NASA/TM—2011-217101 NETS–2011–3609

Natural Convection Cooling of the Advanced Stirling Radioisotope Generator Engineering Unit

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November 2011

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Prepared for the
Nuclear and Emerging Technologies for Space (NETS-2011)
cosponsored by ANS Aerospace Nuclear Science and Technology Division,
the ANS Trinity Section, and the AIAA
Albuquerque, New Mexico, February 7–10, 2011

National Aeronautics and
Space Administration

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November 2011

Acknowledgments

This work is funded through the National Aeronautics and Space Administration (NASA) Science Mission Directorate, the Radioisotope Power Systems Program Office, and the U.S. Department of Energy. Any opinions, findings, conclusions, or recommendations expressed in this article are those of the authors and do not necessarily reflect the views of NASA. The authors wish to acknowledge the many people who supported ASRG EU testing in the Stirling Research Laboratory at the NASA Glenn Research Center and at Lockheed Martin, Valley Forge. The authors further wish to acknowledge Amy Delisa and Amar Setty for thermal analysis results.

This report contains preliminary findings, subject to revision as analysis proceeds.

Level of Review: This material has been technically reviewed by technical management.

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Abstract

After fueling and prior to launch, the Advanced Stirling Radioisotope Generator (ASRG) will be stored for a period of time then moved to the launch pad for integration with the space probe and mounting on the launch vehicle. During this time, which could be as long as 3 years, the ASRG will operate continuously with heat rejected from the housing and fins. Typically, the generator will be cooled by forced convection using fans. During some of the ground operations, maintaining forced convection may add significant complexity, so allowing natural convection may simplify operations. A test was conducted on the ASRG Engineering Unit (EU) to quantify temperatures and operating parameters with natural convection only and determine if the EU could be safely operated in such an environment. The results show that with natural convection cooling the ASRG EU Stirling convertor pressure vessel temperatures and other parameters had significant margins while the EU was operated for several days in this configuration. Additionally, an update is provided on ASRG EU testing at NASA Glenn Research Center, where the ASRG EU has operated for over 16,000 hr and underwent extensive testing.

Introduction

The Advanced Stirling Radioisotope Generator (ASRG) is being developed for flight by Lockheed Martin under contract to the Department of Energy (DOE). In addition to designing the generator itself, all of the processes for fueling, handling, storing, spacecraft integration, and launch need to be planned in sufficient detail taking into account all generator operating parameters. The period from generator fueling to launch can be as long as 3 years and includes numerous activities performed while the generator continues to operate, generating electric power and rejecting heat to the environment. Typically, the generator will be cooled by forced convection using fans. During some of the ground operations, maintaining uninterrupted forced convection may add significant complexity, allowing natural convection to simplify some operations. Examples are unpacking and inspecting the generator after shipment, onsite transportation, spacecraft integration, and space vehicle integration before forced air can be supplied in the fairing. During natural convection cooling the heat transfer from the generator housing and fins to the ambient air is much less efficient, and as a result the generator housing temperatures rise to maintain the same heat flux. While the ASRG is designed to operate over a wide temperature range, temperatures of the Stirling convertor pressure vessel (PV) cannot exceed 115 °C set by the magnet material in the alternator (Ref. 1). As some operations must assume temporary exposure to the Florida summer heat, worst-case thermal analysis predictions using conservative assumptions for natural convection heat transfer predicted minimal temperature margin for operation in these conditions. Test results can be used to correlate models and analysis replacing conservative assumptions with hard data and providing added confidence to finalize procedures.

A test was conducted on the ASRG Engineering Unit (EU) to quantify temperatures and operating parameters with natural convection only. The EU was designed and fabricated by Lockheed Martin. It underwent a series of system-level tests to qualification-level thermal and dynamic environments at Lockheed Martin and was delivered to the NASA Glenn Research Center (GRC) on August 28, 2008, for extended operation. The EU underwent inspection at GRC followed by integration into a test facility specially designed for it. The natural convection cooling test was conducted in this facility (Ref. 2).

Nomenclature

ASC	Advanced Stirling Convertor
ASRG	Advanced Stirling Radioisotope Generator
BOM	Beginning of Mission
CSAF	cold-side adapter flange
DOE	Department of Energy
EDU	Engineering Development Unit
EU	Engineering Unit
GPHS	General Purpose Heat Source
GRC	Glenn Research Center
HVAC	heating, ventilation, and air conditioning
PV	pressure vessel

Test Configuration

The natural convection test was conducted using the ASRG EU under Engineering Development Unit (EDU) 1 Advanced Stirling Convertors (ASCs) Controller Unit (ACU) control. The EDU 1 ACU controls and synchronizes the two ASCs using power electronics. The ASRG EU was mounted vertically on a rigid test table in GRC's Stirling Research Laboratory with the outboard end pointing up (Figs. 1 and 2). The outboard convertor, ASC A, is ASC–E #2 and the inboard convertor, ASC B, is ASC–E #3. The heat sources consist of cartridge heaters in a nickel block controlled to a fixed heat input.

