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Assembly, Integration, and Initial Test Results of a Stirling Radioisotope Power System Generator Testbed

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The Stirling Generator Testbed is an on-going effort to demonstrate performance, behaviors, and typical interfaces that would be present in a flight-like Stirling radioisotope power system. Design of the Testbed occurred over the past several years, with the acquisition of parts beginning in 2022. The assembly, integration and initial test campaign for the Testbed involved an array of steps and processes, culminating with the initial test results.

I. INTRODUCTION

A team at NASA's Glenn Research Center has initiated operation of a four-convertor Stirling Generator Testbed. The Testbed was conceived and designed in-house beginning in 2019[1] and began under the Dynamic Radioisotope Power System (DRPS) Project. (The Testbed was formerly referred to as the DRPS Testbed.) Following a rigorous design and analysis phase, the components were purchased and manufactured, and assembly began in 2022. The Stirling Generator Testbed assembly and integration process was completed in the beginning of 2023, prior to the initial testing effort. Four Stirling convertors were integrated into the Stirling Generator Testbed housing, along with the heat source, insulation, and other internal hardware components. Following the assembly process, the Testbed was integrated with the test stand, the test rack, and instrumentation to monitor performance. Initial testing of the Stirling Generator Testbed occurred in May of 2023, resulting in successful initial operation.

II. ASSEMBLY PROCESS

Assembly of the Stirling Generator Testbed was an involved process, requiring over two hundred steps that were completed over the course of about six months. The majority of the assembly time was spent sealing leak paths through two of the Stirling convertors, which will be discussed further. The planning for assembly was a thorough process with multiple peer reviews of the assembly sequence. A formal procedure was developed and thoroughly reviewed per rigorous quality management system requirements prior to the initiation of assembly, and the assembly process itself was documented throughout including notes, photographs, and measurements.

II.A. Heat Source Assembly

The heat source for the Stirling Generator Testbed was designed to simulate the thermal power output of either two or three general purpose heat source (GPHS) Step-2 modules, and the dimensions of the heat source are consistent with a stack of three GPHS blocks. The maximum power output of the heat source is 1,500 W, which is useful for thermally soaking the Testbed faster than simply setting the desired power output and waiting for steady state. The heat source was fabricated from graphite and eight Watlow Firerod cartridge heaters connected in parallel via nickel bus bars (see Figure 1). The heater cartridges and the lead wires were welded to the bus bars and the lead wires were insulated with ceramic beads. Prior to assembly of the heat source, the external faces of the graphite block were coated with a high emissivity coating to enhance the radiative heat transfer capability of those surfaces. Similarly, the graphite heat collector plates described later were also coated with the same high emissivity coating.

Fig. 1. Stirling Generator Testbed electrical heat source

II.B. Stirling Convertor Support Hardware

The Stirling Generator Testbed has the ability to accommodate different Stirling convertor designs. For this initial assembly, four Stirling convertors were installed in the Testbed: two Sunpower Advanced Stirling Convertor (ASC) units and two Infinia Stirling Radioisotope Generator Engineering Unit Stirling Convertor Assembly (SES) units. Per the design of the Stirling Generator Testbed, the CSAF is part of the pressure boundary of the system, similar to other flight-like dynamic radioisotope generator designs.[1] Due to the manufacturing details and design of the ASC units, these convertors required additional preparatory steps before installation into the Stirling Generator Testbed housing that would allow the cold side adapter flange (CSAF) to serve as part of the pressure boundary of the housing. The two leak paths were sealed, and the pressure boundary was tested prior to installation into the housing (see Figure 2). Leak paths on the ASC convertors originate from the assembly method used to attach the CSAF, and do not involve the internal working gas of the convertors. The CSAF was not designed to serve as a pressure boundary but was designed for the convenience of laboratory testing campaigns, therefore there are both bolts that go through the CSAF and a press-fit joint that are not suitable for a pressure boundary in a generator design. To alleviate this issue in future Stirling convertors, the CSAF should be designed and manufactured with the intention of serving as a pressure boundary for dynamic generator systems.

