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Thermal Switch Development for Small Rover Lunar Night Survival

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A passive two-phase thermal switch concept has been developed to provide a high thermal turndown ratio to enable lunar night survival of small lunar rovers. Thermal switches are designed to reduce heat transfer in the Off state, and maximize it when in the On state. The thermal switch developed utilizes a flexible metal bellows containing a two-phase working fluid. Switching between On and Off states is passively driven by the vapor temperature and pressure of the working fluid. At temperatures below the designed switching temperature, the vapor pressure is reduced, and the bellows is contracted and not in contact with the heat sink. At temperatures above the designed switching temperature, the vapor pressure increases, causing the bellows to expand and contact the heat sink for efficient heat rejection. The desiged switching temperature is determined by the effective balance of forces on the bellows. A prototype thermal switch for a small lunar rover with propylene as the bellows working fluid was designed, fabricated, and tested. In this design a radiator panel is offset from the main rover frame to which the avionics are mounted, with the thermal switch situated between the frame and the radiator. Thermal vacuum test results demonstrated the ability of the thermal switch to thermally isolate the rover frame and payload from the radiator as the sink temperature decreased.

Nomenclature

A = Area
ACT = Advanced Cooling Technologies, Inc.
k = bellows spring rate
G_{off} = off thermal conductance
F = view factor
Q = heat transfer rate

I. Introduction

Surviving the lunar night is a paramount challenge for long-term operation of future landers and rovers on the lunar surface. For extended lunar surface operations of these assets, the on-board electronics must be maintained above their survival temperatures throughout the lunar night, which lasts for 14 Earth days. On the other hand, the electronics must also be effectively cooled during the lunar day, which also lasts for 14 Earth days. Therefore, the lunar lander and rover thermal management systems must have significant turndown, which allows for effective heat rejection during the lunar day with relatively high thermal conductance, while minimizing the heat losses during the lunar night be significantly reducting the thermal conductance. The alternative to a high turndown thermal management system is to use survival heaters to keep the electronic warm during the night. However, it has been estimated that each Watt of power supplied during the lunar night requires an additional 5-7 kg of solar cell and battery mass (Ref 1-2). Surviving the lunar night without the use of electric power can be enabled by advanced passive thermal management technologies. Since the system must operate during both the lunar day and night, simply insulating the batteries and

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instrumentation is not sufficient. The heat transport must use a variable thermal link, which transports heat with minimal ΔT during high power usage periods, and passively shuts down at night, minimizing heat losses.

Thermal switches are among the passive thermal control devices that can be utilized in lunar lander and rover thermal management systems. Thermal switches are designed to minimize heat transport when in the “Off” condition, and to maximize heat transfer when in the “On” condition. The actuation of the thermal switch often happens at a specified set point temperature. To date, most passive thermal switches use the expansion/contraction of a volume to make/break a mechanical contact between two surfaces (Ref. 3-5). These thermal switches typically have a capacity of only a few Watts. As an alternative, a new passive thermal switch design concept has been developed, capable of transferring higher powers with a high On/Off thermal conductance ratio. This thermal switch design utilizes a sealed flexible bellows that contains a saturated two-phase working fluid. The actuation of the thermal switch is driven by the saturation temperature and pressure of the fluid within the bellows.

In this paper, a thermal switch prototype for a small lunar rover is developed. The thermal switch prototype provides a themal link between the electronics heat collection frame and the radiator. The radiator panel has a heat pipe integrated to distribute the heat along the radiator panel. The thermal switch prototype device and the radiator panel were fabricated and tested for concept demonstration.

II. Thermal Switch Design for Small Lunar Rovers

A. Thermal Switch Operation

A conceptual diagram of the thermal switch concept is shown in Figure 1. The thermal switch utilizes a sealed metal bellows which contains a two-phase working fluid. One end of the bellows is fixed to the heat source, while the other is free to extend axially, and is offset from a heat sink surface. At low temperatures, the vapor pressure of the fluid within the bellows is low, and the bellows is not extended to the point of contact with the heat sink. At higher temperatures, the vapor pressure increases, causing the bellows to expand until it comes into contact with the heat sink, allowing heat to be transferred by evaporation and condensation of the working fluid. The vapor pressure, and thus vapor temperature, at which the bellows initially contacts the sink is determined by the balance of forces between the vapor pressure, the bellows restoring force, and any external pressure. An internal capillary wick structure can be incorporated to enable gravity- and orientation-independent operation.

