# The European Radioisotope Power Systems Program: Updates & Synergies

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*Radioisotope power systems (RPS) are an essential building block of the space exploration strategies of a number of countries around the world. The UK, US and the European Space Agency (ESA) view RPS technologies as enabling for a range of scientific space missions targeting the most challenging, distant, and cold environments in the solar system over the coming decades. However, RPS interest and associated capabilities are growing across the globe, where drivers include the increasing importance of space to address defense and commercial interests. Most missions have utilized $^{238}$Pu as the radioisotope of choice to generate electrical power and to produce heat for the operation and thermal management of spacecraft systems. In Europe, since 2009, $^{241}$Am in ceramic form has been selected for the ESA RPS development program. The ESA program has evolved in the past few years into a cross directorate program. This paper provides an update on this RPS technology program with a focus on technology updates, missions and partnerships.*

## I. INTRODUCTION

Radioisotope power systems are both enabling and enhancing technologies for a range of space science, exploration (Ref. 1) and increasingly defense applications in space and on Earth. These systems provide electrical power as well as the heat for spacecraft systems to survive the most inhospitable environments in the solar system. While on Earth, historical deployments in remote locations and deep oceans have offered the opportunity to power the strategic deployment of sensors and other systems to address defense interests. The increasing interest in targeting new destinations in the solar system is opening new opportunities for radioisotope power and heat. The global interest in the Moon, by space agencies and commercial space companies, as well as interest in having a permanent human presence on the lunar surface, will require a range of complementary thermal and electrical power sources. Radioisotope systems provide affordable baseline power and heat for the evolving lunar and deep space exploration economy. Science missions to the outer solar system and icy moons will require innovations in radioisotope development and power generation architectures.

The radioisotope that has been used in space missions to date is $^{238}$Pu-based in ceramic form. For more than a decade, ESA has been developing RPS technologies that will exploit the heat produced by a $^{241}$Am-based ceramic fuel. Both of these radioisotopes have the characteristics of relatively long half-lives i.e., 88 years for $^{238}$Pu and 432 years for $^{241}$Am. The UK's National Nuclear Laboratory leads on all activities related to the $^{241}$Am fuel production and fuel form development. This work on the $^{241}$Am fuel form is supported by the University of Leicester and a number of national and international partners.

The University of Leicester has been leading the development of radioisotope thermoelectric generators (RTGs) and heater units (RHUs) for more than a decade see Ambrosi et al. (Ref 1). The maturity and launch readiness of the portfolio of space power systems based on americium-241 is unparalleled. A Stirling-engine based radioisotope power system is being studied as part of a US-UK collaboration (Ref. 2). More recently expansion into other complementary technologies includes: power conditioning, enhancements to americium radioisotope fuels, space reactor heat to electricity conversion technologies and terrestrial systems.

The RTG is based on a 200 $W_{th}$, 10 $W_e$ modular architecture that can be scaled up to 50 $W_e$ (Ref. 1). The specific power is 1 $W_e$/kg. The RHU is a 3 $W_{th}$ system with a specific thermal power of 15 $W_{th}$/kg. In addition, a RHU holder has been designed to accommodate single or multiple RHUs depending on the mission requirements.

The University of Leicester's RPS program has been based at the new flagship facility of Space Park Leicester (Fig. 1) for a number of years. As part of the long-standing collaboration with the National Nuclear Laboratory and the expanding collaboration with UK's both NNL and the Atomic Weapons Establishment (AWE) have a significant presence at Space Park Leicester.


**Fig. 1.** Space Park Leicester housing full end-to-end space system lifecycle facilities [1]. (Top left) External view. (Bottom left) Atrium. (Top right) Cleanroom. (Bottom right) Concurrent design facility.

## II. ESA ENDURE PROGRAM – EUROPEAN DEVICES USING RADIOISOTOPE ENERGY

ESA's Voyage 2050 (Ref. 3) and Terrae Novae visions (Ref. 4) for science and exploration are the equivalent of the US Decadal Survey process. These programs identified many space science and exploration missions between 2020 and 2040 that would require radioisotope power systems (RPS). To deliver this end-to-end operational capability for RPS heat and power, ESA's multi-directorate program kicked-off in 2023 on the back of a successful ESA Council of Ministers meeting in late 2022. The directorates responsible for exploration, science, technology and space transportation are all included in the ESA ENDURE[2] RPS program. One of the most pressing targets is the Rosalind Franklin Mission to Mars scheduled for launch in 2028, followed by the lunar surface (Fig. 2), with multiple Argonaut missions planned in the 2030s, and subsequently deep space outer solar system missions in late 2030s. For the Rosalind Franklin Mars Mission, an americium RHU will be included on the lander module and the rover will be launched from US territory. A study carried out by NNL and University of Leicester, presented by White et al. (Ref. 5) outlines the programmatic feasibility of a Mars mission launch in 2028 with RHU flight delivery in 2027. A number of missions to Mars, deep space and icy moons are covered by both the Voyage 2050 and Terrae Novae visions.

