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Technology Demonstrator of an Americium-Fuelled Radioisotope Stirling Generator

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Americium-241 is used as the fuel of choice in European Radioisotope Power Systems. The University of Leicester have developed a number of systems using this fuel type, including a 200 W_{th} heat source. To maximise the electrical output that can be generated from the heat source, the University of Leicester and NASA Glenn Research Center have collaborated on a radioisotope Stirling generator concept, building on the long heritage of dynamic power conversion developments at NASA GRC. Here we present the design of a technology demonstrator of the Americium-fuelled Radioisotope Stirling Generator (Am-RSG).

I. INTRODUCTION

I.A. Americium-Fuelled Radioisotope Power Systems

Radioisotope Power Systems (RPS) fuelled with Americium-241 (^{241}Am) have been under development and lead by the University of Leicester (UoL) for over a decade [1]. The RPS developments form part of the European Space Agency's (ESA) EuropeaN Devices Using Radioisotope Energy (ENDURE) program. Americium-241 RPS provide an alternative to the Plutoinum-238 (^{238}Pu)-fuelled RPS that have historically been used in spaceflight. The global supply of ^{238}Pu is limited and alone cannot meet the RPS demand from the space exploration community [2].

The University of Leicester leads the development of several Am-RPS including a Radioisotope Heater Unit (Am-RHU) and a Radioisotope Thermoelectric Generator (Am-RTG) [1]. The Am-RTG is powered by the European Large Heat Source (ELHS) which is also being developed by the University of Leicester, and contains ~2 kg of ^{241}Am fuel.

A summary of the ELHS properties is shown in Table I alongside the properties of the General Purpose Heat Source (GPHS). The GPHS is a ^{238}Pu-fuelled system produced by the U.S. Department of Energy (DOE) and the National Aeronautics and Space Administration (NASA). The GPHS has been used as a thermal power source in GPHS-RTG's to provide heat and electricity to Outer Solar System missions including Galileo and Cassini [3]. It can be seen that the ELHS has a much lower specific power compared to the GPHS, however, the long life-time of the ELHS, and the availability of the ^{241}Am fuel makes it a complementary thermal power source available for space missions. A particularly unique feature of the ELHS design is its shape, which is in the form of a triangular prism as it emerged as the most mass and thermally efficient geometry (Figure I). Consequently, the ELHS tends to lend itself towards power convertor architectures that are also tri-configured, such as UoL's Am-RTG. The Am-RTG is designed to have a specific power of 1 W_e/kg [1].

Table I ELHS and GPHS properties.

Property	ELHS	GPHS
Beginning of Life Heat Output	200 W_{th}	250 W_{th}
Mass	6.85 kg	1.60 kg
Specific Power	29 W_{th}/kg	156 W_{th}/kg
Volume	1836 cm^3	527 cm^3
½ life	432.2 yrs	87.7 yrs
Primary decay	Alpha	Alpha



Figure I Left: ELHS architecture with color-coded elements, Right: ELHS aeroshell.

I.B. Radioisotope Stirling Generators

Heat from radioisotope heat sources can be used to heat a working gas in a Stirling engine to generate electricity. This dynamic power conversion offers improvement over the baseline thermoelectric-based RPS in several categories: higher conversion efficiency (less radioisotope fuel required), less waste heat to manage/dissipate (smaller thermal management systems required). NASA has been pursuing RPS based on dynamic

energy conversion for many years [4], [5]. In 2016, the pursuit of dynamic RPS was steered towards a concentration on lessons learned from prior projects, such as: reduce the required system-level conversion efficiency to 20%, identify and implement methods of robustness in the conversion devices, and define requirements early. Several dynamic convertor development efforts were initiated in 2017 to design, build, and test various viable technologies. These contracts are now complete, and several dynamic convertors have been delivered to NASA GRC. Sunpower Inc. has provided five gas-bearing Stirling-cycle convertors of their latest design, the Sunpower Robust Stirling Convertor (SRSC). These have completed a gamut of environmental tests and are currently undergoing continuous long-term operation. System designs have been produced to couple the latest Stirling convertor to various radioisotope heat sources, such as the GPHS and ELHS. To date, results have been encouraging and showed that a GPHS-RSG could have a specific power close to that of the baseline GPHS-RTGs. System designs of an RSG utilising an ELHS showed its specific power could be at least as good as the MMRTG [6]. Significant progress in demonstrating the performance and reliability of the SRSC has taken place recently [4]. The SRSC has been exposed to a multitude of relevant environments (such as launch qual-level random vibe, and 22.5 g static acceleration), and shown to have no loss in performance. Several units have undergone long-term operation, with two units in particular having operated for over 2 years.

