

Extended Operation of Stirling Convertors in a Thermal Vacuum Environment

Salvatore M. Oriti
Glenn Research Center, Cleveland, Ohio

The NASA STI Program Office . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program Office plays a key part in helping NASA maintain this important role.

The NASA STI Program Office is operated by Langley Research Center, the Lead Center for NASA's scientific and technical information. The NASA STI Program Office provides access to the NASA STI Database, the largest collection of aeronautical and space science STI in the world. The Program Office is also NASA's institutional mechanism for disseminating the results of its research and development activities. These results are published by NASA in the NASA STI Report Series, which includes the following report types:

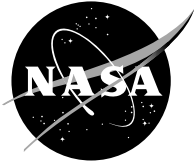
- **TECHNICAL PUBLICATION.** Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA's counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.
- **TECHNICAL MEMORANDUM.** Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.
- **CONTRACTOR REPORT.** Scientific and technical findings by NASA-sponsored contractors and grantees.

- **CONFERENCE PUBLICATION.** Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.
- **SPECIAL PUBLICATION.** Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.
- **TECHNICAL TRANSLATION.** English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services that complement the STI Program Office's diverse offerings include creating custom thesauri, building customized databases, organizing and publishing research results . . . even providing videos.

For more information about the NASA STI Program Office, see the following:

- Access the NASA STI Program Home Page at <http://www.sti.nasa.gov>
- E-mail your question via the Internet to help@sti.nasa.gov
- Fax your question to the NASA Access Help Desk at 301-621-0134
- Telephone the NASA Access Help Desk at 301-621-0390
- Write to:
NASA Access Help Desk
NASA Center for AeroSpace Information
7121 Standard Drive
Hanover, MD 21076



Extended Operation of Stirling Convertors in a Thermal Vacuum Environment

Salvatore M. Oriti
Glenn Research Center, Cleveland, Ohio

Prepared for the
Third International Energy Conversion Engineering Conference
sponsored by the American Institute of Aeronautics and Astronautics
San Francisco, California, August 15-18, 2005

National Aeronautics and
Space Administration

Glenn Research Center

Acknowledgments

The work described in this paper was performed for the Science Mission Directorate (SMD) and the Radioisotope Power System (RPS) Program, which provided funding for these projects.

Trade names or manufacturers' names are used in this report for identification only. This usage does not constitute an official endorsement, either expressed or implied, by the National Aeronautics and Space Administration.

Available from

NASA Center for Aerospace Information
7121 Standard Drive
Hanover, MD 21076

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22100

Available electronically at <http://gltrs.grc.nasa.gov>

Extended Operation of Stirling Convertors in a Thermal Vacuum Environment

Salvatore M. Oriti
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

A 110 watt Stirling Radioisotope Generator (SRG110) is being developed for potential use on future NASA exploration missions. The development effort is being performed by Lockheed Martin under contract to the Department of Energy (DOE). Infinia, Corp. supplies the free-piston Stirling power convertors, and NASA Glenn Research Center (GRC) provides support to the effort in a range of technologies. This generator features higher efficiency and specific power compared to alternatives. One potential application for the generator would entail significant cruise time in the vacuum of deep space. A test has been initiated at GRC to demonstrate functionality of the Stirling convertors in a thermal vacuum environment. The test article resembles the configuration of the SRG110, however the requirement for low mass was not considered. This test demonstrates the operation of the Stirling convertors in the thermal vacuum environment, simulating deep space, over an extended period of operation. The status of the test as well as the data gathered will be presented in this paper.

Nomenclature

<i>LMA</i>	Lockheed Martin Astronautics
<i>DOE</i>	Department of Energy
W_e	Watt electric
<i>GPHS</i>	General Purpose Heat Source
<i>SRG110</i>	Stirling Radioisotope Generator 110 W
<i>RTG</i>	Radioisotope Thermoelectric Generator
<i>TDC</i>	Technology Demonstration Convertor
<i>GRC</i>	Glenn Research Center
<i>LN2</i>	Liquid Nitrogen
<i>TRL</i>	Technology Readiness Level

