

Development of Radioisotope Stirling Generators for High Efficiency Space Power Generation

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Abstract – Radioisotope power systems have been powering space missions for decades, historically using radioisotope thermoelectric generators to convert heat to usable electricity. Teams at NASA’s Glenn Research Center have been studying and testing free-piston Stirling convertors, which provide significant efficiency gains for space power generation when compared to state-of-the-art thermoelectric power conversion. Stirling convertors have been validated as stand-alone units with extensive environmental and extended lifetime testing. Recently, several efforts have integrated multiple Stirling convertors in generator configurations representing the interfaces and geometry that would be present in a flight system. Three separate radioisotope Stirling generator testbeds have been designed or conceived: the Plutonium-238 Stirling Generator Testbed, an internal NASA effort; the Americium-241 Stirling Generator Testbed, an international collaboration with a team from the University of Leicester; and the Heat Source Agnostic Stirling Generator Testbed, a conceptual study. The Plutonium-238 Stirling Generator Testbed (originally named the Dynamic Radioisotope Power System Testbed) began the initial design process in 2019, with more resources for the effort added in 2021 for design, analysis, and drawing creation. First testing occurred in 2023, with follow-on testing occurring in 2024 and 2025. Initially, the Americium-241 Stirling Generator Testbed was part of a conceptual design in 2022 which showed promise and led to an international collaboration effort to build hardware and test the design in a laboratory environment. The first integration and testing of the Americium-241 Testbed occurred in 2025 at NASA Glenn Research Center, was successful, and validated thermal

models of the system. Further efforts are ongoing to implement improvements to the design and test a second version in 2026. The Heat Source Agnostic Stirling Generator Testbed effort began as an idea to adapt to the changing environment surrounding fuel production and planned usage. Debates have been ongoing about the best mission options for the available radioactive material, and due to the current dynamic environment, a Stirling generator that can accommodate various heat sources, while still utilizing significantly less fuel to produce similar power output, is attractive. Recently, the Heat Source Agnostic Stirling Generator Testbed idea received funding to develop a project plan for a conceptual design study leading to hardware build, integration, and an environmental testing campaign, contingent on approval of the project plan. Design and analysis efforts for the Heat Source Agnostic Stirling Generator Testbed will show the feasibility and limitations of a Stirling generator design that can accommodate a variety of heat sources.

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1. INTRODUCTION

Deep space missions to regions where solar power is impractical are typically powered by converting heat from the decay of radioactive elements to usable electricity. Historically, the conversion mechanism has been to use thermoelectric conversion, which, at the current state-of-the-art, only provides about 6% thermal to electric efficiency [1]. Developing a more efficient system without sacrificing reliability is advantageous to achieving ambitious space exploration missions in the future such as the potential NASA Flagship missions: Uranus Orbiter and Probe and Enceladus Orbilander, as called out in the most recent decadal survey [2].

Free-piston Stirling convertors are a reliable and significantly more efficient method of providing electricity from heat. For the past several decades, the NASA Glenn Research Center (GRC) has been developing and testing Stirling convertors to prove reliability and demonstrate performance in relevant, non-nuclear environments including extended operation life testing, static acceleration testing, launch vibration tests, and thermal cycling. [10] Multiple designs of Stirling convertors have successfully passed all these environmental tests and do not show any signs of degradation in performance. The world record holder for the longest running heat engine has accumulated over 17 years of lifetime testing in the Stirling Research Laboratory (SRL) at GRC, demonstrating the long lifetime required for deep space missions. [3, 9]

The Sunpower Robust Stirling Convertor (SRSC) is the latest edition of Stirling convertor designs that has passed the verification and validation testing sequences conducted by the SRL. Performance ranges and the nominal operation point for the SRSC are shown below in Table 1, and the specific operating point can be tuned to meet mission specifications and environments.

Table 1. Performance range of the SRSC

Parameter	Minimum	Nominal	Maximum
Hot-End Temperature	20 °C	700 °C	750 °C
Cold-End Temperature	20 °C	100 °C	185 °C
Alternator Housing Temperature	20 °C	110 °C	195 °C
Piston Amplitude	2.0 mm	3.62 mm	5.0 mm

While testing and advancing the Stirling convertor individually is important, testing the Stirling convertors in the generator configuration, the arrangement that resembles the complete, flight-like RPS and demonstrates the generator level interfaces, is crucial. Current topology of Radioisotope Stirling Generators (RSGs) is a radial arrangement of Stirling convertors radiatively coupled to a centrally located heat source. Multiple test articles have been conceived to demonstrate the configuration, including the Plutonium-238 (Pu-238) Stirling Generator (SG) Testbed (formerly called the DRPS Testbed, [4], [5]), the Americium-241 (Am-241) SG Testbed, and the Heat Source Agnostic SG Testbed. The Pu-238 SG Testbed and Am-241 SG Testbed were both assembled and tested in the SRL, and the Heat Source Agnostic SG Testbed is a conceptual study that has potential to lead to hardware manufacture and testing.

2. PU-238 STIRLING GENERATOR TESTBED

Design

Design of the Pu-238 SG Testbed began in 2019 as the first hardware demonstration of the current Stirling generator topology and was a fully in-house, NASA design effort. Overarching requirements were developed to drive the design and included the following:

Layout—The Stirling convertors are arranged in an array of co-planar, dual-opposed pairs configuration, and the generator testbed design can accommodate up to two pairs of convertors.

Heat Source—The electric heat source is centrally located in the generator, radiatively coupled to the hot ends of the Stirling convertors, simulates the heat produced by two or three general purpose heat source (GPHS) modules (500 W_{th} or 750 W_{th}), and maintains the same form factor as a GPHS stack.

