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

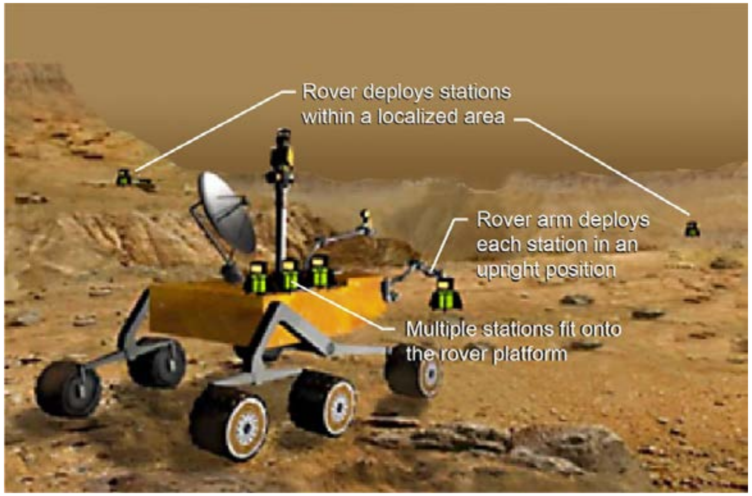
- Converts heat to electricity for powering spacecraft sensors and communications
  - Fractional GPHS (General Purpose Heat Source) outputs ~60 watts thermal
  - LWRHU (Light Weight Radioisotope Heater Unit, often called RHU)
  - LWRHU outputs ~1 watt thermal for each heater unit
- Operates in vacuum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



