

Oral Presentation/Viewgraphs Summary:

This paper focuses on extended operation testing and data analysis of free-piston Stirling convertors at the NASA Glenn Research Center (GRC). Extended operation testing is essential to the development of radioisotope power systems and their potential use for long duration missions. To document the reliability of the convertors, regular monitoring and analysis of the extended operation data is particularly valuable; allowing us to better understand and quantify the long life characteristics of the convertors. Further, investigation and comparison of the extended operation data to baseline performance data provides us an opportunity for understanding system behavior should any off-nominal performance occur. GRC currently has 14 Stirling convertors under 24-hour unattended extended operation testing, including two operating the Advanced Stirling Radioisotope Generator Engineering Unit (ASRG-EU). 10 of the 14 Stirling convertors at GRC are the Advanced Stirling Convertors (ASC) developed by Sunpower, Incorporated. These are highly efficient (up to > 33.5% conversion efficiency), low mass convertors that have evolved through technologically progressive convertor builds. The remaining four convertors at GRC are Technology Demonstration Convertors (TDC) from Infinia Corporation. They have achieved > 27% conversion efficiency and have accumulated over 178,000 of the total 250,622 hours of extended operation currently at GRC. A synopsis of the Stirling convertor extended operation testing and data analysis at NASA GRC is presented in this paper, as well as how this testing has contributed to the Stirling convertor's progression toward flight.



Stirling Converter Extended Operation Testing and Data Analysis at GRC

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Introduction

- Extended operation tests of Stirling convertors were initiated as a means to establish a life and reliability database
 - The missions where Stirling power conversion is often considered are generally long-duration missions of up to 14 years
- Glenn Research Center (GRC) has tested 16 convertors under 24-hour unattended extended operation
 - Four in a thermal vacuum environment
 - Two in the Advanced Stirling Radioisotope Generator Engineering Unit (ASRG EU)
 - Ten of the sixteen convertors tested at GRC are from different phases of Advanced Stirling Convertor (ASC) technology developed by GRC and Sunpower, Inc
 - Six convertors tested at GRC are Technology Demonstration Convertors (TDC) from Infinia Corporation



Convertors tested

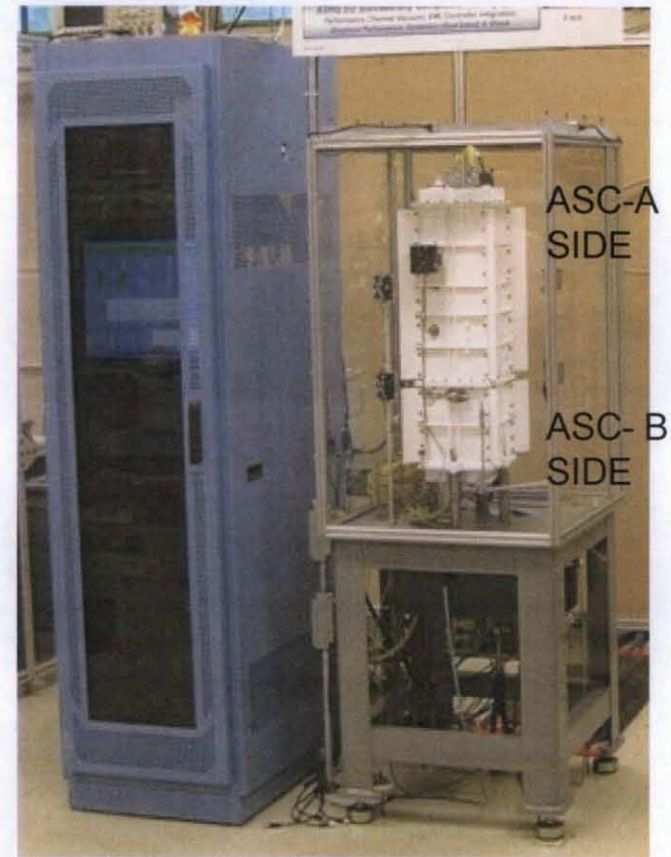
Convertor	Testing environment	Nominal operating temperature (hot/cold), °C	Date operation initiated	GRC hours per convertor	Status
TDC #13 & #14	In air	650/80	June 2003	47,200	Ongoing test
TDC #5 & #6	Thermal vacuum	630/70	Nov. 2004	10,543 & 10,382 as of Aug 2006	Completed test Aug 2006
TDC #15 & #16	In air	650/80	Mar. 2005	33,400	Ongoing test
ASC-0 #1 & #2	In air & thermal vacuum	645/72	Feb. 2007	15,363 as of Jan 2009	Ongoing test
ASC-0 #3 & #4	In air & launch simulation	650/90	Aug. 2007	12,700	Ongoing test
ASC-1 #3 & #4	In air	850/90	May 2007	1,817 as of June 2009	EMI testing
ASC-1HS #1 & #2	In air & launch simulation	850/90	Feb. 2008	2,823 & 4,106	Ongoing test
ASC-E #2 & #3	Generator in air & environmental	625/70	Oct. 2008	5,000	Ongoing test
ASC-E #1 & #4	In air & launch simulation	650/90	2009	53 & 0 as of April 2009	Future test
ASC-E2 #1 to #8	In air & launch simulation		2009		Future test