During most of the ASRG EU testing at GRC, heat rejection from the EU has been accomplished by circulating cooled air around the EU in a Lexan cage (Fig. 2). Auxiliary fans were incorporated to improve heat transfer through forced convection from the ASRG EU housing to the air.

For the natural convection test, the air around the ASRG EU was made as quiescent as possible. The air duct above the EU was blocked off with foam. The ASRG EU is located in a partitioned area in a corner of the Stirling Research Lab. The partitioned area is 3.4 by 4.9 m with a 2.9-m drop ceiling above. The bottom 0.79 m of the partition is an open grille, and there is a 0.74 m gap between the top of the partition and the drop ceiling, leaving a 1.4-m Lexan barrier. The heating, ventilation, and air conditioning (HVAC) unit for the room was located outside the partitioned area, but created strong air currents that carried into the partitioned area. To prevent these currents from affecting the test, plastic sheeting was taped over the grille and between the top of the partition wall and the drop ceiling (Fig. 3). After installing the plastic sheeting there still was a 0.81 m gap to the windows (left side of Fig. 3), as the drop ceiling did not extend all the way back to the windows. But this was on the side away from the air currents and likely had minimal effect inside the partitioned area.

Figure 1.—ASRG EU in test facility at NASA GRC's Stirling Research Laboratory.

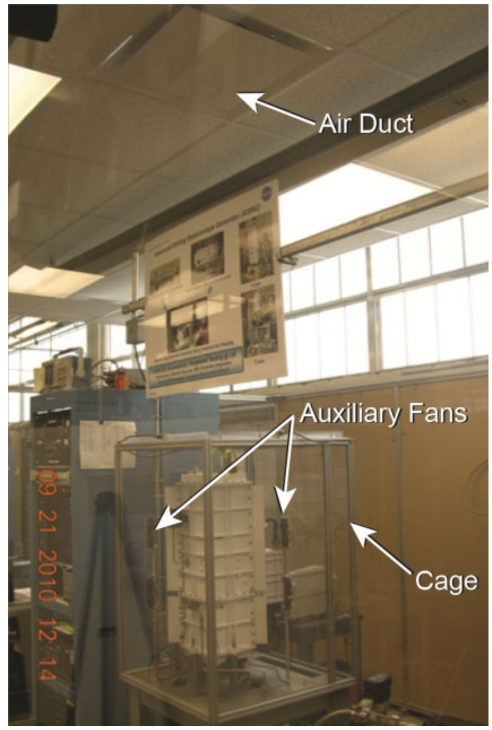


Figure 2.—ASRG EU in the test facility; auxiliary fans and overhead ventilation duct.

Figure 3.—Partitioned test area with plastic sheeting to block air currents.

Rejected Heat Load

This test was conducted with a rejected heat load that was slightly higher than is expected for the ASRG flight unit. Power into the heat sources was 252.9 and 266.0 W for ASC A and ASC B, respectively. Electric power from the alternators was 61.0 and 62.9 W. The difference between heat input to the ASRG EU and electric power output is the total amount of heat rejected through insulation loss, rejection at the convertor cold end, and other losses. Ultimately, the difference of 395 W is conveyed to the ASRG EU housing.

The ASRG flight unit rejected heat load is estimated knowing the Beginning of Mission (BOM) General Purpose Heat Source (GPHS) module heat output is between 244 and 258 W (Ref. 1). The electric heat input to the convertors during ground operations will be less than BOM in vacuum due to increased insulation losses from the argon cover gas inside the ASRG. For example, with nominal fuel loading of 250 W, if the alternator electrical output is only 112 W, the flight heat load would be 250 W × 2 – 112 W = 388 W.

In addition, the ASRG EU has the controller mounted on one side, decreasing effectiveness of that side whereas the flight controller will be mounted remotely on the spacecraft. The controller also generates some heat from internal electrical losses. Housing temperatures on the controller side were generally a degree or more higher than temperatures on other sides of the ASRG EU.

Test Results

Although this test focused on natural convection cooling, data were taken under other conditions for comparison. Four test cases were studied:

1. Forced convection cooling with ASRG EU inside cage, vertical orientation
2. Forced convection cooling with ASRG EU in ambient air, vertical orientation
3. Natural convection cooling with ASRG EU in ambient air, vertical orientation
4. Natural convection cooling with ASRG EU in ambient air, horizontal orientation, not steady-state

Data were recorded during the transitions from one test case to the next, providing a clear indication of relative changes and quantifying thermal response times. Table I chronicles the steps taken in transitioning from test case 1 (forced convection in cage) to test case 2 (forced convection in ambient air) to test case 3 (natural convection). Case 4 is a natural convection test briefly run at Lockheed Martin with the ASRG EU in the horizontal orientation. The test was performed at the end of an EMI test in an anechoic chamber. Due to the necessity to eliminate all outside sources of electrical noise, normal air ventilation in the 15- by 8-m and 8-m-high chamber is limited, resulting in a very quiescent environment. The generator was operated for about 65 min with cooling fans turned off, and temperatures had not reached steady state when the test was terminated.