Conceptualization of Seismic Monitoring Stations Being Deployed from Rover**

**JPL Pub 04-10, Sept-2004

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

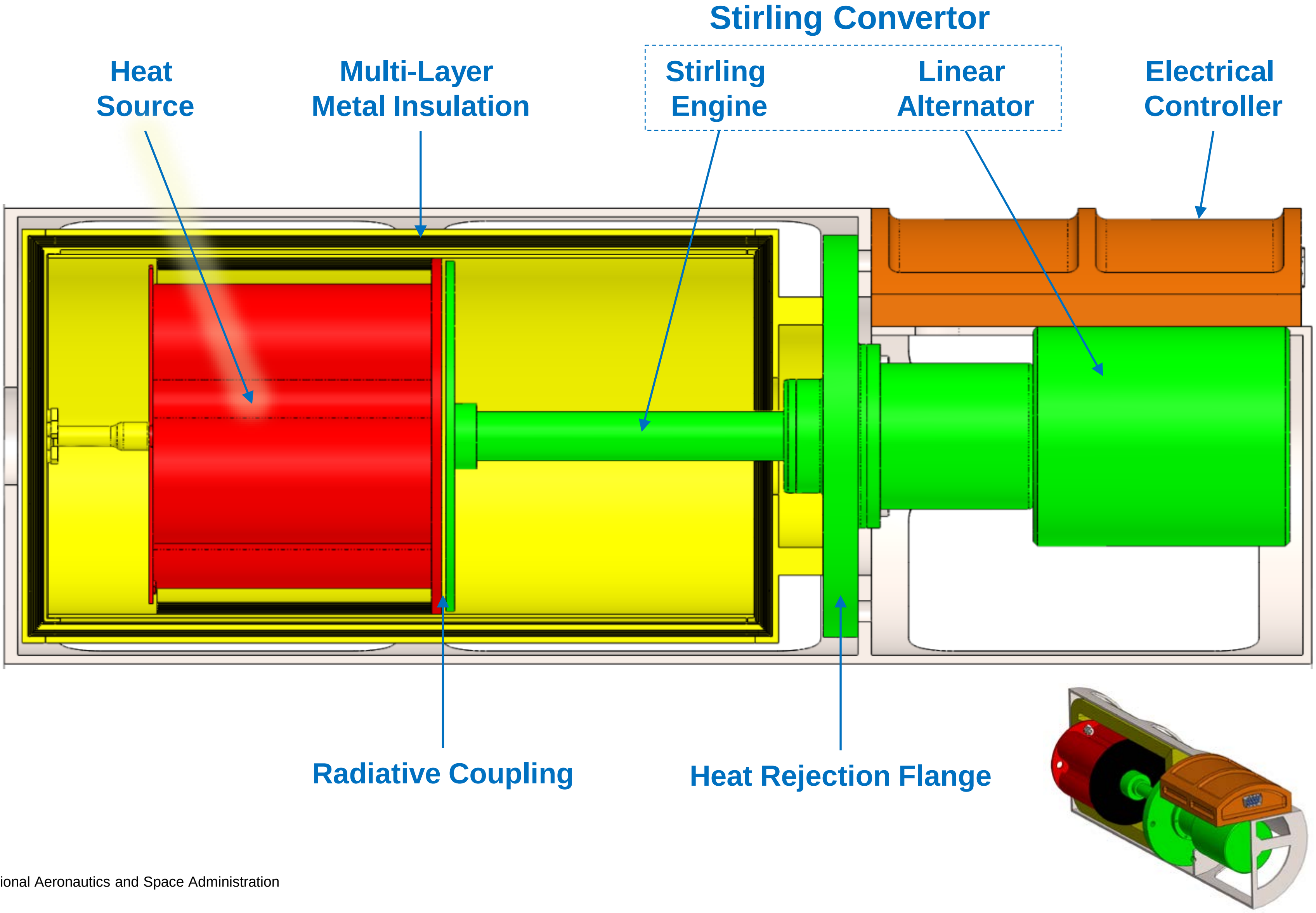
GRC 1-W Dynamic RPS Concept

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)