ASRG EU

IN718 heater head ($650\text{ }^{\circ}\text{C } T_{\text{hot}}$), hermetically sealed

- System integrator Lockheed Martin (LM) is under contract to the Department of Energy (DOE) to develop the ASRG
- The ASRG EU was designed and fabricated by LM
 - Incorporates two ASC-E converters from GRC and Sunpower, Inc.
 - Completed over 1,000 hours of environmental testing at LM
- Started extended operation at GRC in November 2008
 - A special test facility was designed and fabricated to operate the vertically oriented ASRG EU under controlled conditions
 - Enclosed in housing
 - Cooled air flowing over the unit



ASRG EU test station

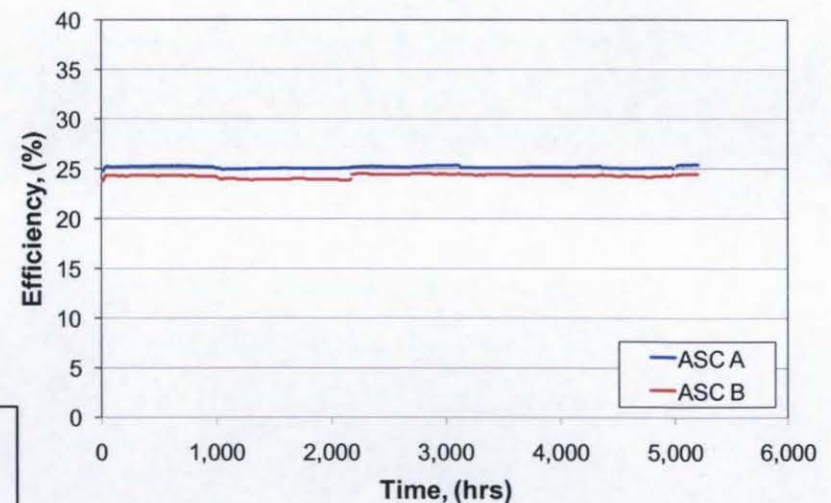
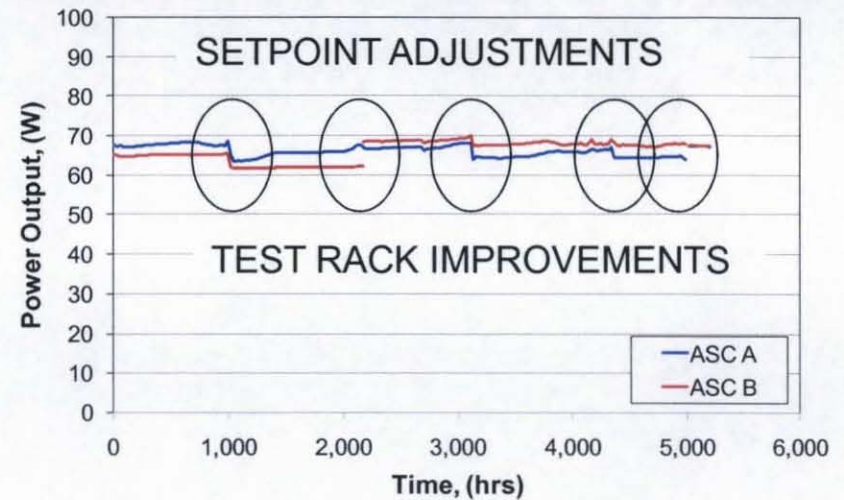
ASRG EU



