Institution: University of Leicester		
Unit of Assessment: UoA 9		
Title of case study: Transforming Space Power Generation and Thermal Management in Space		
Period when the underpinning research was undertaken: 2006–2020		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s): Richard Ambrosi	**Role(s) (e.g. job title):** Professor of Space Instrumentation and Space Nuclear Power Systems	**Period(s) employed by submitting HEI:** 2000–Present
Period when the claimed impact occurred: 2014–2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact

A major obstacle in space exploration is power generation, where both distance from the Sun or missions beneath planetary surfaces preclude traditional power sources. Researchers at the University of Leicester (UoL) have transformed spacecraft power generation and thermal management by pioneering novel Americium-based radioisotope power systems. The global impact has: **enabled exploration** of previously inaccessible regions of space; had **economic impact** by creating new international export markets and job creation; and led to **policy and practice changes**, and **environmental impact** by developing energy harvesting technologies and reducing the environmental cost of nuclear power generation.

2. Underpinning research

In 2008, pioneering research led by Professor Richard Ambrosi demonstrated the viability of Americium-241 (^{241}Am) as an alternative to plutonium-238 (^{238}Pu) for use in power systems **[R1]**. Their research also showed that whilst ^{238}Pu is in short supply globally, ^{241}Am can be extracted from transuranic waste (a by-product of civilian nuclear power generation)—long considered to be useless **[R3, R4]**. Their results were later verified by an independent study commissioned by the European Space Agency (ESA), which grew into the current ESA radioisotope power programme **[R3]**. This ground-breaking discovery encouraged ESA to commission further interdisciplinary research beginning in 2010 and continuing beyond 2021, with the programme led by Ambrosi since its inception in 2006 **[R1, R3, R4, R5]**.

In the UK, nuclear power generation produces around 6 tonnes of plutonium as a by-product every year. By 2019, over 140 tonnes of reprocessed civil plutonium were stored at the Sellafield site, dating back over 40 years. Based on the ability to use ^{241}Am as a fuel source, the UoL team collaborated with the National Nuclear Laboratory (NNL) and Joint Research Centre in Karlsruhe to establish a European production capability and technology for the extraction and pelleting of ^{241}Am for use in space applications **[R3, R4, R5].**

In order to be effective as a power source in space, the ^{241}Am **Radioisotope Thermoelectric Generator** (RTG) needed to be reliable, mass efficient and safe. Ambrosi's team developed the new containment systems including platinum-based alloy cladding: innovative clad venting technologies were developed, and carbon-carbon composite materials were utilised **[G1–G8]**. In addition, novel bismuth-telluride-based thermoelectric generators were developed in collaboration with European Thermodynamics Ltd. These thermoelectric generators convert the heat produced to electrical power. The containment systems and thermoelectric generators are now used in European radioisotope power systems for space applications. The links between containment, radioisotope fuel and thermoelectric generators enabled the development of radioisotope power systems and the utilisation of these technologies in space missions baselined for 2026/27 **[R1–R6]**.

With European space community backing, ^{241}Am is now recognised as the best radioisotope power source for space missions where solar power cannot be used or where alternatives are not possible. As a result, Ambrosi's team led industrial (Airbus UK, Lockheed Martin, European Thermodynamics and the NNL) and UK government collaborations to develop the first working prototype RTG system; delivering a fully functional RTG to ESA in 2018 capable of providing 200W of heat and 10W of electrical power. This RTG was uniquely designed to work with ^{241}Am-based fuel and was a global first in radioisotope power technology. The same year, UoL provided the world's first 3W thermal ^{241}Am based Radioisotope Heater Unit (RHU) to ESA.

