasting, including review of the existing Nuclear Workforce Model and process, and would establish a credible approach for demand modelling linked to the Market Analysis study. The study would take advantage of the latest Skills Foresighting techniques being trialed in the Space sector.

4. Establishing the Nuclear for Space Skills Programme

Resourcing, organising and funding the Nuclear for Space Skills Programme. The theme of Getting Organised and a Programmatic approach depends on stepping up a small team with delivery funding to coordinate and deliver industry efforts to scope, define and implement identified projects. This would include a lead manager and a small supporting team potentially populated from industry secondments.

5. Space and Nuclear Skills Collaboration to share and learn from good practices

Linking together Space and Nuclear Skills through the Nuclear for Space Skills Programme to encourage collaboration, sharing and learning. This Programme can act as a "bridge" between the two sectors to facilitate joint action on common skills issues, joint learning from good practices and the movement of people and trainees between the sectors. Nuclear for Space could act in a facilitation role to bring together the Strategic Skills Bodies for both sectors and create opportunities for joint working. This could cover the following scope as a set of initial ideas:

- Cross sector movement of people between Space and Nuclear to enhance people development. It is recognised that Nuclear is "over recruiting" in the near term given the lead time to competence and in anticipation of future demand which might provide opportunities for cross sector secondments, etc.
- Attraction and Retention through Destination Nuclear and a future equivalent for Space. Destination Nuclear is a national advertising and branding campaign to encourage recruits into Nuclear. Collaboration could encourage the sharing of experience and development of a Space equivalent. Nuclear for Space can also feature in future campaigns as a new destination.
- Extension of Nuclear Graduates into a new Space Graduates equivalent. Nuclear Graduates is a cross nuclear graduate development program involving lengthy secondments with different employers over the initial 2 years of a graduates working experience post graduation.
- Wider learning across the Skills Plans of both sectors to encourage the adoption of best practice in both directions.

6. New Skills Delivery JV for the Space Sector

Creation of a new Space sector skills delivery Joint Venture adopting the National College for Nuclear franchise model, establishing a regional network of FE and HE partners to facilitate local delivery.

This model provides a central coordinating “hub” that does not directly deliver teaching but provides coordination of a network of regional partners located in selected locations, so that teaching is distributed in the locations where it is needed. The central JV would be employer led with a small number of FE and HE partners and leads on development of a common curriculum, developed once and delivered by the regional network.

The hub would focus on the less well established part of the sectors’ education curriculum and would aim to facilitate delivery of career pathways that provide education routes into employment in the Space sector. Nuclear for Space would be an early focus and act as a catalyst to develop the JV model. This might cover:

- A focus on level 5 to level 7 education that supports technician and degree apprenticeships with a top up modular approach to those with degree and masters qualifications
- Development of sector pivot programmes to support those with existing qualifications moving into the Space sector
- Top up education to develop the Space knowledge and understanding of existing staff within Nuclear
- Creation of a network of regional education delivery partners for both FE and HE and collaboration across the network to establish a “develop once and deliver in many places” approach including the sharing of curriculum across the network
- Work readiness through the inherent development of behaviours
- The synergy of academic and vocational development with training and courses designed from bottom up
- Seeking investment in the use of existing facilities to support collaborative access and branding, repurposing and enhancing facilities where needed
- Development of teaching staff across levels 5 to 7 by collaborating across the network in new ways of encouraging growth of teaching capability
- Also where applicable skills boot camps and level 2/3 Access training feeding Apprenticeship and Technician roles to support young people towards higher qualifications

Next steps – proposed way forward

The approach described is a significant undertaking and one which will demand public and private sector support. Greater definition is needed to create clarity of the scale of opportunity and the path forward, although this exercise has supported early action to make rapid progress.

A way forward might prioritise the following steps to be undertaken in parallel:

- The early formation of the overall Programme level task force, project 1, to bring leadership and a coordinated joint process with pace so that they can focus on the roadmap to scale up and capture this opportunity, gaining policy alignment as a matter of priority.
- To define in more detail the specifications for the studies identified as projects 2 and 3, market analysis and the development of a future workforce and skills model and forecast. Those study specifications can be developed in advance of the task force above with leadership from UK Space Agency in lieu of the task force. It is proposed that the NW and Midlands Space Clusters continue to lead detailed work to support and maintain pace in those developments.
- The North West and the Midlands Space Clusters should both be invited to lead the bringing together of a small number of appropriate candidates to discuss the formation of the Space sector skills delivery Joint Venture proposed as project 6. That group should seek agreement on the model and implementation steps, with employer leadership, to bring forward a plan for implementation.
- Collaboration between the Space and Nuclear sectors on workforce and skills learning, project 5, can also be managed alongside the above projects. It is suggested that a broader discussion, led by UKSA and the Nuclear Skills Delivery Group is initiated to consider how this can best be undertaken. The significance of the Strategic Leadership and Alignment that has been achieved in Nuclear cannot be underestimated; this is a very significant enabler for future success on skills. The proposals by the Space Skills Alliance to establish a Strategic Skills Body for Space would be of significant benefit to the sector. There is much learning to be gained on how Nuclear has achieved alignment.
- The creation of a Nuclear for Space programmatic approach will emerge from the actions above. The studies described to understand the market and the future demand for skills will drive the need. The approach above will be enabled by gaining Policy support to align Government to support the wider commercial market for Nuclear for Space.
- It is also proposed that through all the work above the North West and the Midlands Space Clusters continue to focus on the development of their Pan Regional Partnership, and they continue to act in a lead role to work with UKSA to develop the opportunities above.

Workshop 3: Industry Engagement

Convening both North West and Midlands Space Clusters, as well as businesses working in space and/or nuclear, this event provided an introduction to Power4Space project, alongside an overview of the key technologies, insights from previous workshops, and ample networking opportunities.

Date: 03/10/2024

Time: 10:00 to 16:00

Location: The Engine Rooms, Birchwood Park, Cheshire

For list of companies registered to attend, see Appendix 2.

Following initial networking over refreshments, delegates received an introduction from both the North West Space Cluster Manager, and the Midlands Space Cluster Manager, outlining the structure and function of their respective regional Space Clusters.

The North West Space Cluster Manager gave an overview of the Power4Space project, including a draft version of the 'Facilities' list and insights from Workshops 1a, 1b, 2a, and 2b, whilst the Midlands Space Cluster Manager gave an overview of their 'Pivot Into Space' programme, including a list of businesses who have received support via the programme, the technologies explored, and reflections from the users.

There followed technical overviews of both RPSs and AMRs, given remotely by United Kingdom National Nuclear Laboratory and Rolls Royce Ltd, respectively.

A series of pre-agreed 'Lightning Pitches' were then delivered by selected delegates, with each speaker being allocated two minutes and a single slide to introduce themselves. Those 'Lightning Pitches' were delivered by:

1. Amazon Web Services
2. University of Cumbria
3. 3D360 Ltd
4. Flintloque
5. ADM Project Consultants
6. Civil Aviation Authority (CAA)
7. Defence And Security Accelerator (DASA)
8. Light Coatings Ltd
9. Department for Business and Trade (DBT)
10. Tuv Sud Nuclear Technologies
11. Liverpool John Moores University
12. Hyde Aero Products

13. ESA Business Applications
14. PWHytek
15. Space Specialists Ltd
16. Technia UK Ltd

There then followed an 'Open Floor', where delegates who had not presented 'Lightning Pitches' were given 30 seconds to take to the stage and introduce themselves to their fellow attendees. Over two dozen delegates took this opportunity.

Following lunch and further networking, keynote presentations were delivered by ESR Technologies Ltd, and Amentum Ltd. Both organisations are based at Birchwood Park and have complimentary capabilities across Space and Nuclear.

ESR Technologies Ltd, an SME, used this opportunity to highlight their 52 years hosting the European Space Tribology Laboratory, as well as their latest venture, ESR Space, focusing on developing and delivering mechanisms and lubricants for the commercial space market.

Multinational corporation Amentum Ltd, formerly Jacobs, used the opportunity to explain their recent acquisition and rebranding, as well as their wide range of space and nuclear capabilities, both in the UK and internationally.

Both ESR Technologies Ltd, and Amentum Ltd, clearly and repeatedly expressed their desire for collaboration and cooperation across geographical regions and industrial sectors.

After thanking all the speakers, delegates were encouraged to attend the remaining Power4Space workshops to be held in late October in Leicester and Harwell, upon which, the event ended.

Workshops 4a and 4b: Developing Power4Space Use Cases

In late October 2024, Workshops 4a and 4b were delivered, inviting industry and academy to ideate potential uses for Power4Space technologies, framed around the following:

- Imagine if you had long-term access to power and heat, from watts to kilowatts, anywhere in the Solar System.
- What capabilities, missions, or markets could your organisation develop if you were no longer limited by access to sunlight?
- What would you launch? Where would you go? What would you do?

