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Americium-Fuelled Radioisotope Stirling Generator Elegant Breadboard

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ABSTRACT

High power solutions for spacecraft are becoming increasingly sought after in the new era of space exploration, with energy intensive in-situ lunar surface exploration becoming a key part of the roadmap for major space agencies, as well as commercial companies. Nuclear power provides the most feasible solution to achieve continued operation through the long lunar night, and in extended periods in Permanently Shadowed Regions (PSRs). Americium-241 (^{241}Am) is used as the fuel of choice in European Radioisotope Power Systems (RPS). The University of Leicester have developed a number of systems using this fuel type, including a 200 W_{th} heat source. Building on existing international partnerships, the University of Leicester is continuing to work with NASA Glenn Research Center (GRC) to maximise the electrical output that can be generated from the heat source by progressing the radioisotope-Stirling generator concept to elegant breadboard level, building on the long heritage of dynamic power conversion developments at NASA Glenn. Presented in the following conference paper is the next iteration of the Americium-fuelled Radioisotope Stirling Generator (Am-RSG) Elegant Breadboard, following on from a successful technology demonstration design conducted at NASA Glenn in early 2025. The design laid-out in this paper is a more flight-like version of the technology demonstrator, and is intended to pair with the next generation of Stirling convertor technology, the SunPower Robust Stirling Converter (SRSC). The SRSC is able to operate more efficiently at lower thermal power levels than the previous Advanced Stirling Convertor (ASC), making it more suitable for the ^{241}Am system.

Keywords: 241-Americium, Stirling, Radioisotope, Lunar

1. INTRODUCTION

Americium-241 (^{241}Am) fuelled Radioisotope Power Systems (RPS) have been the central focus of space nuclear power research and development activities at the University of Leicester (UoL) for over a decade [1]. This work has received sustained support from the European Space Agency (ESA), most recently through the EuropeaN Devices Using Radioisotope Energy (ENDURE) program. Alongside this activity, Perpetual Atomics, a University of Leicester spin-out company, supports the commercialisation and industrialisation of this technology.

The ESA program has supported the development of several Am-RPS projects that the UoL has been leading, including a Radioisotope Heater Unit (Am-RHU) and a Radioisotope Thermoelectric Generator (Am-RTG) [1]. The Am-RHU contains a 3 W_{th} heat source for maintaining operating temperatures of a

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spacecrafts on-board electronics. The Am-RTG is powered by the UoL developed European Large Heat Source (ELHS), which provides 200 W_{th} to the Am-RTG for conversion to electrical power from ~2 kg of ^{241}Am fuel. RTGs usually have a conversion efficiency at system level around 5-7%. The Am-RTG can also dissipate heat throughout a spacecraft by using its integrated pumped-fluid loop system.

Traditional RPS's have utilised Plutonium-238 (^{238}Pu) as the fuel of choice, however, it is not readily available to ESA, with its production process being highly regulated and expensive. ^{241}Am is a viable alternative that can be effectively utilized by the space exploration community to satisfy their current appetite for space nuclear power systems [2].

The latest development in ^{241}Am power systems at the UoL, supported by the United Kingdom Space Agency (UKSA), is a next-generation high power solution that utilises multiple ELHS's in a single system, paired with an Advanced Stirling Convertor (ASC), a dynamic power conversion technology designed and developed by SunPower in partnership with NASA Glenn, which are high efficiency energy conversion devices compared to traditional solid-state thermoelectric generators. The electrically heated Americium Radioisotope Stirling Generator (Am-RSG) technology demonstrator showed for the first time that an Americium heat source could be successfully paired with a Stirling convertor to produce electrical power.

