Two-Phase Thermal Switch for Lunar Rover Thermal Management and Lunar Night Survival

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Agenda

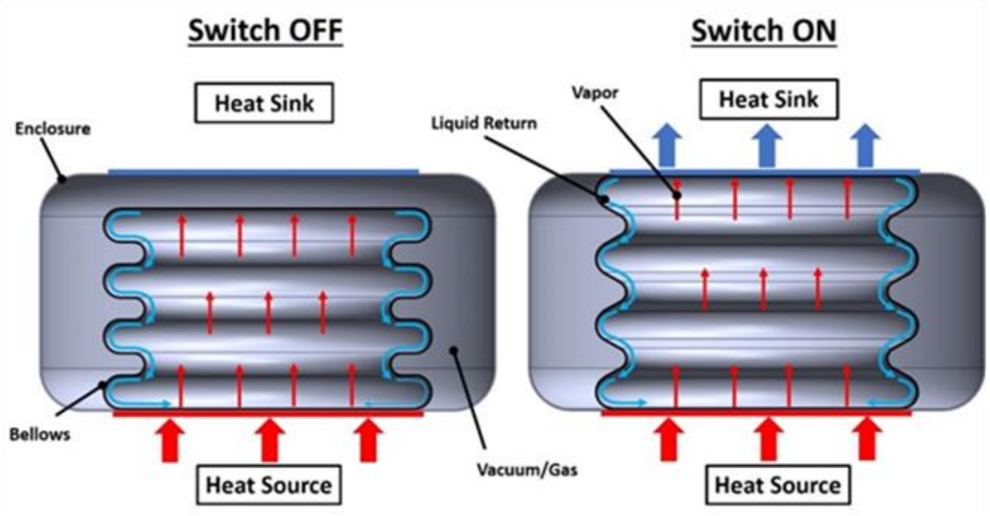
- Agenda
  - Motivation
  - Bellows Thermal Switch Concept
  - Thermal Switch Model Development
  - Prototype Fabrication and Testing
  - Design of Thermal Switch for Small Rovers
  - Conclusions
  - Future Work
  - Acknowledgements

Motivation

- Thermal management for the Moon is much more complicated than it is for near-Earth spacecraft and Mars Rovers, due to both the 14-day long Lunar Night and by the Moon's lack of atmosphere.
- Since many Lunar Landers and Rovers are solar powered, batteries are required to provide survival power.
  - Required survival power must be minimized, since providing 1 Watt over the 14-day long Lunar Night ***requires about 5 kg of extra solar cells and batteries*****.**
- Second portion of the Lunar thermal challenge is to survive the Lunar Day, that also lasts for 14 Earth Days.
- Thermal control device must reject the power generated during the Lunar Day with a relatively high thermal conductance, while minimizing the heat losses during the night.
  - Since the system must operate during both the Lunar day and night, we can't just insulate the batteries and instrumentation.
- The heat transport must use one or more Variable Thermal Links, which transports heat with minimal ΔT during high power usage periods, and passively shuts down at night, minimizing heat losses.

Design Concept

- Bellows-Based Thermal Switch Concept
  - Sealed bellows containing working fluid and wick
    - "On" when bellows in contact with sink;
    - "Off" when disconnected
  - Balance of forces between working fluid saturation pressure, NCG pressure, and spring force determine contact (minimum) temperature – "set point"
  - Depending on conditions (Temperature or Power driven) the switch can act as:
  - On/Off thermal switch (disconnected surfaces)
  - Variable conductance device to maintain heat source at a set temperature (through intermittent contact)



Model Development

- Thermal switch approximated as lumped thermal capacitance-resistance network
- Vapor temperature determines vapor pressure input to bellows mass-spring model
- Dynamic model implemented in MATLAB Simulink

$$\frac{dT_A}{dt} = \frac{1}{C_A}\left[\dot{Q}_{in} - \frac{T_A - T_B}{R_2} - \frac{T_A - T_C}{R_3}\right]$$

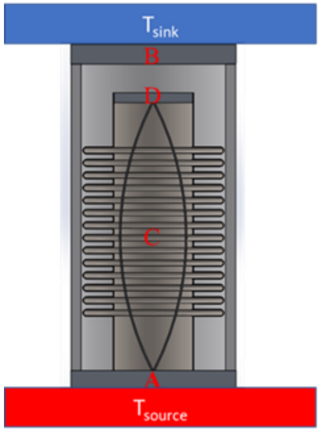
$$\frac{dT_B}{dt} = \frac{1}{C_B}\left[\frac{T_A - T_B}{R_2} + \frac{T_D - T_B}{R_5} - \frac{T_B - T_{sink}}{R_6}\right]$$

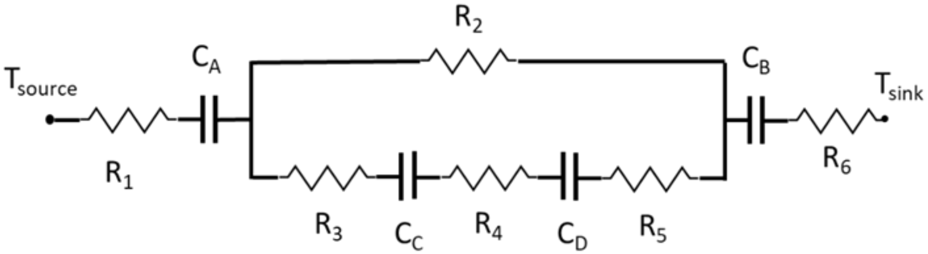
$$\frac{dT_C}{dt} = \frac{1}{C_C}\left[\frac{T_A - T_C}{R_3} + \frac{T_C - T_D}{R_4}\right]$$

$$\frac{dT_D}{dt} = \frac{1}{C_D}\left[\frac{T_C - T_D}{R_4} - \frac{T_D - T_B}{R_5}\right]$$

$$M\ddot{y} + b\dot{y} + ky = F(t)$$

$$F(t) = F_{NCG} + F_{contact} - F_{saturation}$$

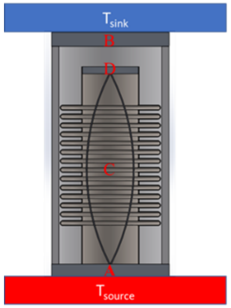


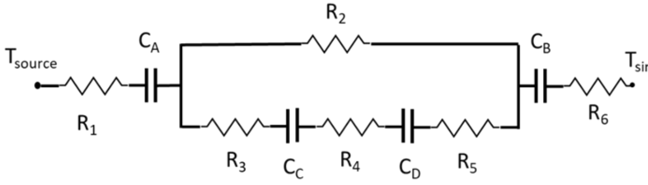


Model Development

- **Challenge of model is obtaining relevant values for thermal resistances and capacitances**
- **Model for pressure-dependent bellows contact resistance implemented in model**
  - **Solid-spot conductance**
  - **Gas-gap conductance**
- **Using a lumped capacitance for vapor in bellows**
  - **Next step to implement relevant thermodynamic processes into bellows equations**
  - **Assume bellows is critically damped**

