



Characterization of the Advanced Stirling Radioisotope Generator Engineering Unit 2

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Abstract

Significant progress was made developing the Advanced Stirling Radioisotope Generator (ASRG) 140-W radioisotope power system. While the ASRG flight development project has ended, the hardware that was designed and built under the project is continuing to be tested to support future Stirling-based power system development. NASA Glenn Research Center recently completed the assembly of the ASRG Engineering Unit 2 (EU2). The ASRG EU2 consists of the first pair of Sunpower's Advanced Stirling Converter E3 (ASC-E3) Stirling converters mounted in an aluminum housing, and Lockheed Martin's Engineering Development Unit (EDU) 4 controller (a fourth-generation controller). The ASC-E3 converters and Generator Housing Assembly (GHA) closely match the intended ASRG Qualification Unit flight design. A series of tests were conducted to characterize the EU2, its controller, and the converters in the flight-like GHA. The GHA contained an argon cover gas for these tests. The tests included measurement of converter, controller, and generator performance and efficiency; quantification of control authority of the controller; disturbance force measurement with varying piston phase and piston amplitude; and measurement of the effect of spacecraft direct current (DC) bus voltage on EU2 performance. The results of these tests are discussed and summarized, providing a basic understanding of EU2 characteristics and the performance and capability of the EDU 4 controller.

Symbols

- F_A, F_B total dynamic force for Advanced Stirling Converter (ASC) A, ASC B (N); sum of piston and displacer inertial forces
- F_D disturbance force (N)
- F_{dA}, F_{dB} displacer inertial force for ASC A, ASC B (N)
- F_{pA}, F_{pB} piston inertial force for ASC A, ASC B (N)
- Φ_{dA}, Φ_{dB} displacer to piston phase angle for ASC A, ASC B ($^\circ$)
- $\Phi_{B/A}$ relative phase angle between ASC A and ASC B dynamic forces ($^\circ$)

Introduction

NASA continues to make progress on maturing Stirling-based energy conversion technology for future space missions. By offering the potential of high efficiency, low heat rejection, and low mass, Stirling power systems enable some deep space missions. The Department of Energy (DOE) and NASA made significant progress developing the Advanced Stirling Radioisotope Generator (ASRG), until the flight development project was terminated in late 2013. NASA Glenn Research Center then contracted with Lockheed Martin (LM) to complete two engineering level Advanced Stirling Converter (ASC) Controller Units (ACUs) known as Engineering Development Unit (EDU) 4.0 and 4.1, based on the flight ACU design. The controllers were delivered to NASA Glenn in 2014. These controllers plus hardware from the ASRG flight development contract were integrated into the ASRG Engineering Unit 2 (EU2). While ASRG flight development has ended, hardware from the ASRG project is being put on test to

support future Stirling-based power system development (Ref. 1). Although future flight hardware may not be identical to the hardware that was developed under the ASRG flight development project, many components will likely be similar, and system architectures may have heritage to ASRG.

This paper describes a series of tests conducted to characterize the EU2, its controller, and the converters in the flight-like Generator Housing Assembly (GHA). The GHA contained an argon cover gas for these tests. The tests included measurement of converter, controller, and generator performance and efficiency, quantification of control authority of the controller, disturbance force measurement with varying piston phase and piston amplitude, and measurement of the effect of spacecraft direct current (DC) bus voltage on EU2 performance. The results of these tests provide a basic understanding of EU2 characteristics and the performance and capability of the EDU 4 controller.

ASRG EU2

The ASRG EU2 is based on the ASRG flight design. Figure 1 shows a diagram of the ASRG flight unit, as designed by LM under contract to the DOE. The ASRG contains two ASCs secured to one another with an interconnect tube. A General Purpose Heat Source (GPHS) module is held against each ASC heat collector to provide the heat input. The cold-side adapter flanges (CSAFs) conduct waste heat rejected from the converters to the beryllium housing and fins, for radiation in a vacuum environment or convection to air. During ground operations argon fills the housing, sealed by o-rings and gaskets. A gas management valve allows access to the argon. A pressure relief device is provided to vent the argon during launch as the surrounding air pressure approaches the vacuum of space, improving effectiveness of the insulation that surrounds the heat source. The controller is remotely mounted in a location determined by the mission and connected electrically to the GHA via cables. Connectors on the housing and controller provide electrical interfaces to the alternators, sensors, power input and output, control, and telemetry. The GHA is secured to a spacecraft interface or support via four mounting tabs on one end of the GHA.

The ASRG EU2 consists of the first pair of Sunpower ASC-E3 converters (ASC-E3 #1 and #2), LM's EDU 4.1 controller (a fourth-generation controller), and an aluminum housing. In this paper ASC-E3 #1 is identified as ASC A, the inboard converter, and ASC-E3 #2 is ASC B, the outboard converter. The integration of these converters into the GHA, which closely matches the intended electrically heated ASRG Qualification Unit design, is discussed in Reference 2.

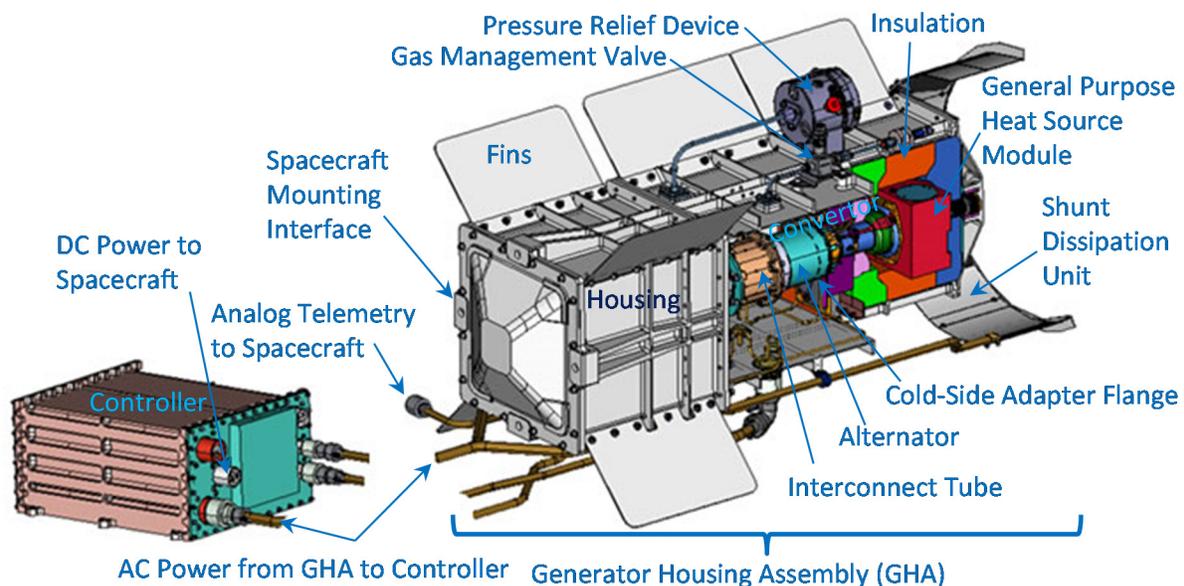


Figure 1.—Advanced Stirling Radioisotope Generator (ASRG) flight design.



