

Advanced Stirling Radioisotope Generator Engineering Unit 2 (ASRG EU2) Final Assembly

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Abstract. NASA Glenn Research Center (GRC) has recently completed the assembly of a unique Stirling generator test article for laboratory experimentation. Under the Advanced Stirling Radioisotope Generator (ASRG) flight development contract, NASA GRC initiated a task to design and fabricate a flight-like generator for in-house testing. This test article was given the name ASRG Engineering Unit 2 (EU2) as it was effectively the second engineering unit to be built within the ASRG project. The intent of the test article was to duplicate Lockheed Martin's qualification unit ASRG design as much as possible to enable system-level tests not previously possible at GRC. After the cancellation of the ASRG flight development project, the decision was made to continue the EU2 build, and make use of a portion of the hardware from the flight development project. GRC and Lockheed Martin engineers collaborated to develop assembly procedures, leveraging the valuable knowledge gathered by Lockheed Martin during the ASRG development contract. The ASRG EU2 was then assembled per these procedures at GRC with Lockheed Martin engineers on site. The assembly was completed in August 2014. This paper details the components that were used for the assembly, and the assembly process itself.

Keywords: ASRG, Stirling, Radioisotope

BACKGROUND

During the Advanced Stirling Radioisotope Generator (ASRG) flight development project, the team decided to pursue development of a flight-like test article for ground testing in the Stirling Research Laboratory (SRL) at NASA Glenn Research Center (GRC). The goal of this test article was to achieve a system-like assembly of a Stirling convertor generator, rather than the more research-style test articles that had previously been implemented in the SRL, and achieve a test article that would enable system-level tests [1]. The most notable differences were: assembly of the convertors into a dual-opposed pair inside a flight-like housing that acted as the heat rejection device, a flight-like insulation package, and a flight-like controller. The previous method for implementing support hardware on Advanced Stirling Convertor (ASCs) was tailored for research and measurements of performance at the convertor level. As such, the support hardware did not resemble a flight configuration, as it was designed to facilitate installation, enable specialty temperature measurements of the insulation, and enable precise temperature control on the various convertor interfaces. A flight-like assembly permits measurement of performance at the system level. During the development of this flight-like configuration, it was given the name ASRG Engineering Unit 2 (EU2), since it effectively became the second engineering unit produced by the project. Engineering Unit 1 was built by Lockheed Martin, subsequently tested, and delivered to GRC in 2008. EU1 operated for 33,000 hours before a fault in convertor operation required its shutdown and disassembly [2].

The support hardware for ASC-E3 performance mapping is illustrated in FIGURE 1. Notice that it does not resemble the geometry of the flight Generator Housing Assembly (GHA). The performance mapping hardware utilizes a round housing, a cooling loop attached directly to the convertor's Cold-side Adapter Flange (CSAF), and a method for controlling the alternator housing surface temperature. The heat source was also made small and compact, and does not resemble the General Purpose Heat Source (GPHS) module. These design decisions were made to enable accurate modelling and instrumentation, such that the convertor performance could be accurately measured.

