1-Watt Radioisotope Power System for Small Spacecraft

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Session: Powering Small Deep Space Missions
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Why Low Power RPS?

Small nuclear power systems could provide electricity to power probes, landers, rovers, or communication repeaters for space science and exploration

- Converts heat to electricity for powering spacecraft sensors and communications
  - Fractional GPHS (General Purpose Heat Source) outputs ~60 watts thermal
  - LWRHU (Light Weight Radioisotope Heater Unit, often called RHU)
  - LWRHU outputs ~1 watt thermal for each heater unit
- Operates in vacuum or on planetary surface (ie. Moon, Mars, More...)

Development Goals

- Sufficient power for spacecraft functions
- Long-life and low degradation to ensure sufficient power at EOM
- Robust to critical environments (vibration, shock, constant acceleration, radiation)
- Thermal capability and high efficiency

Dynamic Power Conversion

- 12-16% overall system efficiency possible from 1 to 10 watts electrical power output
Technology Development at GRC

In-house dynamic RPS from 1-10 \( W_e \) DC power output

- Demonstrate practicality at 1 watt power level by maturing subassemblies and interfaces. Perform scaling study at 5 W and 10 W to understand scaling

Initial Demonstration (2018)

- Controller breadboard testing
- Free-Piston Stirling convertor proof of concept and performance mapping
- Multi-layered metal foil insulation functionality using thermal simulator in air

Mature Fidelity (2019)

- Formalize requirements
- Controller brassboard development
- Stirling convertor performance mapping
- Electrically heated prototype system in air

System Testing (2020)

- Electrically heated prototype system in vacuum
- Stirling convertor characterization in random vibration environment
GRC 1-W Dynamic RPS Concept

Design goals
- Effort has used initial goals to guide development thus far
- Goals are not final, some are TBD, more need to be defined
- Plan to formalize requirements in FY19 (shock, transmitted forces, EMI, etc.)
- Long life design has margin for wear mechanisms (creep, high cycle fatigue)

<table>
<thead>
<tr>
<th>Category</th>
<th>Goal (TBR)</th>
<th>Current Best Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design life</td>
<td>20 years</td>
<td>20 years</td>
</tr>
<tr>
<td>Heat input</td>
<td>7 to 8 watts to convertor</td>
<td>8 watts</td>
</tr>
<tr>
<td>Power output</td>
<td>At least 1 W_e DC from controller</td>
<td>&gt; 1 W_e DC</td>
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<tr>
<td>Heat source surface temperature</td>
<td>TBD</td>
<td>&lt; 450 ºC</td>
</tr>
<tr>
<td>Stirling hot-side temperature</td>
<td>325 to 375 ºC</td>
<td>350 ºC</td>
</tr>
<tr>
<td>Stirling cold-side temperature</td>
<td>-150 to 50 ºC</td>
<td>-150 to 50 ºC</td>
</tr>
<tr>
<td>Robustness</td>
<td>Overstroke tolerant</td>
<td>Tolerant to overstroke events</td>
</tr>
<tr>
<td>Random vibration level</td>
<td>TBD</td>
<td>Tolerant to DRPS PSD</td>
</tr>
<tr>
<td>Environment</td>
<td>vacuum or atmosphere</td>
<td>vacuum and atmosphere</td>
</tr>
<tr>
<td>Constant acceleration</td>
<td>20 g</td>
<td>19 g</td>
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</table>
GRC 1-W Dynamic RPS Concept

- Heat Source
- Multi-Layer Metal Insulation
- Stirling Engine
- Linear Alternator
- Electrical Controller
- Stirling Convertor
- Radiative Coupling
- Heat Rejection Flange
Heat Source

Light Weight Radioisotope Heater Unit (LWRHU)

- Long history of use on many space missions for heating spacecraft electronics
- Aeroshell designed to survive reentry into Earth’s atmosphere for safety
- Diameter: 1.0 inch, Length: 1.3 inch (1.1 watts of thermal energy at BOL)

Generator concept uses 8x LWRHU

- 8 $W_{th}$ Heat to 1 $W_e$ DC electrical power

GRC testing will use electric heaters to simulate the LWRHUs

- Designed to provide similar thermal gradients compared to LWRHU
- There are four resistance cartridge heater total, each one simulates two LWRHUs
Insulation - Design

Objectives

- Due to low thermal input, high performing insulation is critical to minimize losses
- Peregrine Falcon Corp. provided Multi-Layered Metal Insulation (MLMI) package
- 8 watts of thermal input, around 7 watts conducted through Stirling simulator
- Anticipate up to 50 °C temperature drop from heat source to the 350 °C Stirling hot end, across the radiative coupled interfaces
- Insulation package is evacuated to enable low thermal losses
- Prototype is non-hermetic to allow disassembly
Controller - Design

Objectives

• Rectify AC power for load focused on controller design with generic load
• Provide 1 $W_e$ DC on 5 Vdc bus for rechargeable battery and sensors
• Charging battery enables periodic transmission of measured data to orbiting spacecraft

• 5V to system load to allow for generic electronics
• Keep engine at a constant power level
• Shunt excess power when battery is fully charged and power is not required by the load
Controller – Functional Testing