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

GRC 1-W Dynamic RPS Concept



Stirling Convertor

Heat Source

Multi-Layer Metal Insulation

Stirling Engine

Linear Alternator

Electrical Controller

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

LWRHU Assembly

Generator concept uses 8x LWRHU

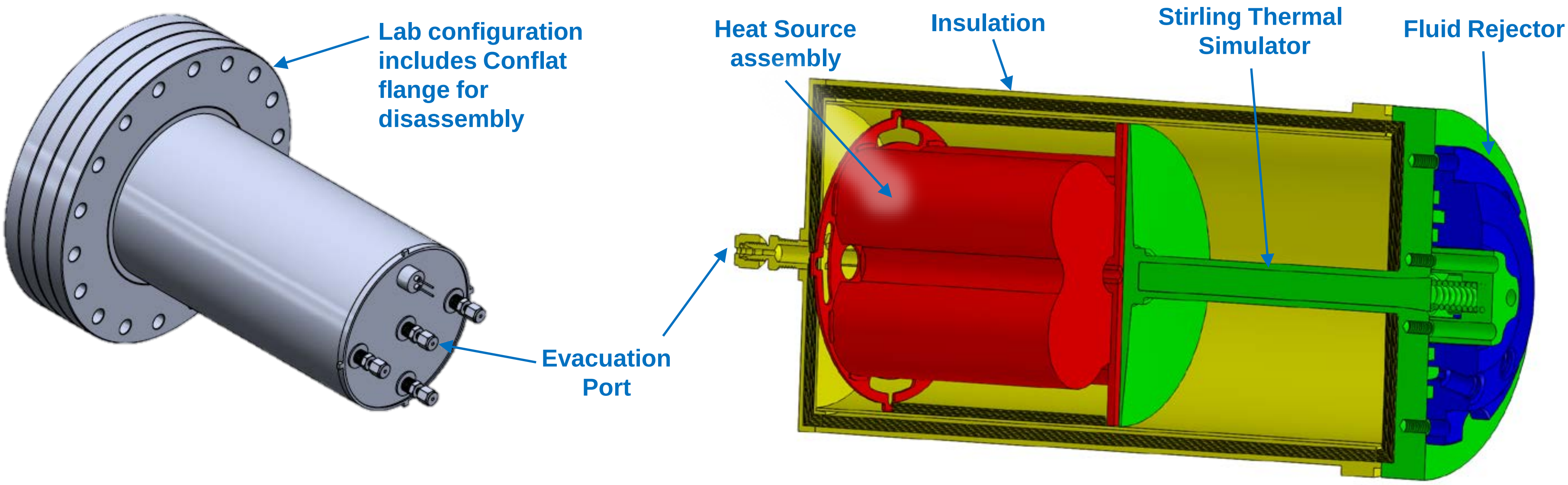
LWRHU Simulator uses electric heaters

Cross-section view *Test Hardware*

Insulation - Design

Objectives

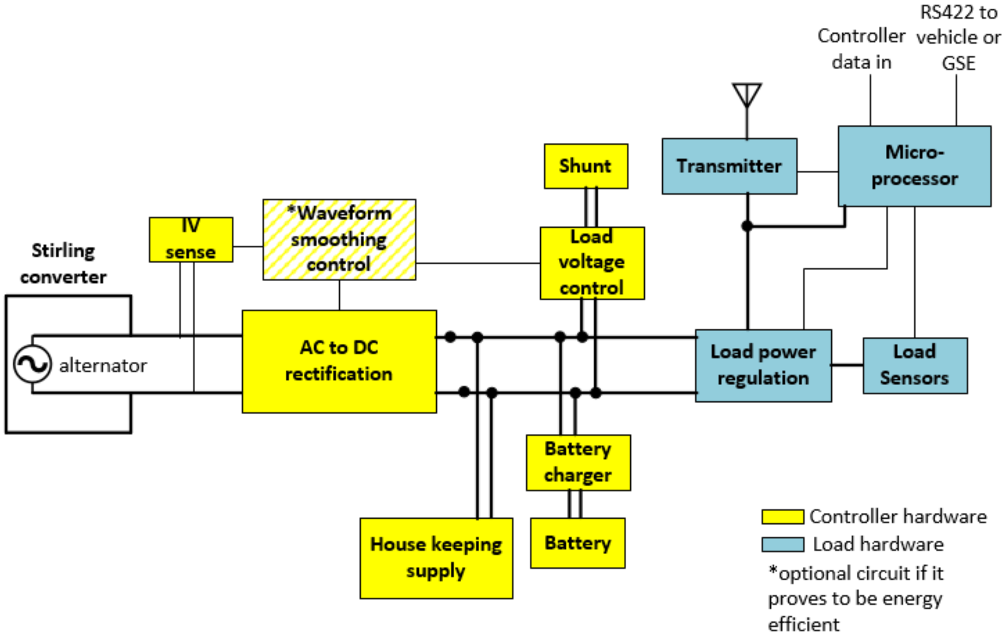
- Due to low thermal input, high performing insulation is critical to minimize losses
- Peregrine Falcon Corp. provided Multi-Layered Metal Insulation (MLMI) package
- 8 watts of thermal input, around 7 watts conducted through Stirling simulator
- Anticipate up to 50 ºC temperature drop from heat source to the 350 ºC 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