Thermal Resistance	Description
R_1	Contact resistance between heat source and enclosure base (A)
R_2	Conduction resistance through enclosure wall (kA_c/L)
R_3	Evaporation thermal resistance in bellows
R_4	Condensation thermal resistance in bellows
R_5	Contact resistance between bellows end cap (D) and top of enclosure (B) – contact (On/Off) and contact pressure dependent
R_6	Contact resistance between top of enclosure (B) and heat sink



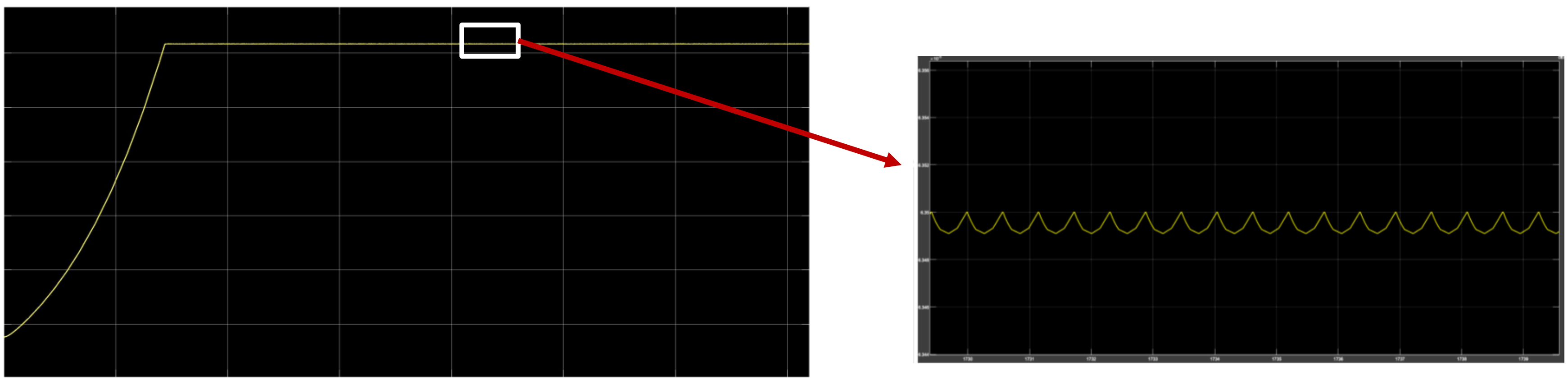


Model Development

- **Model shows expected behavior of bellows thermal switch**

- **Example:**
  - **Stock bellows SS-750-26-34, 0.25” offset**
  - **Acetone working fluid – 350 K setpoint**
  - **“Steady state” oscillations of around 1.7 Hz**

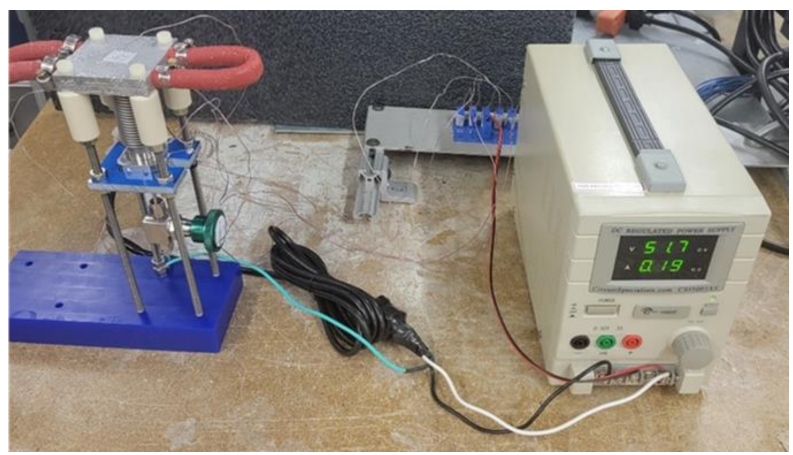
Bellows Position



Prototype Demonstration

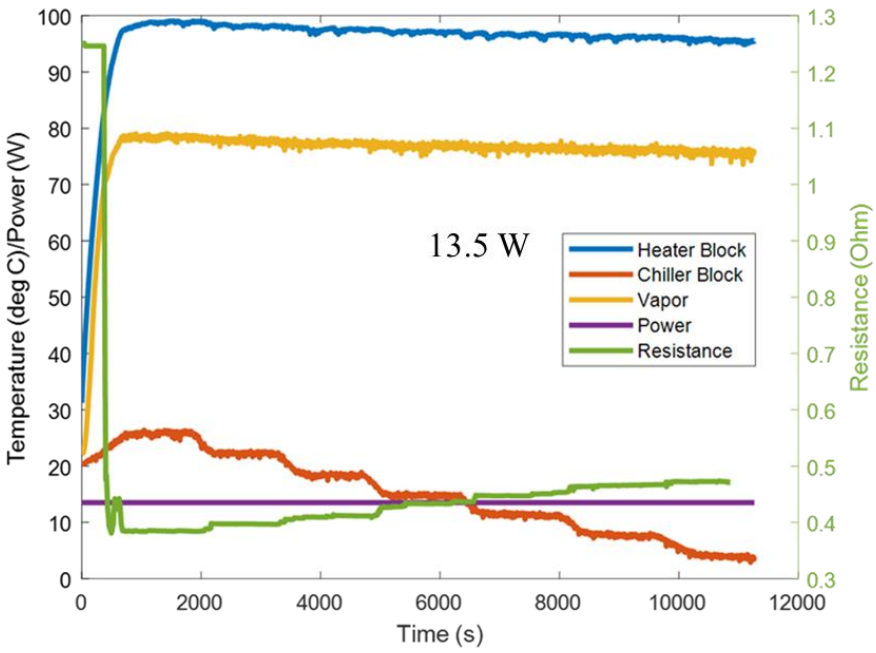
- Two thermal switch devices fabricated using bellows with different spring rates
  - Integrated electric heaters in base
  - LN cooled cold plate
- Characterize the intermittent contact of the bellows by measuring electrical resistance through thermal switch setup.
  - Keithley Sourcemeter 2450
  - Parallel resistor for finite resistance measurement
- Tested in range of conditions
  - Ambient pressure, vacuum
  - Different set point temperatures
  - Acetone and methanol as working fluids

