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Advanced Stirling Convertor (ASC-E2) Characterization Testing

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Advanced Stirling Convertor (ASC–E2) Characterization Testing

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Abstract

Testing has been conducted on Advanced Stirling Convertors (ASCs)–E2 at NASA Glenn Research Center in support of the Advanced Stirling Radioisotope Generator (ASRG) project. This testing has been conducted to understand sensitivities of convertor parameters due to environmental and operational changes during operation of the ASRG in missions to space. This paper summarizes test results and explains the operation of the ASRG during space missions.

Introduction

As a part of the continued support of the Advanced Stirling Radioisotope Generator (ASRG) project's path to flight, Advanced Stirling Convertors (ASCs) from Sunpower, Inc., are on test at NASA Glenn Research Center's (GRC's) Stirling Research Lab (SRL). The latest convertors manufactured and currently under test are the ASC–E2 convertors. Testing is being conducted for extended life reliability and parameter characterization for system integration. To fully understand effects of convertor performance, parameter variation tests need to be conducted.

This paper outlines two tests that were conducted on ASC–E2 convertors. The first test was to support controller development. This test was called the AC bus variation test and was conducted to help understand the sensitivities of key parameters due to AC bus voltage changes. A better understanding of the sensitivities of these parameters will help quantify tolerances of the controller and help finalize control strategies.

The second series of tests was a simulation of argon venting of an ASRG during launch. This testing was to simulate the effect of ascent through the atmosphere during launch of the ASRG and quantify the effects. This series of tests was conducted in three phases. Each of these phases simulated different events that the convertor would undergo throughout the mission.

Nomenclature

ASC	Advanced Stirling Convertor
ASRG	Advanced Stirling Radioisotope Generator
BOM HR	Beginning of Mission High Reject temperature
BOM LR	Beginning of Mission Low Reject temperature
EU	Engineering Unit
GRC	Glenn Research Center
SRL	Stirling Research Lab
W_{th}	Watts thermal

Test Setup

The ASC–E2 convertors were tested on a test stand that was designed specifically for ASC–E2 testing. These test stands are shown in Figures 1 and 2. Further details can be found in Reference 1.

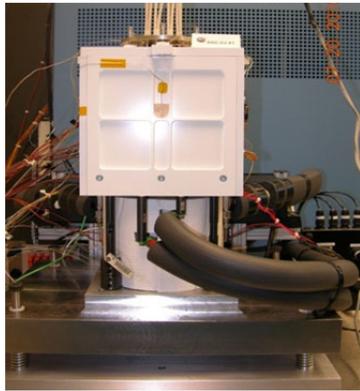


Figure 1.—ASC-E2 #1 on test stand.



Figure 2.—ASC-E2 #5 on test stand with test rack in background.

AC Bus Voltage Variation Test

The AC bus voltage variation test was conducted in the SRL at GRC using ASC-E2 #1. AC bus voltage is analogous to a key control input to the ASRG. The purpose of this test was to characterize convertor response to AC bus voltage variation.

During testing, the convertor was operating at ASC-E2 specification Beginning of Mission Low Reject (BOM LR) conditions (Ref. 2) in a single-vertical setup with heater head up. The convertor was being controlled with constant heat input. More information on test stations in the SRL can be found in Reference 2.

The test was terminated when the compact electrical heat source failed. After failure, the compact heat source was replaced with an HT FIREROD (Watlow) heat source, and the first four points of the test were repeated. Further details on the HT FIREROD heat source can be found in Reference 3.

The test was conducted by adjusting the AC bus voltage in incremental steps while observing hot-end temperatures with other convertor parameters held constant. The AC bus voltage directly controls the piston amplitude of the convertor. An increase in AC bus voltage results in an increase in piston amplitude. During the test, the AC bus voltage was increased by an increment every day and then the system was allowed at least 8 h to reach a steady-state point.