TABLE I.—TEST SEQUENCE OF EVENTS

Date	Time	Hours (Fig. 4)	Event
21 Sept 10	17:30	<0	Blocked HVAC duct above ASRG EU with foam. **Test case 1.**
22 Sept 10	10:24:08	0.0	Popped open top and duct door on cage around ASRG EU; fans off
22 Sept 10	10:24:26	0.005	Turned on fans to maintain cooling
22 Sept 10	10:45:38	0.358	Turn off fans. Install four thermocouples near ASRG EU housing
22 Sept 10	10:52:30	0.473	Turn on fans; begin taking data with forced convection. **Test case 2.**
22 Sept 10	13:09:52	2.762	Turn off fans to begin natural convection cooling
22 Sept 10	17:30	7.098	Put up plastic sheeting over door to partition
23 Sept 10	10:00 to 10:45	23.598 to 24.348	Install plastic sheeting around top of partition
23 Sept 10	13:00 to 13:45	26.598 to 27.348	Install plastic sheeting around base of partition. **Test case 3.**
23 Sept 10	19:22	32.964	Open plastic sheeting over door and around a portion of base of partition
27 Sept 10	10:59 to 11:30		Remove all plastic from around partition; HVAC duct remains blocked

TABLE II.—ASRG EU COOLING TEST CASES

Parameter	1. Forced convection cooling in cage		2. Forced convection cooling in ambient air		3. Natural convection cooling in ambient air		4. Natural convection cooling in ambient air horizontal	
	ASC A	ASC B	ASC A	ASC B	ASC A	ASC B	ASC A	ASC B
PV temperature (°C)	66.8	66.7	61.7	62.8	92.6	90.6	[a]86.0	[a]84.9
Hot-end temperature (°C)	616.2	612.6	614.2	610.3	628.6	635.2	611.2	604.4
Cold-end temperature (°C)	62.2	61.8	56.9	57.9	88.9	86.6	[a]84.6	[a]83.5
CSAF temperature (°C)	59.4	58.9	54.0	55.0	86.2	83.9	[a]81.9	[a]80.8
Average housing temperature (°C)	42.6	40.8	37.2	37.2	68.7	64.2	[a]64.2	[a]60.8
Piston amplitude (mm)	4.30	4.36	4.31	4.36	4.27	4.29	b	b
Alternator power (W)	63.58	65.91	64.39	66.23	60.35	62.45	62.3	61.0
Alternator voltage (Vrms)	9.98	9.74	9.85	9.61	10.79	10.55	10.81	10.08
Alternator current (Arms)	7.93	8.42	8.02	8.49	7.67	8.11	7.95	8.02
Ambient temperature (°C)	22.2		22.6		25.4		[c]19	

[a]Not steady-state values; steady-state values will be higher.
[b]Adjusted to maintain hot-end temperature below 630 °C.
[c]Estimated.

Temperatures and other parameters from the four test cases are summarized in Table II. The PV temperatures represent the reading from a thermocouple mounted on the PV surrounding the alternator. The hot-end temperature is an average of three thermocouple measurements in the heat collector. The cold-end temperature is an estimate of the temperature of the cold-end heat exchanger inside the convertor based on surface temperatures of the cold-side adapter flange (CSAF), a part of the ASC that conducts rejected heat to the housing. The average housing temperature is an average of four or five thermocouples mounted around the ASRG EU housing adjacent to the point on the housing where the CSAF is attached. These will be among the highest temperatures on the surface of the generator.

The data in Table II show the maximum PV temperature reached was 92.6 °C, occurring during natural convection cooling in ambient air. This temperature results in a magnet temperature that is sufficiently below the maximum allowable. In almost all cases the temperatures on the inboard (lower) half of the generator (with ASC B convertor) are slightly lower than the temperatures on the outboard (upper) half of the generator (with ASC A convertor). The reason in the case of the vertically oriented generator may be that the air temperature surrounding the generator rises with height above the table as it picks up heat from the generator. Also, the four steel standoffs that support the ASRG EU conduct some heat away from the inboard end of the generator. This latter explanation may also apply when the generator is mounted horizontally.

Temperatures over time are shown in Figure 4. The time history shows that temperatures actually dropped by about 5 °C when the cage around the ASRG EU was removed. This is perhaps due to improved convection from changing airflow and reduced air temperatures, especially around the top part of the generator, which saw air temperatures several degrees above ambient temperature with the cage in place. The time history also illustrates how small changes in the ambient airflow influence generator temperatures. Note that temperatures consistently rose each time the airflow around the test area was successively impeded. The data in Figure 4 also provides an indication that the ASRG EU had reached steady-state condition for the various test cases.