Housing—All waste heat is dissipated through the housing and is designed to maintain the cold ends of the Stirling convertors at or below 100 °C in both ambient natural convection and thermal vacuum with a liquid nitrogen cold wall. Testbed design can accommodate any Stirling convertor available for testing in the SRL. Inner volume of the housing can be either evacuated or filled with 10 psig of inert cover gas.

The finalized exterior design is shown below in Figure 1. Each Stirling convertor has an adapter plate to interface between the cold-side adapter flange (CSAF) and the housing wall which has an integrated coolant loop to provide an optional auxiliary cooling mechanism. Radiator fins are detachable to accommodate options to test with various fin configurations and easily experiment with different fin materials and sizes. On top of the housing are feedthroughs for thermocouples and heat source power in addition to the gas fill and vacuum ports.

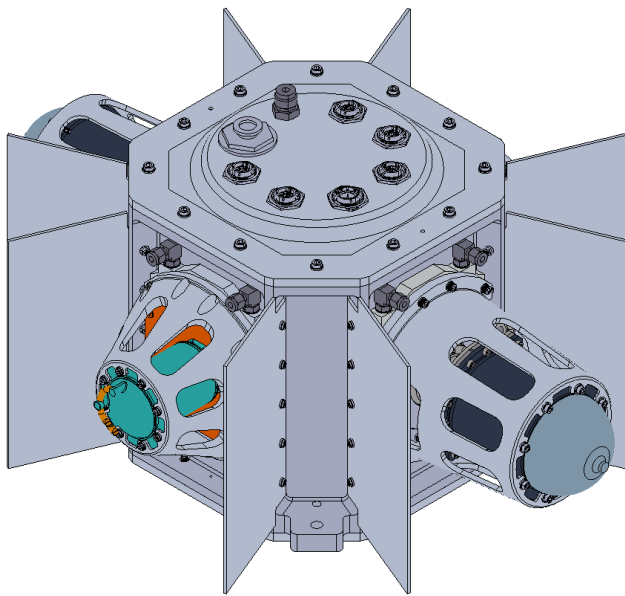


Figure 1. Exterior model of the Pu-238 SG Testbed

In Figure 2, the interior design of the testbed is primarily filled with machinable microporous insulation pieces designed with interlocking step features to eliminate line-of-sight losses from the heat source and secured via a small spring load. The heat source is a graphite block having the same dimensions as a stack of three GPHS modules and is embedded with eight cartridge heaters to provide the required thermal output and supported by spring loaded load studs. The hot ends of the Stirling convertors are augmented with graphite heat collector plates to expand the area of the hot end and improve the view factor to the heat source. Draw rod assemblies shown in Figure 3 hold the heat collector plates to the convertor hot ends via spring loads, since no modifications could be made to the Stirling convertors.

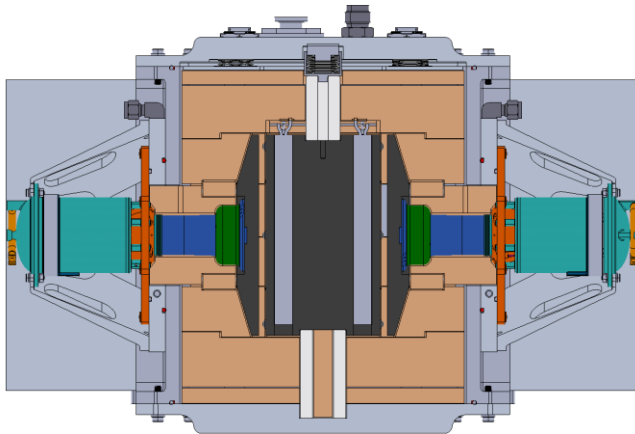


Figure 2. Cross section of the Pu-238 SG Testbed

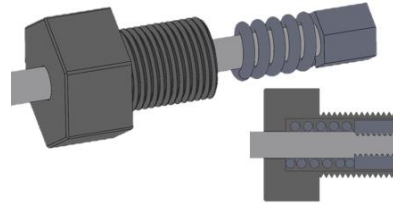


Figure 3. Draw rod design and cross section

Analysis

Several analyses were performed to inform the design process including structural, thermal, and modal analyses, in addition to drawing reviews prior to initiating the manufacturing process. Thoroughly completing the drawing review process ensured proper geometric dimensioning and tolerancing standards per the ASME-Y14.5-2018 standard, and carefully considered each tolerance stack-up in the full assembly. In the end, the final drawing package was complete and resulted in a straightforward assembly process.

Structural—For the major components, structural analyses were performed to ensure sufficient margins for each material based on the stresses in the system. Highlighted here is the structural analysis of the housing for each possible operational state (evacuated or internal pressure), along with the modal analysis results. Modal analysis is important to ensure the housing resonance is not near the operating frequency of the Stirling convertors. The structural modeling was performed in Ansys Workbench with proper loads applied for the heat source and insulation load stud spring forces, bolt preloads, and internal or external pressure based on operational state. Finally, proper material properties were set for the aluminum housing, and the model was meshed as shown in Figure 4. For the case with internal pressure, the average stress resulted in 0.904 ksi, and 0.763 ksi for the evacuated state, which is significantly less than the material yield strength of 38 ksi. Figure 5 and Figure 6 show the stress analysis results for the two cases, noting that the maximum stresses shown on the scale are an artifact of the modeling method for the bolt preload, but are still less than the yield strength of the aluminum.