A number of objectives will be addressed by ENDURE:

1. Fuel and pellet production and integration into welded clads to produce sealed sources.
2. Migration from research and development to manufacturing and production given the maturity of European RPS technologies.
3. Completion of RPS systems launch safety testing and modelling to create product specific safety data and outputs required for launch from different jurisdictions (Ref. 6 and Ref. 7)[3].
4. Launch safety authorisation process (LSAP), launch site and launcher adaptations. This is the focus of the team at ArianeGroup in France and includes collaboration with the University of Leicester (Ref. 6 and Ref. 7).

The overall objective of the program is to reach an operational capability of production and launch certification from European territory of RPS units for space in the latter half of the 2020s. However, the UK team of NNL, the University of Leicester and AWE with support from the UK Space Agency is also exploring a range of opportunities for the inclusion of Am-fuelled RPS systems in the latter half of the 2020s in a range of missions. Therefore, the UK team's program is centred on production of the systems at scale for scientific and commercial use by 2025; fuel production at scale online by 2026; launch qualification for RHUs and the 200W European Large Heat Source by 2026; flight RHU delivery by 2027. The

[1] Space Park Leicester

[2] ENDURE - European Devices Using Radioisotope Energy

[3] Please see Alessandra Barco's NETS24 presentation.

University of Leicester and Space Park Leicester are the design authority for these systems under the ESA ENDURE program.

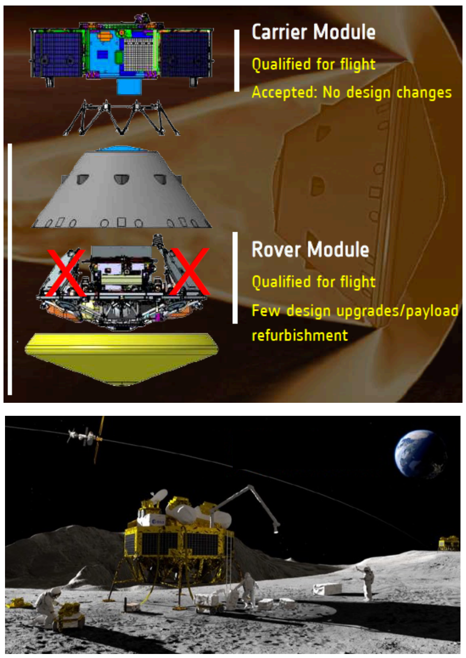


**Fig. 2.** (Top) Rosalind Franklin Mission showing the lander and rover modules. (Bottom) An artist's impression of ESA's Argonaut lunar lander. Radioisotope power to provide at a minimum lunar night survival capability. Image credits ESA.

## III. AMERICIUM PRODUCTION & FUELS

The production of $^{241}$Am for the ESA RPS program is led by the U.K.'s National Nuclear Laboratory, and the process is outlined in detail by Sarsfield et al. (Ref. 8, Ref. 9). The NNL (Ref. 8, Ref. 9) has developed a method to extract $^{241}$Am from the reprocessed and stored civil plutonium fuel. The $^{241}$Am-based consolidated fuel form development is part of a broader collaboration that includes the Joint Research Centre (JRC Karlsruhe), the U.K.'s National Nuclear Laboratory, the University of Leicester[4] and a number of partners in the UK. The fuel form, and the addition of uranium in a solid solution with $^{241}$Am producing a stable fuel matrix (Ref. 10), has been refined and is now the baseline for the ESA program (Ref. 11 to Ref. 13). This fuel matrix produced at JRC has remained in a consolidated pellet-like geometry for more than five years to date. The fuel for the European RTG will be composed of a stack of discs rather than single pellets. Ongoing fuels work between Leicester and JRC Karlsruhe is focused on pelleting, compatibility testing with platinum-based cladding materials (Fig. 3) as well as the measurement of He outgassing, measurement of thermal properties: heat capacity, enthalpy, thermal conductivity as a function of temperature (Ref. 11 to Ref 13). The thermal conductivity work by Watkinson et al. (Ref. 13) for example was used to evaluate the expected thermal performance of heat sources e.g. ELHS, which is verified experimentally during tests.

