



Performance Measurement of Advanced Stirling Convertors (ASC-E3)

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Abstract

NASA Glenn Research Center has been supporting development of the Advanced Stirling Radioisotope Generator (ASRG) since 2006. A key element of the ASRG project is providing life, reliability, and performance data for the Advanced Stirling Convertor (ASC). The latest version of the ASC (ASC–E3, to represent the third cycle of engineering model test hardware) is of a design identical to the forthcoming flight convertors. For this generation of hardware, a joint Sunpower, Inc., and Glenn effort was initiated to improve and standardize the test support hardware. After this effort was completed, the first pair of ASC–E3 units was produced by Sunpower and then delivered to Glenn in December 2012. Glenn has begun operation of these units, including performance verification, which examined the data from various tests to validate the convertor performance to the product specification. Other tests included detailed performance mapping that encompassed the wide range of operating conditions that will exist during a mission. These convertors will be transferred to Lockheed Martin for controller checkout testing. The results of this latest convertor performance verification activity are summarized in this paper.

Nomenclature

AC	alternating current
ASC	Advanced Stirling Convertor
ASRG	Advanced Stirling Radioisotope Generator
BOM	beginning of mission
DOE	Department of Energy
EOM	end of mission
EU	engineering unit
GPHS	General Purpose Heat Source
IV&V	independent verification and validation
LMSS	Lockheed Martin Space Systems
LR	low rejection
HR	high rejection
SRL	Stirling Research Laboratory

Introduction

The Thermal Energy Conversion Branch at NASA Glenn Research Center has been supporting the development of the Advanced Stirling Radioisotope Generator (ASRG). The ASRG (Figure 1) was identified for use on two of the three candidate Discovery 12 missions (Ref. 1). A key element of the ASRG project is providing life, reliability, and performance data for Sunpower's Advanced Stirling Convertor (ASC). For this purpose, NASA Glenn has established a laboratory that is conducting extended operation of several ASCs (Ref. 2). The goal of this effort is to generate performance data over a sufficiently long period of time (tens of thousands of hours) to support probabilistic reliability analyses. As of May 2013, a total of 269 000 hr have been accumulated on 27 convertors. This hardware set spans the history of Sunpower's ASC technology development, and includes developmental units (ASC–0s),

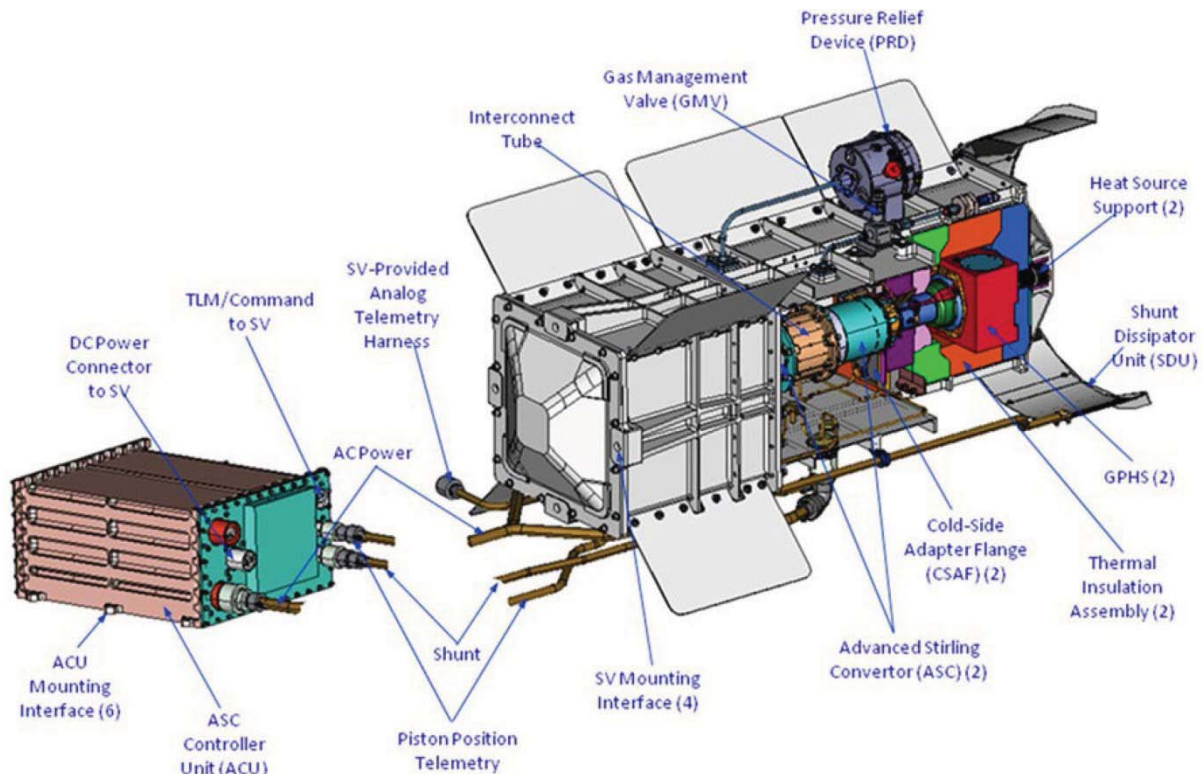


Figure 1.—Advanced Stirling Radioisotope Generator (ASRG) flight unit. (Image courtesy of Lockheed Martin Space Systems Corp.)

engineering units (ASC-Es and ASC-E2s), and the most recent ASC-E3s. Other facets of the Glenn test include independent measurement of the convertor's performance to its specification, and durability tests on ASC-E2s to demonstrate margin in the convertor design.

