Design and Development of the ESA Am-Fueled Radioisotope Power Systems

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Abstract—**Radioisotope heater units (RHU) and radioisotope thermoelectric generators (RTG) are currently being developed for the ESA radioisotope power system program. The state-of-the-art for the USA and Russian systems is to use plutonium-238 as the radioisotope fuel; however, for the ESA applications americium-241 has been selected due to its availability and relatively cost-effective production in the European context. The proposed designs implement a multi-layer containment approach for safety reasons, with a platinum-rhodium alloy for the inner containment of the fuel and carbon-based materials for the outer layers. The Am-fueled RHU provides 3 W of thermal power, and makes this design competitive with existing models in relation to specific power. The heat source for the RTG has a 6-side polygonal shape, with a distributed 3-fuel pellet architecture: this configuration allows to maximize the specific power of the RTG, since Am-based fuels have a lower power density than Pu-based fuels. The heat supplied by the fuel is 200 W, with an expected electrical power output of 10 W provided by six Bi-Te thermoelectric modules. Finite element structural and thermal analyses have been performed to assess the theoretical feasibility of the components as initially conceived. Mechanical and electrically-heated prototypes for the systems have already been tested in a representative lab environment at the University of Leicester; these tests have provided initial estimates for the efficiency of the systems. Both the RHU and RTG architectures are currently undergoing a new design iteration process. This paper reports on the overall architecture and design of the Am-fueled RTG and RHU, the modelling results and the experimental data obtained so far.**

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1. INTRODUCTION

RTG and RHU

Nuclear power sources can be a solution to some of the challenges related to space applications, such as the use of solar power for missions to the outer planets, or during long-duration planetary missions (like on Mars and Moon), where a vehicle may be required to operate in a night or dust environment. Due to their high energy densities, some isotopes are capable of generating substantial amounts of heat for long periods of time, independently on the solar flux; this heat can then be used to keep the spacecraft instrumentation in the right operating temperatures, or it can be converted to electrical power.

The aim of a RHU is to provide localized heat to critical spacecraft elements, with the significant advantages of no

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moving parts and a nearly-constant thermal energy output. It also enables the use of photovoltaic electrical generation in 'marginal' mission contexts, because resistive heating loads are eliminated or significantly reduced (making therefore a photovoltaic solution viable where it would not otherwise be). The current RHU architectures are the US LWRHU (Light-Weight RHU) and the Russian Angel-RHU, which have a thermal power output, respectively, of 1 W_{th} and 8.5 W_{th} [1,2].

An RTG converts the heat energy produced by radioisotope decay into electricity via the thermoelectric effect. It is a static system with no moving parts, and its lifetime is limited only by component degradation and the half-life of the radioisotope. The most recent configuration is the US MMRTG (Multi-Mission RTG) [1].

The ESA Radioisotope Power System Program

The ESA RPS program has been conceived with the aim to enable Europe to independently design, manage and launch RPS. The development activities have three main targets [3]:

- Isotope production, where ^{241}Am is the selected radioisotope, due its availability and relatively cost-effective production in the European context;
- Encapsulation technologies, which allow to design the building blocks for both the RHU and RTG;
- Power conversion technologies (Stirling and thermoelectric).

The separation process of americium from Pu-stockpiles has been demonstrated at concentration levels relevant to full-scale plant [4], and the first (reduced scale) americium oxide pellets have been produced by the National Nuclear Laboratory (NNL) in the UK.
The chemical form of the fuel is still under investigation (with potential choices ranging from AmO_2 to Am_2O_3), in order to create an intact fuel form with the most suitable properties for an Am-based system. Suitable surrogates are also being examined to investigate all the variables that can influence meeting the fuel requirements, e.g. powder characteristics, crystallography and sintering, in order to inform future studies with the active americium oxide material [5,6].

While Thales Alenia Space UK is the prime contractor to design a 100 W_e Stirling Radioisotope Generator, the University of Leicester is leading the development of a 10 W_e RTG (with a specific electric power of 1 W_{el}/kg) and a 3W_{th} RHU (with a specific thermal power of 14.7 W_{th}/kg).

2. DEVELOPING THE HEAT SOURCE

The design for a radioisotope heat source implements a multi-layer containment approach for safety reasons. The fuel is encased within a system of physical barriers to remain undamaged during the nominal environments of launch, and to minimize the risk of dispersal under extreme accident conditions. The same philosophy has been applied to both the RHU and the RTG heat source (Figures 1 and 2).

The inner containment, known as cladding, is made of a Pt-Rh alloy: Pt-based alloys seem to be the most compatible, stable and least reactive materials that could meet the safety requirements, and offer a good starting point for developing and testing a primary containment layer for Am-based systems. In the early iterations of the European design, Pt-30Rh was selected; however, it has been recently changed to Pt-20Rh, since the latter has a higher ductility, it is easier to manufacture and available off-the-shelf. This material has not been tested under the operational and accident conditions relevant to the Am-based RTG and RHU systems; additional research is being performed at the University of Leicester, in order to obtain crucial high-strain rate data at elevated temperatures.

