Extended Operation Testing of Stirling Convertors in Support of Stirling Radioisotope Power System Development

100 We class Stirling convertors began extended operation testing at NASA Glenn Research Center (GRC) in 2003 with a pair of Technology Demonstration Convertors (TDCs) operating in air. Currently, the number of convertors on extended operation test has grown to 12, including both TDCs and Advanced Stirling Convertors (ASCs) operating both in air and in thermal vacuum. Additional convertors and an electrically heated radioisotope generator will be put on test in the near future. This testing has provided data to support life and reliability estimates and the quality improvements and design changes that have been made to the convertor.

The convertors operated 24/7 at the nominal amplitude and power levels. Performance data were recorded on an hourly basis. Techniques to monitor the convertors for change in internal operation included gas analysis, vibration measurements and acoustic emission measurements. This data provided a baseline for future comparison.

This paper summarizes the results of over 145,000 hours of TDC testing and 40,000 hours of ASC testing and discusses trends in the data. Data shows the importance of improved materials, hermetic sealing, and quality processes in maintaining convertor performance over long life.
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Outline

• Convertors under test
• Extended operation test system
• Test sequence
• Test results to date
Introduction

• Convertors being developed for long duration missions of up to 14 years after 3 years of storage
• Accelerated life tests cannot adequately quantify extended life characteristics of all components
• Changes in performance characterized under nominal operation
## Convertors under test

<table>
<thead>
<tr>
<th>Convertor</th>
<th>Testing environment</th>
<th>Nominal Thot &amp; Tcold °C</th>
<th>Hours to date</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>TDC #13</td>
<td>In air</td>
<td>650/80</td>
<td>38,400</td>
<td>Ongoing test</td>
</tr>
<tr>
<td>TDC #14</td>
<td>In air</td>
<td>650/80</td>
<td>38,400</td>
<td>Ongoing test</td>
</tr>
<tr>
<td>TDC #5</td>
<td>Thermal vacuum</td>
<td>630/70</td>
<td>10,500</td>
<td>Test ended</td>
</tr>
<tr>
<td>TDC #6</td>
<td>Thermal vacuum</td>
<td>630/70</td>
<td>10,400</td>
<td>Test ended</td>
</tr>
<tr>
<td>TDC #15</td>
<td>In air</td>
<td>650/80</td>
<td>24,600</td>
<td>Ongoing test</td>
</tr>
<tr>
<td>TDC #16</td>
<td>In air</td>
<td>650/80</td>
<td>24,600</td>
<td>Ongoing test</td>
</tr>
<tr>
<td>ASC-0 #1</td>
<td>In air and thermal vacuum</td>
<td>645/72</td>
<td>11,000</td>
<td>Ongoing test</td>
</tr>
<tr>
<td>ASC-0 #2</td>
<td>In air and thermal vacuum</td>
<td>645/72</td>
<td>11,000</td>
<td>Ongoing test</td>
</tr>
<tr>
<td>ASC-0 #3</td>
<td>In air; launch simulation</td>
<td>650/90</td>
<td>6,700</td>
<td>Ongoing test</td>
</tr>
<tr>
<td>ASC-1 #3</td>
<td>In air</td>
<td>850/90</td>
<td>1,800</td>
<td>Being repaired</td>
</tr>
<tr>
<td>ASC-1 #4</td>
<td>In air</td>
<td>850/90</td>
<td>1,800</td>
<td>Being repaired</td>
</tr>
<tr>
<td>ASC-1HS #1</td>
<td>In air and thermal vacuum; launch simulation</td>
<td>850/90</td>
<td>2,200</td>
<td>Ongoing test</td>
</tr>
<tr>
<td>ASC-1HS #2</td>
<td>In air and thermal vacuum; launch simulation</td>
<td>850/90</td>
<td>2,200</td>
<td>Ongoing test</td>
</tr>
<tr>
<td>AEGK-EU, with ASC-E #2 &amp; #3</td>
<td>In air; environmental testing at LM</td>
<td>640/90</td>
<td></td>
<td>Future test</td>
</tr>
<tr>
<td>ASC-E #1</td>
<td>In air; launch simulation</td>
<td>650/90</td>
<td></td>
<td>Future test</td>
</tr>
<tr>
<td>ASC-E #4</td>
<td>In air; launch simulation</td>
<td>650/90</td>
<td></td>
<td>Future test</td>
</tr>
<tr>
<td>ASC-E2 #1</td>
<td>In air; launch simulation</td>
<td>650/90</td>
<td></td>
<td>Future test</td>
</tr>
<tr>
<td>ASC-E2 #2</td>
<td>In air; launch simulation</td>
<td>650/90</td>
<td></td>
<td>Future test</td>
</tr>
<tr>
<td>ASC-E2 #3</td>
<td>In air; launch simulation</td>
<td>650/90</td>
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<td>ASC-E3 #1</td>
<td>In air; launch simulation</td>
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<td>In air; launch simulation</td>
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<td>Future test</td>
</tr>
</tbody>
</table>
Extended operation test system