The ASC A PV temperature was used to estimate the time response of the system when transitioning from forced to natural convection cooling. When fans were turned off at 2.762 hr, the ASC A PV temperature was 61.8 °C. Temperatures reached a quasi-steady-state condition by 7.098 hr, prior to plastic sheeting being put over the door to the partition, when the ASC A PV temperature was 87.5 °C. From the start of natural convection it took approximately 30 min to reach 63.2 percent of the steady-state temperature and 77 min to reach 90 percent of the steady-state temperature.

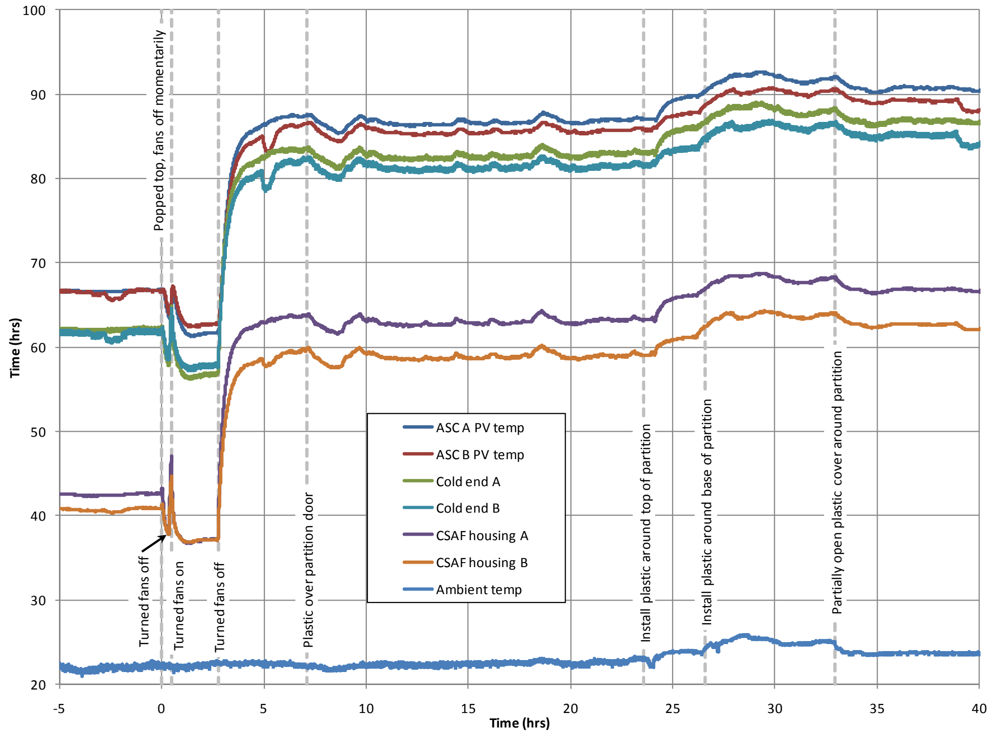


Figure 4.—Temperatures during test under forced and natural convection cooling.