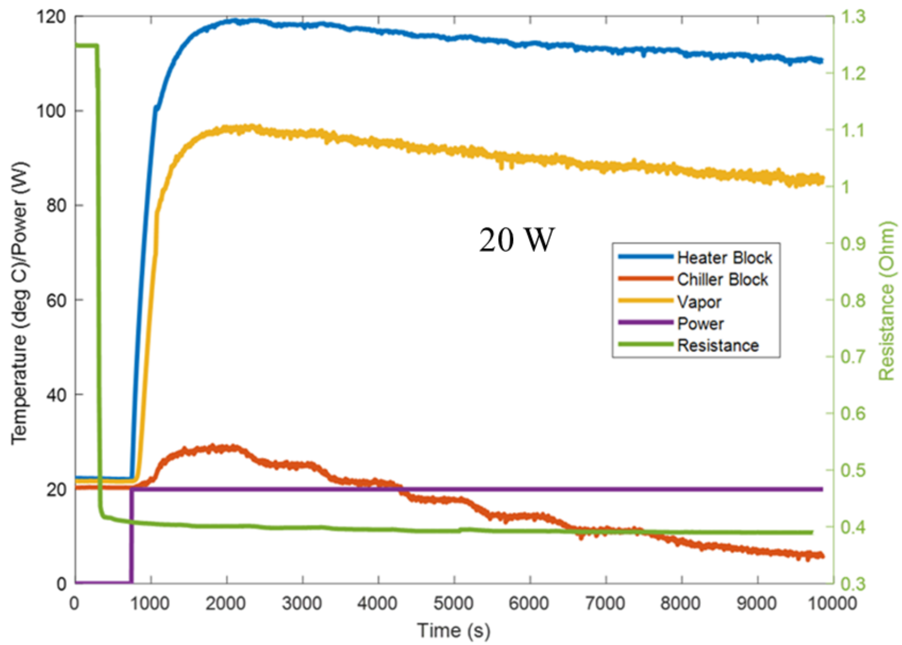
Stock number	ID cm (in)	OD cm (in)	Free Length cm (in)	Spring Rate - Vendor N/M	Spring Rate – Measured N/m
SS-750-36-24	1.877 (0.739)	2.723 (1.072)	5.118 (2.015)	4203	~2200
SS-750-65-97	1.829 (0.72)	2.730 (1.075)	5.334 (2.1)	20140	20000



Prototype Demonstration

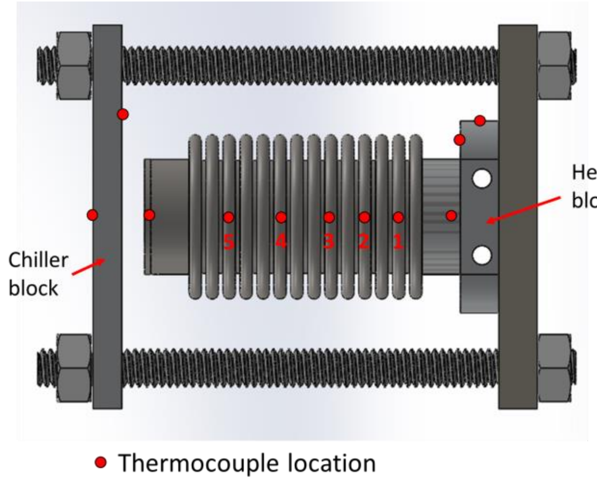
- **First tests of thermal switch with stiffer bellows in ambient**
  - **Constant power, variable sink**
  - **Acetone working fluid**
- **Bellows contact pressure observed in electrical resistance signal**

