Paper Number

Design and Flight Qualification of a Paraffin-Actuated Heat Switch for Mars Surface Applications

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ABSTRACT

Missions to the surface of Mars pose unique thermal control challenges to rover and lander systems. With diurnal temperature changes greater than 100 °C, the presence of a Mars atmosphere, and limited power for night time heating the thermal control engineer is faced with a fundamental problem: how to successfully keep components above their survival or operating temperatures at night while managing higher environmental temperatures and dissipation rates during the day. Payload and avionics elements, among others, must be well insulated to survive night conditions at the risk of overheating during the day. This problem will be magnified in future missions as higher demand on electrical components will result in increased dissipations. One solution is a heat switch that changes thermal conductance to reject excess heat during the day and conserve heat during the night.

INTRODUCTION

The Mars Exploration Rover (MER) flight system which is currently being designed and built by the Jet Propulsion Laboratory (JPL) will be using a paraffin-actuated heat switch as part of the thermal control system for the Rover secondary battery. This passive heat switch has been developed and qualified by Starsys Research Corporation for JPL. The switch is mounted between the battery assembly and an external radiator. Over a predetermined temperature range the heat conductance of the switch varies by nearly two orders of magnitude to help maintain battery temperatures within the allowable flight temperature (AFT) limits.

Because the thermal control system for the secondary battery is critical to its performance and survival, the heat switch was subjected to a rigorous qualification and life test program. Both thermal and mechanical life testing as well as qualification-level random vibration, pyrotechnic shock, and landing loads representative of a hard Mars landing were performed. Figure 1 is a photograph of a qualification heat switch assembly.

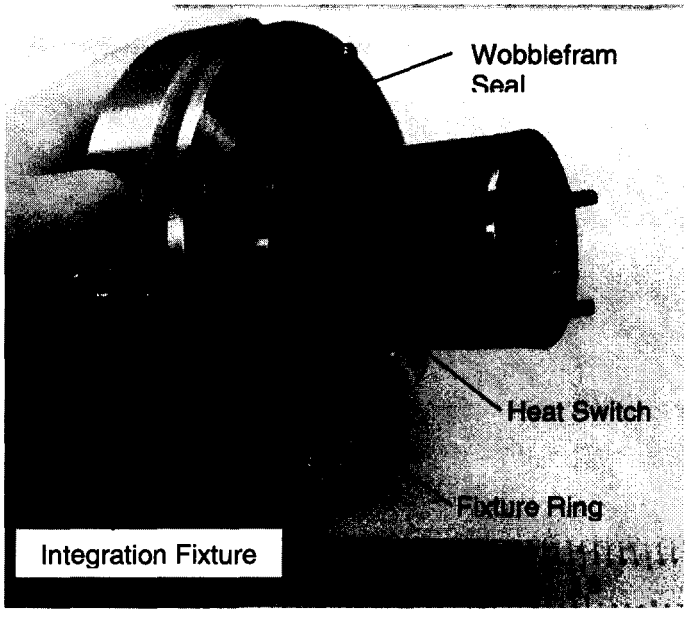

Figure 1. One of the qualification unit heat switch assemblies shown in an integration fixture.

DESIGN DESCRIPTION

The mechanical actuation of the heat switch stems from a seal boot containing paraffin wax of a chosen melt- or set-point. As the wax melts and continues to expand with increasing temperature, the work is utilized to draw two surfaces into contact to provide a heat conduction path. As the wax cools and freezes, compression springs are allowed to push the two surfaces apart, removing the primary conduction path. The heat switch design for the MER mission consists of two cylindrical halves. The half attached to the external radiator rides on four internally mounted rods to move into or out of contact with the other stationary half of the switch. The rods are thermally isolative, but there is some parasitic

heat conduction through them in the switch-open condition. Also, the paraffin wax seal boot resides in the stationary half of the switch such that the activation is based on the temperature of the item mounted to this half, the Rover battery assembly. The physical size and shape of the heat switch is largely dictated by the required switch-on/off thermal conductance. Figure 2 shows the approximate size of the heat switch to be used on the MER mission.

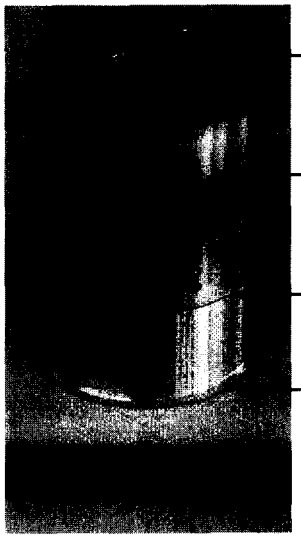

Figure 2. The heat switch slated for use on the MER mission is about 36 mm in diameter and 51 mm in length when in the switch-closed condition, as shown. When in the switch-open condition, the two halves of the switch are separated by about 1 mm. (Note: The scale shown in the figure is graduated in English units).

The Rover uses two heat switches to attach the battery assembly to two separate external radiators as shown in Figure 3. The battery resides in an Aerogel insulated Warm Electronics Box (WEB) and each switch resides in a clearance through-hole in the WEB. The 1 mm x 170 mm x 240 mm radiator and heat switch are cantilevered off of the battery assembly. A Wobblefram seal assembly consisting of a Teflon diaphragm is used to seal the hole in the WEB wall to comply with planetary protection requirements. Both the cantilevered design and flexible Wobblefram seal were necessary to allow free movement of the heat switch through its 1 mm stroke.