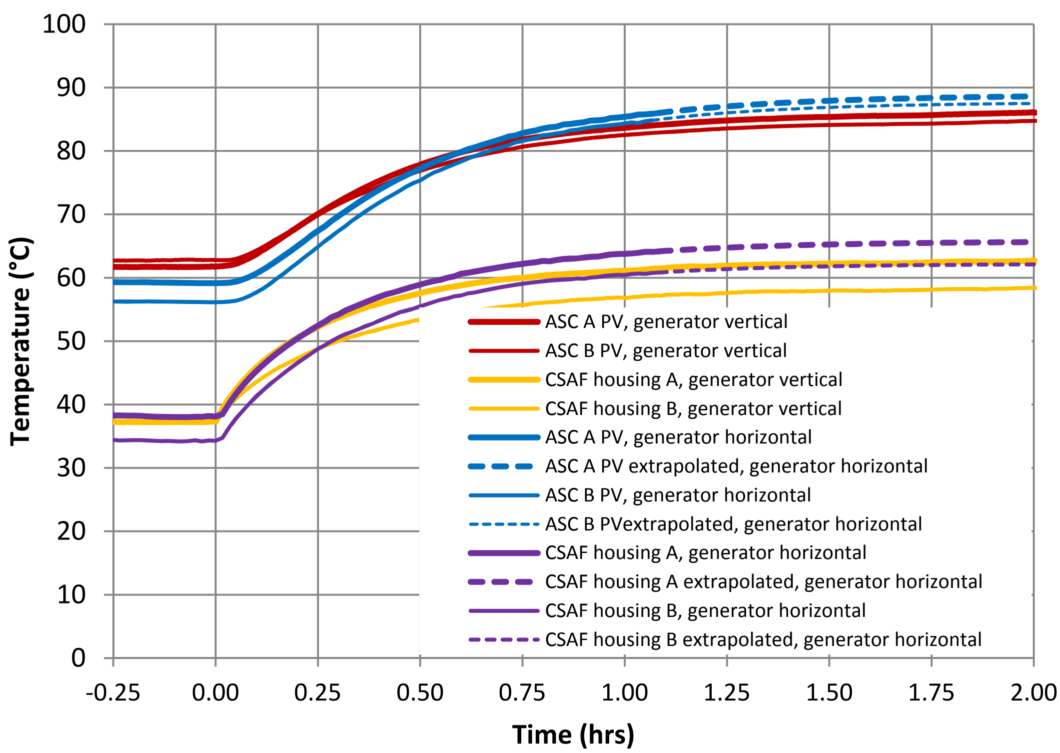


Figure 5.—Temperatures during transition from forced to natural convection cooling, vertical versus horizontal orientation.

It is expected that cooling would be less efficient with the generator horizontal since the air currents would not develop velocities as high as in the vertical orientation, and since a large face of the generator is pointed downward, limiting airflow. Figure 5 shows the temperature rise over time with natural convection cooling of a horizontally oriented generator and compares temperature rise over time with vertical versus horizontal orientation. Since the horizontal test was terminated before reaching steady-state, temperatures were extrapolated by the methodology described in Reference 3. Although the test conditions are not identical between the test conducted at GRC and the test conducted at Lockheed Martin, it can be reasonably inferred from the figure that the steady-state temperatures for a horizontally oriented generator would be a few degrees higher than a vertically oriented generator.

Airflow Measurements

To quantify to some extent the amount of forced convection and natural convection, air velocity measurements were made using a Model 8385A VelociCalc Plus air velocity meter. The measurements were made by holding the end of the probe against the ASRG EU (Fig. 6). This put the probe sensor about 10 mm from the ASRG EU. A small piece of foam insulation was taped to the probe tip (Fig. 6) so that the cool metal probe did not directly contact the warm ASRG EU housing, potentially causing thermal changes that would affect the air velocity reading. Air velocity measurements under forced convection are shown in Figure 7. The green arrow next to each air velocity reading indicates the orientation of the probe when the measurement was taken. In Figure 7, the yellow “8” with blue arrows indicate location and orientation of the auxiliary fans. Measurements were taken in line with the fans that are located at elevations corresponding to the locations of the convertor’s CSAFs, which conduct most of the rejected heat to the ASRG EU housing. Air velocities near the fans were between 2.2 and 6.6 m/s and decreased as the probe moved away from the fans.

Figure 6.—Air velocity probe held against ASRG EU housing (left); insulation on air velocity probe tip (right).

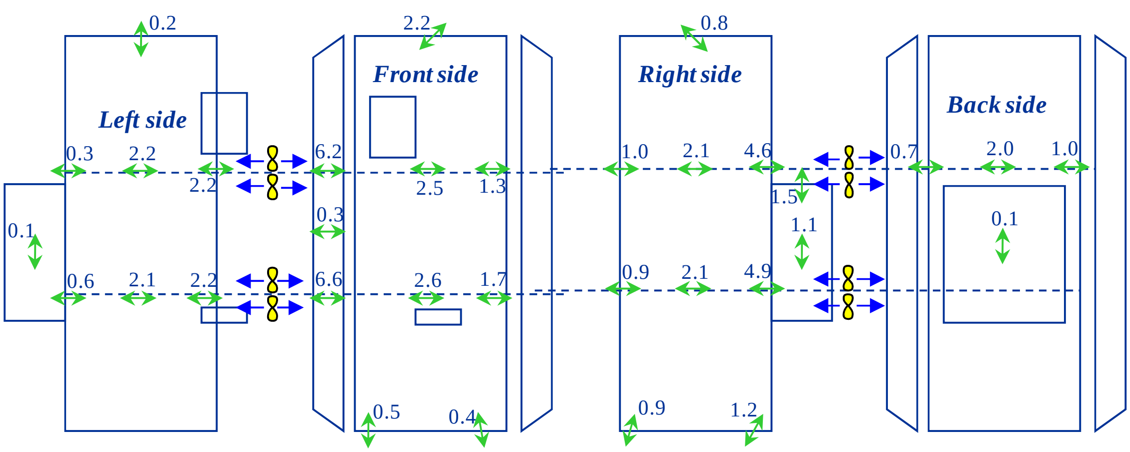


Figure 7.—Airflow measurements (m/s) under forced convection.

Under natural convection the air velocity measurements were read on the right side only. The other three sides had obstructions, which interfered to varying degrees with airflow, so the readings on the right side were deemed the most representative. The readings in Figure 8 show that air velocities were lowest at the bottom of the ASRG EU and reached 0.21 to 0.30 m/s at the top of the ASRG EU.