The gases generated from oxygen release from the americium-oxide fuel at elevated temperature or the helium build up over time from radioactive alpha decay could pressurize the clad from within, leading to its breaching. To avoid this pressurization, a vent hole covered by a porous frit

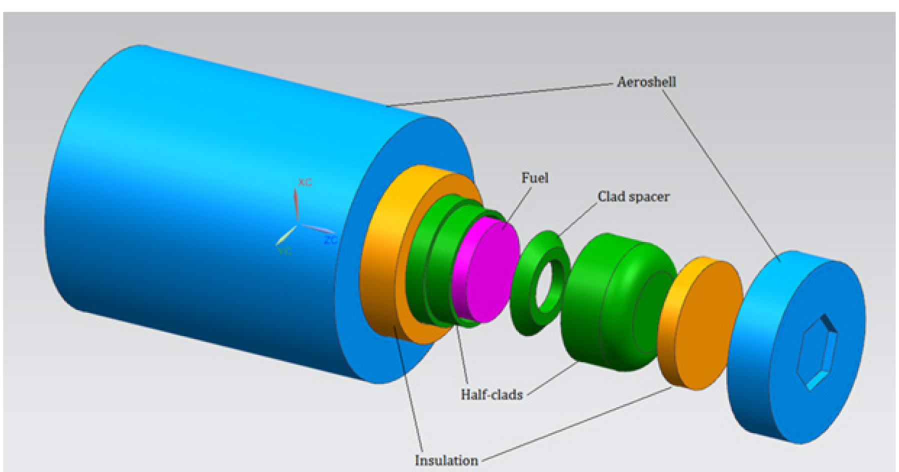

Figure 1: CAD model for the current Am-based RHU design (external diameter of 40 mm and height of 50 mm)

(made of sintered pure platinum powder) will be included into the cladding, to allow the gases out while keeping any contamination in.

In addition to the Pt-Rh cladding, there are other layers for the outer containment to protect the fuel from the high temperatures and thermal flux associated with accident scenarios:

- A carbon-carbon composite aeroshell (a number of 2.5D and 3D C-C composites have been identified as options);
- A CBCF insulation layer, between the aeroshell and the cladding, with very low thermal conductivity.

All the materials currently in use for the flight design are available in Europe: platinum alloys are sourced in the UK, while carbon-based materials are available in both France and the UK.

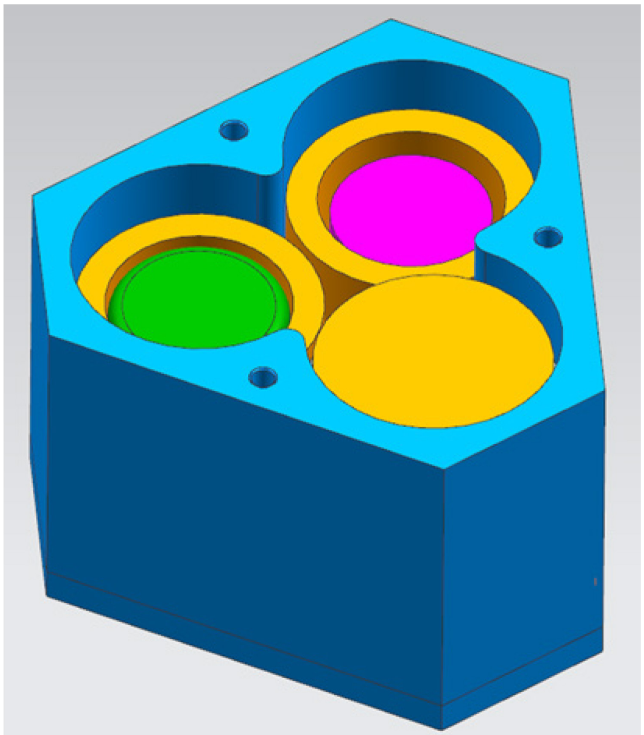

Figure 2: CAD model for the current Am-based RTG design (height of 115 mm)

The RTG heat source has a 6-side polygonal shape, with a distributed 3-fuel pellet architecture; this allows to maximize the specific power of the RTG while minimizing the total volume, since Am-based fuels have a lower power density than Pu-based fuels.

Aerothermal modelling and re-entry studies have been carried out by Lockheed Martin UK, for both the RHU and the RTG heat source [7]. They have been performed as the first step, before the consolidation of the architecture and the modelling analyses: once the heat source is demonstrated to be compliant with the safety requirements, it is possible to build the system around it.

The study had three critical objectives, mainly focused on the aeroshell structural integrity:

- The recession of the aeroshell does not exceed 50% of its thickness;
- The mechanical stresses do not exceed the maximum strength;
- The fuel temperatures remain within reasonable limits, i.e. less than 1000^{o}C under accident conditions.

Different conditions and trajectories have been considered:

- Side-On and End-On orientations for both systems;
- Three re-entry conditions, with different initial velocity, flight path angle and altitude. They were identified by previous studies, and are expected to cover the most likely conditions in the case of an accident during launch, Earth fly-by or re-entry.

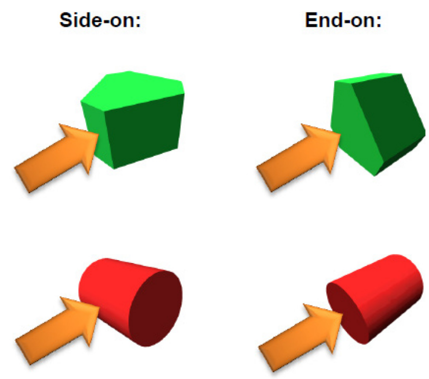

Figure 3: Side-On and End-On orientations for the RTG (top) and RHU (bottom)

Results from the model indicate that the current geometries are compliant with the three critical objectives:

- The maximum temperature in the fuel is around 900^{o}C;
- The aeroshell recession is 45% for the RTG and 40% for the RHU;
- The reserve factors are greater than unity (i.e., the components do not fail whilst in flight);
- The ground impact speeds are between 70m/s and 100m/s for the RTG, and between 30m/s and 50m/s for the RHU.

Tumbling has been briefly considered only for comparison, and it appears to reduce the aeroshell recession to a third of the values reported above.

