Institution: University of Leicester

Unit of Assessment: 9: Physics

Title of case study: Space Nuclear Power Programme

1. Summary of the impact

The Unit is a pioneer in the field of americium-based radioisotope space nuclear power systems, referred to as radioisotope thermoelectric generators or RTGs, and has established key partnerships with industry in the UK and US. Americium-241 has been chosen as a solution given the global shortage of supply of plutonium-238. This research has made rapid progress, developed the first working prototype system for the European programme and shaped government policy resulting in an announcement in November 2012 of the decision by government to invest £18.4 million in innovative space technologies including space nuclear power as part of the next 4-year cycle of UK investment in the European Space Agency (ESA). As a direct result, prioritisation of space nuclear power systems is now part of a new UK strategy of investment in enabling technologies for space applications with technology transfer opportunities for the terrestrial energy sector. High value jobs have been created and sustained in UK industry and academia with the investment of >£4 million in the UK.

2. Underpinning research

Radioisotope Thermoelectric Generators (RTGs) exploit radiogenic decay from heat from radioisotopes and convert it to electrical power using semiconductors in the form of thermoelectric generators. The Unit's research in RTGs as well as isotope containment methods started in 2006 as part of an EPSRC-funded programme (EP/D030277/1, £550,000) to develop innovative technologies for extreme environments, and now forms part of a research programme in Space Nuclear Power. The activity in space nuclear power then grew rapidly within the Unit and resulted in major project leadership in 2 large ESA contracts and an additional 4 contracts from industry and UK Space Agency (UKSA) funding, with a total value in excess of £1M. Outputs have included both highly cited publications in peer review journals [**5-6**] over 20 technical reports as well as the only working RTG prototype based on an americium fuelled design. The Unit has also rapidly grown its related collaborative links with industry in the UK, e.g. National Nuclear Laboratory (NNL), System Engineering and Assessment Ltd (SEA), Astrium UK, Lockheed Martin UK, all of whom have contributed specific expertise to the ESA programme and in the USA (e.g. Centre for Space Nuclear Research, the University of Dayton, and Oregon State University) primarily in knowledge exchange and peer review of the research activities at Leicester.

The underpinning research includes:

- The Unit (as part of an EPSRC funded research programme mentioned above) published a paper in 2008 [**6**], in which americium-241 was compared to a number of isotopes and was highlighted as a viable alternative to plutonium-238 as a result of the shortage of supply of plutonium-238. Americium was selected as a strategically important enabling solution for RTGs in this initial work given the shortage of plutonium-238. In this paper the extraction of americium-241 from transuranic waste was mentioned as a potential source [**6**, p 509]. NNL led an independent study in 2009 funded by the ESA and concluded that americium-241 was a viable option for Europe in terms of availability and cost.
- Americium containment using a novel material processing method called spark plasma sintering to create a metal matrix ceramic fuel composite. The Unit was first to propose this solution for isotope containment for RTGs in a paper published in 2009 [**5**]. This was subsequently adopted as part of an ESA study on isotope containment and safety. This study concluded that this technique reduces the fuel processing requirements and presents an inherently safer containment solution [**1**]. This technique is now being developed further as part of a new study, funded through the investment in space nuclear power resulting from the UK government's policy decision and as part of the increasing collaboration between NNL and the Unit. The technique was also used to determine whether neutron sources for in-situ planetary applications could be developed [**4**].

- First generation European radioisotope thermoelectric generator prototype system (producing 80 watts of heat to generate 5 W of electrical power) development led by the Unit. Working prototype delivered to ESA in 2012. [**2**].
- The RTG prototype system, developed (between 2010 and 2012) and led by the Unit in collaboration with industry (Astrium UK), uses commercial thermoelectric generator solutions developed with non-space industry partners (an SME in the East Midlands, European Thermodynamics Ltd). This prototype RTG is the first for the European space industry. This also marks a spinout of thermoelectric technology to the space sector from the non-space sector, where thermoelectric generators are increasingly of interest in energy harvesting systems, harvesting waste heat to produce electrical power as part of a suite of low-carbon energy generation technologies.
- Application of this enabling technology for future more innovative exploration missions [**3**] resulted in a contract from ESA to explore this Mars mission concept in greater detail.