I. Introduction

Lockheed Martin Astronautics (LMA) has been contracted by the Department of Energy (DOE) to develop a radioisotope powered generator for potential use in future exploration missions¹. The generator would nominally produce 110 W_e from two Plutonium-238 General Purpose Heat Source (GPHS) modules. The generator would use two Stirling cycle machines to convert thermal energy from the GPHS modules into electrical power, and has thus been named 110 watt Stirling Radioisotope Generator (SRG110). The SRG110 has potential multi-mission applications for Mars surface (i.e., in atmospheres) as well as deep space missions. The SRG110 offers the potential for higher efficiency and specific power than Radioisotope Thermoelectric Generators (RTG's). LMA's design for the SRG110 is shown in Fig. 1. The design consists of two 55 W_e Stirling convertors each being supplied heat by a GPHS module.

The power convertors used in the SRG110 were designed and manufactured by Infinia, Corp. of Kennewick WA. The convertor was designated the Technology Demonstration Convertor (TDC) while being developed under contract to DOE². A schematic of the 55 W_e TDC is shown in Fig. 2. Infinia, Corp. is presently a subcontractor to LMA as the development of the SRG110 continues.

NASA Glenn Research Center (GRC) has been supporting LMA's development of the SRG110³. Exploration missions that may utilize the SRG110 could involve continuous operation of the generator for upwards of 14 years. One of the ongoing experiments at GRC has two TDC's being operated in a thermal vacuum environment. The purpose of this experiment is to provide data for TDC's operating in a configuration and environment similar to the SRG110.

The experiment makes use of a vacuum chamber (Fig. 3) to simulate the vacuum of space, and a liquid nitrogen (LN2) cold shroud to simulate space-like temperatures. Per request of NASA Headquarters, the TDC's are planned to be operated in the thermal vacuum configuration for three years.

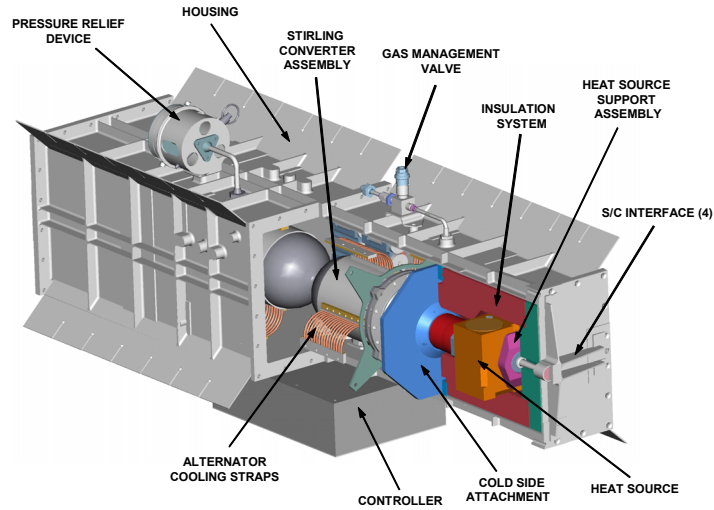


Figure 1.—Schematic of the SRG110 design by LMA.

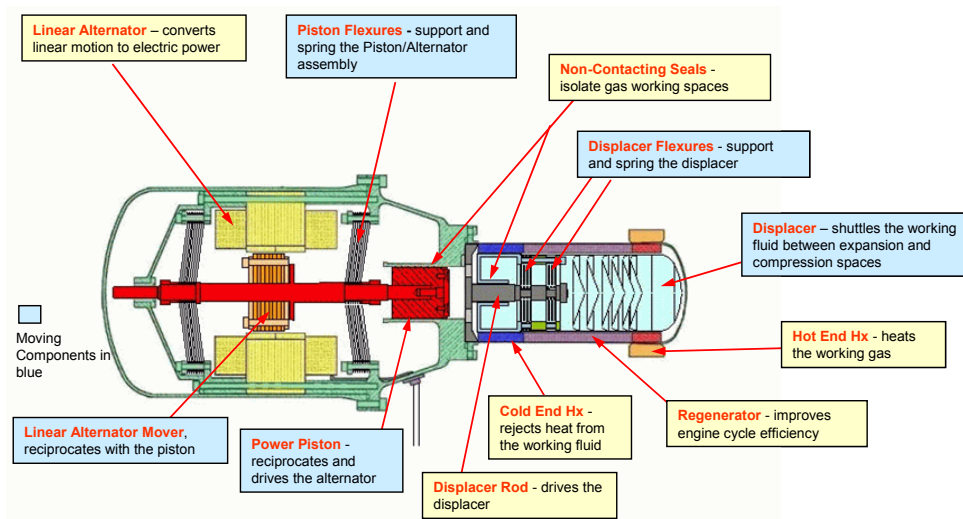


Figure 2.—Infinia, Corp. 55 W_c Technology Demonstration Converter (TDC).