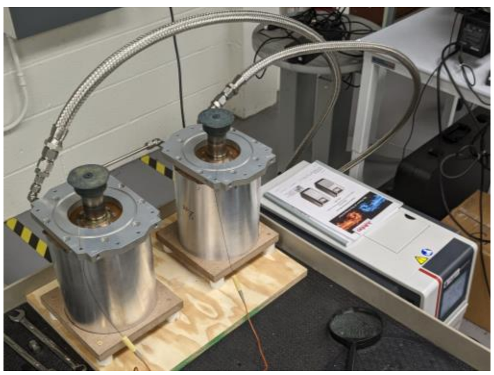

Fig. 2. ASC convertors in CSAF leak check setup

The housing of the Stirling Generator Testbed was designed to be axially symmetric, which resulted in the need for adapter plates to interface between the Stirling convertors and the housing. The adapter plates were the first support hardware integrated with the Stirling convertors, and the internal coolant loop in the adapter plates was used to heat the sealants on the CSAF interface of the ASC convertors.

Thermocouples (TC) were installed on each convertor to monitor the operating conditions. Three thermocouples were installed in each hot end and two in each cold end. These were potted in place and secured with quartz yarn (see Figure 3a). Next, the hot end, clam-shell insulation pieces were installed as shown in Figure 3b, and also secured with quartz yarn.

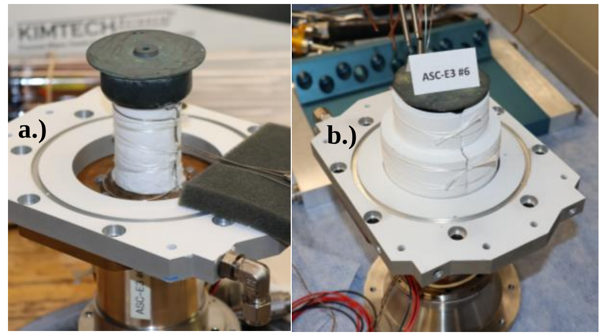

Fig. 3. a) ASC convertor with hot end and CSAF TCs installed. **b)** ASC convertor with clamshell insulation installed

II.C. Integration of Convertors and Heat Collectors

Once the Stirling convertors were integrated with all the support hardware, they were installed into the Testbed housing. Each convertor was installed individually via a plate mounted to the aft end of each convertor and lowered into the port on the housing using scissor jacks as shown in Figure 4.

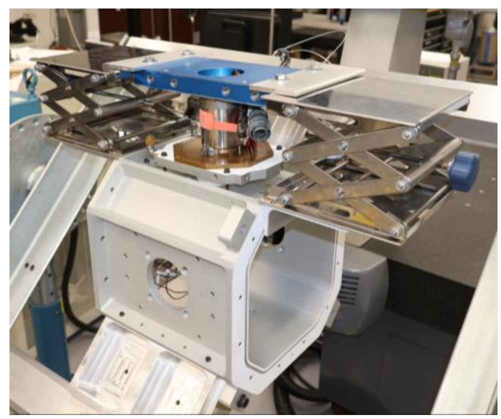

Fig. 4. Scissor jacks lowering convertor into housing

Once each convertor was lowered through their respective ports on the housing, the heat collector plates were installed on the hot ends of each convertor to expand the area of the hot end and provide improved radiant heat transfer between the heat source and the Stirling convertors. The heat collector plates were secured to the convertor hot ends via four draw rods and spring assemblies that provided about 100 pounds of force on each heat collector plate (see Figure 5). To ensure good thermal contact, a boron nitride coating was added at the conduction interface and at all other conductive heat transfer interfaces. An example of the white boron nitride coating can be seen on the surface of the adapter plates in Figure 3.