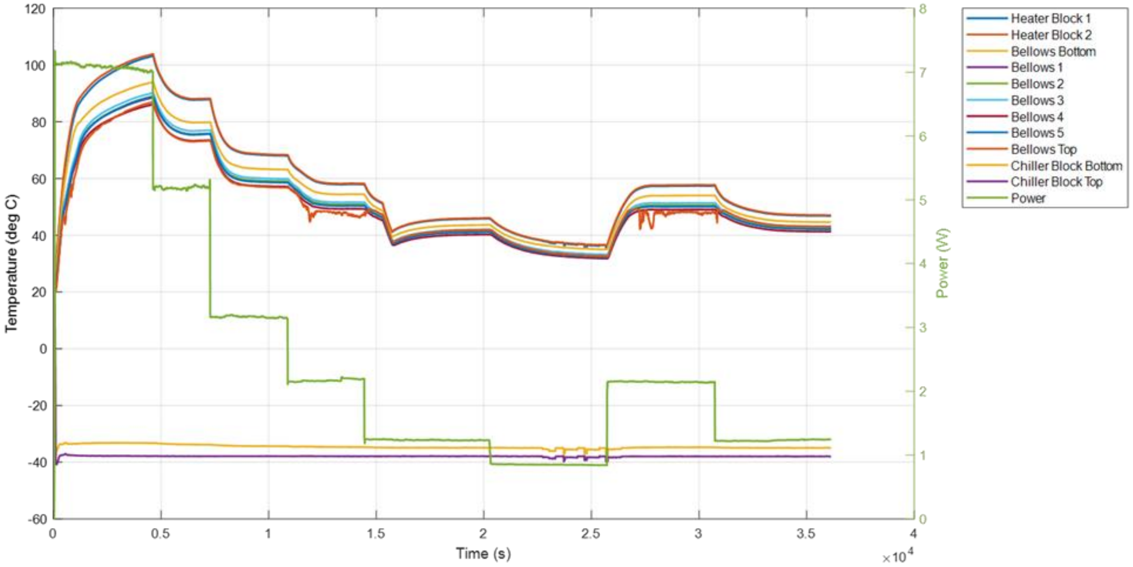


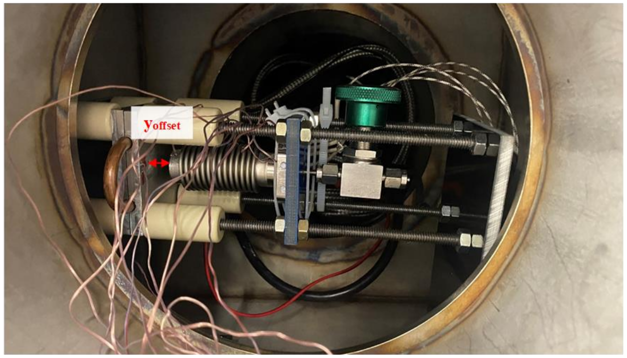


Prototype Demonstration

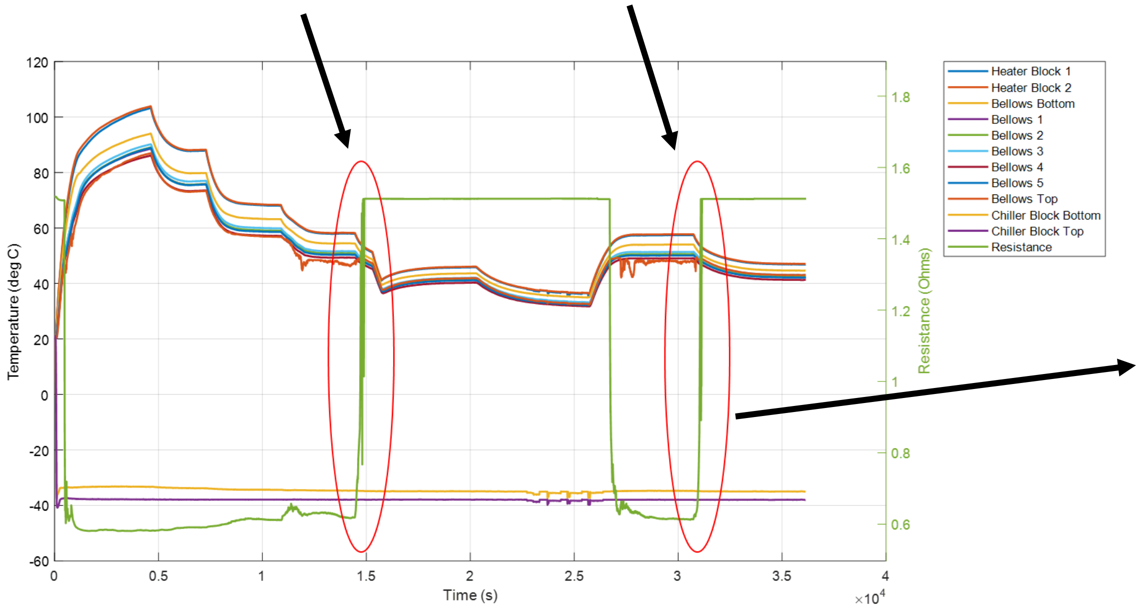
- **First tests of thermal switch with second bellows assembly in vacuum**
  - **Additional temperature measurements along bellows**
  - **Constant sink, variable power**
  - **Acetone working fluid**

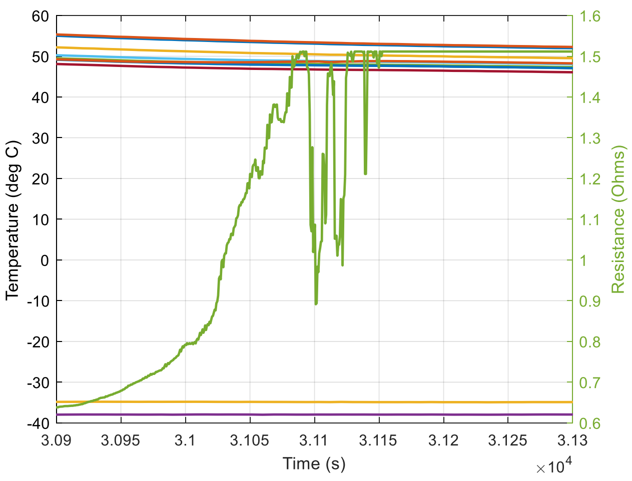






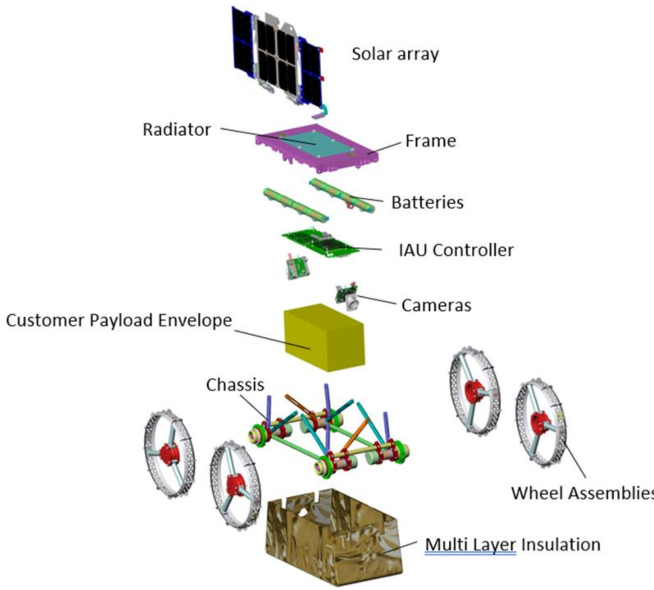
- **First tests of thermal switch with second bellows assembly in vacuum**
  - **Intermittent contact for ~100 s as bellows detaches**





