



Dynamic Power Conversion Maturation for Small Radioisotope Power Systems

Conference on Advanced Power Systems for Deep Space Exploration

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Why are Small RPS needed?

- Small nuclear power systems could provide long lived electricity to power **probes, landers, rovers, or communication repeaters** for space science and exploration missions
- These systems would convert heat from the decay of nuclear fuel to usable electricity for powering spacecraft **mobility, science, and communications**
- Power range of interest is **10's of milliwatts to 50 watts using only thermoelectrics** (Enabling Exploration with Small RPS, JPL Pub 04-10)
- Future studies should also consider dynamic power
- Heat sources needed to fuel small RPS

- Enabling Exploration with Small RPS (JPL Pub 04-10)
 - 51 mission concepts studied using thermoelectrics (5% eff. assumed)
 - 24 studies used GPHS-class 12-50 We
 - 13 studies used fractional GPHS 3-9 We
 - 14 studies used LWRHU 5-500 mWe

Heat Source	Thermal Output	Potential System Power @ 5% eff.	Potential System Power @ 20% eff.	Heat Source Qualified?
GPHS	250 W _{th}	13 watts electric	50 watts electric	Yes
Fractional GPHS	60 W _{th}	3 watts electric	12 watts electric	No
LWRHU (8x)	8 W _{th}	0.4 watts electric	1 watts electric	Yes



- **Using LWRHUs reduces amount of Pu238 and LWRHU is a qualified form factor**

What applications could be enabled by efficient power conversion?

- Example of mission concept in need of a small efficient RPS
 - **Europa Tunnelbot** (NASA/TP – 2019-220054) selected the 1W Stirling RPS for powering the communication repeaters needed to send data from Tunnelbot to the lander on the surface of Europa (Jupiter's 4th largest moon)
 - Drivers for selecting power conversion
 - Volume/diameter drove pressure vessel size and resulting mass
 - Power level drove communication rate and data transmission
 - Traded 3 power systems
 - 12 We BOL, 1 GPHS eMMRTG (12,000 cm³, 6 kg)
 - 1 We BOL, 36 RHU Hi-Z RTG (10,000 cm³, 9 kg)
 - 1 We BOL, 8 RHU Stirling RPS (4,000 cm³ 3 kg)
 - Trade Results
 - RHU Stirling selected (RHUSTIR) 
 - At least 1 watt was needed for communication to enable battery charging and transmission
 - Stirling offered lowest mass, volume, length

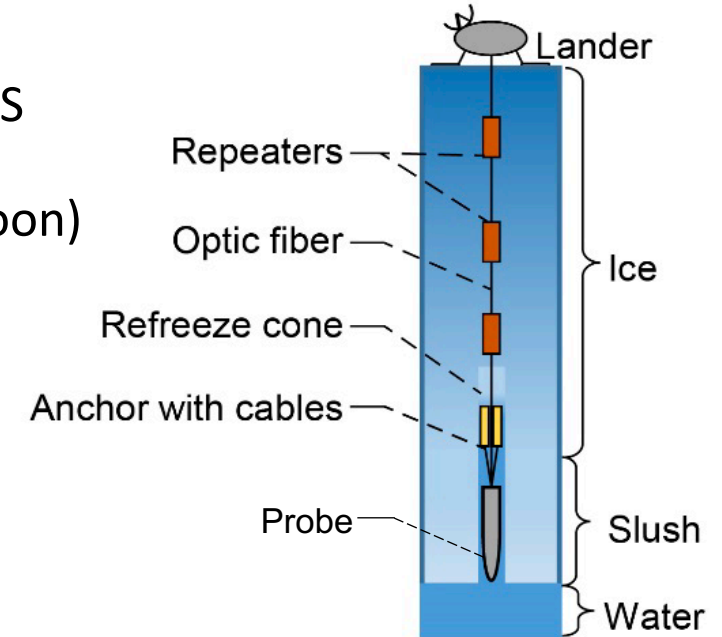


TABLE 17.—PERFORMANCE SUMMARY

Item	RHUSTIR ^a
Thermal inventory.....	eight-RHU ^b producing 8 W _{th} BOL ^c
BOM ^d power	1 W _e
EODL ^e power.....	0.83 W _e
Voltage range	5 Vdc
Stirling hot end temperature.....	500 °C
Stirling cold end temperature	50 °C
Efficiency.....	13 percent
Mass	3.0 kg
Volume	11- by 11- by 32-cm cube

^aStirling radioisotope heater unit.

^bRadioisotope heater unit.

^cBeginning of life.

^dBeginning of mission.

^eEnd of design life.

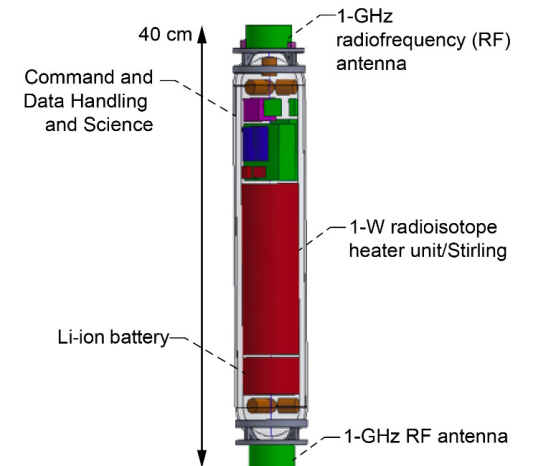
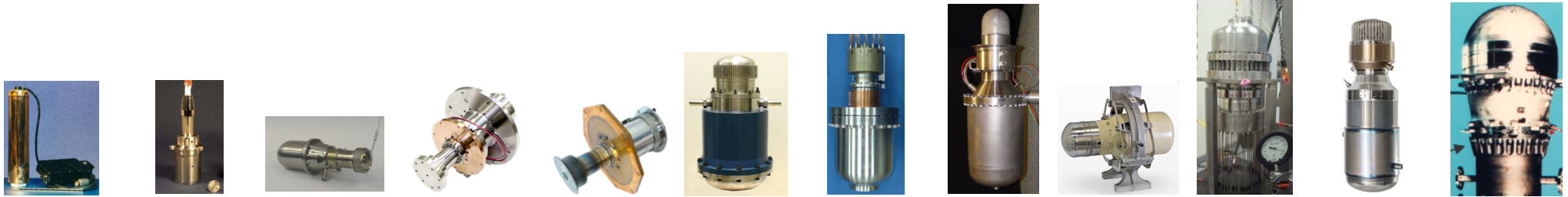


Figure 40.—Tunnelbot repeater.

Why dynamic power conversion?

