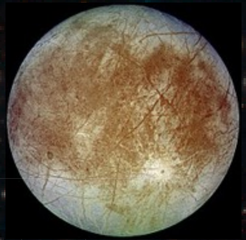
National Aeronautics and Space Administration



Small Stirling Technology Exploration Power for Future Space Science Missions

Scott Wilson, Nicholas Schifer, NASA Glenn Research Center

Michael Casciani, Vantage Partners, LLC.

March 4, 2019
2019 IEEE Aerospace Conference

Low Power RPS for Small Spacecraft

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

- Would convert heat to electricity for powering spacecraft sensors and communication
- Fractional GPHS (General Purpose Heat Source) output: ~60 watts thermal output (good for 10-Watt Generator)
- LWRHU (Light Weight Radioisotope Heater Unit, often called RHU) ~1 watt thermal output for each heater unit

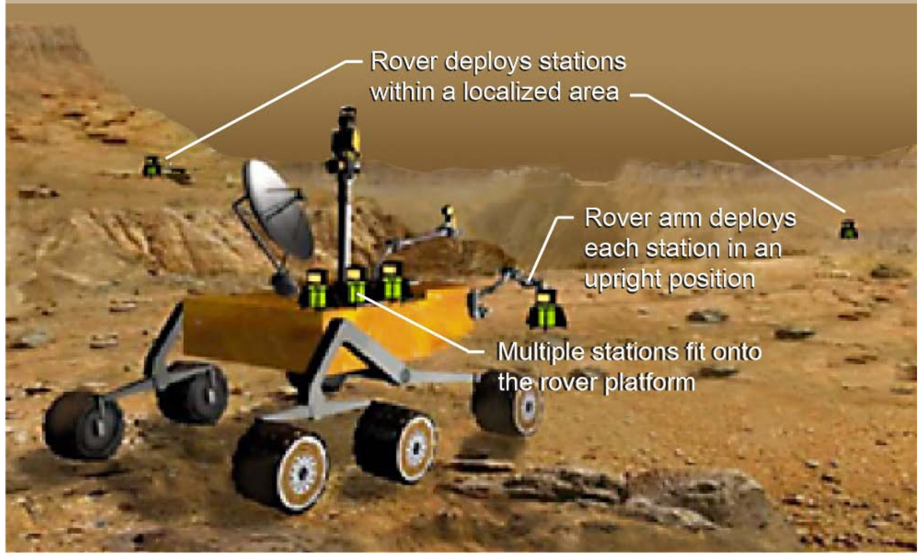
GRC Development Goals

- Sufficient power for small spacecraft functions
- Long-life and low degradation to ensure sufficient power at EOM
- Robust to critical environments (vibration, shock, constant acceleration, radiation, etc.)
- Thermal capability and high efficiency
- Operates in vacuum or atmosphere

Dynamic Power Conversion System Efficiency

- 1 watt generator efficiency projected to be 12-13%
- 10 watt generator efficiency projected to be 16%

JPL Pub 04-10, Sept-2004: 51 mission concepts, 14 RHU-based, 13 fractional-GPH



Conceptualization of Seismic Monitoring Stations Being Deployed from Rover

GRC 1-W Dynamic RPS Concept - Goals

- Subassemblies under development include convertor, controller, and insulation
- Need to formalize requirements later this year (Fundamental Research Project to help)
- Goals are based on existing DPC requirements

Category	Goals	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	-100 to 50 ºC	-100 to 50 ºC
Robustness	Overstroke tolerant	
Random vibration level	TBD	
Environment	vacuum or atmosphere	vacuum and atmosphere
Constant acceleration	20 g	19 g

Technology Development at GRC

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

- Demonstrate practicality of 1 watt power level by maturing subassemblies and interfaces
- Complete engine design at 10 watts power output (62 W_{th} heat source)

Initial Demonstration

- Controller breadboard
- Free-piston Stirling convertor
- Multi-layered metal foil insulation (using Stirling thermal simulator)

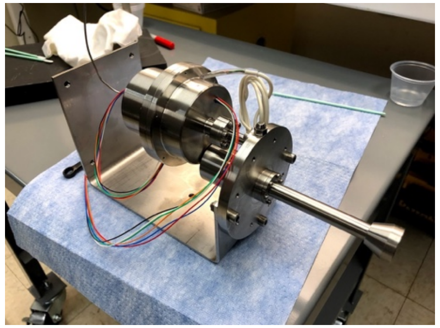
Increased Fidelity

- Controller brassboard fabrication and test
- Stirling convertor durability testing

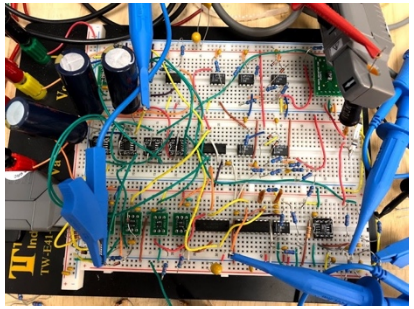
System Testing

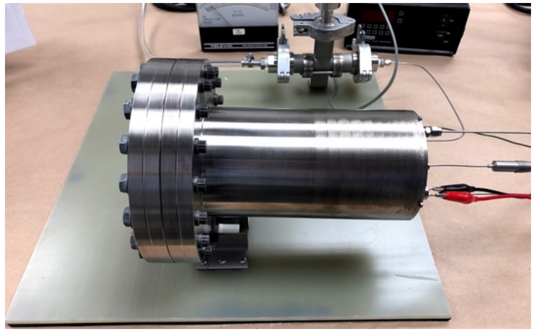
- Stirling convertor + controller
- Electrically heated prototype system (includes insulation)

Pneumatic Testing



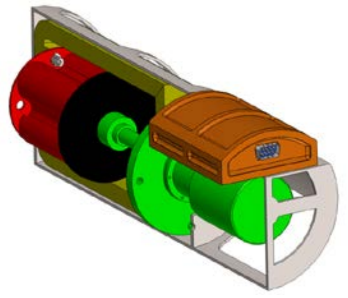
Controller Testing





Insulation Testing (at vendor)