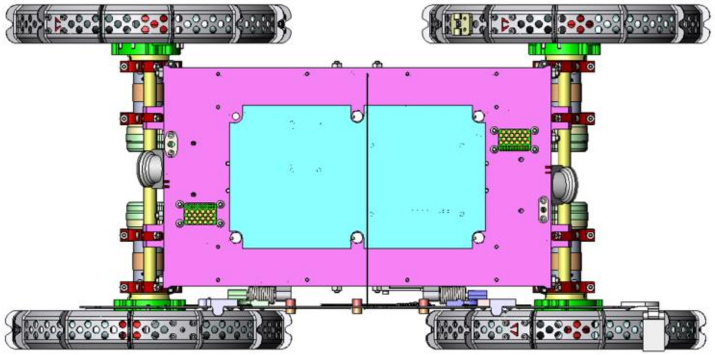
Small Rover Thermal Switch Development

- **Astrobotic CubeRover thermal switch requirements**
  - Power dissipated: 7 W
  - Radiator/frame footprint: 30 cm x 16 cm
  - Target height: <3 cm
  - Target mass: < 0.3 kg
  - Maximize ON/OFF conductance ratio
  - Minimize OFF conductance



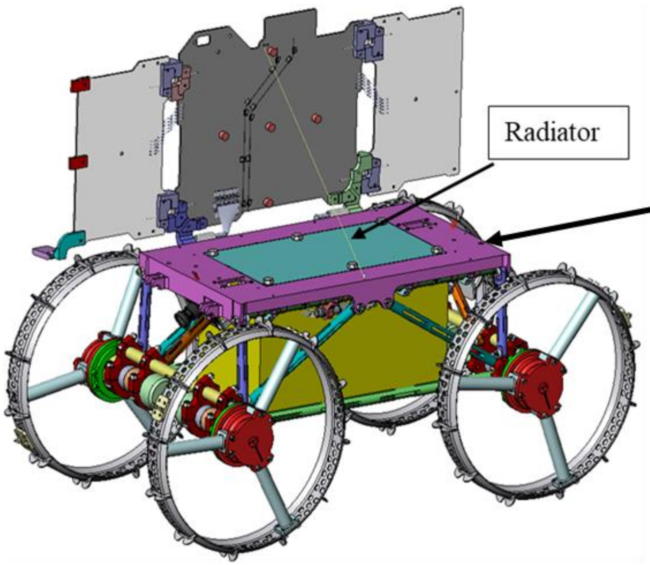
Temperature Requirements

	Min Survival Temp (°C)	Max Survival Temp (°C)	Min Operating Temp (°C)	Max Operating Temp (°C)
Battery	-20	60	0	45
Camera	-20	60	0	55

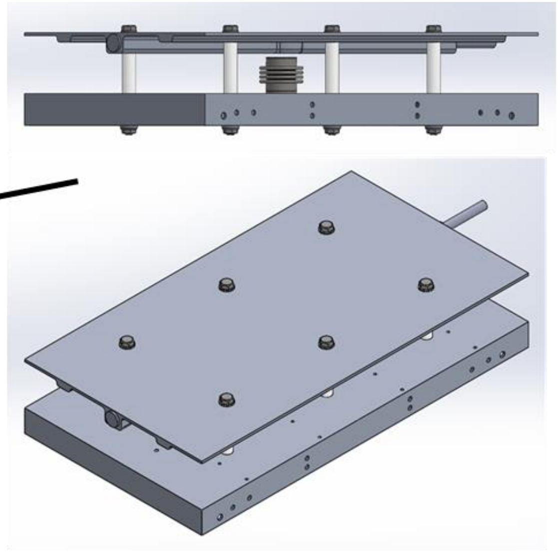


Small Rover Thermal Switch Development

- **CubeRover thermal switch design concept**
  - **Convert current radiator/frame to a heat collector plate to which the electronics are mounted**
  - **Radiator panel isolated from heat collector by low conductivity standoffs**
  - **One or more bellows thermal switches located between collector plate and radiator panel**
    - **Thermal switch setpoint temperature: -10°C (263 K)**



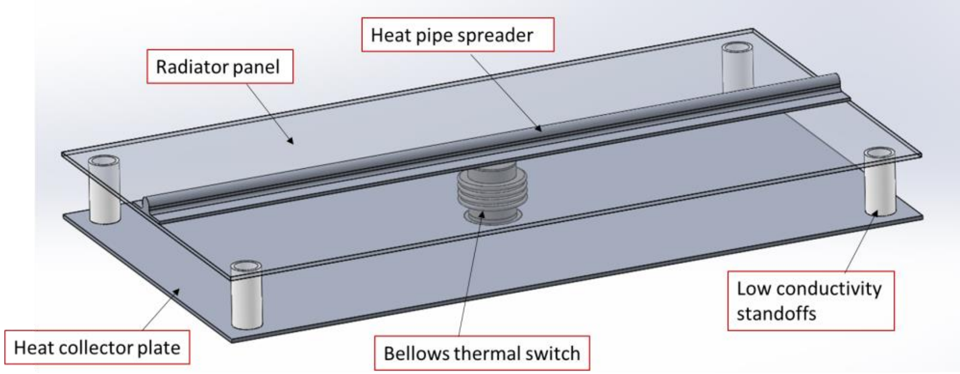
Astrobotic CubeRover

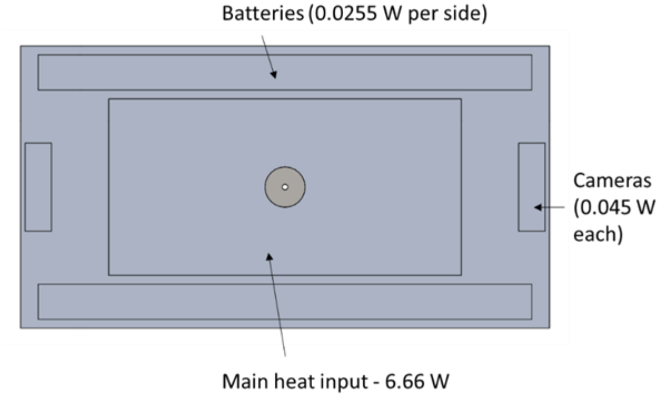


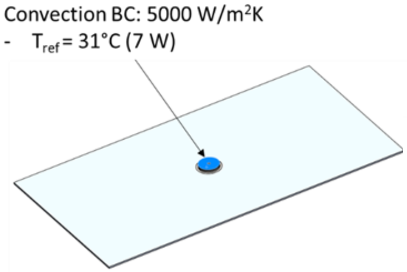
ACT Thermal Switch – offset from current radiator