Figure 2.—Advanced Stirling Radioisotope Generator (ASRG) Engineering Unit 2 under test in NASA Glenn Research Center Stirling Research Laboratory.

EDU 4 Controller

The controller is a significant component of the ASRG system, and it must perform several critical functions in any Stirling-based space power system. LM has evolved the controller design over the past several years to reach the level of a flight-like design. The ASRG controller functions include the following (Ref. 3):

- Rectifying the AC power from the Stirling convertors
- Synchronizing the two convertors to reduce disturbance force
- Controlling the convertors' operating frequency and voltage (which then controls the piston amplitude)
- Maintaining piston amplitude and hot-end temperature within desired ranges
- Providing power to the spacecraft's DC power bus over a voltage range, with capability to handle overvoltage and undervoltage conditions
- Receiving and responding to commands from the spacecraft
- Providing telemetry to the spacecraft
- Incorporating fault management functionality at the controller box level and integrating into the spacecraft's fault management system

The controller uses power electronics technology to eliminate the need for tuning capacitors to compensate for alternator inductance, thereby reducing mass and improving reliability. It incorporates high-frequency pulse-width modulated (PWM) switching of an H-bridge to control the convertors

(Ref. 4). The controller algorithms and other functionality are implemented using field programmable gate arrays (FPGAs).

The ASRG EU incorporated EDU 1, a first-generation controller (Ref. 5). As an early implementation of a Stirling convertor controller for a space radioisotope system, it differs in many ways from the EDU 4 design. The EDU 1 controller included a temperature control loop and piston stroke limiting, features that are not in the EDU 4. There are many other changes as well, which further underscores the importance of characterizing the EU2 with the EDU 4.1 ACU. Additionally, EU testing uncovered a number of EDU 1-related issues (Fig. 2). Some of these findings included

- The piston amplitude was not steady but varied from cycle to cycle. This piston amplitude “jitter” was resolved by a change to how the control algorithm was coded.
- Operating frequency resolution was too coarse, so the operating frequency could not be set to the recommended value of 102.2 Hz. This was resolved by improving the resolution of controller variables.
- There was a phase difference of several degrees between controller cards 1 and 2, which each controlled one of the convertors. As a result, the dynamic forces from the two convertor pistons were not cancelled. This was resolved by improving the controller card synchronization design.
- EDU 1’s ASC voltage setpoint resolution by design was 1/8 V. Tests showed this was too coarse and did not permit the fine adjustment likely needed at some points in the mission. Later controllers significantly improved resolution.
- There was inaccuracy in some of the telemetry. This was corrected in later controllers.
- Changing DC bus voltage resulted in a higher than allowable change in the hot-end temperature. This was resolved with control algorithm improvements in later controllers.
- There was a slow drift in control output. This was resolved with several design improvements to later controllers.

Extensive effort went into determining root causes of the above-mentioned issues, both at Glenn and at LM. Subsequent to the EDU 1 ACU build, LM built and tested several generations of controllers: EDU 2, EDU 2+, EDU 3, and EDU 4 (Fig. 3). EU2 characterization tests confirmed that these issues have been resolved, and in some cases provided data to quantify EDU 4 capability, which will be discussed later in this paper.

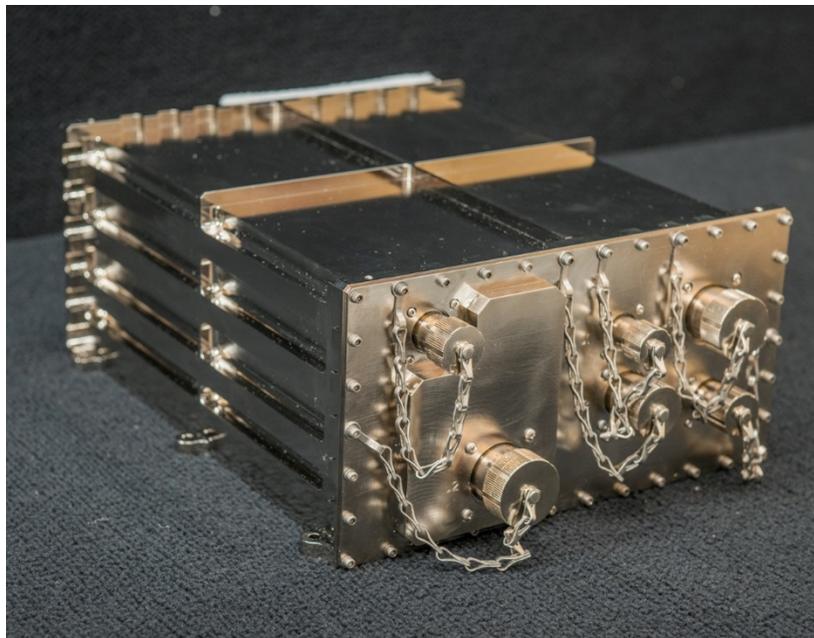


Figure 3.—Lockheed Martin Engineering Development Unit 4 (EDU 4) controller.

ASRG EU2 Characterization Test Results

This section summarizes ASRG EU2 characterization test results. The characterization tests were selected from EU tests that were found to be the most informative for understanding generator behavior.

Overview of ASRG EU2 Characterization Tests

Table I summarizes the tests that were conducted on the EU and the EU2. Some of the results of EU testing have been published previously, and can be referenced for comparison to EU2 results (Ref. 6).

Tests were conducted on the EU2 with two different control configurations: ACU control and AC bus control. Figure 4 shows the EU2 configuration with the ACU. The EDU 4.1 was used to control the two convertors in the GHA, and the spacecraft DC bus was simulated by a DC electronic load plus capacitors.

Figure 5 shows the AC bus control configuration. In this configuration, the ACU was replaced with tuning capacitors and a simulated AC bus, which was connected directly to the convertors in the GHA. This configuration more closely matched how the convertors were tested prior to integration into the GHA. The AC bus control configuration was used to provide ASC and GHA performance data independent of the ACU. Data from this configuration allowed for comparison to convertor-level performance test data, to quantify the effect of the ACU, and to provide a benchmark for assessing the ACU's performance as a convertor controller.