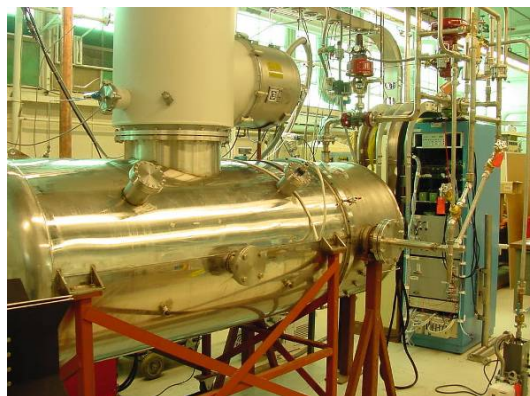


Figure 3.—Vacuum facility 67 at NASA GRC.

II. Test Setup

The test article consists of two Stirling TDC's (#5 and #6) mounted in the dual-opposed configuration. This means that the two converters are rigidly attached through their mounting flanges and their alternator sections are oriented toward the center as shown in Fig. 4. This configuration allows for dynamically balanced operation because the pistons move synchronously, but in opposite directions. Heat is provided to the Stirling cycle via an electric heater coupled to a heat collector (Fig. 5a). The heat collector is a cup-shaped component machined from nickel 201 that directs the thermal energy from the rectangular heater to the circumferential heat input zone of the TDC heater head. Heat is rejected from the Stirling cycle via a flange with attached radiation panels. The radiation panels then dissipate the heat to the liquid nitrogen shroud surrounding the entire test article.

The heat rejection flange is an assembly of nickel and copper sections (Fig. 5b). The nickel section is brazed to the heat rejection zone of the TDC heater head. Four triangular copper sections are then assembled onto each nickel section to increase the effective thermal conductivity of the flange. The copper pieces also form the four flat sides to which the radiation panels are attached. T-gon[®] 800 thermal interface material is installed between the contacting

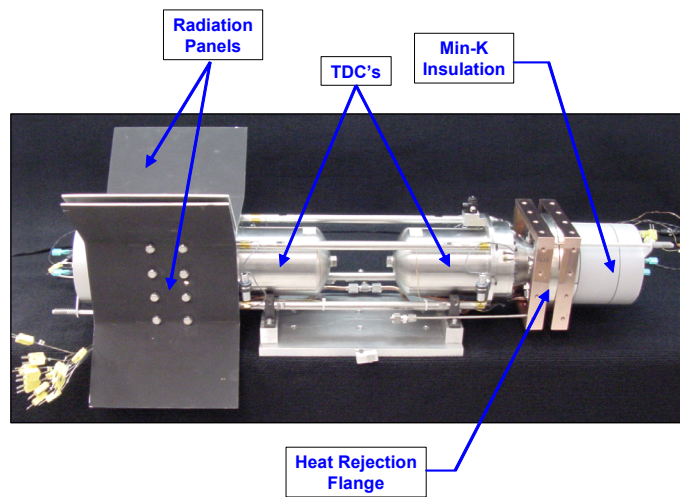


Figure 4.—TDC's in thermal vacuum configuration.