The latest set of hardware, ASC-E3, are being produced to the flight unit drawings and quality practices, and as such will exercise the fabrication process planned for the ASRG flight unit convertors. With this, the ASC-E3s are the most flightlike units that have ever been put on test. However, they will not be installed in a qualification or flight generator. The E3 design represents the culmination of the ASC development effort. It includes design features such as hermetic sealing, a lower current alternator, and the capability for a hot-end operating temperature up to 850 °C. A total of eight ASC-E3s are planned to be built. The first pair, ASC-E3 #1 and #2 were delivered to Glenn in November 2012. The remaining units are at various stages of the fabrication process. The Glenn test sequence for E3 operation consists of four stages: (1) Receipt/Inspection/Installation, (2) Insulation Loss Characterization, (3) Performance Mapping, and (4) Extended Operation. The receipt stage consists of a procedure to inspect the shipment and set up the convertors on the test stand. The insulation loss stage consists of a test to calibrate the thermal losses through the insulation package, and enable calculation of net heat input. The independent verification of convertor performance occurs during the performance mapping stage. During this test, the convertors are operated at the points contained in the ASC product specification. Prior to delivery, Sunpower also measured performance at these points. AS-E3 #1 and #2 have completed the first three stages of this sequence. These units were earmarked for controller checkout testing at Lockheed Martin. Following the controller testing, the convertors will be returned to Glenn and then begin extended operation. Extended operation will consist of continuous operation to achieve the aforementioned runtime in support of reliability analyses. Accumulation of operating hours on ASC-E3 units is most important, as these are most representative of the ASCs that will be used in the flight generator.

Test Methodology

The goal of the Glenn testing effort is to provide convertor performance data, both for product verification and demonstration of dynamic conversion for space applications. The Stirling Research Laboratory (SRL) at Glenn serves this purpose. The SRL came into existence in 2000 and has been evolving and adapting to the project needs ever since. The lab currently consists of 15 test stations each capable of operating a pair of convertors. A typical test station is shown in Figure 2. One of these test stations includes a thermal vacuum facility for space-like environmental testing. Each test station includes data system software capable of monitoring all convertor operating parameters. The software includes autonomous functionality, and can safely shut down operation should an alarm condition arise. Hardware safeties are also in place, should the software malfunction.

An overall schematic for convertor operation is also shown in Figure 2. The purpose of the test support hardware is to achieve the wide range of operating conditions that a convertor might experience during a mission. An electric heat source is used to simulate the thermal energy input of radioisotope fuel. An electric heat source was chosen because the gross thermal energy input can be measured easily. The heat source is pressed against the convertor with a spring and the preload is adjusted to match the flight unit design. The cold end of the convertor is controlled with a fluid loop and a heat exchanger attached directly to the rejection flange of the convertor. In the flight generator, the convertor rejects heat to the housing of the generator which acts as a radiator. Thus, in flight the cold-end temperature of the convertor is a function of the environment of the mission. With a fluid loop, the convertor cold-end temperature can be manually controlled. The power output from the convertor's alternator is taken from two feedthroughs.

The details of the convertor instrumentation can be found in Figure 3. This is the scheme used to measure convertor performance. The heat input to the convertor is controlled by a feedback loop. Either hot-end temperature or gross heat input can be used as the feedback variable. Hot-end temperature control allows the user to achieve a desired temperature quickly. However, the radioisotope fuel is a constant thermal power source that degrades according to its half-life. When performance points are recorded, the