1.1. Radioisotope Stirling Generators

Thermal power generated from radioisotope sources can be used to heat a working gas in a Stirling engine to generate electricity. This dynamic power conversion offers improvements over typical thermoelectric-based RPS, with both higher conversion efficiency (less radioisotope fuel required) and less waste heat to manage/dissipate (smaller thermal management systems required). RPS that utilise dynamic means of power conversion have been developed by NASA Glenn for many years, producing systems such as the Stirling Radioisotope Generator 110 (SRG-110), the Advanced Stirling Radioisotope Generator (ASRG) and most recently the Dynamic Radioisotope Power System (DRPS) [3]. These systems have baselined the General-Purpose Heat Source (GPHS) that utilises ^{238}Pu to provide the necessary thermal power to the system.

Results from these early developments have been encouraging and subsequently led to the 2022 study between UoL and NASA Glenn to determine the feasibility of an Am-RSG design for enhancing the capability of the VIPER mission [4]. 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. A comparison of the ELHS and GPHS properties can be seen in Table 1-1 with the design of the Am-RSG from the concept study presented in Figure 1-1.

Table 1-1. 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

A technology demonstrator was built and successfully tested in early 2025 to experimentally evaluate the Am-RSG concept, and demonstrate that 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. [4], and was iterated in detail using higher fidelity thermal and structural modelling than was employed in the initial design concept study. The technology demonstrator represented one half of the full design-concept system; two ELHSs and, three Stirling convertors, which permit exercising all functional and performance tests of the generator concept while reducing cost and complexity. This design is shown in Figure 1-1.

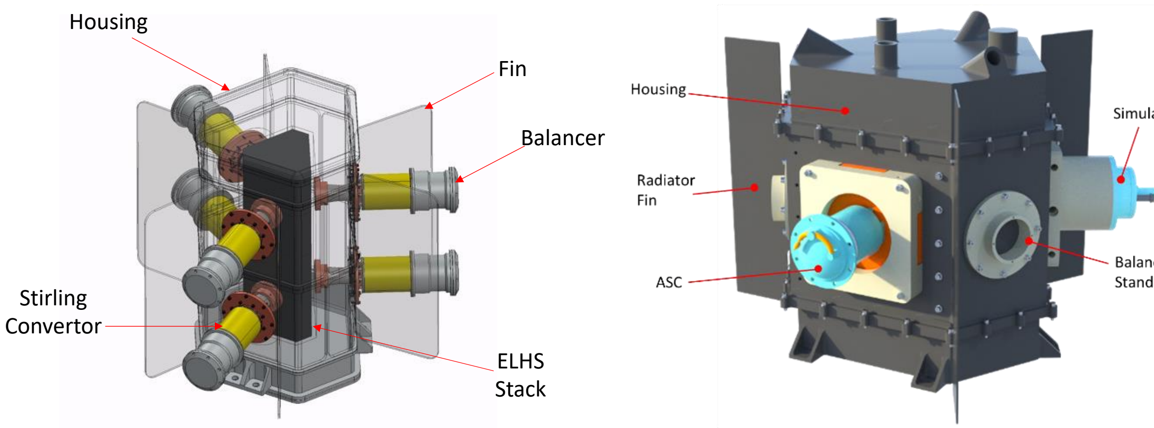

Figure 1-1. Left: Am-RSG design from Mesalam et al [4]. Right: Am-RSG technology demonstrator

Insights learned from this initial testing campaign have informed the next phase of development to the elegant breadboard stage, where the design is more flight-like, and next-generation convertor technology has been incorporated via SRSCs.

2. ELEGANT BREADBOARD DESIGN

The Am-RSG Elegant Breadboard was designed to further the development of an Am-RSG system to a more flight-like level to demonstrate its competitiveness in the range of available options for space power systems. In the previous iteration, legacy hardware was identified to fast-track the readiness of the demonstrator. During this phase of development, UoL have made bespoke changes to the ELHS design to simplify the assembly process, contributing two electrically heated units (200 W_{th} each). UoL also improved upon the design of both the thermal insulation and the radiator housing to boost specific power by reducing mass while simultaneously increasing the thermal efficiency of the system.