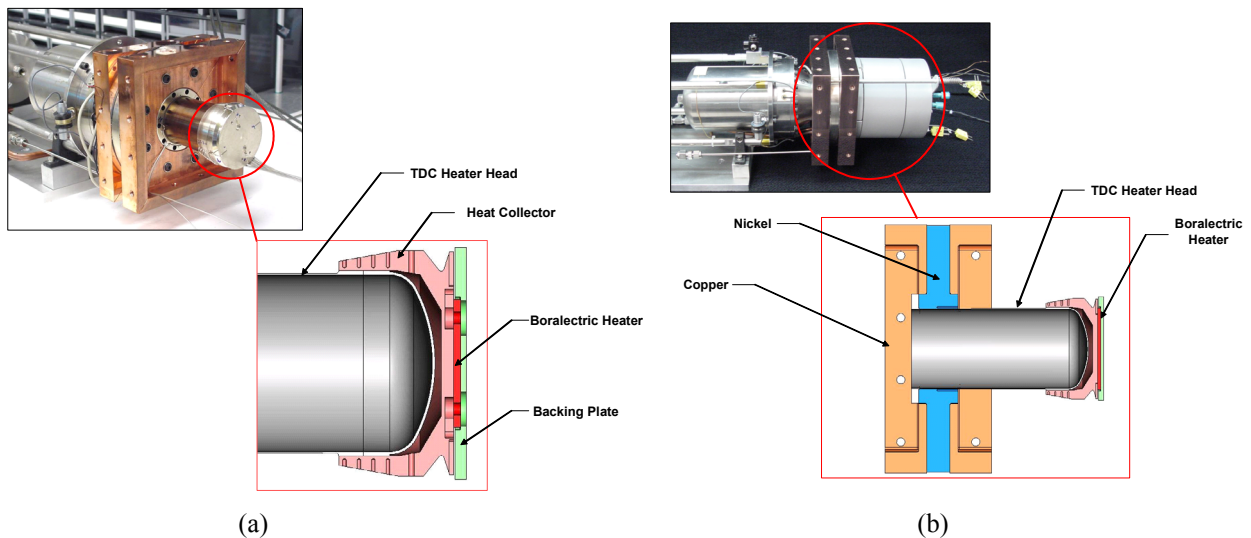


Figure 5.— (a) Heat input hardware. (b) Heat rejection hardware.

surfaces. This material consists of a 0.005 inch thick graphite sheet that helps reduce thermal contact resistance. The radiation panels are made of aluminum and coated with MIL-1-8625 to increase their surface emissivity. The hot-end and regenerator sections are insulated by Min-K[®] 1302, a machinable ceramic insulation manufactured by Thermal Ceramics, Inc.

III. Measured Versus Predicted Data

A system-level thermal analysis was performed to obtain temperature estimates of various components of the test article during steady-state operation. The ANSYS[®] three-dimensional model consisted of one convertor with its supporting hardware (radiation panels, heat rejection flange, heat collector, and insulation.). Figure 6a illustrates the applied boundary conditions used in the analysis. A heat load of +235 W was applied to the face of the heat collector, evenly distributed over the area occupied by the heating element. A temperature of 650°C was applied at the heat collector – heater head interface. A heat load of -220 W was applied to the inner diameter of the heater head, along the region occupied by the hot heat exchanger. A heat load of +170 W was applied to the inner diameter of the heater head along the region occupied by the cold heat exchanger. The heat generated in the alternator was modeled by applying a heat load of 10 W to the inner diameter of the alternator housing (alternator not shown). Each heat load boundary condition was applied in the form of heat flux applied over each respective area. The heat flux values were calculated by dividing each heat load by the appropriate area. A space node at a temperature of -109°C was used to model the LN2 shroud. These boundary conditions were determined from full power operating parameters measured during previous TDC testing at GRC.

Figure 6b compares data from the thermal analysis to data gathered during a comparable operating point in thermal vacuum. The axial temperature gradient along the heat collector agrees closely with the prediction. The measured rejection temperatures were 4% higher than those predicted while the radiator panel temperatures were 0.7% lower*. This suggests the thermal contact resistances between mating components of the heat rejection hardware is not negligible, as was assumed in the thermal analysis. The pressure vessel temperatures differ greatly from the predictions. The analytical results suggested the aft end of the pressure vessel (*PV top* in Fig. 6b), would be 63°C cooler than the fore end (*PV bottom* in Fig. 6b). The measured data shows a negligible difference between these two temperatures. Also, the maximum measured pressure vessel temperature is 6% higher than the prediction. One possible explanation for the inaccuracy is that the motion of the helium working fluid in the pressure vessel was not modeled. The helium in the bounce space experiences an oscillating motion which enhances heat transfer between the aft and fore ends of the pressure vessel. This may account for the reduced temperature gradient along the axial length. The minimum attainable LN2 shroud temperature was 38% lower than that used for the analysis, suggesting that the shroud has a larger heat dissipation capacity than predicted.