TABLE I.—TESTS CONDUCTED WITH ADVANCED STIRLING RADIOISOTOPE GENERATOR (ASRG) ENGINEERING UNIT (EU) AND EU2

	Test	ASRG EU	ASRG EU2
ASRG under AC bus control	Alternating current bus voltage variation	X	
	Heat input variation	X	
	Cold-end and pressure vessel temperature variation	X	
ASRG under EDU 1 or EDU 4.1 ACU control	Performance test		X
	Advanced Stirling Convertor (ASC) voltage setpoint variation	X	X
	Direct current bus voltage variation	X	X
	Heat input variation	X	
	Natural convection cooling test	X	
	Core loss test	X	
	ASC control stability	X	X
	ASC Controller Units (ACU) stability and drift	X	
	ASC voltage setpoint command resolution	X	X
	Operating frequency command resolution	X	
	Controller card interaction test	X	X
Extended operation	X		

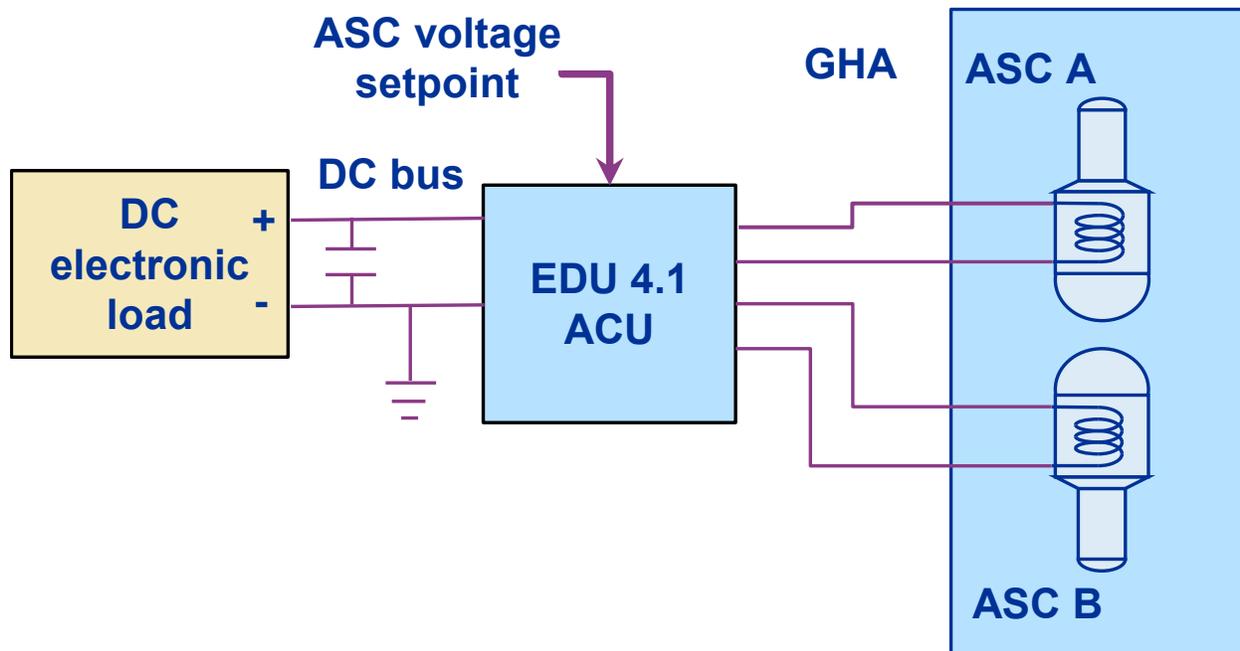


Figure 4.—Advanced Stirling Converter (ASC) Controller Unit (ACU) control configuration for Advanced Stirling Radioisotope Generator (ASRG) Engineering Unit 2 (EU2) testing. DC is direct current. EDU is Engineering Development Unit. GHA is Generator Housing Assembly.

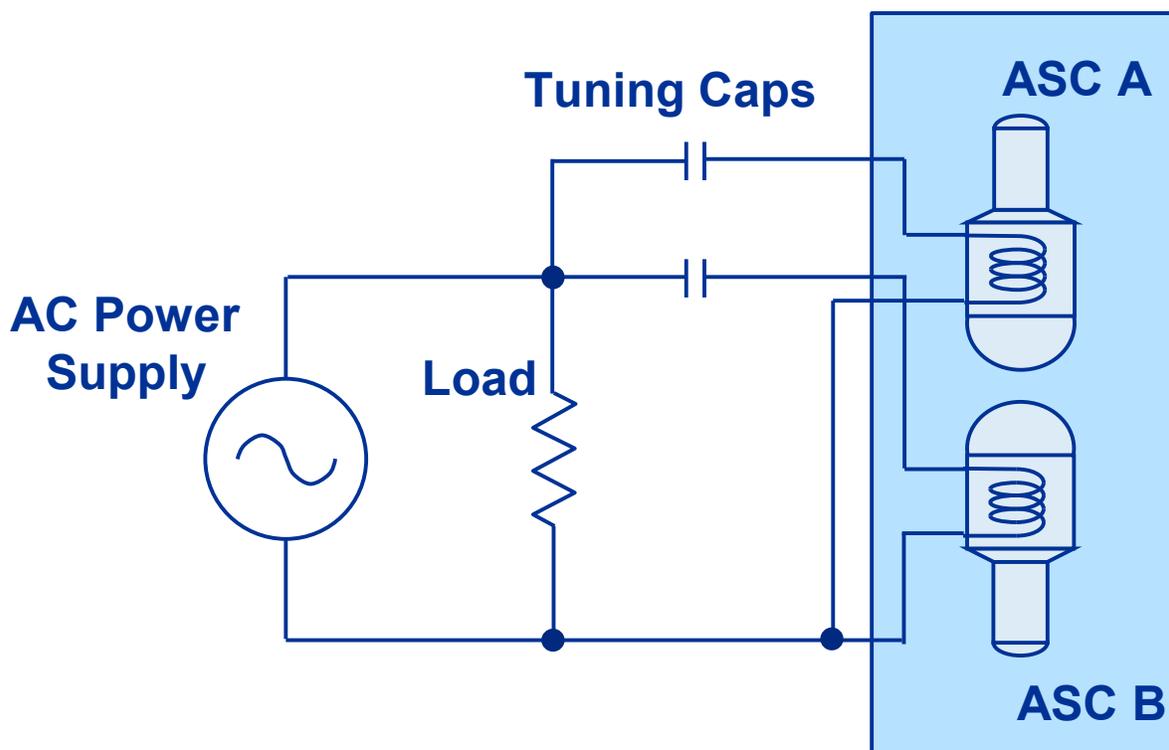


Figure 5.—Alternating current (AC) bus controller configuration for Advanced Stirling Radioisotope Generator (ASRG) Engineering Unit 2 (EU2) testing.