3. MODELLING THE EUROPEAN RPS

Finite element (FE) models have been developed for both the thermal and the structural analyses of the RHU and RTG, employing the software Siemens NX®.

Good contact has been assumed between the different layers of the heat source during nominal operating conditions. The components, assembled cold, will rapidly heat up when the fuel is inserted, leading to a thermal expansion that will compress all the layers.

Modelling of the RHU

It is still unclear how the Am-based RHU will operate; therefore, three different cases have been analyzed, in order to cover all the possible configurations of the RHU installation on a spacecraft:

- Both radiation to the internal spacecraft environment and conduction to the spacecraft (in vacuum), as the most general case;
- Mostly conduction through the interface with the spacecraft, which has a temperature of 20°C;
- Mainly radiation from the aeroshell to the internal spacecraft environment (20°C).

Table 1 reports the maximum temperatures obtained in the fuel core and on the aeroshell, for a steady-state analysis.

Table 1: RHU thermal modelling results

Case	Aeroshell temperature [°C]	Fuel temperature [°C]
Conduction & Radiation	24	190
Conduction	25	191
Radiation	67	233

Higher values are obtained for the 'mainly radiation' case, while the other two cases have almost the same temperature values: in the general case, the heat transferred by radiation accounts only for a very small amount. For the initial design with a Pt-30Rh clad, the temperatures were approximately 30°C lower, since Pt-30Rh has a higher thermal conductivity.

The results of the FE thermal analysis have been mapped to a structural solution, to calculate the thermomechanical strain and stress: based on the available material properties, none of the components is expected to fail during nominal operating conditions.

A normal mode analysis of the system has then been performed. The lower frequencies are related to the mode shapes of the fuelled clad, while for higher frequencies also the outer components (aeroshell and insulation) are concerned. The following figures illustrate some of the mode shapes obtained.

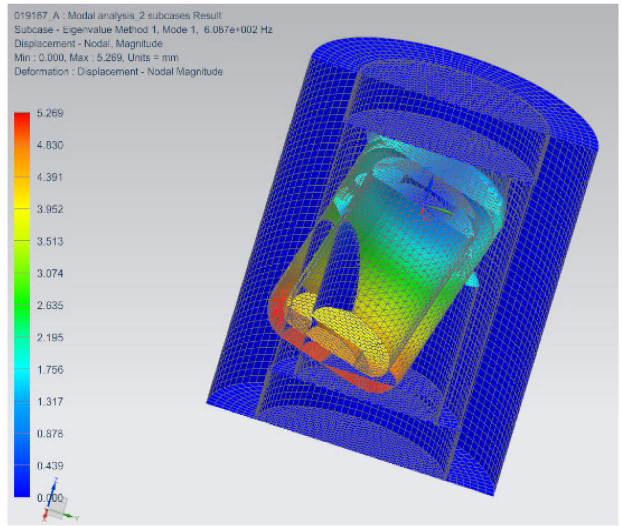

Figure 4: 1st mode (609 Hz)

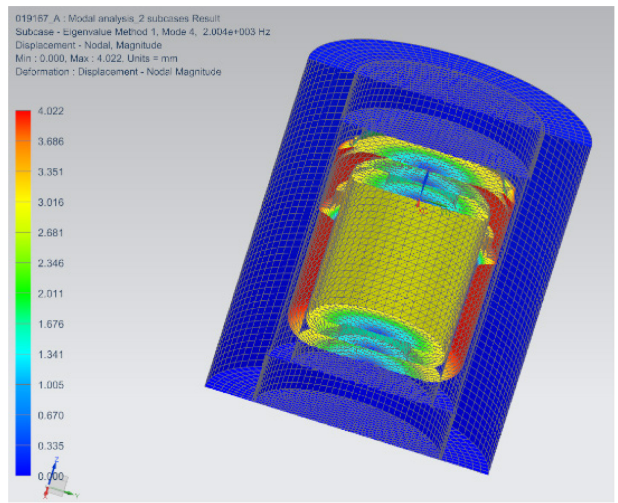

Figure 5: 4th mode (2004 Hz)

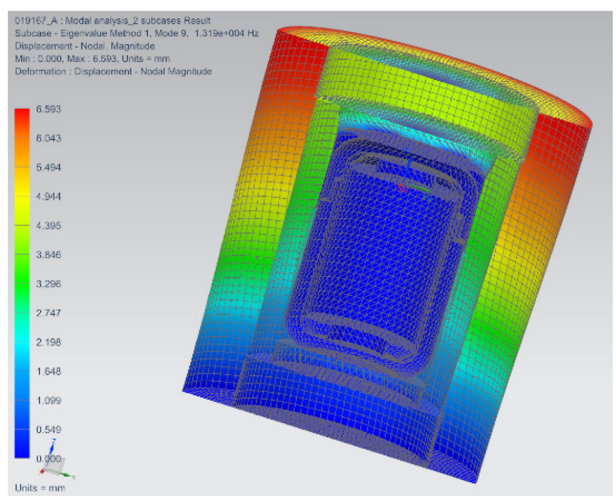

Figure 6: 9th mode (13190 Hz)

Modelling of the RTG

The current Am-based RTG is designed to accommodate six thermoelectric modules on the shortest sides of the aeroshell, 2 per each side, and conductively coupled with the aeroshell. Bismuth telluride TEGs have been introduced due to the lower Am-system operating temperatures than in the Pu-based systems. This lower temperature for the hot side will ease material compatibility issues.