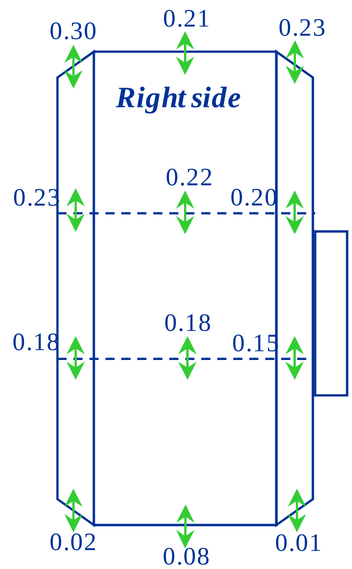
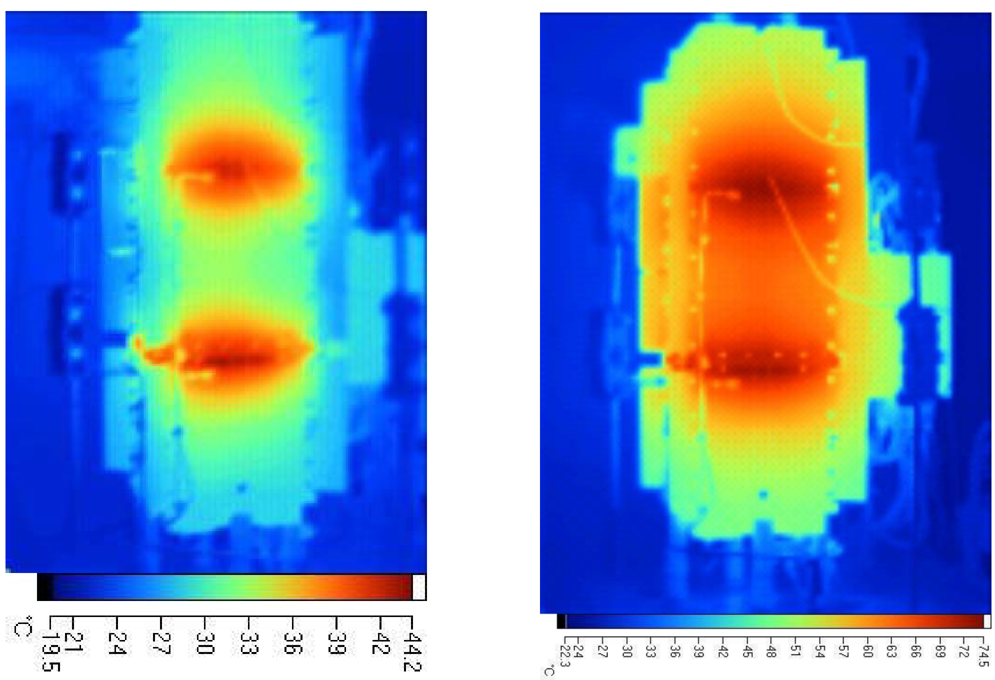


Figure 8.—Airflow measurements (m/s) under natural convection.

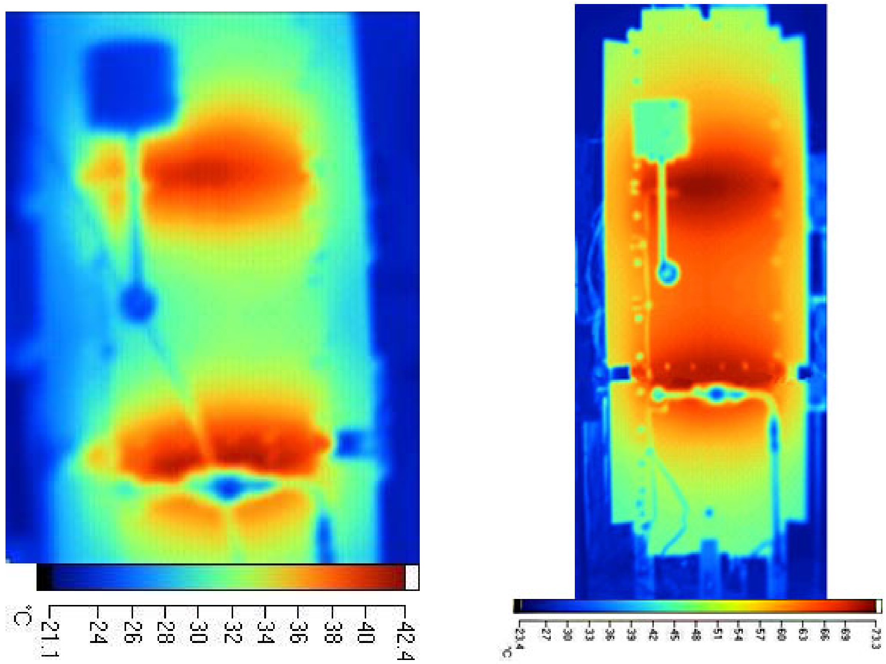
Thermal Imaging

An infrared (IR) camera, Fluke Ti45, was used to record thermal images of the ASRG EU to characterize temperature distribution on the housing and fins in both forced and natural convection conditions. IR images of the ASRG EU are compared in Figures 9 and 10. Under forced convection, housing temperatures are hottest near where heat is rejected internally at the CSAFs, then fall off quickly as one moves away from the area. In contrast, for the natural convection case, the temperature of the center portion of the generator is closer to that of the peak temperature and the peak temperature itself is 30 °C higher than the forced convection case. This illustrates how forced air cooling greatly enhances convection heat transfer.