• Mounting

• Heat source

• Heat rejection

• Controller
Instrumentation

- Heater voltage, current, and power
- Heat source temperature
- Hot-end temperature
- Cold-end temperature
- Cold-end coolant inlet and outlet temperatures
- Cold-end coolant flow rates
- Pressure vessel temperature
- Alternator RMS voltage, RMS current, and power
- Piston amplitudes
- Helium charge pressure
- Operating frequency

- Record saved every hour
- 24-hour buffer of two-second data
**Instrumentation**

- Heater voltage, current, and power
- Heat source temperature
- **Hot-end temperature – high or low**
- **Cold-end temperature - high**
- Cold-end coolant inlet and outlet temperatures
- Cold-end coolant flow rates
- **Pressure vessel temperature - high**
- Alternator RMS voltage, RMS current, and power
- **Piston amplitudes - high**
- **Helium charge pressure – high or low**
- Operating frequency

- Record saved every hour
- 24-hour buffer of two-second data

**Convertor Protection**

- Controlled shutdown when abnormal event detected
- Uninterruptible Power Supply (UPS) for backup power
- Backup generator

Failsafe protection circuit
Monitoring

1. Gas analysis – monitor for organics

2. Vibration monitoring – change in displacer or piston amplitude or phasing

3. Acoustic emissions – change in acoustic signature

4. Heater head creep – submicron accuracy; 0.05 µm resolution
Extended operation test sequence

1. **Instrumentation** – install thermocouples on the hot end and cold end
2. **Installation** – add heat source, insulation, and other hardware
3. **Bake-out** – for non-hermetically sealed convertors, remove contaminants before operation
4. **Thermal loss characterization** – characterize insulation heat loss to accurately calculate convertor efficiency
5. **Low temperature check-out** – operate convertors at low temperature to verify sensor signals, piston amplitudes, convertor synchronization, cooling system, and other aspects of the test system
6. **Full power demonstration** – document full power performance
7. **Extended operation**
8. **Acceptance test and launch simulation vibration exposure**
9. **Continued extended operation**
Acceptance test and launch simulation vibration exposure

• Convertors on extended operation to see operational and environmental profile similar to the actual mission
• Workmanship test
• After 5,000 to 10,000 hours, perform Acceptance Vibration test
• Launch simulation vibration exposure
  – X, Y, and Z-axes for 1 minute in each axis
  – Convertor operating during vibration
  – $8.70 \text{ g}_{\text{rms}}$ flight vibration profile, modified based on dynamic testing of ASRG-EU
Extended operation of TDCs #13 and #14

- 38,400 hours (4.4 years) operation
- Slight degradation in power and efficiency prior to 19,000 hours due to regenerator oxidation prior to hermetically sealing
- Negligible change in performance since then
- Regular maintenance performed at 32,000 hours
Extended operation of TDCs #15 and #16

• 24,600 hours (2.8 years) of operation
• Operated at reduced hot-end temperature prior to hermetically sealing at 4,400 hours
• Slight decrease in power from 6,000 to 13,000 hours
• Recent performance unchanged
Extended operation of TDC’s #5 and #6

- First low-power convertors operated in thermal vacuum
- 10,016 hours between Nov. 2004 to Aug. 2006
- Steady operation; no degradation in performance
Extended operation of ASC-0 #1 and #2

• 11,000 hours, with first 600 hours in air followed by thermal vacuum operation
• Hermetically sealed flanges
• Some potential degradation in performance in ASC-0 #1
• Change in ASC-0 #1 performance can affect ASC-0 #2 (Change in operating frequency through zener diode controller)
• Near future: convertors will return to in-air operation
• Convertors were built prior to Sunpower implementing their Quality Assurance system
Extended operation of ASC-0 #3 and #4

- 6,700 hours of in-air operation
- Gas analysis shows evolution of CO2 over the first 2,500 hours, then decrease in concentration
- Not unexpected with adsorption from stainless steel and stainless steel-like materials
- Gas analysis typical of other ASCs
Extended operation of ASC-1 #3 and #4

- Product of NASA NRA development, not intended for extended operation
- Has 850 °C-capable MarM247 heater head
- Thermal loss characterization conducted under vacuum → damage to displacer epoxy joint
- Epoxy joint would not be used in a long life convertor
- Designed with 9 o-ring seals
- Enclosure being added to surround pressure vessel o-rings with argon
Conclusion

- Extended operation of Stirling convertors providing valuable data to establish long life database of convertors
- Over 185,000 hours of extended operation accumulated to date
- On track to operate 80,000 total hours in 2008 and well over 100,000 hours in 2009
- Testing to continue, with convertors approaching flight level quality processes in the near future
Acknowledgment

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