IN718 heater head (650 °C T_{hot}), hermetically sealed

- Over 5,000 hours of continuous extended operation
- Initially under AC bus control to characterize performance independent of the Advanced Stirling Converter Control Unit (ACU)
 - Will operate on ACU control in August/September 2009
- Changes in test rack impedance resulted in a change in the operating point, affecting the piston amplitude and output power
 - Upgrades were made to the test rack to reduce the variations in impedance
 - Re-seated capacitor connections
 - Soldering/improving other connections

Overall performance data shows stable operation (with exception of manual adjustments) and no measurable change in performance



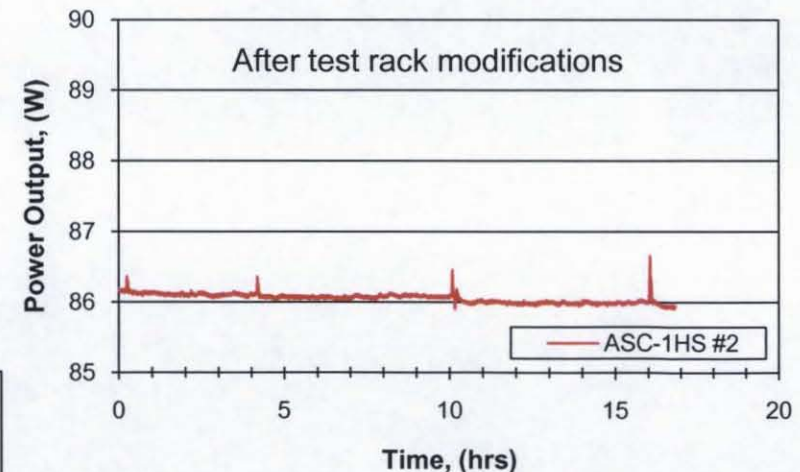
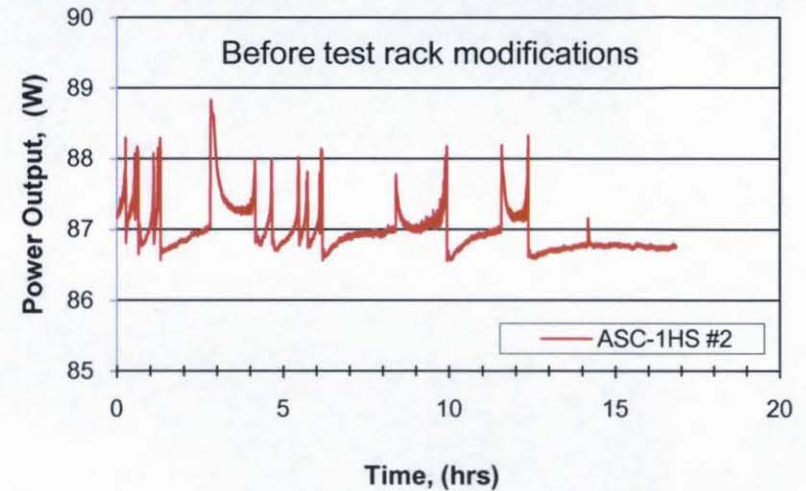


ASC-1 HS #1 & #2

MarM-247 heater head ($850\text{ }^{\circ}\text{C } T_{\text{hot}}$), hermetically sealed flange joints