For the tests described in this paper, the GHA was operated with an argon cover gas. The argon cover gas was intended to be used for much of ASRG ground operations and would have been vented during launch. As noted in Reference 2, the GHA was assembled with a thin alumina disk between the convertor’s heat collector and the electric heat source. This interface created too much thermal resistance in a vacuum environment, and the alumina disk will be replaced with graphitic material in the future to provide adequate heat transfer in vacuum.

ASRG EU2 Power Output

The ASRG performance specification requires the generator to produce a minimum of 130 W_e at the beginning of mission (BOM) reference operating point, with 244 W_{th} input from each GPHS module. The BOM reference operating point is defined as the point when the ASRG reaches equilibrium just after launch, in deep space vacuum environment, with a 4 K sink temperature and no solar flux. This condition results in about a 38 °C rejection temperature at the convertor and is commonly referred to as the “low reject” point.

To assess ASRG EU2 performance relative to this power output requirement, the heat input from each heat source was increased by about 30 W_{th} to compensate for the thermal losses associated with operating with an argon cover gas in the GHA. Table II summarizes the ASRG EU2 performance at the BOM low reject operating point and a nominal spacecraft DC bus voltage of 28 V.

The ASRG EU2 produced 139.6 W_e of power at the BOM low reject operating point. Based on this result, we would expect that a generator built to the ASRG flight design would meet the 130 W_e power output requirement with margin.

Note that the gross heat input was actually set slightly higher than the 30 W_{th} delta to compensate for the argon cover gas (33.3 W_{th} for ASC A and 31.4 W_{th} for ASC B). This is because the convertor operating point for this test was actually set to match previously measured ASC performance data at BOM low reject. This test point incorporated the results of multidimensional numerical modeling validated by test data to accurately estimate convertor net heat input (Ref. 7). Had the gross heat input been decreased to 274 W_{th} , the DC power output would have decreased by only 1.3 to 138.3 W_e , and still would have had significant margin to the specification.

It should also be noted that the ASC A convertor’s power output was only 77.9 W_e , compared with ASC B’s output of 82.3 W_e . ASC A, which is more specifically ASC–E3 #1, is the lowest efficiency ASC–E3 convertor produced to date. ASC B’s performance is more typical of ASC–E3 convertors, and so the EU2 underestimates the performance that would be achieved with nominal ASC convertors.

TABLE II.—ADVANCED STIRLING RADIOISOTOPE GENERATOR (ASRG) ENGINEERING UNIT 2 (EU2) PERFORMANCE AT BEGINNING OF MISSION (BOM) LOW REJECT OPERATING POINT

Parameter	Units	Value	
		Advanced Stirling Convertor (ASC) A	ASC B
Electric heat source power input (gross heat input)	W_{th}	277.3	275.4
Hot-end temperature	°C	760	760
Rejection temperature	°C	37	38
Alternator power output	W_e	77.9	82.3
Convertor gross efficiency (alternator power/gross heat input)	%	28.1	29.9
ASC Controller Unit (ACU) power input (sum of alternator power output)	W_e	160.2	
ACU power consumption	W_e	20.6	
Direct current output power	W_e	139.6	

Converter Stability Under ACU Control

One of the controller functions mentioned earlier is that the controller must control each Stirling convertor so that the piston maintains a steady amplitude from cycle to cycle, and the mean piston position does not shift in or out. Piston amplitude variation from cycle-to-cycle results in a higher disturbance force. This can appear as jitter in piston position signals and was observed when the ASRG EU was operated with the EDU 1 controller. Algorithm improvements since EDU 1 have addressed the jitter issue.

Converter stability under AC bus control is often used as a reference standard of comparison. A digital controller should be able to control a convertor similar to an AC bus controller.

To evaluate the control stability of EDU 4.1, the EU2 was operated at the same convertor operating point under AC bus control and then under ACU control (Figs. 4 and 5). Piston position was recorded every cycle for 1 min (over 6,100 cycles). The amplitude and mean position were calculated for each cycle and then plotted on frequency distribution histograms (Fig. 6). (Fig. 9 provides an example of how piston amplitude varies from cycle to cycle).

Figure 6 shows that EDU 4.1 had better control stability over piston position than an AC bus controller. There was less cycle-to-cycle variability in amplitude and mean piston position with the ACU. Table III shows the standard deviation for piston amplitude and mean piston position, with ACU control having at least a 22 percent reduction in standard deviation. While this result may at first seem surprising, one must realize that the analog AC bus control system adds its own bandwidth limitations and dynamics. It is possible for a properly designed digital ACU controller, with its high-frequency control loops, fine parameter resolution, and greater algorithm flexibility, to achieve superior stability versus an analog controller.

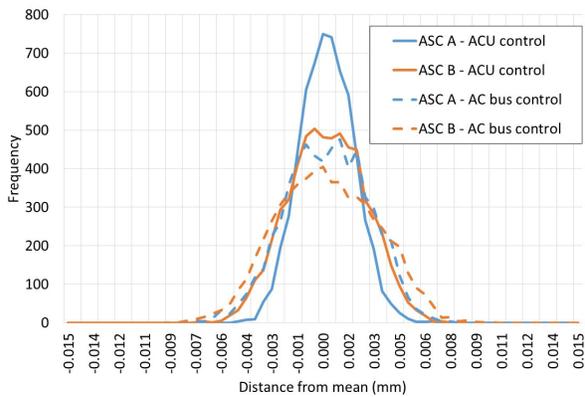


Figure 6(a).—Piston amplitude histogram.

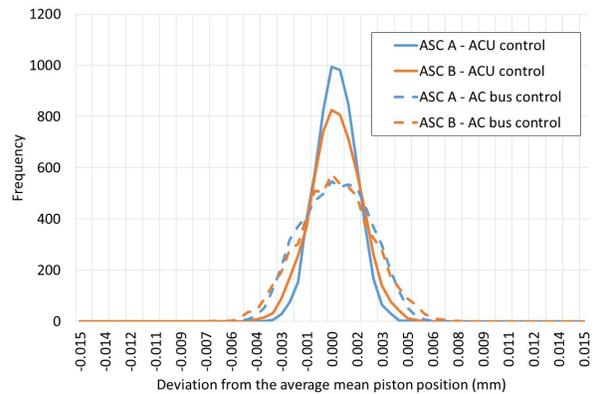


Figure 6(b).—Mean piston position histogram.