GRC 1-W Dynamic RPS Concept



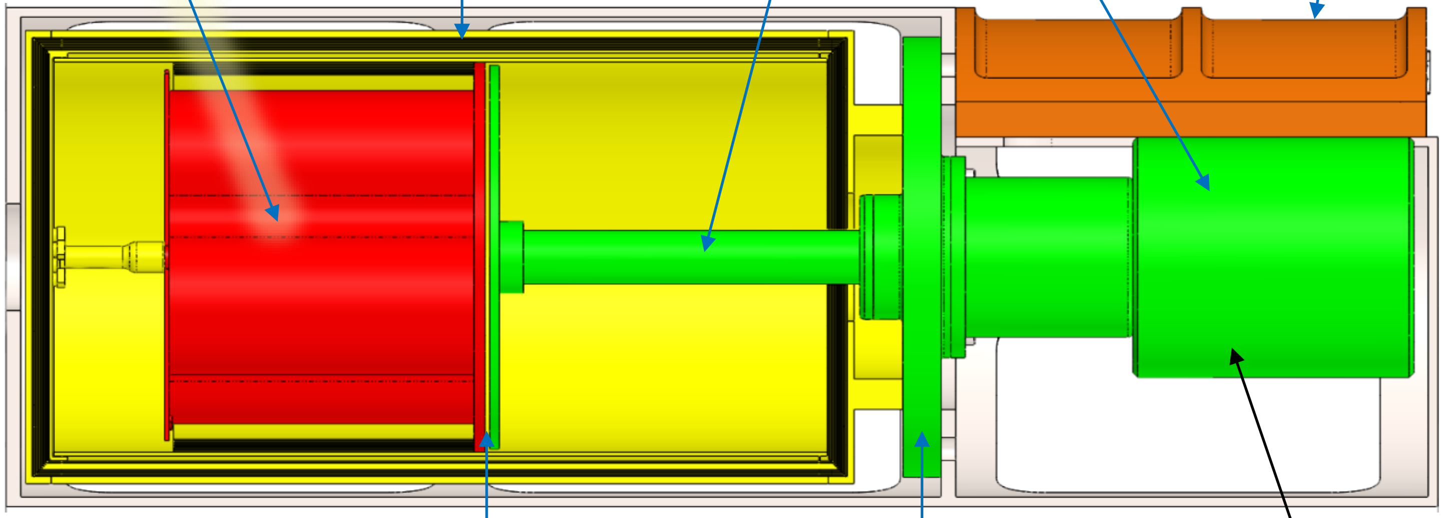


Table 1: smallSTEP Concept Characteristics

Item	smallSTEP
Nuclear Fuel	8 LWRHU
Thermal Inventory Beginning of Life (BOL) - when the RPS is fueled	8 watts (thermal)
Beginning of Mission (BOM) Power - up to 3 years after fueling	1 watt
End Of Design Life (EODL) Power - 14 years after BOM	0.83 watts
Power Conversion	Stirling Convertor
Environment	Multi-Mission Capable
Voltage Range	4 to 5 V DC
Degradation Rate	1.2%/yr
Efficiency	13%
Mass (including controller)	6 pounds (3 kilograms)
Volume	4.3 inch (11 centimeter) X 12.5 inch (32 centimeter) cube

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)

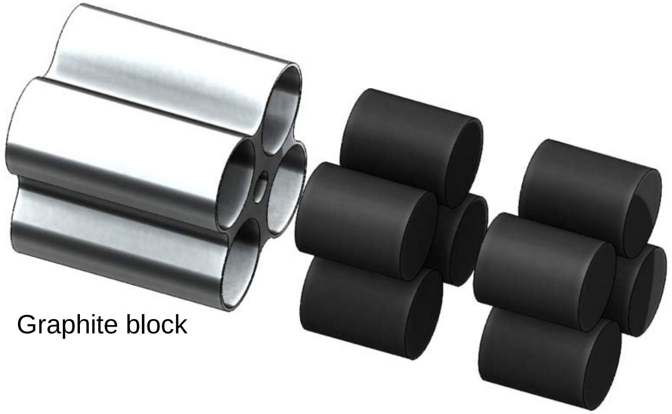
Generator concept uses 8x LWRHU

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

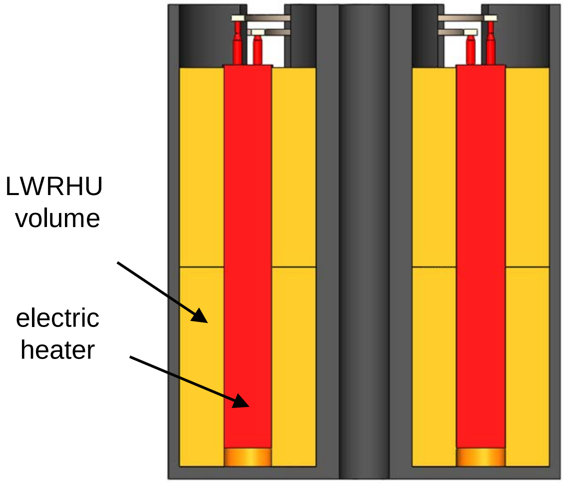
GRC testing will use electric heaters to simulate the LWRHUs

- 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



cross-section view

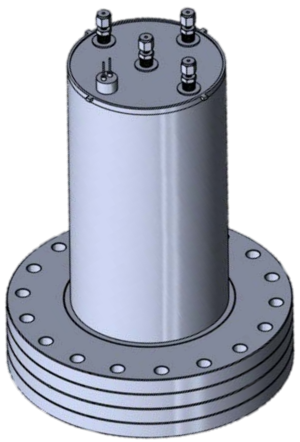
Test Hardware

LWRHU Simulator uses electric heaters

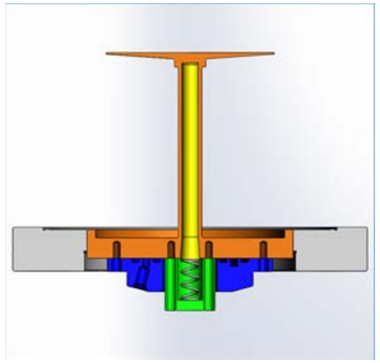
Insulation Design

Objectives

- High performance is critical to minimize losses
- Peregrine Falcon Corp. provided Multi-Layered Metal Insulation (MLMI) package in October 2018
- MLI design considerations
  - 8 watts thermal input, targeted >90% efficient
  - Evacuated to enable low thermal losses
  - Lab unit allows disassembly for inspection
- Thermal simulator design considerations
  - Reject 7 watts
  - Radiation coupling to heat source
  - Instrumented with TCs along the length to calculate heat transfer, also enables model comparison
- Efficiency is flat with achievable emissivity values