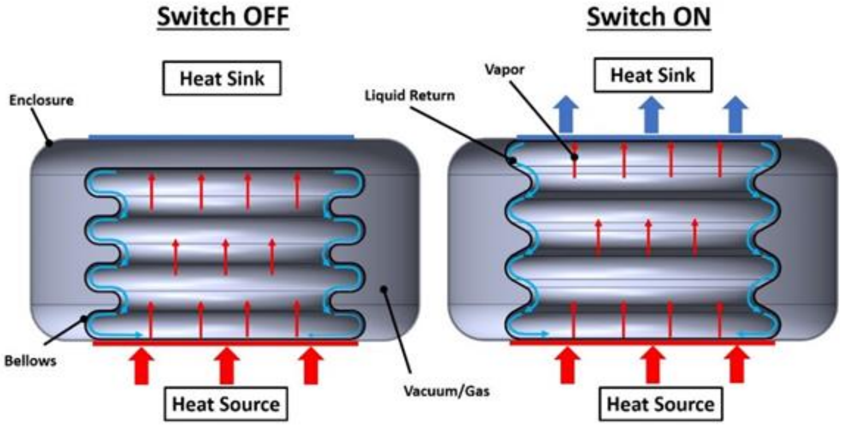


Figure 1: Two-Phase Thermal Switch principle of operation.

B. Small Rover Thermal Management Concept

One of the potential applications for the two-phase thermal switch is for enabling a high turndown ratio thermal management system for small planetary rovers. This class of rovers have masses on the order of a few kilogram, and heat dissipation requirements on the order of 10 W or less. Here we consider the case of a rover at the lunar south pole, but the concept is similarly applicable to other environments such as the lunar equator or the Martian surface. Heat is rejected during the lunar day by a radiator that forms the top surface of the rover. The heat generating components may be mounted directly to the underside of the radiator. While this is effective for heat rejection during the lunar day, this configuration would not allow the rover to survive the lunar night.

A thermal management system based on a two-phase thermal switch has been developed to enable small rovers to survive the lunar night. This thermal management system concept is shown in Figure 2. In this concept, the frame to which the payload is mounted, which would also serve as a radiator surface, is incorporated with one or more themal switch bellows assemblies. Multiple thermal switch assemblies may be used to provide redundancy. A new radiator panel is located above the frame, supported by low thermal conductivity standoffs. The bellows of the thermal switch assemblies are designed to come into contact with the radiator at a specified temperature corresponding to the minimum allowable temperature of the electronics. A thermal interface material or other surface treatment can be applied to the bellows end cap to improve contact thermal resistance and prevent cold welding. During the lunar night, the switch will disengage from the radiator when the vapor pressure (and temperature) drops below the design setpoint. This thermally isolates the electronics from the radiator, with the only heat leaks due to minimal conduction through the standoffs and any radiation between the frame and the underside of the radiator. Depending on the set point temperature and effective Off conductance, this may enable the electronics payload to stay above its minimum temperature though the lunar night due to its thermal mass. Alternatively, a very small amount of survival power may be applied, corresponding to Off conductance heat leaks, to keep the bellows, and correspondingly, the payload, at its setpoint temperature.