TABLE III.—PISTON AMPLITUDE AND MEAN PISTON POSITION STANDARD DEVIATIONS (mm)

		AC bus control	ACU control	Percent reduction
Piston amplitude	Advanced Stirling Convertor (ASC) A	0.0024	0.0016	35%
	ASC B	0.0029	0.0023	22%
Mean piston position	ASC A	0.0020	0.0012	41%
	ASC B	0.0022	0.0015	31%

ASC Voltage Setpoint Command Resolution

The primary control input for the ASRG is the ASC voltage setpoint. There is one ASC voltage setpoint for each convertor. The ASC voltage setpoint directly determines the piston amplitude, although the ASC voltage setpoint does not fix the piston amplitude, as piston amplitude can vary slightly for a given ASC voltage setpoint as other convertor parameters vary, such as the rejection temperature. (Note that the ASC voltage setpoint controls the convertor operating point, not the spacecraft DC bus voltage. The DC bus voltage is regulated on the spacecraft side of the electrical interface (Fig. 4).)

The operator would use the ASC voltage setpoint to maintain the hot-end temperature within a desired operating band as the radioisotope fuel decays or as the generator's operating environment, specifically rejection temperature, changes. As the fuel decays less heat enters the Stirling convertor and hot-end temperature decreases. Hot-end temperature can be increased by decreasing piston amplitude, maintaining generator efficiency, and maximizing output power.

A reason that the ASC voltage might be adjusted is to minimize the disturbance force from the generator (see Disturbance Force section). Matching the amplitudes of the two convertors tends to minimize the disturbance force.

The resolution of ASC voltage setpoint command determines how finely the hot-end temperature and piston amplitude can be controlled. Having fine resolution also helps with margin uncertainty analysis. The control resolution should be fine enough that additional margin allowance for the command resolution does not need to be added when allowing for uncertainties in the system. For example, the hot-end temperature cannot exceed a certain limit, but since there is no direct measurement of hot-end temperature, it is controlled open loop. In determining the allowable range for the ASC voltage setpoint at a particular time in a mission, allowance needs to be made for uncertainties in factors that affect hot-end temperature in order to ensure that the maximum temperature limit is not exceeded. A coarse command resolution could limit how well the operating point can be optimized.

The EDU 4.1 ACU voltage setpoint has a resolution of 0.008 V. A test was conducted where the ASC voltage setpoint was first decreased by 0.008 V, and then 173 min later, was increased back to the original setpoint. The system response to this command input would be first an increase in hot-end temperature and then a decrease in hot-end temperature. The test results are shown in Figure 7.

The test was conducted during a slow transient where hot-end temperatures were slowly decreasing (~0.1 °C/hr). In spite of the downward drift in hot-end temperature, both hot-end temperatures increased slightly when the ASC voltage setpoint was decreased by 0.008 V. In steady state, this might result in perhaps a 1° change in hot-end temperature, which is adequate resolution for power system control.

ASC Voltage Setpoint Variation

To determine specific ASC voltage setpoint commands during operation, the effect of an ASC voltage setpoint change on piston amplitude and hot-end temperature would be characterized under the various operating conditions expected during a mission. With the generator performance mapped out during ground operations, operators could then determine appropriate setpoint commands in response to slow changes like fuel decay, or fast changes like a launch transient.

A test was conducted to characterize the generator response to a large step change in ASC voltage setpoint. This test was similar to the ASC voltage setpoint command resolution test, except that the step size was closer to a change that might be made more typically during operation. The ASC voltage setpoint was decreased by 0.40 V and allowed to approach steady state. The next day the ASC voltage setpoint on ASC A was increased by 0.40 V and ASC B's setpoint was increased a few hours later. The results are plotted in Figure 8.

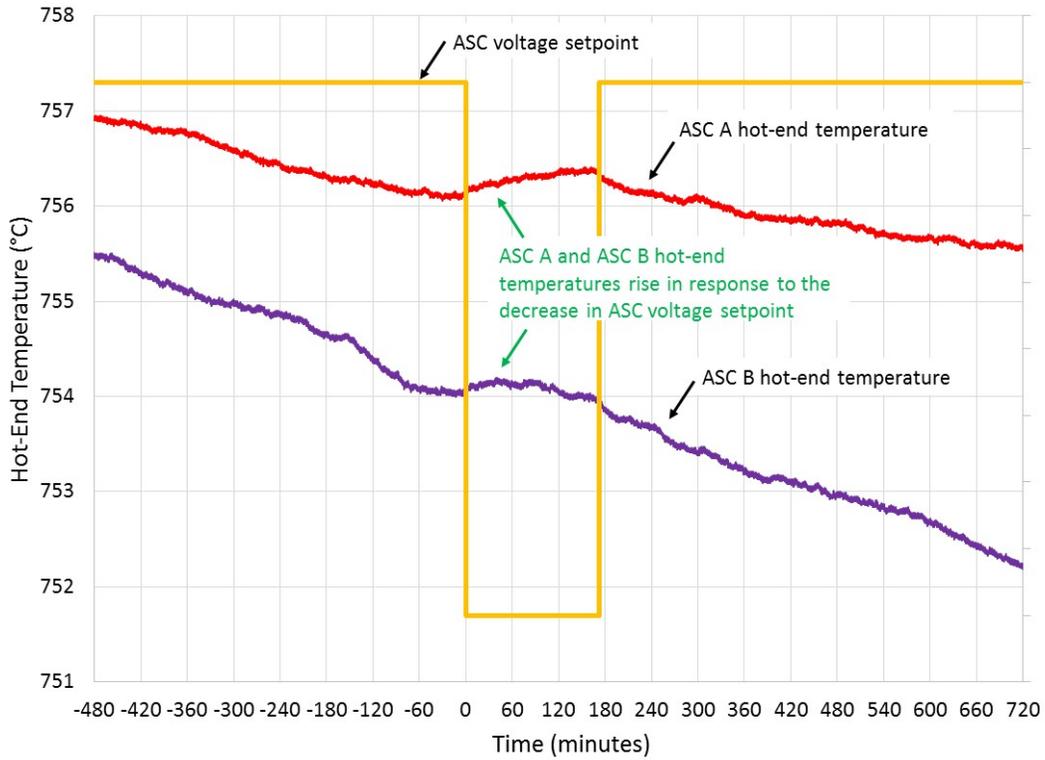


Figure 7.—Effect of a small change in Advanced Stirling Converter (ASC) voltage setpoint on ASC hot-end temperature.