Data was gathered using a LabVIEW (National Instruments) data acquisition system. Most parameters were sampled at 2000 Hz and averaged over 1 sec. The averaged data, called 2-sec data, was saved every 2 sec. For steady-state data, the 2-sec data was averaged over a 5 min time span and was saved as a point and is called 5-min average data.

Argon Venting Simulation Test

The argon venting simulation test was also conducted in the SRL at GRC but was performed using ASC-E2 #5, which utilizes an HT FIREROD heat source. The purpose of this test was to simulate the convertor environment during launch and collect data useful in developing the launch concept of operation strategies.

Data was collected for this test using the same type of data acquisition system as the AC bus voltage variation test. This test began with ASC-E2 #5 operating at ASC-E3 and ASC-F specification BOM-HR. This point was chosen because it better represents the operating condition of a convertor in the payload fairing prior to launch. During this test, the convertor was controlled in constant-heat-input mode.

After the convertor achieved steady state at this point, phase 1 of the test was started. This included decreasing the gross heat input by 20 W to get a baseline and allow the convertor to reach steady state. Once steady-state conditions were achieved, a 5-min average was recorded and the convertor was returned to a baseline ASC-E3 and ASC-F BOM HR operating point. Again the system was allowed to reach steady state, a 5-min average point was collected, and then the gross heat input was increased by 15 W_{th} . The convertor was allowed to reach steady state and another 5-min average was taken for this point. The convertor was then returned to a baseline ASC-E3 and ASC-F BOM HR point, allowed to steady, and a final 5-min average point was collected to conclude phase 1.

Phase 2 began with ASC-E2 #5 operating at ASC-E3 and ASC-F BOM HR conditions. A 5-min average data point was taken to establish a baseline. Subsequently, the net heat input was increased by 30 W_{th} to simulate venting of argon and increased effectiveness of thermal insulation. As the hot-end temperature rose, the net heat input was adjusted so that it matched the hot-end temperature/net heat input relationship of the ASRG flight unit. Once the convertor reached a steady state at this point, a 5-min average was taken, and the convertor returned to baseline ASC-E3 and ASC-F BOM HR conditions.

Phase 3 started at steady-state ASC-E3 and ASC-F BOM HR conditions. The next step in this test was to reduce the rejector and alternator housing temperatures by 30 °C. This simulates the sink temperature change as the ASRG ascends from within the spacecraft fairing to the lowest expected radiation sink temperature of 4 K. This represents a worst-case scenario, since a spacecraft leaving Earth’s atmosphere sees a radiation sink temperature much higher than 4 K. As the hot-end temperature rose, the net heat input was adjusted to match the hot-end temperature/net heat input relationship of the ASRG flight unit. After this point reached steady state, a 5-min average data point was taken, and the system returned to baseline ASC-E3 and ASC-F BOM HR conditions.

Test Results

AC Bus Variation Test

There were nine data points collected with the compact heat source. These points were plotted and can be found in Figure 3. Reported in the graph is 5-min average data from a time in which the convertor reached a steady-state operating point.

From this data the incremental sensitivities of the hot-end temperature and piston amplitude was calculated by dividing the change in the parameter (e.g., change in piston amplitude) by the change in AC bus voltage. The incremental sensitivities that were calculated for piston amplitude and hot-end temperature are plotted versus hot-end temperature in Figure 4.

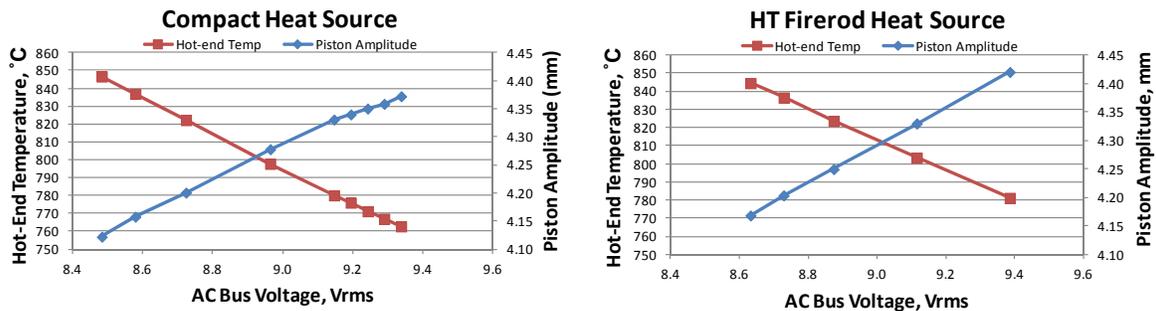


Figure 3.—Data from AC bus voltage variation test.