Key academic staff: Dr Richard Ambrosi (Reader and programme lead; 2000-), Dr Nigel Bannister (Senior Lecturer; 2001-), Dr Hugo Williams (Lecturer; 2010-).

3. References to the research

1. Williams, H. R., Ambrosi, R. M., Bannister, N. P., et al. (2013, February). Metal matrix composite fuel for space radioisotope energy sources. *Journal of Nuclear Materials*, *433*(1), 116-123. doi:10.1016/j.jnucmat.2012.09.030

2. Williams, H. R., Ambrosi, R. M., Bannister, et al. (2012, October 10). A conceptual spacecraft radioisotope thermoelectric and heating unit (RTHU). *International Journal of Energy Research*, *36*(12), 1192-1200. doi:10.1002/er.1864

3. Williams, H. R., Ambrosi, R. M., Bannister, N. P. (2011, May 8). A Mars hopping vehicle propelled by a radioisotope thermal rocket: thermofluid design and materials selection. *Proceedings of the Royal Society A*, *467*(2129), 1290-1309. doi:10.1098/rspa.2010.0438

4. Skidmore, M., Ambrosi, R. M., O'Brien, C. (2009). Neutron sources for in-situ planetary science applications. *Nuclear Instruments and Methods in Physics Research A*, *3*(608), 1019-1029. doi:10.1016/j.nima.2009.07.011

5. O'Brien, R. C., Ambrosi, R. M., Bannister, N. P. (2009). Spark plasma sintering of simulated radioisotope materials within tungsten cermets. *Journal of Nuclear Materials*, *393*, 108-113. doi:10.1016/j.jnucmat.2009.05.012

6. O'Brien, R. C., Ambrosi, R. M., Bannister, N. P. (2008). Safe Radioisotope Thermoelectric Generators and Heat Sources for Space Applications. *Journal of Nuclear Materials*, 377, 506-521. doi:10.1016/j.jnucmat.2008.04.009

4. Details of the impact

Policy and Economic Impact. Pioneering work at the Unit [**A**] and close collaboration with NNL [**A,B,C**] has resulted directly in a clear policy decision by the UK government to further invest £18.4M in a programme focused on enabling technologies for innovative space missions including space nuclear power [**E**]. The work of the Unit, NNL and UK space industry has hence resulted in the creation of a new industry in the field of space nuclear power. New missions are being considered which will be powered by radioisotope systems. On 21 November 2012 16:00, a Department for Business, Innovation and Skills press release included the following statement: ***"…this optional technology programme will see the UK take the leadership in developing nuclear power sources for space missions in synergy with the future civil nuclear power programme…This complements the work on future international missions to succeed the current ExoMars mission, and could potentially demonstrate strong spin-out technology in the terrestrial economy.*** This part of the press release refers to the policy decision by UK government at the ESA Ministerial meeting in November 2012 to invest £18.4 million in an optional

ESA programme, which includes space nuclear power [**A,B,E**].

This impact is a result of a sustained campaign by the Unit and NNL to inform and educate policy makers [**A,B,D,E**] about the role that these systems can make in leveraging a position for UK industry and academia in future space missions together with the wider benefits from technology spinouts, e.g. new materials and material processing methods applied to the nuclear industry for radioisotope containment safety and fuel form. The outputs of the research by the Unit in the form of working prototype systems, novel safer radioisotope encapsulation and containment systems were demonstrated as examples of the benefits that sustained investment in technology can have.

The total investment in technology development including: RTGs, isotope production and containment and Stirling engine conversion systems in the UK between 2008 and 2012 has been in excess of >£4M. In industry and academia this has had a very significant impact by sustaining and creating tens high-value jobs [**A**].

The confirmation [April 2013, **A, B, E**] of the release of a yet further ~£2M will see further investment in space nuclear power systems in industry and academia.

<u>*Spin Offs.*</u> Americium is extensively used in production of smoke alarms, oil well logging systems, gamma-ray and neutron radiation sources [4]. The policy decision made by the UK government which is referred to above is also aimed at producing a competitive UK supply of americium-241 for a terrestrial market currently dominated by Russia. The development of a novel radioisotope containment method using spark plasma sintering in refractory metals by the Unit to create a composite of the metal and americium has been shown experimentally [1, 5, 6] to reduce the need to process the radioisotope thus reducing the risk to radiation workers to immobilise and disperse the radioisotope in a metal structure to reduce the risk of exposure, impact on the environment and improve prevention of release. This method will be adopted as part of the study on fuel form fabrication that will be led by the NNL as part of the policy decision by government to invest in space nuclear power.