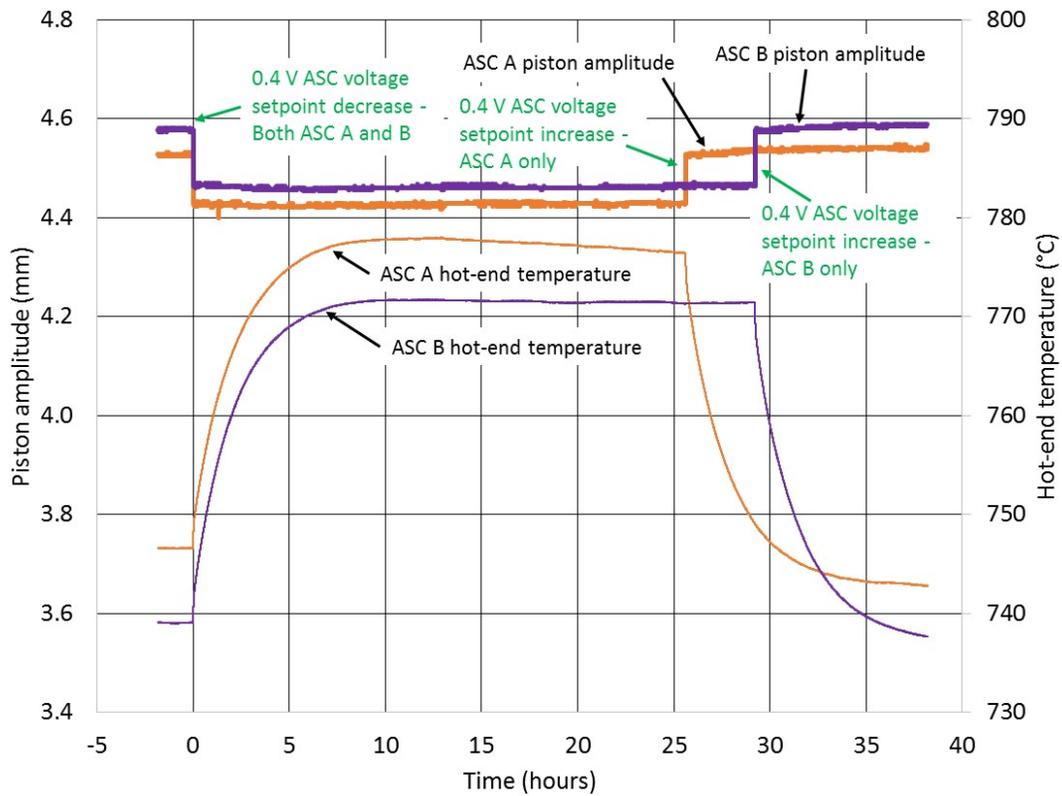


Figure 8.—Advanced Stirling Radioisotope Generator (ASRG) Engineering Unit 2 (EU2) response to step changes in Advanced Stirling Converter (ASC) voltage setpoint.

The step-change in ASC voltage setpoint resulted in an immediate decrease in piston amplitude, followed by a slower increase in hot-end temperature, which took about 10 hr to approach a new equilibrium point. A similar lag in hot-end temperature is seen when piston amplitude was later increased. The ASRG EU2's electric heat source has thermal inertia that is similar to that of a GPHS module, so this time response should be approximately what would be seen with a GPHS module. On the cold side, the current test configuration does not simulate the dynamics of heat rejection to a space environment. The EU2's aluminum housing as a lower thermal inertia than the beryllium housing, and more importantly, the heat rejection temperature was controlled with blocks attached to the housing. So the heat source transient may be reasonably simulated with the EU2 in this configuration, but the slower transient expected with a generator in a radiative deep space environment was not. Since the rejection temperature has a smaller effect on hot-end temperature, the hot-end temperature transient would differ only slightly in a representative deep space environment from the response shown in Figure 8.

The piston amplitude cycle-by-cycle response to the step change is shown in Figure 9 when the ASC voltage setpoint was increased by 0.4 V for ASC A only (corresponds to ~26 hr in Fig. 8). This figure shows that ASC A's piston amplitude approached the steady-state amplitude within two cycles, with a small overshoot and oscillation, and then continued to rise slightly over the next approximately 30 cycles.

Over the next several hours, the piston amplitude increased due to the decrease in hot-end temperature, as shown in Figure 8, between 26 and 35 hr for ASC A. Likewise, Figure 8 shows the ASC A and ASC B piston amplitudes decreased slightly with increasing hot-end temperature between 1 and 10 hr. This additional change in piston amplitude is relatively small for the ASC-E3 convertors in this ASRG configuration. Other convertors tested in the Stirling Research Laboratory have shown different and larger response to the change in hot-end temperature following the equivalent of an ASC voltage setpoint change. For example, the ASC-E convertors in the ASRG EU showed a *decrease* in piston amplitude in response to the hot-end temperature decrease (Ref. 6). This difference in behavior is not unexpected, as convertor response to various inputs involves a complex interaction of a number of factors, and the way these factors interact can depend on the specific convertor design and hardware configurations.

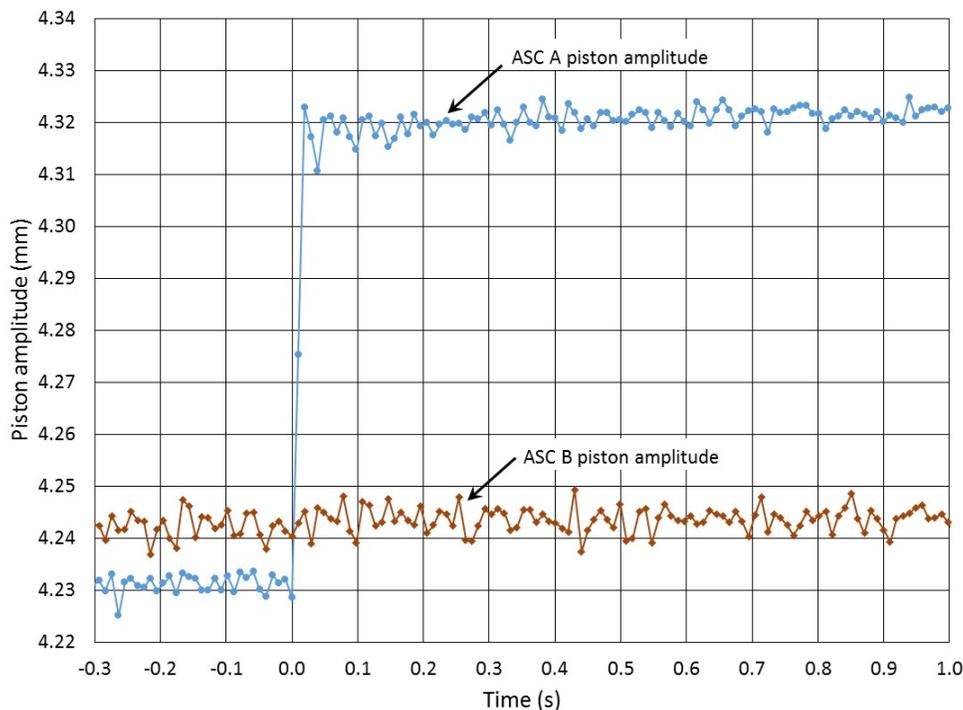


Figure 9.—Piston amplitude response to a step change in Advanced Stirling Convertor (ASC) setpoint voltage.