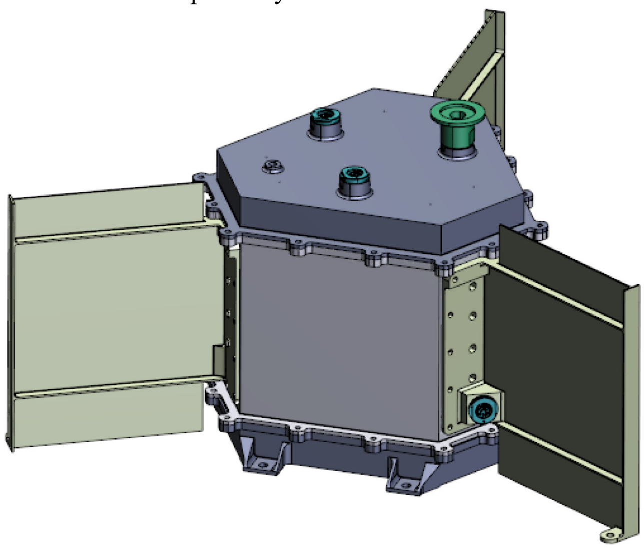

Figure 7: CAD model for the Am-based RTG prototype

The dynamic analysis for the complete RTG system has been performed by Airbus UK. The first resonant modes are at 154 Hz when the contact between the TEGs and the aeroshell is radial only, and 162 Hz (corresponding to the fin flexure, reported in the picture) when the contact is both radial and tangential.

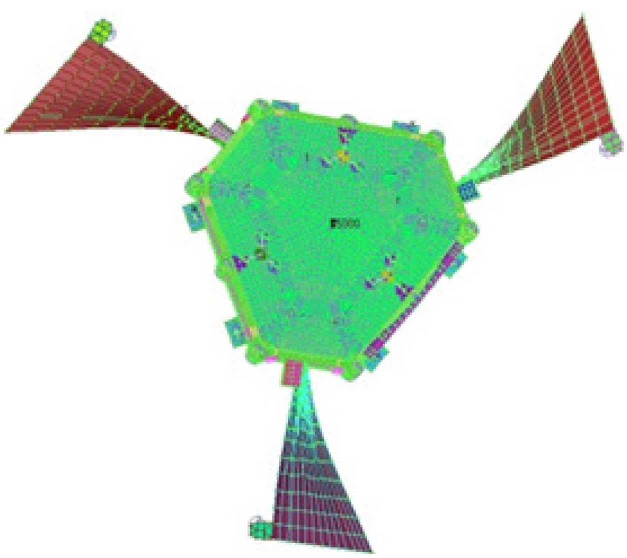

Figure 8: RTG fin flexure mode (162 Hz)

The current RTG FE models meet, therefore, the stiffness requirements specified at the beginning of the project (at least 140 Hz + 10%).

As a conservative assumption, the heat flowing through the three sides supporting the TEGs is expected to be at least 75% of the total heat released by the fuel. This is the lowest boundary of the thermal efficiency as demonstrated by the tests.

The operating environments considered in the RTG driving requirements include deep space missions (in vacuum) and planetary surface operations (with cover gas in the internal volume). However, for the thermal analyses here reported, only operations in a deep space environment (3 K) have been taken into account.

The fins and the external sides of the radiator have been assumed black-coated to allow a high emissivity coefficient. In the FE model, the TEG modules have been modelled as simple conductive elements. Table 2 reports the temperatures obtained for some significant components.

Table 2: RTG thermal modelling results

Component	Fuel temperature [ºC]
Fuel	639
Aeroshell	209
TEG cold face	97
Fin	66
Radiator housing	63

The temperatures obtained for the TEG cold face, radiator and fins are higher than expected. This is likely to be caused by a total radiator area which may be smaller than required.

More information on this aspect is reported in chapter 6 of this paper.

4. BUILDING THE RHU AND RTG PROTOTYPES

When manufacturing the RHU and RTG prototypes for thermal and mechanical tests, the philosophy was to focus on using materials and developing models that were as close as possible to the flight design, but taking into consideration the need to use off-the-shelf solutions.

This has implied:

- Changing the thickness of the CBCF insulation layer for the RHU, from 3 mm to 6 mm, as driven by the manufacturability of the component by its producer (a bespoken activity would be required for the 3 mm configuration);
- Creating electrically-heated prototypes for the thermal tests (conventional resistive heating in a ceramic support structure);
- Introducing a mass dummy for the fuel for the vibration tests: molybdenum has been used in the RHU prototype (it has a density similar to americium oxide), while for the RTG model the electrical heaters are representative of the volume

occupied by the fuel, cladding and insulation layers, but do not include the materials specified in the flight design.

The following photos (not in scale) have been taken during the assembly process of the systems.