Workshop #1:

Date: 30/10/24

Venue: Space Park Leicester

Attendees:

1. TuvSud
2. Pinnacle Freight
3. University of Leicester/Perpetual Atomics
4. Rolls Royce (Online presentation/Q&A only)

Workshop #2:

Date: 31/10/24

Venue: Harwell Campus, Oxfordshire

Attendees:

1. RAL Space
2. Thales Alenia Space
3. Space Specialists Ltd
4. Red Dog Transformation Ltd
5. Airbus Space & Defence
6. Red Kite Management Consulting
7. UK Space Agency
8. Lucideon
9. Magdrive
10. Know.Space
11. D-Risq Ltd
12. Hollyhock Consultants Ltd
13. Graviscalar
14. University of Portsmouth/Space South Central
15. Rolls Royce (Online presentation/Q&A only)

The workshops began by outlining the status of both Radioisotope Power Systems (RPS) and Microreactors, with presentations and/or Q&As from, or on behalf of, Rolls Royce, United Kingdom National Nuclear Laboratory and/or University of Leicester/Perpetual Atomics concerning the technology, and the missions currently in pipeline for both systems.

Following this, the workshops focused on the development of use cases to showcase how academic or commercial organisations might leverage these technologies to develop new capabilities, create new partnerships, or capture new markets.

Questions arose from TuvSud, asking if there were any relevant paper studies that demonstrated a lack of power availability as a critical challenge. UoL/PA advised that this may be the case for some In Situ Resource Utilisation (ISRU) studies, but that NASAs Surface Fission Power (SFP) programme is directly addressing these concerns, and that ISRU is part of the 'Global Space Exploration Roadmap'.

Questions also arose querying the level of Human interaction required with a Microreactor on the Lunar surface. It is understood from Rolls Royce that minimal Human interaction is preferable, with Microreactors being stationed at a distance from Human habitats, likely with a line-of-sight shielding structure. Command and control of the reactor would be highly autonomous, with levels of Human interaction taking place remotely from the Lunar base, the orbiting Lunar Gateway, and from terrestrial support infrastructure, with the highest concentration of interaction taking place the further they are from the reactor. As a result, secure communications and cybersecurity were cited by the group as an opportunity, albeit beyond the scope of this workshop.

In addition, a discussion developed concerning launch approval from Earth, which, it was agreed, is likely the biggest threat to the Power4Space market. It was observed that launch approval processes are well established in the United States for RPSs, as they have over 50 years of experience launching Pu-238 powered systems. However, there may be challenges concerning the transfer of ownership of material from the UK to the US for Am-241 systems. It was noted that these processes are being addressed and tested as part of the Rosalind Franklin mission; an ESA led rover mission to Mars, launched on a US launch vehicle, and carrying an Am-241 RPS. For similar questions regarding Microreactors, it was noted that "Principles Relevant to the Use of Nuclear Power Sources in Outer Space" (1992) states that nuclear power systems must only achieve criticality after launch. In the case of FSP, the group assumed criticality would only be achieved following installation on the Lunar surface. A question arose regarding transfer of ownership of a UK built microreactor to fly on a US launch vehicle. Assuming enriched Uranium as a fuel, two scenarios were assumed:

1. The Microreactor is built and fuelled in the UK, to then be transferred to the US for integration and launch
2. The Microreactor is built in the UK, and then transferred to the US for fuelling, integration and launch

It was agreed by the group that scenario 2 would present fewer challenges for the transporting and transfer of the Microreactor, thus streamlining regulatory requirements. However, scenario 1, whilst more challenging, might be advantageous to UK industry and academia, enhancing sovereign capabilities that might underpin a range of civil and defence considerations.

In this regard, and considering a potential reintroduction of 'America First' policies, it was considered that there may be value in examining Europe as an alternative route to market for these systems. Whilst NASA is licenced to launch nuclear technologies from KSC on a limited range of launch vehicles, the ESA launch facility at Guiana and the Arianne launch vehicles may be considered for launching future nuclear systems.

Further questions were raised around the development of appropriate safety cases:

- As no one has been through the process to developing non-US nuclear systems for space, and transferring them to the US for launch, are the Office of Nuclear Regulation working in parallel with the US Department of Energy?

Use Cases for Power4Space Systems

Given the reduced numbers at the first workshop, it was agreed the attendees would form a single group for the day.

The following high-level topics were suggested by the group:

Lunar Polar Craters:

- Residual heat from nuclear power systems for thermal mining

Outer Solar System:

- Communications relay network (~ 30 year life span)

Earth Orbit:

- Defence applications
- Extended manoeuvring

In-Orbit Servicing Manufacturing (ISAM):

- Use of these systems to power orbital construction infrastructure

It was agreed that the following Use Cases would be developed through the Workshop:

Microreactor:

- High Power Extraction of chemicals from Lunar regolith using molten electrolysis

RPS:

- Thermal Garages for non-RPS powered mobile systems (rovers etc) to survive Lunar night, or long duration missions in deep shadow

Use Case #1: Microreactor - High Power Extraction for the Lunar Surface

Summary:

Research from the group identified the Colorado School of Mines 'Lunar Alloy Metal Propulsion Plant (LAMPP)'[1] study as a baseline for this Use Case.

LAMPP proposes a Lunar surface Molten Regolith Electrolysis (MRE) reactor to extract materials directly from Lunar regolith. This approach enables the extraction of resources and some consumables anywhere on the Lunar surface, rather than only from water ice deposits, as found around the Lunar south pole, thereby expanding opportunities for Human exploration, or resource extraction.

Requiring 15 ~ 20kw, LAMPP is envisaged to work with a reaction temperature between 1,300°C and 1,700°C, producing ~5,900kg of metal, ~8,700kg of oxygen, and ~4,700kg slag per year. This totals in ~19,500 kg of total material output per year. The LAMPP assumes operating for 288 hours, before cooling throughout the Lunar night. Thus, 15 cycles may be assumed per year.

The group agreed that the use of a Microreactor might enable LAMPP to spread its production cycling throughout the Lunar day/night cycle, thus increasing yearly yields and reducing thermal stress on the system, potentially extending its operation lifetime. In addition, given LAMPPs 15-20kw power requirement, a Microreactor (operating at 40kw) could allow multiple LAMPPs to operate in a given location. Batch resourcing of power, coupled with cooling cycling, might allow four LAMPPs to operate (two on, two off), further increasing yields per year.

It was estimated that such a LAMPP/Microreactor cluster could produce ~29,500 kg of metal, ~43,500 kg of oxygen, and ~23,500 slag per year. This totals to ~97,500 kg of total material output per year.

The group also discussed the possibility of clustering other industrial infrastructure around the Microreactor, thereby enabling self-contained operations for a range activities at any location on the Lunar surface.
This may also be extended to Human operations or extend Lunar surface exploration.

1. Lunar Alloy Metal Production Plant (LAMPP), Colorado School of Mines, 2023

Road Map:

The group comprised representatives from TuvSud, a nuclear services consultancy, and University of Leicester/Perpetual Atomics, and chose to map the required developments for the deployment of a Microreactor powered MRE cluster on the Lunar surface in 2040, which is summarised as follows:

The development and launch process for the microreactor (MR) begins with early-phase MR design, followed by defining launch approval requirements from U.S. regulators such as the DoE, FAA, or DoD. This leads to design iteration and extensive safety testing and analysis, forming a safety data pack that undergoes a review by U.S. launch regulators — a process that can take years and cost tens of millions of pounds. Once the MR is manufactured, it is qualified in its unfuelled state, then fuelled, and subsequently qualified again as a fuelled MR. The MR then departs the UK licensed site and is transported to the U.S., involving a transfer of ownership under the appropriate authority (DoE, FAA, or DoD). Upon arrival, it is stored in a licensed facility near the launch site. Later, the MR is integrated onto the launch vehicle and ultimately launched in 2038, with deployment of the Molten Regoltih Electrolysis reactor on the lunar surface expected by 2040.

1. Early phase Microreactor (MR) design

2. Defining launch approval requirements for design (DoE? FAA? DoD?)

3. US Launch regulator review of safety data pack

Process taking years and £10s millions

Design iteration → Safety testing and analysis

4. Manufacture of MR

5. Qualification of unfuelled MR

6. Fuelling of MR

7. Qualification of fuelled MR

8. MR leaves UK licenced site

9. Transport of MR from UK to US + transfer of ownership (DOE? FAA? DoD?)

10. MR stored in licensed facility near launch site

11. Intergration of MR onto launch vehicle

12. 2038: MR on Lunar surface

13. 2040: Launch of MRE reactor

Use Case #2: RPS – Thermal Garages

Summary

An RPS, or a cluster of RPSs, could be used to provide electrical and thermal power on demand to service non-RPS powered mobile systems, such as rovers, allowing them to survive the lunar night, or to enable extended operations in deep shadow locations.