The heat sources are secured in place by preloading the solid insulation above and below as seen by the cross-section view in Figure 2-1. NASA Glenn committed to using a minimum of two next generation SRSCs, with the hope that a third would also be made available in time for testing. All three convertor ports are designed to accommodate either an SRSC or a convertor simulator (from the KRUSTY demonstration test) [8] should less than three SRSCs be available. These simulators utilise controlled gas flow to emulate the heat flow behavior of an operating convertor and will thus exercise the thermal design of the tri-configured system. Although these simulators do not reject heat into the housing directly, the system accounts for this by using auxiliary surface heaters. The ELHS' are radiatively coupled with the SRSCs (and simulators), that are distributed evenly around the aluminium housing as seen in Figure 2-1 which are in turn mechanically fixed to the housing to effectively transfer waste heat from the Stirling cycle to the radiator body and fins. The radiator housing and fins are painted in a high emissivity, low absorptivity white paint to promote heat transfer to the surrounding environment and limit incident solar radiation absorption. This elegant breadboard Am-RSG will undergo environmental testing under Thermal Vacuum (TVAC) conditions to mimic in-space operation conditions. NASA Glenn will also contribute convertor balancers for each SRSC that can be situated on the aft flange of the SRSC or directly onto the radiator body via a standoff. The balancer is necessary to ensure dynamic balance of the generator is maintained across also operating conditions including in an engine-out scenario.

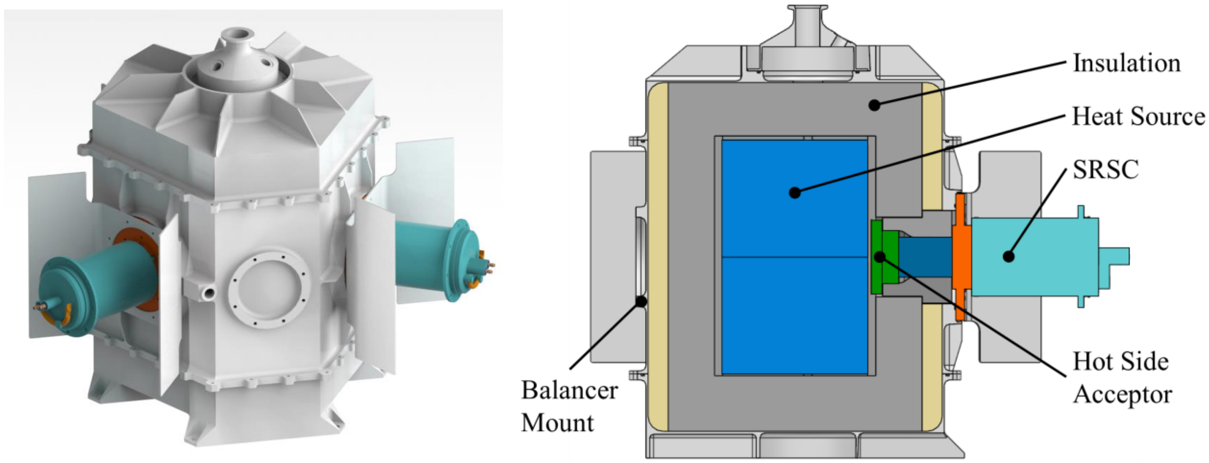

Figure 2-1. Left: Am-RSG Elegant Breadboard. Right: Cross section of Am-RSG Elegant Breadboard

The demonstrator Am-RSG could only validate the effectiveness of a single balancer with only one ASC available for testing. In the case of the elegant breadboard, the effectiveness of multiple balancers shall be investigated including in engine out scenarios. Engine out, or convertor failures may be simulated by either forcing the SRSC idle, or by turning off the gas flow to a thermal simulator. Investigations into the dynamics of the system under nominal operation and convertor failure conditions will provide invaluable data for the development of a bespoke controller, and will provide a unique understanding of the role balancers have to play across all foreseeable operational scenarios.