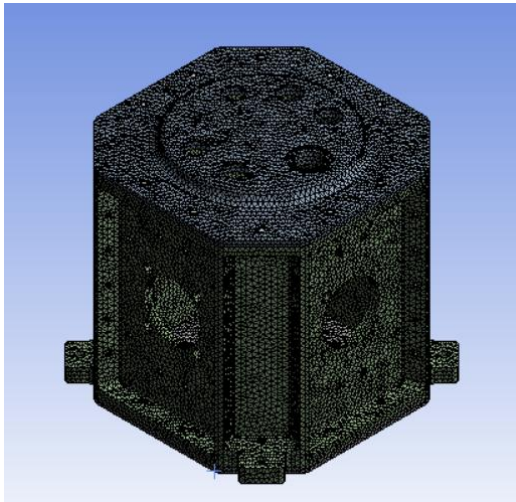


Figure 4. Mesh of Pu-238 SG Testbed housing for stress analysis

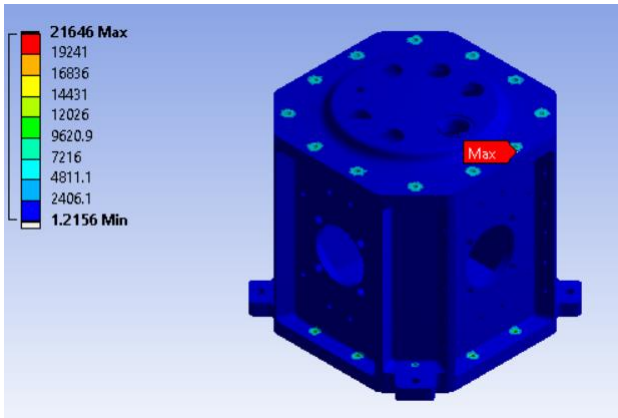


Figure 5. Stress (psi) of the Pu-238 SG Testbed housing under internal pressure

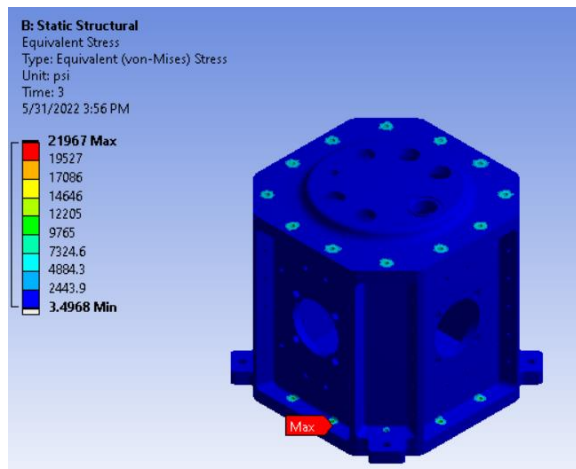


Figure 6. Stress of the Pu-238 SG Testbed housing under internal vacuum

Modal analysis indicated that the mode 1 frequency was 565 Hz for both the internal pressure and evacuated states,

which is well above the Stirling convertor operating frequency.

Thermal—Similarly to the structural analyses, thermal analyses were performed to ensure the thermal performance of the system and components. One particular analysis highlighted here is the thermal analysis on the final housing concept. COMSOL modeling was utilized to iterate and analyze various housing shapes and fin configurations until an octagon shape with eight thin fins was selected. When compared with a variety of other options, the selected configuration maintained the cold end temperature of the Stirling convertors at or below the required limit and is a relatively compact and simple design. The model mesh is shown below in Figure 7 and the plot of surface temperature is shown in Figure 8.

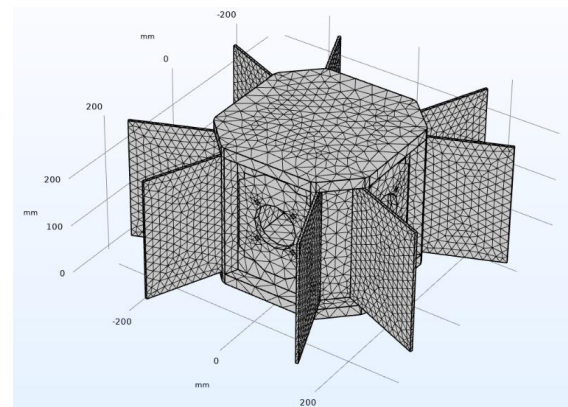


Figure 7. Mesh of Pu-238 SG Testbed for thermal analysis

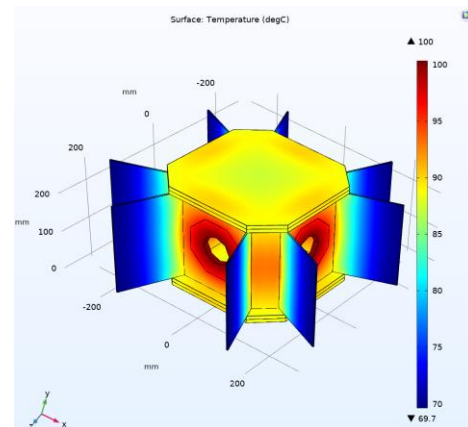


Figure 8. Surface temperature plot of worst-case thermal analysis for Pu-238 SG Testbed housing design

Boundary conditions utilized in the model were thermal insulation on all interior surfaces, exterior surfaces seeing the environment of radiating to ambient temperature of 24 °C and ambient natural convection with convective coefficient of 5 W/m²K, and heat flux of 614.4 W was applied to the where the convertor waste heat is rejected. Assuming all waste heat is flowing through the convertor rejection area allows for a conservative housing design because the convertor rejection

area is the most critical temperature present on the housing and must be maintained to keep the cold end of the convertors at or below the maximum acceptable temperature. The heat flux was determined by taking the maximum thermal output of the GPHS module, multiplying by three, and assuming the Stirling convertors are operating at 20% thermal to electric conversion efficiency. Stirling convertors are capable of producing higher efficiency, upwards of 30%, depending on the convertor design, but assuming 20% efficiency for housing design represents the conservative boundary condition. Additional analysis cases were run to represent the other operating points, namely, operation in thermal vacuum and with the heat source simulating only two GPHS modules, but the worst-case environment was represented by the boundary conditions described above, and therefore, informed the housing design to fulfill the thermal requirements.