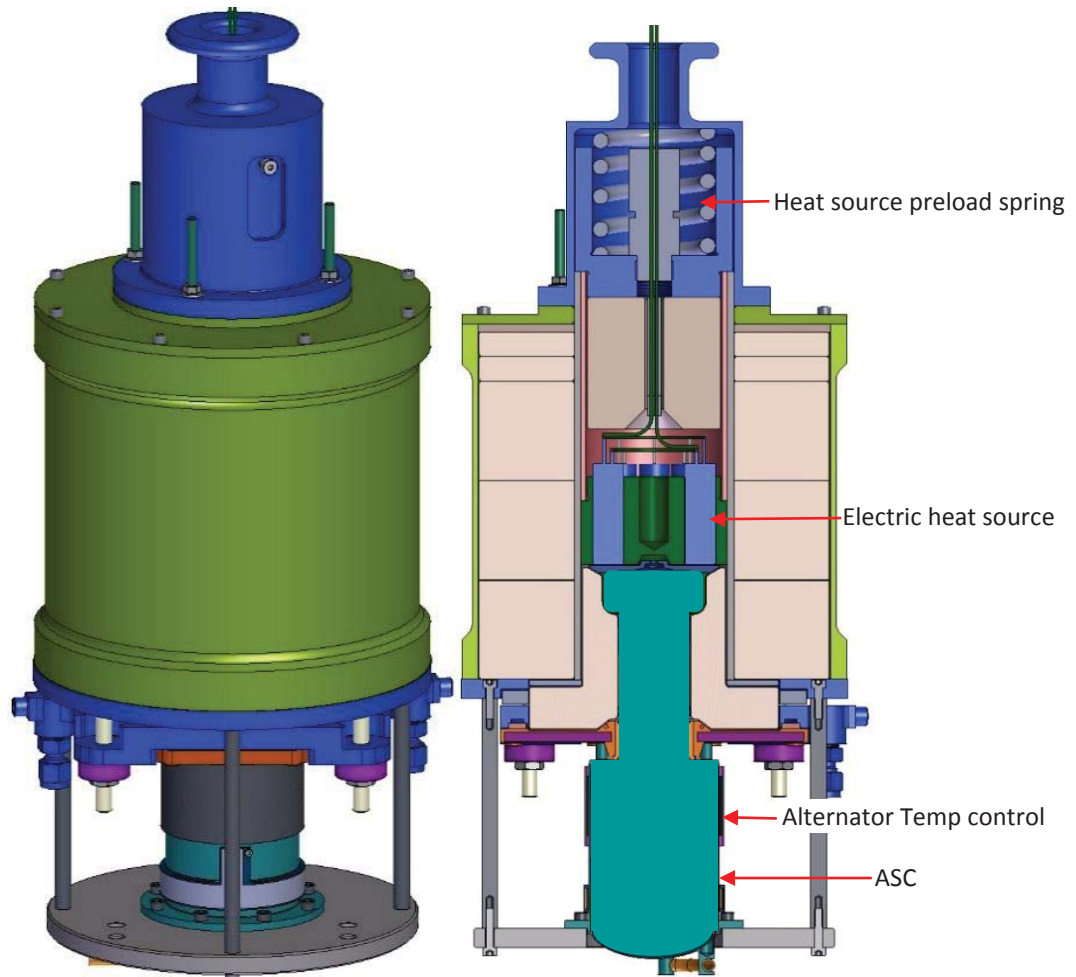


FIGURE 1. ASC-E3 Performance Mapping Support Hardware

The flight-like support hardware design is illustrated in FIGURE 2. Notice how it resembles the flight ASRG GHA. Deviations from the Lockheed Martin (LM) flight design were made to save cost, or adopt practices to improve extended operation. The differences from LM's flight design are highlighted in blue. Most notable is the use of aluminum for the housing material rather than beryllium. It was known from the initiation of the design effort that beryllium was not practical due to cost, lead time, and additional safety requirements. By way of quantification, the aluminum housing was fabricated for approximately \$50,000 with a lead time of 6 weeks, while a beryllium housing required approximately 1 year of fabrication time. The aluminum housing segments (inboard and outboard) were fabricated from a solid billet of 6061 aluminum. With this, the bulkhead to which the converters attach could be machined integral to the rest of the housing. This eliminated the need to braze the bulkhead piece into the housing, and the complexities associated with such an operation. This also made the critical heat rejection thermal pathway more reliable, as there is one less joint in the heat rejection path with an integral bulkhead feature. The thickness of all conduction pathways in the housing were increased to give the aluminum housing the same thermal resistance as the beryllium design. This was done by displacing only the outer surface of a thickness, so that the internal geometry and converter interfaces remained the same as the LM design. The electric heat source also diverged from the LM flight design. GRC opted to make use of heritage heat source design knowledge. The EU2 electric heat source is comprised of a block of molybdenum with cartridge heaters inserted in a circular array. This is in contrast to LM's electric heat source, which utilizes flat-disc Boralectric heaters in a graphite shell. Empirical data suggest the GRC design will have a life greater than 10,000 hours, as an effort was made to reduce the cartridge heater heat flux as much as possible. The EU2 design makes use a GRC-style heat source load stud. This machinable ceramic (Cotronics Rescor 902) has been used in the past for the heat source preload path, as it has good temperature capability, low thermal conductivity, and good strength at temperature. This load stud was designed to have the same thermal resistance as the LM load stud assembly.