In late 2020 the UK Space Agency made an announcement to invest in a National Nuclear Laboratory facility, PuMA2, to scale-up of production of $^{241}$Am, from the current lab-scale production in PuMA1, to 500g or more per year[5]. PuMA2 will take about 2 years to become operational and PuMA1 will continue to produce lab-scale quantities of $^{241}$Am in parallel to address both ESA R&D program needs as well as opportunities for potential early deployment of an $^{241}$Am RHU (Ref. 14).

## IV. RADIOSOTPE HEATER UNIT & EUROPEAN LARGE HEAT SOURCE

Heat source geometries for RHU and RTG are shown in Fig. 4. The RTG heat source is also termed the European Large Heat Source (ELHS), and the diagram shows the 2020 version of the design. The evolution in the RHU and ELHS design are shown in Fig.4 and Fig. 5 respectively. This evolution spans the last decade. Four generations of heat sources for both RHU and RTG have been produced and fully evaluated experimentally. Further and more recent updates to the RHU and ELHS flight units are not reflected in this paper; however, the overall shapes of the two heat sources have not changed.

Cladding for both heat sources is in the form of Pt-20Rh cladding with incorporated venting technology. In both cases, the same 3D carbon-carbon composite aeroshell material is used (Ref. 1). This 3D composite material is light, resistant to thermal shock, and mechanically stable to temperatures in excess of 3000 K. In addition to the common use of aeroshell materials, the insulation layer between the cladding structure and the aeroshell is a carbon based insulator. This insulation is used in both the ELHS and RHU. The ELHS is designed to induce tumbling during re-entry to reduce the rate of ablation of the aeroshell and also distribute the mechanical stresses across the aeroshell.

[4] See Emily Jane Watkinson's NETS23 presentation.
[5] UK Space Agency Press Release 2022

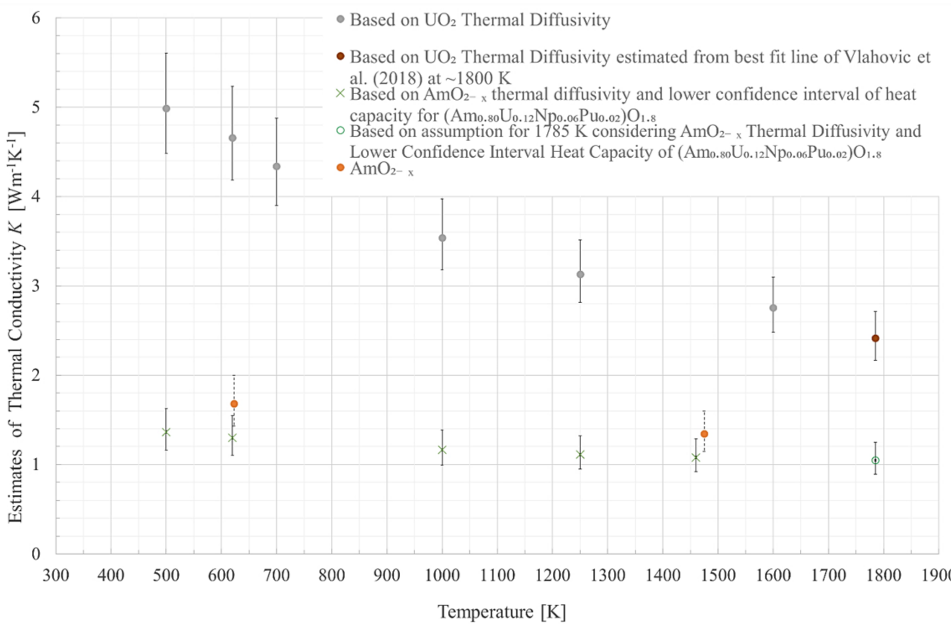


**Fig. 3.** Thermal conductivity estimates for Am based fuels based on experimental data and calculations. These data can be used to evaluate operational temperatures for systems. The Am fuel data is benchmarked against $UO_2$ in the graph. Reproduced here under Creative Commons CC BY license from the article by Watkinson et al. (Ref. 13).