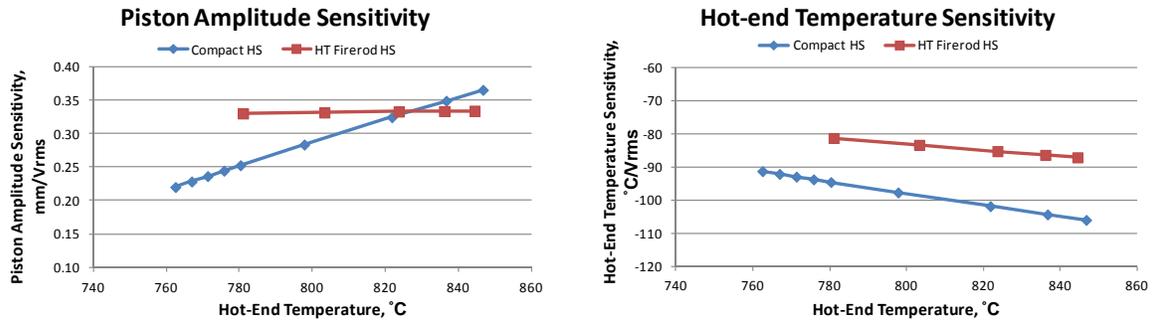


Figure 4.—Sensitivities plotted vs. hot-end temperature.

With the compact heat source, the hot-end temperature sensitivity varied between -91 and -109 °C/V and the piston amplitude sensitivity varied between 0.21 and 0.37 mm/V. These numbers are similar to the numbers from the AC bus voltage variation test conducted with the ASRG EU, which had a hot-end temperature sensitivity of -73 to -81 °C/V and a piston amplitude sensitivity of 0.23 to 0.30 mm/V (Ref. 4). The difference between the operating points may account for some of the differences in the two sets of numbers. The ASRG Engineering Unit (EU) hot-end temperature was about 625 °C at the beginning of that test and the ASC-E2 #1 hot-end temperature was at about 850 °C.

After the compact heat source failed, it was replaced with a HT-FIREROD heat source and the first four points of the test were repeated. The results of this repeated test are plotted in Figure 3. The incremental sensitivities were calculated the same way as in the first test. The data was also plotted in Figure 4. The hot-end incremental sensitivities of the second test ranged from -81 to -89 °C/V and the piston amplitude sensitivity varied between 0.32 and 0.35 mm/V. These slightly higher numbers may be due to changing some of the support hardware for the new heat source which affected the insulation characteristics. The HT FIREROD heat source has greater heat loss compared to the compact heat source, and its heat loss versus temperature characteristics are different. These differences caused changes in hot-end temperature and piston amplitude as AC bus voltage was increased or decreased. These test results may differ from test results for the flight ASRG, since the flight ASRG has different thermal characteristics. It should also be mentioned that operation in vacuum will affect system response to AC bus voltage changes.

Some sources of potential error during testing include a failing heater during the first test. This could cause nonuniform heating of the hot-end and could possibly affect the results. Also, ASC-E2 #1 has a known helium leak that could affect the results and may be a cause of variability while repeating the test.

An interesting observation during testing was the relationship between the alternator terminal voltage and AC bus voltage. As shown in Figure 5, as the AC bus voltage increased, the alternator terminal voltage decreased slightly. While this result is not intuitive, the complex relationship between convertor parameters can produce this result. As AC bus voltage increased, piston amplitude increased, and hot-end temperature decreased. Decreasing hot-end temperature decreased the convertor's mean pressure, which changed the convertor's natural frequency. This led to an increase in the alternator power factor required to maintain the operating frequency. As a result, the alternator terminal voltage decreased slightly for this particular test.