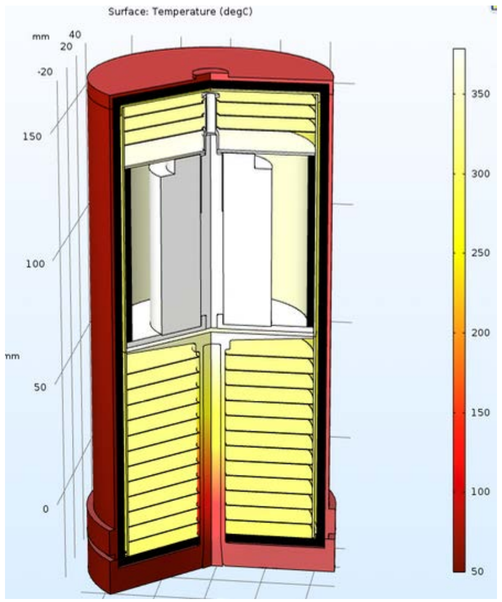


MLI Package

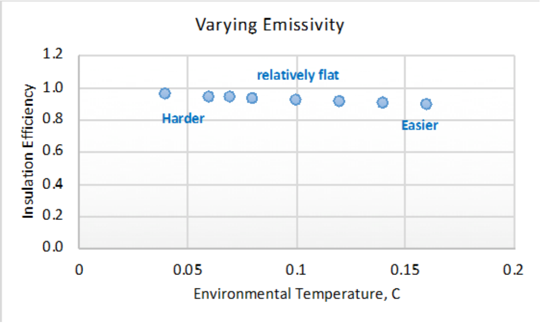


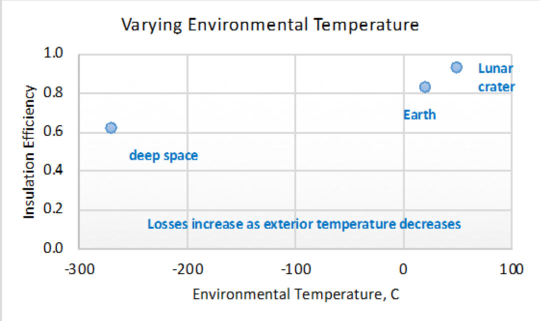
Thermal Simulator

Thermal Simulator Fabricated



Thermal Analysis Study





Exploratory cases for 10-W DRPS

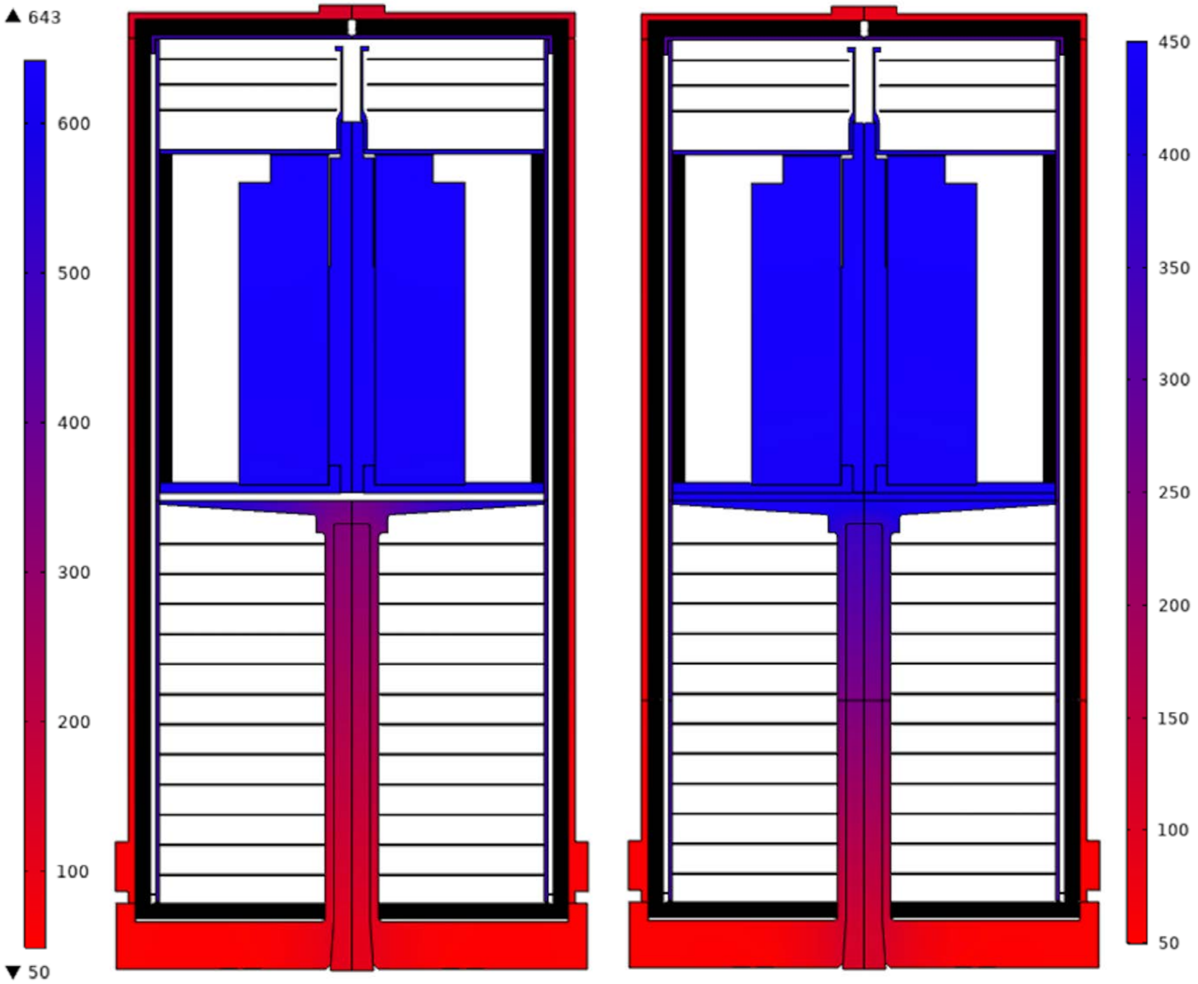
As-is

- Radiative coupling
- No additional layers
- Heat source temperature = 643 C
- Stirling hot-end temperature = 450 C

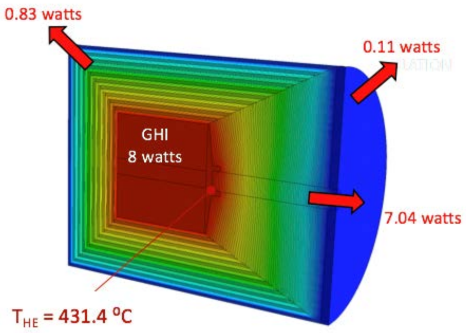
Minor modification

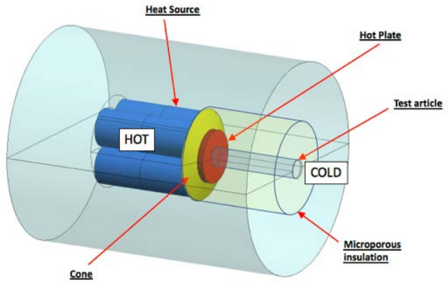
- Compliant thermal interface
- Heat source temperature = 450 C
- Stirling hot-end temperature = 450 C

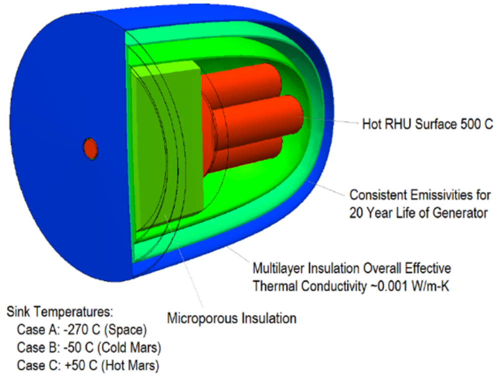
- Appears it could work for a 10-W DRPS with minor modification