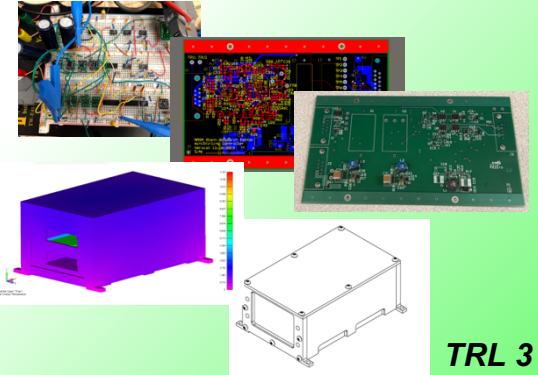
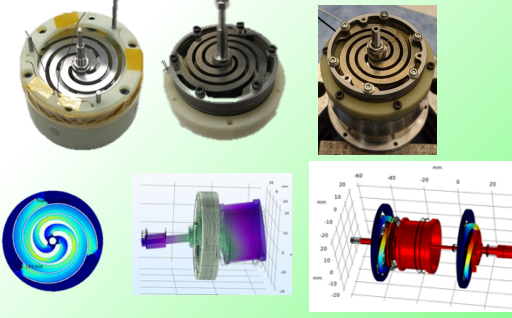
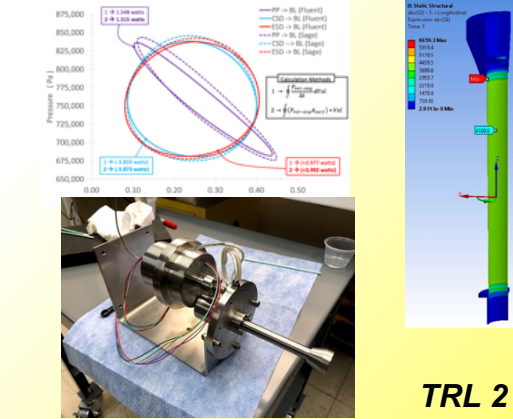
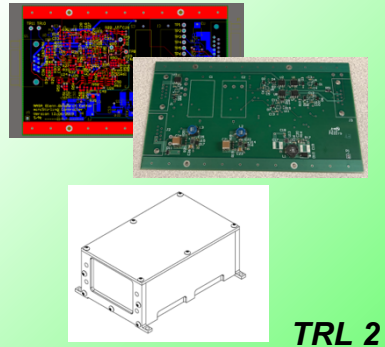
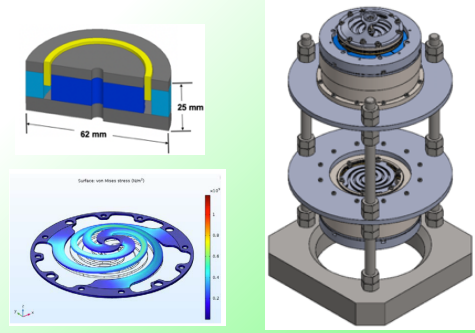
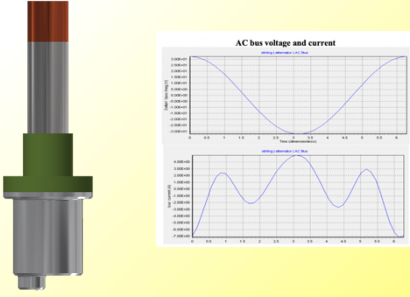
- Dynamic power convertors have achieved a fraction of Carnot efficiency of 50%, requiring less fuel for equal power or enabling more power for equal fuel compared to SOA RPS
- Stirling cycle machines have been demonstrated across a wide range of power levels (10 W to 25 kW)



	STC RG-10	Sunpower EE-35	Infinia TDC (RG-55)	Sunpower RSC	Sunpower ASC	Sunpower P2A	Sunpower GENSETS	AMSC GENSETS	Qnergy QB-3500	Sunpower PCU	Qnergy QB-7500	MTI CTPC
Project	RSG	SBIR	SRG-110	DRPS	ASRG	CHP	GENSETS	GENSETS	Powerdish	Fission TDU	CHP	SP-100
Nominal Power	10 W	35 W	55 W	64 W	80 W	1 kW	1 kW	1 kW	3.5 kW	6 kW	7.5 kW	12.5 / 25 kW
Thot / Tcold	650 °C / 70 °C	650 °C / 80 °C	650 °C / 120 °C	700 °C / 100 °C	760 °C / 90 °C	550 °C / 50 °C	650-850 °C / 80 °C	670 °C / 60 °C	Proprietary	575 °C / 100 °C	Proprietary	357°C -777°C /42 °C -252 °C
Approx. Mass	Coming soon	1.4 kg	4.7 kg	7.2 kg (flange) 3.4 kg (flight)	2.5 kg	35 kg	23 kg hermetic	56 kg	67 kg	100 kg	103 kg	
Bearings	Flexure	Gas hydrostatic	Flexure	Gas hydrostatic	Gas hydrostatic	Gas hydrostatic	Gas hydrostatic	Flexure	Flexure	Gas hydrostatic	Flexure	Gas hydrodynamic
Units	6x	6x	16x	2x	29x	>10,000 units	3x	1x	430x	2x	>100	2x
Operation (single unit)	100,000 hrs	1,377 hrs	120,000 hrs	< 500 hrs	92,000 hrs			~200 hrs		< 50 hrs		1,500 hrs
Operation (cumulative)		3,903 hrs	480,838 hrs		575,473 hrs					< 100 hrs		3,000 hrs
Demonstration	Long-life terrestrial application	Single and dual- opposed demonstration	GRC continues to operate relevant units	Future government V&V testing	GRC continues to operate relevant units	Microgen built for residential CHP	Natural Gas, CHP demo, UMW power demo	Natural Gas Demo	Solar farm demo at Tooele Army Depot	12 kW system demo at GRC	Commercial 5.65kW generator	25 kW system demo at GRC

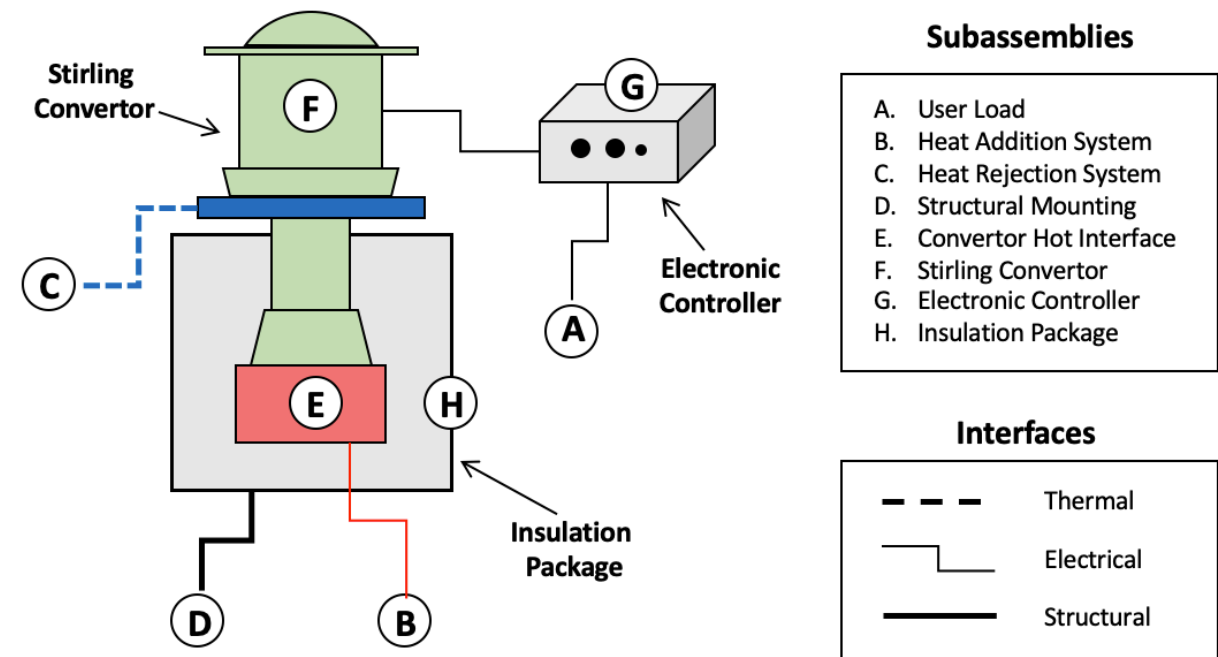
What is the approach to providing small dynamic power conversion?