Integration of the SRSCs has been considered in detail in this iteration of the housing design so that upon delivery of the Leicester hardware to the Stirling Research Laboratory (SRL) at NASA Glenn, the teams can spend less time assembling the system and more time testing.

3. THERMAL MODELLING

A one-dimensional mathematical thermal model was produced during the development of the technology demonstrator to serve as a first order validation for higher fidelity finite element models (FEM). This model has been fine-tuned following the test data gathered during the test campaign in Q1 2025 and used to inform the initial design of the Am-RSG elegant breadboard. 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.

There are key limitations associated with a one-dimensional thermal model which the higher fidelity FEM aimed to capture. Internal radiative heat transfer, thermal losses through more complex geometry and transient behaviors are all better suited to being modelled in FEM than the one-dimensional model. However, both are equally useful in the design process with comparisons drawn between the two below.

3.1. Thermal Performance Results for Three SRSCs

Siemens NX Space Systems Thermal was used to investigate the thermal performance of the complete system with three SRSC’s connected to the Am-RSG in the tri-configuration. The boundary conditions applied to the simulation were chosen to mimic lunar operation in a Permanently Shadowed Region (PSR) in which the system is thermally balanced across each of the convertors. This means that nominal SRSC performance data can be more easily replicated in a simulation environment, providing model validation. This corresponds to operation in no sunlight; thus, the environmental sink boundary conditions were modelled as 4 K under vacuum, with no incident solar flux applied. 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 3-1** and the thermal performance at specific locations of interest are compared to the analytical model and displayed in Table 3-1. The aeroshell temperature value quoted in Table 3-1 is taken from the surface of the aeroshell that faces the convertor acceptor face. Hence, the maximum temperature value in the legend of Figure 3-1 is higher because it represents the temperature at the centre of the heat source.

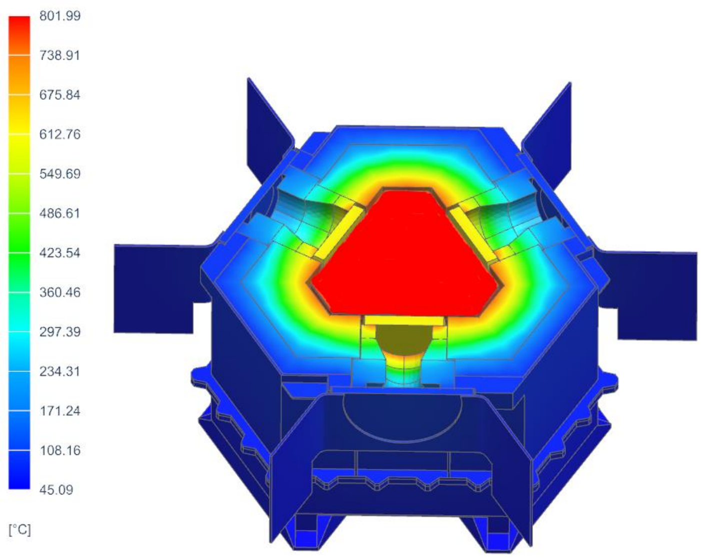

Figure 3-1. Thermal simulation results for a section-view of the Am-RSG in a Lunar PSR

The results of the FEM simulation show's each SRSC to have a temperature difference from hot-end to cold-end of 549 ºC, and a maximum insulation temperature less than 800 ºC is predicted by the FEM. The method for modelling the operation of the convertors has been greatly improved upon, following the technology demonstration. The simulation can solve in real-time, through the use of simplified equations that govern the operating parameters of the convertors. This allows transient scenarios to be more accurately simulated than was possible in the previous phase. The outputs are accurate temperature profiles of the acceptor faces and Cold Side Adapter Flange (CSAF), as well as an accurate calculation of the electrical power generated, hence, thermal energy removed from the system as electrical energy.