(a) (b)

Figure 9.—ASRG EU right side thermal images: (a) forced convection, (b) natural convection.



(a) (b)

Figure 10.—ASRG EU front side thermal images: (a) forced convection, (b) natural convection.

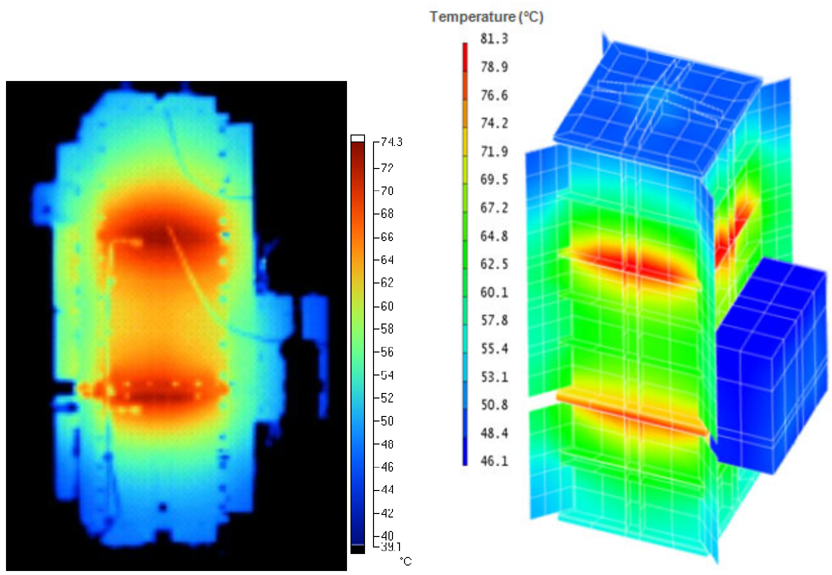


Figure 11.—ASRG EU natural convection cooling, IR image and analysis prediction.

Comparison of Thermal Model and Test Results

Figure 11 displays the IR camera image aside the temperature prediction determined by analysis prior to the test. The two images are very similar in that the hottest parts of the generator is shown where waste heat is rejected by the ASCs and temperature in the middle section of the generator is elevated. The peak temperature predicted by analysis is 7 °C higher than the measured temperature indicating that heat transfer via natural convection is more efficient than assumed in the analysis. The plan going forward is for the analytical model to be tuned to match the test data. Model tuning will yield more accurate heat transfer coefficients and allow more temperature margin to be demonstrated for operation scenarios where heat rejection via natural convection could be advantageous.

ASRG EU Update

The natural convection cooling test is just one of many tests that have been conducted on the ASRG EU at GRC since the generator began extended operation in 2008. A series of tests were conducted in 2009 and 2010 to characterize generator performance and operation in response to varying parameters and system inputs such as piston amplitude, heat input, cold-end temperature, PV temperature and DC bus voltage. These tests were conducted with an AC bus controller and with two different engineering-level controllers developed by Lockheed Martin. Some of these test results are documented in Reference 4. These tests have generated data for Lockheed Martin to use to develop system-level control and management strategies and to update the controller design in preparation for future Qualification and Flight generators.

The EU continues extended operation when it is not undergoing special tests. The purpose of the extended operation test is to demonstrate extended operation of an integrated system, to monitor for trends in generator performance, and to provide additional data from long-term operation of Stirling convertors. Representative convertor and generator power data from steady-state extended operation is shown in Figure 12. Convertor power represents the AC power measured from the convertors and input into the controller. Generator power is the DC power output from the controller into the DC bus. Data from time periods during which the generator was operated in off-nominal conditions for test purposes, such as the current effort, has been excluded from the plot for clarity. The ASRG EU was initially operated under AC bus control (Ref. 4) while the EDU 1 ACU underwent additional testing by Lockheed Martin. The ASRG EU began operation under EDU 1 ACU control on September 8, 2009, at 5234 hr. It has continued operation under ACU control since then, except for one brief period of operation under AC bus control for special tests. Additional details on ASRG EU testing can be found in Reference 5.

Comparing initial and current power levels for the convertors and the generator, there has been no significant change in power within the accuracy of the instrumentation. The small change in convertor power levels at 13,512 hr is due to a change in the test rack to reduce wiring impedance. Performance will continue to be monitored and tracked.