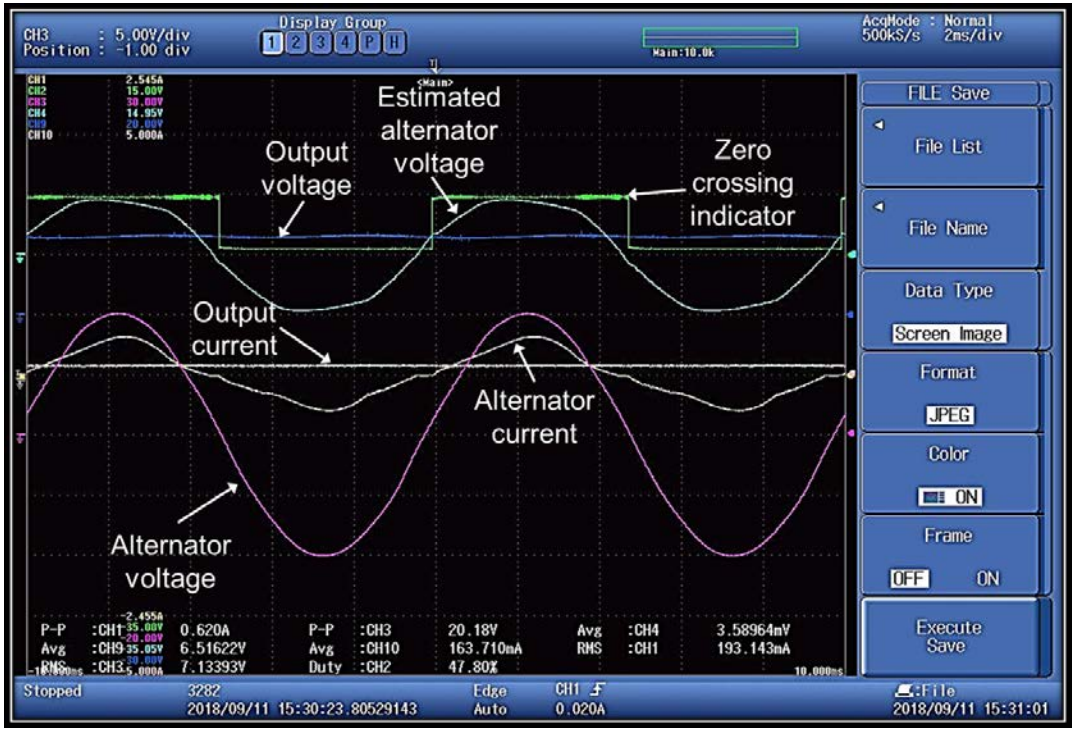


Controller – Functional Testing

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

Value	Ideal diode rectifier	Wave form smoothing
Alternator Voltage, $V_{p\text{-}p}$	25.3	25.4
Alternator Power, W_e	1.37	1.34
Controller voltage, V_{dc}	11.7	11.5
Controller Power, W_e	1.11	1.22
Controller efficiency	80%	91%



```
CH3      : 5.00V/div
Position : -1.00 div
AcqMode : Normal
500kS/s   2ms/div
Main:10.0k

CH1   2.545A
CH2   15.00V
CH3   30.00V
CH4   14.95V
CH9   20.00V
CH10  5.000A

P-P  :CH1   0.620A       P-P   :CH3    20.18V       Avg  :CH4  3.58964mV
Avg  :CH9   6.51622V     Avg   :CH10   163.710mA    RMS  :CH1  193.143mA
RMS  :CH3   7.13393V     Duty  :CH2    47.80%

Stopped   3282                             Edge   CH1     :File
          2018/09/11 15:30:23.80529143     Auto   0.020A  2018/09/11 15:31:01
```

Next Steps

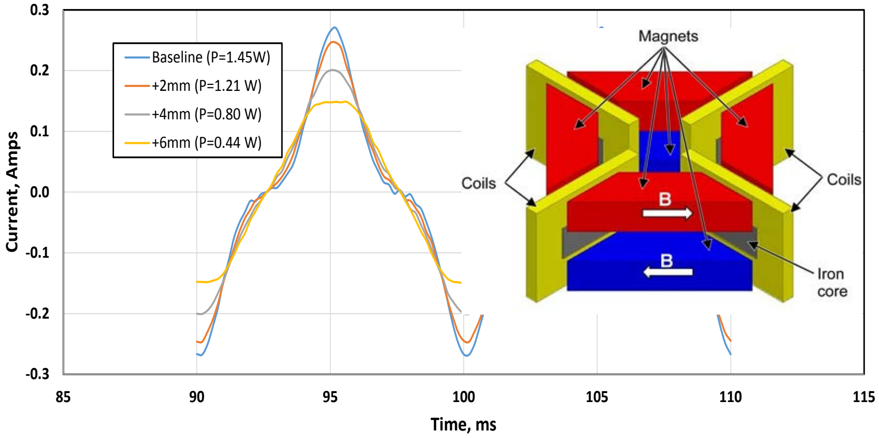
- Brassboard design with printed circuit boards and enclosure
- Demonstration with convertor

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 W**, Avg Inductance = 0.485 mH
- Near perfect power factor (.99)
- Pathfinding assembly processes