The RPS Thermal Garage would be a physical shelter on the Lunar surface with an RPS at its core, to maintain approximate 'room temperature', around which rovers and other mobile systems could huddle, with the possibility of interfaces for charging to keep users in stand-by without draining onboard battery power. Similarly, the Thermal Garages could also include comms infrastructure, allowing the users to transfer data. During the Lunar Day, the Thermal Garages could serve as part of the wider Lunar comms infrastructure.

RPS Thermal Garages might be located throughout industrial zones, or sites of special scientific interest, as part of established operations to service fleets of autonomous assets. A network of RPS Thermal Garages might also be established at strategic locations across the lunar surface, allowing ad-hoc use by long distance exploration or prospecting missions.

In this way, the RPS Thermal Garages unlock the thermal uses and mission longevity of RPS systems for operators relying on 'traditional' non-thermal power sources, such as solar with battery storage.

It was noted that the Thermal Garage concept was also applicable to the above Microreactor use case, using either excess power from the Microreactor for the Garage, or using excess heat from the MRE.

Road Map

Some consideration was given to the requirements for enabling the production of RPSs and Microreactors at scale (beyond the current commitments or ambitions to ESA or NASA missions):

1. National commitment to Power4Space at scale
2. HMG allow access to fuels (via NDA)
3. Confirmation of fuel availability (Am241 and/or HALEU)
4. UK facility(s) to manufacture + fuel MR and RPS at scale

Use Cases from Workshop #2

The Workshop consisted of 4 groups, assigned randomly. The Groups were as follows:

Group 1

- John Vrublevskis – Thales Alenia Space
- Sreekumar Thaithara Balan – Graviscalar
- Robin Tucker – Red Kite Consulting

Group 2

- Ernst Pozzoni – Red Dog Transformation
- Yuvraj Jain – RAL Space
- George Kersey – RAL Space
- Maxi Erazu – RAL Space

Group 3

- Adam Baker – Magdrive
- Ralph Turral – Know.Space
- David Pearmain – Lucideon
- Steve Gibson – Hollyhock Consultants

Group 4

- Ray Stott – Space Specialists Ltd
- Nick Tudor – D-Risq Ltd
- James Greer – Airbus Space & Defence
- Dan Smith – University of Portsmouth/Space South Central

For the first exercise, the Use Cases from the previous workshop were shared, and each group was then asked to create 5 high level Use Cases for Microreactors and/or RPS:

Group 1

1. Data Centres in Low Earth Orbit (LEO)
2. Satellite with no solar panels (for a post-Kessler orbital environment)
3. Lunar Far Side Observatory
4. Mars Transfer Vehicle, using Nuclear Electric Power, or Steam Jet
5. Asteroid Mining, including propulsion, extraction and processing

Group 2

1. Accelerated Logistics, and Direct Trajectories
2. Standardised probe/spacecraft design
3. Communications relays, transponders, and receivers
4. Lunar Base
5. Orbital Technology Development Labs (materials, biomanufacturing, etc)

Group 3

1. Communications relay: Mars, Jupiter, Saturn
2. Persistent military satellites
3. Building large scale Solar energy infrastructure in space
4. Data centres in GEO
5. Rapid Deep Space Propulsion

Group 4

1. Powering safety critical exploration infrastructure (ie, spacesuits)
2. Asteroid mining: In-situ mineral utilisation, separation from regolith etc
3. Nuclear powered space tug
4. In-orbit servicing and manufacturing (ISAM)
5. Planetary Defence, including laser-based debris removal and asteroid deflection

After lunch, each group presented their chosen 5 high level use cases, they then passed their chosen 5 onto the next group, in an anti-clock wise direction. Each group was then asked to choose 2 use cases from the 5 they had received from the other group, and develop them further.

Group 1

Use Case #1: Safety Critical Exploration Infrastructure

RPS utilising 16.5kg of Am-241, supplying 245w of energy

Charge equipment (24v) and provide warmth

Universal charging infrastructure

Modular/stackable (simultaneously accommodating different sized users)

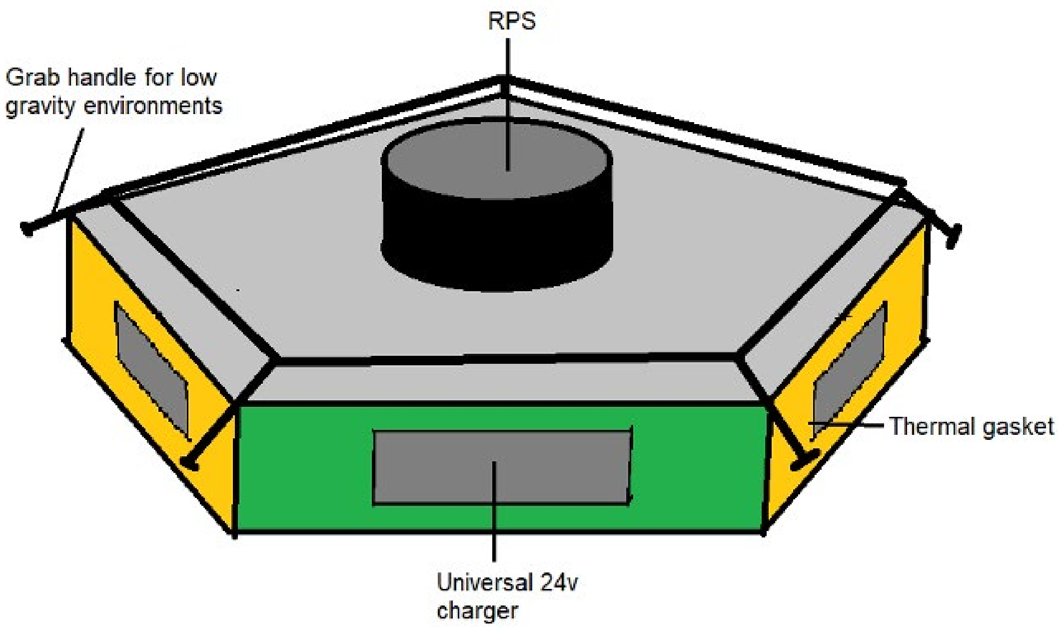
Use on Moon, Mars, in Space

Possible Earth applications (eg maritime)

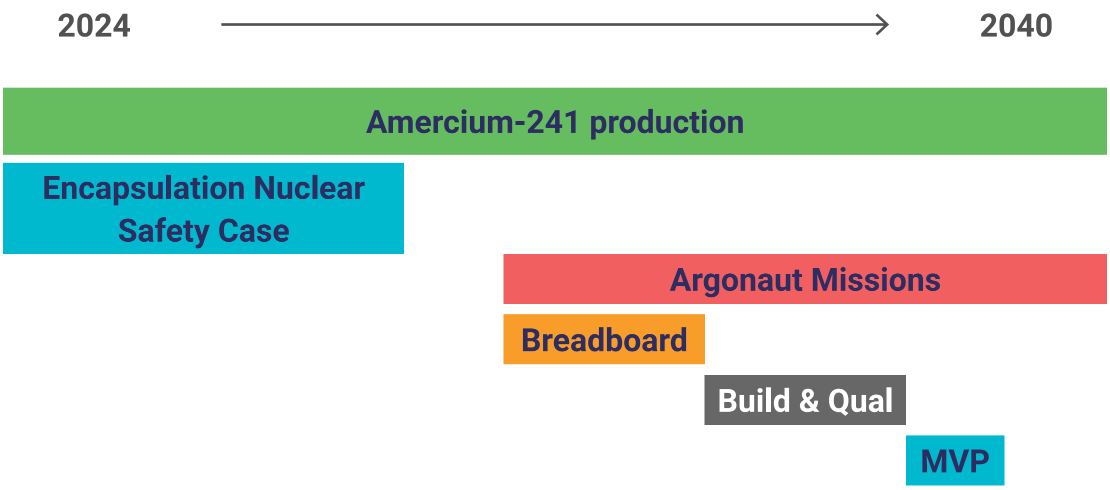
Potential incorporation within ‘Thermal Garages’ Use Case

Challenges:

- Shielding from Alpha emissions
- Regolith contamination of charging ports (wireless charging considered)
- Temperature extremes



Potential timeline:



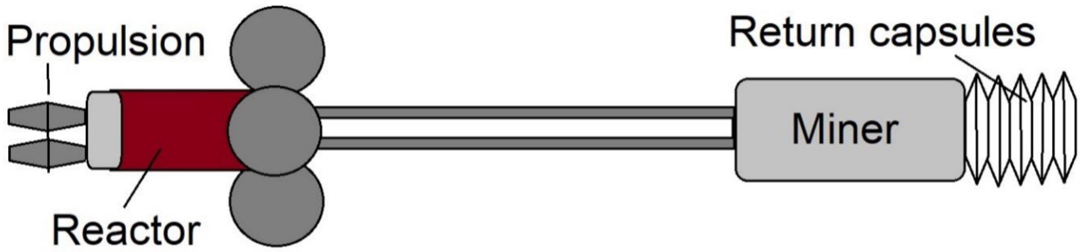
Use Care #2: Asteroid Mining – Propulsion and Surface Operations

- In-space application for Microreactor
- Nuclear Electric Propulsion (NEP)
- Nuclear power for surface operations (extraction + processing)

Objective: Every 4 years, mine 100 tonnes of Platinum and Rare Earths from an asteroid and return the material to Earth orbit.