Argon Venting Simulation Test

Phase 1 of the argon venting simulation test consisted of operating in constant heater power mode then changing gross heat input by $-20/+15$ W_{th} . This was necessary to gather baseline data for acceptor temperature sensitivity to gross heat input changes. The acceptor temperature is measured at the hot-end heat exchanger inside heater head of the convertor. It is 2.5 °C lower than the hot-end temperature due to thermocouple locations. Data for each of the points of the test was collected and is plotted in Figure 6.

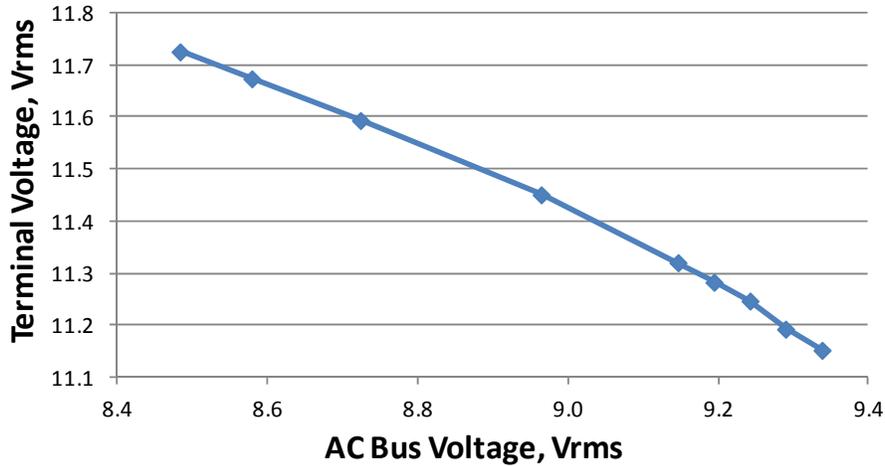


Figure 5.—AC bus voltage and terminal voltage plot.

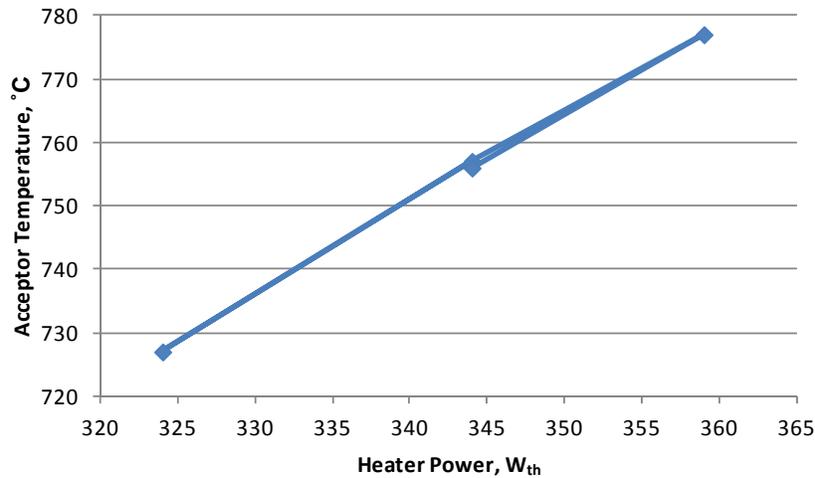


Figure 6.—Argon venting phase 1 results.

The 20 W_{th} decrease in gross heat input resulted in a 30 °C decrease in acceptor temperature. The 15 W_{th} increase resulted in a 20 °C increase in acceptor temperature. Therefore, the sensitivity of acceptor temperature to gross heat input was an average of 1.4 °C/W_{th}.