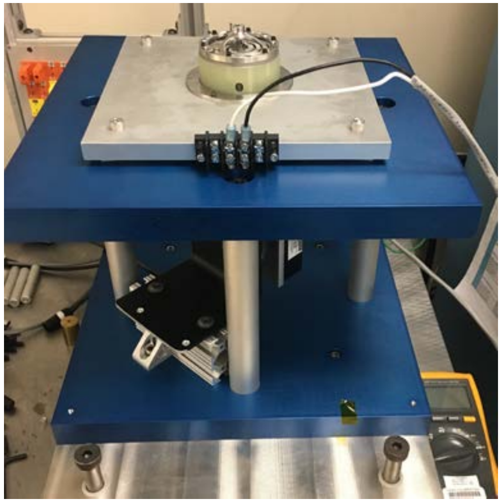


Testing to Date

- 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



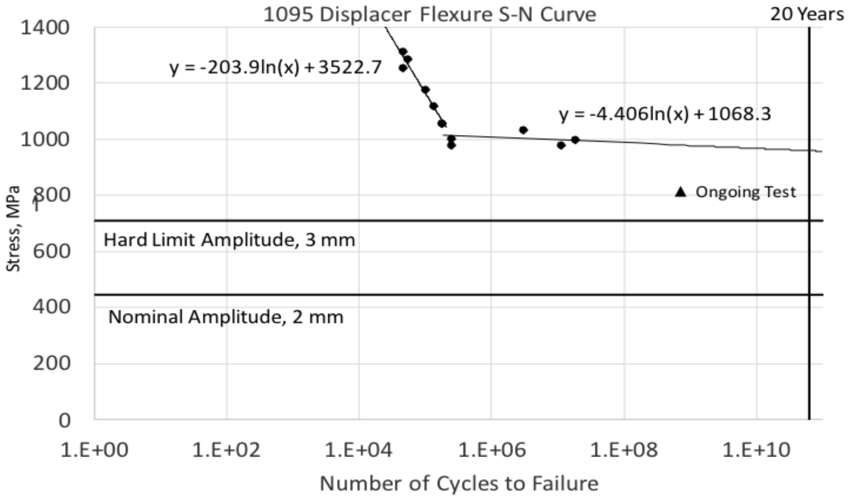
Component Testing – Flexures

- 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.

Flexure Bearing Test Setup

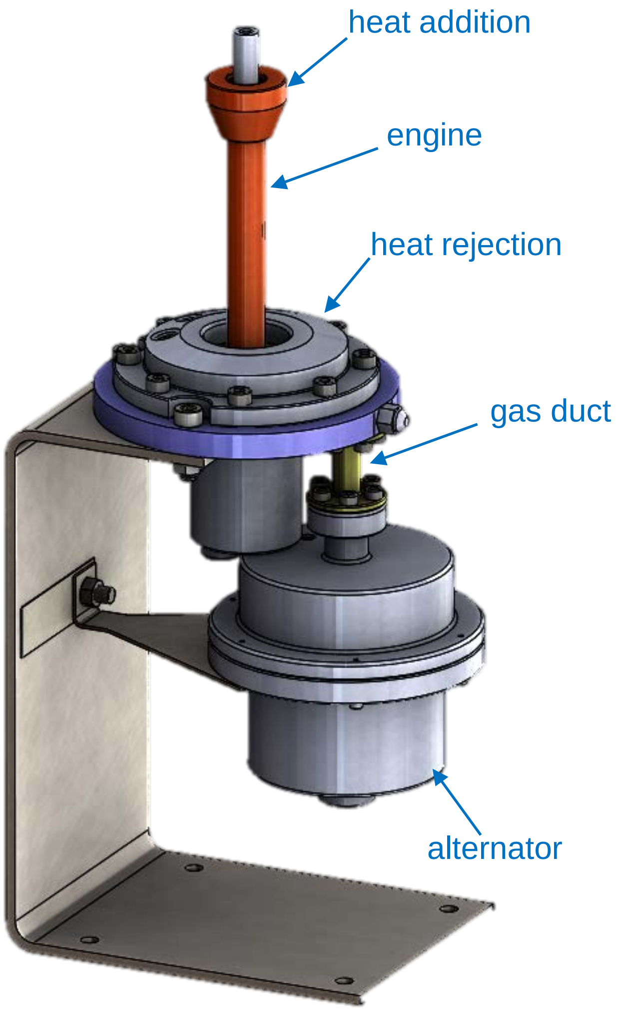


Stress vs. # of Cycles Data

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 ºC hot end temperature
- Fluid cooling loop to achieve 50 ºC cold end temperature
- Operating frequency is 100 Hz
- Operating pressure is 110 psig helium,
- Piston amplitude is 4.5 mm
- Displacer amplitude is 2mm