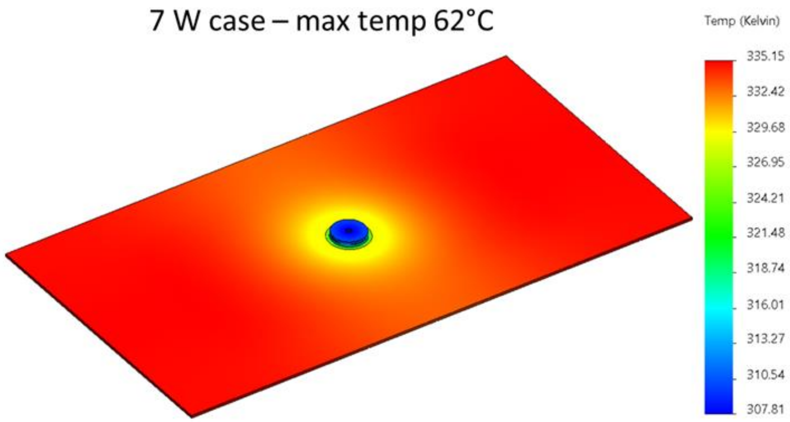
Small Rover Thermal Switch Development

- **Initial thermal analysis of thermal switch design concept**
  - **Estimated ON conductance: ~0.5 W/K**
    - **Case of Polar Noon**
  - **Estimated OFF conductance: 10^{-4} - 10^{-3} W/K**
    - **Case of Night Survival**