Spacecraft configuration:

- Assembled in orbit
- Length to reduce potential impact of radiation
- Reactor/Propulsion/Miner refuellable and reusable
- Low power thrusters close to and on asteroid
- Mission profile (very approximate): 0.5-1 year outbound, 2 years mining/processing, 0.5-1 year return, 0.5 year refurbishment.



Power considerations:

- Power required 100t x 8t/MJ = 800,000MJ
- Power available over 2 years
  - 40kw x 3600 x 24 x 365 x 2 = 2,600,000MJ

Challenges:

- Is 40kw NEP appropriate for this configuration?
- Assembly in orbit (similar to ISS?)
- Autonomous Mining Operations (in very low gravity)
  - Exploration (precursor missions, tech development missions?)
  - Discovery
  - Development
  - Production
- Regulation – who has rights to ET minerals?
- Market impact (scarcity vs utility)
- Competition

Group 2

Use Case #1: Lunar Far Side Radio Astronomy

Considering RPS suitability to support a Lunar Far Side Radio telescope, such as the proposed LCRT.

- Lunar South Pole
- Crater spanning mesh (approx. 1km), deployed using rovers
- 20 year lifetime
- 6Mhz to 30Mhz (critical cosmological frequency) scope to increase frequency
  - Radio emissions from extrasolar planets
- Multiple antennas
  - ~100w/antenna
  - x1 RPS/antenna
- In situ data storage and processing?

Impact

- Science - Such a telescope can observe the universe at wavelengths greater than 10m (i.e., frequencies below 30MHz), which are reflected by the Earth's ionosphere and are hitherto largely unexplored by humans, and the Moon acts as a physical shield that isolates the lunar-surface telescope from radio interferences/noises from Earth-based sources, ionosphere, Earth-orbiting satellites, and Sun's radio-noise during the lunar night
- The development of new enabling technologies

Feasibility

- Currently under review by NASA

Innovation

- Robotics for deployment and maintenance

Key Technologies and Resources

- Lunar crater
- RPS manufacture (terrestrial)
- Robotics
- Shielding
- Materials (+1km mesh antenna structure constructed and suspended over lunar crater)
- Data processing and storage (potential further use for RPS or Microreactor)

Challenges

- Identifying a suitable crater
- Construction and maintenance
- Cost
- Lunar environment (electrostatic dust, temperature extremes, micro-meteoroids, solar and cosmological radiation
- RF interference from increasingly cis-Lunar activities
- Regulation and policy
- Commissioning, reuse, or recycling

	Design, Development, Verification, and Validation	Implementation	Operations	Decommissioning
Nuclear	RTG Procurement Facility design for Lunar Surface	Construction of Lunar facility to hold nuclear system Launch of nuclear system	Operation and maintain nuclear system	Removal or replacement of nuclear system
Robotics	Design + construction of robotics v&v campaign for robotics Facility for v+v campaign	Launch and deployment of robotic infrastructure	Autonomous + robotic maintainance and monitoring of LCRT + associated facilties	Robotic decommissioning of facilitiy
Antenna	Research antenna design and materials v&v antenna design Control centre design Facility for v+v campaign	Launch antenna materials Construction of antenna + control centres on Lunar surface	Observational operations with processing, storage and transmission of data	Potentially dismantle antenna and re-use material Maintain antenna if mission extended
Regs + Policy	UK Nuclear Safety ITU IAEA UNOOSA	Operator’s license	Not applicable	Renewal of operating agreement

Use Case #2: General Purpose Collision Resistant Satellite (SolSat Platform)

Feasible

- No solar panels or deployed radiators
- Capable of operations anywhere in the solar system
- 100kw Microreactor
- 1600k reactor outlet temp, HEXE gas or Na vapour
- 1400k Mo-TZM alloy wall mounted radiators
- General purpose platform – 3mx1.3mx1.5m (not including microreactor) GEO bus, 10 year missions

Impact

- Reduced development and deployment costs
- 117kw electrical output in a single, compact spacecraft
- Collision and fragmentation design, useful in ‘dirty’ space environments
- Self-contained autonomous platform for commercial applications
- Comms, transponders, laser science, manufacturing/ISAM materials depot

Challenges

- Radiator manufacturing and raw materials cost
- UN, ONR, CAA launch restrictions & lack of regulation (Env, Nuclear, and flight)
- Turbine reliability & service requirement removal
- Reactor flight qualifications (vibrations & T-VAC) – T-VAC can’t handle 100kw
- Capital costs & market access for business
- Launch systems with a nuclear rating and +3 tonne payload mass
- Orbital operations restrictions (no nuclear in LEO)
- Competitive analysis
- Stakeholder Assessment
- Long term market forecasting and ROI

	2024 →					2035
Nuclear	Mo-TZM Radiator demo Reactor demo concept Raw material and supply chain establishment	EM Model Design Subsystem Env Test	FM Model Design QM Env Test	Launch vehicle intergration	Launch	Platform operational
Launch	Market Analysis Satellite Size Definition	Launch vehicle selection	Site selection	Launch vehicle intergration	Launch	Not applicable
Market	Project Planning Competitive analysis	Funding/ bidding Impact Quantification	Sustainability / Decommissioning	Consolidate supply chain	Launch	Sell services
Policy/ Regs	CAA + ONR decides regs	UKSA funds multiyear programme	UK/US/NSG policy & legal pact	Site & range licencing Launch licence approved	Launch	Liability & insurance regs

Group 3

Use Case #1: Data Centres in Geo Synchronous Orbit (GEO)

- Nuclear powered data centres and Outer Solar System communications relays
- Secure isolation of storage data (aka, 'Air Gapping')
  - Single point of entry (cyber security implications)
  - Highly remote locations reduce possibility of physical interference (5 publicly acknowledged physical attacks on terrestrial data centres between 2006 & 2016)
- More environmentally sustainable than terrestrial data centres
- Microreactor reduces the in-orbit assembly required
- What is the willingness to pay (WTP?)
  - Does the volume or value of the data justify it being stored in space?
  - Is government the likely highest WTP for off-world data storage?

Challenges

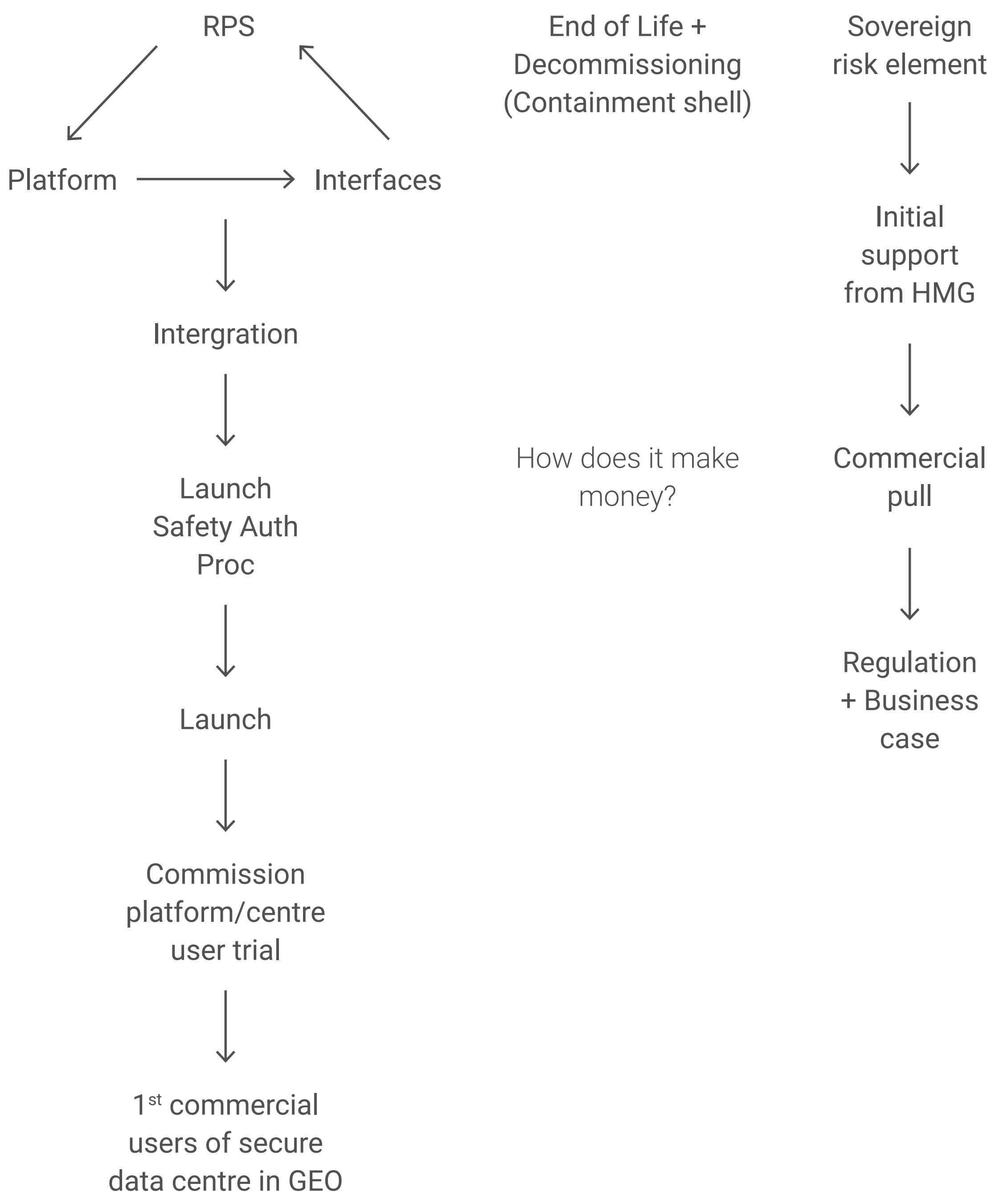
- Will radiation from Microreactor impact data?
- Data storage and communications.
- Nuclear powered generates heat and radiation.
  - Select a location where heat elucidates better?
    - » Lunar surface (under regolith?)
    - » Sun-Earth L2?
- Size and weight concerns for launch
- Willingness to pay
  - Can private companies afford the investment?
  - Are governments therefore the mostly likely source of investment?