I.C. Am-RSG Design Concept

A study was conducted in 2019 between UoL and NASA GRC to determine the feasibility of an Am-RSG design for enhancing the capability of the VIPER mission [6]. The Am-RSG design includes four ELHS modules to produce 800 W_{th}. The heat sources are radiatively coupled to six SRSC's with individual balancers. The design of the Am-RSG from the study can be seen in Figure II.

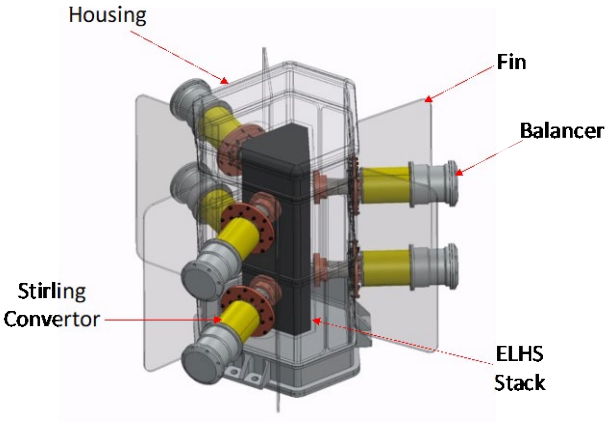


Figure II Am-RSG design from Mesalam et al. [6].

The results of the Am-RSG study showed that the Am-RSG would have a mass on the order of 110 kg (including controller mass) and a DC power output of 216 W. The specific power of the Am-RSG is therefore predicted to be ~2 W_e/kg, double that of the Am-RTG. A key output from the study was that an ^{241}Am heat source, with a lower power density than ^{238}Pu-fueled heat sources, can still drive SRSCs to efficiently produce electrical power. An additional benefit of the Am-RSG design is its robustness, as it has been designed to accommodate failure of two of the six SRSCs and remain functional. This design feature is particularly advantageous when considering long-duration missions that can benefit from the long half-life of ^{241}Am.

A technology demonstrator was proposed in 2023 to experimentally evaluate the Am-RSG concept and demonstrate whether an ^{241}Am heat source could be effectively coupled to Stirling convertors in this configuration. The technology demonstrator design is a variation of the original design from Mesalam et al. [6], and was iterated using higher fidelity thermal and structural modelling. Here we present the Am-RSG technology demonstrator design and modelling activities.

II. TECHNOLOGY DEMONSTRATOR DESIGN

The Am-RSG demonstrator was designed to experimentally investigate the candidate Am-RSG concept arrived at by the aforementioned Leicester/GRC collaboration [6]. The team rapidly designed an elegant breadboard test article representing one half of the full system: two ELHSs and three Stirling convertors. This would permit exercising all functional and performance tests of the generator concept. Opting for two ELHS' over four also kept both the footprint and cost low.

Legacy hardware was identified to fast-track the readiness of the demonstrator. The University of Leicester contributed two electrically heated (200 W_{th} each) ELHS modules, thermal insulation, and the radiator housing to accommodate the Stirling convertors. The heat sources are secured in place by preloading the solid insulation above and below as seen by the cross-sectional view in Figure III. NASA GRC committed to using an existing Advanced Stirling Convertor (ASC, a predecessor of the SRSC), that was in storage and at-the-ready for use. While the other two convertor ports in the housing are populated by Stirling convertor thermal simulators (from the KRUSTY demonstration test) [7]. These utilise controlled gas flow to simulate the heat flow rate of an operating convertor and will thus exercise the thermal design of the tri-configured system design. The heat sources are radiatively coupled with the ASC and simulators, that are distributed evenly around the aluminium housing as seen in Figure IV. The ASC and simulators are mechanically fixed to the housing to effectively transfer heat to the radiator body and fins. The radiator housing is painted in a high emissivity black

paint to aid heat transfer to the surrounding environment in both open-air and thermal vacuum operation. GRC also contributed an available convertor balancer that can be situated on the ASC or radiator body via a standoff. The balancer is necessary to achieve dynamic balance of the generator.