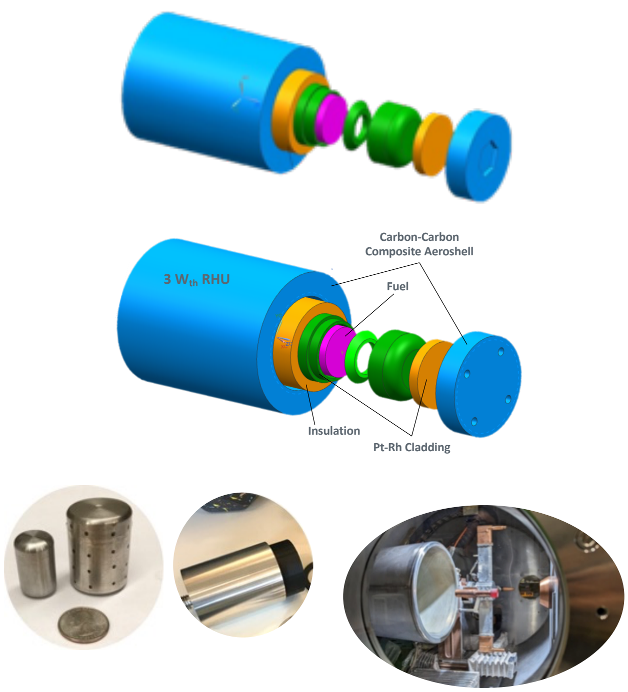


**Fig. 4.** The Am-RHU early generation design (top) and 2020 design (bottom) along with cladding structures and an early holder design for the RHU. Plasma test campaign image is also shown. The latest RHU flight unit design is not shown here.

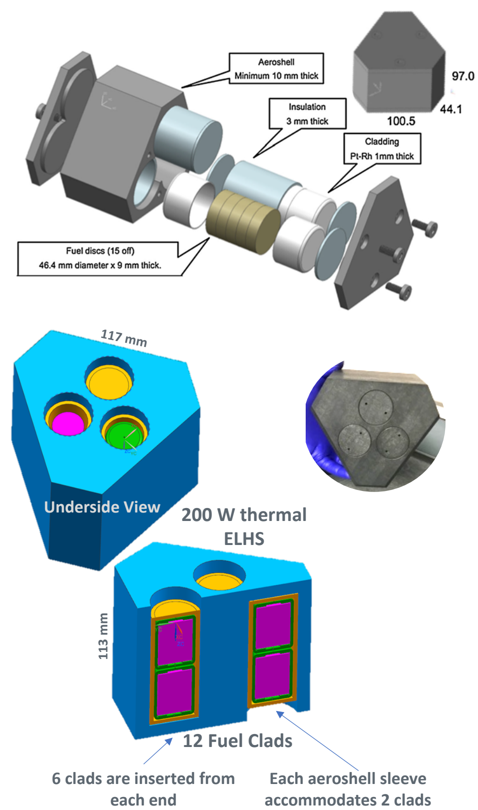


**Fig. 5.** The 2013 ELHS design (top) and 2020 ELHS design (bottom) along with a fully assembled unit. The cladding and layering are the standardized across the ELHS and RHU. The latest ELHS flight unit design is not shown here.

Recently electrically heated and structural models of RHUs and ELHS have undergone a series of tests including vibration (See Fig. 7) and evaluation in different operational conditions: vacuum and atmospheric environment. RHU aeroshells have recently undergone plasma re-entry heating testing outlining behavior as expected from extensive modelling campaigns. In addition, cladding structures for both the RHU and ELHS have been subjected to impact testing to simulate ground impact after re-entry at expected elevated temperatures. In the case of the latter, clads survived impact testing at the University of Dayton's Research Institute facilities. In the case of the former. results of testing met the requirement of a recession depth of less than 50% of the total aeroshell thickness. These data corroborate the outcomes of earlier tests from previous studies (Ref. 1).

## V. RADIOSOTPE THERMOELECTRIC GENERATOR

The thermoelectric converters for the RTG system are bismuth telluride-based, operating between 220°C and room temperature, these are well-suited to americium-based RPS (Ref. 1, Ref. 15, Ref. 16). The program is focused on the complete end-to-end production capability in the U.K., from producing the thermoelectric materials from the constituent elements, using appropriate materials processing and consolidation methods, through to segmentation into unicouples and module production.