- Mature technologies for 1W and 50W based on available heat sources

Goals	Controller	Alternator	Convertor	Insulation
8-watt Heat Source 1W DC Power 12% to 18% system efficiency	Breadboard demo completed, new common PCBs and enclosures purchased in FY20, need to complete functional testing  TRL 3	Tested 3 versions, need to complete full characterization of Version 3  TRL 3	Demonstration in work, need to complete characterization testing  TRL 2	Initial demo completed, insufficient performance, relaxing requirements to vacuum only design in FY21  TRL 1
250-watt Heat Source 50W DC Power 20% system efficiency	Analysis completed, new common PCBs and enclosures purchased in FY20, need to complete functional testing  TRL 2	Demonstration in work, hardware purchased in FY20, need assembly and test  TRL 2	Engine scaling in work, detailed design in work, need production dwgs  TRL 1-2	Analysis planned TRL 0

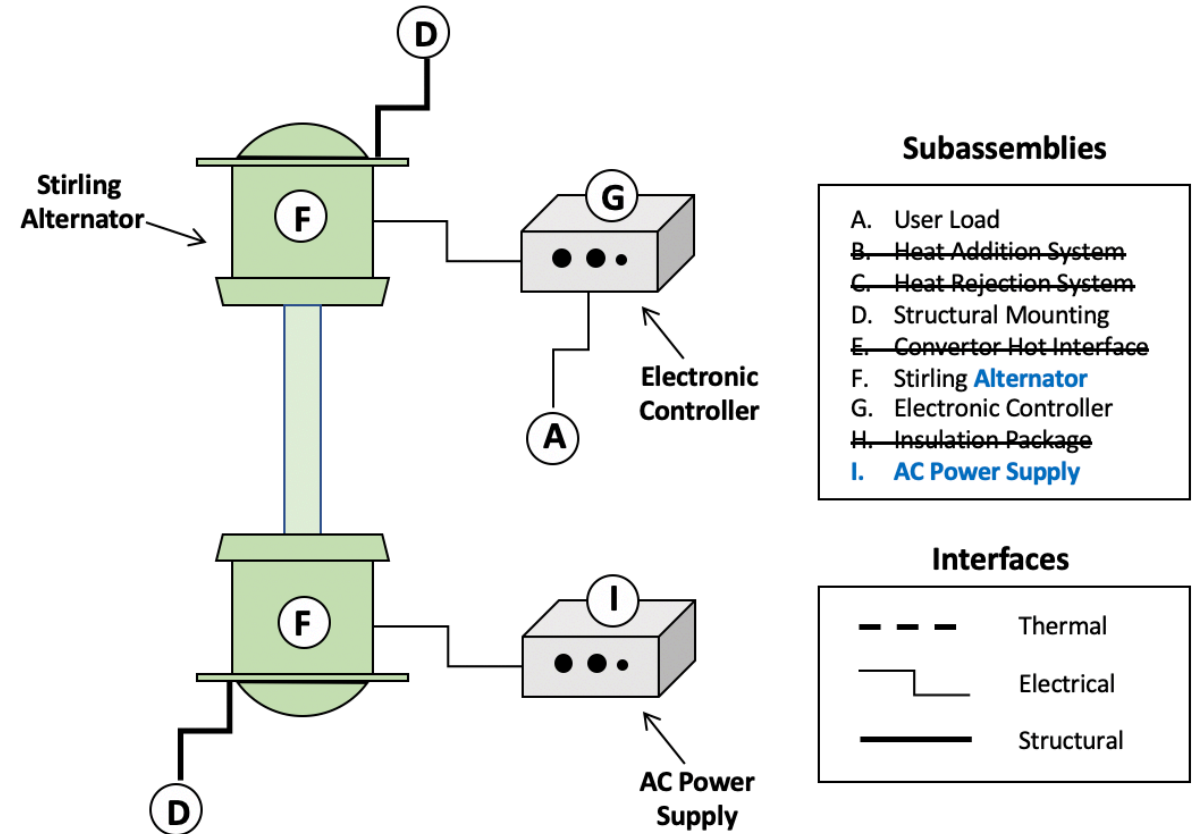
Task Goals and Objectives

- Goal to mature small Stirling RPS technologies for potential future use on planetary science missions
- Objectives for 1 W power level
 - Model and test major subsystems of a scalable power conversion architecture from 1W to 50W of DC electrical power output
 - Characterize performance
 - 1 W convertor in a laboratory environment
 - 1 W controller in a laboratory environment
 - Multi-Layered Insulation (MLI) for a RHU-Based DRPS in a laboratory environment
 - Demonstrate functionality of 1 W convertor/controller combination in a laboratory environment.
 - Demonstrate functionality of 1 W electrically heated DRPS in a vacuum environment.



Task Goals and Objectives (cont.)

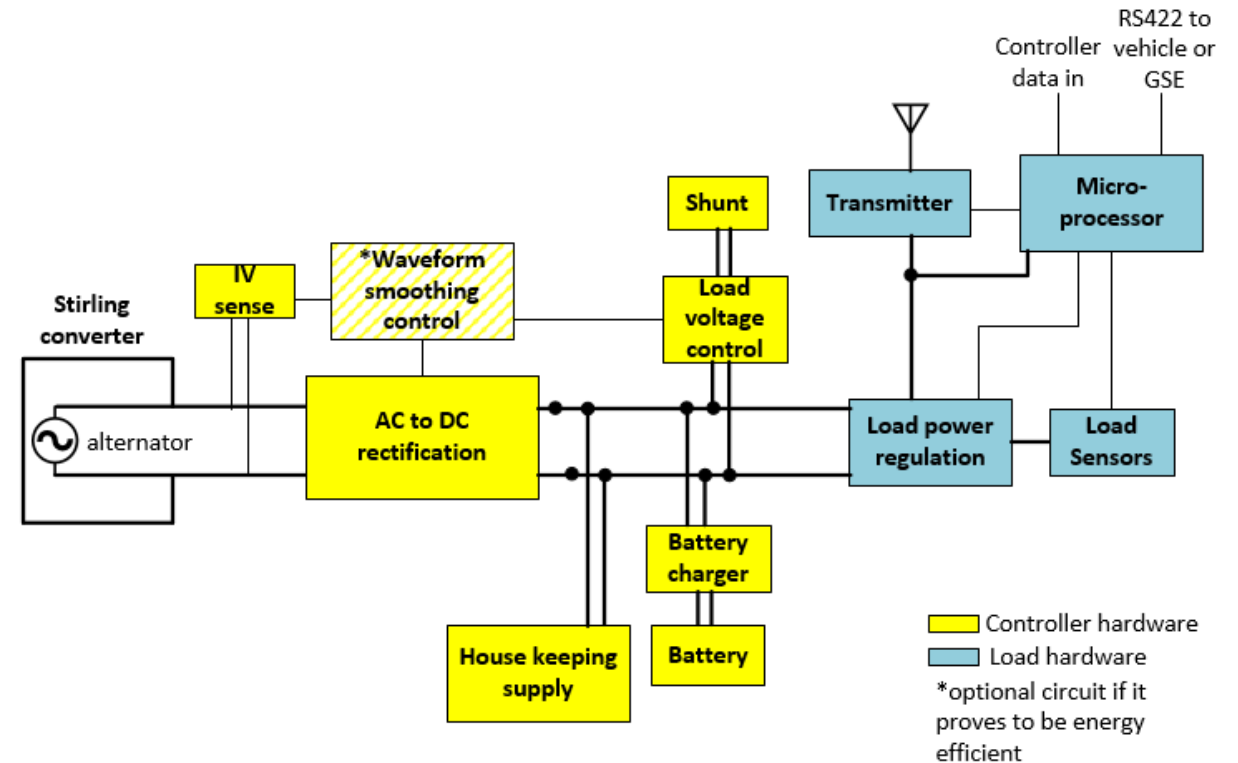
- Objectives for 50 W power level
 - Characterize performance of 50 W alternator in a laboratory environment
 - Back to back configuration
 - Initial testing would not include controller
 - Characterize performance of 50 W controller in laboratory environment using alternator AC power output of driven alternator
 - Back to back configuration
 - Include controller and user load
 - Demonstrate AC-DC conversion, THD reduction, passive startup function
 - Engine design and convertor testing are also planned as time permits