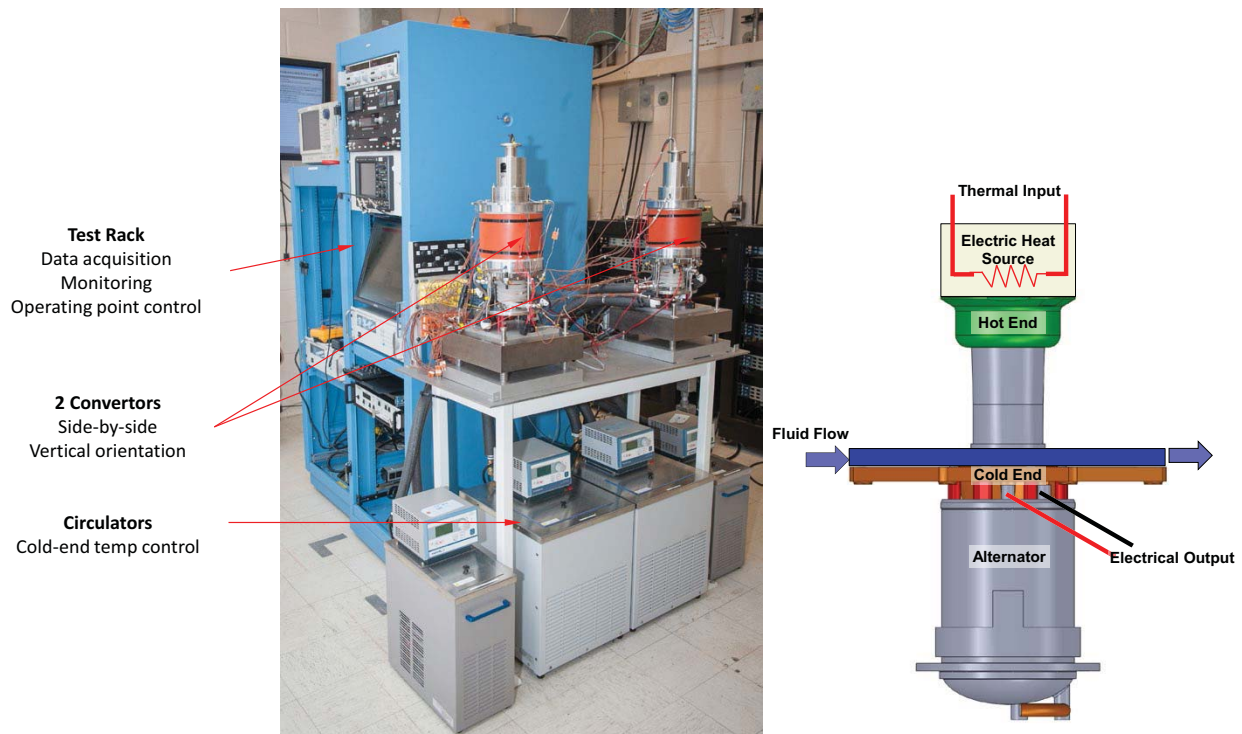


Figure 2.—Typical Stirling Research Laboratory (SRL) test station for a pair of Advanced Stirling Convertor (ASC-E3s).

hot-end control mode is transitioned to constant heater power to make the operating point as flightlike as possible. The power into the electric heat source is measured by a power meter, which also measures heater voltage and current. The voltage measurement point is taken as close to the convertor as possible. This is done so that line losses between the power supply and heater are not counted as thermal input into the system. Key temperature measurements are made at four points: heat source, hot end, cold end, and alternator. The heat source and hot-end temperature measurements are made using thermocouple probes. The cold-end and alternator housing temperature measurements are made with thermocouple probes and thermistors. The net heat input is a calculation based on analysis. It is a function of the gross thermal input and the operating temperatures. The insulation package thermal losses are calibrated during the aforementioned insulation loss characterization test. The process for correlation insulation losses to the test article temperatures is documented in previous publications by Wilson (Ref. 3). Stable operation of the convertor is maintained by connection of the alternator to an alternating current (AC) bus. The AC bus consists of a tuning capacitor, a load resistor, and an AC power supply in parallel with the resistor. This method permits simultaneous control of the convertor's piston amplitude and frequency of operation. The power output of the convertor is measured using a power meter, which also reports voltage, current, and power factor. The voltage measurement point is made as close to the convertor feedthroughs as possible so as to not count the lead wire losses. The alternator current measurement is made with a Pearson coil. This is most useful during regular power meter calibration, since the power meter may be removed and replaced without disturbing the alternator power path. The piston motion is monitored by a position