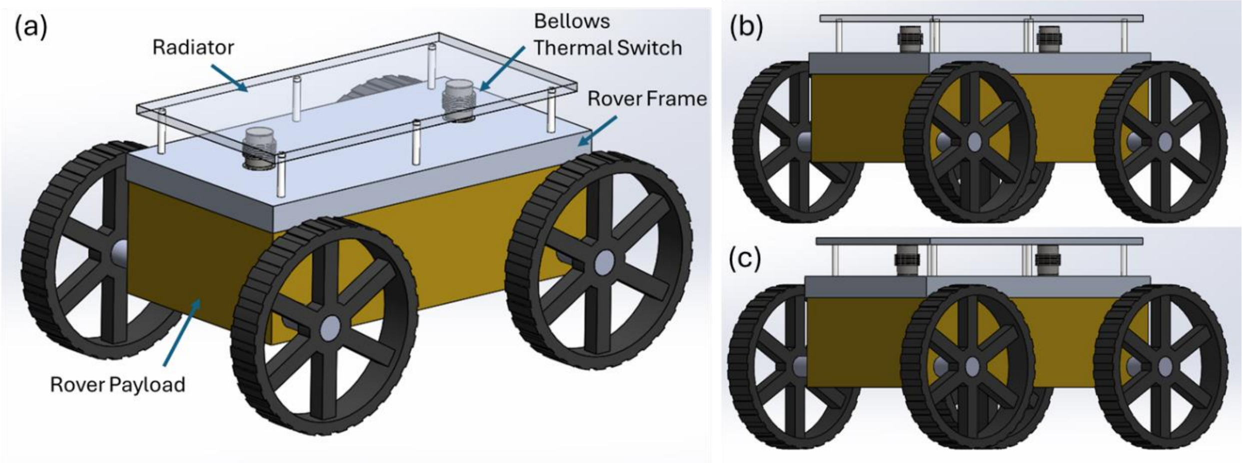


Figure 2: (a) Concept for small rover thermal management system based on two-phase thermal switch. Two bellows switch assemblies shown as an example. (b) Thermal switches disengaged from radiator (Off condition). (c) Thermal switches engaged with radiator (On condition).

An initial estimation of the On and Off thermal conductances was performed, assuming the bellows fully in contact with a full heat load of 7 W from the payload for the On case, and the bellows fully disconnected for the Off case. A preliminary thermal analysis of this design concept was performed. In this case of noon at the lunar south pole, the lunar surface is estimated to have a surface temperature T_g of -50°C (223 K). Taking a worst-case scenario of a 30° tilt, the radiator would see the lunar surface with an estimated view factor of 0.067. Using the specified radiator area (10 cm × 20 cm) and emissivity (0.85), the radiator temperature can be estimated for a given heat load from the following equation:

$$Q_{rad} = \sigma\varepsilon A F_{A\to g}\left(T_A^4 - T_g^4\right) + \sigma\varepsilon A F_{A\to sky}\left(T_A^4 - T_{sky}^4\right) \tag{7}$$

For a total heat load of 7 W, the radiator temperature is estimated to be 20°C. Next, the vapor temperature within the bellows may be estimated based on a thermal resistance network of the thermal switch (Ref. 6). Using an estimated order of magnitude contact resistance between the bellows and the radiator estimated from the contact pressure due to the bellows vapor pressure (~10^{-4} m^2K/W), conduction through the end cap, and an estimated condensation heat transfer coefficient (h = 7500 W/m^2K), the vapor temperature is estimated to be around 31°C. This is then used as a boundary condition for a finite element thermal simulation of the heat collector plate. Using an estimated evaporation heat transfer coefficient of 5000 W/m^2K, the maximum temperature of the heat collector plate is found to be around

62°C. From this analysis, the overall estimated ON conductance for the thermal switch based thermal management system is on the order of 0.5 W/K.

During the OFF condition for the thermal switch during the lunar night, the switch thermally decouples the heat collector plate and the radiator, enabling the rover electronics to be maintained above their minimum temperatures, while allowing the radiator to reach low temperatures. Thus, it is essential to minimize heat leak paths from the heat collector plate to the radiator. Layers of MLI can be placed in the space between heat collector plate and the radiator to minimize radiative losses. The primary heat leak path is then through the radiator standoffs. By clever design of these standoffs and utilizing low thermal conductivity materials such as PEI (Ultem), an OFF conductance G_{off} on the order of 10^{-4} – 10^{-3} W/K can be achieved. A quick analysis can determine the effect of the OFF conductance on survival heater power required to maintain electronics above their minimum survival temperature. If it is desired to maintain the heat collector plate temperature at the minimum survival temperature of -20°C, the heat leak through thermal switch system (i.e., the required survival power) can be estimated from the following equations:

$$Q_{rad} = \sigma \varepsilon A F_{rad \to g}\left(T_{rad}^4 - T_g^4\right) + \sigma \varepsilon A F_{rad \to sky}\left(T_{rad}^4 - T_{sky}^4\right) \tag{8}$$

$$Q_{rad} = G_{off}\left(T_{plate} - T_{rad}\right) \tag{9}$$

For the same radiator configuration as above, the heat leaks to maintain the plate at 253 K were calculated, with the resulting radiator temperatures are given in Table 1 for the full range of estimated Off conductances.