Controller Design

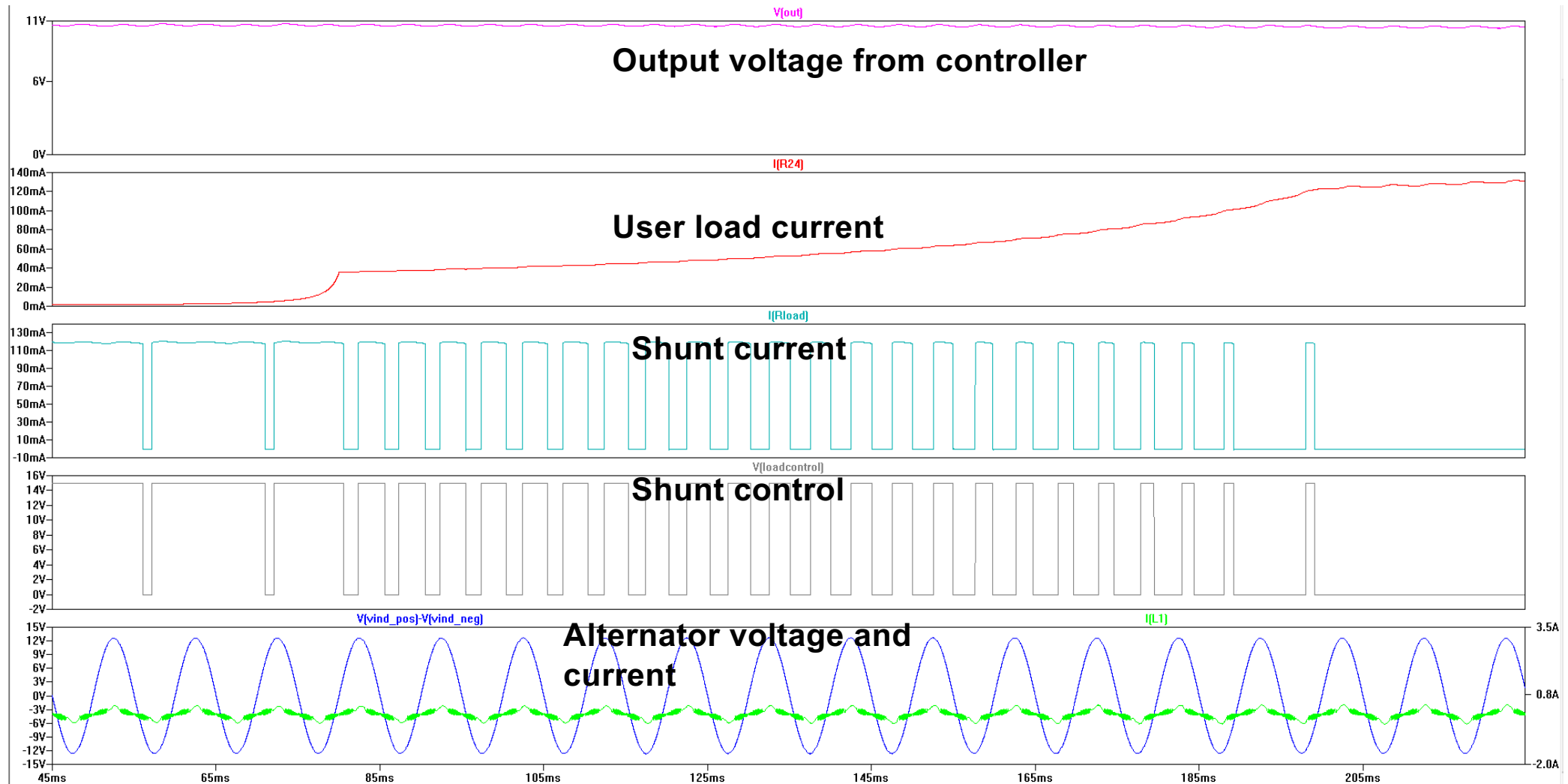
Basic requirements

- Rectify AC power for use by the load, focused on controller design interfacing a battery charger and a generic load
- Provide 1 W_e DC on 5 Vdc bus for rechargeable battery and sensors
- Charging battery enables house keeping power and periodic transmission of measured data to an orbiting spacecraft
- Maintain stable piston amplitude, based on load level
- Shunt excess power when battery is fully charged and power is not required by the load



Controller Modeling

- Final controller design includes a passive startup circuit to ease fueling operations



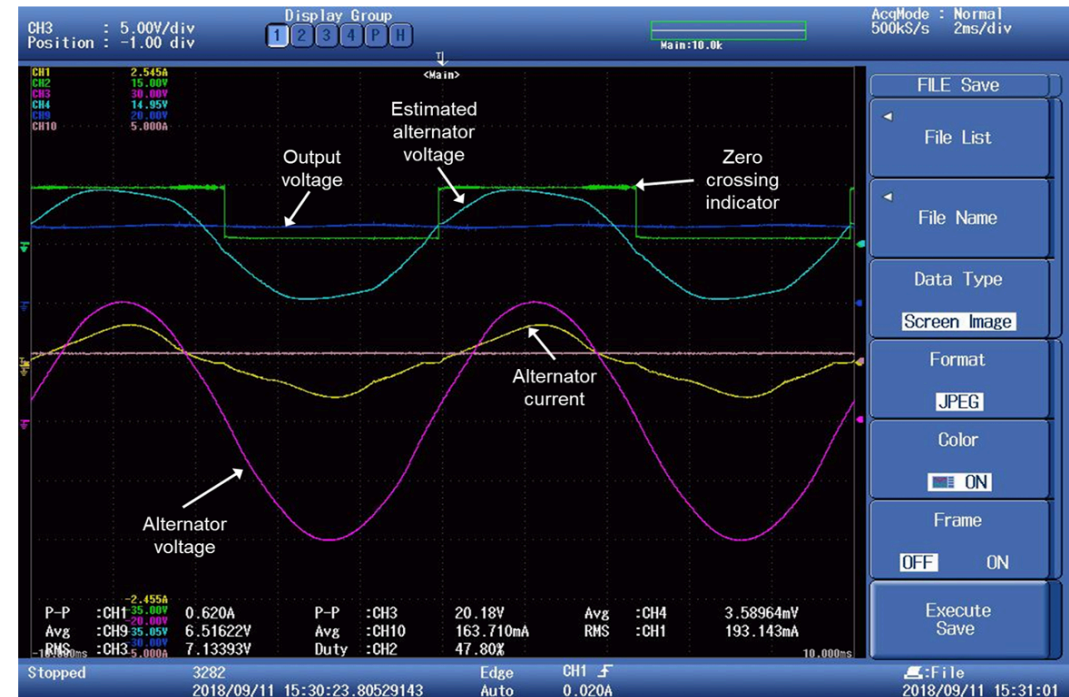
Controller Testing

- Controller testing was ultimately successful, informed future fabrication and testing

Initial testing met the power output goals

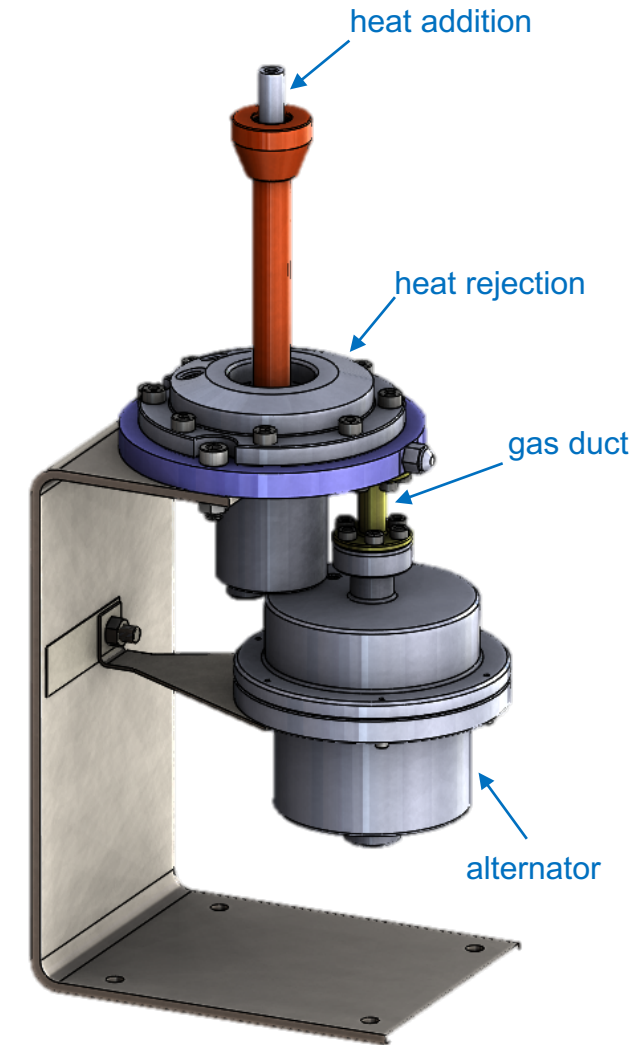
- Demonstrated linear AC regulator controller using a MOSFET H-bridge
- Analog circuit controlling FETs for AC to DC rectification and alternator current control to improve power factor
- Load voltage monitoring allows for load control and shunting of unused power