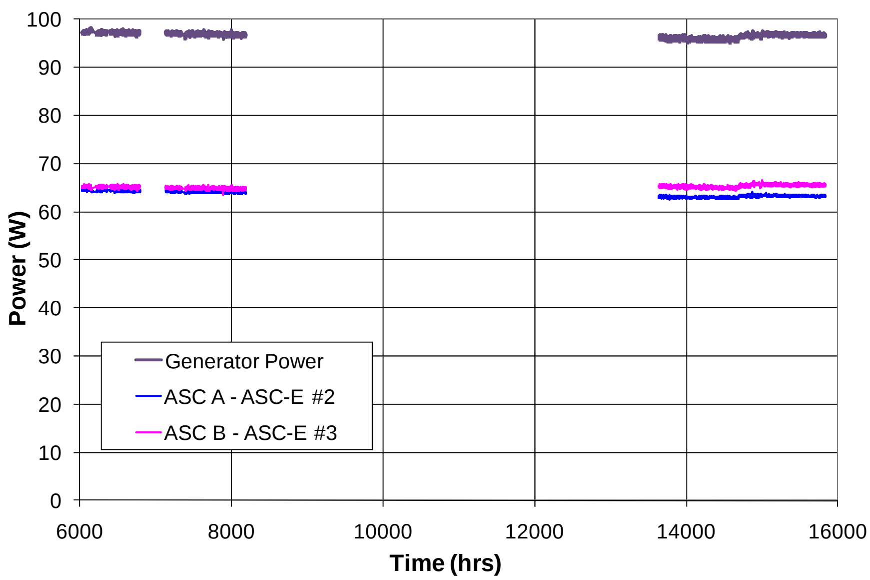


Figure 12.—ASRG EU and convertor power.

The ASRG EU's output power is less than the flight unit's output for a number of reasons. The EU was not designed to demonstrate full performance but to provide the opportunity to test a generator as an integrated system. EU incorporates the ASC–E convertors with a maximum hot-end temperature of 650 °C, not the more efficient ASC–E2 and later convertors with a maximum hot-end temperature of 850 °C. The generator housing is filled with argon, as the flight generator will be for ground operations. The argon reduces the efficiency of the insulation, resulting in less heat into the convertors and ultimately less power output. The ACU circuitry has not been optimized for performance as later controller designs have. Finally the power path uses a smaller gauge of wire than ideal, resulting in several watts power loss just in the lines.

Conclusion

The ASRG EU was operated with natural convection cooling in quiescent ambient air to characterize temperatures throughout the generator in this environment. With a rejected heat load near the upper limit of that expected for the flight unit and with a non-optimal cooling from a controller mounted to the side of the generator, the ASRG EU was able to maintain acceptable operating temperatures throughout the generator.

The ASRG EU continues extended operation at NASA Glenn Research Center and provides a platform for system-level tests in support of the ASRG flight project.

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REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

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1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
01-11-2011	Technical Memorandum	

4. TITLE AND SUBTITLE
Natural Convection Cooling of the Advanced Stirling Radioisotope Generator Engineering Unit

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Lewandowski, Edward, J.; Hill, Dennis

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER
WBS 138494.05.02.04.02

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
John H. Glenn Research Center at Lewis Field
Cleveland, Ohio 44135-3191

8. PERFORMING ORGANIZATION REPORT NUMBER
E-17609

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSORING/MONITOR'S ACRONYM(S)
NASA

11. SPONSORING/MONITORING REPORT NUMBER
NASA/TM-2011-217101

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified-Unlimited
Subject Category: 20
Available electronically at http://www.sti.nasa.gov
This publication is available from the NASA Center for AeroSpace Information, 443-757-5802

13. SUPPLEMENTARY NOTES

14. ABSTRACT
After fueling and prior to launch, the Advanced Stirling Radioisotope Generator (ASRG) will be stored for a period of time then moved to the launch pad for integration with the space probe and mounting on the launch vehicle. During this time, which could be as long as 3 years, the ASRG will operate continuously with heat rejected from the housing and fins. Typically, the generator will be cooled by forced convection using fans. During some of the ground operations, maintaining forced convection may add significant complexity, so allowing natural convection may simplify operations. A test was conducted on the ASRG Engineering Unit (EU) to quantify temperatures and operating parameters with natural convection only and determine if the EU could be safely operated in such an environment. The results show that with natural convection cooling the ASRG EU Stirling convertor pressure vessel temperatures and other parameters had significant margins while the EU was operated for several days in this configuration. Additionally, an update is provided on ASRG EU testing at NASA Glenn Research Center, where the ASRG EU has operated for over 16,000 hr and underwent extensive testing.

15. SUBJECT TERMS
Stirling convertor; Stirling radioisotope generator; Cooling; Heat transfer

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			STI Help Desk (email:help@sti.nasa.gov)
U	U	U	UU	17	**19b. TELEPHONE NUMBER** *(include area code)* 443-757-5802

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39-18