With critical input by Williams, Watkinson, Mesalam, Barco, Crawford and Bicknell **[R2, R3, R6]**, the UoL team established that the use of the radioisotope in a stack of pellets, achieved via cold-press sintering, in conjunction with a platinum-based cladding system, outer carbon-carbon aeroshell and bismuth telluride thermoelectrics is the most effective and efficient configuration for a rapid development programme. The same team have also been working with international partners on launch safety related research and regulations **[G4, G5]**. The RTG design developed in 2018 and further refined by UoL in 2019 has resulted in a ^{241}Am RTG design that can be scaled to generate 50W of electrical power.

In 2019, the UoL team working with the NNL reached a significant milestone: successful extraction of ^{241}Am from stockpiled nuclear waste and its incorporation into a small nuclear battery. This battery successfully produced electricity, thus simultaneously solving the problem of European space power generation while finding a use for a nuclear waste product. Plutonium 'cleaned' by the extraction of ^{241}Am could be re-used as a fuel source in civil power reactors to generate zero carbon electricity. **[G4, G5]**.

3. References to the research

PUBLICATIONS

[R1] O'Brien R, **Ambrosi R**, Bannister N, *Safe Radioisotope Thermoelectric Generators and Heat Sources for Space Applications,* Journal of Nuclear Materials 377, (2008). 10.1016/j.jnucmat.2008.04.009

[R2] 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). https://doi.org/10.1016/j.jallcom.2014.12.010

[R3] Richard M. Ambrosi, H. Williams, Emily Jane Watkinson, et al., *European Radioisotope Thermoelectric Generators (RTGs) and Radioisotope Heater Units (RHUs) for Space Science and Exploration*, Space Science Reviews (2019). https://doi.org/10.1007/s11214-019-0623-9

[R4] Watkinson EJ, **Ambrosi R**, et al, *Sintering-trials of analogues of americium oxides for radioisotope power systems*, Journal of Nuclear Materials 491 (2017). 10.1016/j.jnucmat.2017.01.011

[R5] Watkinson EJ, **Ambrosi R**, 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

[R6] 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

GRANTS

[G1] 2005–2010, EPSRC, GBP550,000, 'Sensors in Extreme Environments'.
[G2] 2010–2014, ESA, [EUR660,000], GBP591,000 (17/11/2020), 'Thermoelectric Converter for Small Scale RTG' (including uplift through ESA CCN in 2013).
[G3] 2015–2018 ESA, [EUR500,000], GBP448,000 (17/11/2020), 'Thermoelectric Converter for Small Scale RTG' (Phase 2).
[G4] 2015–2018, ESA, [EUR360,000], GBP322,000. (17/11/2020), 'Radioisotope Heater Unit Prototype Development' (including uplift through ESA CCN in 2017).
[G5] 2018–2021, ESA, [EUR500,000], GBP448,000 (17/11/2020), 'Radioisotope Heater Unit Prototype Development – Phase 2'.
[G6] 2010–2020, ESA and UKSA, [EUR130,000], GBP116,000 (17/11/2020), Various Nuclear Fuel and Launch Safety Related Contracts including ESA Network Partnering Initiative (NPI).
[G7] 2020–2023, ESA, [EUR500,000], GBP448,000 (17/11/2020), 'Thermoelectric Generator'
[G8] 2020–2022, ESA, [EUR100,000], GBP90,000 (17/11/2020), 'Americium Fuel Pellet Development Phase 2'.

4. Details of the impact

The University of Leicester (UoL) is the 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, European access to radioisotope power sources (RPS) for space applications was possible only through collaboration with USA or Russia. These sources utilise Plutonium-238 (^{238}Pu) as fuel, which is both scarce and costly. RPS is a crucial enabling technology for deep space and planetary missions. The identification of both the viability and efficacy of Americium-241(^{241}Am) instead of ^{238}Pu by Ambrosi's team in 2008 **[R1]** 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 **[G3, G4, G5, G8]**. 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 future ESA missions to Uranus and Neptune in the next decade. Without methodologies and technologies created at UoL, none of these missions are 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's research **[E4]**.