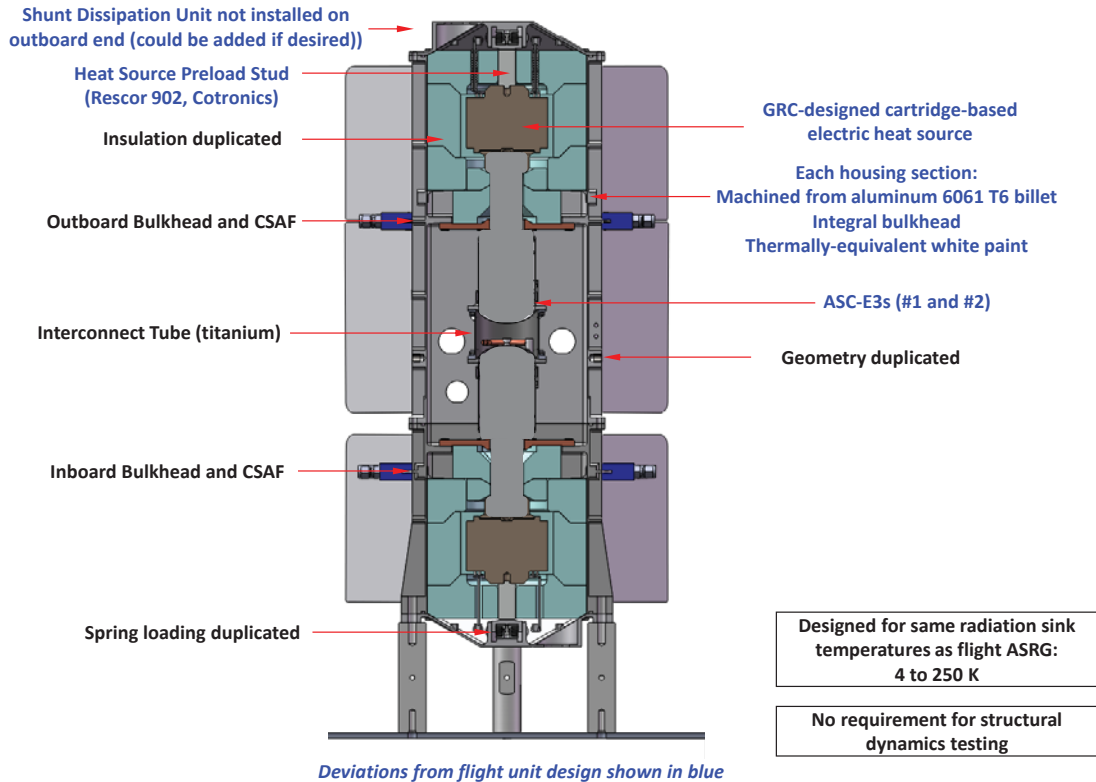


FIGURE 2. ASC Flight-like Support Hardware

ASC-E3 #1 and #2 were chosen for installation into the EU2. These convertors are the first pair of the ASC-E3 generation, which were being fabricated in parallel with the flight convertors (ASC-F). The ASC-E3s are the build closest to the flight design, and were the preferred choice for this effort. These convertors underwent the standard GRC set of tests including performance mapping [3], during which their performance was steady with no deviations from Sunpower's measurements prior to delivery. They were then reconfigured in a dual-opposed horizontal configuration for LM controller testing in Louisville, CO. The controller testing took place in February of 2014 [4]. The convertors were then returned to GRC in March 2014. A checkout test was performed upon their return to verify baseline performance. Following this, they were removed from their support hardware and the process of assembly into the EU2 began.

HARDWARE FROM LOCKHEED MARTIN

After the cancellation of the DOE flight development contract in October 2013, the decision was made to make use of some of the now-available LM hardware for assembly of EU2. At this point in time, the following items had already been procured and received by GRC:

- Inboard housing, Outboard housing, Housing end caps, Interconnect tube, Heat source spring load components, Heat source load stud, Insulation compression plate, Heat source components Electrical feedthroughs (Glenair)

The following items were transferred from LM to GRC for use on EU2:

- Convertor pair alignment fixture, GHA assembly fixture with Flotron, Convertor instrumentation and harnessing fixture, Hot-end thermal insulation (Microtherm), Insulation support brackets, Resistance Temperature Detector (RTD) mounting hardware (including specialty fasteners), RTD sensors, Accelerometers (internal), Accelerometer mounting brackets, Quartz yarn (unbaked), Various fasteners, for assembly

The availability of the LM's insulation and assembly fixtures greatly expedited the completion of EU2. GRC had previously designed fixtures to perform the convertor alignment and assembly into the housing, but these items were not fabricated.

ASSEMBLY SEQUENCE

Convertor alignment and pairing

The convertors (ASC-E3 #1 and #2) were first removed from their performance mapping support hardware. Only the affixed alternator and ASC Piston Sensor (APS) wires remained on the convertors. A joint GRC-LM procedure was developed to guide the convertor pairing process. The first step was to measure the housing geometry. Two housings have been built to date. Housing parts S/N 1 were used for EU2. The housing geometry was measured on May 13, 2014. The inboard and outboard housings were measured individually and a bulkhead-to-bulkhead distance was calculated by summing the distances between each housing's bulkhead and interface flange. The flatness of the bulkhead CSAF interface, the flatness of the interface flanges, and the parallelism between bulkhead and interface flange were also measured. Two trials of these measurements were made. The two trials agreed well, showing variances of only .0003 inches. The parallelism between the bulkhead and interface flanges was well within that required by the design.

The convertors were assembled into the convertor pair alignment fixture. The fixture was designed by LM to create two hole patterns in space that matched the CSAF mounting fastener patterns. This was achieved by using high-precision plates, guide rods, and linear bearings, similar to the techniques employed by the stamping industry (where alignment of dies is critical during up and down motion). Alignment pins were installed into the CSAF fastener holes to locate them in the patterns created by the plates. After the alignment plates were in place and properly engaging the CSAF alignment pins, the interconnect tube fasteners were then tightened, creating a dual-opposed pair assembly in which the CSAF mounting patterns were aligned in space. The upper alignment plate was then removed so that the CSAF flatness, parallelism, and distance could be measured using the Zeiss CMM (FIGURE 3). The convertors were installed such that the A convertor (inboard, ASC-E3 #1) was on the top, and the B convertor (outboard, ASC-E3 #2), was on the bottom.