Table 3-1. Thermal modelling results for the Am-RSG with SRSCs

Parameter		**Analytical**			**FEM**	
Engine No.	SRSC 1	SRSC 2	SRSC 3	SRSC 1	SRSC 2	SRSC 3
Aeroshell temperature	751 ºC	751 ºC	751 ºC	757 ºC	757 ºC	757 ºC
HSA temperature	589 ºC	589 ºC	589 ºC	616 ºC	616 ºC	616 ºC
AVG Radiator temperature	75 ºC	75 ºC	75 ºC	67 ºC	67 ºC	67 ºC
View factor (aer-hsa)		0.11			0.11	
Heat to HSAs	108 W_{th}	108 W_{th}	108 W_{th}	105 W_{th}	105 W_{th}	105 W_{th}
Heat to insulation (axially)		18 W_{th}			24 W_{th}	
Heat to insulation (radially)		58 W_{th}			61 W_{th}	
Thermal efficiency		81%			79%	
Power Output		74 W_e			72 W_e	

The radiation method used in the FEM simulation is the Monte Carlo method. Advantageously, it can calculate for multiple reflecting and absorbing faces within a defined enclosure. This method also allows the utilisation of a dedicated graphics card that can significantly boost computation speeds. An example of environmental view factors from the body, radiators, internal features, and the lunar surface can be seen in Figure 3-2. This was used to optimise the radiator fin length and mass.

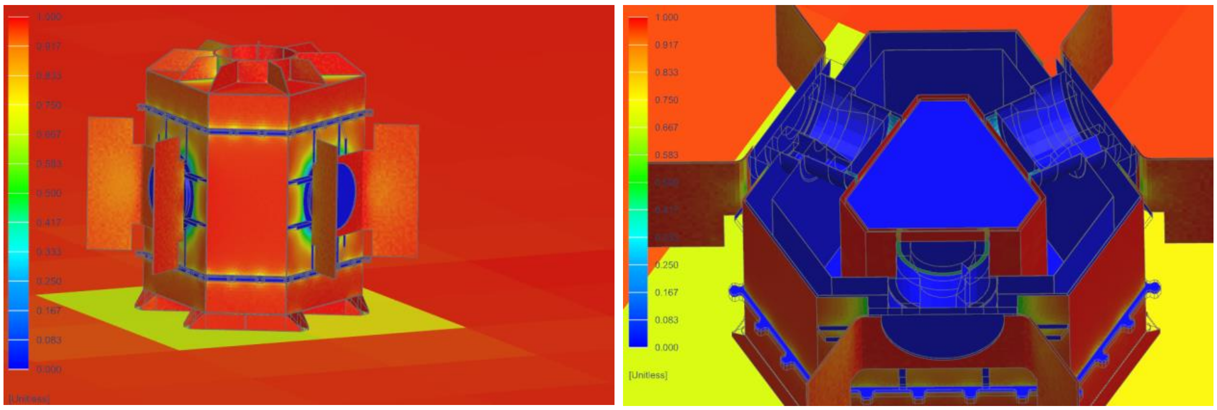

Figure 3-2. Left: External view factor for the radiator housing to the environment. Right: Internal View factors between the heat source and the convertors and insulation

Figure 3-2 presents the internal view factors of the Am-RSG. The internal surfaces of the aeroshell, insulation, and hot-side acceptor (HSA), all show a view factor of close to 1. However, the low view factor of 0.11 as presented in Table 3-1, is a result of the much larger surface area of the aeroshell compared to the HSA. Because of the low thermal conductivity of the insulation, 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 as significant to thermal efficiency as initially thought for this system, 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.

3.2. Thermal Performance of the Am-RSG at the Lunar Equator

From initial simulations, the operating conditions of an SRSC have been obtained, which can be translated into operational requirements for the simulators to satisfy if they are to be utilised. The simulators that are available for this elegant breadboard stage will be the same KRUSTY simulators that were integrated into the technology demonstrator. It is important for the Am-RSG Elegant Breadboard model to show operative capability in a range of lunar environments; therefore, the most extreme hot case is presented, that being operation on the lunar equator at peak solar illumination, including a single failed engine scenario. A scenario involving 2 failed engines would result in operative temperature limits being exceeded in several components and is therefore not included in this analysis. Operation in other lunar environments has been conducted but is not presented here because the equator environment can be considered as an enveloping scenario for all other lunar environments given the extreme temperature fluctuations that occur at this location.