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%



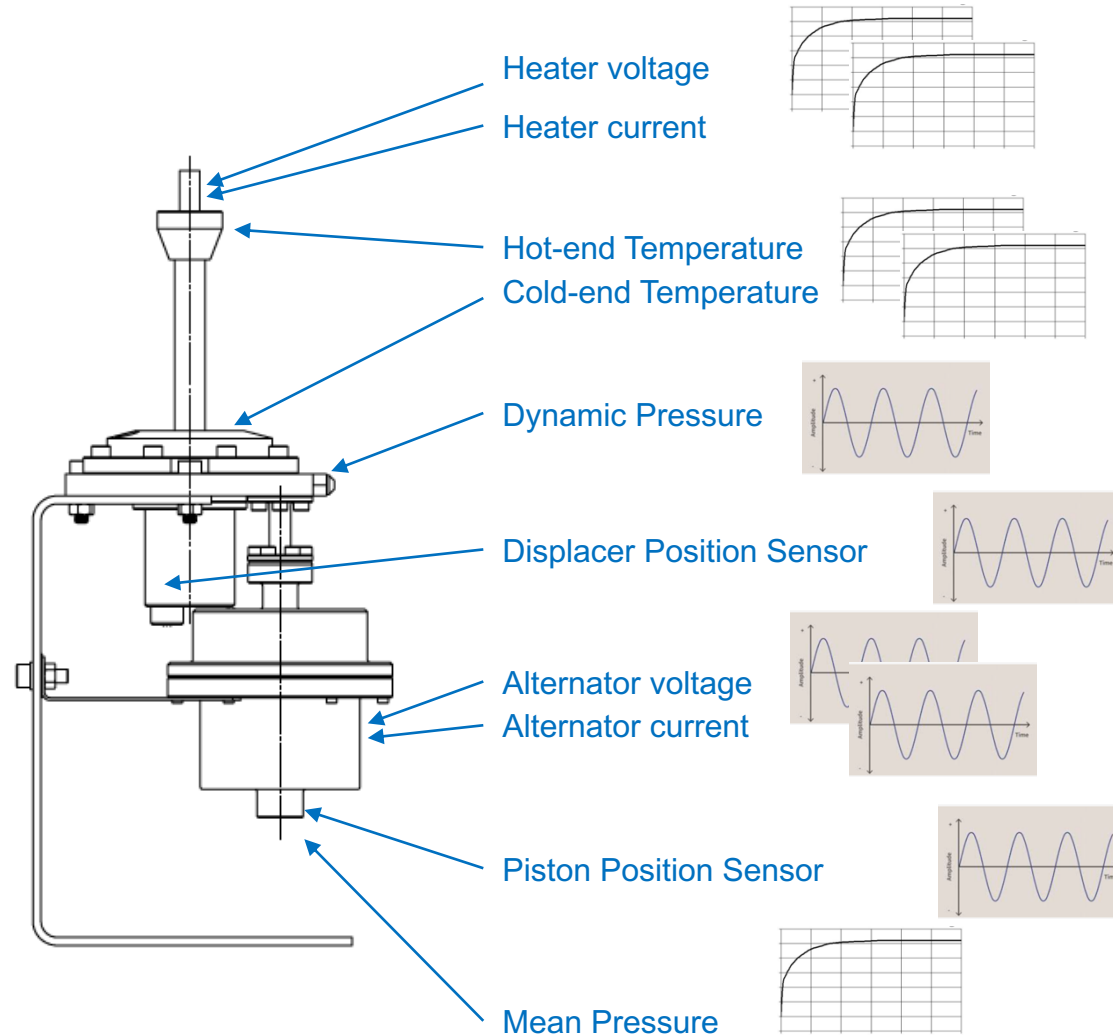
Convertor Design

- 1 W design features
 - Split-Stirling for initial demonstration
 - Bolted flanges for easy assembly, can be assembled within few hours
 - Gap regenerator – no porous matrix, not relevant at 50 watts
 - Flexure bearings
 - Lab design is massive compared to what it could be if optimized
 - Electrically heated to achieve 350 °C at hot end
 - Fluid cooling loop to achieve 0 to 50 °C at cold end
 - 100 Hz operating frequency
 - Helium working gas at 110 psig
 - Piston amplitude is 4.5 mm, displacer amplitude is 2mm
 - Original goal was 1 watt available from 7 Wth heat input
 - Analysis suggests 1.8 watts is possible from 7.8 Wth convertor heat input



Convertor Design

- Initial operation of the prototype requires more instrumentation to enable full characterization and code validation



Slow signals require only 2-sec data

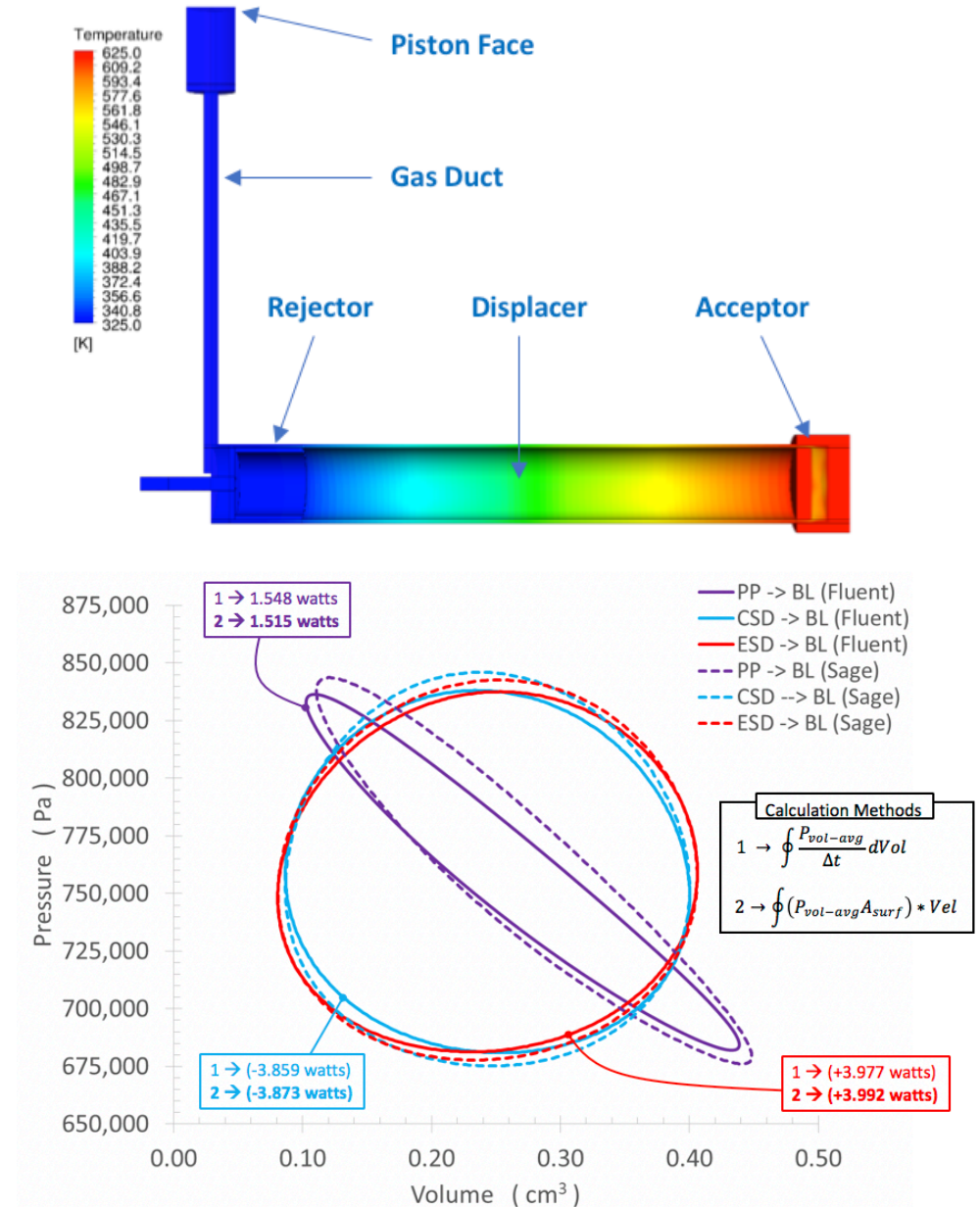
Dynamic signals require high rate data

Convertor Modeling

- 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 temperatures 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