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Friday 3 May 2019

**UK scientists generate electricity from rare element to power future space missions**

Experts have generated electricity from a rare chemical element for the first time which may mean future space missions can be powered for up to 400 years.

The rare element americium is not found in nature but is a by-product of the decay of plutonium, which itself is produced during the operation of nuclear reactors.

An amazing scientific advancement.

A team of scientists led by the National Nuclear Laboratory (NNL), working with the University of Leicester, have extracted americium from some of the UK's plutonium stockpile and used the heat generated from this highly radioactive material to generate enough electric current to light up a small lightbulb within a special shielded area in NNL's Central Laboratory in Cumbria.

**Fig. 6.** First test of americium powered system producing light in a laboratory setting[6]. Image Credit NNL.

The early demonstration of producing electrical power from americium ceramic fuel with the thermoelectric generators produced for ESA was shown in 2019 as part of the collaboration between University of Leicester and National Nuclear Laboratory. This was a first test with electrical power generated used to produce light.

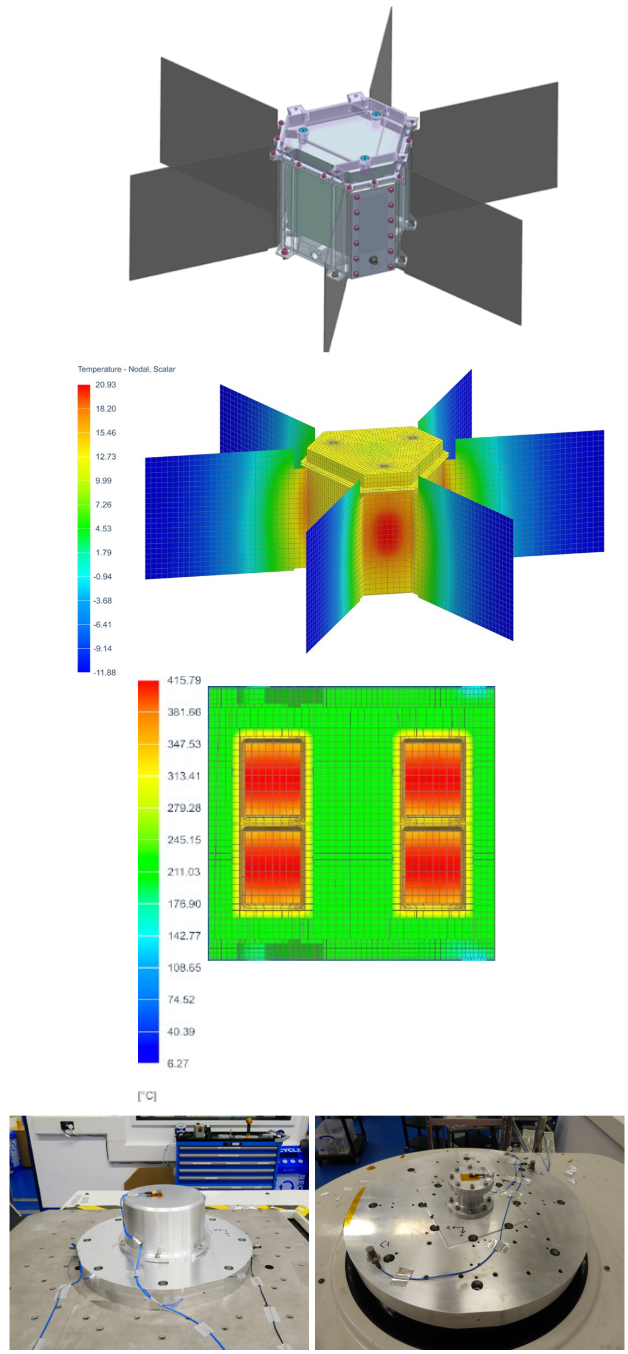


**Fig. 7.** European 10$W_e$ RTG along with the temperature distribution from the radiator to the fuel core. This is for a deep space case. Included in the image sequence (bottom)

[6] The news item can be found via this link.

are images from the vibration test campaigns for both the ELHS (bottom left) and the RHU (bottom right).