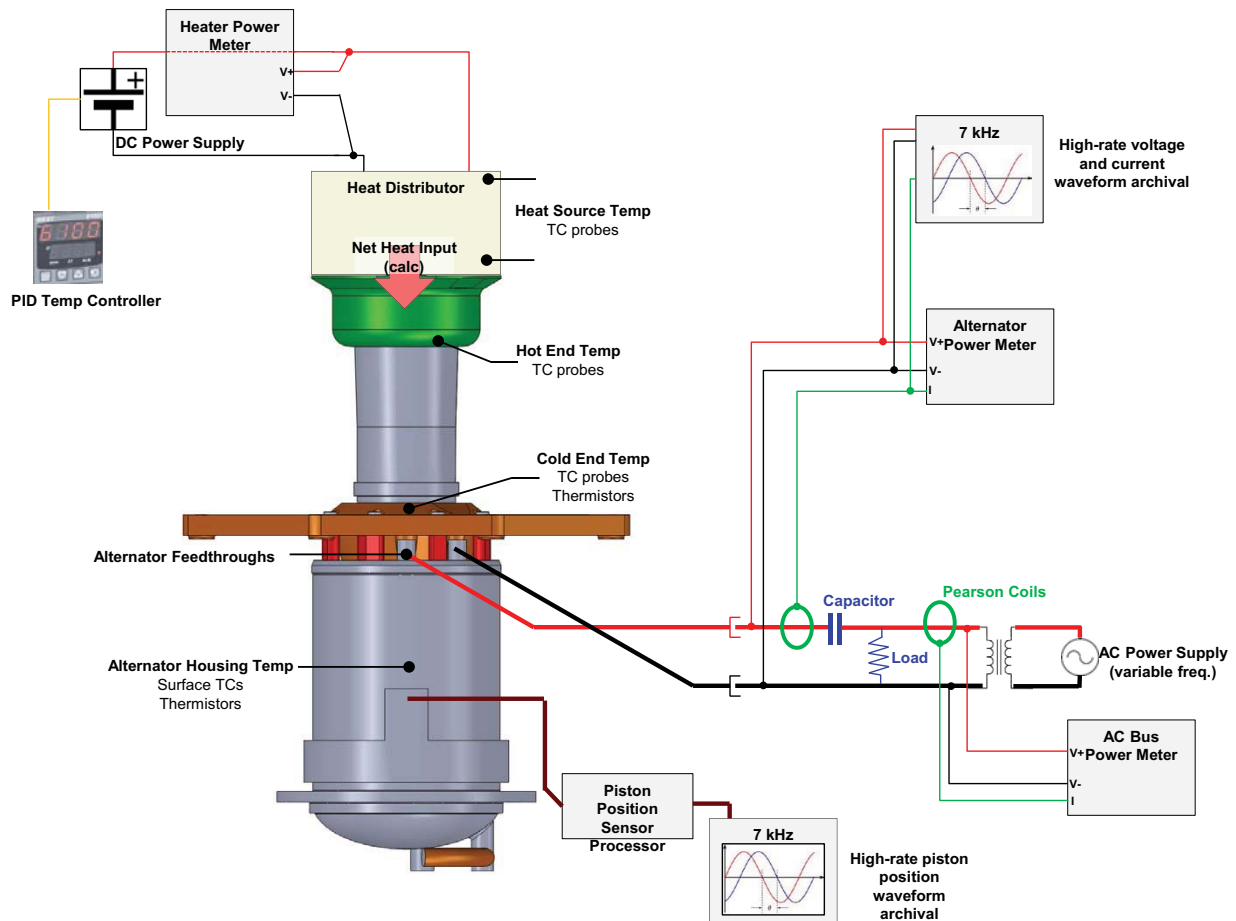


Figure 3.—Advanced Stirling Converter (ASC-E3) instrumentation scheme.

sensor capable of resolving the 100 Hz motion. The analog waveform from this sensor is used to calculate piston amplitude and operating frequency. The data system is also capable of high frequency (7-kHz) storage of the dynamic data. The alternator voltage, alternator current, accelerometer, and piston position sensor waveforms can be stored continuously for analysis later.

Improvements for E3 Test Support Hardware

Previous test support hardware designs were found to be lacking in certain areas. The measurement of the convertor performance is largely dependent on the support equipment. For example, a different insulation package would alter the thermal losses from the hot end and require a new analysis to calculate net heat input. Net heat input is the most critical parameter for validating convertor performance, as it is part of the net conversion efficiency metric. In the past, such as during ASC-E2 testing, the convertor performance was measured at Sunpower and later Glenn, but with different support hardware. Discrepancies as large as 7.7 percent existed that were attributed to the differences in the support hardware. To address this, an effort was initiated in November 2011 to develop a common design for the test support hardware. With this, the convertor would undergo final performance verification at Sunpower, then be delivered to Glenn without removing this support hardware. Glenn could then execute their independent performance measurement using the same hardware, with reduced chance of discrepancy.

This opportunity was also used to improve several deficiencies in both the Sunpower and Glenn E2 support hardware. These deficiencies are illustrated in Figure 4. Most notable was the relatively high amount of insulation losses. This was due to the type of cartridges used in the E2 electric heat source. These cartridges required a cooler temperature at their lead wire end, so they needed to protrude through the insulation. This introduced high conduction losses that needed to be accounted for via insulation loss characterization and the subsequent analysis. The E2 support hardware was designed to aesthetically resemble the ASRG flight design. As such it was square and of similar size. This made the geometry nonaxisymmetric, which was undesirable for the thermal modeling. It also introduced air gaps between insulation segments, which were also difficult to model. All these factors introduced uncertainty in the net heat input calculation, thus possibly corrupting the measurement of convertor net efficiency. These undesirable traits existed in similar form in Sunpower's support hardware design.