Comparing results from 1D Sage to 3D CFD

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



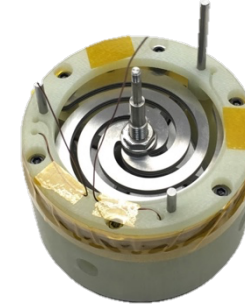
Alternator Testing

- Design includes a moving coil that conducts current across flexure bearings to a wire feedthrough, stator contains solid iron parts

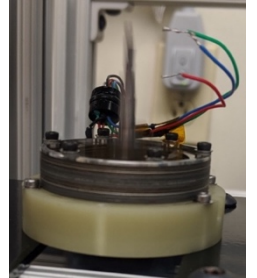
Demonstrated three linear alternators

- Mark 1: Assembly was complicated and the interfaces made piston alignment more difficult
- Mark 2: Assembly was simple, wiring to feedthrough was complicated, could not achieve full piston amplitude due to excessive rubbing caused by activation of a lateral mode at around 2 mm amplitude
- Mark 3: Easy assembly, easy wiring, interfaces designed to simplify piston alignment, refined analysis shows 100 Hz margin between operating frequency and lateral mode, successfully tested up to 2.5 mm

Trial 1

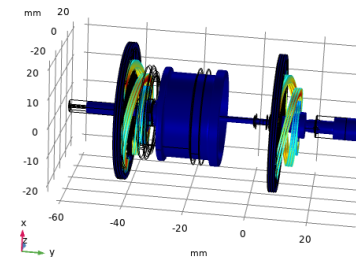
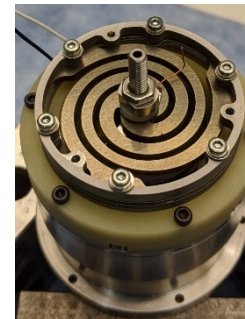


Trial 2



Lateral Mode During Testing

Trial 3

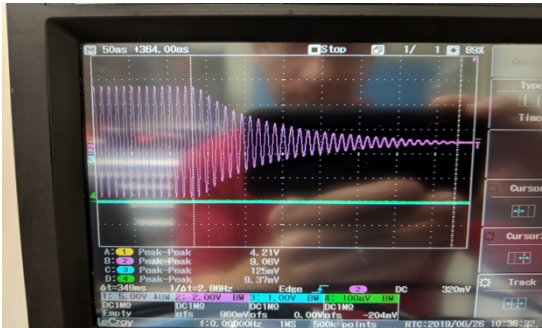
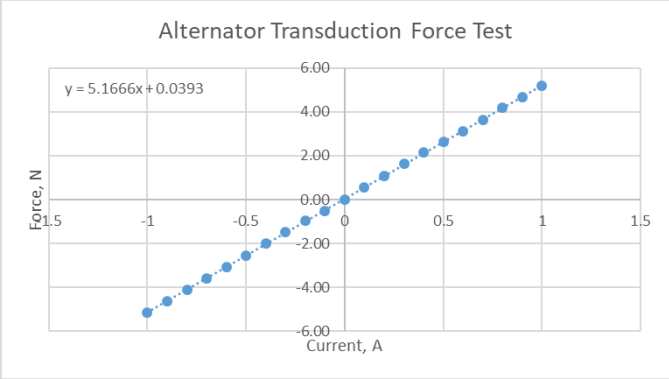
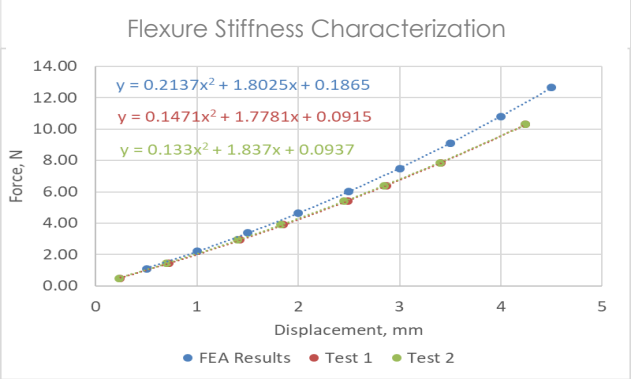


Modal Analysis

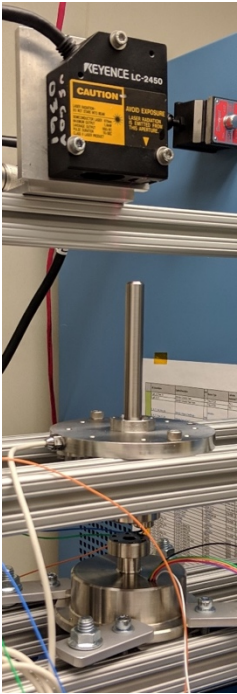
Convertor Testing

Test Objectives: Tune, align, and demonstrate convertor subassemblies and assembly. Compare analysis to predictions.

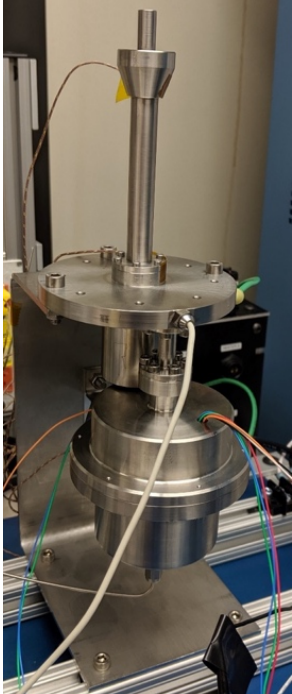
Name	Purpose
Flexure Force vs. Displacement	Determine the spring rate of the flexure stacks to be used in the alternator.
Alternator Transduction Test	Relate electrical current to mechanical force. Compared against analytical models.
Alternator Ringdown	Verify the piston is ringing freely and characterize the resonant frequency.
Displacer Resonance Test	Verify the displacer is ringing free throughout its entire range of motion. Characterize the displacer resonance over range of amplitude and make tuning adjustments early in process.
Nominal Test Condition	Performance Mapping: Verify efficiency predictions



Ringdown response



Displacer Assembly
Resonance Characterization



Convertor Assembly

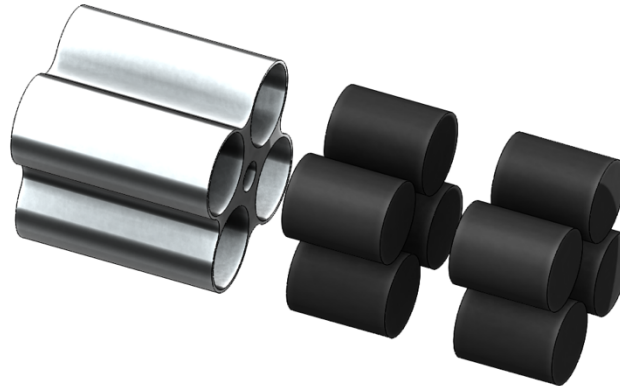
Insulation Design – Heat Source

- Heat source design would use 8x Light Weight Radioisotope Heater Units (LWRHU)
- Electric heaters are to simulate the nuclear fuel
- Heat source designed to provide similar thermal gradients compared to packaged LWRHUs
- Four resistance cartridge heaters to simulate 8x LWRHUs
- Heat source is vacuum rated