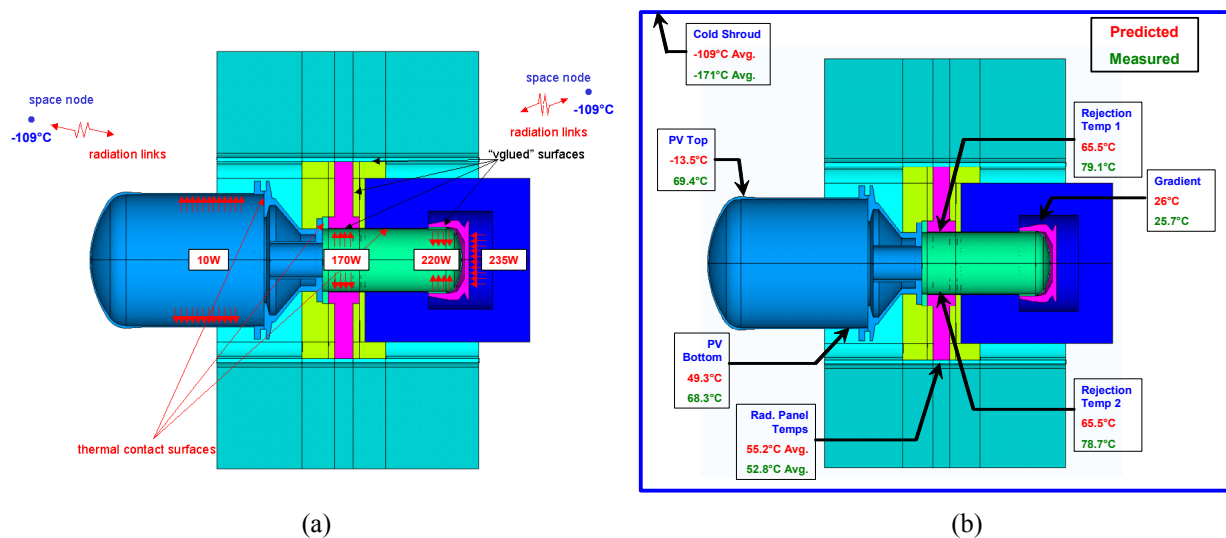


Figure 6.—(a) Thermal FEA boundary conditions. (b) Predicted vs. measured data.

* Temperature comparisons in this section are made using the absolute temperature scale.

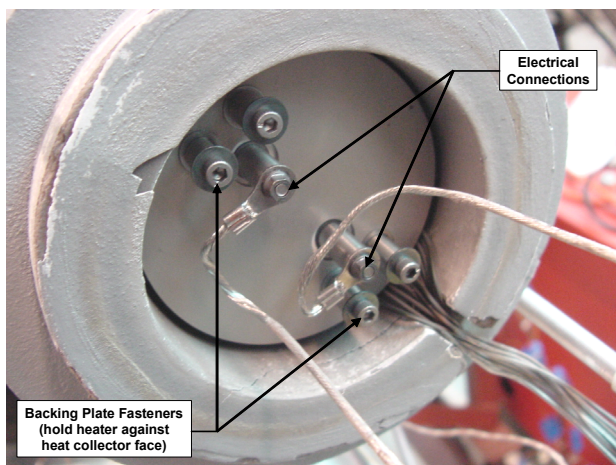


Figure 7.—Hot-end fastener redesign.

IV. Hot-End Fasteners

The initial test article design utilized molybdenum fasteners for the heater electrical connection and for the backing plate preload. The fasteners functioned during the initial checkout but lost preload upon return to ambient temperature. Analysis indicated the failure was caused by thermally induced stresses from differing thermal expansion coefficients. The thermal expansion coefficient of the heater is approximately 7.4 times that of molybdenum. The heater and fasteners both experienced a temperature change greater than 600°C. This induced a stress higher than the yield strength of molybdenum at that temperature, resulting in a permanent deformation. The connections were redesigned to improve their tolerance of the high temperatures. The goal of the new design was to minimize the stiffness of the fastening system and thus minimize the thermally induced stress. This was accomplished by maximizing the fastener lengths and minimizing the thickness of the spacers that filled each gap created by the longer fasteners (Fig. 7). The maximum length of the fasteners was restricted to 0.75 inches by the physical space available under the insulation cap. The spacers were fabricated from solid ¼ inch OD rod, with the minimum wall thickness limited to 0.015 inches by machining capability. The fasteners and spacers were made of A286 stainless steel; a precipitation hardened alloy exhibiting good yield strength and rupture life at the temperature range of interest.