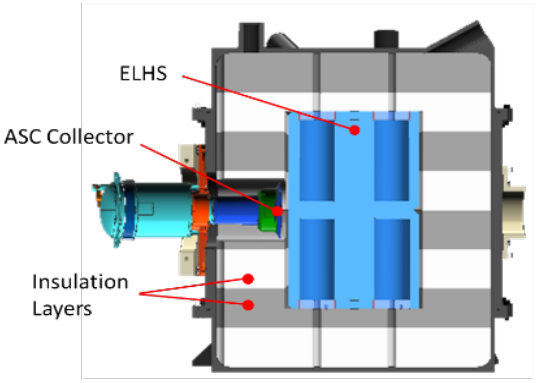


Figure III Cross section of Am-RSG demonstrator

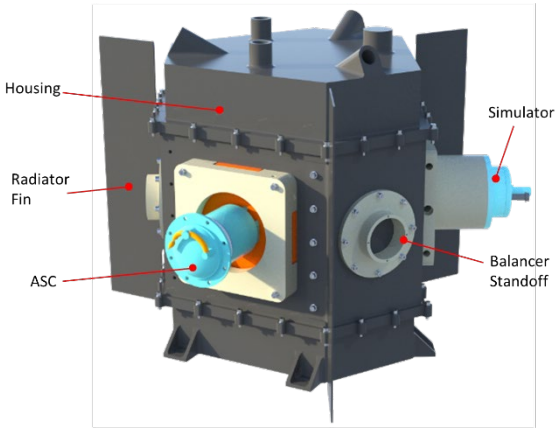


Figure IV AM-RSG Demonstrator

A full-level generator with six convertors (Figure II) would require an equal number of balancers to handle convertor-failed situations. In the case of the demonstrator, the single balancer is required to remain operating while the ASC is functioning due to the convertor simulators not providing any dynamic feedback. Convertor failures can be simulated by either forcing the ASC idle, or by turning off the gas flow to one of the thermal simulators.

NASA GRC conveyed the required interface details for the Stirling convertor/simulator hardware, and the Leicester team designed the housing and mounting hardware to abide by these specifications. Leicester has fabricated the housing components and internals necessary to insulate and secure the electrical ELHS simulators. This assembly will be transported to the Stirling Research Laboratory (SRL) at NASA GRC, and the team will install the Stirling convertor hardware. The housing design was tailored to allow easy, rapid installation of the hardware without major disassembly.

Due to the rapid development schedule, it was determined early on that a solid insulation design approach would be more feasible than high-temperature multi-layer insulation. Preliminary thermal modelling determined the optimal thickness of the solid insulation needed to achieve ideal operating conditions for the convertors, while maximising specific power. This along with the two ELHS' design, determined the current size and shape of the Am-RSG. A solid insulation design approach also enables its use for planetary science missions which require operation under an atmosphere.

Flexibility in the demonstrator's design was deemed necessary so that further studies with a variety of convertor/balancer configurations could be readily tested. Additional fixture points for different balancer configurations, installation of additional radiators and potential for additional ASCs or SRSCs are included in the design as a result. More so, the demonstrator will serve as a platform for testing resilience against different convertor failure scenarios.

Previous RSG designs have incorporated enlarged radiative collectors on the hot end of the convectors however to improve ease of installation, these have been omitted from the demonstrator's design. Thermal simulations have been conducted to verify that this practical design change can be accommodated with minimal impact on the functionality of the demonstrator.

III. THERMAL MODELLING

A one-dimensional mathematical thermal model has been employed to perform general sizing calculations and analytically determine the thermal performance of the Am-RSG. Physical, thermal and thermo-optical properties of the Am-RSG design have been used as inputs into the analytical model from which, temperatures and heat flows have been solved for iteratively using the Newton-Raphson method. Results from the analytical investigation have been used for first order validation of a higher fidelity finite element model (FEM).

The demonstrator test at GRC will make use of one ASC and two Stirling simulator units. To give some understanding on how to tune the simulators so that they can accurately mimic the performance of the ASC, the temperature profile of a three-ASC configuration must first be understood. To do this, a 'calibration' FEM, modelling three ASCs, was created. This gives the baseline thermal operational conditions of an ASC, and can be directly compared to the analytical model. This information can then be used to identify operational requirements of the simulators to allow the remaining ASC to operate as it would do in a three-ASC configuration. In this scenario,

valuable operational data about the full three-ASC system can be predicted through the use of only one ASC.

