Institution: University of Leicester		
Unit of Assessment: 12		
Title of case study: Transforming Space Power Generation and Thermal Management in Space		
Period when the underpinning research was undertaken: 2013–2019		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s): 1) Hugo Williams 2) David Weston	**Role(s) (e.g. job title):** 1) Associate Professor Aerospace Engineering 2) Lecturer Materials Engineering	**Period(s) employed by submitting HEI:** 1) 2010–Present 2) 2008–Present
Period when the claimed impact occurred: 2014–Present		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact

A major obstacle to advancement in space exploration is the lack of solar power due to distance from the Sun. This significantly impedes deep space and planetary missions. Engineering researchers at the University of Leicester have played a critical role in a multidisciplinary programme that has transformed spacecraft power and thermal control by pioneering novel americium-based Radioisotope Heater Units (RHUs) and Radioisotope Thermoelectric Generators (RTGs). The impact has enabled exploration of previously inaccessible regions of space, had economic impact by creating new international export markets and job creation, led to policy and practice changes, and positive environmental impact by developing energy harvesting technologies and reducing the environmental cost of nuclear power.

2. Underpinning research

In 2013, Engineering researchers Williams and Weston at the University Leicester (UoL) commenced interdisciplinary research with Ambrosi (Physics and Astronomy at UoL) to develop radioisotope power systems fuelled by americium-241 (^{241}Am). Prior physics work by Ambrosi at the University of Leicester had succeeded in demonstrating the viability of ^{241}Am as an alternative to plutonium-238 (^{238}Pu). Whilst ^{238}Pu is in short supply globally, ^{241}Am can be extracted from transuranic waste (a waste product of civilian nuclear power generation) long considered useless. However, huge engineering challenges existed in the development of successful ^{241}Am-fuelled systems. Between 2013 and 2019, Williams's engineering expertise and Weston's materials chemistry (with critical support from team members Watkinson, Mesalam and Barco) were used to lead on crucial engineering materials and system performance advances that proved integral to this highly successful interdisciplinary programme **[R1–R5]**.

In the UK, nuclear power generation produces around 6 tonnes of plutonium by-product every year. By 2019, over 140 tonnes were stored at the Sellafield site, dating back over 40 years. Building on the successful identification of ^{241}Am as a fuel source, from 2013 the Leicester team collaborated with the National Nuclear Laboratory to establish a trial production line for ^{241}Am extraction using a non-radioactive surrogate **[G1]**. Alongside this work, the researchers turned their attention to the problem of safety containment, driving forward with new research into space nuclear fuel development **[R1–R3]**.

Utilising a Metal Matrix Composite (MMC), Williams's team was able to improve the integrity of the brittle ceramic-based fuel. They used spark plasma sintering (SPS) to successfully produce

Nd_2O_3-niobium MMCs **[R1]**. This use of Nd_2O_3 as a non-radioactive surrogate for Am_2O_3 ceramic, pioneered by Watkinson under Williams and Weston's supervision, led directly to the novel discovery in 2017 that mixed Nd_2O_3 and CeO_2 ceramics could be surrogates for the chemical production of the radioactive fuel **[R2]**. This allowed the first demonstration of appropriate sintering parameters to achieve the required density of 85-90% with minimal additional handling of the fuel whilst in powder form – a significant benefit for nuclear safety – and selecting cold-press sintering as the preferred method **[R3].** These developments were critical in enabling the production of ^{241}Am-oxide ceramic fuel required for space energy projects.

From 2015, ESA funded development of a ^{241}Am Radioisotope Heater Unit (RHU) design **[G2]**. As PI, Williams produced a specification and design based on the novel fuel work, which included a safety containment system of platinum-based alloys, carbon-bonded-carbon-fibre insulation and carbon-carbon composites.

In parallel with the fuels and RHU work, the Leicester team began collaborations with both industrial and government partners to develop the first working prototype ^{241}Am Radioisotope Thermoelectric Generator (RTG) system. Williams focused on the overall system performance and in particular the thermoelectric materials that provide the critical conversion of thermal to electrical energy. His team mechanically strengthened the thermoelectric materials by the novel addition of boron carbide **[R4]**. Mesalam, under Williams's supervision, developed an impedance spectroscopy method to measure thermoelectric performance and diagnose manufacturing and service defects **[R5]** and used it to show that the novel thermoelectric materials were sufficiently radiation resistant for missions exceeding 10 years **[R6]**. Weston's electrochemistry expertise and laboratory facilities were critical to this work.