V. Extended Operation Performance Data

The initial operating point (Fig. 8, label A) was limited to a 513°C hot-end temperature by several factors. It became evident early in thermal vacuum testing that the pressure vessel cooling was insufficient. At point A, the pressure vessel temperature exceeded 70°C and came close to the imposed limit of 75°C. The displacer was operating at its design amplitude while the piston was operating at only 5.75 mm; slightly less than its design amplitude of 6.00 mm. The rejection temperature also reached its design point of 80°C prematurely, indicating insufficient heat rejection capacity. All of these parameters prevented operation at the hot-end design temperature of 650°C. This scenario was alleviated by reducing the piston amplitude to 5.45 mm via the variable zener-diode controller while simultaneously increasing the hot-end temperature. This combination allowed an increase in hot-end temperature to 604°C while maintaining the rejection and pressure vessel temperatures (Fig. 8, label B). The power output increased slightly due to the greater Carnot efficiency from the higher temperature ratio. The hot-end fasteners survived for 157 hours at the 604°C temperature, at which time one of the spacers on the TDC 5 heater electrical connection melted, precipitating an automatic shutdown. This is depicted in the performance graphs by the sharp decline of all parameters shortly after point B. The hot-end fasteners were replaced and operation resumed. The data between points B and C was erratic due to multiple shutdowns related to facility issues such as power outages, vacuum leaks, and LN2 system failures. At point C, steady operation was achieved, but at a reduced hot-end temperature of approximately 430°C to prevent another fastener failure. The replacement fasteners have survived for over 1860 hours at this temperature, but there is evidence of fastener failure on the TDC 6 heater. The real-time average hot-end temperature plot of TDC 6 fluctuates by $\pm 0.5^\circ\text{C}$ in a sinusoidal fashion at a frequency of