High level development roadmap:

The GEO Data Centre development process begins with the integration of key components, including the Remote Processing System (RPS), platform, and interfaces. Following integration, the launch safety authorization procedure is initiated and completed, leading to the actual launch of the system. After launch, the platform and data centre undergo user trials to ensure functionality and performance, which then enables the onboarding of the first commercial users of the secure data centre in geostationary orbit (GEO). As the system reaches the end of its operational life, decommissioning procedures, including the use of a containment shell, are implemented to safely retire the infrastructure.

In parallel, the commercial and regulatory pathway involves addressing the sovereign risk element and securing initial support from Her Majesty's Government (HMG). This support facilitates the creation of a commercial pull by exploring how the GEO Data Centre will generate revenue. Ultimately, a regulatory framework and a comprehensive business case are developed to support long-term commercial viability and governance.

GEO Data Centre



Use Case #2: Uninterrupted power for building & operating a Lunar regolith building

Establishing a UK built presence on the Lunar surface, using in-situ resources and manufacturing

- Utilising a 40kw Microreactor
- Feasibility → Decommissioning → End of Life procedure
- What does it enable? → Regolith Building Blocks
- Requires lunar surface welding and refining
- Furnaces to manufacture building materials
    - 1.2Mj/kg to make concrete
    - 9Mj/kg for metal
- Structural integrity of building required for low g?

Impact:

- Promotes innovation

Challenges:

- Microreactor fuelled on the ground
- Planetary protection (although environmental protection argument is smaller for The Moon)
- Lunar geographical/political competition
- Suitability of particular regolith
- Multi-molecular chemistry very different on Moon. Jaggered, non uniform. Very sharp and abrasive.

High level development roadmap:

The regolith building process begins with R&D funding of TRL 1-3 projects in the mid-2020s through academic and industry partnerships. This enables the establishment of lab-based techniques using regolith simulant. These techniques support the development of a process for regolith capture and refinement, alongside collaboration between the UK and US to create a standard for regolith use. This foundation leads to the production of building materials on the Moon and the prototyping of simulant materials there. Concurrently, policies are needed in the UK to support nuclear power in space, which triggers the UK Lunar Lander Pathfinder mission. This mission fosters appetite for lunar development and contributes to the establishment of a lunar site as part of Artemis 3 and beyond. The site development includes the creation of transportation infrastructure, leading to construction activities such as site surveys, laying foundations, and ultimately fitting out structures with wiring and other essentials. This process culminates in an eventual opening ceremony at an unspecified future date before the middle of the century.

Regolith Building

2025: R+D funding of TRL 1-3 projects (Academic/Industry Partnerships)

↓

Establish lab based techniques using regolith simulation

↙ ↘

UK/US collab for regolith standard

Establish process of regolith capture and refinement

↘ ↙

UK needs policy to establish support for nuclear power in space

Fosters appitite ↓ Triggers Pathfinder

UK Lunar Lander Pathfinder

↓

Establishment of lunar site (Artemis 3+)

↓

Establish transportation infrastructure

↓

Prototype simulation on the Moon

↓

Production of building materials on the Moon

↓

Site survey + foundation

↓

Construction

↓

Fit out (wiring, etc)

↓

20??: Opening ceremony

Group 4

Use Case #1: Ubiquitous, Safe, Plug + Play Power Supply for Space Exploration

RPS powered universal charging infrastructure and interface for use surface or in-space use

Mass produced Am-241 powered RPS could enable UK to become a leading supplier for Artemis and beyond

Feasibility

- UK based Am241 supply chain being developed
- Low human impact of radiation from RPS
- Can be mass produced
- Can be made 'plug+play'
- Commercial export market
  - Demonstrable ROI for investors

Impact

- Wide variety of applications
  - Emergency comms for Human exploration
- Plug+Play interoperability for off-world infrastructure
- Enabling technology for innovation and capabilities

Required Key Technologies + Resources:

- Shielding for Human applications
  - Decay products
- Thermal management
- Access to Am241
- Control of Am241 material quality in supply chain
- Additive Manufacturing for off-world manufacturing
- Standardisation of interfaces and both robotic and human applications
  - Development of ECSS Standards for Nuclear Power (and Electrical in general)
- Disposal mitigation, including locations
- Development funding
- Identifying Market adoption opportunities
- Regulation for ubiquitous adoption
- Political considerations (and opportunities)
- Technological theft by competitors
- Opportunities for international partnerships

High Level Development Roadmap:

The process map titled **"Ubiquitous, Safe, Plug + Play Power Supply for Space Exploration"** outlines a comprehensive roadmap for developing and deploying a Radioisotope Power System (RPS) for space missions. The journey begins with the **formation of an industrial consortium** and the **securing of funding** for a research and development program. A critical early milestone is the **confirmation of access to Americium-241 (Am241)** from the UK government (HMG), which is essential for the power system.

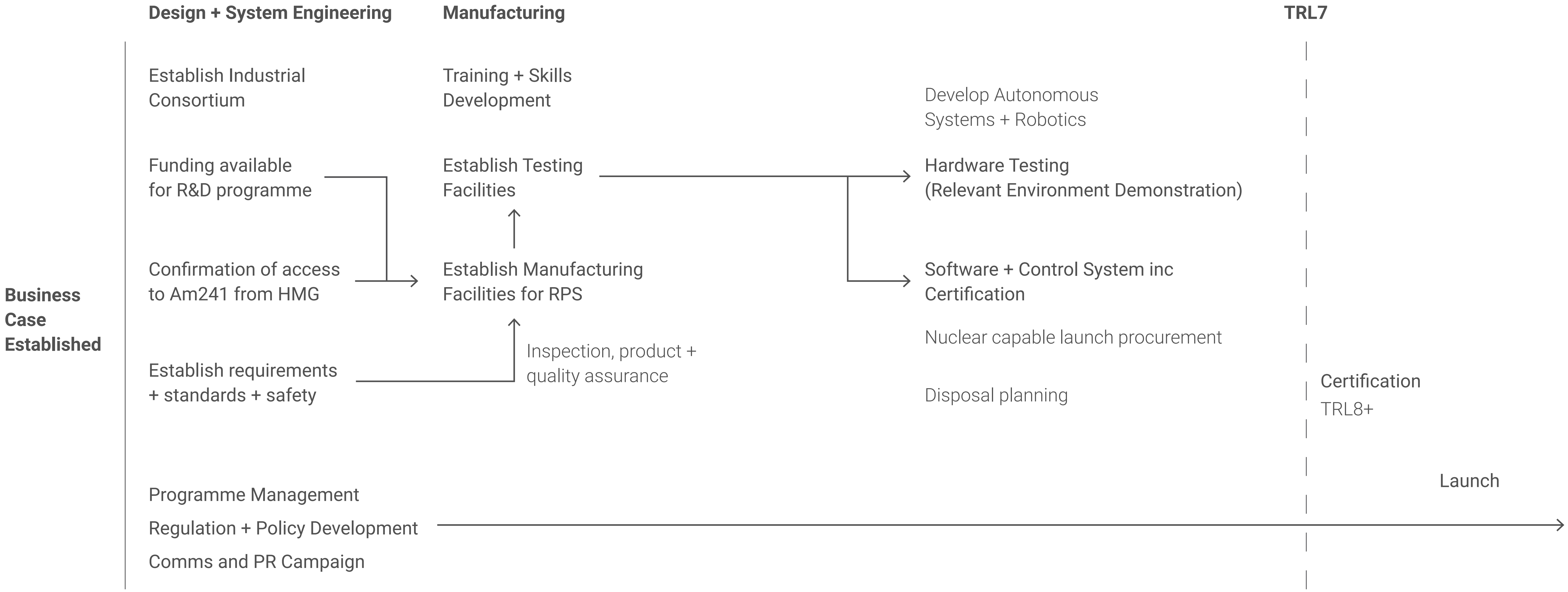
Following this, the project moves into the r**equirements and standards definition phase**, where safety protocols are established. Simultaneously, **program management activities** are initiated, including regulatory compliance, policy development, communication strategies, and public relations campaigns to support the initiative.

