Extended Operation of Stirling Convertors at NASA Glenn Research Center

International Energy Conversion Engineering Conference
August 2, 2011

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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

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at Lewis Field
Ongoing Stirling Convertor Testing

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

<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>Sunpower</td>
<td>Aug 2007</td>
<td>25,000</td>
</tr>
<tr>
<td>ASC-E #2 &amp; #3</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>(ASRG-EU)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></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-E2 #1*</td>
<td>850/50</td>
<td>80</td>
<td>15</td>
<td>Sunpower</td>
<td>Mar 2010</td>
<td>6,200</td>
</tr>
<tr>
<td>ASC-E2 #2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Feb 2010</td>
<td>2,700</td>
</tr>
<tr>
<td>ASC-E2 #3 &amp; #4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Aug 2010</td>
<td>800</td>
</tr>
<tr>
<td>ASC-E2 #5 &amp; #6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Aug 2010</td>
<td>4,800</td>
</tr>
<tr>
<td>ASC-E2 #7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Nov 2010</td>
<td>2,100</td>
</tr>
<tr>
<td>ASC-E2 #8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Jun 2011</td>
<td>20</td>
</tr>
</tbody>
</table>

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

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

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

Example ASC-E2 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

ASC-E2

Cold end fluid plumbing

Circulators
Cold-end and alternator housing temp control

Heat Collector
Heat Input

Cold-Side Adapter Flange (CSAF)
Heat Rejection

Alternator
Electricity Output

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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

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

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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 August 2011</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>Centrifugal Acceleration September 2011</td>
<td>Expose operating convertor to 30 g static load using a centrifuge facility to observe response in moving components</td>
</tr>
<tr>
<td>Contact Events During Launch</td>
<td>Simulate a limited number of contact events during off-nominal launch by adjusting piston amplitude</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>
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at Lewis Field
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

This work was funded through the NASA Science Mission Directorate and the Radioisotope Power Systems Program Office. Any opinions, findings, and conclusions or recommendations expressed in this article are those of the authors and do not necessarily reflect the views of the National Aeronautics and Space Administration.