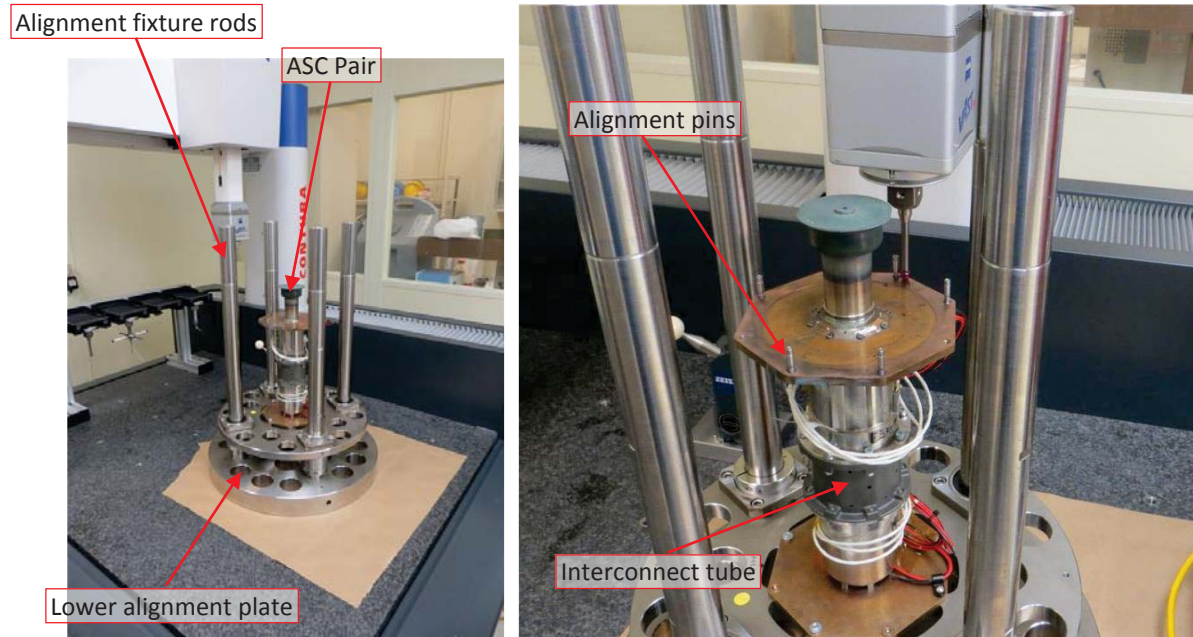


FIGURE 3. Measuring CSAF flatness, parallelism, and distance on CMM, with the convertors installed in the alignment fixture.

The CSAF-to-CSAF distance and parallelism were measured. The measurement data show that there was good parallelism between the CSAFs already, suggesting that a slanted trim cut of the interconnect tube would not be required. With these measurements, the required final geometry of the interconnect tube was calculated and represented in a dimensional drawing. The interconnect tube was cut such that the convertor pair CSAF-to-CSAF distance was .008 inches less than the bulkhead-to-bulkhead distance. The reason for the .008 gap is to make room for the thermal interface material (T-gon 805). The sheets of T-gon are .005-inches thick, so a zero-stress assembly would have the gap set at .010 inches. However, it was previously calculated that increasing the interconnect tube

length by .002 inches from the zero-stress state would most closely match thermal expansion forces to the LM flight design. Thus the CSAF-bulkhead assembly gap target was set at $.010 - .002 = .008$ inches. This required removing .084 inches from the machinable face of the interconnect tube.

The convertors and trimmed interconnect tube were then reinstalled into the alignment fixture in the same manner as the first iteration. The clocking of the convertors in the fixture, the clocking of the convertors relative to each other, and the clocking of the interconnect tube relative to the convertors was duplicated. The CSAF-to-CSAF distance, flatness, and parallelism was again measured, to observe if the target geometry had been achieved. The measurements showed that both the target CSAF-to-CSAF distance and parallelism had indeed been achieved. The interconnect tube thread inserts were then installed, and the interconnect tube was reinstalled into the stackup. The target geometry had been achieved, so the interconnect tube fasteners were tightened to their final installation torque. This marked the completion of the alignment and assembly of the two convertors. At this point the convertors were in their final paired attachment configuration.

Convertor Instrumentation

Another procedure was jointly developed by LM and GRC engineers for this stage of assembly. The convertor pair was removed from the alignment fixture and installed into LM's instrumentation and harnessing fixture. The purpose of this fixture is to provide a mounting for the convertors convenient for installation of the instrumentation, the first layer of hot-end insulation, and to position the electrical feedthroughs. The feedthroughs are located by the fixture's base plate, which has cutouts of the same shape and locations as those in the GHA, relative to the convertors. This allows the installer to route and trim instrumentation and power wires to the proper lengths before attaching to the feedthroughs.

The RTD hardware was installed to check its fit on the heater head (FIGURE 4). The circular band that goes around the heater head required a custom-fabricated spreader to fit it over the heater head diameter. The RTDs were then formed (using mandrels of appropriate diameter) so that their sheaths followed the desired path. The hot-end and CSAF thermocouples were then formed in a similar manner. Accelerometers were then installed onto their mounting brackets, one per convertor. After the temperature instrumentation leads were pre-formed in the vicinity of the heater head, the items were removed to make way for wrapping of the quartz yarn around the heater head. To accomplish this, the convertors were removed from the fixture and attached to an inboard housing section, which was set on a rotating base. This allowed us to rotate the convertors while the yarn was held taut. The resulting layer of quartz yarn was uniform and without compromise. When the wrap reached the collector, the loose end was staked down using high-temperature ceramic adhesive.