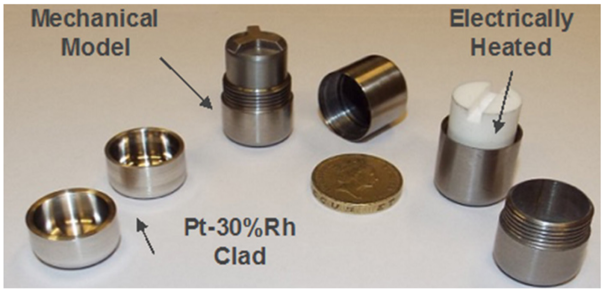

Figure 9: Mechanical and electrically-heated models for the RHU clad

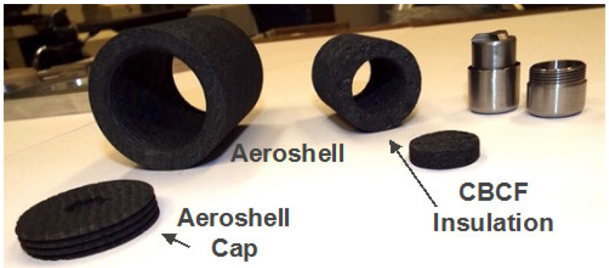

Figure 10: Aeroshell and insulation for the RHU

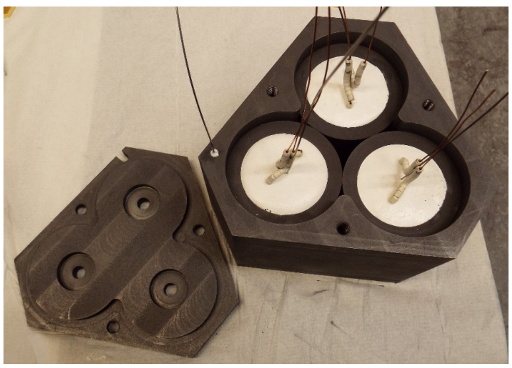

Figure 11: RTG heat source prototype

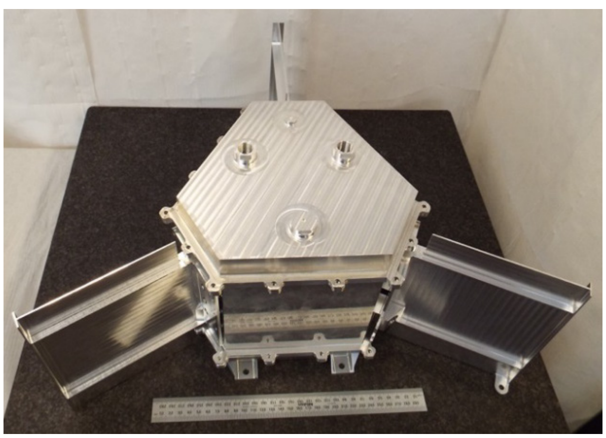

Figure 12: RTG radiator

5. Testing the RHU and RTG Prototypes

Tests for the RHU

The thermal tests on the RHU were initially performed in June 2017 (with the Pt-30Rh clad), and then again in June 2018 (with the Pt-20Rh clad).

The electrically-heated prototype was tested in various configurations at constant power. A spacecraft interface simulator was developed specifically for testing: the heat produced was managed via an Al-based interface plate, a cooling block and a pumped fluid loop.

Figure 13: RHU surrounded by MLI, to model the 'mainly conduction' case

When analyzing the results, it is possible to notice two main trends:

- The temperatures for the most recent configuration (Pt-20Rh) are generally higher than in the first prototype (Pt-30Rh), as predicted by the thermal FE analyses;
- The core temperatures are higher than those predicted in the FE model. This is due to the errors introduced through experimental technique, but also to the thicker insulation layer (6 mm instead of 3 mm).

The thermal coefficients in the prototype FE simulation have been updated to reflect the differences in the contact between layers, and a model that can be used to predict the RHU experimental behavior has been obtained.

Vibration testing was performed on the RHU by using the Laser Doppler Vibrometry (LDV) technique, at the former ASDEC facility of the University of Leicester.

Laser vibrometry is a non-destructive technique. During a LDV test, a moving surface, excited via contact through a stinger and force gauge with an appropriate shaker unit, causes a shift in frequency of the light backscattered when exposed to a laser light source. An optical transducer is then used to determine both the velocity and displacement at a fixed point induced by the vibration.

In the RHU prototype, holes were drilled in the aeroshell and the insulation to allow optical access to the internal layers, which according to the software simulations drive the lowest natural frequencies. The experimental natural frequencies were different from those previously predicted in the FE model, but the results indicate an overall behavior which is still consistent with the original predictions: the frequencies are above the critical values of 140-150 Hz and the mode shapes reflect those predicted in the model.

Testing the RTG

The electrically-heated prototype of the RTG has been tested on the bench in the lab and, as October 2018, is currently undergoing tests in a thermal vacuum chamber.

The thermal management system is attached via cooling plates to the external components of the elegant breadboard, i.e. fins and main radiator body (figure 14). This allows the temperature of the radiator and cold side of the TEGs to be controlled, and also to remove the waste heat from the heat sources that is not converted.

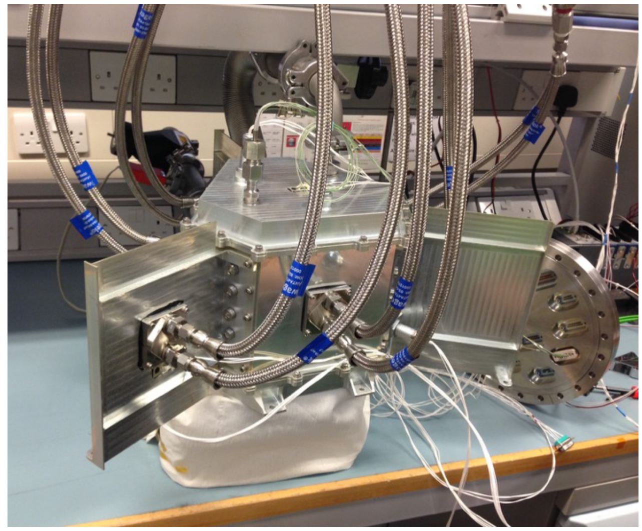

Figure 14: Complete RTG breadboard integrated with the thermal management system (pumping port and electrical feedthroughs for heaters and thermal sensors are visible on the lid)

The breadboard has been tested in the lab on the bench at ambient conditions (lab temperature of 20°C). Two configurations for the internal volume of the RTG have been considered: no cover gas (under vacuum), and refill with a cover gas (argon).