III.A. Thermal performance results for three ASCs

Siemens NX Space Systems Thermal was used to investigate the thermal performance of the complete system with three ASC's connected to the Am-RSG in the tri-configuration. The boundary conditions applied to the simulation were chosen to replicate a lab bench-test scenario. However, the analytical model was not setup to investigate convective transfer. Thus, the environmental sink boundary conditions was modeled as 24ºC under vacuum. The internal heat generation of two ELHS blocks totals 400 W_{th}, with internal heat transfer also under vacuum conditions. Results of the calibrated simulation can be found in Figure V and the thermal performance at specific locations of interest are compared to the analytical model and displayed in Table II.

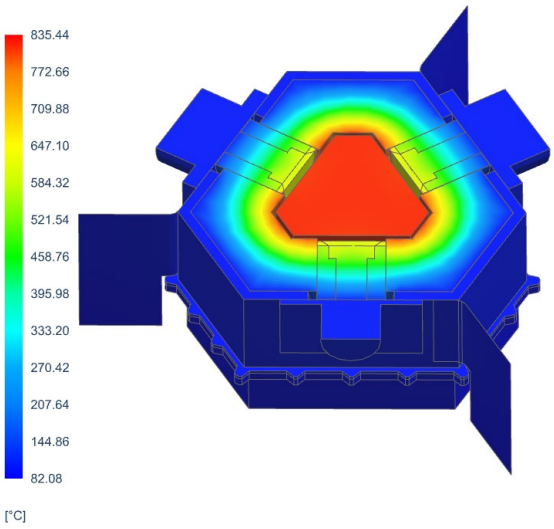


Figure V: Thermal simulation results for a section-view of the Am-RSG

The results of the FEM simulation show a temperature difference across the ASC of >500 ºC, which gives a Carnot efficiency of ~57%. A worst-case maximum heat source temperature of 870 ºC is observed in the analytical model. Yet, a maximum insulation temperature less than 781 ºC is predicted by the FEM. The maximum operating temperature of the insulation is 1000 ºC, giving a >20% design margin.

The one-dimensional analytical solver shows a higher thermal efficiency compared to the FEM, this is due to the idealised nature of the assumptions made in the solver. Consequently, this gives rise to more heat flowing through the ASCs in the analytical model in comparison to what is predicted by the FEM, as shown in Table III. This presents a challenge when attempting to accurately model the ASCs in the FEM.

The analytical model represents the ASC as a simple cylinder of a defined length, and its effective thermal conductance (K_{eff}) is later calculated from the thermal outputs of the model. In the FEM, the geometry of the ASCs are representative of the real physical geometry, and their thermal conductance is matched to the K_{eff} value extracted from the analytical model by applying/adjusting a fictious thermal conductivity. The scaling of this thermal conductivity value accounts for the change in geometry for a given heat flow. The temperature difference across the ASC observed in the FEM was found to be smaller, as can be seen in Table II.

Table II: Thermal modelling results for the Am-RSG with three ASCs

Parameter	Analytical	FEM
Aeroshell temperature	870 ºC	816 ºC
HSA temperature	652 ºC	636 ºC
Radiator temperature	95 ºC	116 ºC
View factor (aer-hsa)	0.08	~0.08
Heat to HSAs	112 W_{th}	109 W_{th}
Heat to insulation (axially)	15 W_{th}	18 W_{th}
Heat to insulation (radially)	49 W_{th}	55 W_{th}
Thermal efficiency	84%	82%

The radiation method used in the FEM simulation is the Oppenheim method [8]. Advantageously, it is able to calculate for multiple reflecting and absorbing faces within a defined enclosure. However, this comes at the cost of computing time when compared to simpler radiation modelling techniques such as gap radiation. An example of environmental view factors from the body and radiators can be seen in Figure VI. This was used to optimise the radiator fin length and mass.