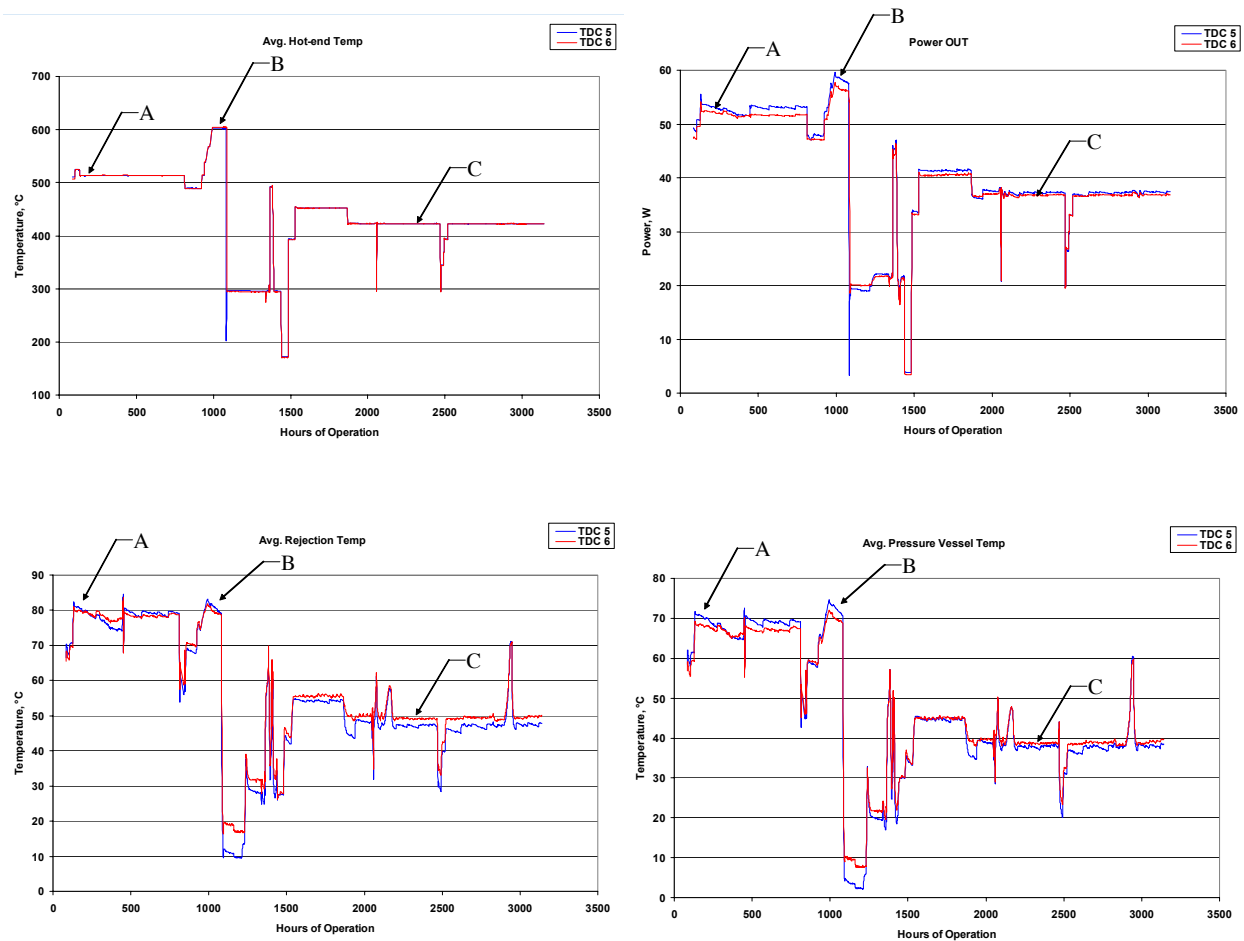


Figure 8.—Extended operation performance data.

1/80th Hz. This may be the result of loss of preload of the backing plate fasteners. This scenario is confirmed by the fluctuations in heater electrical resistance. The resistance of the pyrolytic graphite element decreases linearly with temperature. The electrical resistance also fluctuated, indicating a temperature change of the heater in accord with loss of thermal connectivity to the heat collector face. It is unknown why the cycle repeats rather than reaching a static deflection. Steady-state operation was also disrupted by helium leakage. The charge pressure of TDC 5 dropped about 1.3 psig per day, and required daily adjustment. The charge pressure of TDC 6 dropped at a slower rate, and required adjustment only once per week. The leak on TDC 5 has been attributed to a faulty weld on the feedthrough ring used to pass the piston position signal through the convertor housing (Fig. 9). Plans have been implemented to repair the deficiencies in the test article. The radiation panels will be replaced with larger units to allow more heat dissipation at the same 80°C rejection temperature. The heater electrical connection will be replaced with an entirely new mechanism using a spring loaded lead rather than a threaded fastener. This will enhance the reliability of the electrical connection during temperature cycles by better accommodating the thermal expansion of the heater. The material of the backing plate and its fasteners will be changed to Inconel 718[®] to better maintain clamping force at the high temperature. The pressure vessel will be modified to increase its emissivity by adding a layer of Kapton[®] tape. This will allow the same amount of heat to be dissipated at a lower surface temperature. The faulty feedthrough ring will be replaced with a spare unit.

