Extended Operation of Stirling Convertors at NASA Glenn Research Center

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Introduction

Advanced Stirling Radioisotope Generator (ASRG) being developed by Lockheed Martin, DOE, Sunpower, NASA GRC

- 4 times more efficient than thermoelectric conversion
- Requires ¼ amount of Pu-238 for same electrical power output
- Two Advanced Stirling Convertors (ASCs) operating up to 850 °C hot-end temperature
- 130 W_e from 2 heat source modules (beginning-of-mission, current best estimate)

GRC Provides Technical Support for ASC Life and Reliability:

- Structural benchmark testing
- Vibration testing
- High-temperature materials
- Magnet life testing
- Convertor extended operation
  - 38 free-piston Stirling convertors, 18 ongoing

ASRG Flight Unit Design

Image Courtesy of Lockheed Martin Space Systems
## Ongoing Stirling Convertor Testing

### Purpose:
- Generate performance data over tens of thousands of hours to observe long-term trends
- Support reliability database

### Nominal Operating Temperatures (Hot/Cold, °C)

<table>
<thead>
<tr>
<th>Convertors</th>
<th>Nominal Operating Temperatures (Hot/Cold, °C)</th>
<th>Nominal Per-Convertor Power Output ($W_e$)</th>
<th>Convertor Output Voltage ($V_{rms}$)</th>
<th>Supplier</th>
<th>Date Initiated</th>
<th>Per-Convertor Runtime (Hrs) As of July 1, 2011</th>
</tr>
</thead>
<tbody>
<tr>
<td>TDC #13 &amp; #14</td>
<td>650/80</td>
<td>65</td>
<td>85</td>
<td>Infinia</td>
<td>Jun 2003</td>
<td>60,000</td>
</tr>
<tr>
<td>TDC #15 &amp; #16</td>
<td>650/80</td>
<td>65</td>
<td>85</td>
<td>Infinia</td>
<td>Mar 2005</td>
<td>49,000</td>
</tr>
<tr>
<td>ASC-0 #3 &amp; #4</td>
<td>650/90</td>
<td>75</td>
<td>25</td>
<td></td>
<td>Aug 2007</td>
<td>25,000</td>
</tr>
<tr>
<td>ASC-E #2 &amp;# 3 (ASRG-EU)</td>
<td>625/70</td>
<td>65</td>
<td>11</td>
<td>Sunpower</td>
<td>Nov 2008</td>
<td>19,000</td>
</tr>
<tr>
<td>ASC-E #1 &amp; #4</td>
<td>650/70</td>
<td>65</td>
<td>11</td>
<td>Sunpower</td>
<td>Dec 2009</td>
<td>10,000</td>
</tr>
<tr>
<td>ASC-E #1*</td>
<td>850/50</td>
<td>80</td>
<td>15</td>
<td>Sunpower</td>
<td>Feb 2010</td>
<td>2,700</td>
</tr>
<tr>
<td>ASC-E #2</td>
<td>850/50</td>
<td>80</td>
<td>15</td>
<td>Sunpower</td>
<td>Aug 2010</td>
<td>800</td>
</tr>
<tr>
<td>ASC-E #3 &amp; #4</td>
<td>850/50</td>
<td>80</td>
<td>15</td>
<td>Sunpower</td>
<td>Aug 2010</td>
<td>4,800</td>
</tr>
<tr>
<td>ASC-E #5 &amp; #6</td>
<td>850/50</td>
<td>80</td>
<td>15</td>
<td>Sunpower</td>
<td>Nov 2010</td>
<td>2,100</td>
</tr>
<tr>
<td>ASC-E #7</td>
<td>850/50</td>
<td>80</td>
<td>15</td>
<td>Sunpower</td>
<td>Jun 2011</td>
<td>20</td>
</tr>
<tr>
<td>ASC-E #8</td>
<td>850/50</td>
<td>80</td>
<td>15</td>
<td>Sunpower</td>
<td>Jun 2011</td>
<td>20</td>
</tr>
</tbody>
</table>

*ASC-E2 #1 delivery delayed due to heater head manufacturing flaw

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**Discovery 12 proposed missions:** 7 years + 3 years max storage (87,000 hours)

**Outer planet missions:** 17 years (150,000 hours)
Convertor Test Station

Test Rack
- Operator controls
- Data acquisition
- Software protection
- Hard-wired protection
- Automated error notification via email and text messaging
- UPS and generator backup

Example ASC-E2 Test Station

- ASC-E2
- Cold end fluid plumbing
- Circulators
  - Cold-end and alternator housing temp control

Heat Collector
- Heat input

Heat Rejection
- Cold-Side Adapter Flange (CSAF)
- Alternator
- Electricity output

ASC-E2
Test Methodology

- **24/7 Operation**
- **Data acquisition:**
  - 2-second – All parameters recorded once every two seconds, for transient or 24-hr period evaluation
  - 5-min – Each parameter’s 2-second data averaged over 5-minute period, recorded once per hour, for long-term performance data evaluation
- **Maintain constant operating conditions (during extended operation):**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Control Methods</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot-end temperature</td>
<td>PID control, thermocouple feedback</td>
</tr>
<tr>
<td></td>
<td>Constant heat input, heater power feedback</td>
</tr>
<tr>
<td>Cold-end temperature</td>
<td>Circulator with fluid temperature PID control</td>
</tr>
<tr>
<td>Alternator housing temperature</td>
<td>Auxiliary surface heaters</td>
</tr>
<tr>
<td></td>
<td>Fluid heat exchanger</td>
</tr>
<tr>
<td>Piston amplitude</td>
<td>AC Bus power supply voltage setpoint</td>
</tr>
<tr>
<td></td>
<td>Zener-diode controller DC output setpoint</td>
</tr>
<tr>
<td></td>
<td>ASC Controller Unit (ACU, flight method)</td>
</tr>
</tbody>
</table>