The design and analysis details referenced here are sourced from “Design of a Dynamic Radioisotope Power System Generator Testbed” E. Wozniak, et. al. [4], where complete details of the design process and analyses of the Pu-238 SG Testbed can be found.

Build and Integration

In 2022, all fabrication and purchases of off-the-shelf components were completed. Initial assembly and integration were performed over the end of 2022 and beginning of 2023, and utilized two Advanced Stirling Convertors (ASCs, heritage gas bearing Stirling convertor design from Sunpower Inc.) and two Stirling Radioisotope Generator Engineering Unit Stirling Convertor Assembly (SES, heritage flexure Stirling convertor design from Infinia) units. The ASC convertors were developed through the Advanced Radioisotope Stirling Generator (ASRG) project [11] and were the starting place for the current SRSC convertor design. Selection of these particular Stirling convertors for use in the Pu-238 SG Testbed was purely based on availability of the units in the SRL. In a flight Stirling generator design, only one type of convertor would be selected to simplify the control mechanics.

Careful planning resulted in the development of a detailed assembly procedure for the Pu-238 SG Testbed, which ensured a smooth assembly process. Assembly occurred in a rotating assembly fixture, shown in Figure 9, which allowed the housing to be rotated to various orientations and made assembly convenient. To generalize the procedure, first the Stirling convertors were instrumented with thermocouples and insulated using custom microporous insulation clamshells shown in Figure 10. Next, the convertors were installed into the housing and lowered via a custom scissor jack setup as shown in Figure 11. The heat collector plates, and more solid insulation were installed, followed by the lower end plate and more layers of insulation. The heat source was then lowered into place and the remaining layers of insulation were installed. Feedthroughs were installed in the top end plate for the heat source power and thermocouples. Finally, the springs loading the heat source

and insulation were placed and the top end cap installed. The finished assembly is shown in Figure 12.

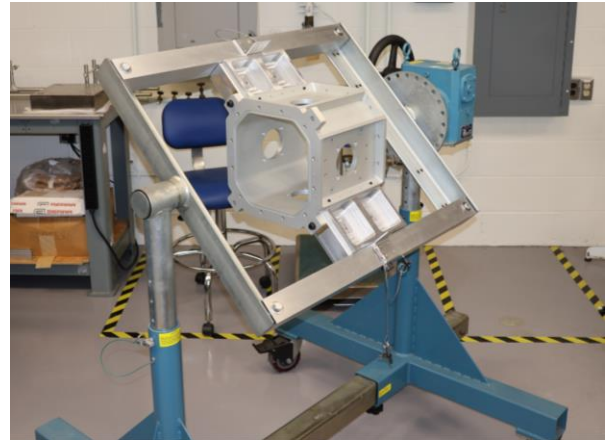


Figure 9. Assembly fixture with Pu-238 SG Testbed housing



Figure 10. ASC convertor with thermocouples and insulation installed

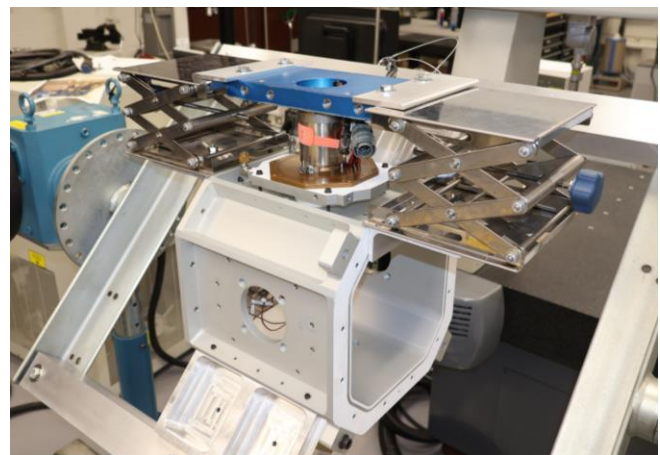


Figure 11. Scissor jack assembly mechanism



Figure 12. Assembled Pu-238 SG Testbed in the assembly fixture

Integration on the test stand was accomplished by moving the full assembly to the table using an engine hoist and secure lifting eyes and straps. Between the assembly fixture and table, the total mass of the Pu-238 SG Testbed was measured to be 60.5 kg. The test stand shown in Figure 13 was robustly designed and includes an isolation system to provide near-zero mounting stiffness in both convertor axes and vertically. Theoretically, there would be no vibrations present with dual opposed pairs of convertors, but the isolation system was designed to disconnect the Pu-238 SG Testbed from the test table so that any vibrations resulting from imperfections in convertor balance, or any unexpected vibrations could be measured by the housing accelerometer.



Figure 13. Pu-238 SG Testbed integrated on the test stand. For scale, blue test rack is standard height of 42 U (1.87 m)

The assembly and integration details referenced here are sourced from “Assembly, Integration and Initial Test Results of a Stirling Radioisotope Power System Generator Testbed” E. Wozniak, et. al. [5], where complete details of the assembly and integration of the Pu-238 SG Testbed can be found.