- MarM-247 heater head allows for operation up to $850\text{ }^{\circ}\text{C}$
- Began operation in March 2008
 - Nearly 3,000 hours of operation on ASC-1 HS #1
 - 4,200 hours of operation on ASC-1 HS #2
- From $650\text{ }^{\circ}\text{C}$ to $850\text{ }^{\circ}\text{C}$ operation, power anomalies of 1-2 W above nominal occurred
 - Frequency of anomalies increased with hot-end temperature
- An investigation indicated the test rack's load panel was responsible for the anomalies. Test rack load panel modifications included:
 - Replaced the wire nuts on the transformer leads with solder joints
 - Repaired a poor solder joint found in the alternator power path
 - Removed an unnecessary relay in the power circuit

Although some anomalies still occur, there is a significant improvement in stability of the convertor operating point since modification

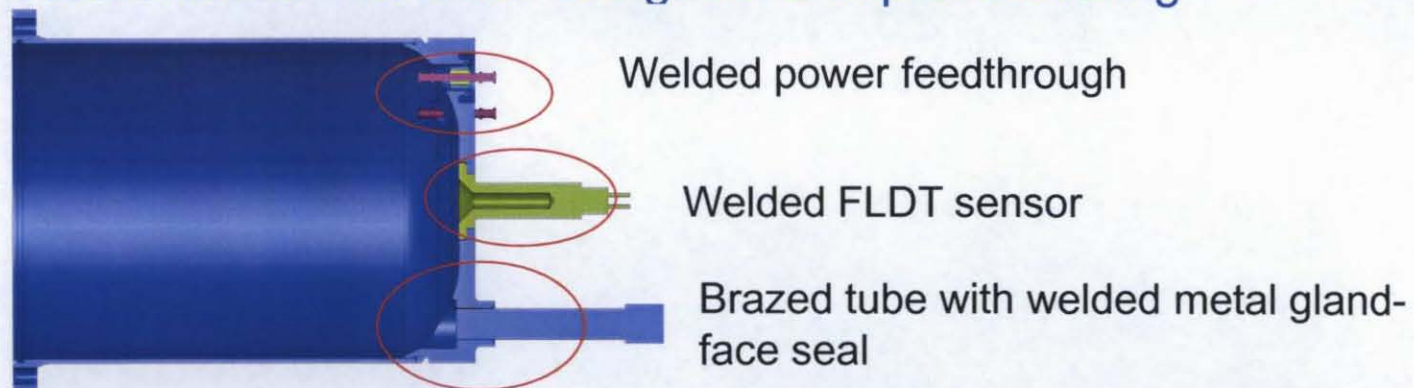




ASC-1 #3 & #4

MarM-247 heater head (850 °C T_{hot}), non-hermetically sealed flange joints

- MarM-247 heater head allows for operation up to 850 °C
- These convertors underwent three EMI testing activities
 - Dual-opposed configuration in June 2007
 - Bucking coil implementation in December 2007
 - Bucking coil with Carpenter High Permeability Perm-49 pressure vessel in June 2009
- After nearly 1,800 hours of operation, the convertors were returned to Sunpower for inspection
 - The displacer epoxy joint failed due to an over-temperature condition encountered during an insulation loss test
 - Oxygen had permeated the o-ring seals
- Developmental non-hermetic convertors not ideal for extended operation -
A new pressure vessel has been designed to improve sealing



