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AMERICIUM-241 RADIOISOTOPE THERMOELECTRIC GENERATOR DEVELOPMENT FOR SPACE APPLICATIONS

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ABSTRACT

Space nuclear power systems are under development in the UK in collaboration with European partners as part of a European Space Agency (ESA) programme. Radioisotope thermoelectric generators (RTG) are an important element of this new capability in Europe. RTG systems being developed in Europe are targeting the 10 W electric to 50 W electric power generation range adopting a modular scalable approach to the design. Radiogenic decay heat from radioisotopes can be converted to electrical power by using appropriate semiconductor based thermoelectric materials. The plan for Europe is to develop radioisotope space nuclear power systems based on both thermoelectric and Stirling power conversion systems. Although primarily focused on delivering up to 50 W of electrical power, the European radioisotope thermoelectric system development programme is targeting americium-241 as a fuel source and is maximizing the use of commercially available thermoelectric manufacturing processes in order to accelerate the development of power conversion systems. The use of americium provides an economic solution at high isotopic purity and is product of a separation process from stored plutonium produced during the reprocessing of civil nuclear fuel. A laboratory prototype that uses electrical heating as a substitute for the radioisotope was developed to validate the designs. This prototype has now been tested. This paper outlines the requirements for a European americium-241 fuelled RTG, describes the most recent updates in system design and provides further insight into recent laboratory prototype test campaigns.

1. INTRODUCTION

The European Space Agency (ESA) funded space nuclear power programme brings the expertise of the space and nuclear industries together to create new technologies, produce new materials and develop new manufacturing methods that benefit space exploration, the wider economy and new markets. Radioisotope power sources are an important technology for European space exploration missions as their use would result in more capable spacecraft and landed probes that can access distant, cold, dark and inhospitable environments. Missions using nuclear power present better value for money, with one mission delivering the science that might only be achieved from several missions using solar power, and offering considerably longer operational lifetimes. In many cases nuclear systems can enable missions that would otherwise be impossible.

The European space nuclear power programme is currently primarily focused on the development of power systems that exploit radiogenic decay heat in order to produce electrical power using thermoelectric or Stirling generators. The UK's National Nuclear Laboratory is responsible for the production of the americium-241, which is the radioisotope selected for the European programme. Am fuel can be produced economically and at high isotopic purity by separation from stored separated plutonium produced during reprocessing of civil fuel [1]. System Engineering and Assessment Ltd in the UK leads the Stirling generator development programme. The current RTG programme consists of three primary strands: the development of TEGs, the design, development and testing of a laboratory prototype system and the iterative design of flight systems.

The top-level requirements include: targeting of modular and scalable designs that can meet power outputs in the 10 W to 50 W range, deployment on planetary surfaces e.g. Mars and in deep space, development of TEGs using existing and available technology solutions and commercial production methods and processes.

The University of Leicester in the UK has led the development of the RTG system in collaboration with Astrium Ltd (UK) European Thermodynamics Ltd (UK), Queen Mary

University of London (UK) and Fraunhofer IPM (Germany). TEG modules developed in the UK are based on bismuth telluride, while those developed by Fraunhofer IPM, Germany focused on lead telluride. Based on a number of industry academic partnerships other key technology areas under development include radioisotope fuel production and containment in the event of launcher failure or unscheduled spacecraft re-entry [2].

This paper describes the most recent updates in system design and provides further insight into recent laboratory prototype test campaigns.

2. FLIGHT DESIGN CONCEPTS

Preliminary designs assume an Am_2O_3 ceramic fuel in a multilayer containment structure similar to that of the general-purpose heat source (GPHS) system [3] developed by the US and used in the GPHS RTG and Multi Mission RTG (MMRTG) [4]. A variety of structural, thermal and electrical design trade-offs were performed, concluding that a scalable or module designs could feasibly be produced for the range 10 W to 50 W electric range, but that very small power requirements at the ~1 W level required an alternative approach.