Table 1: Estimated heat leaks/survival power and resulting radiator temperature to maintain collector plate at minimum survival temperature during lunar night

Off Conductance (W/K)	Heat Leaks (W)	Radiator Temperature (K)	On/Off Conductance Ratio
10^{-4}	0.014	67	~4500
10^{-3}	0.186	110	~450

C. Small rover Thermal Switch Prototype Design

To demonstrate the feasibility of the thermal switch concept for small rover lunar night survival, a prototype small rover surrogate with a bellows thermal switch and offset radiator was designed and fabricated. A CAD model of the design is shown in Figure 3. The prototype consists of an aluminum frame, to which heaters can be mounted to the underside. An aluminum radiator panel is located offset above the frame, and separated by standoffs constructed from PEI. A single bellows is integrated into the aluminum frame. As most commercially available bellows are constructed from stainless steel, the bottom end cap of the bellows assembly which is welded to the bellows is shrink fit into the aluminum frame. For a target contact temperature in the range of -10°C to +10°C, and the expected operating temperature during the lunar day when the switch is On, propylene was selected as the working fluid for the bellows. The vapor pressure of propylene is used to select the bellows spring rate and the radiator offset. The thermal switch is oriented to operate in a gravity-aided orientation (maximum tilt of the small lunar rover is ± 30°), thus a wick structure is not strictly required. However, a screen wick bridge may be included connecting the top and bottom internal bellows surface for improved liquid return.

From the force balance on the free bellows end cap that determines the extension of the bellows, a characteristic parameter can be defined: *k/A*. Here *k* is the spring rate of the bellows (N/m), and *A* is the bellows effective area (mm^2). The parameter *k/A* then has units of kPa/mm. For a selected working fluid, the displacement of the bellows as a function of *k/A* for a given set point temperature can be calculated, as shown in Figure 4(a) for proplylene, assuming zero ambient pressure (i.e., vacuum). From a survey of commercial off the shelf bellows, one was selected with a *k/A* value of 475 kPa/mm. This bellows has a relatively high stiffness, which enables it to be used with propylene as the working fluid. This stiffness, combined with the small displacement required to actuate the switch, ensures the bellows expands axially and makes good contact with the radiator. From the specified *k/A* values, a 0.9 mm offset results in a contact temperature of -10°C, and a 1.6 mm offset results in a contact temperature of 10°C. The contact temperature as a function of initial offset is given in Figure 4(b).

When the thermal switch is On and the bellows is engaged with the radiator, a large force can be applied to the radiator due to the high vapor pressure of the propylene within the bellows. To stiffen the radiator, a heat pipe is incorporated into its structure, as well as additional thickness along the axes of the bolt patterns. In addition to providing rigidity to the radiator, the heat pipe may also improve the radiator efficiency. To enhance the emissivity of the radiator surface for testing, it is coated with a high-emissivity white paint. The heat pipe was wicked with stainless steel mesh screen, and charged with acetone as the working fluid.