Currently at Sunpower for installation of the new pressure vessel

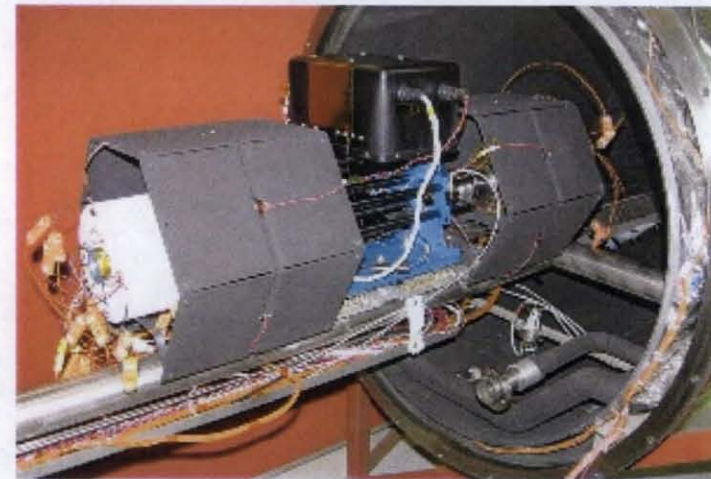
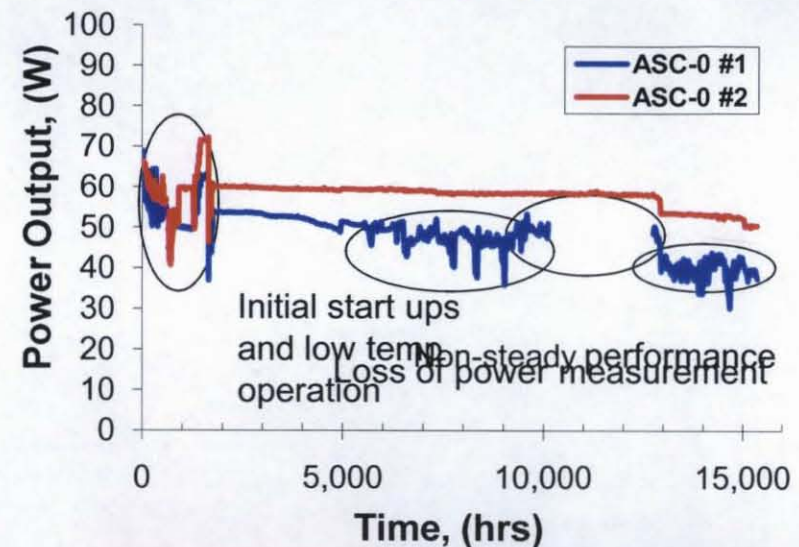


ASC-0 #1 & #2

IN718 heater head ($650\text{ }^{\circ}\text{C } T_{\text{hot}}$), hermetically sealed flange joints

- Began operation in February 2007
 - Early developmental convertors delivered with known quality issues
 - 15,400 hours with first 600 hours in air followed by thermal vacuum operation
- Several periods of non-steady performance were observed
 - Attributed to questionable instrumentation or convertor behavior
 - Piston amplitude was manually decreased to less than nominal
- Cursory assessment of the convertors was completed at GRC following thermal vacuum operation
 - All GRC-designed hardware was intact and functioned as required

Currently at Sunpower for inspection



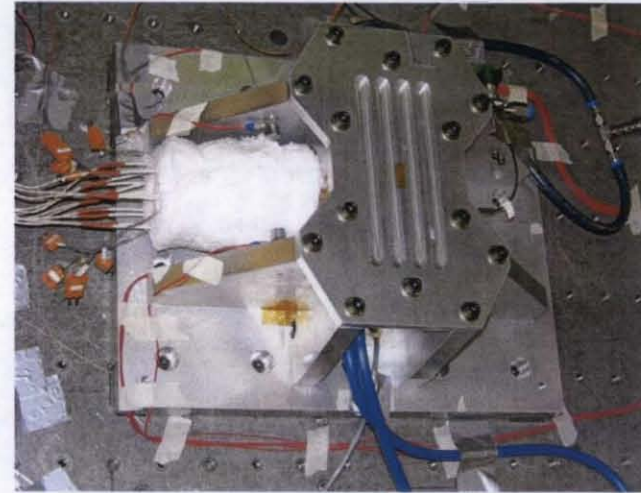
Convertors being installed in thermal vacuum tank

ASC-0 #3 & #4



IN718 heater head ($650\text{ }^{\circ}\text{C } T_{\text{hot}}$), hermetically sealed flange joints