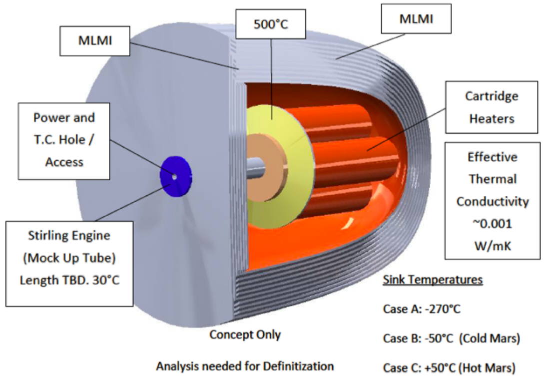


Insulation Evolution









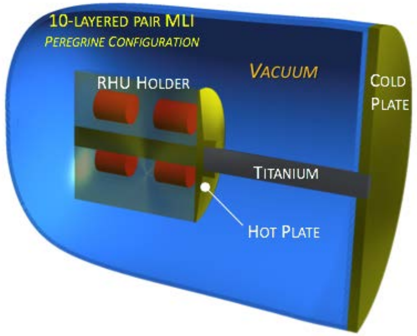
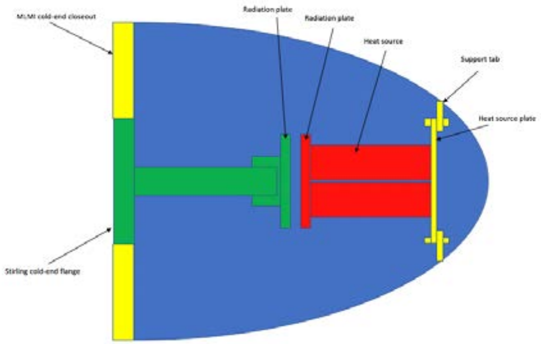
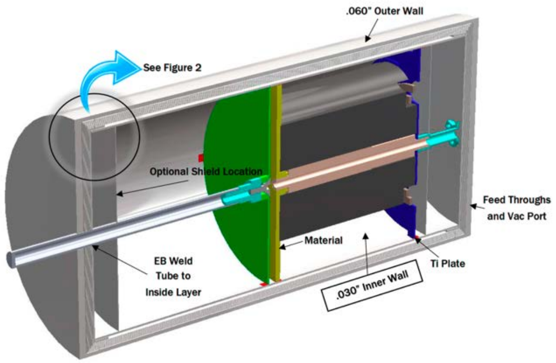


Figure 1: MLMI in Cross Section





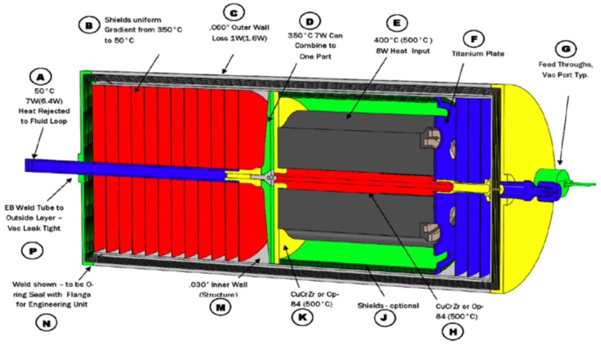
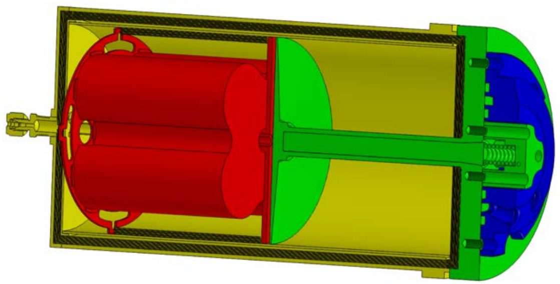
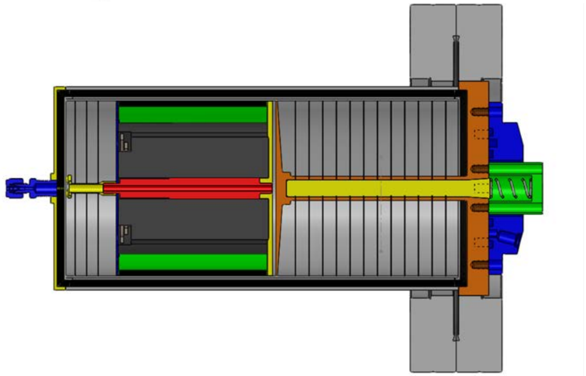