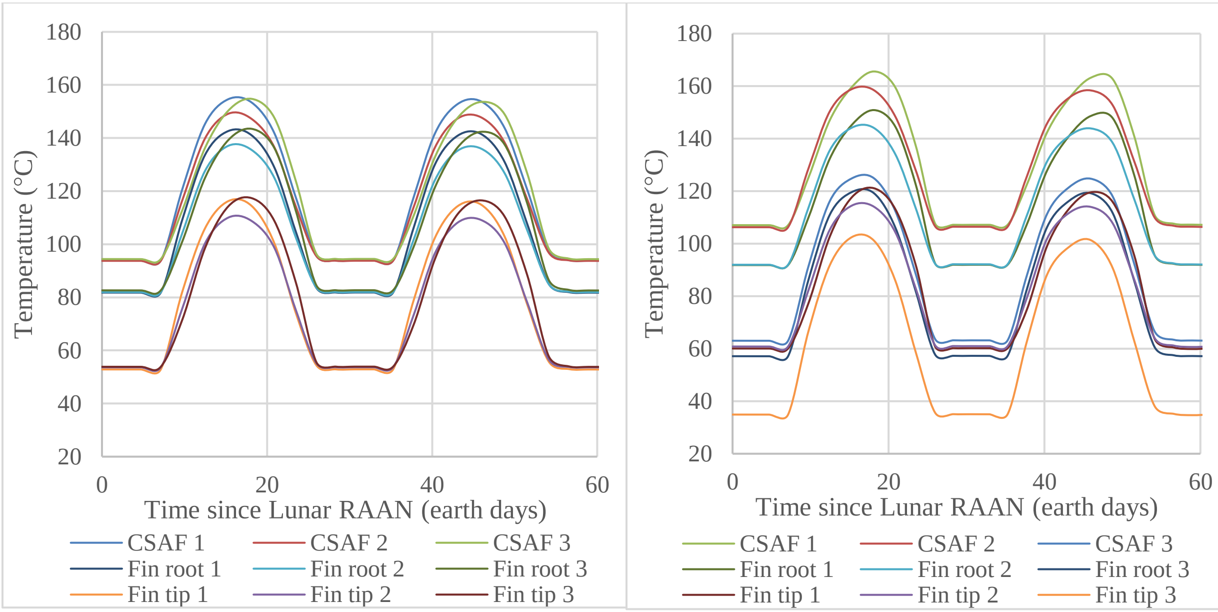

Figure 3-3. Left: Temperature profile of external components (Lunar equator). Right: Temperature profile of external components (Lunar equator with a single engine failure).