Phase 2 consisted of simulating argon venting by increasing the convertor net heat input. This was accomplished by increasing the net heat input by 30 W_{th} (the increase in gross heat input was greater because of the thermal loss characteristics of the insulation package with the HT FIREROD heat source). Data for this phase of the test was collected and is plotted in Figure 7. The net effect of argon venting was an increase in the acceptor temperature by 53 °C (from 756 to 809 °C) due to a net heat input increase of 29 W_{th}.

Phase 3 consisted of reducing the rejector and alternator housing temperature to simulate temperature sink change as the generator ascends from storage in the fairing to space. As shown by the plot in Figure 8, the effect of reducing the rejector and alternator housing temperatures by 30 °C was an increase of the acceptor temperature by 61 °C (from 760 to 821 °C). Therefore, the sensitivity of acceptor temperature to rejector/alternator housing temperature change is -2.0 °C/°C.

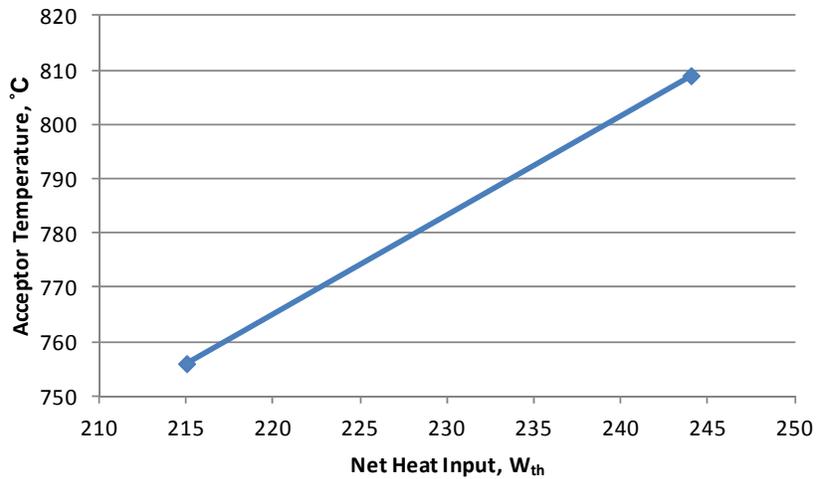


Figure 7.—Argon venting phase 2 results.

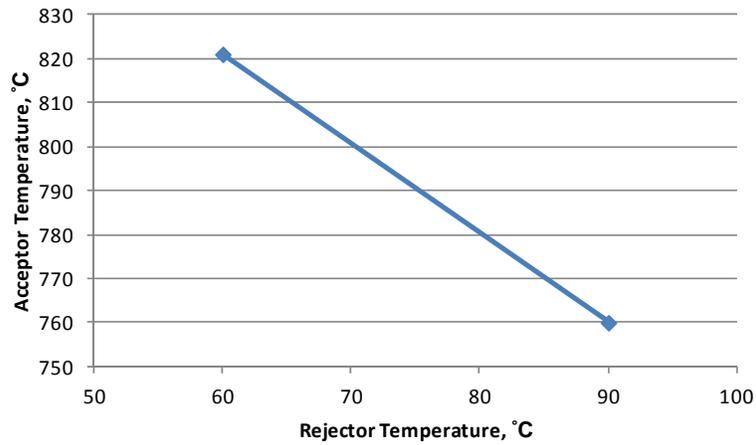


Figure 8.—Argon venting phase 3 results.

Conclusion

The Advanced Stirling Converter (ASC)–E2 #1 sensitivity to AC bus voltage variation is similar to that of the ASC–E converters in the Advanced Stirling Radioisotope Generator (ASRG) Engineering Unit (EU). This sensitivity is a useful parameter for system integration and control.

The argon venting testing on ASC–E2 #5 helps us to understand how the converter will react during the launch stage of a mission. Further testing of mission-specific conditions will help us to understand how the converter will operate in space.

Performance variation tests need to continue to be conducted on future generations of hardware as the technology matures to the flight configuration. These tests will help advance the ASRG toward flight by providing information to us to fully characterize and understand the converters and how they will operate in a variety of conditions.

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