In the **manufacturing phase**, emphasis is placed on **training and skills development**, followed by the **establishment of testing facilities**. Once these are in place, **manufacturing facilities for the RPS** are developed, incorporating i**nspection and product quality assurance** processes. Planning for the **disposal of radioactive materials** is also integrated into this phase.

The next stage focuses on **developing autonomous systems and robotics**, which are essential for handling and deploying the RPS in space environments. This is followed by **hardware testing in relevant environments** to ensure reliability. **Software and control systems** are then subjected to rigorous **certification processes**.

With these systems in place, the project **proceeds to procure a nuclear-capable launch vehicle**. The final steps involve achieving **Technology Readiness Level 7 (TRL7)**, followed by **certification at TRL8+**, culminating in the **launch phase** of the RPS into space.

Ubiquitous, Safe, Plug + Play Power Supply for Space Exploration



Use Case #2: PRISM – Persistent, Resilient, In-Space for Military

Independent high power supply for military applications

- Develop the capability to provide high power, resilient capability for the long-term

Feasibility

- Rolls Royce have heritage and expertise in producing small nuclear reactors
- Microreactor (~40kw) currently under development for Lunar surface deployment (early 2030s)

Impact

- Improved Sovereign and Allied capabilities
- Platform for multiple technologies
  - Laser comms
  - Defence

Required Key Technologies and Resources

- Microreactor
- Thermal management + power management
  - For Microreactor
  - For Payload
    - » Radiators
- Secure and safe control system
  - Software
- Access to nuclear fuel (assumed U238)
- Political will + regulatory framework
  - Licencing
  - Legal and certification
- Workforce, skills, training, certification
- Security clearance of available personnel
- Servicing and maintenance of the design
- Development funding
- Political constraints (and opportunities)
  - UK-UK relations
  - AUKUS?
- Technological theft by competitors

High Level Development Roadmap:

The PRISM timeline outlines a strategic roadmap for system deployment, beginning in 2025. The first major milestone is the **establishment of an industrial consortium**, notably involving **Rolls Royce**, which signifies a foundational partnership for the initiative. Concurrently, the project aims to **address safety and security issues**, particularly those related to **military applications**, highlighting the importance of robust risk management and compliance.

Another key consideration is navigating **geopolitical differences**, which may influence international collaboration and regulatory alignment. The timeline also raises the question of **secondary markets**, suggesting an exploration of additional commercial or strategic opportunities beyond the primary deployment.

Looking ahead, the project sets a **target window between 2031 and 2035**, indicating a long-term vision for full-scale implementation. Engagement with **military customers** is also anticipated, reinforcing the dual-use nature of the system.

To support this trajectory, the plan includes identifying the s**kills and training required** to build a capable workforce, alongside **service planning** to ensure operational readiness. Finally, the establishment of a **National Testing Facility** is a critical infrastructure goal, providing a dedicated environment for validation and demonstration.

PRISM

2025 → **System deployment**

Deltas

Establish Industrial Consortium (with Rolls Royce)

Identify skills and training required

Establish National Testing Facility

Address safety & security issues (military)

Service planning

Geopolitical differences

Secondary markets?

2031-2035 Target

Military Customer(s) →

Further Refining of Use Cases

Whilst the workshops were intended to stimulate high level publicly available Use Cases, with the development of more detailed concepts being out of scope for this project, it may be useful for interested parties to group these ideas into the following (note, some Use Cases fall into multiple groups):

- In-situ Resource Utilisation (ISRU):
  - High Power Extraction on the Lunar Surface
  - Uninterrupted power for building & operating a Lunar regolith building
  - Asteroid Mining (Surface Operations)
- Surface Logistics:
  - Thermal Garages
  - Safety Critical Exploration Infrastructure
  - Ubiquitous, Safe, Plug + Play Power Supply for Space Exploration
- Advanced Capability Spacecraft
  - PRISM
  - Data Centres In GEO
  - General Purpose Collision Resistant Satellite (SolSat Platform)
  - Asteroid Mining (Propulsion)
  - Lunar Far Side Radio Astronomy

Alternatively, several of the Use Cases may be provisionally consolidated as the following concepts:

1. Exploration Support Network

A network of strategically placed RPS powered 'Thermal 'Garages' across the Lunar surface, using 'Safety Critical Exploration Infrastructure' and/or 'Ubiquitous, Safe, Plug + Play Power Supply for Space Exploration' to support long distance non-nuclear powered robotic or Human exploration. The Exploration Support Network might also be incorporated as a secondary function of other remote nuclear-powered infrastructure, such as 'Lunar Far Side Radio Astronomy'.

2. Surface Operations Hub

Centred on Microreactor powered 'High Power Extraction on the Lunar Surface', potentially also carrying out Uninterrupted power for building & operating a Lunar regolith building, with residual heat enabling 'Thermal 'Garages', using 'Safety Critical Exploration Infrastructure' and/or 'Ubiquitous, Safe, Plug + Play Power Supply for Space Exploration' to support non-nuclear powered robotic or Human operations around the site, or the immediate vicinity. This concept might also be applicable to Asteroid Mining.

3. In-Space Services Platform

A ‘General Purpose Collision Resistant Satellite (SolSat Platform)’, or, for defence applications, ‘PRISM - Persistent, Resilient, In-Space for Military’ utilising ‘Safety Critical Exploration Infrastructure’ and/or ‘Ubiquitous, Safe, Plug + Play Power Supply for Space Exploration’ to service other orbital assets. The In-Space Services Platform might also function as a ‘Data Centre’ providing at-scale secure data storage, processing, or transfer, as a service for other spacecraft.

Appendix 2: Companies registered to attended Workshop 3: 'Industrial Engagement'

Organisation Registered to Attend

- 3D 360 Ltd
- 2DHeat Limited
- 4wardfutures
- ADM Project Consultants Ltd
- Airbus Protect
- Amentum
- Ampode
- Astec Precision Limited
- Asteroid Mining Corporation
- Austin Consultants
- AWS
- BAE Systems
- Bodycote
- Boneham & Turner Ltd
- Businesswise Solutions
- CAA
- Cervberus Nuclear
- Cheshire and Warrington Growth Hub
- Cygnus Space
- Department for Business and Trade
- Dream Big Composites
- Engineering and Consultancy
- eQeOUTDOORS
- ESR Space
- ESR Technology
- Eutelsat OneWeb
- Flintloque and QuantaLeap
- Geospatial Ventures Limited
- Global Invacom
- Graham Engineering Ltd
- Growth Platform
- Gunnercooke LLP
- Haption
- Hutchinson Engineering
- Institute of Physics
- Institution of Engineering & Technology
- Kernow Oils
- Krypton TV Ltd
- KUKA Robotics UK LTD
- Lancaster University
- Leybold UK Ltd
- Liberty360ltd.com
- Light Coatings Ltd
- Liverpool John Moores University
- LYVALABS
- MIDAS Greater Manchester
- Midlands Aerospace Alliance
- MoD - DASA
- United Kingdom National Nuclear Laboratory
- Olsen Actuators & Drives Ltd
- One-O-Five Precision Limited
- Open Mind Technologies
- PDS CNC Engineering
- Power and Energy Ltd
- PWHytek Ltd
- Radical Moves
- Satellite Applications Catapult
- Seriun

- Hyde Aero Products Ltd
- Innovestech
- methera global
- SHD Composite Materials Ltd
- Siemens
- SpaceSpecialists Ltd
- Steel Dynamics Ltd
- Supernova Labs
- Sylatech Limited
- TECHNIA UK
- The Northern Space Consortium
- The University of Cumbria
- TPAC (The Phased Array Company)
- UK Civil Aviation Authority
- UKRI - STFC
- University of Bradford
- University of Central Lancashire
- University of Liverpool
- University of Manchester
- University of Salford
- University of Sheffield
- Victoria Production engineering - Hyde Group
- Washington Mills
- Wright Solutions
- Sixty82 Ltd
- Solid State Dynamics Ltd
- Sonatest
- TÜV SÜD Nuclear Technologies

Appendix 3: University of Manchester (Dalton Nuclear Institute) Power4Space Case Study, an excerpt (full report due Q3 2025)

Case Study: DCF Report on UK Radiation Facilities for Testing Americium-Based Space Batteries and Space-Deployable Nuclear Reactors

(Focusing on Northwest & Midlands vs. Rest of UK, Gaps, and Practical Considerations for Lunar/Martian Missions)

1. Relevant Facilities in the Northwest or Midlands

Below is an overview of facilities in the Northwest or Midlands of England that could support radiation testing for both americium-based space batteries and nuclear reactor components destined for extended lunar/Martian operations. These facilities can provide a variety of particle beams (protons, ions, electrons), gamma sources, or combined capabilities. Given that you plan mostly coupon-scale or small board-scale tests, these facilities can generally accommodate such sample sizes.

