Status of Dynamic Power Convertor Development for RPS at NASA GRC

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May 3, 2018
IAPG Mechanical Working Group Meeting
Dynamic Conversion Power System Background

Advantages:
- Higher efficiency, less waste heat for spacecraft
- Low generator power decline (fuel decay only)
- Large multi-mission generator design space
- Extensible to high power levels

SRG-110
- ~114 W_e output
- Infinia’s Technology Demonstration Convertor (TDC)
- 2 GPHS modules
- Overall efficiency = 23%
- 4.2 W_e/kg (before engineering unit build)
- Developed during 2001 to 2006 timeframe

ASRG
- ~140 W_e output
- Sunpower’s Advanced Stirling Convertor (ASC)
- 2 GPHS modules
- Overall efficiency = 28%
- 4.4 W_e/kg
- Developed during 2006 to 2013 timeframe
Key Convertor Performance Goals

<table>
<thead>
<tr>
<th>Item</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Life</td>
<td>20 years</td>
</tr>
<tr>
<td>Efficiency</td>
<td>$\geq 24%$ at $T_{\text{cold}} &gt; 100 , ^\circ\text{C}$</td>
</tr>
<tr>
<td>Specific Power</td>
<td>$20 , \text{W}_e/\text{kg}$ (convertor only)</td>
</tr>
<tr>
<td>Partial power</td>
<td>Can be throttled down to 50%</td>
</tr>
<tr>
<td>Degradation</td>
<td>$&lt; 0.5% / \text{year}$</td>
</tr>
<tr>
<td>Hot-End Temp</td>
<td>$&lt; 1000 ^\circ\text{C}$</td>
</tr>
<tr>
<td>Cold-End Temp</td>
<td>20 to 175 $^\circ\text{C}$</td>
</tr>
<tr>
<td>Random Vibe</td>
<td>Launch qual</td>
</tr>
<tr>
<td>Static Accel</td>
<td>20g for 1 minute, 5g for 5 days</td>
</tr>
<tr>
<td>Radiation</td>
<td>300 krad</td>
</tr>
<tr>
<td>Size</td>
<td>Enables generator that can fit in DOE shipping container</td>
</tr>
</tbody>
</table>

Robustness goals also defined:
- Design has margin to tolerate events outside expected environments
- Fewer single-point-failures is more robust
- Tolerant of loss of electrical load
- Tolerant of operational error
- Manufacturability not dependent on specialized workmanship

Multi-Mission Capable:
- Mars
- Titan
- Moon
- Europa
- Deep Space
Convertor Development Timeline

- RFP via Research Opportunities in Space and Earth Sciences (ROSES-2016), August 2016
- Received 14 proposals, encompassing multiple dynamic conversion methods
- 4 contracts awarded in FY2017:

<table>
<thead>
<tr>
<th>Contractor</th>
<th>Convertor Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>American Super Conductor</td>
<td>Flexure Isotope Stirling Convertor (FISC)</td>
</tr>
<tr>
<td>Creare, LLC</td>
<td>Turbo-Brayton Convertor (TBC)</td>
</tr>
<tr>
<td>Northrop Grumman Aerospace Systems</td>
<td>Thermo-Acoustic Power Convertor (TAPC)</td>
</tr>
<tr>
<td>Sunpower, Inc.</td>
<td>Sunpower Robust Stirling Convertor (SRSC)</td>
</tr>
</tbody>
</table>

- Contracts consist of up to 3 Phases:

<table>
<thead>
<tr>
<th>Phase</th>
<th>Duration</th>
<th>Work Focus</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6 months</td>
<td>Design</td>
</tr>
<tr>
<td>2</td>
<td>18 months</td>
<td>Prototype Fabrication Performance Demonstration</td>
</tr>
<tr>
<td>3</td>
<td>12 months</td>
<td>IV&amp;V Test Support</td>
</tr>
</tbody>
</table>

Decision Gate 1

Decision Gate 2

Flight Development

New Frontiers 5 AO

NASA Contracts

DOE Contract + NASA Partnership
Flexure Isotope Stirling Convertor (FISC)
American SuperConductor (AMSC), formerly Infinia Tech Corp.