Figure 15 reports the results obtained for the first tests on the bench. For the vacuum steady state configuration, the experimental power output is slightly below 8 W_{el}, with a total efficiency of nearly 4%. The temperatures for the hot and cold sides of the TEGs are, respectively, 187°C and 20°C. When argon is pumped into the internal volume, both the

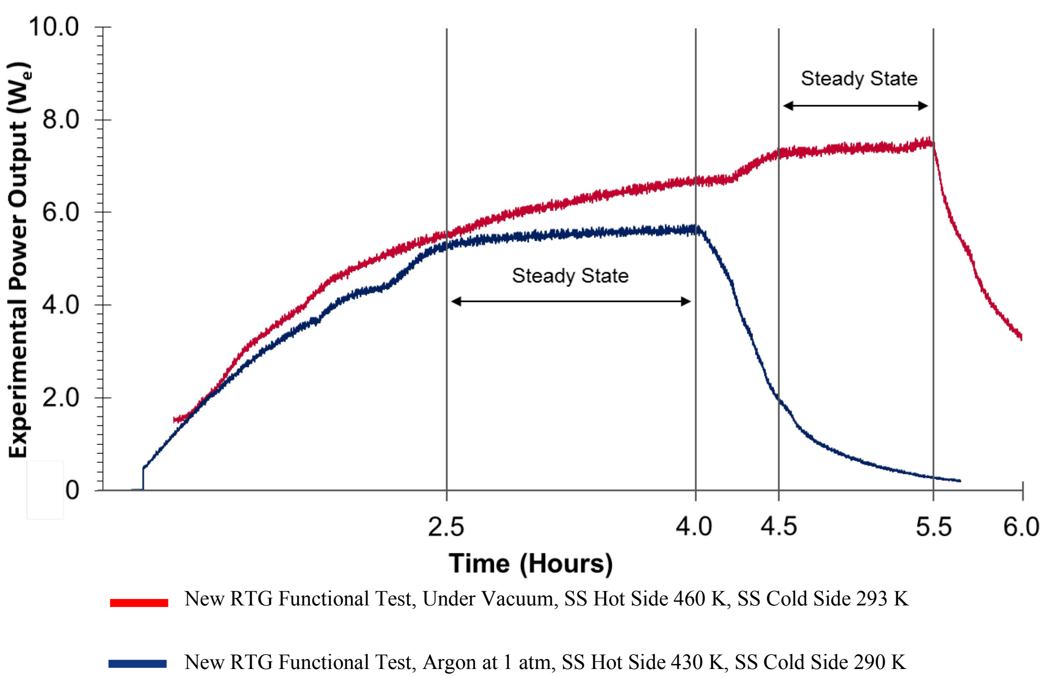

Figure 15: Tests results for the RTG breadboard on the bench

power output and the total efficiency are lower (around 5.5 W_{el} for an efficiency higher than 3%), with 157ºC on the TEG hot side and 17ºC on the cold side.

In addition, as part of the extended test campaign activities, the impedance spectroscopy method, used for the characterization and selection of thermoelectric generators, features centrally throughout the thermal test phase. More information can be found in [8].

Regarding the vibration analysis, the RTG has been tested in two different configurations:

- With fins;
- Without fins, as in Figure 16, to investigate the behavior of the heat source, which is supported by six struts, inside the radiator.

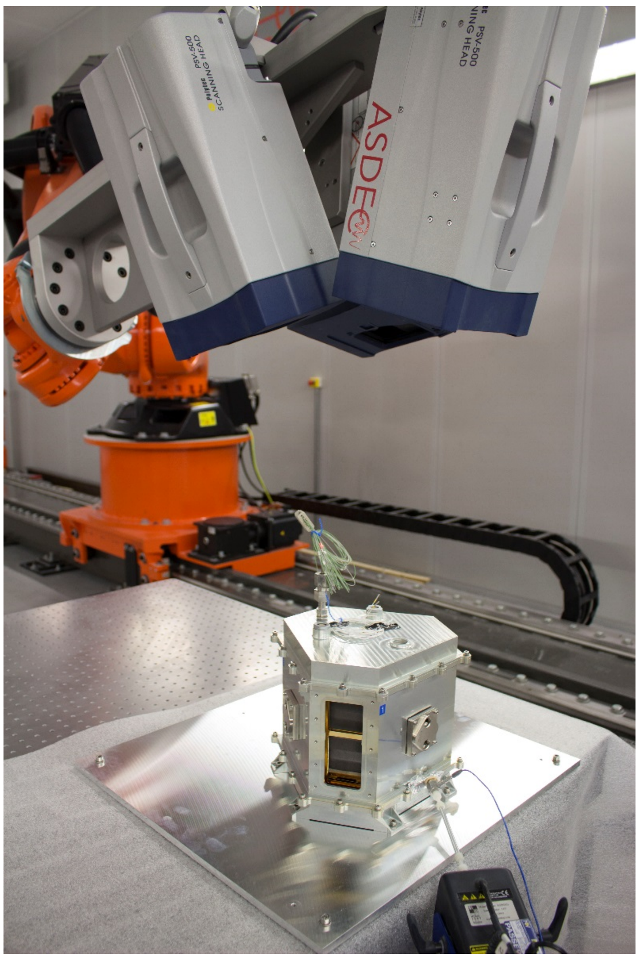

Figure 16: RTG body set-up for the vibration test

The experimental data show lower frequencies than expected, and related to different components (95.4 Hz for the heat source). The difference is likely to be caused by the different internal arrangement, since the fuel mass would be higher than the electrical heaters used in the prototype. The lowest natural frequency for the fins is now 150 Hz: the corresponding mode is very similar to the fin bending mode obtained in the FE modelling. This can be considered as a confirmation of the software simulation.