Testing

Initial testing occurred in May and June of 2023 with additional testing occurring in November and December of 2024 and late summer of 2025. The baseline test point consisted of the heat source set to provide a constant power of 500 W (simulating two GPHS modules) and the piston amplitude of the Stirling convertors was modulated to achieve 500 °C Stirling hot end temperature. While piston amplitude is an indirect mechanism for controlling hot end temperature, adjusting the throttle of the convertors when operating in constant heat input mode controls the hot end temperature by changing the amount of heat being drawn through the convertors. The November/December 2024 test point was a higher piston amplitude point, where the heat source temperature was set to achieve 640 °C on the hot end of the convertors with a higher piston amplitude of 4.4 mm on the ASC convertors. Maintaining the cold end temperature of the Stirling convertors was purely through the radiator housing and fins via natural convection and radiation to the ambient SRL environment during both operation points, therefore changes to ambient conditions can be easily observed in the data. Additionally, the 2023 and 2024 test points were both run under about 10 psig of inert argon gas for the interior housing environment. Table 2 below compares both operational points.

Table 2. Operation Points from Pu-238 SG Testbed

Parameter	2023	2024
Avg. ASC Hot-End Temperature	499.7 °C	465.0 °C
Avg. SES Hot-End Temperature	496.9 °C	499.6 °C
Avg. ASC Cold-End Temperature	62.7 °C	79.9 °C
Avg. SES Cold-End Temperature	68.7 °C	82.9 °C
Avg. ASC Alternator Housing Temperature	56.6 °C	69.3 °C
Avg. SES Alternator Housing Temperature	48.4 °C	54.1 °C
Avg. Heat Source Temperature	609.4 °C	649.9 °C
ASC Piston Amplitude	2.8 mm	4.1 mm
SES Piston Amplitude	3.6 mm	5.2 mm

ASC Frequency	101.3 Hz	100.7 Hz
SES Frequency	78.4 Hz	79.4 Hz
Heater Power	500.8 W	725.2 W
Total Power Output	84.3 W _e	135.8 W _e
Gross Efficiency	16.8%	18.7%
Housing Pressure	23.3 psia	21.2 psia

Late summer 2025 testing of the Pu-238 SG Testbed consisted of thermal loss testing to characterize the performance of the insulation package. The series of test points are all static (Stirling convertors stalled) to measure losses in the system. A range of test points were collected under both vacuum and inert gas fill at various heat source and housing temperatures. The points will then be compared to a computational fluid dynamics analysis to predict the thermal losses in the system.

3. AM-241 STIRLING GENERATOR TESTBED

Background

Am-241 is a novel radioisotope fuel being pursued by the European Space Agency (ESA). Am-241 is attractive due to the availability of the radioisotope in Europe and the long half-life of 432 years. ESA in coordination with the University of Leicester has been developing the European Large Heat Source (ELHS), which uses Am-241 to produce approximately 200 W_{th} from each module, see Figure 14 [6].

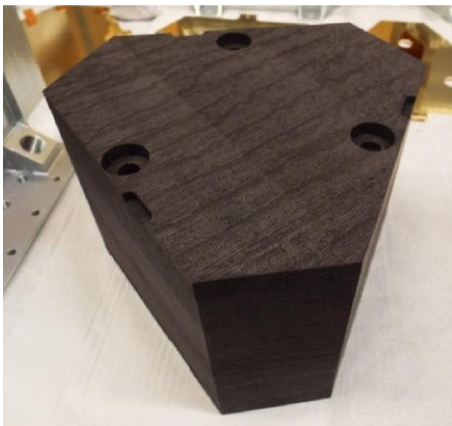


Figure 14. ELHS aeroshell [7]

In 2022, the University of Leicester and NASA collaborated for a mission analysis study in which a Stirling generator utilizing ELHS modules as the heat source was designed and integrated on a theoretical lunar rover mission [7], see

Figure 15 for an image of the final design from the study. The results of the study were promising, and in 2023, the University of Leicester approached NASA to demonstrate and electrically heated lab prototype of the Stirling generator design. An International Space Act Agreement was established between the University of Leicester and NASA to formalize the relationship, and progress began to demonstrate a hardware prototype of the Am-241 SG Testbed.

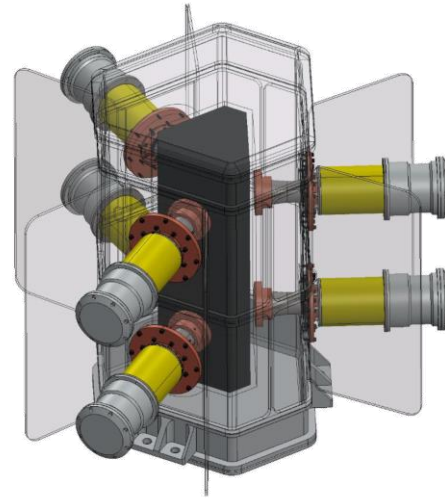


Figure 15. Final design of Am-241 SG from Compass study

Design

Design of the Am-241 SG Testbed utilized the conceptual mission design study results as the starting point, and to accommodate the fast-paced effort, the half-sized design utilized existing and available hardware. The University of Leicester provided the housing, electric heat sources, and insulation package, while GRC provided an ASC with a balancer and two convertor simulators. Collaborative meetings were held on a weekly basis to jointly design the interfaces, confer on analyses and test stand design, and plan the initial test campaign.

The Am-241 SG Testbed design consists of a triangular housing, reflecting the triangular shape of the ELHS, see Figure 16. Stirling convertors are arranged radially about and radiatively coupled to the centrally located heat source, and balancers pair with each Stirling convertor to cancel out the dynamic motion of the convertors. Similar to the Pu-238 SG Testbed, the housing is filled with insulation, but in the Am-241 SG Testbed, the insulation supports the heat source instead of utilizing load studs. Thermocouple wires and electrical power leads for the heat source are routed to feedthroughs on the top of the housing. Thermal simulators populated two of the three housing ports and use nitrogen gas flow to draw heat in the same manner as an ASC. Mounting sleeves were designed to secure the simulators in the Am-241 SG Testbed housing and outfitted with cartridge heaters to simulate the heat rejection into the housing. Designing the housing included provisions for various radiator fin

configurations so that up to six total fins could be mounted to the housing as needed.