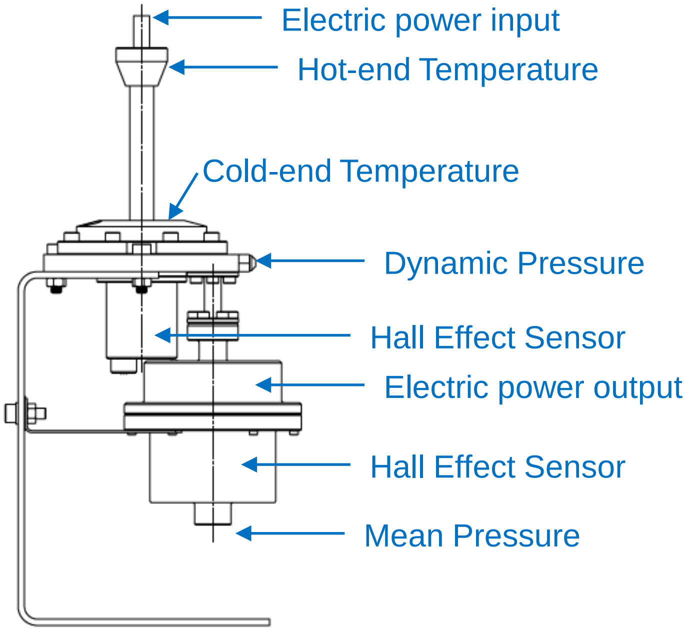


In-Air Test Setup
(insulation not shown)