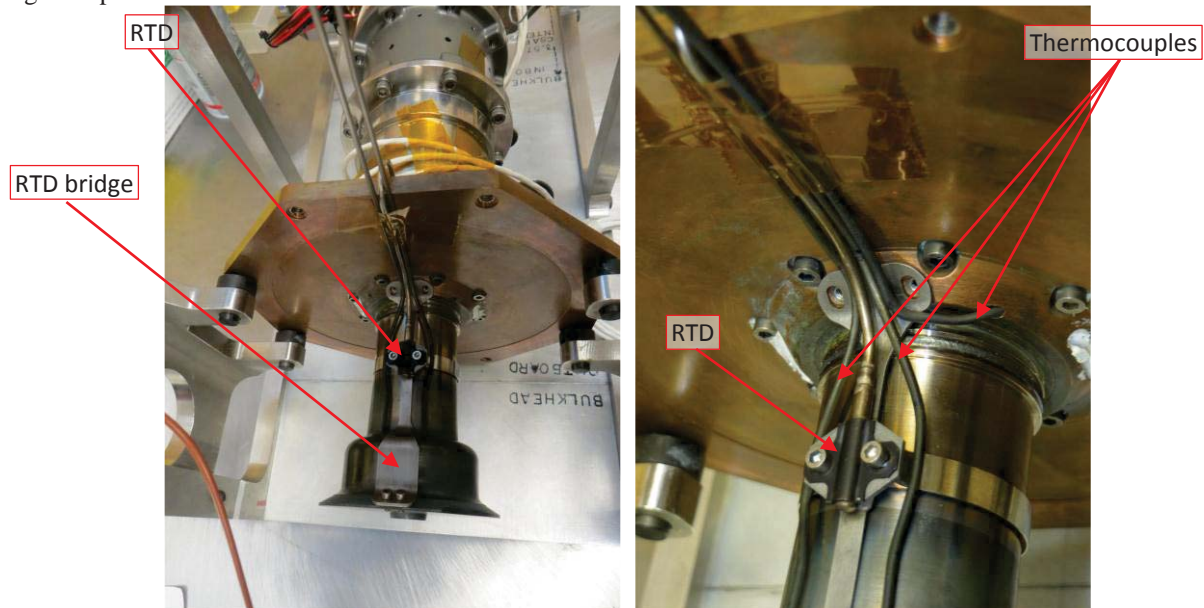


FIGURE 4. Fit check of RTD mounting hardware and forming of RTDs and thermocouples (TCs)

The RTD mounting hardware was then installed over the quartz yarn wrap. The convertors were returned to the horizontal instrumentation fixture. The hot-end thermocouples (TCs) were installed into the collector with nickel adhesive putty. The TC and RTD sheaths were staked to the face of the CSAF using a urethane potting compound. The transition of the RTD on the back side of the CSAF was also staked using urethane. Thermistors were installed into the CSAFs in an area near the CSAF TCs. The CSAF TCs and thermistors (TMs) were embedded in the CSAF features with the urethane potting compound. Thermistors were attached to the alternator housing with urethane and a layer of nickel foil over top of them. The completed instrumentation is shown in FIGURE 5.

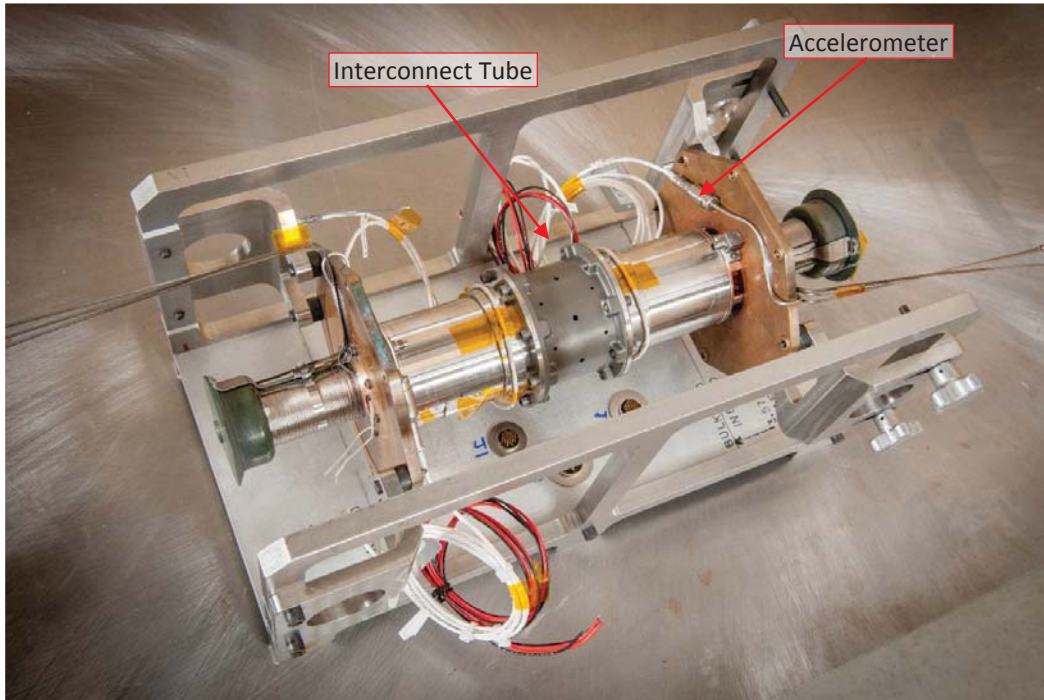


FIGURE 5. Instrumentation installation completed.