2.1. Scalable or Modular Concepts Producing 10 W to 50 W of Electrical Power

The first design (See Figure 1) included an on-axis cylindrical fuel pellet in modular heat sources arranged in 5 W or 10 W electric modules and the option of using bismuth telluride or lead telluride TEGs. The assumption in this first design case was that ~6% of the total heat generated by the heat source would be converted to electrical power and therefore a 5 W electric power output would require ~80 W of heat. Increasing the power output to 50 W required stacking multiple heat sources. The length of the RTG housing and radiator varied with power output but the cross-sectional dimensions remained fixed. Multiple RTG units could be used to provide the total power requirement of a mission. These initial designs predicted a specific power output of ~2.0 W/kg.

Recent design iterations have focused on bismuth telluride TEGs conductively coupled to the heat source. These updated flight designs are based on modular heat sources generating 200 W of thermal power. The efficiency of the system (in terms of conversion of thermal power to electrical power) was revised down to 5% based on test results obtained during the prototype testing campaign (See Section 3). Recent designs have also altered the geometric distribution of the fuel targeting a distributed fuel arrangement. A more conservative ~1.5 W/kg was predicted at the end of this design iteration.

2.2. Small-Scale 1 W Radioisotope Thermoelectric Heater Unit

At very low electrical power outputs, using a radiator for thermal management was found to be too large for the thermal requirements and the geometric constraints. This study highlighted that the spacecraft structure could be used to reject the waste heat. At electrical power outputs of 1 W, a specific electrical power of 0.75 W/kg was estimated (budget mass of 1.3 kg including margins) with approximately 20 W of thermal power conducted to the

spacecraft structure. This concept (also based on commercial bismuth telluride TEG) was shown to be competitive with ^{238}Pu fuelled small RTG concepts because at these small scales the relative effect of the lower specific power of the fuel decreased (See Figure 2).

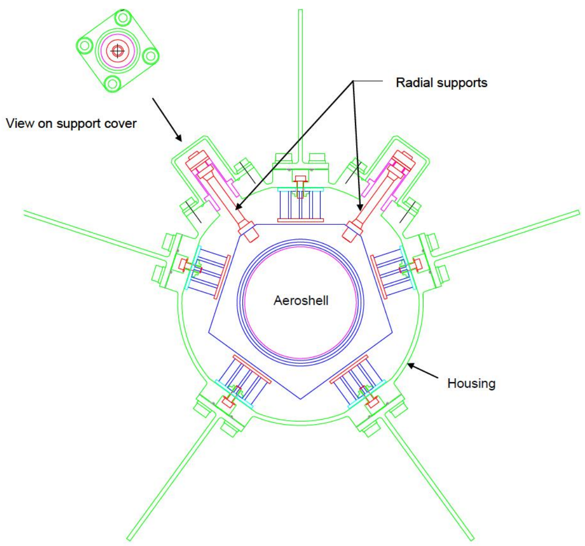

Figure 1: RTG concept design illustrating cross-section and a schematic of a modular design with the fuel on-axis and the radiator structure is used to improve overall structural performance to achieve the required first lateral natural frequency at lower mass. Radiative or conductive coupling can be used between the TEG modules and the heat source. In this first design iteration the TEGs were radiatively coupled.

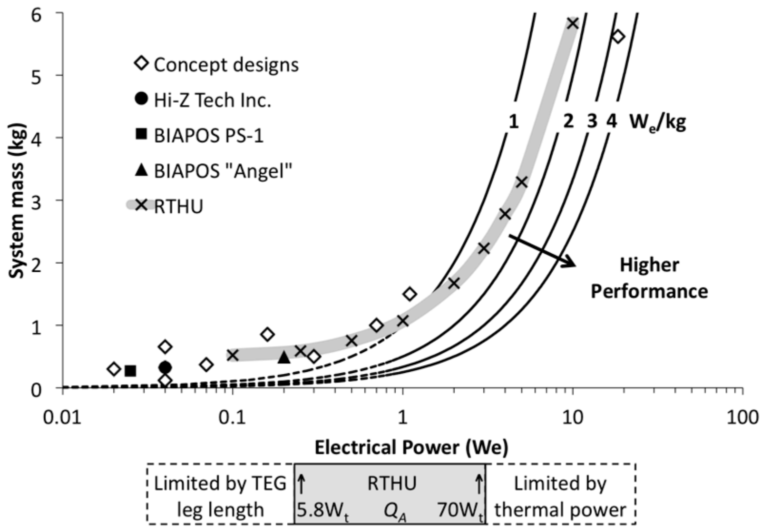

Figure 2: Comparison of RTHU with a ^{238}Pu fuelled small-scale RTG concepts [5].