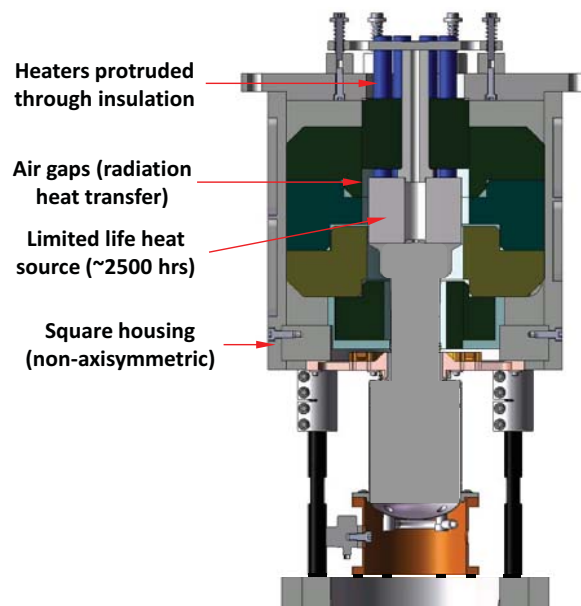


Figure 4.—Advanced Stirling Convertor (ASC-E2)
Glenn support hardware deficiencies.

The E3 support hardware design effort moved forward with the goal of resolving these deficiencies, and achieving a common design that would accommodate both Sunpower’s and Glenn’s test sequences. Figure 5 illustrates the final common hardware design for ASC–E3s. The form factor was made circular for axisymmetric finite element modeling. The insulation segments were designed to eliminate line-of-sight gaps. A layer of compressible insulation was used as a “gap filler” where spaces were not filled by the solid insulation. The heat source was revised to minimize parasitic conduction losses, as well as improve life. The conduction losses were reduced by changing the cartridge type to a unit that can reside entirely inside the insulation package. A method for connecting the cartridges in parallel was developed, so that only two main leads exited through the insulation. This alone reduced the insulation losses by about 50 percent when compared to the E2-style heat source. The life of the heat source was improved relative to the E2 version. The cartridges were designed with more contact area to reduce heat flux. They were also procured with a centerless-ground outer diameter option. The pockets in the nickel block of the heat source were accurately bored to match the cartridge diameter, giving a better fit than those of the E2 heat source. These design features were implemented to reduce the heat flux through the cartridge and maximize the thermal conductance from the cartridge. These parameters are most closely coupled to the heater life as they work to minimize the element temperature.

Additional instrumentation was also integrated into the E3 support hardware design that did not exist in the E2 hardware. The thermal modeling effort necessary for calculating net heat input relies on a multitude of temperature measurements throughout the insulation package. During the E2 test effort, these thermocouples were added after test hardware was assembled, and the placement was inaccurate and sometimes undesirable. Provisions for these thermocouples were included from the beginning of the E3 support hardware design effort. An example of these auxiliary thermocouples is shown in Figure 6. The number and placement of the thermocouples was decided based on the previous modeling effort undertaken during E2 testing. These measurements provide the critical boundary conditions that are used

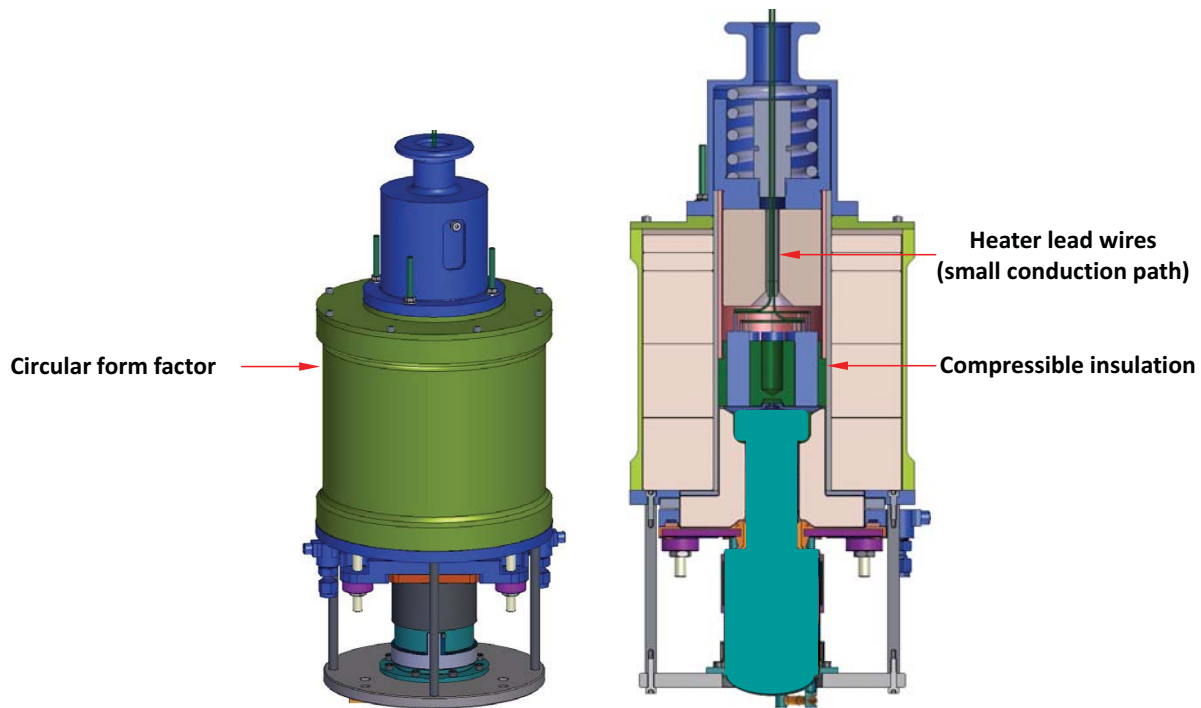


Figure 5.—ASC–E3 support hardware improvements relative to E2 design.