<u>*Technology.*</u> First generation European radioisotope thermoelectric generator prototype system (producing 80 watts of heat to generate 5 W of electrical power) development led by the Unit. Working prototype delivered to ESA in 2012 [**B**].

<u>*Evolution of Impact.*</u> The Unit and NNL, led a number of initiatives [**A, D**] to engage with and inform MPs and Ministers of the work being carried out in the UK, future benefits to space and technology transfer activities. These initiatives are highlighted in sequence below.

- An independent ESA funded study (€150,000) by NNL and SEA Ltd follows the Unit pioneering work funded by the EPSRC (as mentioned above) and in collaboration with Centre for Space Nuclear Research, Idaho, USA, and concludes in 2010 that americium-241 is the isotope of choice for Europe’s space nuclear power programme.
- The early work done by the Unit leads to an ESA contract award to lead the development of a RTG (€660,000). Collaboration established with Astrium UK. A working prototype system is developed.
- ESA, in 2010, award a contract (€200,000) to SEA Ltd, the Unit, Lockheed Martin UK and National Nuclear Laboratory to develop two concepts for radioisotope containment and safety, one being a pioneering method developed by Leicester. A prototype containment method is developed.
- NNL win an ESA contract in 2011 (€1,000,000) to lead and develop the extraction process for americium from the UK’s separated civil plutonium stocks. The Unit and SEA Ltd are included in that programme.
- Representatives from NASA and US Department of Energy travel to the UK and visit the NNL and the Unit to explore areas for collaboration as part of a series of planned exchanges. This is direct result of NNL and the Unit strategy to engage in discussions with US e.g. by participating in key conferences between 2009 and 2012 [**C**].
- UKSA award a contract (£100,000) to Astrium UK, SEA Ltd and the Unit to develop a roadmap for the future, explore mission opportunities and requirements by building on current activities and existing knowledge.
- ESA award a contract (€200,000) to Astrium UK and the Unit in 2013 to explore a new mission concept that will use space nuclear power and a novel propulsion system. Large Mars Hopper

vehicle concept is designed [3].

5. Sources to corroborate the impact

A. Strategic Business Development Manager, National Nuclear Laboratory.
B. Head of Planetary and Solar System Exploration Studies Section (SRE-PAP) Advanced Studies and Technology Preparation Division (SRE-PA), European Space Agency.
C. Program Executive, Radioisotope Power Systems Program, Planetary Sciences Division, Science Mission Directorate, NASA.
D. Letter to Rt Hon David Willetts MP highlighting the importance and impact of the UK's involvement and leadership in space nuclear power systems signed by industry including: National Nuclear Laboratory, SEA Ltd, National Physical Laboratory, Nanoforce Technology Ltd, European Thermodynamics Ltd. Invitation to provide a business proposition and briefing in support of the activity included in the response from the Minister.
E. An invitation received to brief Mr David Morris MP, member of the Parliamentary Space Committee by University of Leicester and SEA Ltd on 5 December 2011. This highlights the importance of the programme in terms of technology development, use of a waste product of reprocessed nuclear fuel, space exploration and resulted in: **Early Day Motion 2523** entitled "Americium-241" on 8 December 2011, which explicitly mentions the Unit's work on RTGs. An invitation to University of Leicester, National Nuclear Laboratory, SEA Ltd and Astrium UK to present a summary of the work underway in the UK at a special event in Westminster on 19 April 2012 organised by the Conservative Friends of Nuclear Energy. University of Leicester amongst the key speakers. Mrs Nicky Morgan MP for Loughborough and current economic secretary to The Treasury visits the National Nuclear Laboratory on 19 October 2012.
F. Policy decision by UK government at the ESA Ministerial meeting in November 2012. Investment of £18.4 million in an optional programme which includes space nuclear power announced in November: http://news.bis.gov.uk/Press-Releases/UK-secures-1-2-billion-package-of-space-investment-683b9.aspx.