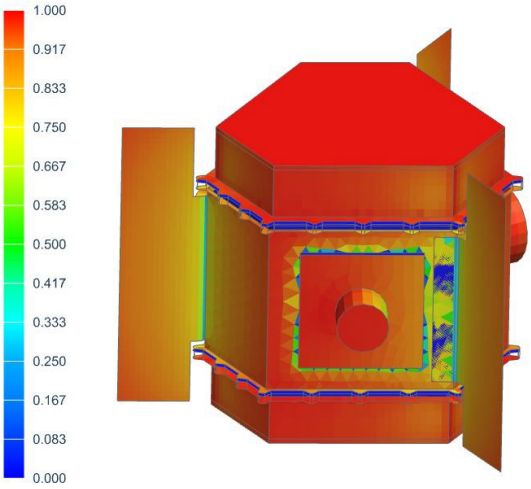


Figure VI: External view factor for the radiator housing to the environment

Figure VII presents the internal view factors of the Am-RSG. The internal surfaces of the aeroshell, insulation, and hot-side acceptor (HAS), all show a view factor of close to 1. However, the low view factor of 0.08 as presented in Table II, is a result of the much larger surface area of the aeroshell and insulation compared to the HSA. Because of the low thermal conductivity of the insulation (~0.04 W/m^{2}K at 800ºC), heat is unable to readily leave the system via the insulation, so it is forced to exit via a less resistive path, which is through the HSAs. It is this interaction that means the view factor is not a large contributor to thermal efficiency, and hence, electrical power output is not greatly compromised. However, this internal view factor has a measurable impact on the aeroshell temperature needed to effectively radiate heat to the HSA. This in turn limits the materials available in the industry that can withstand the higher temperatures.

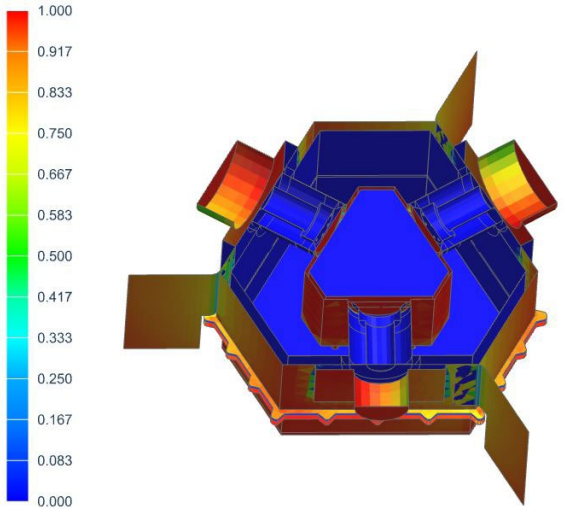


Figure VII: Internal view factors between the heat source and the convertors and insulation

III.B. Thermal performance results for one ASC and two simulators.

From the initial calibration simulation, the operating conditions of a single ASC have been obtained, which can be translated into operational requirements for the simulators to satisfy. The simulators use a pressurised flow of nitrogen gas through a heat exchanger to remove heat from its equivalent HSA, replicating the thermal operation of an ASC without the power conversion capability. The flow of nitrogen can be controlled to replicate the heat being removed by the remaining ASC. Table III and Table IV show the effect of conductance at the simulator hot end to the nitrogen flow thermal sink on the thermal performance of the RSG.

The results obtained from simulations show that the simulators are capable of being effectively controlled to adjust the direction of heat flowing out of the system in such a way so as to replicate the heat flow in a three-ASC configuration. The radiator temperatures are lower when using two simulators as the simulators completely remove heat from the model. Whereas, in the calibration model, the heat flows through the ASCs and into the body, minus the thermal power converted into electrical, and then radiates to environment. This means the body has less heat flowing into it in a bench test configuration, therefore the temperature is lower. To account for this interaction, heat load can be applied to the body on the sides that have simulators. This will then equalize the total heat flowing into the body between the two models, and the temperatures will then also equalize. The predicted Am-RSG demonstrator properties are shown in Table V.

Table III: Thermal performance with one ASC and two simulators (conductance to sink is 0.734W/K)

Parameter	ASC	Sim 1	Sim 1
$T_{aeroshell}$	704 ºC	702 ºC	702 ºC
$T_{hot\text{-}side\ acceptor}$	488 ºC	234 ºC	234 ºC
$T_{radiator}$	73.9 ºC	N/A	N/A
$Q_{hot\text{-}side\ acceptor}$	87 W_{th}	126 W_{th}	126 W_{th}

Table IV: Thermal performance with one ASC and two simulators (conductance to sink is 0.186W/K)

Parameter	ASC	Sim 1	Sim 1
$T_{aeroshell}$	811 ºC	811 ºC	811 ºC
$T_{hot\text{-}side\ acceptor}$	622 ºC	631 ºC	631 ºC
$T_{radiator}$	90 ºC	N/A	N/A
$Q_{hot\text{-}side\ acceptor}$	111 W_{th}	108 W_{th}	108 W_{th}

Table V Predicted Am-RSG Demonstrator Properties

Property	Am-RSG
Beginning of Life Heat Output	400 W_{th}
Mass	48 kg
Expected Electrical Power	88 W_e
Specific Electrical Power	1.83 W_e/kg

The expected electrical power output of this system is obtained using the calculated conversion efficiency of the Am-RSG (26%). This value is then multiplied by the total heat input at the hot-side of the convertors (~ 337 W_{th}), as can be seen in Equation (1).

$$P_e = \eta_{Am-RSG} Q_A \quad (1)$$

It is important to note that the current design being investigated has not yet been optimized for thermal efficiency, as would be necessary in a flight-like design. This is a technology demonstrator to prove this novel configuration, that being the 'Y' convertor configuration and a radiative couple without extended collector plates,

produces a competitive level of electrical power. In a flight-like design, it can be expected that the total mass of the Am-RSG will be reduced, resulting in a higher specific power.