The convertor pair was then transported to a flight-qualified technician for completion of the wiring to the connectors. The wiring was completed on July 22, 2014 per LM drawings. This included routing and trimming of the wires, installation of sleeves over the wire bundles, and attachment of the lead wires to the appropriate connectors. A visual inspection of the wiring was completed, then the convertors were transported back to the SRL. A safe-to-mate procedure was completed on the connectors that had been attached at this point, and this check verified that all wires were attached properly. A layer of silica fiber blanket insulation was then fitted over the quartz yarn wrap around the heater head. The heater head microporous (Microtherm brand) insulation pieces were then modified to fit. The original design did not have sufficient clearance for the RTD attachment hardware. The channel in which the RTD and hot-end TCs reside was filled with silica fiber blanket insulation.

GHA Assembly

Once the instrumentation lead wires and heater head insulation were situated, the convertor pair was then placed onto the housing assembly fixture. The assembly fixture was the same used by LM during the ASRG flight development contract for the ASRG EU assembly. It consists of a rotatable holding fixture with a mounting plate designed to hold the GHA sections (FIGURE 6 left).

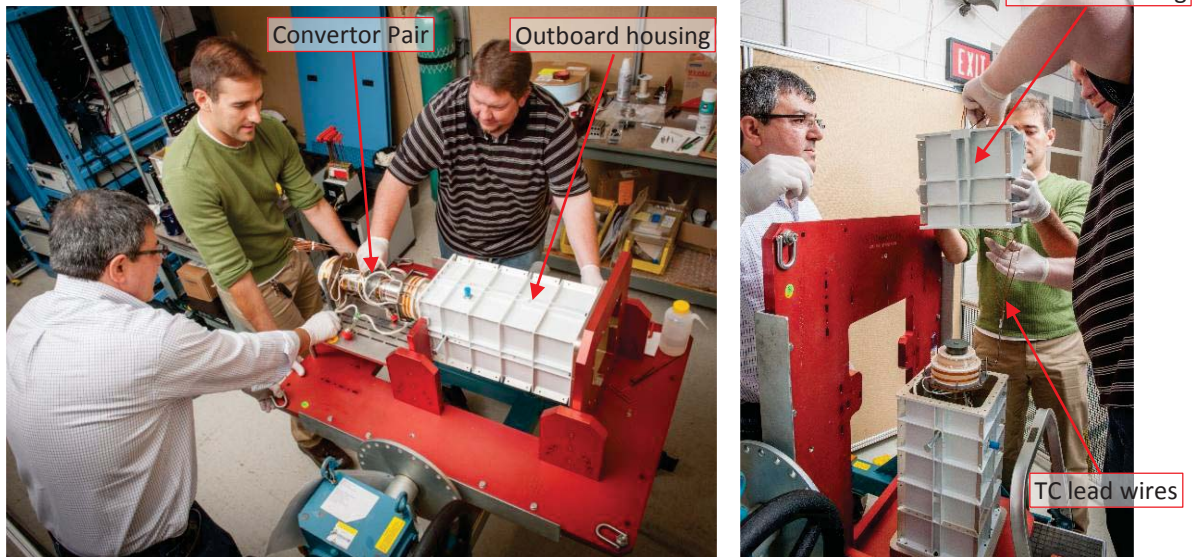


FIGURE 6. Converter pair situated for installation into the aluminum housing (left) and installation of inboard housing section (right).

Alignment pins were installed into the top two outboard CSAF thread inserts to position the converter pair when it would make contact with the housing’s bulkhead. The alignment pins were also used to hold the layer of graphite thermal interface material while the converter pair were slid into the outboard housing. As the converters were then slid into the outboard housing, one person was responsible for guiding the outboard converters’ heater head insulation through the bulkhead cutout as the converters moved into their final position. The CSAF attachment fasteners were then installed in the unoccupied threaded inserts to hold the CSAF against the bulkhead. The connectors were then pulled into their respective ports in the housing from the outside.

The assembly fixture was then rotated to place the converter pair vertically, with the inboard end facing upwards (FIGURE 6 right). Alignment pins were installed into the inboard converters’ CSAF thread inserts, and a layer of graphite thermal interface material was placed onto the CSAF. The inboard housing section was then lowered onto the inboard CSAF, with an o-ring placed between the housing sections. As the housing section was moved into position, the thermocouple leads of the inboard converter were pulled through the housing. The inboard CSAF fasteners were then installed after removing the alignment pins. The housing interface flange fasteners were then installed to fasten the two sections together (inboard to outboard).

The electric heat source, insulation pieces, and load stud were then installed into the inboard side of the GHA (FIGURE 7). This insulation came from the LM flight contract inventory. They are the same parts that were intended for use on LM’s qualification unit ASRG. A thin disc of alumina was placed between the heat collector of the converter and the molybdenum electric heat source. It was later discovered that this interface did not perform well under vacuum, and the disc will be replaced with a piece of graphite later. The molybdenum heater blocks had undergone an oxidation step so that their surface emissivity would closely match that of a GPHS. It was discovered during heater build checkout testing that the oxide layer sublimates quickly at the temperature of use, which would introduce a contaminant inside the GHA. The oxide layer was thus removed from the majority of the surfaces via a sand-blasting operation. Thus the EU2 heat source emissivity is lower than that of a GPHS. Estimates of the effect on heat transfer were made, and these suggested the overall heat loss from the heat source would only change by 1 watt. The heat source was designed to have only two thin wires for electrical power protruding through the insulation. They can be seen in the right image of the figure.