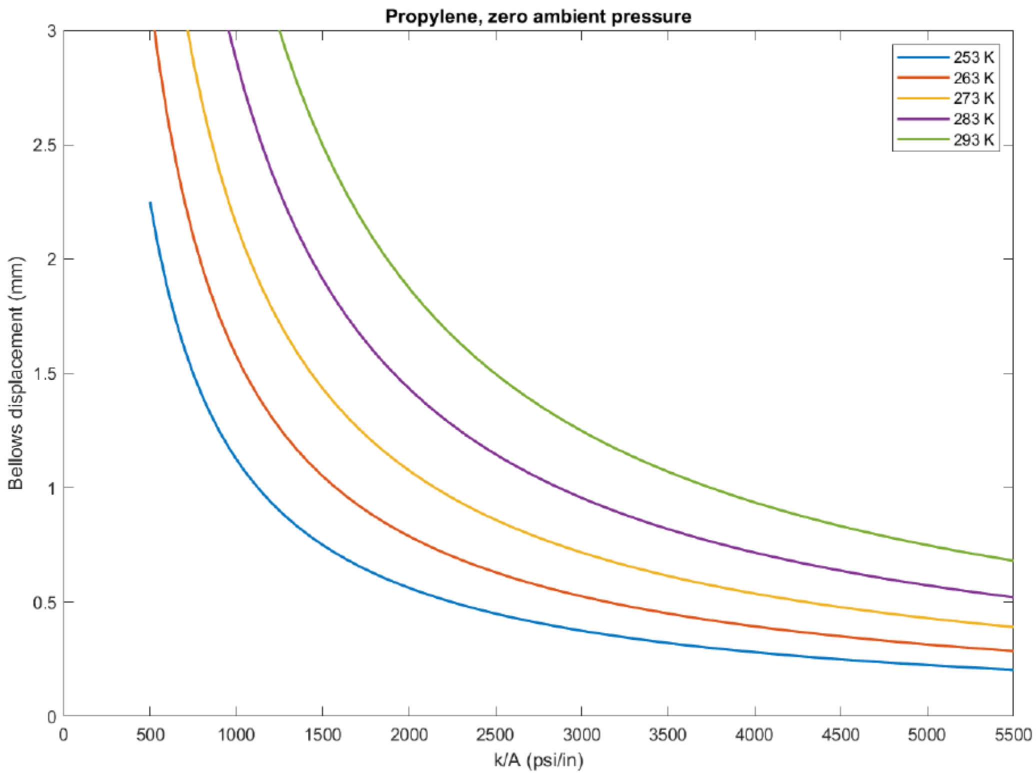


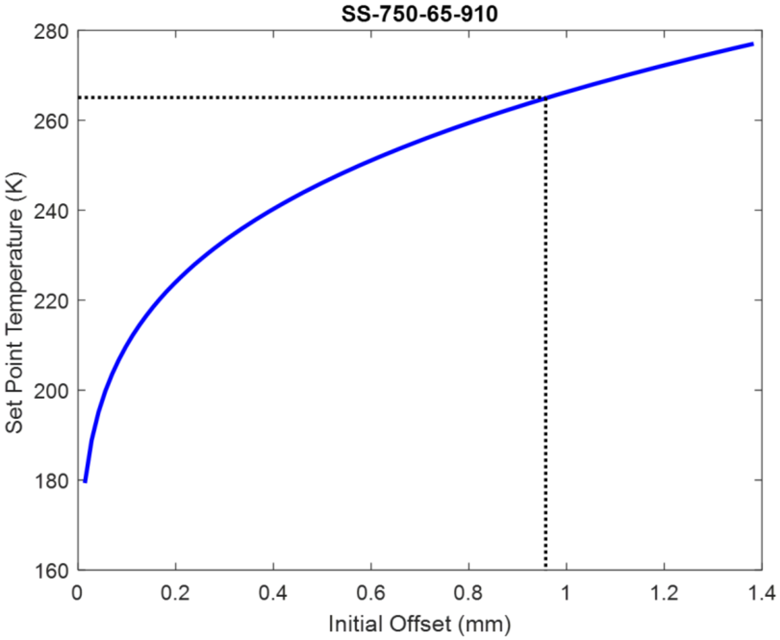




Small Rover Thermal Switch Development

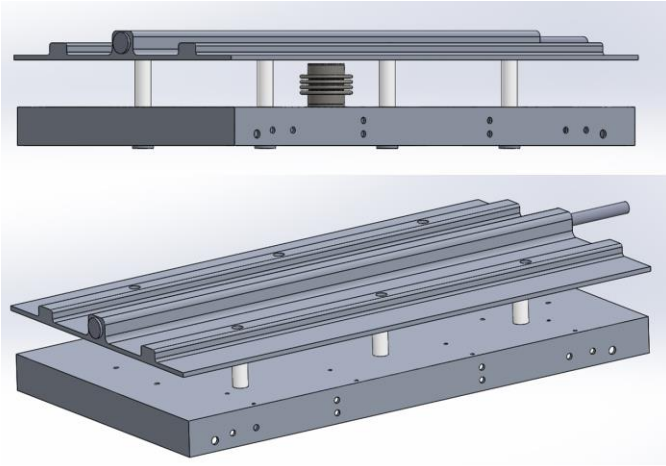
- **Bellows Selection**
  - **Propylene working fluid**
  - **Target contact temperature: 263 K**
  - **Find bellows with ratio k/A_{eff} that satisfied contact with reasonable displacement**

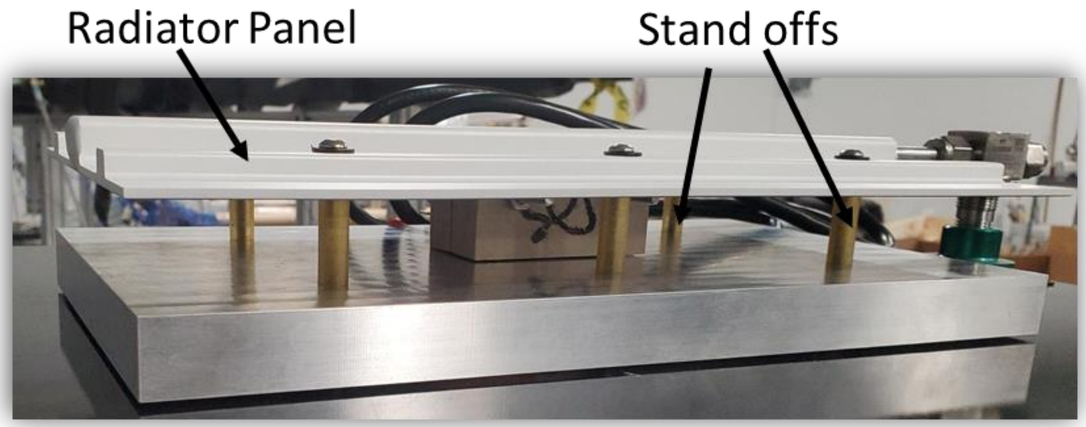




Small Rover Thermal Switch Prototype

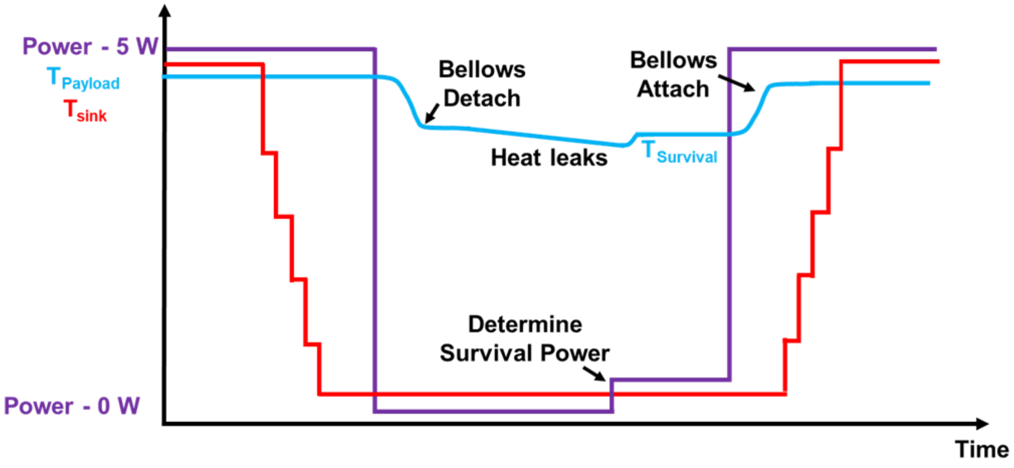
- **First iteration prototype**
  - Bellows working fluid - propylene
  - Heat pipe working fluid – acetone
  - Contours of radiator heat pipe/structure ribs facing up
  - PEI standoffs/washers w/ steel bolts/nuts
  - Radiator coated with high-emissivity paint