IV. INTEGRATION OF HARDWARE

The fully assembled heat source and housing for the laboratory test campaign can be seen in Figure VIII. The heat source and housing will be integrated with the ASC and simulators at NASA GRC. The existing capability of the SRL at NASA GRC was leveraged for this collaboration (Figure IX), and the joint experimental activities are being carried out under an International Space Act Agreement.

The SRL was established in 2000 and has been performing sophisticated research to support the use of Stirling conversion in space power systems. The lab consists of several automated test stations that can operate several Stirling convertors continuously, providing a constant stream of operational data, and with watchdog data acquisition software to autonomously handle faults. One of the several test stations was earmarked for this collaboration. The SRL is providing a data acquisition rack to measure all necessary parameters, such as temperatures, power input, power output, thermal heat flows. The facility has been modified to support the test article, which requires nitrogen gas supply and vent for the thermal simulators. SRL will also provide all necessary procedures and test plans, and perform all data collection, analysis, and reporting.

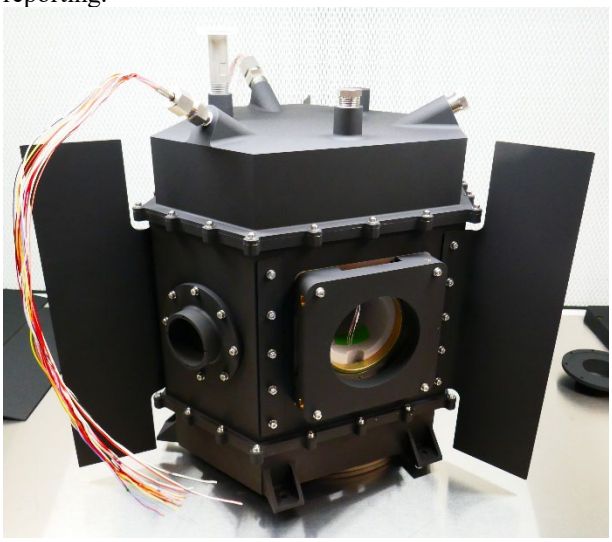


Figure VIII Assembled electrically-heated heat source and housing at University of Leicester.



Figure IX SRL facility at NASA GRC

VII. CONCLUSIONS

A Radioisotope Stirling Generator concept has been developed in collaboration between the University of Leicester and NASA-GRC. The work builds upon a concept study in which ^{241}Am heat sources were used to power SRSCs in an Am-RSG design for a lunar rover. An Am-RSG demonstrator design has been iterated upon based on the results of thermal models. The results show that the Am-RSG is expected to produce ~88We from 400 W_{th}. Electrically heated heat sources that replicate the ^{241}Am heat sources will be coupled with the Am-RSG hardware and an ASC (with two ASC simulators) as part of lab test campaign at NASA-GRC in Q1 2025.

Acknowledgements

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Nomenclature

Acronym	Definition
Am-RHU	Americium Radioisotope Heater Unit
Am-RTG	Americium Radioisotope Thermoelectric Generator
ASC	Advance Stirling Convertor
DC	Direct Current
ELHS	European Large Heat Source
ENDURE	EuropeaN Devices Using Radioisotope Energy
ESA	European Space Agency
FEM	Finite Element Method
GPHS	General Purpose Heat Source
GRC	Glenn Research Center
HSA	Hot-Side Acceptor
KRUSTY	Kilowatt Reactor Using Stirling TechnologY

MMRTG	Multi-Mission Radioisotope Thermoelectric Generator
NASA	National Aeronautics and Space Administration
RHU	Radioisotope Heater Unit
RPS	Radioisotope Power System
RSG	Radioisotope Stirling Generator
RTG	Radioisotope Thermoelectric Generator
SRL	Stirling Research Laboratory
SRSC	Sunpower Robust Stirling Convertor
UKSA	UK Space Agency
UoL	University of Leicester
VIPER	Volatiles Investigating Polar Exploration Rover

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