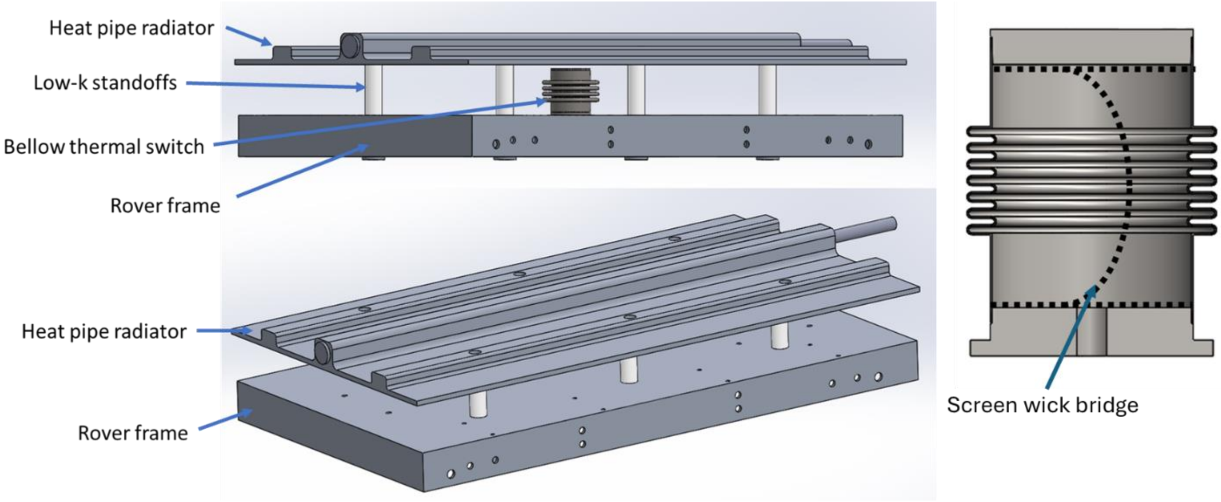


Figure 3: CAD model of small rover thermal switch prototype design (left). Ilustration of screen wick bridge between top and bottom end caps for fluid management

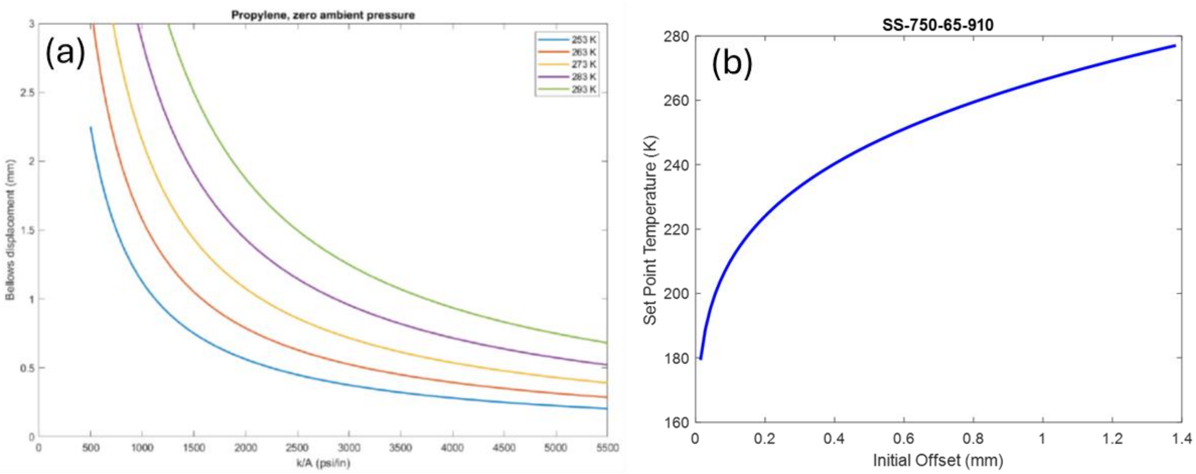


Figure 4: (a) Bellows displacement as function of bellows parameter *k/A* for several contact temperatures, with propylene as the working fluid and zero ambient pressure. (b) Contact temperature of selected bellows as function of initial offset from bellows free length.

III. Lunar Rover Thermal Switch Experimental Demonstration

A test stand was fabricated for an experimental demonstration of the small rover thermal switch prototype. The test setup consists of the thermal switch test article (frame, radiator, bellows assembly, and standoffs) mounted on a thermally insulated test frame. A liquid nitrogen-cooled cold plate is mounted offset from the top of the radiator surface and serves as a radiative heat sink, which is also coated with high-emissivity (and thus high absorptivity) paint. The cold plate is only offset a few cm from the radiator to ensure that the view factor from the radiator to the cold plate is maximized. The heater block is mounted to the underside of the frame, and the entire test article is instrumented with thermocouples. The setup was wrapped with MLI to reduce radiation exchange with the vacuum chamber walls and test stand. The test stand installed in the vacuum chamber is shown in Figure 5.