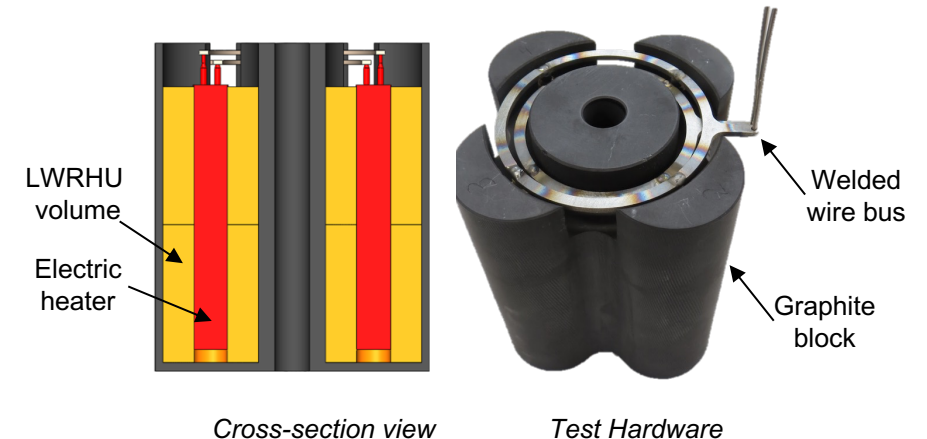
LWRHU Assembly



Generator concept uses 8x LWRHU

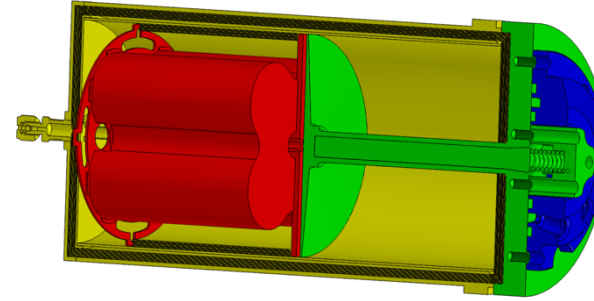


LWRHU Simulator uses electric heaters

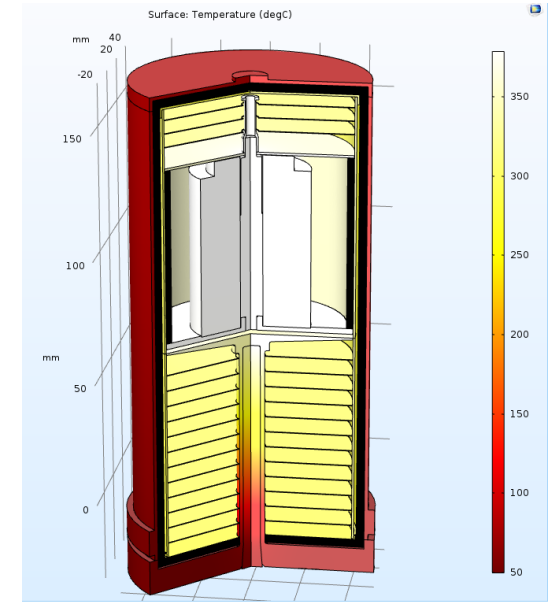


Insulation Design and Modeling

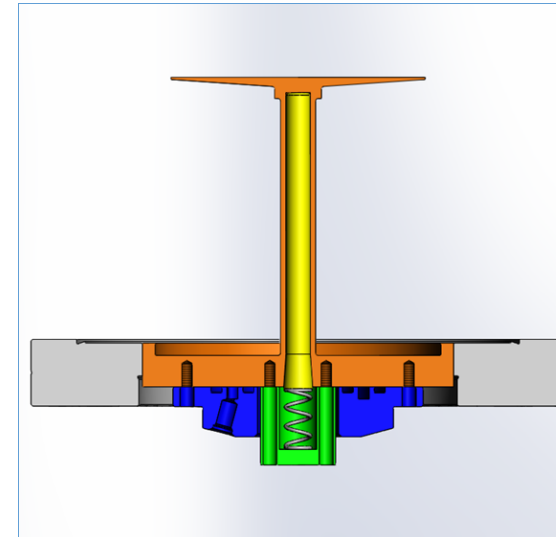
- Stirling hot end is radiatively coupled to the heat source
- Initial characterization was completed using a Stirling thermal simulator to enable direct calculation of heat transfer through convertor (~7 watts)
- Analysis included conductivity through solid materials and radiation between internal surfaces
- Model did not account for realistic contact resistances at internal interfaces
- Model did not contain fill tube or thermocouple ports, which could represent losses
- Analysis suggested reasonable temperatures could be achieved at the Stirling hot end



Insulation Package



Thermal Analysis Results



Thermal Simulator laser
welded into Conflat flange



Thermal Simulator

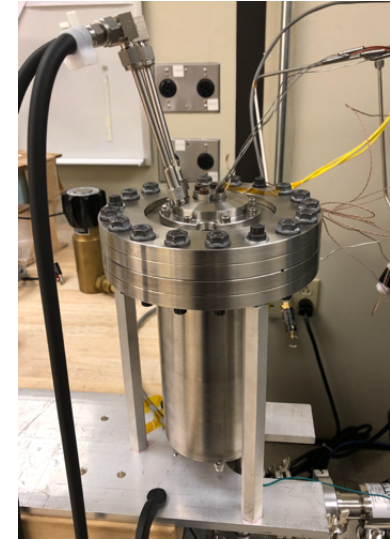
Insulation Testing

- Conflat flanges to enable disassembly
- Case matrix included varying cold end temperature
- Radiant coupling results in temperature difference across the gap

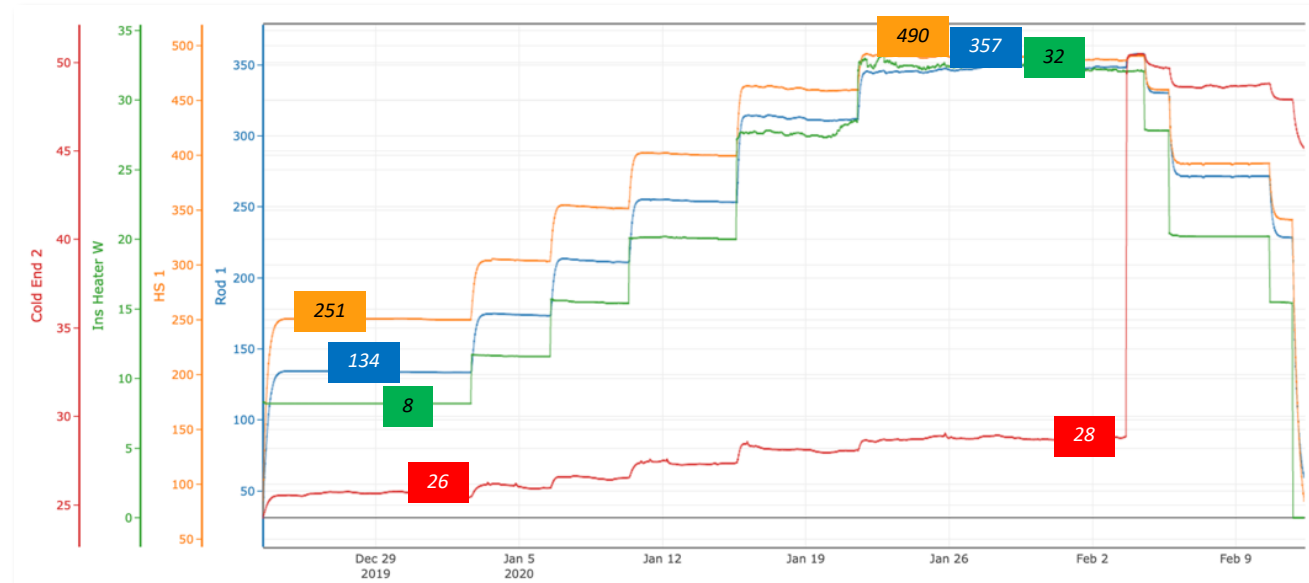
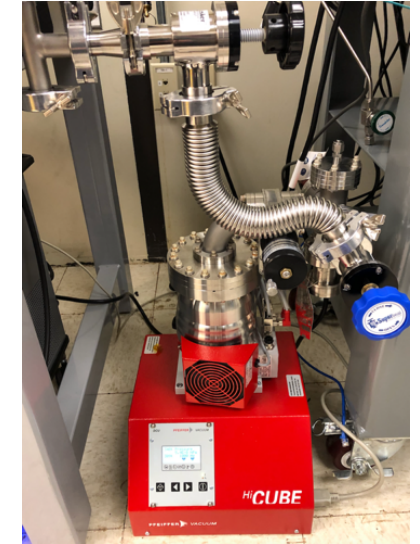
Findings