Figure 9 also shows that when the ACU commanded a voltage setpoint change to ASC A only, the piston amplitude for the other convertor (ASC B) was unaffected. This indicates that there was no cross-talk between the two controller cards (where each controller card controls one convertor).

DC Bus Voltage Variation

Another external effect that was evaluated on the EU2 was how a change in the spacecraft DC bus voltage influenced the convertor operating point. Ideally, a change in the DC bus voltage would have no effect on the ASC operation. However, over part of the DC bus range, changing the DC bus voltage changes the DC voltage being applied to the ASC alternator terminals through the H-bridge (Ref. 4). The controller algorithm compensates for most, but not all of the effect of the DC bus voltage change by adjusting the PWM duty cycle.

A test was conducted to quantify the change in hot-end temperature, ASC alternator voltage, and piston amplitude due to a change in the DC bus voltage over the nominal DC bus voltage range of 22 to 34 V. The results are shown in Figure 10. The DC bus voltage was first increased from 28.5 to 34.4 V in 2-V steps. The EU2 was left in this operating condition overnight to allow it to reach steady state. The DC bus voltage was then decreased back down to 28.5 V and then down to 22.6 V, then the EU2 was allowed to reach steady state overnight. Finally, the DC bus voltage was increased back to 28.5 V.

Sensitivities were calculated as the DC bus voltage changed from 28.5 to 34.4 V. Two values were calculated as the sensitivities were slightly different between ASC A and ASC B. Note also that the sensitivities will vary slightly depending on the generator operating point.

- Hot-end temperature sensitivity: -3.1 to -3.2 °C/V
- ASC voltage sensitivity: -0.024 to -0.030 Vrms/V
- ASC amplitude sensitivity: 0.009 to 0.012 mm/V

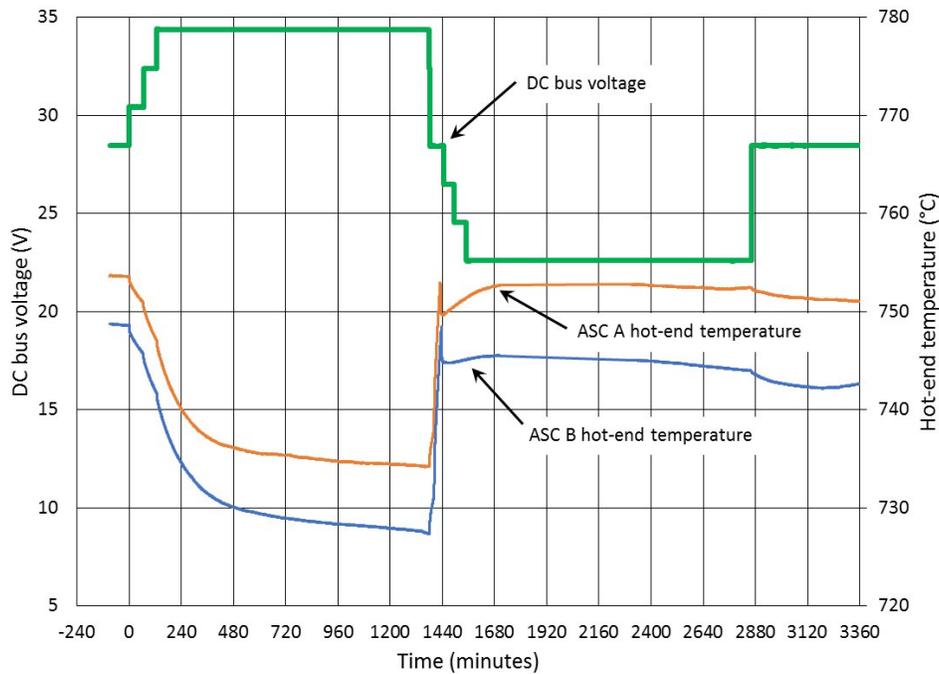


Figure 10.—Direct current (DC) bus voltage variation test results.

Overall, the effect of DC bus voltage change is small and could be part of the mission's considerations when interfacing to the ASRG. Further refinements to the DC bus voltage compensation algorithm could reduce the sensitivities (Ref. 8). The EDU 4.1 sensitivities were significantly smaller than sensitivities observed during EU testing with EDU 1.

The data in Figure 10 also show that between 28.5 and 22.6 V, the effect of changing the DC bus voltage on the ASC operating point was much less. This is because below a certain spacecraft DC bus voltage, the controller does not decrease the DC voltage being applied to the ASC alternator terminals through the H-bridge.

In addition to affecting the ASC operating point, changing the spacecraft DC bus voltage also affects the ACU power consumption. When the DC bus voltage was increased from 28.5 to 34.4 V, the ACU power consumption increased 2.0 W_e from 20.4 to 22.5 W_e (or 0.35 W_e per one volt change in DC bus voltage). ACU power consumption was the lowest around 28 V and it increased as well when DC bus voltage was decreased to 22.6 V.

Disturbance Force

The ASRG is a dynamic power system with moving parts that oscillate at 102.2 Hz. Each moving part generates a sinusoidally varying inertial force, and the sum of those forces approximately equals the disturbance force transmitted to the spacecraft. The actual force depends on the ASRG mounting interface and how the force is transmitted through the GHA. In the ASRG, the ASCs are operated with the pistons moving opposed to each other, so that the dynamic force from one ASC nominally cancels out the dynamic force from the other.

Figure 11 shows a phasor diagram of the inertial forces from the two converters, with the residual force, F_D , as the disturbance force. The ASRG has three parameters that can be used to tune the system to reduce the disturbance force. The most important one is the ASC phase adjust, which controls the phase angle between the two converters ($\phi_{B/A}$ in Fig. 11). The other two parameters are the ASC voltage setpoints, which control the amplitudes of each converter, and thus the magnitudes of the inertial forces. Since displacer amplitude generally increases with piston amplitude, increasing the ASC voltage setpoint increases both the displacer and piston inertial forces. Another parameter shown in Figure 11 is the displacer phase angle, which determines the angle between the displacer and piston inertial forces; however, this can only be changed during fabrication of the converter.