- Nearly 13,000 hours of extended operation
 - Began operation in August 2007
- At 7,400 hours of operation, underwent flight-acceptance-level and launch simulation vibration testing at GRC
 - X, Y, and Z-axes for 2 minutes total in each axis
 - Converter operating during vibration
 - $8.7\text{ }g_{\text{rms}}$ standard RPS specification flight acceptance profile, modified based on dynamic testing of ASRG EU
- Underwent heater head diameter measurements at GRC
 - Laser micrometer scanning technique
 - Provided baseline data to track creep of the heater head assembly resulting from extended operation testing
 - Measurements will be taken throughout extended operation where opportunities exist to repeat measurements



Vibration testing



Heater head measurements

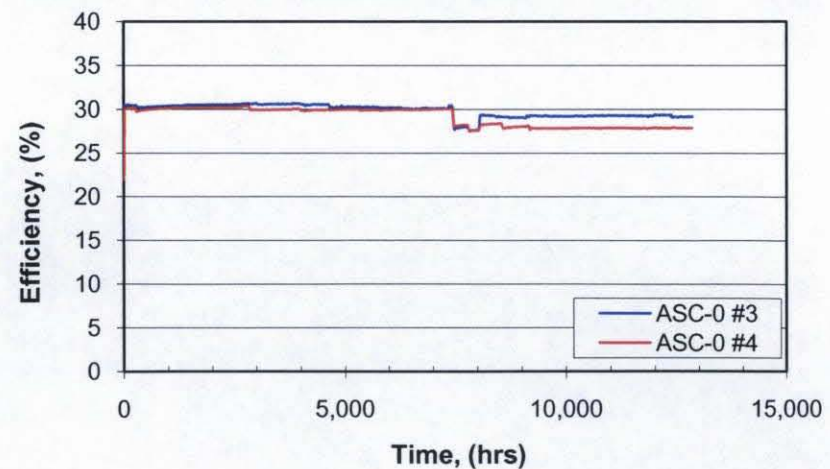
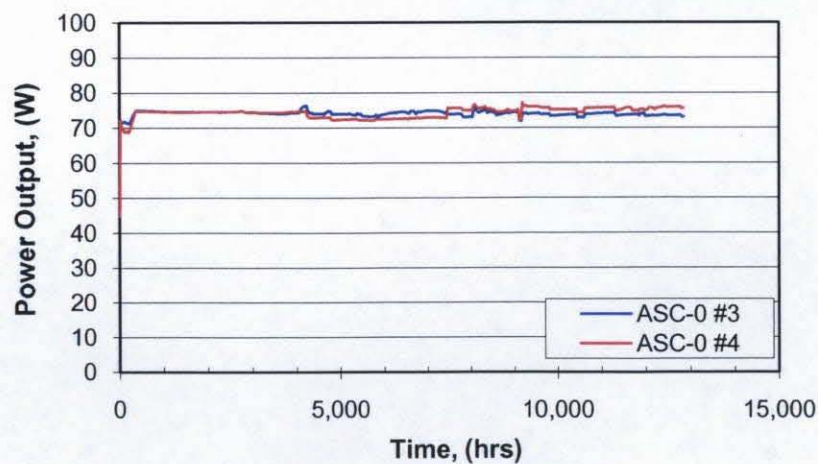
ASC-0 #3 & #4



IN718 heater head ($650\text{ }^{\circ}\text{C } T_{\text{hot}}$), hermetically sealed flange joints

- Power anomalies of $\sim 1\text{ W}$ above nominal as well as piston amplitude drifting was observed
- An investigation indicated the test rack's load panel was responsible for the anomalies. The following test rack load panel modifications were made at 9,000 hours:
 - Replaced the wire nuts on the transformer leads with solder joints
 - Removed an unnecessary relay in the power circuit
- The operating point stabilized with tuning capacitance modifications at 12,300 hours:
 - Changed nominal tuning cap values to $300\text{ }\mu\text{F}$ based on recommendation from Sunpower
 - Replaced quick connect terminals in the Chroma-to-load panel path with spade terminals screwed to a terminal strip

Overall performance data shows stable operation (with exception of manual adjustments) and no measurable change in performance





TDC #13 & #14

IN718 heater head (650 °C T_{hot}), post-operation hermetically sealed flange joints