The design and analysis details referenced here are sourced from “Technology Demonstrator of an Americium-Fuelled Radioisotope Stirling Generator” H. Sargeant, et. al. [8], where complete details of the design process and analyses of the Am-241 SG Testbed can be found.

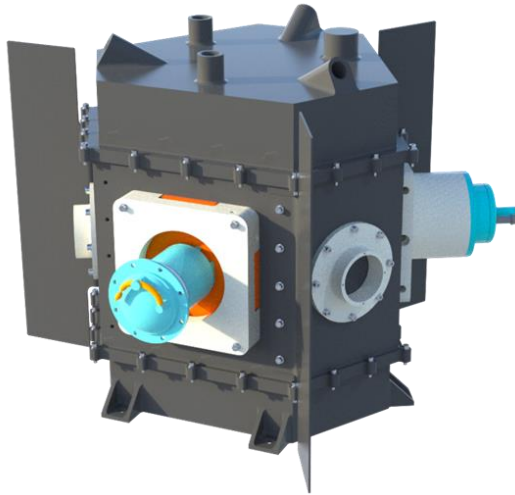


Figure 16. Final design of the Am-241 SG Testbed

Integration and Testing

Initial assembly of the housing, insulation, electric heat sources, and wire routing to feedthroughs occurred at the University of Leicester. The components were then packaged up and shipped to NASA GRC. Concurrently, preparations were made in the SRL to assemble and check-out a testing rack and test table, along with installation of nitrogen gas lines to the test stand for operation of the thermal simulators. To ensure smooth operations, test runs were successfully completed individually with the ASC convertor and the thermal simulators. The team from the University of Leicester traveled to GRC to collaborate for the integration of hardware and test campaign.

One notable feature of the Am-241 SG Testbed design is the exclusion of heat collector plates on the hot ends of the ASC and thermal simulators, a decision confirmed via thermal modeling and compared to the Pu-238 SG Testbed design in Section 5. To improve the radiant heat transfer mechanism, a high emissivity coating was applied to the hot ends of both the Stirling convertor and the thermal simulators. Coating was completed prior to the arrival of the University of Leicester team, but upon a final inspection of the coating prior to integration in the housing, the high emissivity coating on the simulator hot ends was cracked. To resolve the issue, the cracked coating was removed, a surface etching was used to achieve a better surface preparation, and the coating was reapplied. The second application did not crack, and assembly proceeded as planned.

Integration of the Am-241 SG Testbed housing with the Stirling convertor and thermal simulators also took place in the same rotating assembly fixture used for the Pu-238 SG Testbed assembly as shown in Figure 17. The NASA and University of Leicester teams worked together seamlessly, and the assembly process was completed within days. Once the assembly was complete, the Am-241 SG Testbed was transferred to the test stand and connected to the vacuum pumping station as shown in Figure 18.



Figure 17. Am-241 SG Testbed during assembly



Figure 18. Fully assembled Am-241 SG Testbed mounted on to the test stand

Once an acceptable vacuum level on the 10^{-2} torr scale was reached, the heat source was powered and began thermally soaking the system and achieving a better internal vacuum on the housing due to outgassing of the microporous insulation,

which absorbs moisture when exposed to air. Then, the Stirling convertor and thermal simulators were started to achieve the initial baseline test point. To achieve the most realistic operation point for the generator, the heat source was set to a constant power output, the nitrogen flow rates of the thermal simulators were adjusted such that the simulator hot end temperatures matched the ASC hot end temperature, and heat was added via the cartridge heaters in the simulator mounting sleeves such that three thermocouples mounted on the housing near each cold end were similar temperatures. Performance was achieved and maintained for two days, and the data is shown in Table 3. After successful completion of the baseline operation point, a failed convertor simulation test was run to demonstrate the redundancy of the system design in which one of the thermal simulators was shutdown and the system was allowed to settle back into a steady state. There were no adjustments necessary to the operating parameters during the transition and the total power output remained the same, resulting in a passively redundant system. The operating point from the failed convertor simulation test is also shown in Table 3.

Table 3. Operation Points from Am-241 SG Testbed

Parameter	Baseline	Failed Conv. Sim
Avg. ASC Hot-End Temperature	416.5	528.4
Avg. Simulator 1 Hot-End Temperature	420.9	509.3
Avg. Simulator 2 Hot-End Temperature	422.1	699.6
Avg. ASC Cold-End Temperature	62.9	64.0
Radiator Housing Temp. (near ASC)	57.5	57.9
Radiator Housing Temp. (near Sim. 1)	57.6	58.2
Radiator Housing Temp. (near Sim. 2)	57.8	54.8
Avg. ASC Alternator Housing Temperature	61.4	62.9
Avg. Heat Source Temperature	701.8	777.6
ASC Piston Amplitude	3.2 mm	3.3 mm
ASC Frequency	102.2 Hz	102.2 Hz
ASC Power Output	21.4 We	31.6 We
Heater Power	405.8 W	403.1 W
Total Generator Power Calculation	64.2 We	63.2 We
Gross Efficiency Calc.	15.8%	15.7%
Housing Vacuum Level	0.2 torr	0.2 torr

4. HEAT SOURCE AGNOSTIC STIRLING GENERATOR TESTBED

Overview

Multiple options for radioisotope heat sources may be available to power future space flight missions. With funding environments constantly in flux and fuel availability in question, designing a Stirling generator that is flexible to the fuel source is attractive. A project plan is currently in formulation for completing the design, build, integration and testing of the Heat Source Agnostic SG Testbed. Design efforts will begin after the project plan is approved.