Initial Breadboard Testing Met the Power Output Requirement

• Demonstrated linear AC regulator controller using a MOSFET H-bridge with analog circuit to control FETs for AC to DC rectification and alternator current control to improve power factor

• Load voltage monitoring allows for load control and shunting of unused power

<table>
<thead>
<tr>
<th>Value</th>
<th>Ideal diode rectifier</th>
<th>Wave form smoothing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alternator Voltage, $V_{p-p}$</td>
<td>25.3</td>
<td>25.4</td>
</tr>
<tr>
<td>Alternator Power, $W_e$</td>
<td>1.37</td>
<td>1.34</td>
</tr>
<tr>
<td>Controller voltage, $V_{dc}$</td>
<td>11.7</td>
<td>11.5</td>
</tr>
<tr>
<td>Controller Power, $W_e$</td>
<td>1.11</td>
<td>1.22</td>
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<tr>
<td>Controller efficiency</td>
<td>80%</td>
<td>91%</td>
</tr>
</tbody>
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Next Steps

• Brassboard design with printed circuit boards and enclosure

• Demonstration with convertor
Component Testing - Alternator

Initial moving coil alternator (100 Hz)

GRC Design
- Low Inductance, dual flux path
  - 5 mm mover amplitude
  - 4 coils, 80-turn per coil
- Analysis Results
  - $P = 1.26 \text{ W}$, Avg Inductance = 0.485 mH
- Near perfect power factor (.99)
- Pathfinding assembly processes

Testing to Date
- Motored alternator to 4.26 mm @ 104 Hz
- Demonstrated conduction across flexures
- Demonstrated non-contact operation

Next Steps
- Demonstrate full amplitude at 5.0 mm
- Characterize with engine
Component Testing – Flexures

- Flexures used to provide axial springing & radial stiffness for piston and displacer.

Endurance Limit Testing

- Flexure bearings underwent endurance testing to validate design models by intentionally failing specimens.
- Displacer flexures demonstrated up to 1.7x nominal amplitude for 700+ million cycles (100 Hz) without fracture. Test amplitude exceeded hard stop limit in convertor.
- Piston flexures demonstrated up to 1.2x nominal amplitude for 500+ million cycles (100 Hz) without fracture. Test amplitude exceeded hard stop limit in convertor.
Free-Piston Stirling Convertor

Proof of Concept - Design

- Split-Stirling, gas duct between engine and alternator compression space
- Gap regenerator – no porous matrix
- Flexure bearings for piston and displacer
- Laboratory design did not minimize mass
- Heat input using electric heater to achieve 350 °C hot end temperature
- Fluid cooling loop to achieve 50 °C cold end temperature
- Operating frequency is 100 Hz
- Operating pressure is 110 psig helium,
- Piston amplitude is 4.5 mm
- Displacer amplitude is 2mm

In-Air Test Setup
(insulation not shown)
Stirling Convertor

Instrumentation

- Hot and cold end temperatures (8x)
- Dynamic CS pressure transducer (1x)
- Mean pressure transducer (1x)
- Hall effect sensors (2x)
- Electrical heat input, alternator output

Fabrication and Testing

- Fabrication of parts is complete
- Assembly in process
- Alternator testing has started
Advanced Modeling

Confidence in Predictions

- 1D Sage vs. 3D CFD
- Modeled domain was truncated at the piston face and displacer rod (no seals, no bounce space, no displacer gas or radiation)
- Sage connects fixed temperatures directly to ends of the displacer, which artificially elevates displacer temps and associated axial parasitic heat transfer losses, while Fluent model resolves complex thermal and fluid flow fields
- Sage assumes no motion by the displacer when resolving heat flux while Fluent resolves temperature gradients and heat flux by moving components and deforming gas volume meshes

Codes agree well

- The PV power output agree within 2%
- Indicated power predicted at 1.5 watts
Advanced Modeling - movies
Advanced Manufacturing (AM)

- Advantages: 1) reduce part count, 2) replace traditional joints (brazed, welded, etc.), and 3) more efficient & simpler production
- Recent focus on displacer assemblies with embedded radiation baffles
- Specimens used for pressure testing, heat treatment, finish machining trials, emissivity trials, and revised printing methods to improve geometry

- Results:
  - Printed 250 micron thick internal baffles and 300 micron external wall thickness using Inconel 718 metal powder
  - Ground OD. Able to achieve 80 micron wall thickness and still hold displacer pressure
Summary

- Small RPS are being proposed for small spacecraft missions
- They could enable long-life power for small spacecraft on Moon and Mars
- 1-W Stirling RPS is being developed for notional surface missions
- Subassemblies include convertor, controller, and insulation
- FY19 development is funded by Fundamental Research under RPS Program

- **Small Stirling Technology Exploration Power**
  or
- **“smallSTEP”**
Special thanks to:

- **RPS Program and Project**
- **1W Stirling Team**
  - Nick Schifer (fabrication/testing)
  - Steve Geng (alternator design/test)
  - Mike Casciani (controller design/test)
  - Terry Reid (thermal/fluids analysis)
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  - Daniel Goodell (mechanical design)
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  - Roy Tew (Sage analysis)