Environmental Impact

In the UK alone, the civilian nuclear power programme has generated more than 140 tonnes of reprocessed civil plutonium fuel currently stored at the Sellafield site. 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 Americium (^{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 NNL and Joint Research Centre in Karlsruhe) 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 Americium fuel can also be utilised in applications beyond space including oil well logging, smoke alarms, neutron sources and terrestrial power systems in challenging environments **[E4, E5]**.

The importance of the ability to practically utilise nuclear waste (using technologies like RHUs and RTGs developed by the UoL team) has been widely recognised with the UK Minister for Science describing it as being a "*remarkable breakthrough*" highlighting the nation's position *"at the very frontier of developments in space technology*" **[E7]**. The discovery won the Collaborate to Innovate Award for Aerospace and Defence in 2019, the Leicestershire Live Innovation Award for Space Innovation **[E7, E1a, E1b]** and the UoL team are finalists in two categories of the iChemE Global Awards 2020 awards: Energy and Innovative Product **[E1c].**

Economic Impact

UoL team's 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 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]*150k p.a.*" **[E3]**. The products enabled by ETL collaboration and research engagement with UoL is projected to provide them *"*[GBP]*5 million per year by 2030"* **[E3]**.

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)" **[E5]**. Between 2021 and 2026, "*the economic value in sales alone is estimated to be more than* [GBP]*50million*" **[E5]**.

The *London Economics Report* **[E9]** on the space sector provides 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 the GVA on jobs multiplied, this programme sustains an additional 30 people in supply chain and other sectors. A recent study by UKSA on the impact of investment in ESA science programme *"… found that GBP523 million of UK Space Agency funding put into the European Space Agency's Space Science Programme (SSP) has generated* [GBP]*1.4 billion of income for UK industry, with a further GBP1.1 billion from partially attributed and forecast benefits*" **[E10a]**. This presents a maximum 4.8 to 1 multiplication effect. Thus, the research is a gross value added factor of approximately GBP50,000,000 of impact based on the GBP11,000,000 investment **[E10b]**.

Policy

The impact on policy is through direct intervention, strategic planning and leadership by Ambrosi. Pioneering work at UoL 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 and Ambrosi's research has directly influenced international policy. There is greater collaboration between the US and UK through the UK-US Nuclear R&D Action Plan (September 2018) **[E4]**. The latter includes the area of cooperation: "Radioisotopes for use in space technologies". The MOU signed (June 2019) between the UoL, NNL and Korea Atomic Energy Research Institute (KAERI) was brokered directly by UoL **[E8]**. This has influenced South Korea to design the RTG and RHU systems for its lunar exploration programme to use ^{241}Am and the UoL designed platinum containment system. Through the work of UoL, France now plays a significant role and has supported the initiative through a series of measures, including in-kind contributions via access to specialised facilities in France **[E2c]**.

Europe can now independently develop a radioisotope power system capability, and pursue space exploration with a substantial fuel resource, all with a positive environmental result on Earth **[G4]**. UoL research is now integral to ESA baseline for the European Large Logistics Lander (EL3) Mission (2026/27) and is included in mission proposals to Uranus and Neptune (2030s).

5. Sources to corroborate the impact

[E1] (a) Collaborate to Innovate Awards 2019; (b) Leicestershire Live Innovation Award 2020; (c) IChemE Global Awards 2020 (Finalists).
[E2] Testimonies from: (a) UK Space Agency; (b) European Space Agency; (c) Ariane Group.
[E3] Testimonies from: European Thermodynamics Ltd (ETL).
[E4] UK-US Nuclear R&D Action Plan (including confidential emails and documents).
[E5] Testimony from National Nuclear Laboratory**.**
[E6] Collaboration Agreement between UoL and University of Dayton endorsed by US Department of Energy.
[E7] National Nuclear Laboratory Press Release 2019**.**
[E8] UoL/South Korea Space Agency Memorandum of Understanding.
[E9] London Economics Report: The Size and Health of the UK Space Industry 2016.
[E10] UoL ESA Investment Details 2009–2022 – Confidential.