The RTG system has evolved over the past ten years from a design with the fuel on axis to a design with a distributed fuel in a heat source shown in Figure 7. A full thermal and mechanical analysis has been carried out, and the model shown in Fig. 7 has been produced and is currently in testing campaigns. Test results will be presented at NETS 2024. The current design enables the cold side thermoelectric generator temperature to be maintained at 20ºC. The temperature distribution throughout the RTG system is shown in Figure 7 for a deep space case. Core fuel temperature is not expected to exceed 415ºC. The power generation performance of this system is predicted to exceed the performance of previous models.

In previous models power levels of $10W_e$ were targeted and levels of $9.3W_e$ were measured. The current version predicts a power output of between $10W_e$ and 13 $W_e$ due to significant improvements in design and thermoelectric module production methods. Initial thermoelectric testing campaigns show results with at least a 10 $W_e$ measured output at full generator level.

## VI. MICRO-REACTORS

The University of Leicester continues to work on a new phase of research activities focusing on micro-reactors for space applications. The main focus being feasibility studies exploring thermoelectric conversion for small scale systems in the kW range (Ref. 17). This is subject of a more detailed paper at NETS[7].

## VII. COLLABORATIVE TECHNOLOGY PROGRAMS AND MISSION OPPORTUNITIES

Given that the RPS heat sources i.e. RHU and ELHS are mature in design and are on track for launch readiness in a just a few years. There is significant work exploring mission opportunities targeting the Moon, Mars and deep space with icy moons and gas/ice giant planets being the main targets in the outer Solar System. In the context of the lunar exploration case, $^{241}$Am heat sources can support science missions, in-situ resource utilization requiring heat and electrical power, human life support systems requiring heat, heat for Stirling power conversion systems and other use cases. As part of an ongoing growth of activity in space nuclear power at the University of Leicester, Stirling power conversion feasibility studies (using $^{241}$Am) (Ref. 2) and in situ resource utilization mission concepts have been explored in collaboration with partners in the US (Ref. 18).

In the case of a Stirling engine-based radioisotope power system or the outcome of an initial study, as part of a collaboration with NASA GRC and presented at NETS 2023, showed the feasibility of 200W Stirling-based RPS. This study also demonstrated that a specific power of 1.9 W/kg powered by the ELHS was possible (Ref. 2). The design could be subjected to further improvements to provide power and heat for a lunar rover type mission. This has been presented at conferences (Ref. 2) and shown in Fig. 8.

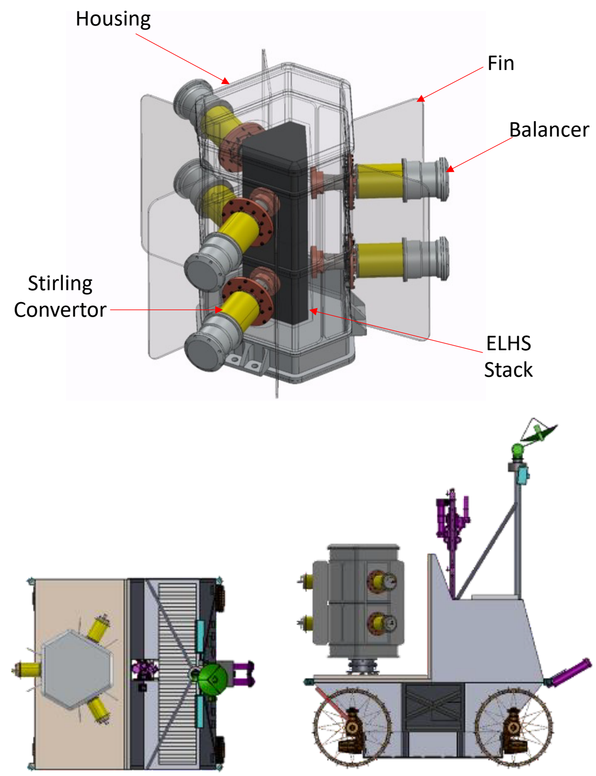


**Fig. 8.** The americium fuelled Stirling radioisotope power system concept design and layout. Top and side view of a representative model of the Am powered Stirling RPS on a Volatiles Investigating Polar Exploration Rover (VIPER) class lunar rover. Image Credits NASA GRC.

The University of Leicester team is exploring a number of bilateral mission opportunities with a range of partners. The outputs from these activities will be presented at future NETS conferences.