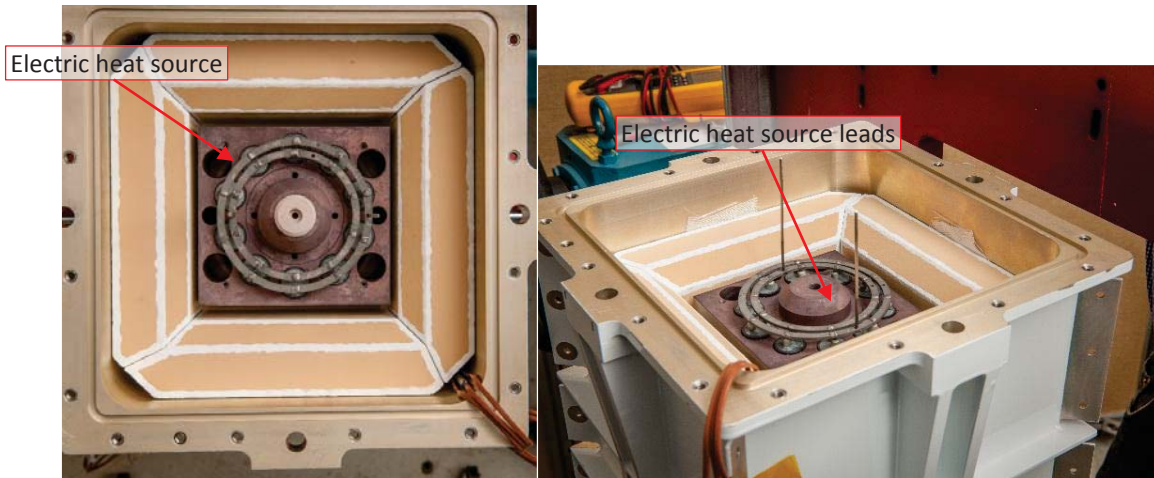


FIGURE 7. Installation of inboard housing section.

The cap piece of insulation was then placed over the heat source (FIGURE 8 left). The insulation compression plate was then placed onto the cap piece of insulation. A layer of quartz cloth was placed under the plate such that the housing end cap would compress the insulation stack the desired amount and hold it in place. This is of particular importance for launch vibration, but there are no plans to expose EU2 to a vibration environment test. After the compression plate was in place, heat source thermocouples were inserted through holes in the insulation cap piece and into blind wells in the heat source block. The thermocouple sheaths and lead wires were then formed to the desired path, and tied down to the compression plate with lacing cord. Thermocouple lead wires were trimmed to the proper length and then soldered to the feedthrough. A short harness was made to connect the two heat source lead wires to the heater power feedthrough. The heat source preload spring stack was placed onto the preload stud. The spring stack consists of a set of Belleville washers sitting in a cup that rests on top of the load stud. Prior to this activity, each spring stack assembly characterized determine its overall stiffness. The preload force between the heat source and ASC heat collector must be set to a particular value. The design of the ASRG permits adjustment of the spring stack compression via installation of shims of various thickness under the spring stack within the cup. With the knowledge of the spring stack stiffness and a measurement of the as-assembled geometry, the required shim thickness was calculated. The inboard housing end cap was then installed. The fasteners were then tightened down in an alternating side-to-side fashion, while alignment pins were in place to position the end cap relative to the inboard housing (FIGURE 8 right). The action of tightening down the end cap fasteners is what compresses the heat source spring stack.

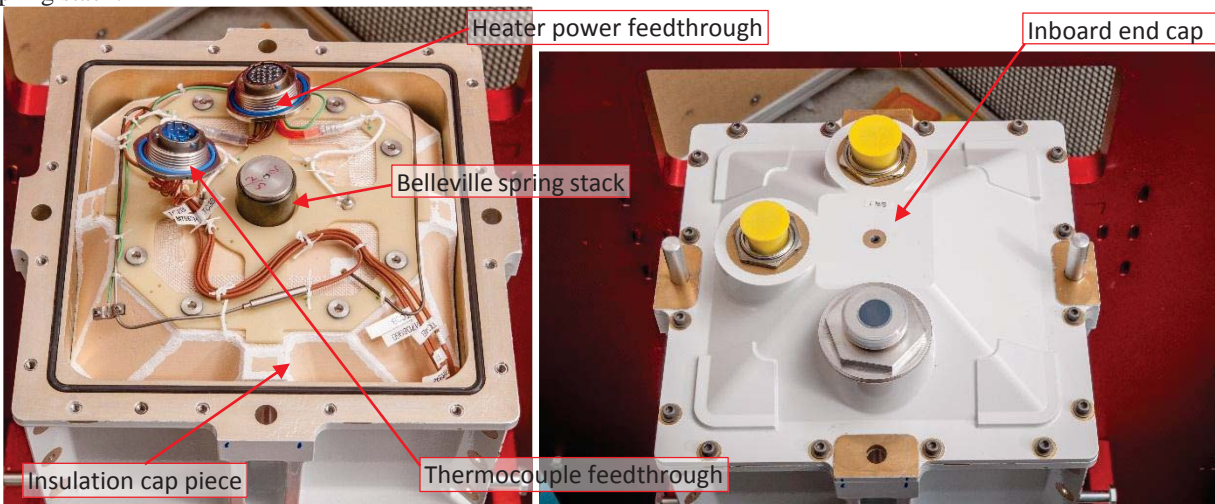


FIGURE 8. Installation of insulation end cap piece, and routing of TC wires.