- Emissivity of internal shields was insufficient for high performance
- Fill port was initially too small, replaced with larger size which improved vacuum level and pump down times
- Cold end coupling dominated losses due to unintended conductive pathways at internal intersections (suspected)
- Resulting input power was 4 times higher than desired when at temperature

Test Setup

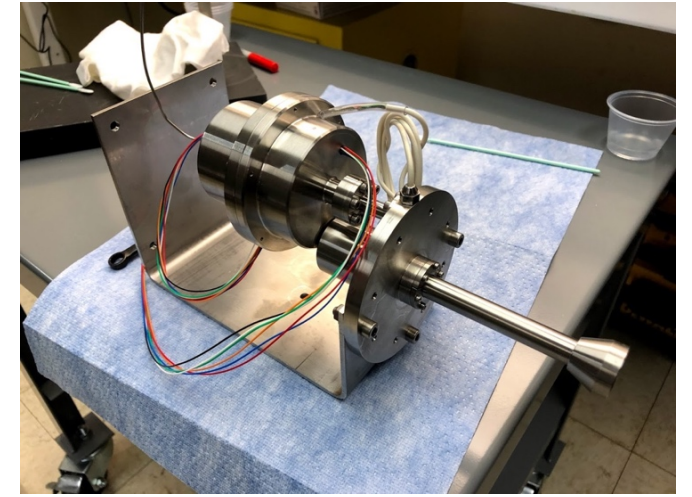


Vacuum Pump

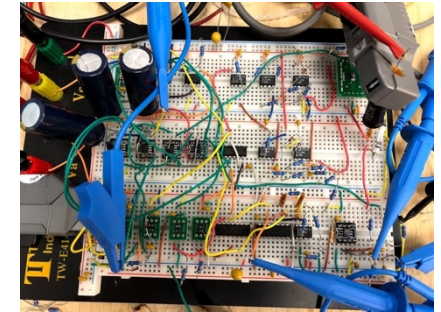


Accomplishments

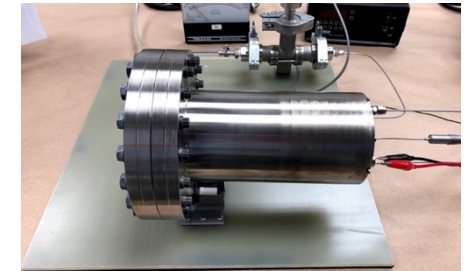
- 1-watt power level
 - Completed design and started breadboard testing of Stirling convertor
 - Completed design and testing of breadboard controller, fabricated new PCBs and enclosure
 - Completed design and testing of breadboard insulation package (didn't go so well but we learned a lot)
- 50-watt power level
 - Completed analysis for 50 watt convertor performance
 - Completed design of 50 watt alternator with controller design
 - Completed design of breadboard controller for 50 watt convertor



Pneumatic Testing



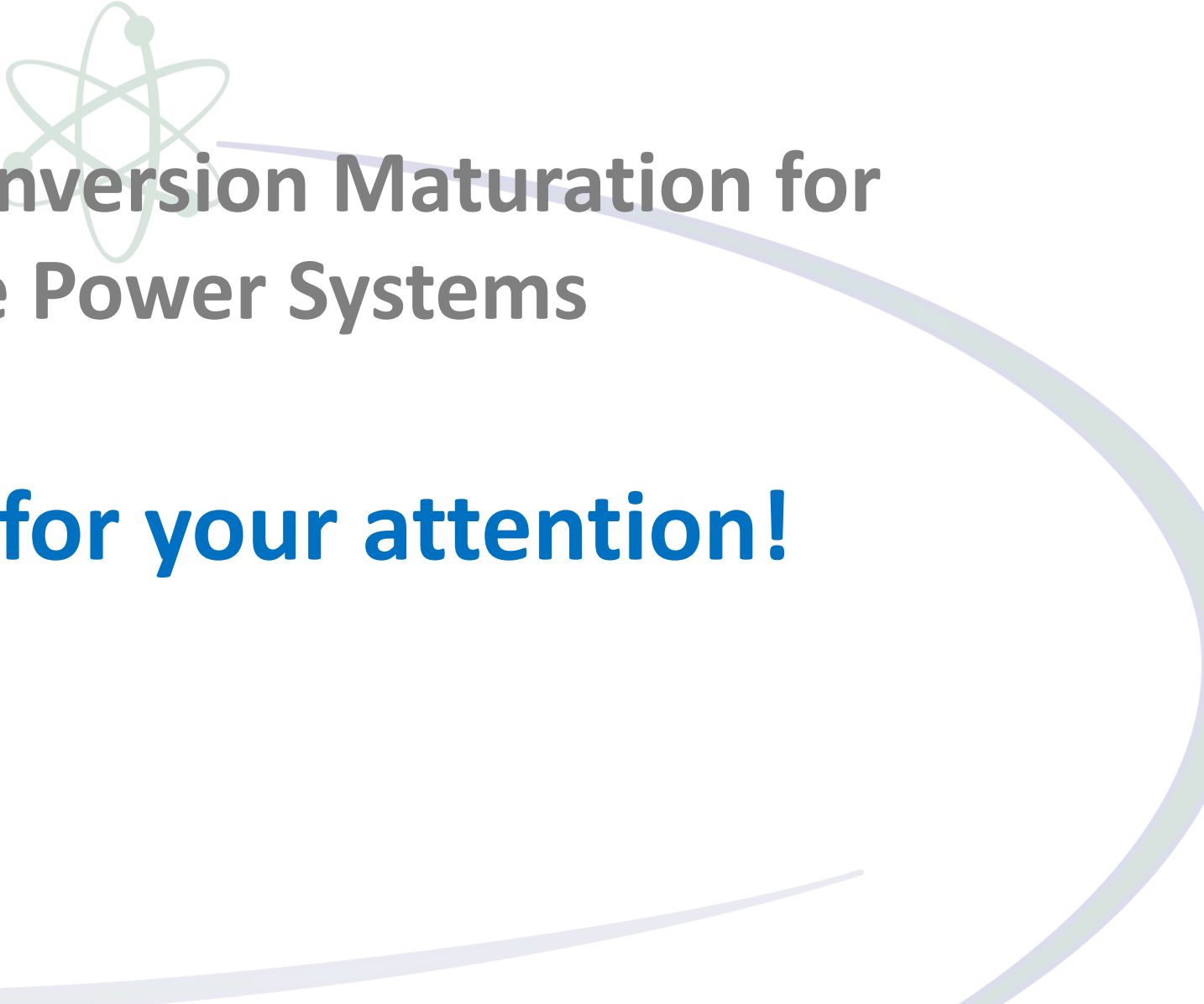
Controller Testing



Insulation Testing

Conclusions

- Striving to mature Small Stirling RPS technologies for future use in space applications
- Objective is to mature subsystems sized for qualified isotope heat sources, including convertor, controller, and insulation
- Breadboard testing is partially completed, testing delayed due to pandemic
 - 1W convertor – includes Mark 3 alternator
 - 1W controller – Mark 2 PCBs with passive startup circuit
 - 50W alternators – dual opposed assembly for functional checkout & efficiency measurement
 - 50W controller – functional checkout
- **We are looking forward to completing our test effort!**



Dynamic Power Conversion Maturation for Small Radioisotope Power Systems

Thank you for your attention!