Initial Design and Testing Plans

The initial design plans include utilizing dual opposed pairs of Stirling convertors arranged around a centrally located heat source. The heat source will be sized to electrically simulate the thermal output of a variety of potential radioisotope power sources and focus on Am-241 (ELHS) and Pu-238 (GPHS) heat sources. A significant feature of the Heat Source Agnostic SG Testbed will be the ability to run consecutive testing campaigns that simulate different radioisotope heat sources without re-configuring the system. Pending the successful outcome of the laboratory testing, the Heat Source Agnostic SG Testbed design could be a springboard for a flight system and inform other future Stirling generator designs.

Numerous trade studies are planned to facilitate the design of the Heat Source Agnostic SG Testbed starting with the selection of which Stirling convertor will be utilized in the design. Further trade studies will be performed to make decisions for the design of the heat source, insulation package, and housing features. A major goal of the design is to keep the total mass as low as possible while maximizing power output. Additionally, the Heat Source Agnostic SG Testbed will be designed to operate in various environmental conditions, such as the lunar and Martian surfaces. Performance estimates along with thermal and structural modeling will inform the design process and provide a basis for iterations in the design.

Once the design is completed, the testing campaign will include baseline performance mapping, thermal insulation loss characterization to determine net efficiency, generator level redundancy testing, launch vibration simulation, thermal vacuum testing, and possibly other environmental tests. The testing campaign will provide a basis for confidence in the generator design and increase the potential for a radioisotope Stirling generator to power a future space flight mission.

5. COMPARISON OF PU-238 AND AM-241 STIRLING GENERATOR TESTBED PERFORMANCE

Both the Pu-238 and the Am-241 SG Testbeds operated with ASCs and while each simulated a different heat source, the operational data may be compared as shown below in

Table 4, where the Pu-238 SG Testbed point is from the 2023 operational data point described above and the Am-241 SG Testbed point is from the baseline point described above.

Table 4. Comparison of ASC performance in Am-241 and Pu-238 SG Testbeds

Parameter	Pu-238 SG Testbed	Am-241 SG Testbed
Avg. ASC Hot-End Temperature	499.7 °C	416.5 °C
Avg. ASC Cold-End Temperature	62.7 °C	62.9 °C
Avg. Housing Temperature	56.9 °C	52.9 °C
Avg. Heat Source Temperature	609.4 °C	701.8 °C
ASC Piston Amplitude	2.8 mm	3.2 mm
Heater Power	500.8 W	405.8 W
ASC Power Output	23.4 W _e	21.4 W _e
Total Generator Power Calc. (If all ASCs)	92.1 W _e	64.2 W _e
Gross Efficiency Calc. (If all ASCs)	18.4%	15.8%

Neither the Pu-238 nor the Am-241 SG Testbeds were optimized designs. Both were simply designed for laboratory testing campaigns as proof-of-concept, therefore, significant improvements in performance can be achieved with more effort placed on optimizing a Stirling generator design. Optimization of performance is planned to be performed with the Heat Source Agnostic SG Testbed design effort, and improvements in optimization are in-work for the second version of the Am-241 SG Testbed. Additionally, although the Pu-238 SG Testbed demonstrated higher gross efficiency than the Am-241 SG Testbed, there are other advantages to utilization of the Am-241 isotope, namely availability and a significantly longer half-life.

One significant difference between the Am-241 and Pu-238 SG Testbeds is the heat collector plates that were included in the Pu-238 SG Testbed design. The University of Leicester performed thermal analyses that showed exclusion of the heat collector plates is viable if the system is sufficiently insulated because the heat will take the path of least thermal resistance through the Stirling convertors but result in a higher heat source temperature. Elevated heat source temperatures were acceptable for the Am-241 SG Testbed design but will also result in higher insulation losses. The results from the Am-241 SG Testbed initial testing confirmed what the analysis predicted, operation without heat collector plates is viable, and a large temperature delta of about 285 °C existed

between the heat source and hot end of the Stirling convertor. Therefore, as long as the aeroshell design can withstand higher temperatures and the generator housing insulation losses are still within an acceptable range for the mission profile, it is possible for the heat collector plates to be excluded in a Stirling generator design. As shown through the Pu-238 SG Testbed design though, inclusion of heat collector plates can reduce losses, with the temperature delta between the hot end of the Stirling convertor and the heat source of 150 °C at the nominal operating point. A lower temperature drop would result in a more optimal overall generator design, even though heat collector plates may also increase the system mass. If elimination of heat collector plates is being considered for a flight Stirling generator design, analysis of the temperature drop between the heat source and hot end will need to be compared with specific mission requirements and operational environments.

In an ideal Stirling generator design, the interfaces on both the hot and cold ends of the Stirling convertors would be adjusted directly and optimized for the specific generator design in lieu of adapting to the current laboratory testing interfaces. Re-designing the convertor interfaces to more optimal generator/flight-like interfaces is a relatively low-risk opportunity to significantly improve Stirling generator designs.

6. FUTURE WORK

The second version of the Am-241 SG Testbed has been designed, manufactured, and is currently in the assembly process. Baseline performance testing along with a failed convertor simulation test and additional characterization testing of the second version is planned to start in March 2026, with further environmental tests planned for late 2026 and into 2027. The Pu-238 SG Testbed will undergo a failed convertor simulation test to demonstrate the redundancy scheme in early 2026. Planning is ongoing for the Heat Source Agnostic SG Testbed effort, and once funding is secured, the design cycle will begin, likely in 2026 followed by assembly and the testing campaign. The Heat Source Agnostic SG Testbed is proposed to be a three-year effort to complete all design and testing phases.