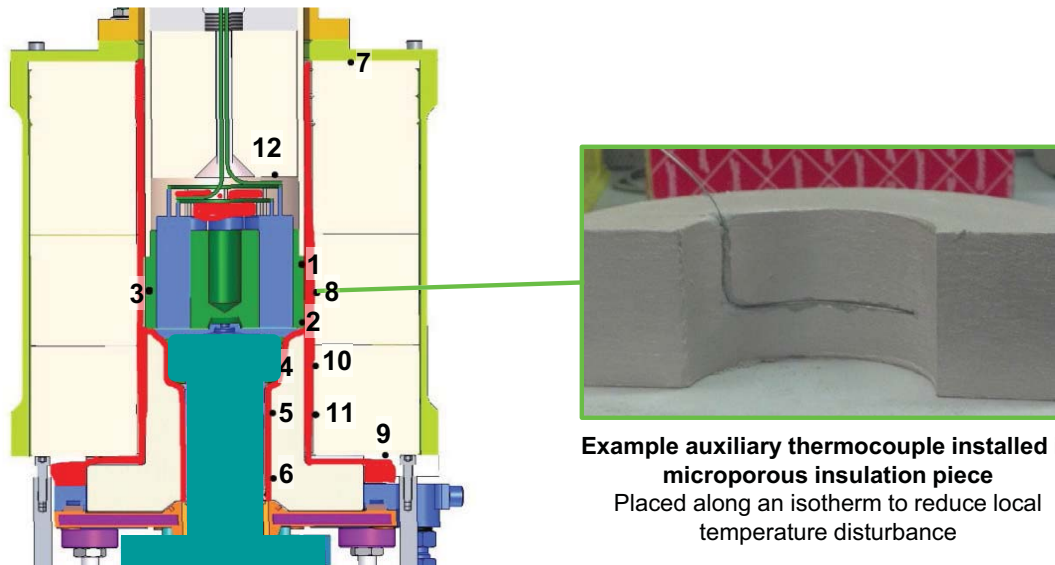


Figure 6.—Auxiliary thermocouple placement in Advanced Stirling Converter (ASC-E3) insulation package.

in the finite element model for calculating net heat input. The thermocouples were embedded at the desired locations in the insulation prior to assembly. They were routed along the isotherm for a large portion of their length. This is a commonly used method to retrieve the most accurate temperature reading, as the conductance of the probe does not corrupt the temperature measurement if it resides along an isotherm. The insulation package was designed in such a way that the assembly sequence would permit filling of all the voids with the “gap-filling” insulation.

Data Archival and Processing

The data system of the E3 test stations comprises all the knowledge learned over the past decade of SRL operation. A schematic of the data collection and processing method is shown in Figure 7. Each test station is connected via Ethernet to a central data server. The previously described performance measurements are made by the instruments in the test rack. The data system software handles all the communication to the various instruments, and devices in the test rack. The software also performs calculations based on the measured parameters. Examples of calculated parameters include net heat input, heater resistance, or piston amplitude. The data system also has functionality for an “electronic event log.” The user may enter a comment as operation is progressing. The data system automatically timestamps the entry and stores it in a local database on the test rack.

There are three rates for data storage: 2-sec 5-min averages and dynamic data (7 kHz). The 2-sec data consists of measurements recorded once every 2-sec window. A rolling cache of 2-sec data is stored on the test rack computer in a database. The data system software also creates a 5-min average of the 2-sec data at a rate specified by the user. By default, a 5-min-average data point is recorded once per hour. The 5-min-average points are stored locally on the test rack computer in a file. Each new point is appended to the file. Each day, an automated program on the data server copies the previous 24-hr of 2-sec data, and the 5-min-average file to a permanent storage location on the server. The user-entered event log is also copied and stored on the server. The 2-sec data is used to examine performance on the order of a few days, or for closer examination of transients. The 5-min-average data is most useful for examining a lengthy span of time, such as thousands of hours to confirm long-term steady performance. The dynamic signals, such as alternator voltage and piston motion, are also recorded by the data system software. The