- Over 47,000 hours (5.4 years) of extended operation
 - Began operation in April 2003
- Lab experience gained from the operation of these long-running convertors
 - Test facility upgrades
 - Test facility maintenance schedules
 - Necessity of hermetic sealing of convertors for extended operation
- Benchmark for extended operation testing
 - Demonstrated long-life capability to support and verify reliability assessments



TDC #13 & #14 test station

Proving free-piston Stirling convertors are capable of providing reliable power for multi-year missions

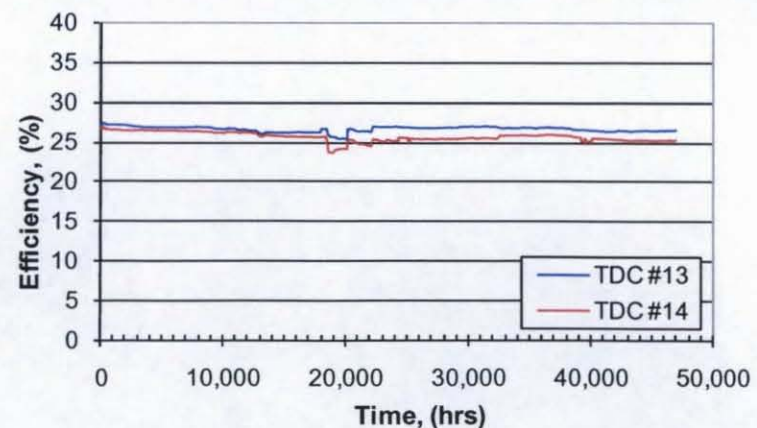
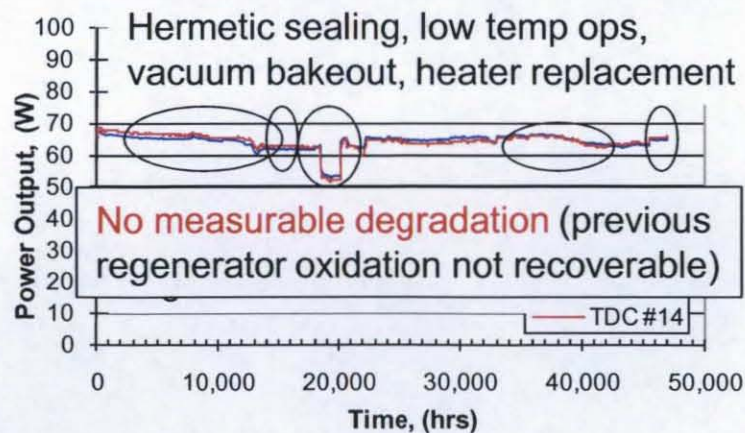
TDC #13 & #14



IN718 heater head ($650\text{ }^{\circ}\text{C } T_{\text{hot}}$), post-operation hermetically sealed flange joints

- Initial operation showed some performance issues, inspected after 18,000 hours of operation
 - Slight degradation in power due to regenerator oxidation
- Hermetically sealed o-ring flanges after 19,000 hours to prevent further oxidation
 - GRC applied the hermetic-sealing solution of regenerator oxidation to other TDC's
 - GRC identified and applied an oxidation-resistant regenerator material for the ASC
- Power output decreased at 38,000 hours due to aging heaters and drift in the Zener diode controller
 - Controller adjustments returned power output to expected levels

Valuable knowledge is gained from these long-running convertors and applied to the development of NASA's next generation of Radioisotope Power Systems