Figure 1: MLMI in Cross Section





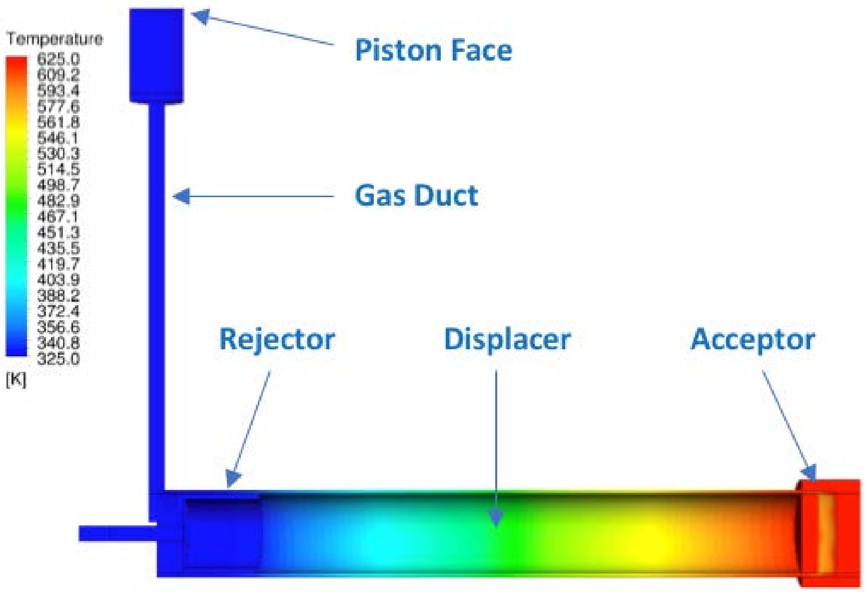
Convertor Modeling

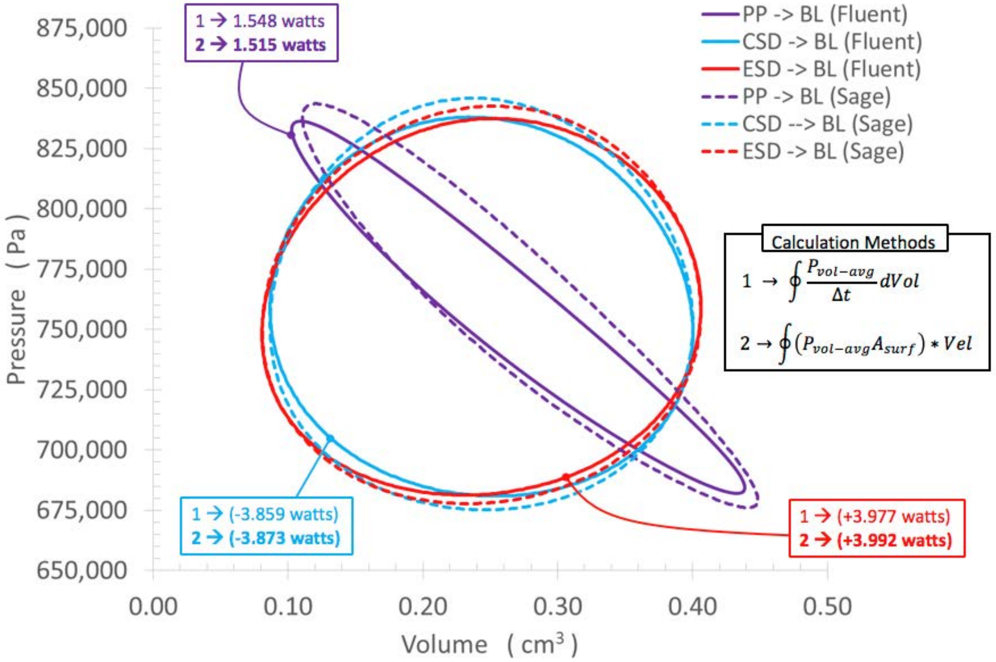
Confidence in Predictions

- 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

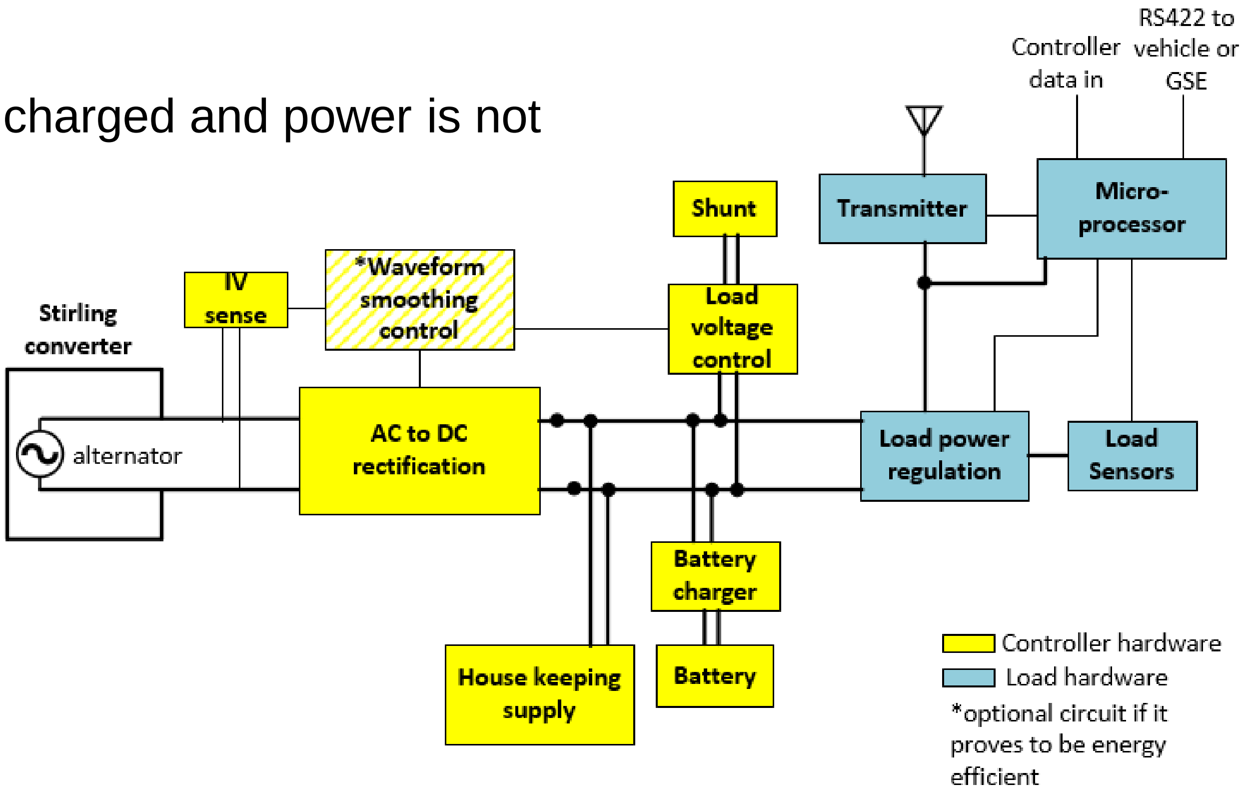




Controller Design

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 system and sensors
- Charging battery enables house keeping power and periodic burst transmission of measured data for communication
- Keep engine at a constant power level
- Shunt excess power when battery is fully charged and power is not required by the load

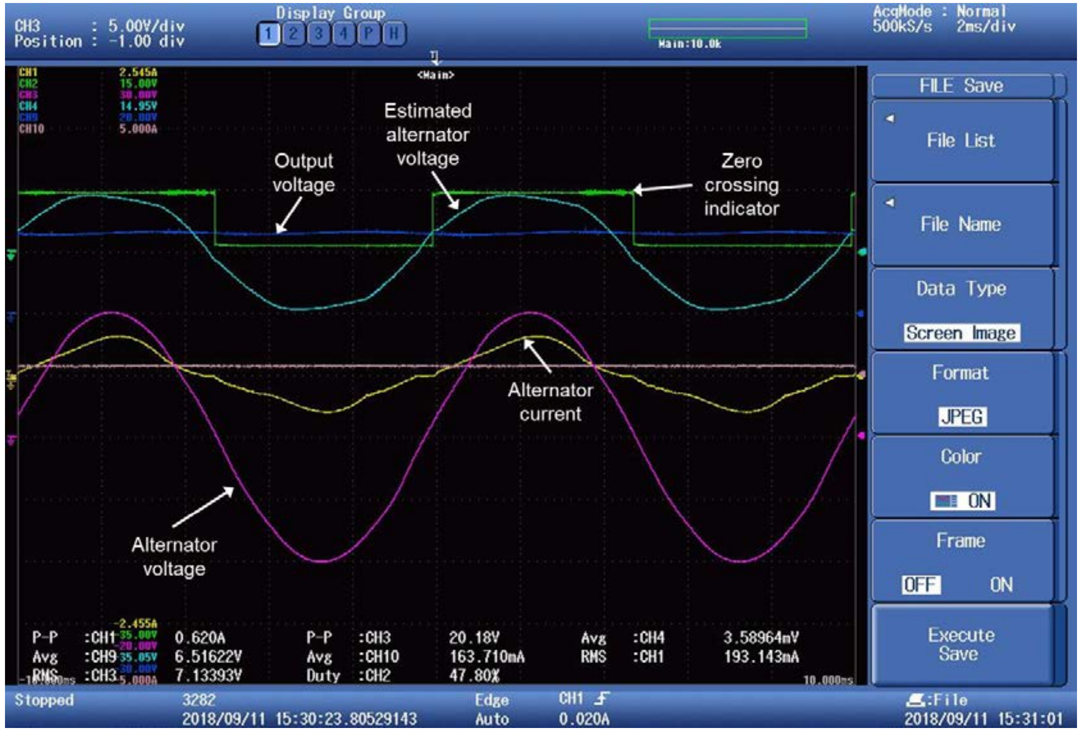


Controller Breadboard Testing

Initial testing met the power output goals

- Demonstrated linear AC regulator controller using a MOSFET H-bridge
- Analog circuit controlling 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

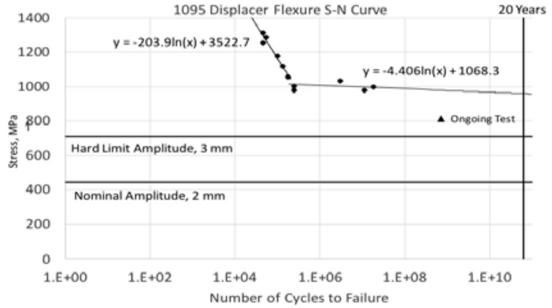
Value	Ideal diode rectifier	Wave form smoothing
Alternator Voltage, V_{p-p}	25.3	25.4
Alternator Power, W_e	1.37	1.34
Controller voltage, V_{dc}	11.7	11.5
Controller Power, W_e	1.11	1.22
Controller efficiency	80%	91%