- Flexure-bearings, beta arrangement free-piston Stirling conv.
- Derivative of Technology Demonstration Convertor (TDC) from a 1990’s SBIR and SRG-110 project
- Design deltas relative to TDC to improve the following:
  1. Higher radial stiffness flexures, overstroke tolerance, hot-end temperature margin
  2. Independently verifiable subassemblies
  3. Higher efficiency alternator, higher cold-end temp capability
  4. System integration : Tailored interfaces

**Convertor Performance**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot-end Temp</td>
<td>650 °C</td>
</tr>
<tr>
<td>Cold-end Temp</td>
<td>20 to 175 °C</td>
</tr>
<tr>
<td>Efficiency</td>
<td>31% @ T_{COLD}=100°C</td>
</tr>
<tr>
<td>Power Output</td>
<td>70 W_{ac}</td>
</tr>
<tr>
<td>Mass</td>
<td>3.3 kg (&gt;20W_{e}/kg)</td>
</tr>
</tbody>
</table>

**Status:**
Decision Gate 1 successfully passed
Phase 2 awarded, April 2018
Turbo-Brayton Convertor (TBC)

Creare, LLC

Closed Brayton continuous flow cycle with recuperation
- Scaled-down from previous designs
- Leverages heritage from Creare’s HST NICMOS cooler
- Two counter-rotating units permits redundancy, and nullifies angular momentum

TBC Performance

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbine Inlet Temp (Hot End)</td>
<td>730 °C</td>
</tr>
<tr>
<td>Compressor Inlet Temp (Cold End)</td>
<td>20 to 175 °C</td>
</tr>
<tr>
<td>Efficiency</td>
<td>26% @ T_{COLD}=100°C</td>
</tr>
<tr>
<td>Power Output</td>
<td>355 W_{ac}</td>
</tr>
<tr>
<td>Mass</td>
<td>15.5 kg (&gt;20W_{ac}/kg)</td>
</tr>
</tbody>
</table>

- Notional 355 W_{e} generator concept with 100% convertor redundancy

Status:
Decision Gate 1 successfully passed
Phase 2 awarded, April 2018
**Thermo-Acoustic Power Convertor (TAPC)**

Northrop Grumman Aerospace Systems

- Thermoacoustic Stirling cycle
- Eliminates physical displacer (no moving parts in hot end)
- Natively balanced, dual-opposed alternator building block
- Alternators driven by shared compression space
- Based on previous development efforts: 2003 NRA, IRAD-developed device

**TAPC Performance**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot-end Temp</td>
<td>700°C</td>
</tr>
<tr>
<td>Cold-end Temp</td>
<td>20 to 175 °C</td>
</tr>
<tr>
<td>Efficiency</td>
<td>26% @ $T_{\text{COLD}}=100°C$</td>
</tr>
<tr>
<td>Power Output</td>
<td>110 W$_{\text{ac}}$</td>
</tr>
<tr>
<td>Mass</td>
<td>6.4 kg (&lt; 20 W$_{\text{e}}$/kg)*</td>
</tr>
</tbody>
</table>

*Options being explored to reduce convertor mass to meet W/kg target

**Notional 220 W$_{\text{e}}$ generator concept with 100% convertor redundancy**

**Status:**

Phase 1 Design Review Completed, April 2018

Phase 2 award pending gov’t decision
Sunpower Robust Stirling Convertor (SRSC)
Sunpower, Inc.

- Gas-bearing based, beta arrangement free-piston Stirling
- Derivative of Advanced Stirling Convertor (ASC) from ASRG Project
- Enables wide generator design space
- Design deltas relative to ASC to improve the following:
  1. Higher radial gas bearing stiffness, overstroke tolerance, regenerator robustness, debris tolerance
  2. Higher cold-end temp capability, static acceleration

SRSC Performance

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot-end Temp</td>
<td>720°C</td>
</tr>
<tr>
<td>Cold-end Temp</td>
<td>20 to 175 °C</td>
</tr>
<tr>
<td>Efficiency</td>
<td>29% @ T_{COLD}=100°C</td>
</tr>
<tr>
<td>Power Output</td>
<td>65 W_{ac}</td>
</tr>
<tr>
<td>Mass</td>
<td>2.0 kg (&gt; 20 W_e/kg)</td>
</tr>
</tbody>
</table>

Notional 500 W_e generator concept with 25% convertor redundancy

Hot End ☰ Cold End ☰ Alternator

Status:
Phase 1 Design Review Completed, April 2018
Phase 2 award pending gov’t decision
Path to Flight

Goal:
Achieve convertor TRL 6, then initiate generator flight development

NASA definition of TRL 6: “System/subsystem model or prototype demonstration in a relevant environment (ground or space)”