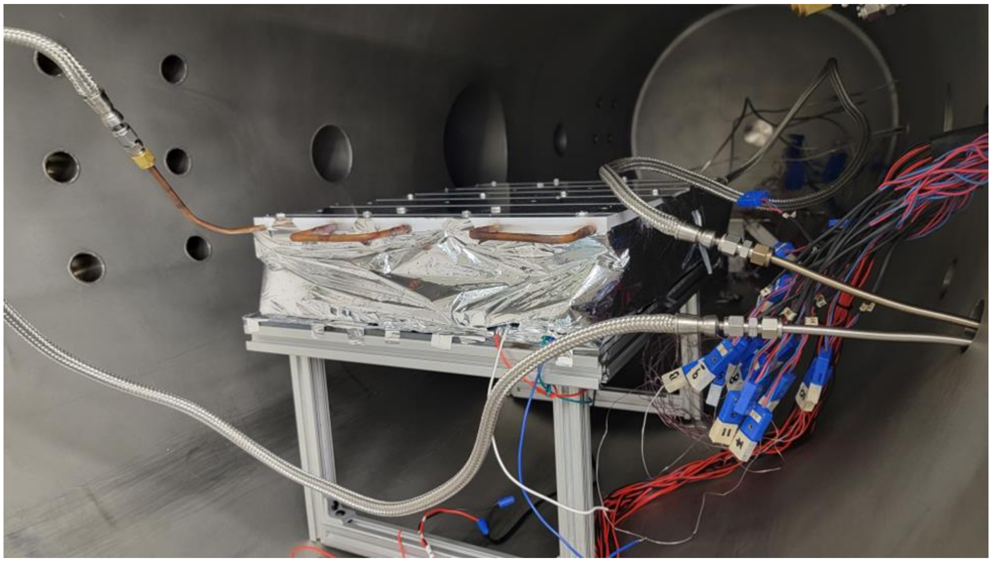


Figure 5: Test setup for experimental evaluation of small rover thermal switch prototype installed in ACT's vacuum chamber.

In the first test, the test began with a constant 5 W of heat applied to the heater mounted to the underside of the frame, and the heat sink held at 0°C. The sink temperature was gradually reduced to -80°C. Up to this point, it is expected that the bellows is in contact with the radiator, and the switch is "On". The heater power is then turned off, and the temperatures of the system begin to drop. With the sink at -80°C, the radiator temperature settles at around -65°C, while the bellows and frame converge to a temperature around -30°C. The temperature of the heat sink is reduced further to around -140°C. As the sink temperature drops, the radiator temperature is also reduced, to around -90°C. However, the temperature of the bellows and frame only reduce by less than 10°C to around -40°C. This decoupling of the frame temperature and radiator temperature as the sink temperature drops indicates that the thermal switch is operating as intended. However, the observed setpoint temperature is lower than was intended (-30°C vs -10°C). When the testing was completed, it was noted that the offset distance of the bellows was only 0.4 mm, while the target was 1.5 – 2.0 mm. Therefore, the offset distance has been adjusted to roughly 1.6 mm, and the test was repeated.