3. LABORATORY PROTOTYPE

An electrically heated RTG laboratory prototype was designed, manufactured and tested to investigate the performance, detailed design features and challenges of RTG systems and to validate the thermal models. Figure 3 shows a blow up of the laboratory prototype as well as the assembled system in a vacuum chamber with the aluminium body of the RTG system attached to the thermal management system via copper straps.

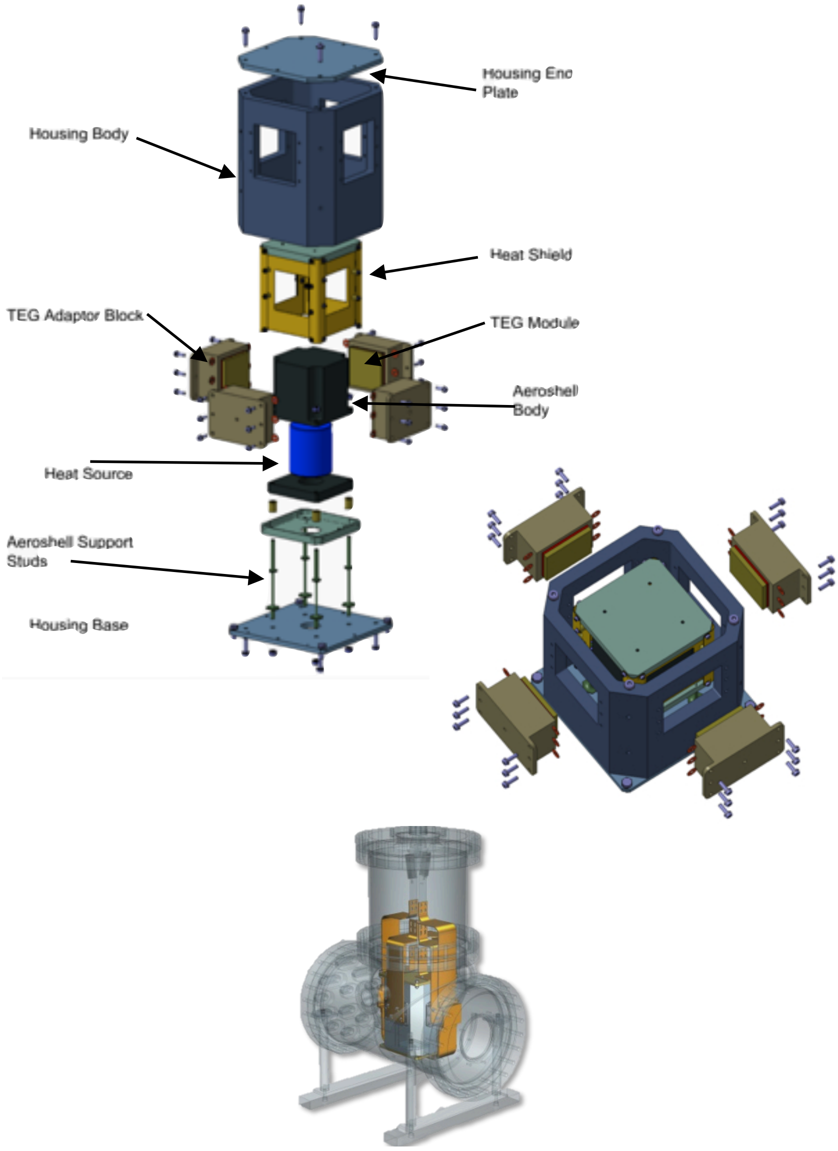

Figure 3: (Top) Blow up of the RTG prototype showing all of the components. (Middle) The RTG breadboard in a vacuum chamber attached to the thermal management system via copper straps.

3.1. Test Programme

The test programme includes testing of commercially available bismuth telluride generator modules, with argon cover gas and in conductively coupled configurations. The laboratory prototype was designed to produce a maximum electrical power output of 5 W (6% overall efficiency for ~80 W of thermal power); however, in a development project of this kind, the headline performance is less critical than model validation and developing a thorough understanding of the performance, design features and development options. The current test campaigns have produced higher than expected overall performance with power output ranges of approximately ~3.5 to ~3.7 W electric at for 83 W of thermal power output, this translates to an overall system efficiency of above 4% and a specific power for this system of ~1.5 W/kg. Figure 4 below provides a comparison of these tests results with the predicted performance from thermal models of the system. The test campaigns indicate that a 5% system efficiency target is a reasonable value for future design improvements and iterations.