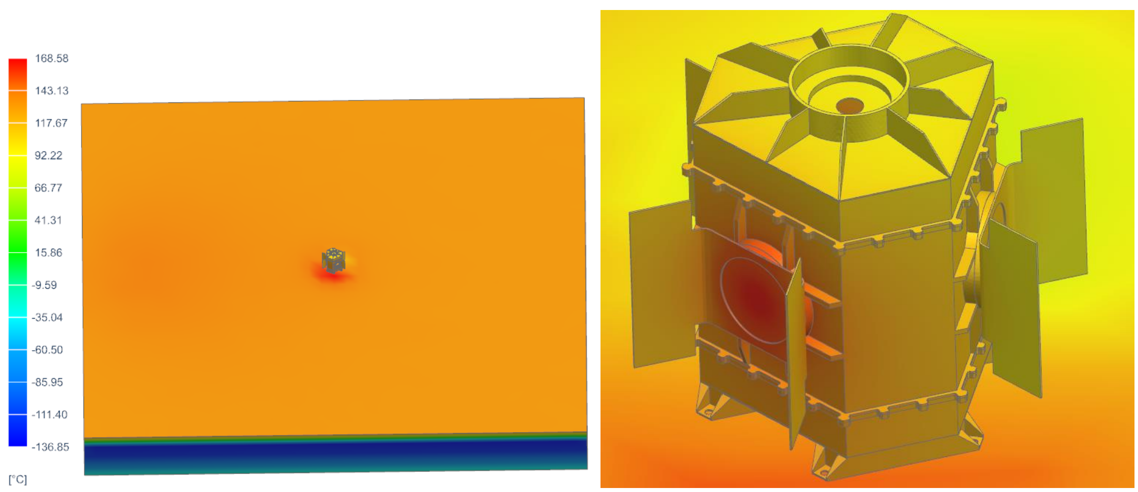

Figure 3-4. External thermal profile of the Am-RSG sat on the lunar surface at peak solar illumination (Sun is incident from bottom left to top right).

Table 3-2. Thermal performance at the lunar equator (peak solar illumiation)

Parameter	SRSC 1	SRSC 2	SRSC 3
$T_{aeroshell}$	795 ºC	791 ºC	793 ºC
$T_{hot\text{-}side\ acceptor}$	675 ºC	673 ºC	674 ºC
T_{CSAF}	147 ºC	141 ºC	147 ºC
$Q_{hot\text{-}side\ acceptor}$	105 W_{th}	105 W_{th}	105 W_{th}
$Q_{power\ output}$	22 W_e	23 W_e	22 W_e

Table 3-3. Thermal performance at the lunar equator with an SRSC 3 engine failure (peak solar illumiation)

Parameter	SRSC 1	SRSC 2	SRSC 3
$T_{aeroshell}$	847 ºC	847 ºC	852 ºC
$T_{hot\text{-}side\ acceptor}$	706 ºC	703 ºC	827 ºC
T_{CSAF}	154 ºC	143 ºC	112 ºC
$Q_{hot\text{-}side\ acceptor}$	139 W_{th}	141 W_{th}	28 W_{th}
$Q_{power\ output}$	32 W_e	33 W_e	0 W_e

When SRSC 3 is in a failure state, the modulation of the remaining two are increased to prevent internal temperatures from rising above the maximum operation temperatures of the internal components. In practice for these two scenarios, the actual operating modulation point for the engines may differ to what is presented here when finding the optimum operating point for maximum electrical power generation in specific scenarios. It is worth noting that SRSC 1 & 2 in the engine out scenario have higher CSAF temperatures than nominal, this is due to the higher modulation pulling more heat out of the heat source. The maximum operating temperature of the CSAF is the limiting factor in these scenarios, therefore this value dictates how high the SRSC can safely modulate. It can be seen that CSAF 1&2 are close to their maximum operating temperatures. However, there is temperature margin to modulate further to bring the temperatures at the hot side acceptor below its operation limits. The engines in the nominal scenario have been set to the lowest modulation achievable, based on real test data provided by NASA Glenn, while maintaining the hot side acceptor below its temperature limits. These two scenarios showcase the versatility of the Am-RSG in its ability to adapt to a dynamic environment to maintain a useable operative state.

4. MECHANICAL MODELLING

The technology demonstrator was designed and assembled with the primary aim of proving that a Stirling convertor could be coupled with an ^{241}Am heat source to provide meaningful electrical output. As such, its structure was designed with excessive margin to ensure safety and limit the time required to complete the design phase. This iteration of the design put greater emphasis on achieving a flight-like architecture, hence, there is more focus on mass efficiency while maintaining structural robustness with regard to expected launch loads.