Stirling Convertor

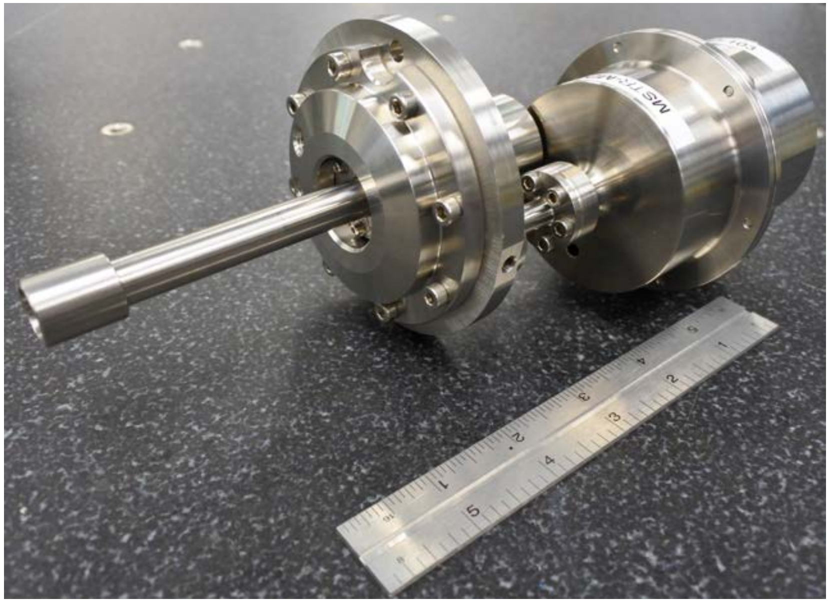
Instrumentation

- 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



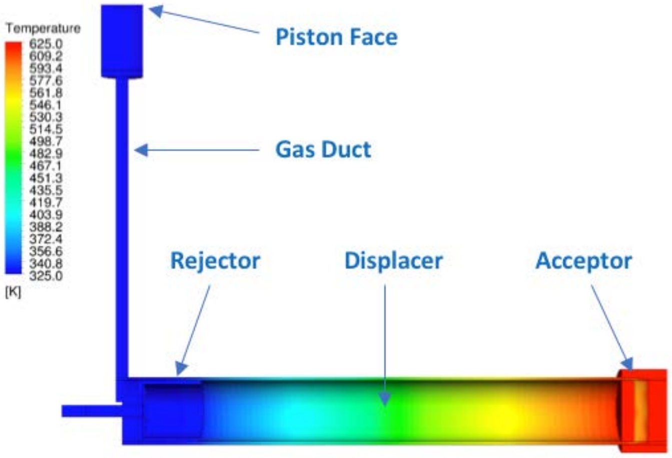
Advanced Modeling

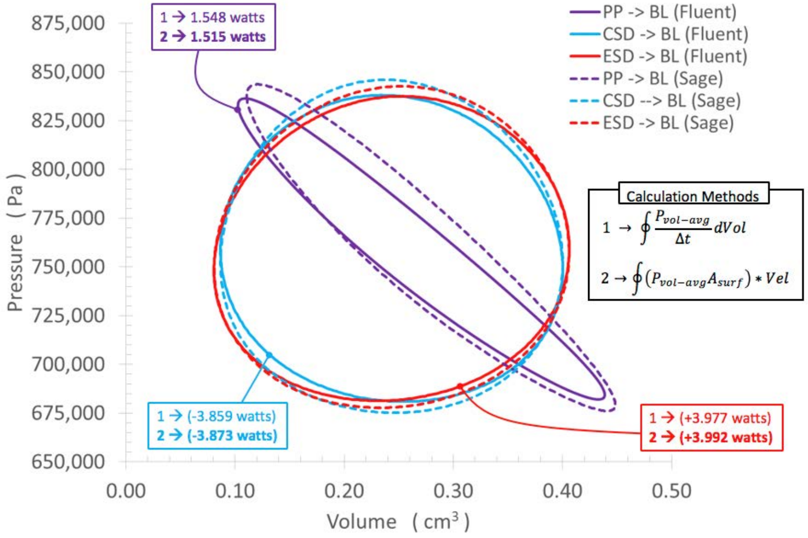
Confidence in Predictions

- 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

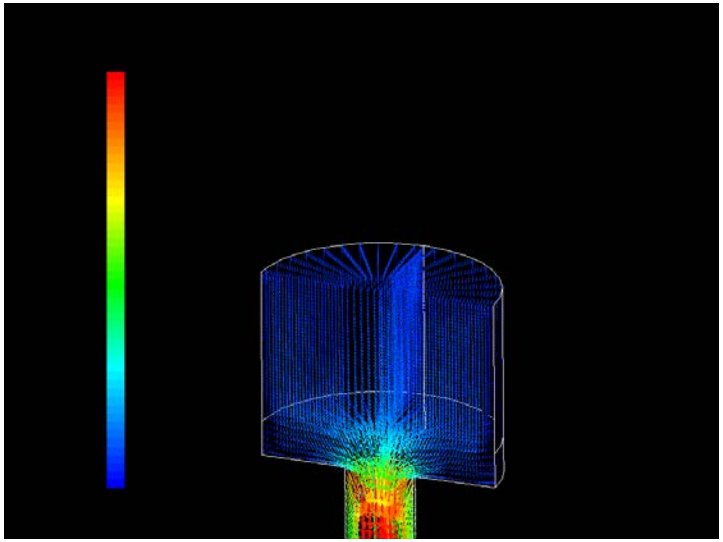
Codes agree well

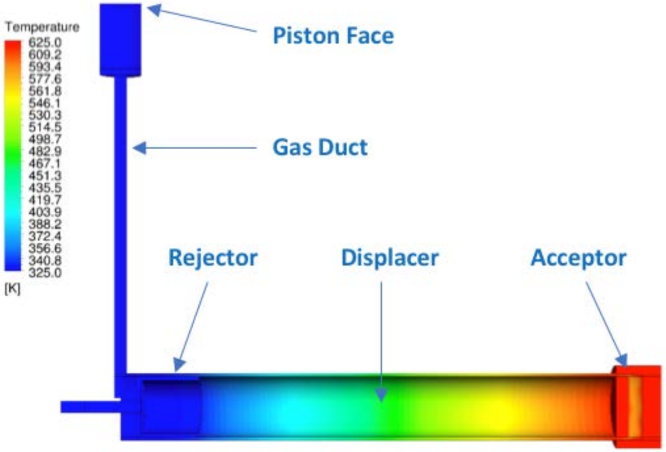
- The PV power output agree within 2%
- Indicated power predicted at 1.5 watts