Surrogate Mission Team (SMT), chartered by RPS Program

- NASA, DOE, JPL, APL, GSFC
- Formulated requirements to provide mission pull
- Integrated with DPC contract progress monitoring
- Formulated a TRL evaluation method
- Providing failure mode and probability of success analysis
- Work phases and deliverables tied to TRL advancement

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**Phase 1 : Design**
- Preliminary DPC design
- Power, thermal, structural analyses
- FMEA
- Req. compliance matrix
- Design review

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**Phase 2 : DPC Fab and Test**
- Demonstrate steady-state perf.
- Performance mapping
- Initial extended operation
- Validate physics-based models

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**Phase 3 : IV&V**
- Independent modeling and analysis
- Launch vibration exposure
- Static acceleration exposure
- Performance mapping
- Half-power operation
- Durability/robustness tests
- Extended operation

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Gate 1
Many convertors from SRG110 and ASRG projects are still undergoing continuous operation today.

<table>
<thead>
<tr>
<th>Project &amp; Provider</th>
<th>Test Article</th>
<th>Years of Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SRG 110</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Infinia, Corp.</td>
<td>TDC #13</td>
<td>12.6(^1)</td>
</tr>
<tr>
<td></td>
<td>TDC #15</td>
<td>11.6</td>
</tr>
<tr>
<td></td>
<td>TDC #16</td>
<td>11.6</td>
</tr>
<tr>
<td></td>
<td>SES #2</td>
<td>0.3</td>
</tr>
<tr>
<td><strong>ASRG</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sunpower, Inc.</td>
<td>ASC-0 #3(^2)</td>
<td>8.3</td>
</tr>
<tr>
<td></td>
<td>ASC-E3 #4(^2)</td>
<td>3.1</td>
</tr>
<tr>
<td></td>
<td>ASC-E3 #6(^2)</td>
<td>2.4</td>
</tr>
<tr>
<td></td>
<td>ASC-E3 #9</td>
<td>1.6</td>
</tr>
<tr>
<td></td>
<td>ASC-E3 #8</td>
<td>1.9</td>
</tr>
<tr>
<td></td>
<td>ASC-L(^2)</td>
<td>4.0</td>
</tr>
</tbody>
</table>

Cumulative Per-Convertor Runtime as of May 2018

1Current record-holder for maintenance-free heat engine
2Have undergone random vibe portion of life certification

TDC #13 and #14 performance data over six year period

<table>
<thead>
<tr>
<th>Date</th>
<th>Nov 20, 2010</th>
<th>Aug 30, 2016</th>
</tr>
</thead>
<tbody>
<tr>
<td>TDC #13</td>
<td>65.4 W</td>
<td>65.4 W</td>
</tr>
<tr>
<td>TDC #14</td>
<td>64.5 W</td>
<td>64.5 W</td>
</tr>
</tbody>
</table>

ASC-E3 Pair Extended Operation Test Article
TDC #14 Disassembly and Inspection

Encouraging results from TDC #14 inspection
105,620 hrs of operation = 12 years, 31 billion cycles
Further disassembly is planned

- No sign of flexure degradation
- Signs of oxidation on expected surfaces – likely from early non-hermetic operation
- Geometric stability verified via Coordinate Measuring Machine (CMM)
- Evidence of oxide residue/dust in various areas – did not degrade operation

TDC #14 displacer after 12 years of operation

TDC #14 aft flexure stack after 12 years of operation

TDC #14 piston after 12 years of operation
Launch Vibration Exposure on SES #2

- 10.35 g_{rms} profile formulated by SMT, encompasses wide span of launch vehicles
- 2 min duration at full random vibe level
- Temporary reduction in power output during lateral axes exposures (expected)
- SES #2 now operating continuously at full power, 2900 hrs accumulated
- Static acceleration exposure test up to 20g recently performed

Engineering Unit convertor from SRG-110 project successfully passed launch simulation while operating

SES #2 undergoing launch vibration exposure

Centrifuge facility for static acceleration tests (Case Western Reserve University)
Conclusions

NASA’s dynamic power convertor development in support of high-efficiency RPS is progressing as planned, and shows promise

• 2 DPC contracts have passed Decision Gate 1, and have been awarded Phase 2 (convertor prototype fabrication and test)
• 2 DPC contracts have completed Phase 1 reviews
• NASA GRC is preparing for DPC prototype IV&V, ~2020
• Ongoing research utilizing existing hardware supports viability of dynamic power conversion for RPS