Component Testing

Flexure Testing

- FEA predicted static stress @deflection, corresponding stress noted for each amplitude to develop S-N curve (fatigue stress vs. number of cycles to failure)
- Both flexure designs easily exceeded 10 million cycles operating at 100 Hz, high end of typical range used as threshold for identifying transition from high cycle fatigue to infinite life. The boundary between the finite-life and infinite-life regimes, or endurance limit, lies somewhere between 1 million and 10 million cycles for steels
- Displacer and piston flexures demonstrated over 100 million cycles with margin over the nominal amplitude without fracture
- Sufficient confidence our test effort will be failure free



Alternator Testing

- Successfully demonstrated (2x) styles of 1-watt moving coil linear alternators, (motored up to ~4 mm amplitude)
- Successfully demonstrated conduction path across flexure stacks and connections
- Demonstrated non-contacting operation of power piston
- Completed alternator design in concert with controller design in order to tune the motor inductance and ensure flight rated components (including capacitors)

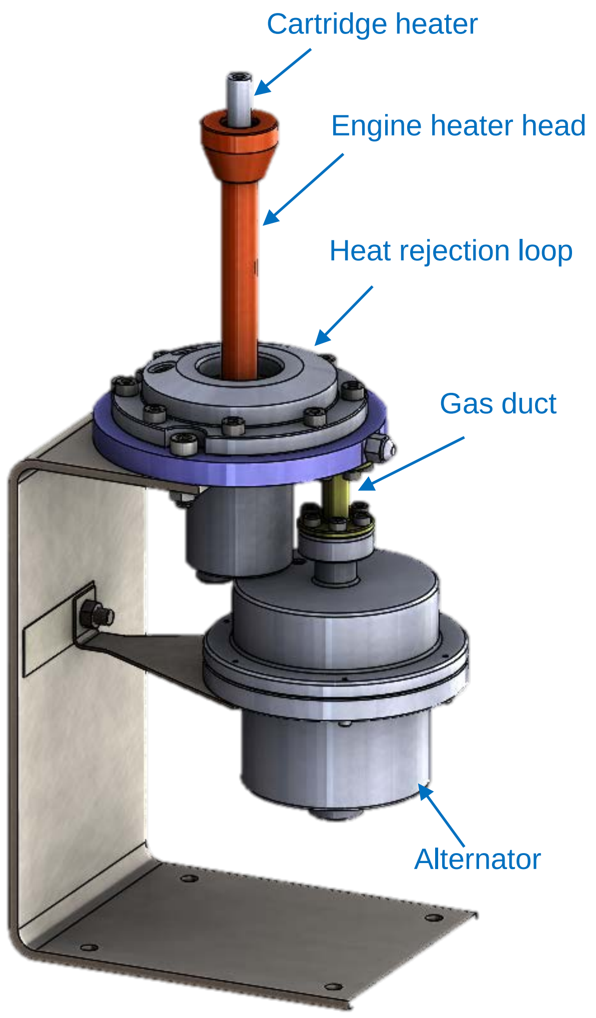
Convertor Description

Design Description

- Split-Stirling, gas duct between engine and alternator compression space
- Moving coil alternator
- Gap regenerator
- Flexure bearings for piston and displacer
- Laboratory design emphasized flexibility (not low mass)

Parameters

- Hot-end temperature, 350 ºC
- Cold-end temperature, 0-50 ºC
- Operating frequency, 100 Hz
- Operating pressure, 110 psig
- Pressure amplitude, 13 psig
- Piston amplitude, 4.5 mm
- Displacer amplitude, 2 mm



Lab Test Setup
(insulation not shown)

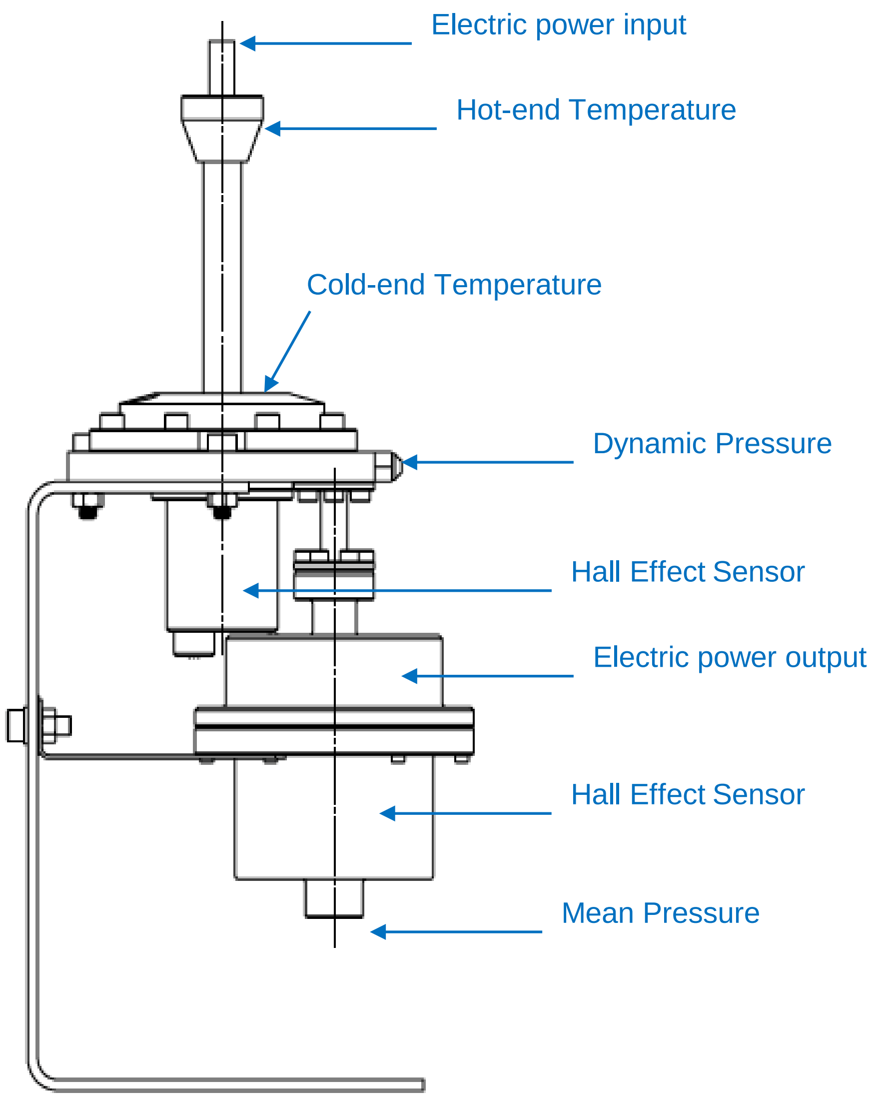
Convertor Instrumentation

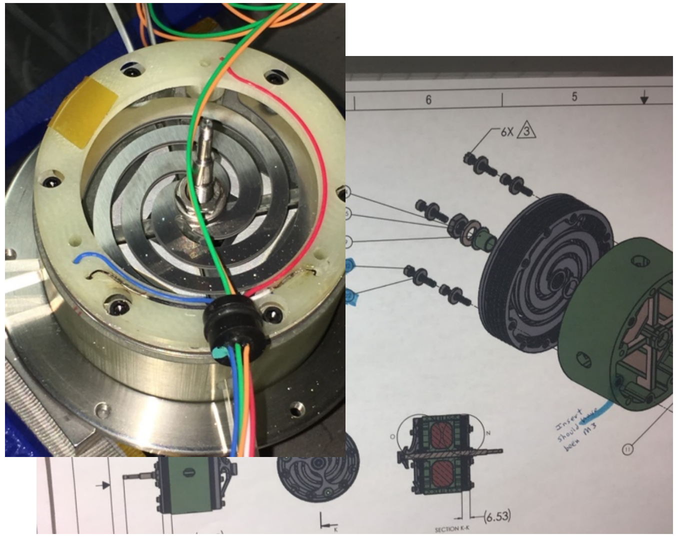
Measurements

- Hot and cold end thermocouples (8x)
- Dynamic CS pressure transducer (1x)
- Mean pressure transducer (1x)
- Hall effect sensors (2x)
- Power meter (power, voltage, current) for electrical heat input and alternator power output