6. Further analyses for the European RTG design

Further studies are currently being conducted to iterate the RTG design, in order to increase the total radiative area. The radiator body still has a hexagonal shape, but the fin arrangement is different, with two fins for each short side.

Preliminary analyses have been performed to find the new aeroshell and the TEG temperatures, as well as the efficiency: they have been derived considering the heat balance equation, which included also the properties of the TEGs as provided by the supplier (European Thermodynamics Ltd., a company based in Leicestershire, UK).

In addition, updated values for the fuel power and mass density have been assumed [9]. The total volume of the heat source has been decreased: this has allowed to shrink the radiator body, while keeping the external dimensions of the fins almost the same.

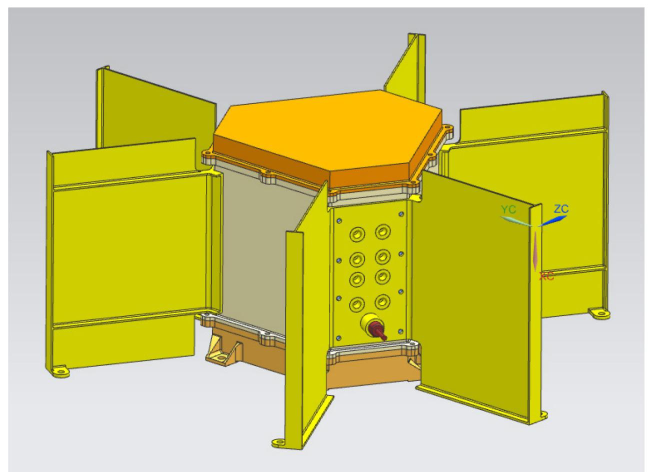

Figure 17: New RTG radiator design

The heat released by the fuel pellets is expected to follow four different paths:

- Conduction from the aeroshell to the thermoelectric modules;
- Radiation from the aeroshell to the surrounding environment;
- Conduction from the aeroshell to the supporting struts;
- Radiation within the thermoelectric modules, between the thermocouples.

The quartic equation obtained from the heat balance of these contributions has been solved using Ferrari's method (to obtain and solve the depressed quartic), and then Cardano's method (to solve the resolvent cubic polynomial).

Table 3 reports some of the results obtained when considering the new radiative area and a deep space environment (3 K). The thermal and conversion efficiencies, and the temperatures are consistent with the experimental results. There is also a slight improvement in terms of specific power and electric power output with respect to the previous configuration model.

Table 3: Properties of the new RTG design

Data	Value
Thermal efficiency	0.74
TEG efficiency	0.06
Aeroshell temperature [ºC]	220
TEG cold face temperature [ºC]	20
Specific power [W_{el}/kg]	1.1
Power output [W_{el}]	11

Detailed FE thermal and vibration analyses are to be performed as the next step in the project, in order to optimize the RTG thermal design (to minimize heat transfer to the radiator via any path other than through the TE modules) and to investigate the RTG mechanical response to vibrations (to find the components that drive the lowest natural frequencies and, if required, to add stiffeners in appropriate locations).

7. SUMMARY

RTG and RHU systems are under development at the University of Leicester, as part of the RPS funded by ESA that is focusing on americium-based radioisotope systems.

For both systems, the results of the FE analyses have confirmed the theoretical feasibility of the components. Prototypes have been manufactured using representative materials; the migration from a proof of concept to a flight-like design has been successful, with first functional tests in representative environments completed.

Based on the results of the FE analyses and of the testing campaigns, an iteration for the RTG heat source and system design is planned after the current test phase. Additional analyses (such as re-entry modelling) and testing (namely impact tests) will be performed for the safety aspects, in order to design a heat source that meets all the safety criteria.

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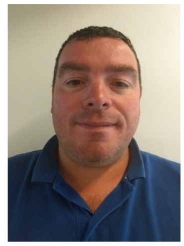
BIOGRAPHY

Alessandra Barco *received her Master's degree in Aerospace Engineering from the Politecnico di Torino in 2014, with a final project on "Human Mars mission with nuclear electric propulsion". In 2015, she did a post-graduation internship at TAS-I in Turin, where she was employed as a mission analysis engineer for ExoMars. Since April 2016, she has been working at the University of Leicester (UK), in a team developing space nuclear power systems as part of a European Space Agency funded program. The focus of her work are the thermo-mechanical analysis and testing of radioisotope thermoelectric generators and heater units, as well as the safety aspects related to the use of these systems in a space mission.*

Richard Ambrosi *obtained his PhD from the University of the Witwatersrand, Johannesburg South Africa. Some of Professor Ambrosi's past technical projects include the development of fast neutron resonance radiography imaging systems, working on the SWIFT Gamma Ray Burst Observatory X-ray Telescope at the University of Leicester, studying the effects of radiation and dust on detectors for ESA's GAIA mission, and development of CCDs for next generation X-ray observatories. Neutron imaging instruments based on amorphous silicon/microchannel plate detectors as well as CCD-scintillator coupled systems are still part of his portfolio of research projects. Prof. Ambrosi was also the UK Technical Lead for the ExoMars X-ray Diffraction instrument MARS-XRD. Since 2008 Prof. Ambrosi has been leading, at the University of Leicester, the development of radioisotope thermoelectric generators, heater units and novel radioisotope containment systems for space nuclear power applications.*