With Leicester leading and directing the overall RTG development project alongside Airbus UK, Lockheed Martin and the National Nuclear Laboratory, delivery of a fully functional ^{241}Am RTG to ESA in 2018 capable of providing 200 W of heat and 10 W of electrical power was achieved. The novel material and measurement methods developed by Williams's team are now a standard feature of future RTG designs and critical to the future production and launch safety of such systems **[R7]**.

3. References to the research

R1. Williams H, Ambrosi R, Bannister N, Metal matrix composite fuel for space radioisotope energy sources, Journal of Nuclear Materials 433 (2013), 10.1016/j.jnucmat.2012.09.030

R2. Watkinson EJ, Ambrosi R**, Williams H**, … **Weston D**. et al, *Cerium neodymium oxide solid solution synthesis as a potential analogue for substoichiometric AmO2 for radioisotope power systems*, Journal of Nuclear Materials 486 (2017), 10.1016/j.jnucmat.2017.01.011

R3. Watkinson EJ, Ambrosi R**, Williams H**, et al, *Sintering-trials of analogues of americium oxides for radioisotope power systems*, Journal of Nuclear Materials 491 (2017), 10.1016/j.jnucmat.2017.04.028

R4. Williams H, Ambrosi R, Bannister N, *Spark Plasma Sintered bismuth telluride-based thermoelectric materials incorporating dispersed boron carbide*, Journal of Alloys and Compounds 626 (2014).

R5. Mesalam R**, Williams H,** Ambrosi R et al, Towards a comprehensive model for characterising and assessing thermoelectric modules by impedance spectroscopy, *Applied Energy* 226 (2018), https://doi.org/10.1016/j.apenergy.2018.05.041

R6. Mesalam R, **Williams H**, Ambrosi R, … **Weston D** et al, Impedance spectroscopy characterization of neutron irradiated thermoelectric modules for space nuclear power, *AIP Advances 9* (2019), https://doi.org/10.1063/1.5095619

R7. Barco A, Ambrosi R, **Williams H**, Stephenson K, Radioisotope power systems in space missions: Overview of the safety aspects and recommendations for the European safety case, *Journal of Space Safety Engineering* (2020), 10.1016/j.jsse.2020.03.001

GRANTS

G1. 2013–2016, National Nuclear Laboratory, GBP71,271, 'RTG Nuclear Fuel Project'.
G2. 2015–2017, ESA, EUR300,000, 'Radioisotope Heater Unit Prototype Development'.

4. Details of the impact

The University of Leicester is a global leader in the development of space nuclear power systems for electrical power generation, spacecraft heating and thermal management in the form of Radioisotope Thermoelectric Generators (RTGs) and Radioisotope Heater Units (RHUs).

Enabling Space Exploration

Prior to UoL intervention, independent European access to Radioisotope Power Systems (RPS) for space applications was not possible. These sources utilised ^{238}Pu as fuel, which is both scarce and costly. RPS is a crucial enabling technology for deep space and planetary missions. The contributions led by Engineering colleagues in materials and system performance were critical in determining the feasibility of ^{241}Am as an alternative to ^{238}Pu fuel. This has enabled independent development of RPS by ESA capable of powering future space '*missions to the distant solar system for 400 years, while also addressing a long-term concern of the UK's nuclear industry*' **[E1a].** ESA have confirmed that the baseline radioisotope fuel considered for use in European Space RPS is **firmly established** to be ^{241}Am, in the form of sintered ceramic pellets **[G2].** RTGs/RHUs based on UoL research are baselined for the European Large Logistics Lander EL3 (2026/27) and proposed by the European science community for ESA missions to Uranus and Neptune in the next decade. Without methodologies and technologies created at Leicester, none of these missions is possible **[E2a, E2b, E2c].**

As a result of these demonstrable benefits, the 2018 'UK-US Nuclear R&D Action Plan' includes provision of explicit cooperation on the development of '*Radioisotopes for use in space technologies*', '*Nuclear Reactor Technologies*' and '*Advanced Fuels*': objectives significantly influenced by UoL research **[E3].**

Environmental Impact

The UK civilian nuclear power programme has generated over 140 tonnes of reprocessed civil plutonium fuel, currently stored at Sellafield. The utilisation of this reprocessed fuel in future generations of nuclear reactors will play a significant role in decarbonising the economy. Plutonium use in nuclear power plants is facilitated by the extraction of minor actinides or contaminants such as ^{241}Am which build up in the reprocessed fuel. The UoL team's research into the fuel form and its consolidation into pellets—in collaboration with the National Nuclear Laboratory (NNL)—as well as leadership of system level design, containment and heat conversion technologies in RTGs, demonstrated the utility of ^{241}Am for space applications. The UoL research incentivises 'cleaning' the plutonium for space applications while providing a fuel for use in terrestrial nuclear power plants. The ^{241}Am can also be utilised in applications beyond space including oil well logging, smoke alarms, neutron sources and terrestrial power systems in challenging environments **[E3, E4]**.