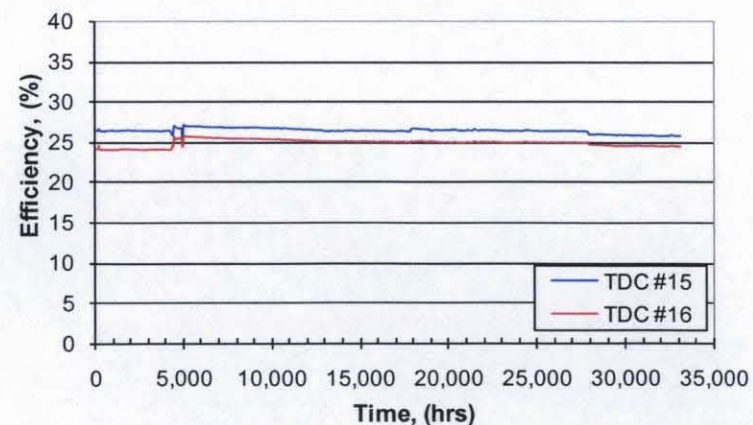
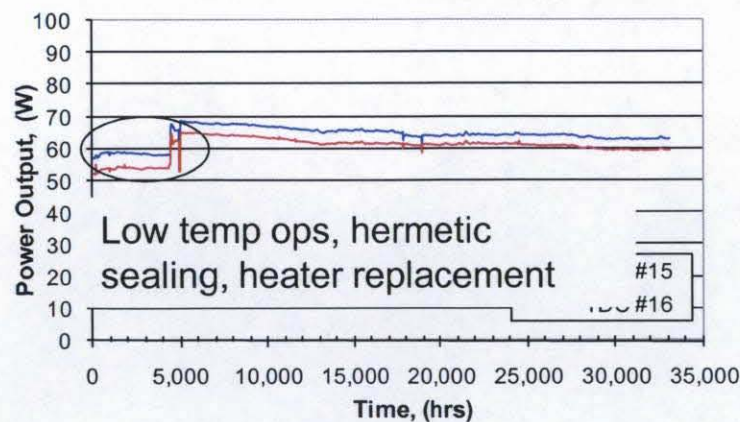
TDC #15 & #16



IN718 heater head ($650\text{ }^{\circ}\text{C } T_{\text{hot}}$), post-operation hermetically sealed flange joints

- 33,400 hours (3.8 years) of operation
 - Began operation in March 2005
 - Operation was at a slightly reduced hot-end temperature to help prevent internal oxidation prior to hermetical sealing
- Hermetically sealed o-ring seal flanges after 4,200 hours
 - Helium fill tubes remain connected to the gas management system to allow for analysis of the working fluid throughout extended operation

Overall performance data shows stable operation over last 20,000 hours



ASC-E #1 & #4



IN718 heater head ($650\text{ }^{\circ}\text{C } T_{\text{hot}}$), hermetically sealed

- ASC-E #1 delivered to GRC in December 2008
 - Spare convertor from fabrication of ASRG EU
- ASC-E #4 delivered to GRC in May 2009
 - Built using parts from ASC-E builds #1 - #3
- Both convertors underwent heater head diameter measurements at GRC
- ASC-E #1 successfully completed vibration testing at GRC with the ACU
 - First operation of a Stirling convertor under control of the ACU at GRC
 - Operated at launch conditions, the ASC-E #1 was exposed to qualification-level vibration in the axial direction and flight-acceptance level vibration in the lateral axes
- ASC-E #4 successfully passed workmanship-level vibration testing in all 3 axes at GRC
- Convertors will be in extended operation at GRC in September 2009



Model of ASC-E #1 & #4 test setup in vertical orientation



Conclusion

- GRC has accumulated over 265,000 hours of combined extended operation data, significantly contributing to the reliability database of long life free-piston Stirling convertors
 - Demonstrated long-life capability to support and verify reliability assessments
- GRC is developing and refining the convertor hardware, facilities, and methods for performing extended operation
 - Applied lessons learned to eliminate degradation and improve future convertor designs
 - Identified key parameters for long-term testing
 - Improved test stations for reliable convertor operation
- Ten of the sixteen convertors tested at GRC are from different phases of ASC technology development progressing toward acceptance for flight
- The present build, designated the ASC-E2, will be on extended operation testing at GRC within the next year. The hermetic ASC-E2 units include MarM-247 heater heads, representative ASRG interfaces, and design refinements progressing toward flight.

Testing to date indicates ASC technology is capable of meeting long life RPS requirements. Performance variations have been traced to set point adjustments, test rack/facility issues, or known issues related to early developmental convertors.



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