Hugo Williams *studied Aerospace Engineering at the University of Bristol, where he subsequently undertook a PhD in polymer composite materials. On completion of his PhD, Hugo worked as a Systems Engineer in the Nuclear industry and later moved to the University of Leicester where his research has supported the development of radioisotope power and thermal control systems, including RTG breadboard rig testing and novel thermoelectric materials. He has led the University of Leicester contribution to UK Space Agency Space Nuclear Power through-life requirements study. Hugo is a Chartered Engineer, Member of the Institution of Mechanical Engineers and is a Senior Fellow of the Higher Education Academy.*



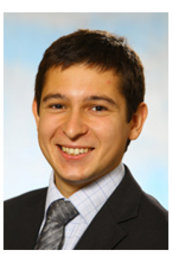
Tony Crawford *has an extensive experience in the design, manufacturing, assembly, testing and integration of space engineering hardware. He joined the University of Leicester in 2001, and he has held a significant role on a number of space projects including SWIFT, ExoMars, GERB (Geostationary Earth Radiation Budget), MIRI (Mid-Infrared Instrument on James Webb Space Telescope), Astrosat (Indian X-ray Astronomy Experiment), MIXS (Mercury Imaging X-ray Spectrometer on Bepi Colombo), SVOM (Space Variable Objects Monitor). Since 2010, Tony has been an integral member of the Leicester team developing radioisotope thermoelectric generator and heater unit system, where he is responsible for the manufacture/procurement, build and testing of the vacuum test facility and the RTG lab based test model.*

Ramy Mesalam *received his Masters in Aerospace Engineering in 2014 from the University of Manchester and is currently in the final stages of his PhD at the University of Leicester. Since the start of his PhD Ramy became a member of the radioisotope power systems team based at the University of Leicester. The team currently leads the development of new power generation technologies, in the form of radioisotope thermoelectric generators, for space exploration activities as part a European Space Agency (ESA) funded program. To date Ramy has focused on aspects of the project regarding thermoelectric generation, from thermoelectric material synthesis to system level modelling, design and testing. In particular his research has developed new mathematical models for characterizing thermoelectric devices using impedance spectroscopy.*

Christopher Bicknell *worked as a test engineer for an industrial lasers company prior to joining the University in 2000. Chris began his appointment at the University working on electronics hardware for the Beagle 2 Mars lander and the Swift XRT camera. The work mostly involved the construction of flight hardware, its test and verification. Towards the end of the decade, Chris began to work on the Astrosat XRT camera and took a more leading role in the construction, test and verification and ultimately its successful delivery to TIFR in Mumbai. In 2013, Chris took on the role as Product Assurance Engineer for the BepiColombo MIXS instrument and has continued in this role as PA Engineer for the SVOM MXT optic that is currently under development at the University of Leicester. Chris has a keen interest in electronics design and software engineering and continues to apply these skills in various projects within the University.*

Emily Jane Watkinson *received her Masters of Physics in 2013 and her PhD in 2017. During her PhD, and since 2017 as a Research Associate and Teaching Fellow, Emily Jane has worked as part of a European Space Agency (ESA) funded team at the University of Leicester. The team leads the R&D of americium-based RTG and RHU technologies as part of the ESA RPS program. Emily Jane specifically leads the surrogate fuels research and works with national and international collaborators across industry, academia and research institutions, including the National Nuclear Laboratory (UK) who she has worked closely with since 2013. Her research focuses on the synthesis, behavior and characterization of the properties of americium oxide surrogates, as well as sintering studies. Emily Jane has also worked on civil nuclear power relevant research. In 2018, she became a Visiting Scientist at the European Commission's Joint Research Centre in Karlsruhe (JRC), Germany to bridge collaborative research between the UL and JRC on research relevant to americium-based RPSs.*

Keith Stephenson *graduated with a BSc in Physics from the University of Manchester in 1995, and began his career on the Sellafield nuclear site in UK, working in the fields of radiometrics, nuclear reactor fuel performance and fuel manufacturing. Keith joined the European Space Agency in 2007, and is based at ESA's technology center "ESTEC" at Noordwijk in the Netherlands. As a Nuclear and Power Systems Engineer, he provides projects and programs with technical support on power systems aspects, and is managing R&D activities aimed towards the development of a European capability in radioisotope power systems.*



Alexander Godfrey *graduated with a MEng (Hons) in Spacecraft Systems Engineering from the University of Southampton and has since worked for Lockheed Martin UK – Ampthill technically driving the pursuit and execution of new civil space programs. Areas of work include; spacecraft systems engineering, spacecraft subsystem design (including Phase A/B1 designs for ESA Space Rider vehicle), integration feasibility studies, thermo-mechanical analysis, trajectory modelling, dynamics modelling and performance modelling of optical systems, as well as technical and programmatic leadership.*

Colin Stroud *graduated with BSc (Hons) Aeronautical Engineering from the University of Salford. He began work as a software engineer covering the aerodynamics / aerothermodynamics of hypersonic re-entry vehicles, and developing a number of physics-based software tools. Career expanded into modelling and simulation, including electro-optic, thermal and infrared domains. Current roles include both technical and managerial duties. Technical duties include modelling the aerodynamic and aerothermal response of re-entry objects as well as optical/thermal signatures. Managerial duties include looking after numerous research-type projects.*

Christopher Burgess *received his Masters of Engineering from the University of Oxford in 2007, and subsequently began working at Airbus Defence and Space in Stevenage, UK. Following graduate placements in the engineering support to manufacture and mechanical analysis groups, Christopher joined the mechanisms department and was part of the team developing the cryogenic cooler system for ESA's Sentinel 3 spacecraft. In 2014 Christopher moved to the chemical propulsion design group, working on Eurostar telecommunications satellites. Since 2016 he has worked in Airbus' future programs department, and led the team which designed the mechanical housing for the americium-based RTG.*