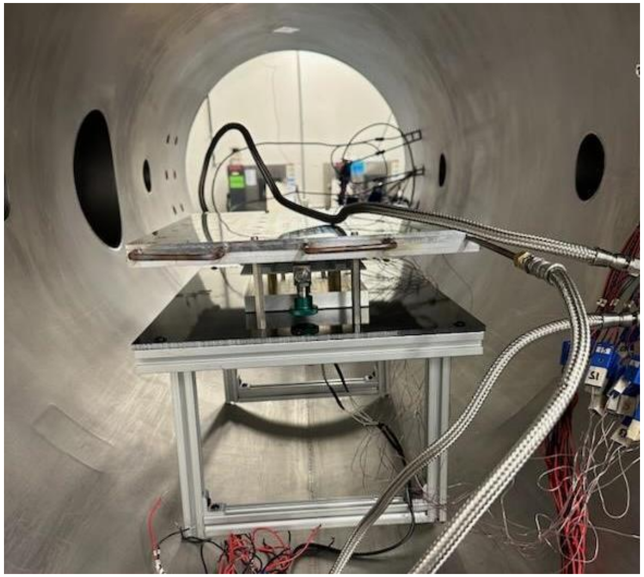


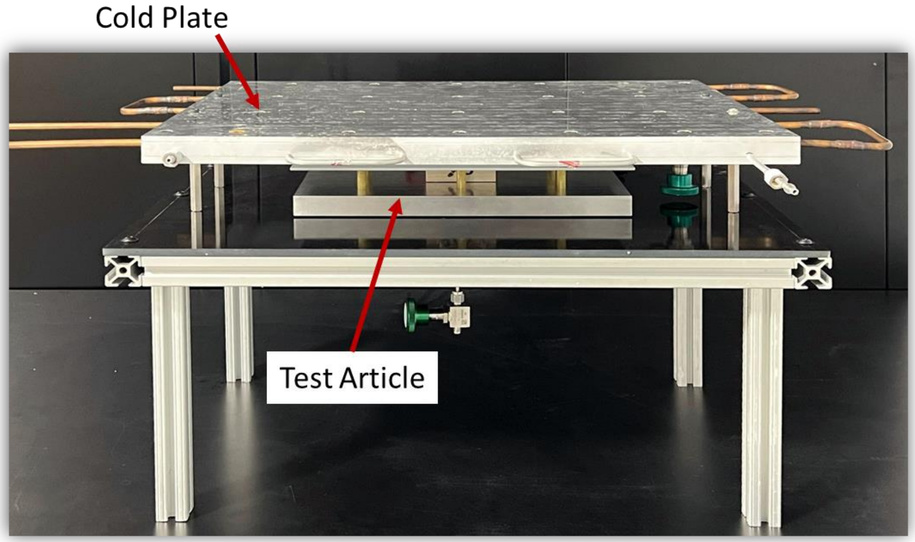


Small Rover Thermal Switch Prototype

- **First iteration prototype test plan**
  - Instrumented with 16 thermocouples to measure temperature distribution
  - LN-cooled cold plate for radiative heat sink
  - Heater block fixed to underside of frame

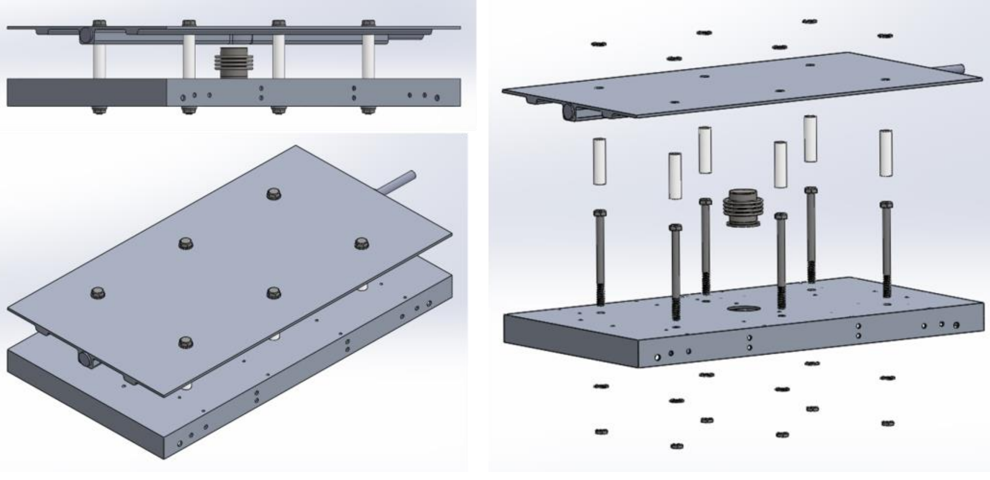


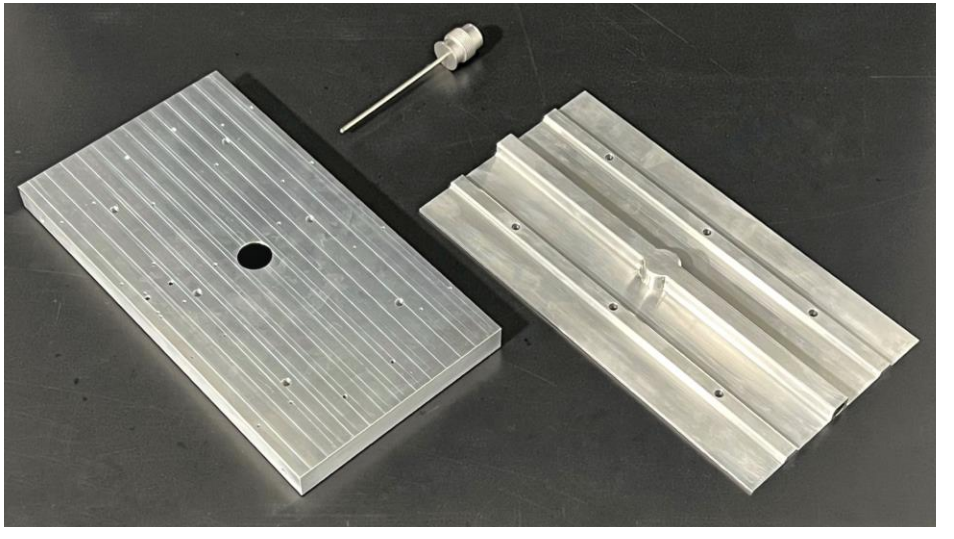




Small Rover Thermal Switch Prototype

- **Fabrication of second prototype thermal switch for small rover is ongoing**
  - **Contours of radiator heat pipe/structure ribs facing down**
  - **Screened Al-NH_3 heat pipe embedded in radiator**
  - **Shrink fit joint between SS bellows end cap and Al frame**
  - **PEI standoffs w/ steel bolts/nuts**
  - **MLI layers between radiator and frame to minimize thermal radiation leak**





Conclusions

- Lunar night survival requires thermal management systems to have high turn-down ratio
- Bellows-based two-phase thermal switch with high On/Off conductance ratio is one potential technology to help enable lunar night survival
- A theoretical model has been developed to evaluate thermal switch dynamic performance
- Several small prototypes were fabricated and tested to demonstrate the concept
- A design concept of a thermal switch for a small lunar rover was developed
- Two iterations of a prototype thermal switch for a small lunar rover are being fabricated for thermal vacuum testing

Future Work

- Start testing first iteration thermal switch prototype for small rovers
- Complete fabrication of second iteration thermal switch prototype for small rovers
- TVAC test of second iteration thermal switch prototype
- Further develop and calibrate the thermal-mechanical model
- Development of higher power/higher temperature thermal switch

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