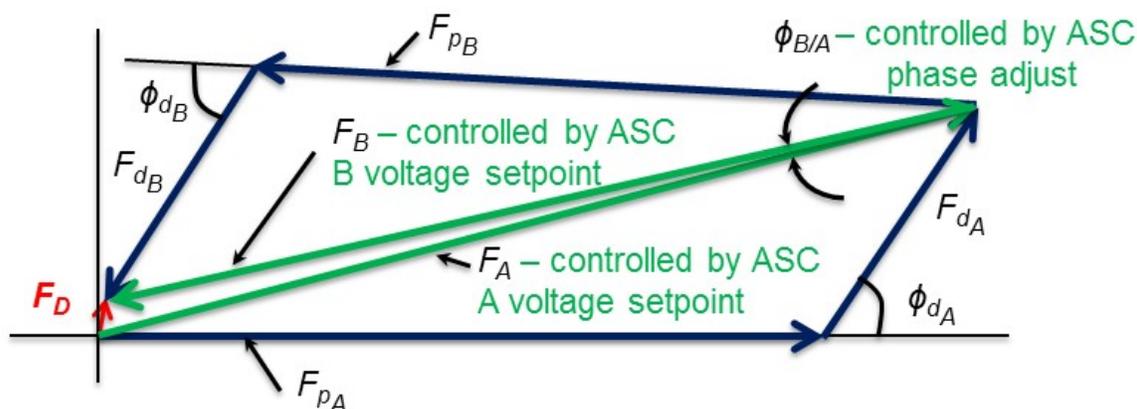


Figure 11.—Phasor diagram of disturbance force as a sum of piston and displacer inertial forces.

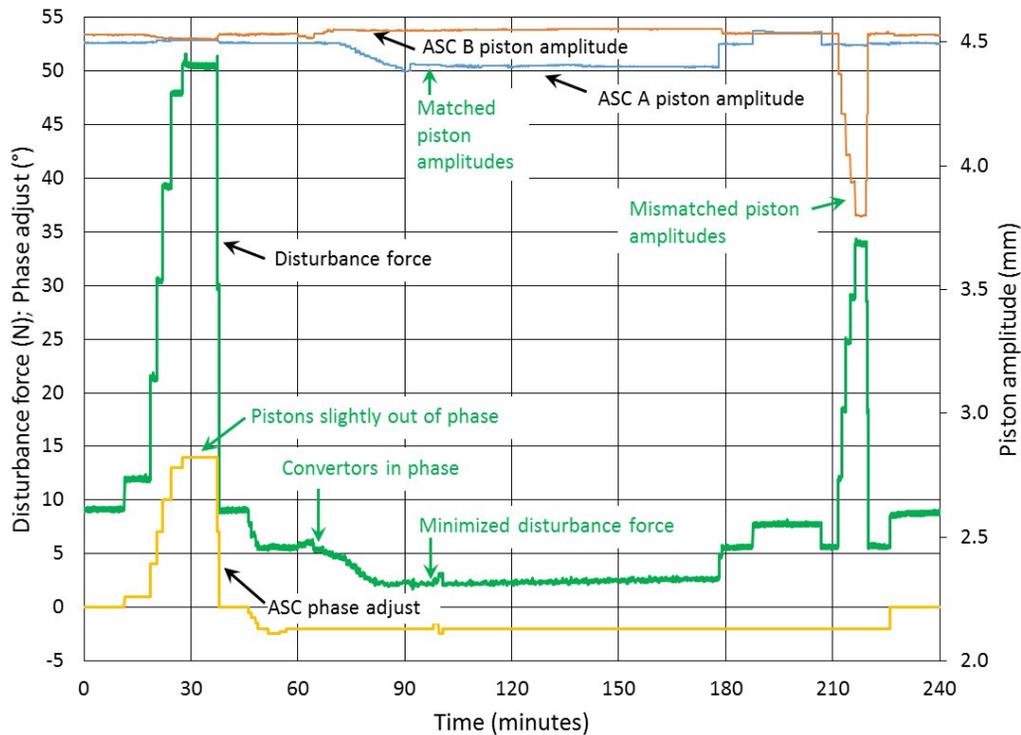


Figure 12.—Effect of varying phase and piston amplitude on the disturbance force.

A test was conducted in which the ASC phase adjust and the piston amplitudes were varied and the effect on disturbance force was measured (Fig. 12). First, the ASC phase adjust was increased to 14° , which resulted in an increase in disturbance force from 9 to 51 N, exceeding the specification limit of 35 N. Disturbance force increased 3.0 N per degree change in phase angle. The phase angle was then decreased below 0 to find the point of minimum disturbance force. This occurred at -2.0° , and it reduced the force to 5.4 N. The reason the minimum did not occur at 0° is that the controller is setting the relative phase of the two ASC voltages to 0° , but because of manufacturing differences in the two convertors, the phase relationships between the voltage and piston motion are not identical.

With the inertial forces of the two convertors in phase, the amplitudes were adjusted to further reduce the disturbance force. It was found that decreasing ASC A voltage setpoint and thus ASC A piston amplitude reduced the disturbance to 2.1 N. At this point the fundamental component of the disturbance force was reduced to less than the second harmonic. (Note that in Fig. 12, it appears that the ASC A piston amplitude was reduced to less than ASC B piston amplitude to minimize the disturbance force. But it is likely that due to uncertainty in the amplitude measurement, the point of minimal disturbance force is where the piston amplitudes are in fact closely matched.)

Lastly, the piston amplitude of one convertor was decreased to measure the effect of piston amplitude on disturbance force. ASC B's piston amplitude was decreased from about 4.5 to 3.6 mm, which increased the disturbance force to 34 N. Expressed as a sensitivity, the disturbance force increased 38 N per mm change in piston amplitude.

The disturbance force test confirmed that control of phase angle is more important to minimizing disturbance force than matching piston amplitudes. The piston amplitude range that was tested exceeded the allowable steady-state operating range, given hot-end temperature constraints.

Conclusion

The Advanced Stirling Radioisotope Generator (ASRG) Engineering Unit 2 (EU2), which is based on the ASRG flight design, has been an important test article for maturing Stirling system technology. Initial characterization of the ASRG EU2 has been completed, with test results that were as expected. The Engineering Development Unit (EDU) 4.1 controller demonstrated stable performance with good convertor control that was even better than alternating current bus control. All of the issues that had been identified during early EU testing were shown to be resolved with the EU2 configuration.

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