Fabrication and Testing

- Fabrication is complete
- Assembly is complete
- Pneumatic testing is complete
- Motor tests have started, some iterative changes are in progress

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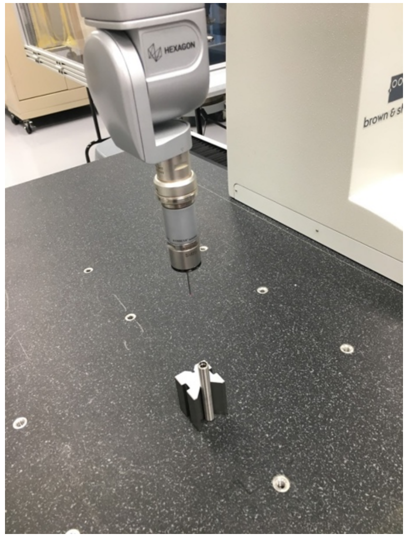
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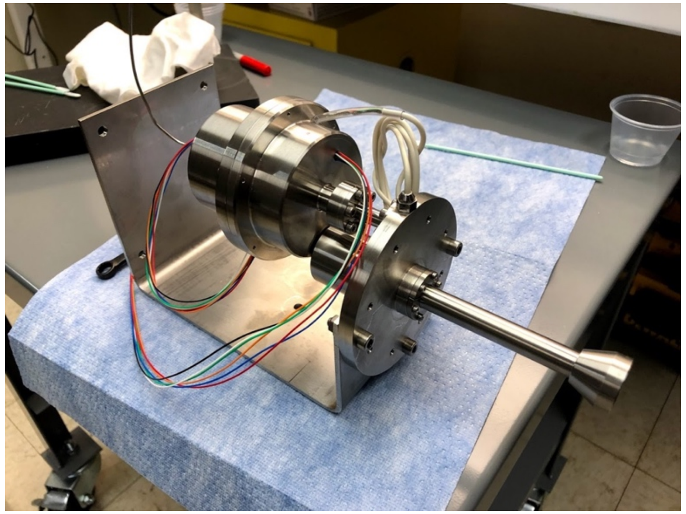

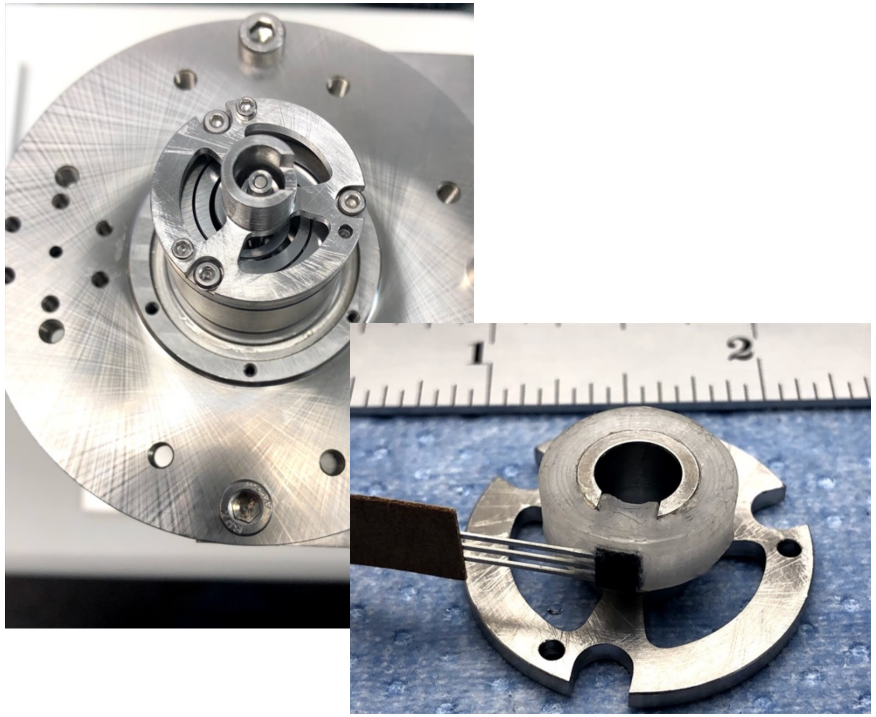
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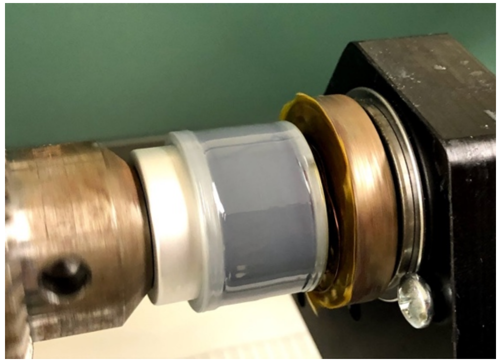
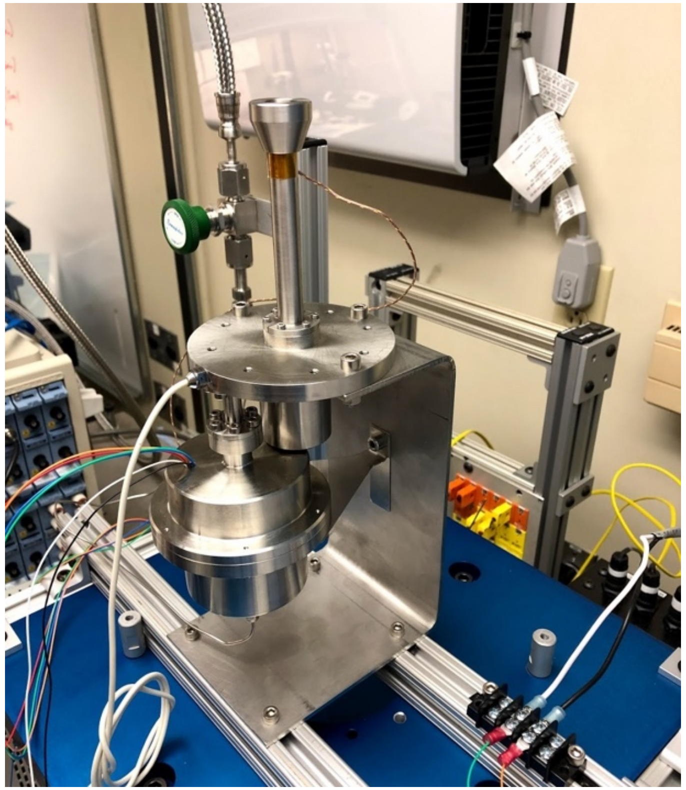
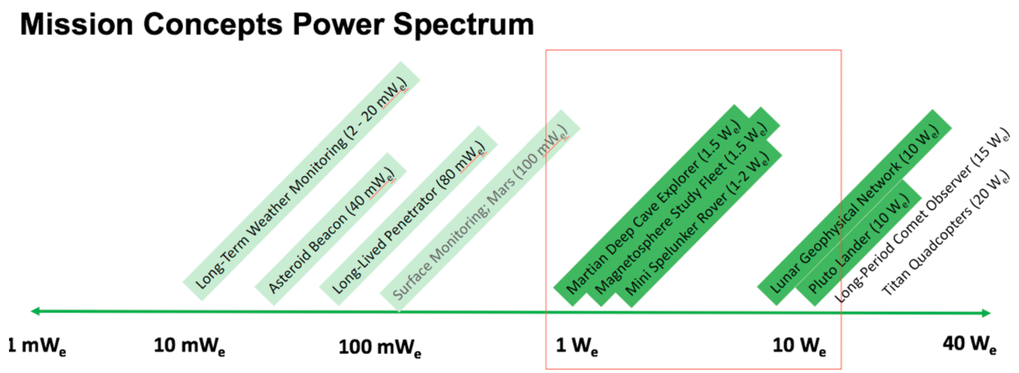