1.1 Dalton Cumbrian Facility (DCF), University of Manchester (Cumbria, NW)

Key Capabilities:

- Ion accelerators: Up to 10 MeV protons, 15 MeV alpha, heavier ions up to ~35 MeV.
- Dual-beam irradiation: Can apply two ion beams simultaneously (e.g., protons + heavier ions), which may be useful to replicate complex radiation fields.
- Gamma (Co-60) up to ~180 Gy/min (planned ~360 Gy/min after source reload) with feedthrough ports for real-time measurements.
- X-rays up to 350 keV at up to 140 Gy/min.
- Potential synergy with in-situ mechanical/thermal treatments, though thermal cycling to ±100–300 °C would require additional engineering.

Typical Turnaround:

- Short exposures (hours to days) are straightforward.
- Very low dose-rate exposures for "realistic" space flux conditions would become lengthy; facility staff can advise on using beam attenuation vs. accelerated dose.

1.2 University of Birmingham MC40 Cyclotron (Midlands)

Key Capabilities:

• Protons to 39 MeV, alpha particles to 50 MeV, with beam currents up to 100 μA (protons).

• Some environmental controls (temperatures up to ~1000 °C and as low as –50 °C using LN2, in either vacuum or air).

• Neutron spallation facility (though space neutron flux is relatively low).

Typical Turnaround:

• Short, high-dose proton irradiations can be done quickly.

• Longer campaigns for lower dose rates are possible but need scheduling around nuclear-physics and medical-physics usage.

1.3 Daresbury Laboratory & Related Developments (NW)

Compact Linear Accelerator for Research & Applications (CLARA)

- **Key Capabilities:** 45–250 MeV electrons at pulse frequencies of 10–200 Hz. Useful if electron-beam testing is required.
- **Sample Environment:** Typically vacuum, with possible add-on sample heating up to ~600 °C.
- **Turnaround:** Being primarily an R&D test accelerator, scheduling may vary; short or repeated runs are feasible.

Relativistic Ultrafast Electron Diffraction & Imaging (RUEDI) (planned)

- **Key Capabilities:** Will eventually offer electrons in the 1–5 MeV range from two sources (RF and DC).
- **Construction Timeline:** Projected to begin in ~2026 over six years. Not available in the immediate term, but relevant for future testing once operational.

Christie Hospital Proton Beam Therapy Centre (Manchester, NW)

- **Key Capabilities:** 250 MeV protons at dose rates up to ~83 Gy/s, with the ability to go down to pA-scale currents for low dose.
- **Turnaround:** Limited research beamtime, but very high instantaneous dose rates can shorten total exposure time significantly if accelerated testing is acceptable.

Clatterbridge Cancer Centre (Wirral, NW)

- **Key Capabilities:** 62 MeV protons. Primarily for ocular therapy; research access may be more limited.
- **Turnaround:** Subject to clinical schedules, so advanced arrangement is essential. Not sure if they would have an interest in supporting this kind of research.

2. Relevant Facilities Elsewhere in the UK

Below are notable facilities outside the Northwest or Midlands. They can complement your testing campaign if unique energies, particles, or test conditions are required.

Surrey Ion Beam Centre (Guildford, SE)

- **Ions** up to ~10 MeV (protons, alpha, heavier ions); specialized in materials analysis (e.g., RBS, PIXE, SIMS).
- **Environment:** Vacuum or moderate temperature extremes; specialized end stations for in-situ characterization.
- **Turnaround:** Flexible for short or moderate exposures; longer tests possible, but capacity is shared with many research users.

Amentum/Jacobs Labyrinth Irradiator (Harwell, Oxfordshire)

- **Co-60** labyrinth with up to ~2 kGy/hour dose rate, large test space for bigger setups.
- **Turnaround:** Quick or extended exposures possible. For low dose rates, additional lead attenuation is typically used, prolonging experiment time significantly.

National Physical Laboratory (Teddington, SW London)

- Multiple **Co-60** sources (1–120 Gy/min) and a neutron generator up to 20 MeV.
- Good for precise dosimetry and calibrations, with strong metrology expertise.

Diamond Light Source (Harwell, Oxfordshire)

- **High-flux X-rays** (5–150 keV on the highest-energy beamline).
- Primarily used for advanced characterization (diffraction, spectroscopy) rather than damage testing.
- Could be relevant if X-ray microbeam analysis of materials post-irradiation is needed.

ISIS Neutron and Muon Source (Harwell, Oxfordshire)

- Neutron beamlines (ChipIr up to 800 MeV spallation spectrum).
- Typically used for microelectronics single-event effects, not as critical for structural damage for your battery/reactor materials (neutron flux in space is relatively low).

Ultra Energy (Wimborne, SW)

- Modest **gamma, neutron, X-ray** sources, plus engineering test support (pressure, helium leak tests).
- Potentially useful if you need combined mechanical + modest radiation testing.

Laser-Driven Sources (Central Laser Facility at Harwell [Vulcan, Gemini], or SCAPA in Strathclyde)

- Provide intense, short-pulse proton/electron/ion beams up to multi-MeV energies.
- Still in a research-focused regime; not typically turnkey for long-duration exposures.

3. Gap Analysis of Missing Facilities

From the standpoint of simulating space radiation for americium-based batteries or nuclear reactors, the UK has solid coverage in many areas. However, certain gaps or cautions apply:

1. Electron Testing (1–45 MeV Range)

- Few dedicated mid-energy electron beamlines exist. Medical linacs (4–20 MeV electrons) could be leveraged, but they require coordination with NHS/private radiotherapy centers. CLARA at Daresbury can reach up to 250 MeV but is a research accelerator with limited "routine" irradiation capacity.
- Until RUEDI comes online (potentially beyond 2030), there is no "simple" mid-energy electron user facility providing, for example, 1–10 MeV electrons at moderate currents in a straightforward, commercial-like setting.

2. Very Long, Low-Dose-Rate Exposures

- Realistic space flux is typically thousands of times lower than what accelerators or gamma cells deliver. Achieving flight-level dose rates would require heavy attenuation or frequent beam pausing, leading to multi-week or multi-month campaigns, which can be cost-prohibitive.
- Many facilities favor higher-dose-rate, accelerated testing. This is generally acceptable to uncover "radiation-induced phenomena" more quickly, but if specific slow thermal/radiation synergy is critical (e.g., mechanical fatigue at low dose rates over 28-day lunar cycles), planning is needed.

3. Combining Radiation with Vacuum or Thermal Cycling

- Several labs (e.g., Dalton Cumbrian Facility, University of Birmingham) can do moderate environment controls (heating/cooling, vacuum). But highly controlled ±100 °C to +300 °C cycling over a month in vacuum while irradiating at a low dose rate is logistically complex. Most labs do not have standard setups for that scenario "off the shelf."
- Facilities like DCF can in principle design specialized end stations, but this requires lead time, funding, and engineering.

4. Access to Extremely High-Energy Protons/Ions

- Above ~250 MeV protons (e.g., simulating deep solar particle events or cosmic rays >1 GeV), UK coverage is sparse. The Christie's cyclotron at 250 MeV is near the top limit of what is routinely available. True cosmic-ray-level energies (GeV) would require laser-driven or large synchrotrons abroad.

5. Simultaneous Multiple-Radiation Exposures

- Only limited co-irradiation setups (e.g., dual-ion beam at DCF). If you wanted, for instance, protons + electrons simultaneously, you would likely need to arrange a custom solution, possibly with a laser plus conventional beam, or two commercial sources, which is not standard in the UK.

Practical Notes on Turnaround vs. Extended Campaigns

Quick Turnaround (Days to ~2 Weeks)

- Most accelerator-based and gamma facilities can achieve high dose rates, simulating a years'-worth of space dose in a short time. This is generally the cost-effective approach if your primary goal is to see whether the material eventually fails under total ionizing dose.
- For simple pass/fail or diagnostic exposures, booking smaller time blocks is typically easier.

Long Campaigns (Weeks to Months)

- Mimicking true space flux and slow thermal cycles (lunar day/night ~28 days each) will require either extremely low dose rates or repeated short pulses. Such campaigns are much more expensive, as you occupy facility time continuously or in a repeated schedule.
- Be sure to coordinate well in advance with the facility's technical staff to ensure stable beam conditions, environmental control, and cost management.