The fixture was then rotated to place the outboard convertor upwards. The same steps for heat source, insulation, and feedthrough installation were repeated for the outboard convertor. The GHA was then removed from the rotating

assembly fixture and installed on the test stand (FIGURE 9). The GHA was installed on four standoffs. Load cells were previously installed between the standoffs and the table. These permit measurement of the mounting interface transmitted force. With this, tests can be conducted to evaluate methods to minimize residual vibration of the converters. An argon supply system was implemented at the test station and connected to the gas port on the front of the GHA. A port was integrated into the end cap designs, onto which a vacuum valve is installed. These ports can be used to evacuate the gas volume from within the GHA. The microporous insulation operates more efficiently when gas is removed. Cooling blocks were attached to the ribs of the housing that coincide with the bulkhead locations. These can be used to adjust the rejection temperature of the converters. This permits a wide range of testable operating conditions for the GHA.

Lockheed Martin's controller ASC Controller Unit (ACU) Engineering Development Unit (EDU) 4.0 was delivered to GRC on August 27, 2014. The ACU was then installed into the test rack and connected to the subsystems of the test stand.

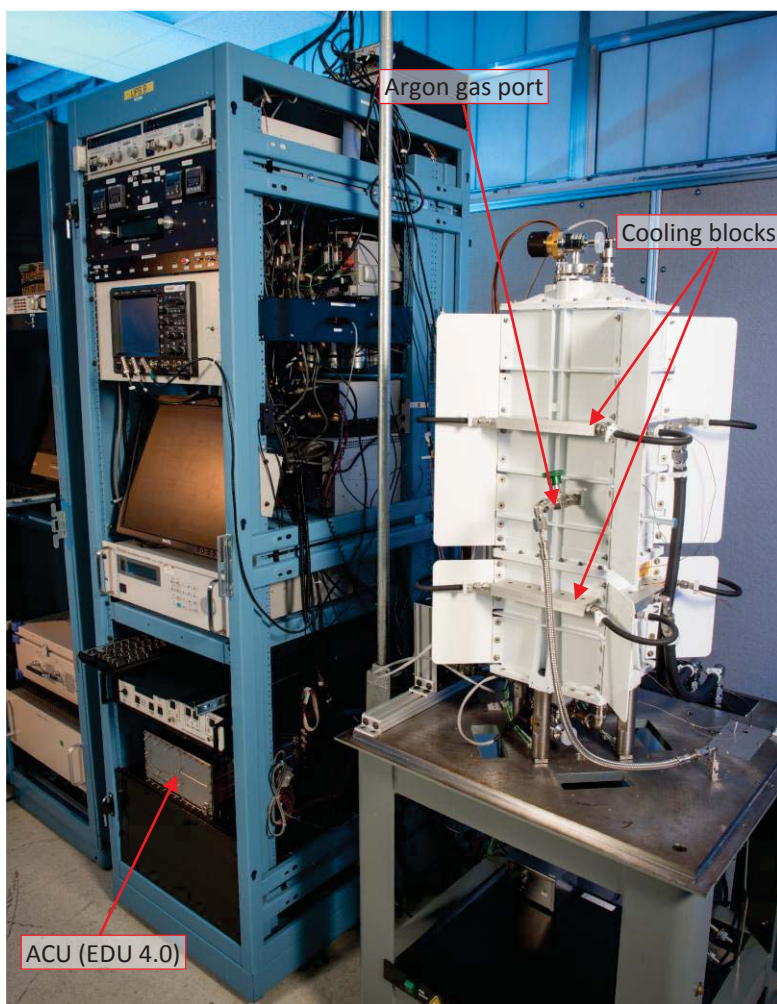


FIGURE 9. EU2 GHA installed on test stand.

CONCLUSION

A unique Stirling convertor test article has been assembled at NASA GRC. The test article is a flight-like configuration that thermally behaves in the same way as the flight ASRG design. The build process made use of Lockheed Martin hardware that became available after cancellation of the ASRG flight development project. NASA GRC and Lockheed Martin Valley Forge engineers collaborated to develop procedures for the assembly process. The assembly process consisted of steps to align the two converters, install instrumentation, and align/install the converters into the housing. The assembly task was fully successful and the test article was ready for operation in August 2014.

NOMENCLATURE

APS	= ASC Piston Sensor
ACU	= ASC Controller Unit
ASC	= Advanced Stirling Convertor
ASC-E3	= Advanced Stirling Convertor model E3
ASRG	= Advanced Stirling Radioisotope Generator
CMM	= Coordinate Measuring Machine
CSAF	= Cold-Side Adapter Flange
EDU	= Engineering Development Unit
EU2	= Engineering Unit 2
GHA	= Generator Housing Assembly
GRC	= Glenn Research Center
GPHS	= General Purpose Heat Source
LM	= Lockheed Martin
RTD	= Resistance Temperature Detector
TC	= Thermocouple
TM	= Thermistor

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