## VIII. CONCLUSIONS

The paper provides an update of the ESA RPS program focusing on ENDURE and on the development of European RTG and RHU systems as well as some new developments on the Stirling engine based RPS front. The project is currently at a point where the program has evolved to a flight program with a number of launch opportunities. The RTG program remains on track to have a generator flight ready by 2028. The Leicester and NNL teams are working closely with a number of entities to explore the different use cases for European RPS with near term focus on RHUs.

[7] See Ramy Mesalam's NETS24 presentation.

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**REFERENCES**

1. R. M AMBROSI, H. WILLIAMS, E J WATKINSON, et al., *European Radioisotope Thermoelectric Generators (RTGs) and Radioisotope Heater Units (RHUs) for Space Science and Exploration*, Space Science Reviews, **215:55** (2019)

   https://doi.org/10.1007/s11214-019-0623-9 .
2. R. MESALAM, R. M. AMBROSI, S. R. OLESON, P. C. SCHMITZ et al., IEEE Proceedings of the European Space Power Conference, October 2023.
3. ESA Voyage 2050, accessed 10 Dec 2023

   https://www.cosmos.esa.int/web/voyage-2050
4. ESA Terrae Novae, accessed 10 Dec 2023

   https://www.esa.int/Science_Exploration/Human_and_Robotic_Exploration/Exploration/Terrae_Novae_Europe_s_exploration_vision
5. J. WHITE, T. TINSLEY, R. AMBROSI et al., American Nuclear Society, Proceedings of Nuclear and Emerging Technologies for Space, Idaho Falls, May 2023, doi.org/10.13182/NETS23-41847
6. A. BARCO, R. M. AMBROSI, C. FONGARLAND, et al., Journal of Space Safety Engineering, (2021), https://doi.org/10.1016/j.jsse.2021.11.001
7. A. BARCO, et al., Journal of Space Safety Engineering, Volume 7, Issue 2, pp. 137-149 (2020), https://doi.org/10.1016/j.jsse.2020.03.001
8. M. SARSFIELD, C. CAMPBELL, C. CARRIGAN, et al., E3S Web Conf. **16**, 05003 (2017)

   https://doi.org/10.1051/e3sconf/20171605003 .
9. M. SARSFIELD, J. BROWN, C. CAMPBELL, et al., Progress in Nuclear Energy, **106**, 396–416 (2018) https://doi.org/10.1016/j.pnucene.2018.02.008 .
10. J-F. VIGIER, D. FREIS, P. PÖML et al., Inorganic Chemistry **578**, 4317–4327 (2018) https://doi.org/10.1021/acs.inorgchem.7b03148 .
11. EJ WATKINSON, B CREMER, P LAJARGE et al., Proceedings of the Nuclear and Emerging Technologies for Space (NETS) 2020, Knoxville, TN, USA, 6–9 April 2020; p. 24.
12. EJ WATKINSON et al., *"Progress in Characterising an Am-U oxide as a Potential Fuel For Future European Radioisotope Power Systems: Thermal Properties And Initial Helium Outgassing Experiments*," Lightning talk in the Proceedings of Nuclear and Emerging Technologies for Space NETS 2020, Available online at https://nets2020.ornl.gov (2020).
13. E.J. WATKINSON, R. MESALAM, J-F VIGIER et al., Thermal Properties and Behaviour of Am-Bearing Fuel in European Space Radioisotope Power Systems", Thermo, 1, 297–331 (2021), https://doi.org/10.3390/thermo1030020
14. R. SANDERSON, M. SARSFIELD, C. MAHER, et. al., American Nuclear Society, Proceedings of Nuclear and Emerging Technologies for Space, Idaho Falls, May 2023, doi.org/10.13182/NETS23-41842
15. R. MESALAM, et al., AIP Advances, 9 (5) (2019) https://doi.org/10.1063/1.5095619
16. R. MESALAM, H. R. WILLIAMS, et al., Applied Energy, 226, 1208-1218, (2018) https://doi.org/10.1016/j.apenergy.2018.05.041
17. R. MESALAM, A. MURATTO, R. M. AMBROSI, American Nuclear Society, Proceedings of Nuclear and Emerging Technologies for Space, Idaho Falls, May 2023, doi.org/10.13182/NETS23-41958
18. H. SARGEANT, R. MESALAM, EJ WATKINSON et al., American Nuclear Society, Proceedings of Nuclear and Emerging Technologies for Space, Idaho Falls, May 2023, doi.org/10.13182/NETS23-41840