- **Off-nominal operation included:**
  - Performance mapping
  - Operating frequency variation
  - Heat input variation
  - Controller variation
  - Individual temperature variation
Technology Demonstration Convertors (TDCs) #13, #14

- Longest-running convertor pair (60,000 hours each)
- Pressure joints welded at 19,000 hours, but helium fill tube remains
- Periodic charge pressure adjustments required, manifests as “saw-tooth” output
- Zener diode controller hardware drift required adjustment to maintain piston amplitude
• Fully hermetically sealed before delivery (pressure joints and pinched fill tube)
• 19,000 hours each (13,000 on Lockheed Martin controller)
• Test rack improvements required during initial operation
• Tests conducted for Lockheed Martin in support of controller development and flight system development
• Good repeatability on ASC controller unit (ACU) with consistent operating conditions
ASRG EU (ASC-E #2, #3)

- 25% conversion efficiency demonstrated at the system level on flight-like controller
- Repeatable and constant conversion efficiency over 19,000 hours of operation

Efficiency = Alternator output power/Heater power

Glenn Research Center
at Lewis Field
### ASC-E2 #1 Performance Data

- **Fully hermetically sealed before delivery (pressure joints and pinched fill tube)**
- **6,200 hours – majority at 850 °C**
- **Known heater head flaw and helium leakage**
- **AC bus voltage requires adjustment to negate helium leakage**

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#### ASC-E2 #1

<table>
<thead>
<tr>
<th>Event</th>
<th>Time (Hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>98: Initiated BOM LR</td>
<td>1000</td>
</tr>
<tr>
<td>1004: Init. Ext Op.</td>
<td>3000</td>
</tr>
<tr>
<td>1304: Init. Ext Op.</td>
<td>4000</td>
</tr>
<tr>
<td>1476: Init. Ext Op.</td>
<td>5000</td>
</tr>
<tr>
<td>2629: Adjust.</td>
<td>6000</td>
</tr>
<tr>
<td>3223: Adjust.</td>
<td></td>
</tr>
<tr>
<td>3849: AC bus Var.</td>
<td></td>
</tr>
<tr>
<td>4696: Restart BOM LR</td>
<td></td>
</tr>
<tr>
<td>4889: Restart BOM LR</td>
<td></td>
</tr>
<tr>
<td>5124: AC loss</td>
<td></td>
</tr>
<tr>
<td>5232: AC loss</td>
<td></td>
</tr>
<tr>
<td>5520: AC loss</td>
<td></td>
</tr>
<tr>
<td>6097: Nat. Freq.</td>
<td></td>
</tr>
<tr>
<td>6193: Trans. BOM LR</td>
<td></td>
</tr>
</tbody>
</table>

**Legend**

- **BOM = Beginning of Mission**
- **EOM = End of Mission**
- **LR = Low Rejection**
- **HR = High Rejection**

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**Glenn Research Center at Lewis Field**
ASC-E2 #5, #6

- Fully hermetically sealed before delivery (pressure joints and pinched fill tube)
- 4,800 hours – all at 850 °C
- Steady when maintaining constant conditions

BOM = Beginning of Mission
EOM = End of Mission
LR = Low Rejection
HR = High Rejection
ASC-E2 #7 & #8

- Slated for durability testing
  Stress components to above-nominal levels
- Removable alternator housings for inspection

<table>
<thead>
<tr>
<th>Test Description</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start/Stop Cycling</td>
<td>Cycle the convertor repeatedly through start/stop cycle to exacerbate any possible wear induced before gas bearings become fully functional</td>
</tr>
<tr>
<td>August 2011</td>
<td></td>
</tr>
<tr>
<td>Centrifugal Acceleration</td>
<td>Expose operating convertor to 30 g static load using a centrifuge facility to observe response in moving components</td>
</tr>
<tr>
<td>September 2011</td>
<td></td>
</tr>
<tr>
<td>Contact Events During</td>
<td>Simulate a limited number of contact events during off-nominal launch by adjusting piston amplitude</td>
</tr>
<tr>
<td>Launch</td>
<td></td>
</tr>
<tr>
<td>Piston Overstroke</td>
<td>Simulate a limited number of contact events with desired relative velocities between the piston and displacer with short-term controller disconnection</td>
</tr>
</tbody>
</table>
Conclusion

GRC is supporting life and reliability database for free-piston Stirling conversion via extended convertor operation

Ongoing convertor operation:

- 18 convertors (4 TDCs from Infinia, 14 ASCs from Sunpower)
- 350,000 total convertor hours of operation
- 218,000 on Infinia units and 132,000 on Sunpower units

Demonstrating steady convertor performance requires precise maintenance of operating conditions

Sources of disruption:

- Investigative tests
  Varying operating frequency, hot-end temp, cold-end temp
- Hot end control method
  Constant heat input mode requires more user-adjustment than constant temperature mode
  Long-term transients in hot end insulation were observed
- Support facility
  Open-bath circulator fluid concentration drifting
  Nuisance shutdowns (instrumentation failure, EMI, power outages)
  Ambient temperature fluctuations due to room HVAC
Acknowledgements

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