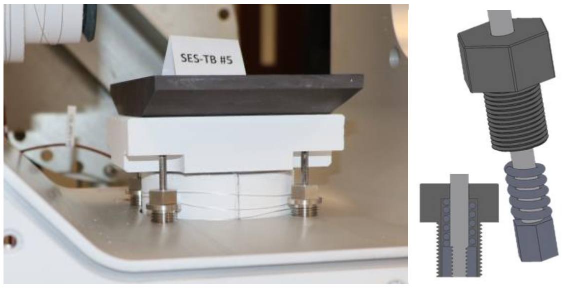

Fig. 5. Draw rod and heat collector plate installation and design

II.D. Installation of Heat Source and Insulation

Following the installation of all convertors and heat collector plates, the bottom layers of insulation were installed along with the bottom end cap of the Testbed. The Testbed was then rotated to access the top, and the leads for the thermocouples for each convertor were routed along the housing walls and secured with aluminum tape as shown in Figure 6a. Next, additional layers of the custom insulation were installed, bringing the insulation stack up to the top of the heat collector plates, followed by the bottom load stud with its insulation core as seen in Figure 6b.

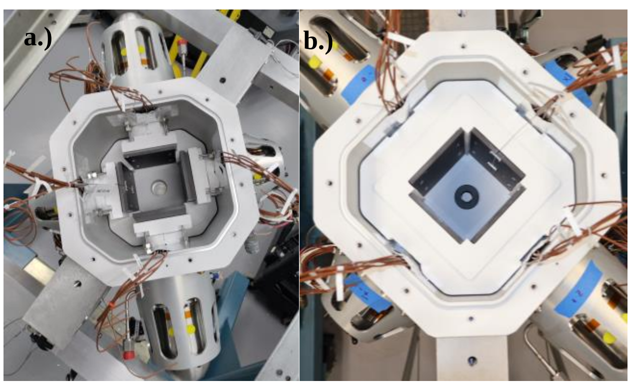

Fig. 6. a) Top-down view with lower layers of insulation installed and TCs routed along housing walls. **b)** Middle layers of insulation and bottom load stud installed.

A t-handle tool was used to lower the fully assembled heat source into place in the center of the Testbed via a threaded hole specifically machined into the top of the heat source for the purpose of assembly (see Figure 7). Next, the final layer of insulation was installed, followed by the top load stud.

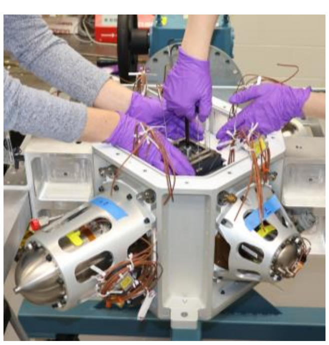

Fig. 7. Lowering the heat source into the housing

Springs were necessary to compress the insulation and provide supportive force to the heat source stack. A G-10 plate with spring cups and wave springs provided about five pounds of compressive force to the insulation stack as shown in Figure 8. For the heat source stack, a set of eight Belleville washers arranged in series within a spring cup with plunger provided about fifty-five pounds of force to stabilize the heat source, also shown in Figure 8.

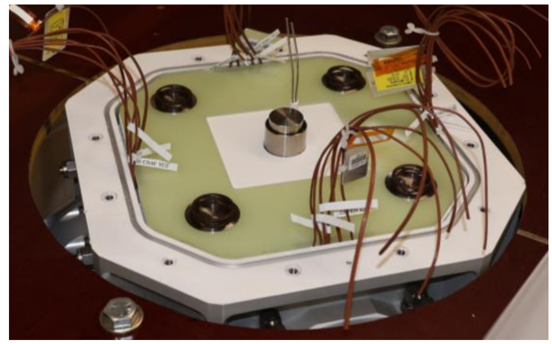

Fig. 8. Insulation springs and heat source load spring stack

II.E. Feedthrough Installation and Final Assembly

The final series of steps for the assembly of the Stirling Generator Testbed was to install the feedthroughs on the housing. A total of six feedthroughs transmit the thermocouple signals and electrical power for the heat source through the top end cap as shown in Figure 9b. Each of the five thermocouple feedthroughs accommodates five thermocouples, therefore one TC feedthrough was dedicated to each convertor for the hot end and CSAF thermocouples, and one for the four heat source TCs along with the one additional thermocouple which was mounted to one heat collector plate. Each feedthrough was soldered to the individual wires. All the wires were coiled up on top of the insulation stack and secured with Kapton tape as seen in Figure 9a, prior to each feedthrough being pulled through the top end cap and sealed via O-rings. The final assembly prior to transport to the test stand is shown below in Figure 10.