The importance of the ability to utilise nuclear waste practically (using technologies like RHUs and RTGs developed by the UoL team) has been widely recognised, with the UK Minister for Science describing it as a '*remarkable breakthrough*' highlighting the nation's position '*at the very frontier of developments in space technology*.' **[E5]**. The discovery won the Collaborate to Innovate Award for Aerospace and Defence in 2019 **[E1a, E5]** and finalist places in two categories of the IChemE Global Awards 2020: Energy and Innovative Product **[E1c].**

Economic Impact

The UoL research has already provided substantial economic benefits across the world. Direct collaboration between UoL and European Thermodynamics Ltd (ETL) has resulted in the development of full end-to-end RTG capability and the utilisation of automated production methods for the manufacture of thermoelectric modules and new energy harvesting products. ETL have incorporated these developments into their core business and product lines for terrestrial customers and low-carbon technology markets. This has both retained and created high-skilled jobs. For example, their "*Adaptive® brand of thermoelectric generator modules (TEG5) . . . has resulted in volume sales of [GBP]150,000 p.a*." **[E6]**. The products enabled by ETL collaboration and research engagement with UoL are projected to provide them *"[GBP]5,000,000 per year by 2030"* **[E6]**.

Similarly, partnership with the NNL *"has directly resulted in the creation of new export markets for Americium sealed heat sources for space nuclear power with both ESA and South Korea"* (as of 2019) **[E4]**. Between 2021 and 2026, *"the economic value in sales alone is estimated to be more than* [GBP] *50,000,000"* **[E4]**.

A 2018 London Economics report **[E7]** on the space sector provides evidence of the economic impact of ESA investments in the UK. This study outlines that the GVA of the investment adds an additional GBP11,500,000 to the GBP12,000,000 invested by ESA. This programme has created and retained skilled jobs in the space and nuclear sectors. Applying an assessment of the GVA on jobs multiplier, this programme sustains an additional 30 people in supply chain and other sectors. A recent study by UKSA on the impact of investment in the ESA science programme *"found that GBP523,000,000 of UK Space Agency funding put into the European Space Agency's Space Science Programme (SSP) has generated [GBP]1,400,000,000 of income for UK industry, with a further GBP1,100,000,000 from partially attributed and forecast benefit"* **[E8]**. This presents a maximum 4.8 to 1 multiplication effect. Thus, the research has a gross value-added factor of around GBP50,000,000 of impact based on the GBP11,000,000 investment **[E8]**.

Policy

The pioneering work of the UoL programme, including the underpinning research conducted in Engineering and close collaboration with NNL, has resulted directly in a series of policy decisions by the UK Government to continue to invest in this programme at the 2012, 2016 and 2019 ESA Council of Ministers meetings **[E2a, E2b]**. UoL is the global focal point for Americium-based radioisotope power system development. The underpinning engineering research was a critical enabler for this. France is now playing a significant role in the ESA programme **[E2c]**, and there is greater collaboration between the US and UK through the UK-US Nuclear R&D Action Plan (September 2018) **[E3]**. The latter includes the area of cooperation: "*Radioisotopes for use in space technologies*". The Memorandum of Understanding signed (June 2019) between the UoL, NNL and Korea Atomic Energy Research Institute (KAERI) was brokered directly by UoL and pledges new areas of cooperation on research on radioisotope thermoelectric power generators for use in space exploration and commits the signatories to developing international standards and safety associated with these space systems **[E9]**.

5. Sources to corroborate the impact

E1. (a) Collaborate to Innovate Awards 2019; (b) IChemE Global Awards 2020 (Finalists).
E2. Testimonies from: (a) UK Space Agency, (b) European Space Agency, (c) Ariane Group
E3. UK-US Nuclear RandD Action Plan (including confidential emails and documents)
E4. Testimony from National Nuclear Laboratory**.**
E5. National Nuclear Laboratory Press Release 2019**.**
E6. Testimonies from: European Thermodynamics Ltd (ETL).
E7. London Economics Report 'Size and Health of the UK Space Industry' 2018.
E8. UoL ESA Investment Details 2009–2022 (Confidential).
E9. UoL/South Korea Space Agency Memorandum of Understanding.