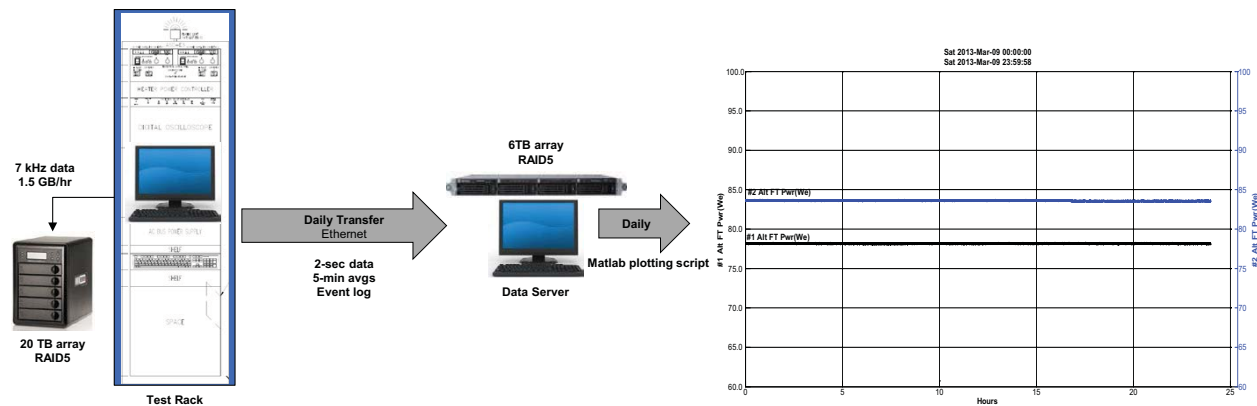


Figure 7.—Stirling Research Laboratory (SRL) data collection and processing overview.

software is capable of sampling and stored the data at a rate of 7 kHz. This results in approximately 1.5 GB of data per hour for the dynamic signals alone. Given this large data rate, a separate storage device was dedicated to the dynamic data. Each pair of convertors has an allocated 20-TB hard disk array that is connected locally to the test station computer. The data system stores the dynamic data directly to this large array rather than to its local hard drive. The dynamic data does not get transferred to the main data server, as this would quickly consume all the storage space on the server. The 7 kHz data is desired when the 2-sec data is too slow. A sample rate of 7 kHz provides 70 data points per cycle of convertor operation, which is far greater than the minimum required by the Nyquist theorem. These data could be used to examine the real-time behavior of the convertor if desired at some future time.

Once data have been stored on the server, an analyst may use the customizable Matlab-based plotting scripts to examine the performance data. Both the 2-sec- and 5-min-average data can be used to generate time domain plots. The plotting scripts also load the electronic event log and automatically populate the plots with these pieces of information at the correct time axis locations. This is helpful when an analyst is examining the data for steady behavior. If a manual adjustment at the test station is made, it is important that it be made obvious on the plot. Otherwise, one might misinterpret the change in performance as unsteady convertor behavior. The process of maintaining an electronic event log and automatically populating these events on the plots streamlines the process, and allows a user to quickly identify performance changes due to user activity.

Performance Measurement Test Results

After delivery of ASC–E3 #1 and #2 to Glenn in November 2012, the convertors were installed on the test station. The convertors were shipped to Glenn in the common test support hardware that was described earlier. As such, there was little inspection performed on the E3s, since the support hardware was not removed. This is in contrast to the E2 units, which were sent as bare convertors with no attached support hardware.

Insulation loss characterization was initiated in January 2013. Data from this test were used later to develop an equation for insulation thermal losses as a function of the various temperatures on the convertor. This test showed that the E3 hardware design effort to reduce insulation losses was successful. For example, at the nominal operating point of 760 °C on the hot end, the insulation losses were 78 W. This is similar to the losses that will exist in the flight unit when filled with argon. A vacuum around and inside the insulation package would reduce the losses further. Previous E2 test articles had an insulation loss of approximately 130 W at this temperature, mostly because of the cartridge protrusion through the insulation.

Once thermal insulation loss characterization was completed, the convertors began the performance mapping test. The ASC product specification contains seven operating points that the performance must achieve. The project expressed need for a more comprehensive performance map around these seven points. This “extended” performance map was initiated in February 2013. The test matrix consisted of 36 points with a hot-end temperature ranging between 640 to 800 °C, and a cold-end temperature ranging from 28 to 75 °C. The performance measurements for the extended performance map agreed well between the Sunpower and Glenn data. In almost every case, the difference in power output was less than 2 percent. This suggests that the effort to standardize the test support hardware was successful. Since the insulation was not disturbed, the measurement of convertor performance at the same operating conditions remained consistent between the Sunpower and Glenn cases.

Operation then continued with the product specification mapping in April 2013. This consisted of seven points representing the boundaries of a flight unit life: beginning of mission (BOM), end of mission (EOM), low rejection (LR), high rejection (HR), maximum qualification, minimum qualification, and maximum temperature. BOM represents the onset of the mission where the thermal power output of the radioisotope fuel is greatest, while EOM represents some number of years later in the mission when there is less energy from the fuel. LR represents a deep space sink temperature, while HR represents a sink temperature such as low Earth orbit. The measured power output was normalized to the specification net heat input for each point. The independent performance measurement at Glenn showed both convertors met the performance specification for all seven points.