Both designs employed the same method for constraining the heat sources; vertical constraint is achieved by preloading the insulation above and below the ELHS' with the friction generated by this compression providing lateral constraint. A simplified 1D spring system was used to provide initial estimates for the amount of displacement required by the insulation to generate sufficient preload. These models attempted to resolve the effects of the reaction force deforming the lid which in turn reduces the effective amount of preload, entering a circular feedback loop but were limited due to the complex geometry of the housing. A FEM model was produced using Simcenter Nastran to model both the feedback loop and geometry of the housing more effectively, utilising the displacement calculated by the 1D spring model as a load case. Only relevant structural components including the radiator body, insulation and ELHS' were included to simplify the model, with boundary conditions as follows; the mounting holes of the base were fully constrained while a prescribed displacement of 4 mm in the negative Z direction was applied to the flange of the radiator lid. One dimensional contact (CGAP) elements were used between surfaces in the simulation to calculate the contact forces and model contact mechanics effectively.

Figure 4-1 shows a section view of the Am-RSG displacement when exposed to the 4 mm prescribed displacement. These simulations have demonstrated significant preload has been achieved for the current design, sufficient to withstand up to 30 g of quasi-static acceleration. Extensive modal analysis has also been conducted with results awaiting correlation during the test campaign at NASA Glenn.

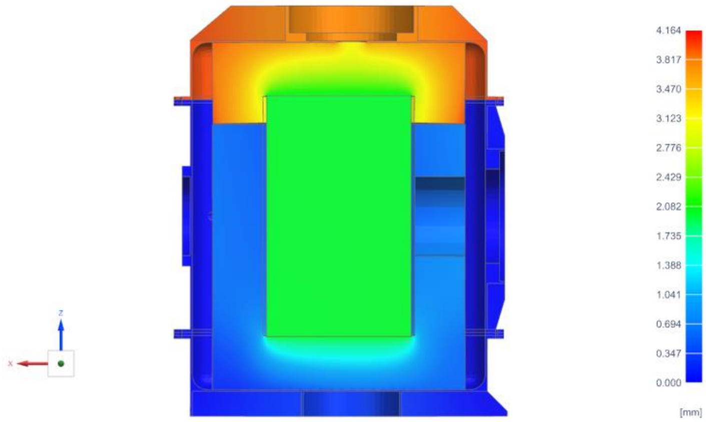

Figure 4-1: Structural simulation results for a section-view of the Am-RSG exposed to 4 mm of preload.

5. INTEGRATION OF HARDWARE

The heat source and housing produced by UoL are presented in Figure 5-1 in their ready-to-use configuration. This elegant breadboard will be integrated with up to three SRSC's and three balancers in the SRL (Figure 5-2) at NASA Glenn. Similar to the previous test campaign, the infrastructure available within the SRL through this collaboration will be utilised to deliver a successful test campaign rapidly 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 5-1: Left: Assembled electrically-heated heat source and housing at the University of Leicester. Right: SRL facility at NASA Glenn

6. CONCLUSIONS

A second iteration of the Am-RSG has been developed in collaboration between UoL and NASA Glenn. The work builds upon the test campaign conducted by the two parties in Q1 2025 which itself was a follow on of the concept study which arrived at an Am-RSG design that used SRSC's and powered a lunar rover. Physical testing remains a key instrument in this project to rapidly progress and improve upon modelling efforts while advancing Technology Readiness Levels (TRL) and confidence in the design. The objective of this elegant breadboard design is to prove that the Am-RSG can produce a meaningful amount of power in an environment similar to expected operational environments on the lunar surface. Many improvements have been made from the technology demonstrator, and this testing campaign will provide critical data on how these changes have affected the performance of the Am-RSG. This data will be key to informing a flight-ready design. The initial simulation results show that the Am-RSG Elegant Breadboard is expected to produce ~72 W_e from 400 W_{th}. Electrically heated heat sources that replicate the ^{241}Am heat sources will be coupled with the Am-RSG hardware two SRSCs and a convertor simulator, with potential to upgrade to a three-SRSC set-up as part of lab test campaign at NASA Glenn in Q1 2026.

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