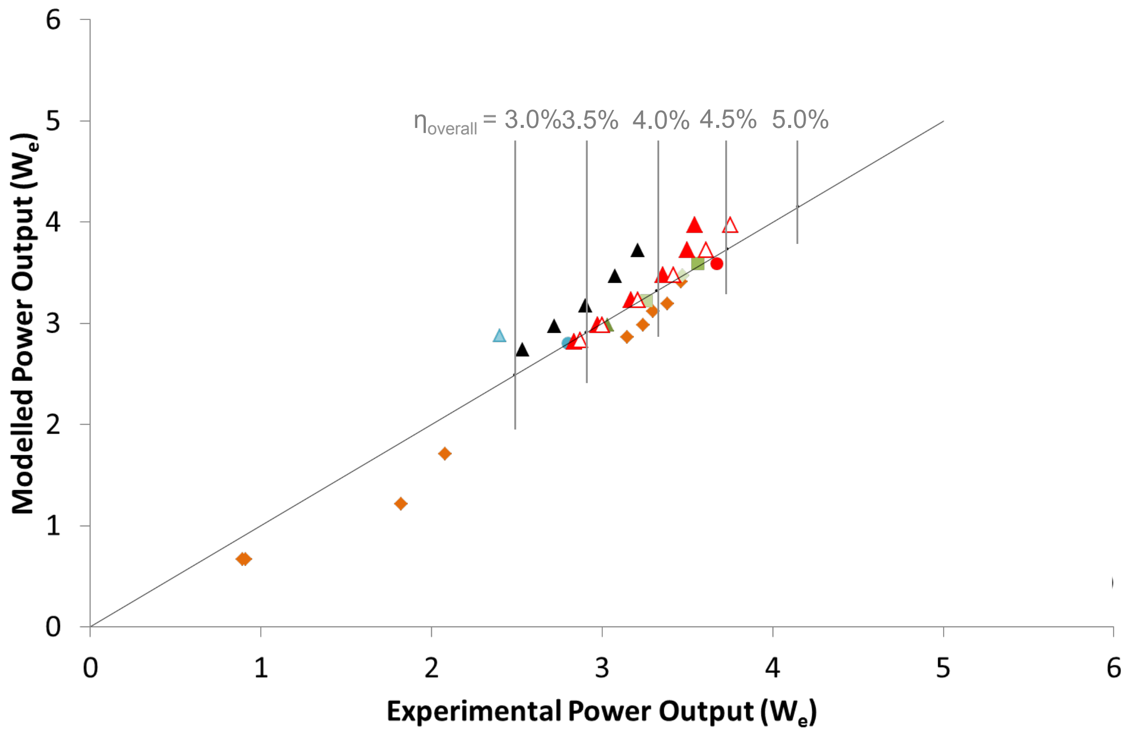

Figure 4: The experimental power output for multiple test campaigns is compared to the modelled power output. The data shows a steady improvement in overall performance and that the results are edging towards the 5% efficiency level.

3. CONCLUSIONS

The specific power of an ^{241}Am-fuelled RTG cannot match that of a ^{238}Pu system (except perhaps at small power output levels); however, the design work undertaken provides confidence in potential capability and performance of ^{241}Am systems for future space missions. Medium-sized RTGs in the 10 W to 50 W range are predicted to achieve an overall specific electrical power output of around ~1.5 W/kg. A novel concept for a small RTG

combining the function of a Radioisotope Heater Unit (RHU), termed an RTHU is predicted to achieve a specific electrical power output of around 0.75 W/kg, which is very competitive with other low power concepts reported in the literature.

An RTG prototype system has been designed, manufactured and tested to confirm the designs and the predictions of models. The RTG prototype system developed by the UK team is the first hardware to be produced as part of the European Space Agency funded programme and to our knowledge this is probably be the first time an integrated RTG system has been tested outside the US or Russia. This is therefore a major step forward for European deep space and innovative planetary exploration ambitions.

ACKNOWLEDGMENTS

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