ASC-E3 #1 and #2 have each accumulated over 2300 hr of runtime during this process. The automated data archival and plotting systems enable examination of every 2-sec data point throughout this history (4.1 million data points). An example 24-hr period of convertor performance (power output at the feedthroughs) is shown in Figure 7. Notice first the flat-line nature of the power output. Over this 24-hr period the convertor performance was steady and unwavering. The width of the plot is 0.3 W, which is less than 1 percent of the nominal convertor output. This is deemed normal, steady convertor behavior. The uncertainty in the power meter is 0.47 W, but this is not indicative of the precision of the measurement. A quantitative assessment of the power meter precision can be obtained via examination of a test rack checkout that is performed prior to convertor delivery. During this checkout, an AC power supply is connected in place of the convertor. This exercises the connections and measurements in the test rack. In this case, the thickness of the alternator power plot is on the order of 0.1 W. This represents an experimentally determined value for the precision of the power meter, since the power flow through a fixed resistance will be steady. Any deviation from flat-line convertor power output with a magnitude 1 W or greater would raise a flag for further analysis. The entire 2300 hr of 2-sec data was periodically reviewed for power fluctuations. Every data plot was as steady as that shown in Figure 8. A similar analysis may be performed by examining the 5-min-average data points. The 5-min-average plots also show steady behavior between each operating point adjustment.

These convertors exhibited a 5-W difference in power output over all test points, with ASC-E3 #2 having a higher power output for the same operating conditions. This was consistent with the Sunpower performance measurements taken prior to delivery. This magnitude performance difference is a result of the variability in the convertor fabrication. A piston seal clearance could explain this variance. ASC-E3 #2 is known to have a smaller clearance. Both convertors were built to the E3 design documents, and both met the product specification.

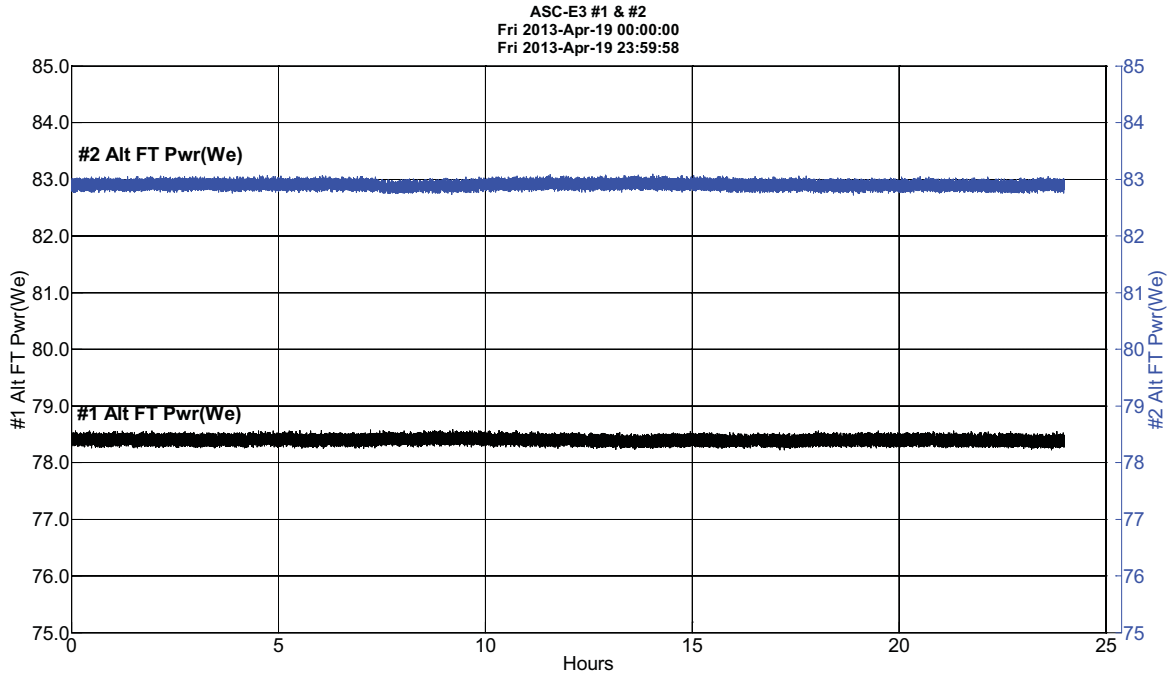


Figure 8.—Example steady 2-sec data over a 24-hr period.

Conclusion

NASA Glenn Research Center is supporting the advancement of the Advanced Stirling Radioisotope Generator (ASRG) towards flight via convertor-level performance testing. Tests include performance measurement and extended operation. The latest generation of Advanced Stirling Convertor (ASC) hardware, model E3, are being built to exercise the flight hardware build process. The first pair of ASC-E3s was delivered to Glenn in November 2012. A new design for the convertor test support hardware was produced via a collaborative effort between Glenn and Sunpower, Inc. This new hardware addressed concerns that arose during previous experimentation with ASC-E2 units. Most notably, the decision was made to ship the E3s in the support hardware, so that the same setup was used for performance measurement at Sunpower and Glenn. The new support hardware design also included improvements to the insulation package and heat source. Thus far, these convertors have operated for 2300 hr each. The convertors have completed performance mapping and are being transferred to Lockheed Martin for controller checkout tests.

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