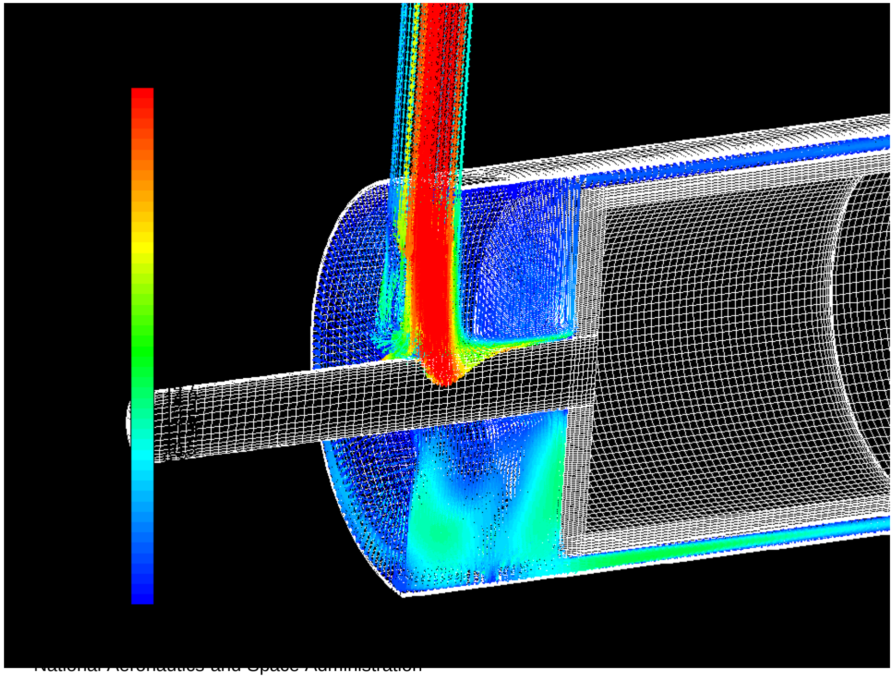


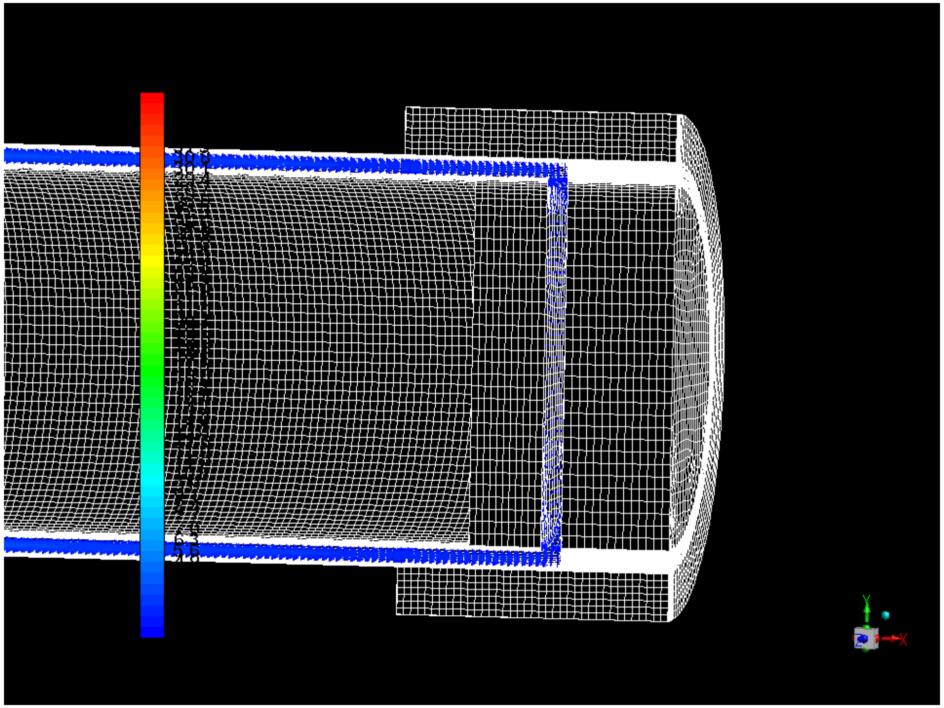


Advanced Modeling - movies







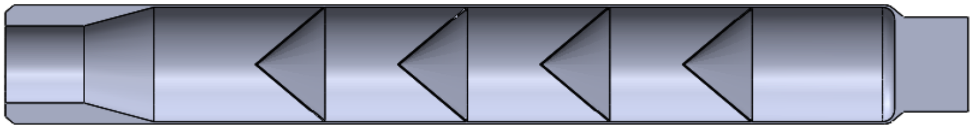


Advanced Manufacturing (AM)

- 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

← print direction

CAD



In718

Machined fitting port

printed baffles

  - Ground OD. Able to achieve 80 micron wall thickness and still hold displacer pressure

In718

← Base is removed

OD ground

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)
  - Barry Penswick (engine design/analysis)
  - Cheryl Bowman (additive manufacturing)
  - Daniel Goodell (mechanical design)
  - Malcolm Robbie (mechanical design)
  - Paul Schmitz (mission guidance)
  - Roy Tew (Sage analysis)