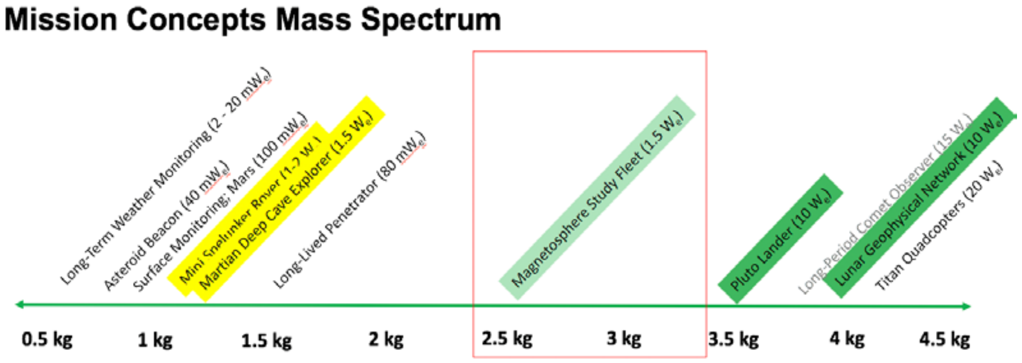


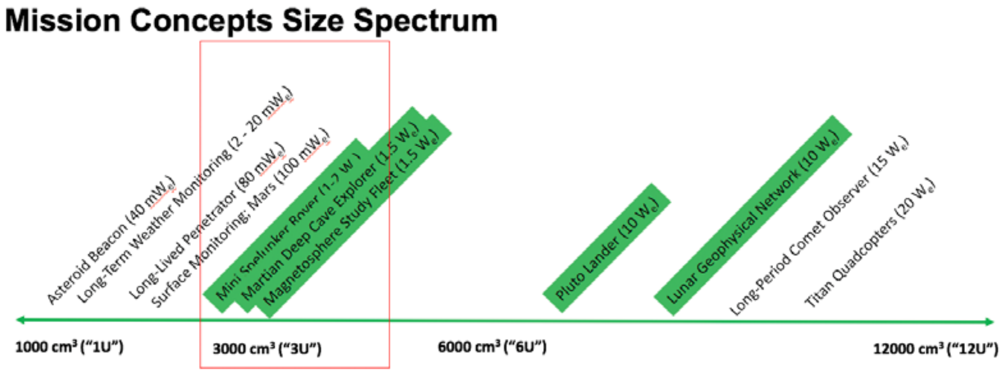
An Exploration of Mission Concepts That Could Utilize Small RPS

2019 NETS (Y. Lee, et al.)

- JPL's Small RPS A-Team Study focused on mission concepts for (1 mW_e to 40 W_e)
- Concepts were generated and reviewed as part of a JPL Innovation Foundry Architecture Team (A-Team) study
- Provided recommendations to RPS Program development activities
- Power, Mass, and Size (of interest for us)
  - 1 to 10 watts
  - 2.5 to 4 kg
  - 3000 cm^3 to 4000 cm^3 (3U to 4U)
- **Best fit for GRC 1-W DRPS**
  1. Lunar Geophysical Network (10 We)
  2. Pluto Lander (10 We)
  3. Magnetosphere Study Fleet (1.5 We)



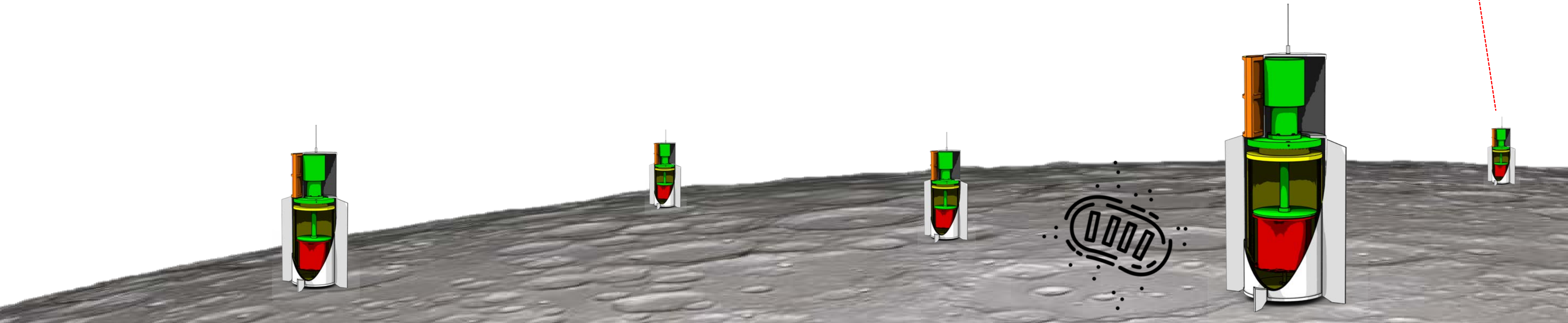




Conclusion

- Small RPS concepts are being studied by NASA for use on small spacecraft
- GRC is working toward demonstration of a 1-watt dynamic RPS
    - Testing is in progress on all subassemblies (convertor, controller, insulation)
    - Completed controller breadboard design and test, Brassboard is next
    - Completed convertor assembly and alignment of moving components, 1st operation is imminent
    - Completed insulation fabrication, test setup in progress
- GRC is also working on a paper design of 10-watt dynamic RPS

Small Stirling Technology Exploration Power or "smallSTEP"



Special thanks to:

- **RPS Program and Project Management**
- **1W Stirling Team**
  - Scott Wilson (Technical Lead)
  - Nick Schifer (Convertor Fabrication & Test)
  - Steve Geng (Alternator Design & Test)
  - Mike Casciani (Controller Design & Test)
  - Daniel Goodell (Thermal Management Design & Test)
  - Terry Reid (Advanced Modeling)
  - Barry Penswick (Engine Modeling & Design)
  - Paul Schmitz (Requirements)
  - Roy Tew (Sage Analysis)