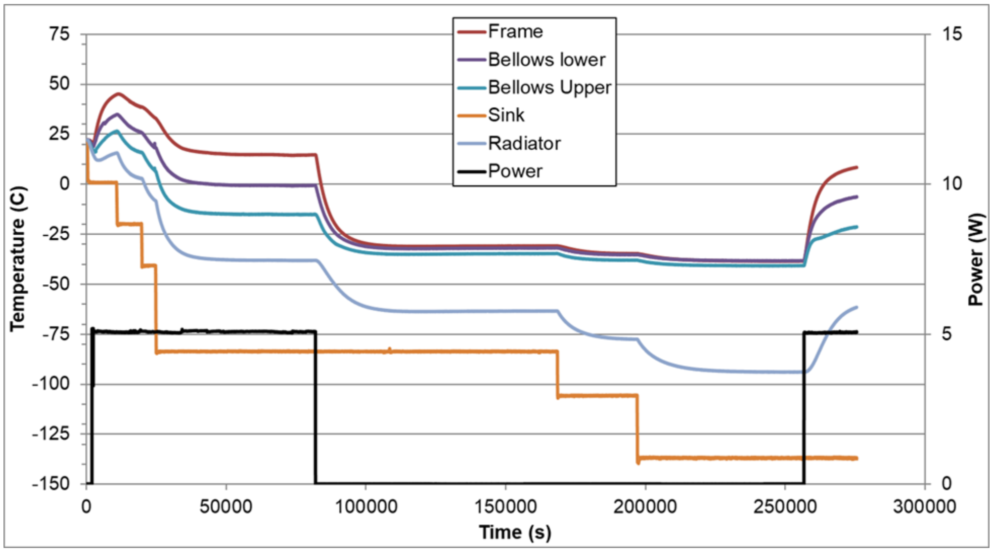
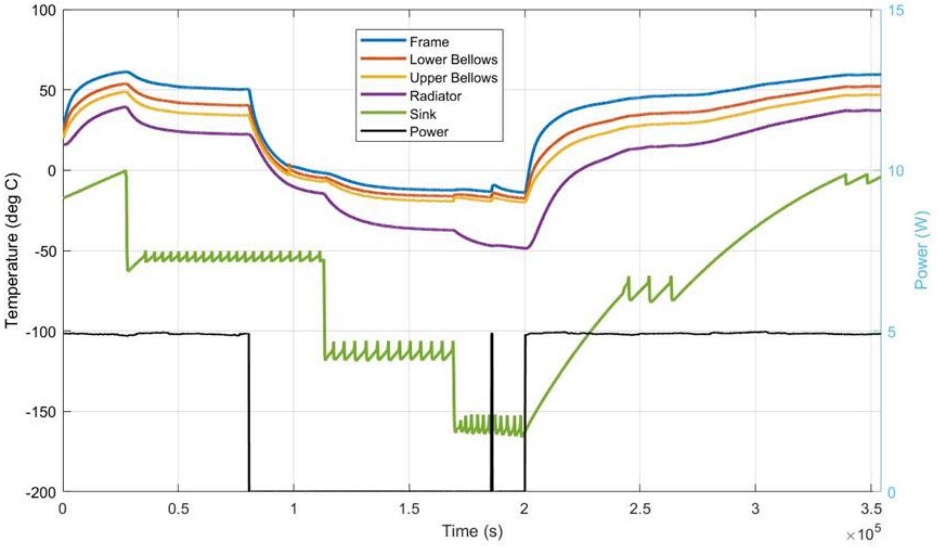


Figure 6: Initial small rover thermal switch prototype test. Bellows offset corresponds to setpoint temperature of roughly -30°C

In the second test, a constant 5 W was applied to the heater mounted to the underside of the frame, and a heat sink temperature of around 0°C. The sink temperature was first reduced to -50°C. Up to this point, the bellows is in contact with the radiator, and the switch is "On". The heater power is then turned off, and the temperatures of the system begin to drop. The sink temperature is then further reduced to around -110°C, and then to below -150°C. As the sink temperature is reduced, the radiator temperature follows, but the temperatures of the bellows and the frame/heater settles around -15°C. The decoupling of the frame and radiator temperatures as the sink drops in temperature demonstrates the operation of the thermal switch, maintaining the temperature of the frame/heater at a target set point temperature. It is likely that the bellows did not fully decouple, but operated in an intermittent contact regime, due to the thermal mass of the frame and/or small heat leaks from the surrounding. At this point, the heater power was turned back on, and the sink temperature allowed to rise, simulating the transition from lunar night to lunar day. The switch to the "On" configuration (constant contact), and the expected temperature gradient returned. In both tests, the temperature distribution when power is applied is reasonably close to that expected from analytical modeling. A full characterization of the "Off" conductance when power is not applied is challenging without fully accounting for all heat leaks in the test setup.



IV. Conclusions

A thermal switch concept based on a two-phase bellows is underdevelopment for the thermal management and lunar night survival of future lunar landers and rovers. This thermal switch concept utilizes the vapor pressure of a saturated working fluid to passively actuate the switch at a target set point temperature. The thermal switch concept can enable high thermal turndown ratios, enabling both effective heat rejection during lunar day and low thermal conductance during lunar night.

A design concept for integrating the two-phase thermal switch into a small lunar rover (< 10 W) was developed. A prototype small rover thermal switch was designed and tested. The concept of integration involved the addition of a separate radiator panel offset from the top of the rover frame, with one or more bellows thermal switches situated in the space between. During lunar day, the bellows would engage with the radiator, allowing effective heat rejection. During the lunar night, the bellows would disengage from the radiator, minimizing the heat rejection to maintain the payload electronics above minimum temperatures.

The small rover thermal switch prototype was tested with different radiator offsets, corresponding to different set point temperatures. In both cases, effective heat rejection was demonstrated when power was applied and the switch was On, while when the power was turned off and the sink temperature reduced, the thermal switch decoupled the temperature of the frame from that of the radiator, effectively providing thermal turndown.

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