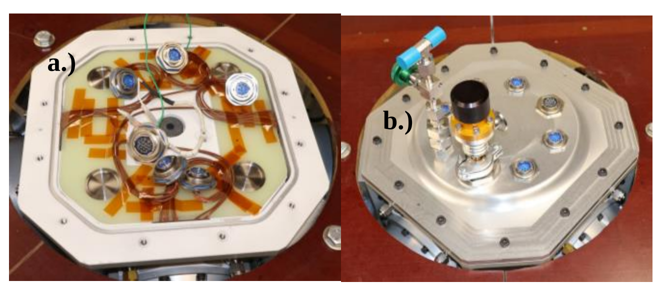

Fig. 9. a) Feedthroughs prior to end cap installation **b)** Top end cap installed with feedthroughs

Fig. 10. Final Testbed assembly prior to transfer to test stand

III. INTEGRATION ON THE TEST STAND

After the majority of assembly was complete, the Stirling Generator Testbed was weighed to determine the final as-built mass, then transferred to the test stand using an engine hoist and lift straps as shown in Figure 11a. The total mass of the Stirling Generator Testbed was 60.5 kilograms. The test stand (Figure 11b) consists of the test rack along with a large table with a custom designed isolation system that allows the Testbed to float in the x, y, and z-axes such that any vibration detected during testing operations is originating from the motion of the Stirling convertors. The test rack is a custom designed rack based on other racks currently used in the Stirling Research Laboratory (SRL). The test rack needed specific electrical and software design work to accommodate the sensors, data acquisition, and simultaneous control of four Stirling convertors because the standard rack design in the SRL is for either one or two convertors. Once on the test stand, the fins were installed, along with additional thermocouples and an accelerometer, and all the instrumentation and power cables were connected to the test rack. The accelerometer was mounted in the center of the top end cap to detect any movement in the x, y, and z-axes. The final completed assembly of the Stirling Generator Testbed integrated with the test stand is shown in Figure 12.

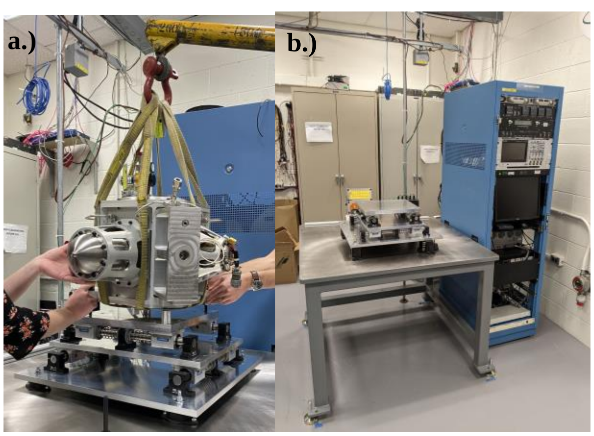

Fig. 11. a) Transfer of Testbed to testing stand. **b)** Test stand and test rack

Fig. 12. Final Testbed assembly integrated on test stand

IV. INITIAL TESTING

The initial test campaign for the Stirling Generator Testbed consisted of baseline operation of the Testbed for an attended 24-hour test at nominal conditions. The point is described below in Table I and corresponds to the electronic heat source simulating two GPHS blocks and the Stirling convertors operating at approximately half nominal power output. Running the Stirling convertors at half nominal power is representative of typical concepts of operation for potential missions using dynamic radioisotope power. When operating at the half power condition, a system containing four Stirling convertors (two pairs) can tolerate the failure of single pair of Stirling convertors and maintain the same output power to the spacecraft by throttling up the remaining pair of convertors. During the test, the heat source was set to a constant power output, and the convertors were throttled to maintain the hot end temperature. Cooling was provided solely by the radiator housing and fins, and sufficiently maintained the cold end of the convertors in ambient natural convection. The test was monitored via the test rack and a LabVIEW software package, similar to all the other test stations in the SRL where the testing took place. The initial baseline testing began on May 31, 2023.