7. CONCLUSIONS

The SRL at NASA GRC has designed, built, and tested multiple Stirling generators which have demonstrated significant efficiency increases over the counterpart thermoelectric generators. Even more efficiency gains are possible with optimization of the Stirling generator designs. Both the Pu-238 and Am-241 SG Testbeds were successful, and informed future design efforts for the Heat Source Agnostic SG Testbed and the second version of the Am-241 SG Testbed. Improvements will continue to advance Stirling generator technology and pave the way for selection of a Stirling generator on upcoming missions.

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BIOGRAPHY



Ernestina Wozniak received three A.A.S. degrees in Mechanical Engineering Technology, Electro-Mechanical Engineering Technology, and Pre-Engineering from Cincinnati State Technical and Community College in 2017, and a B.S. in Aeronautical and Astronautical

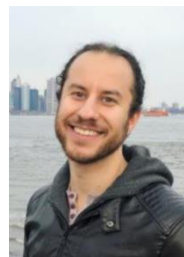
Engineering from Purdue University in 2020. She held various intern positions throughout college both at NASA and in industry and has worked as a design and test engineer in the Thermal Energy Conversion branch at NASA GRC for the past 7 years. Her work in SRL specializes in Stirling Generator Testbed design, analysis, and testing in her current role as Testbed Lead Engineer.



Matthew Stang received his B.S. in mechanical engineering from the University of Akron in Ohio in 2022. He has worked at NASA Glenn Research Center for the past 5 years as a research and test engineer in the Stirling Research Laboratory (SRL) of the Thermal Energy Conversion Branch. His major contributions have been various design and testing campaigns involved in increasing the Technology Readiness Level (TRL) of both Stirling convertors and Stirling generators.



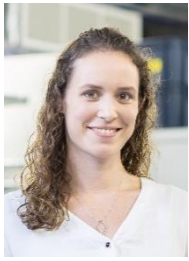
Salvatore Oriti is a researcher in the arena of advanced energy conversion technology for space power systems, with 24 years at NASA Glenn Research Center (GRC) in Cleveland, Ohio. He currently serves as a technical lead for dynamic generator development in the Thermal Energy Conversion Branch at NASA GRC. His work is focused on developing long-life, degradation-free heat engines for NASA space power needs, including radioisotope and fission power systems.



Ronald Leibach is a mechanical designer and thermal analyst in the Thermal Energy Conversion Branch at NASA's Glenn Research Center. His research interests include developing mechanical solutions in the fields of Stirling/Brayton-based power systems and studying the effects of lunar regolith on thermal control systems. Ron received an M.S. from Case Western Reserve University (Cleveland, OH) in 2020, where he studied and designed biologically inspired robots.



Rebecca Buchrle received her B.S. in mechanical engineering from the University of Akron. She has worked at NASA Glenn Research Center as a design engineer in the mechanical systems design and integration branch. During her 6 years at NASA, she has worked on various research including radioisotope power systems, regenerative fuel cells, and inverters for hybrid-electric aircraft.



Hannah Sargeant received her BSc in Physics from the University of Sheffield, MSc in Space Exploration Systems from the University of Leicester, and her PhD in Planetary Science from the Open University. She has held multiple postdoctoral research positions in the UK and the US with research themes of space resources, lunar exploration, and radioisotope power systems. Hannah is currently a Senior Research Associate at the University of Leicester where she is PI for International Bilateral projects investigating applications of radioisotope power systems.



Ramy Mesalam received his PhD in material science from the University of Leicester and his master's in aerospace engineering in 2014 from the University of Manchester. Since the start of his PhD Ramy became a member of the space nuclear power 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, radioisotope fuel cladding, and overall system-level modelling and design.



Kris Bell received his MEng in Aerospace Engineering from the University of Leicester in 2024. In 2021, during his degree, he completed a year placement at Atkins in the aerospace & defense practice where he supported multiple projects as a mechanical engineer. Since graduating he has joined the Space Nuclear Power team at the University of Leicester acting as the mechanical engineer for the Am-RSG benchtop demonstrator delivered to NASA Glenn Research Center. He continues to support and design the next version of the Am-RSG for testing in 2026.



Robert Tute received his BSc in Engineering Physics from Loughborough University, and then his MSc in Space Exploration Systems from the University of Leicester (UoL). Since graduating, he has been working with UoL for 2 years as an aerospace engineer where his main focus has been on the thermal design and analysis of Radioisotope Power

Systems (RPS). A major milestone during this time included a global first laboratory demonstration of a European RPS (electrically heated) using a UoL designed heat source and housing, and NASA energy conversion technology in the form of an Advanced Stirling Converter. He has also published work in the domain of extra-terrestrial construction materials where the focus of this work was to design and carry out a process for synthesizing 'Martian concrete' using only materials abundant on Mars' surface and evaluate its physical properties to determine its suitability as a construction material.



Michael Barron is a Mechanical Technician at NASA's Glenn Research Center, where he has supported the Stirling Research Laboratory and the Fission Surface Power program. His work includes testbed design and assembly, component manufacturing, instrumentation, and the assembly of Advanced Stirling Converter systems. With more than 14 years of experience in the aerospace field, Barron began his career as a CAD Designer, progressing to Design Engineer and later serving as a College Preceptor before joining NASA. Beyond his professional work, Barron is deeply committed to STEM outreach, actively coaching and mentoring robotics teams and encouraging high school students to pursue careers in STEM fields.



Natasha Miller received her A.A.S. in Specialized Technology from the Pittsburg Institute of Aeronautics in 2014. She also obtained FAA certified Airframe and Powerplant licenses and received the Golden Wrench Award for mechanical aptitude. Her career at NASA's Glenn Research Center began in the Research Lab Mechanic Apprenticeship Program which she successfully completed in 2018, and afterwards obtained her Research Lab Mechanic Journeyman's License. Her current role is supporting the development of electric propulsion technology, and she has supported various GRC projects, including the Stirling Research Laboratory, for the past 11 years.