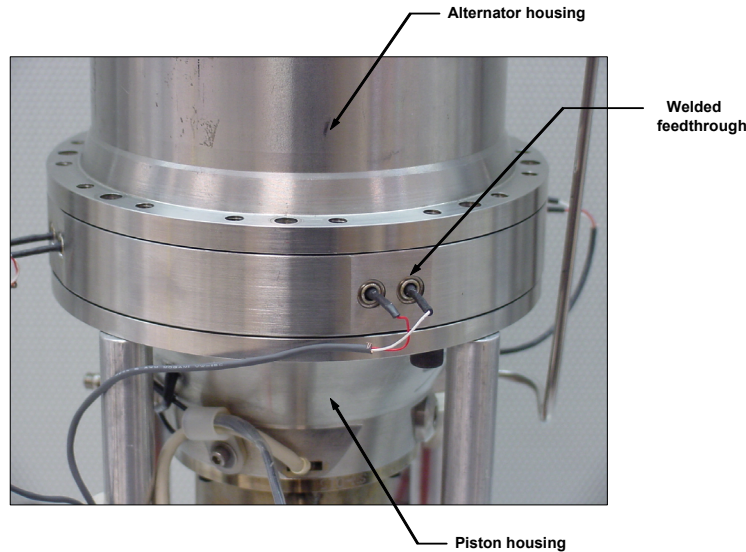


Figure 9.—Feedthrough ring.

VI. Conclusion

An experiment has been initiated at GRC to investigate operation of two TDC's in a thermal vacuum environment. Performance data gathered thus far has been presented, as well as the deficiencies encountered with the supporting hardware. As of July 1st 2005, TDC's #5 and #6 have accumulated 3200 hours of extended operation in the thermal vacuum configuration. After modifications to the supporting hardware have been made, the operating point will be adjusted as close as possible to the design point (650°C hot-end, 80°C cold-end, 6.00 mm piston amplitude). A milestone has been established to accumulate 5000 hours of operation in thermal vacuum by the end of fiscal year 2005. The overall goal of the experiment is to accumulate 25,000 hours of operation in thermal vacuum.

References

- ¹"Stirling Radioisotope Generator for Mars Surface and Deep Space Missions", Robert D. Cockfield and Tak S. Chan, 2002 Intersociety Energy Conversion Engineering Conference, Washington, DC, Paper No. 20188.
- ²"Stirling Converter Performance Mapping and Test Results for Future Radioisotope Power Systems", Songgang Qiu and Allen A. Peterson, 2003 International Energy Conversion Engineering Conference, Portsmouth, VA.
- ³"Extended Operation of Stirling Convertors", Mary Ellen Roth, Jeffrey G. Schreiber, and Stephen V. Pepper, 2004 Second International Energy Conversion Engineering Conference, Providence, RI. Paper No. AIAA 2004-5508

REPORT DOCUMENTATION PAGEForm Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE February 2006	3. REPORT TYPE AND DATES COVERED Technical Memorandum	
4. TITLE AND SUBTITLE Extended Operation of Stirling Convertors in a Thermal Vacuum Environment			5. FUNDING NUMBERS WBS-22-972-20-01	
6. AUTHOR(S) Salvatore M. Oriti				
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-15306	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Washington, DC 20546-0001			10. SPONSORING/MONITORING AGENCY REPORT NUMBER NASA TM-2006-213984 AIAA-2005-5747	
11. SUPPLEMENTARY NOTES Prepared for the Third International Energy Conversion Engineering Conference sponsored by the American Institute of Aeronautics and Astronautics, San Francisco, California, August 15-18, 2005. Responsible person, Salvatore M. Oriti, organization code RPT, 216-433-2066.				
12a. DISTRIBUTION/AVAILABILITY STATEMENT Unclassified - Unlimited Subject Category: 20 Available electronically at http://gltrs.grc.nasa.gov This publication is available from the NASA Center for AeroSpace Information, 301-621-0390.			12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) A 110 watt Stirling Radioisotope Generator (SRG110) is being developed for potential use on future NASA exploration missions. The development effort is being performed by Lockheed Martin under contract to the Department of Energy (DOE). Infinia, Corp. supplies the free-piston Stirling power convertors, and NASA Glenn Research Center (GRC) provides support to the effort in a range of technologies. This generator features higher efficiency and specific power compared to alternatives. One potential application for the generator would entail significant cruise time in the vacuum of deep space. A test has been initiated at GRC to demonstrate functionality of the Stirling convertors in a thermal vacuum environment. The test article resembles the configuration of the SRG110, however the requirement for low mass was not considered. This test demonstrates the operation of the Stirling convertors in the thermal vacuum environment, simulating deep space, over an extended period of operation. The status of the test as well as the data gathered will be presented in this paper.				
14. SUBJECT TERMS Space power experimentation; Stirling; SRG; Thermal vacuum			15. NUMBER OF PAGES 13	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT	