TABLE I. Target Baseline Operating Condition

Heater Power Output, W, ±5	Convertor Hot End Temp., °C, ±2	Piston Amplitude, mm, ±0.01
500	500	*determined during test

V. RESULTS

The results from the initial baseline test are summarized in Table II. Note that the ASC-E3 convertors are pair one (1A and 1B), which are hermetic, gas bearing convertors and do not have sensors for measuring charge pressure. The SES convertors are pair two (2A and 2B), which are non-hermetic, flexure bearing units. Due to the graphite heat source and heat collector plates, the Stirling Generator Testbed must be operated with either a vacuum or positive pressure of inert gas as the interior environment. For this test, the housing was filled with a positive pressure of argon. Due to the large thermal mass of the Testbed, combined with the cooling mechanism of natural ambient convection, the temperatures recorded were drifting by about 3-5 degrees throughout the test execution.

TABLE II. Quasi-steady State Baseline Operation Point

Parameter	1A	1B	2A	2B	Units
Avg. Hot-End Temp.	501.5	497.9	496.4	497.4	°C
Avg. CSAF Temp.	62.0	63.4	69.4	68.0	°C
Avg PV Temp.	57.3	55.9	49.7	47.0	°C
Heat Collector Plate Temp.	545.7	-	-	-	°C
Piston Amplitude	2.8	2.9	3.6	3.6	mm
Alt. Power	22.8	23.3	19.2	19.0	W_e
Charge Pressure	-	-	348.8	347.0	psia
Frequency	101.3		78.4		Hz
Avg. Fin Root Temp.	54.6				°C
Avg. Fin Tip Temp.	48.3				°C
Ambient Temp.	25.5				°C
Avg. Heat Source Temp.	609.4				°C
Heater Power	500.8				W
Total Power Output	84.3				W_e
Gross Efficiency	16.8				%
Housing Pressure	23.3				psia

The test successfully demonstrated operation of Stirling convertors in a generator configuration with realistic thermal interfaces and sizing, which was the primary objective of the effort to design and build the Stirling Generator Testbed. The approximate specific power output of 1.4 W/kg is reasonable, considering that the Testbed was not designed to minimize mass, and proves feasibility of the target specific mass for dynamic generator flight designs. Optimized systems are anticipated to be between 2-3 W/kg. While the conversion efficiency was not available for this publication, the gross efficiency of about 17% is a significant improvement over thermoelectric power conversion systems, even prior to optimization of the operating point.

VI. CONCLUSION

The initial checkout testing of the Stirling Generator Testbed has been completed following the completed assembly process. The Testbed demonstrated the viability and performance potential of the multi-convertor topology with a central radiantly coupled heat source and passive cooling mechanisms. Current plans are to complete the remainder of the test campaign within the fiscal year. Future tests will include thermal loss testing to determine the net heat input and net efficiency of the Stirling Generator Testbed, failure mode testing with one stalled pair of convertors and the other pair operating at full power, as well as potential Stirling convertor controller testing.

NOMENCLATURE

ASC = *Advanced Stirling Convertor*
CSAF = *Cold Side Adapter Flange*
DRPS = *Dynamic Radioisotope Power System*
GPHS = *General Purpose Heat Source*
SES = *Stirling Radioisotope Generator Engineering Unit Stirling Convertor Assembly*
SRL = *Stirling Research Laboratory*
TC = *thermocouple*

ENDNOTES

Roles of co-authors:
Ernestina Wozniak – *lead designer and engineer for the Stirling Generator Testbed*
Salvatore Oriti – *project level and engineering oversight*
Natasha Jackson – *lead technician for Stirling Generator Testbed assembly and integration*
Dr. Tyler Steiner – *engineering support and author of the Stirling Generator Testbed assembly procedure and baseline operation test plan*

Special thank you to the rest of the Stirling Generator Testbed team.

REFERENCES

1. E. WOZNIAK, et. al., "Design of a Dynamic Radioisotope Power System Generator Testbed," NETS-2022, American Nuclear Society (2022).