Appendix 1: Facilities in the NW/Midlands

Facility	Radiation Type	Maximum Energy	Current/ Dose Rate	Miscellaneous
Christie Hospital, Manchester	Protons	250 MeV	1 pA-800 nA 83 Gy/s	Not applicable
The Clatterbridge Cancer Centre, Scanditronix 62 MeV cyclotron	Protons	62 MeV	50 nA	Unclear if access would be available
Daresbury Ion Therapy Research Facility (ITRF)/ Laser-hybrid Accelerator for Radiobiological Applications (LhARA)	Ions	33 MeV/u	No data	Construction anticipated to take 5-7 years.
	Protons	15 MeV (127 MeV)	No data	15 MeV available at testbed in Strathclyde. 127 MeV anticipated upon facility completion
Birmingham MC40 Cyclotron	Protons/ He^{2+}	39 MeV/ 50 MeV	100μA 40μA	Currently going through ion source upgrade to recover maximum current
Birmingham High Flux Accelerator-Driven Neutron Facility	Protons	2.5 MeV	30 mA	Not applicable
	Neutrons	0.9 MeV	3´ 10^{13}n/s	Not applicable
Dalton Cumbrian Facility (DCF)	Ions	10 MeV protons 15 MeV He^{2+} 35 MeV Ions	Up to 50 μA for protons, 15 μA for He^{2+} ions and various other currents for heavier ions	Not applicable
	Ions – Gaseous	2.5 MeV	100 μA maximum for protons	Not applicable
	Gamma (Chamber)	Co-60	<180 Gy/min ~ 360 Gy/ min after scheduled source reload	Not applicable
	X-rays	350 keV	<140 Gy/min (unfiltered)	Not applicable

Facility	Radiation Type	Maximum Energy	Current/ Dose Rate	Miscellaneous
Compact Linear Accelerator for Research and Applications (CLARA)	Electrons	250 MeV	No data	Not applicable
Relativistic Ultrafast Electron Diffraction and Imaging (RUEDI)	Electrons (Radiofrequency)	5 MeV	No data	Construction expected to commence 2026
	Electrons (Direct Current)	2 MeV	1 mA	Not applicable
	Protons	15 MeV	No data	Not applicable
	Electrons	4 GeV	No data	Not applicable

Appendix 2: Facilities elsewhere in the UK

Facility	Radiation Type	Maximum Energy	Current/ Dose Rate	Miscellaneous
Surrey Ion Beam Centre	Ions	4 MeV protons 10 MeV Ions	No data	Not applicable
	Ions – Implantation	200 keV	No data	Not applicable
Amentum (formerly Jacobs)	Gamma (Labyrinth)	Co-60	2 kGy/hr	Not applicable
Diamond Light Source	X-rays	5 keV – 150 keV	No data	Not applicable
National Physical Laboratories	Gamma (Chamber)	Co-60	120 Gy/min	Not applicable
	Gamma (Source)	Co-60	1 Gy/min @ 80 cm from source	Not applicable
	Neutrons	20 MeV	No data	Not applicable
Ultra Energy Wimbourne	Neutrons	Thermal	10^7 nv	Not applicable
	Gamma	Cs-137/ Am-241	0.5 Gy/hr @ 1m from source	Not applicable
	X-rays	225 keV	17.7 mA	Not applicable
ISIS Neutron and Muon Source	Neutrons (ChipIr)	800 MeV	$5x10^6$ n/ cm^2/s (Integrated above 10 MeV)	Spectrum of energies following atmospheric characteristics
	Neutrons (Neutron Irradiation Laboratory for Electronics (NILE)	14 MeV 2.5 MeV	10^{10} n/s (14 MeV) 10^9 n/s (2.5 MeV)	Point sources, flux depends on distance

Facility	Radiation Type	Maximum Energy	Current/ Dose Rate	Miscellaneous
Taranis Laser (Queen's University Belfast)	Protons	10 MeV	No data	Laser excitation, produces a spectrum of energies
	Electrons	1 MeV	No data	
	X-rays	1 MeV	No data	
Scottish Centre for the Application of Plasma-based Accelerators (SCAPA) (Strathclyde University)	Ions	No data	No data	Ion irradiation has not previously been carried out but is deemed possible
	Protons	15 MeV	No data	Not applicable
	Electrons	4 GeV	No data	Not applicable
Central Laser Facility (CLF) Harwell Vulcan	Not applicable	No data	No data	Not applicable
CLF Harwell Gemini	Not applicable	No data	No data	Not applicable

4. 5 Scenarios: Thermal and Radiation Characteristics

4.1 Journey to the Moon/L2

Journey Phase	LEO	MEO	GEO	Interlunar Space
Minimum Temperature (C)	-65	-150	-196	-200
Maximum Temperature (C)	125	150	128	260
Gamma Flux ($p/cm^2/s$)	$\sim 10^8 - 10^{10}$	$\sim 10^6 - 10^8$	$\sim 10^6 - 10^8$	No data
Beta Flux ($p/cm^2/s$)	$\sim 10^3 - 10^5$	$\sim 10^4 - 10^6$	$\sim 10^3 - 10^6$	No data
Maximum Ion Energy (eV)	400MeV	>60 MeV[2]	Cosmic Rays (10^{18} eV)	No data
Ion Flux ($p/cm^2/s$)	$\sim 10^1 - 10^5$	$\sim 10^4 - 10^6$	$\sim 10^{-1} - 10^1$	No data
Environmental Concerns	No data	No data	No data	No data

4.2 Journey to Mars

Journey Phase	LEO	MEO	GEO	Interlunar Space
Minimum Temperature (C)	-65	-150	-196	-200
Maximum Temperature (C)	125	150	128	260
Gamma Flux ($p/cm^2/s$)	$\sim 10^8 - 10^{10}$	$\sim 10^6 - 10^8$	$\sim 10^6 - 10^8$	No data
Beta Flux ($p/cm^2/s$)	$\sim 10^3 - 10^5$	$\sim 10^4 - 10^6$	$\sim 10^3 - 10^6$	No data
Maximum Ion Energy (eV)	400MeV	>60 MeV[2]	Cosmic Rays (10^{18} eV)	No data
Ion Flux ($p/cm^2/s$)	$\sim 10^1 - 10^5$	$\sim 10^4 - 10^6$	$\sim 10^{-1} - 10^1$	No data
Environmental Concerns	No data	No data	No data	No data

4.3 Being on the Moon – 20 Years

Minimum Temperature (C)	Maximum Temperature (C)	Gamma Dose (mGy/yr)	Beta Flux (p/cm2/s)	Maximum Ion Energy (ev)	Ion Flux (p/cm2/s)	Environmental Concerns
-171	111	3.42	Not applicable	GCR	~10^5	Not applicable

4.4 Being at L2 – 20 Years

Minimum Temperature (C)	Maximum Temperature (C)	Gamma Dose (mGy/yr)	Beta Flux (p/cm2/s)	Maximum Ion Energy (ev)	Ion Flux (p/cm2/s)	Environmental Concerns
Nontrivial	Nontrivial	Not applicable	Not applicable	Not applicable	Not applicable	Intense Space Weather over Mission Time

4.5 Being on Mars – 20 Years

Minimum Temperature (C)	Maximum Temperature (C)	Gamma Dose (mGy/yr)	Beta Flux (p/cm2/s)	Maximum Ion Energy (ev)	Ion Flux (p/cm2/s)	Environmental Concerns
-143	27	Not applicable	Not applicable	Not applicable	~10^0	Dust and Martian weather patterns

4.5 Being on Mars – 20 Years

Material	Area Density	Effective Radiation Types	Miscellaneous Concerns
Aluminium	10 g/cm^2 – 40g/cm^2	Ions/ Protons/ Electrons	Not applicable
Polyethylene	5 g/cm^2 – 100g/cm^2	Protons/ Neutrons	Not applicable
Novel Materials	Not applicable	Not applicable	Not applicable

6. Fission Effects (Subject to Disclosure)

Americium Space Batteries operating off a thermal principle are likely to be highly susceptible to increased degradation due to fissioning of overall material degrading lifespan. Further information collected from papers to be added on the likely effects of radiation upon Americium Space batteries.

Micro-reactors may be susceptible to fission effects but the structural components of the micro-reactor are likely to shield the fuel itself.

7. Effects on Space Electronics (Subject to Disclosure)

Relevant information pending understanding of relevant electronics.

8. Effects on Cooling Circuits (Subject to Disclosure)

Coolant used in the micro reactor may be subject to radiolysis and change in chemical composition due to space radiation. Effects will be dependent on materials used to construct the coolant circuit as well as the coolant used. Literature exists on the effects of water radiolysis and on coolant used in terrestrial PWR and BWR designs.

Science and Technology Facilities Council

Innovation Clusters | North West Space

MIDLANDS SPACE CLUSTER

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

UK SPACE AGENCY