The Rover battery allowable flight temperature range is –20 °C to +30 °C during discharge and 0 °C to +30 °C during charge. Combined with a Mars diurnal climate that can vary by over 100 °C and reach temperatures as cold as –100 °C at night, the thermal design engineer is presented with a formidable challenge. A paraffin wax with an activation set-point of +18 °C was chosen to optimize battery operation and to sufficiently hot-bias the thermal design to help conserve night time heater energy. Although the switch will open and result in a sharp drop in thermal conductance at wax temperatures below 18 °C, the switch-closed thermal conductance will increase with temperature at temperatures higher than 18 °C. This variable conductance property of the switch works to regulate the battery to temperatures near the set-point. In terms of thermal performance, the switch is not merely an on/off actuator; it is one which works to regulate temperature by varying thermal conductance over two orders of magnitude.

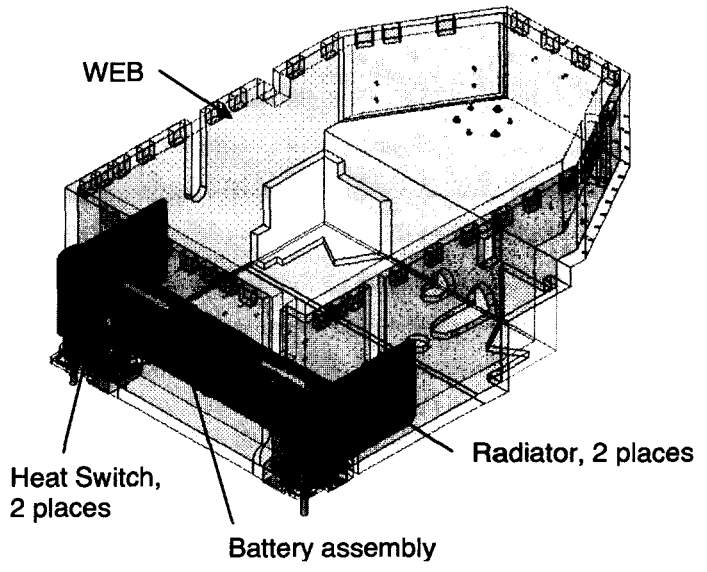

Figure 3. MER secondary battery thermal control design utilizes two heat switches with external radiators in addition to warm-up and survival heaters.

As previously mentioned, the heat switch was developed and built by the Starsys Research Corporation and is based on their previous work. However, the Mars atmosphere necessitated a design change over previous space-based prototypes. Instead of a 0.127 mm gap between switch halves in the open condition, a 1 mm gap was required to compensate for parasitic leaks due to Mars atmospheric gas conduction. Consisting largely of CO_2 at about 8 torr, the atmosphere can greatly compromise the thermal isolation of the switch at night when survival heater power is scarce. This gap between switch halves has raised concerns over the structural robustness of the design. During the hard landing on Mars, the battery temperature will result in a switch-open condition and is predicted to face loads approaching 40 Gs. Moreover, to allow the physical movement of the switch to go uninhibited, the switch structural design was required to support a cantilevered external radiator. As a result, the final heat switch design was based on structural as well as thermal requirements, the driving ones shown in Table 1.

During launch, the switch will be in the closed position. There were concerns that during this period the switch halves may rub away any oxidation layer at the interface and a possibility of cold welding existed. To mitigate this risk, two options were investigated: 1) hard anodizing one of the contact surfaces, and 2) grease plating the interface. Option 2 was chosen as the baseline because

it enhanced thermal conduction while option 1 severely degraded it.

TABLE 1. Key design requirements for the heat switch were based on structural as well as thermal needs.

Requirement Description	Value
Switch-Open Conductance	< 0.018 W/K at T<18 °C
Switch –Closed Conductance	> 0.45 W/K at T>25 °C
Heat Switch Assembly Mass	< 160 g
Landing Loads (qualification)	48 Gs
Random Vibration (qualification)	7.8 Grms, 2 min./axis (20-80 Hz: +6db/Oct. 80-450 Hz: 0.08 G^2/Hz 450-2000Hz: -6db/Oct.)

FLIGHT QUALIFICATION

The flight qualification program consisted of the following tests:

- 20,000 cycle seal boot hydraulic life test
- Force calibration test
- Thermal performance test at 8 torr CO_2
- Random vibration: 7.8 Grms, 2 min./axis (20-80 Hz:+6db/Oct. 80-450 Hz:0.08G^2/Hz 450-2000Hz: -6db/Oct.)
- Pyrotechnic shock:2000g SRS, 1600–10,000 Hz
- Landing loads: 48 g static (done via sine burst)
- Thermal life cycle test: 350 cycles
- Wobblefram seal pliancy and pressure test
- Dimensional, mass, visual examination

* Performance verification tests performed after all life tests and dynamics tests

The thermal performance of the heat switch as measured on flight qualification units met or exceeded the requirements. Figure 4 reveals how the thermal conductance rises sharply between the temperature range from 20 °C to 30 °C. This change is due to the increased interface pressure: as the wax continues to expand with increasing temperature, the switch halves are pulled together more tightly.

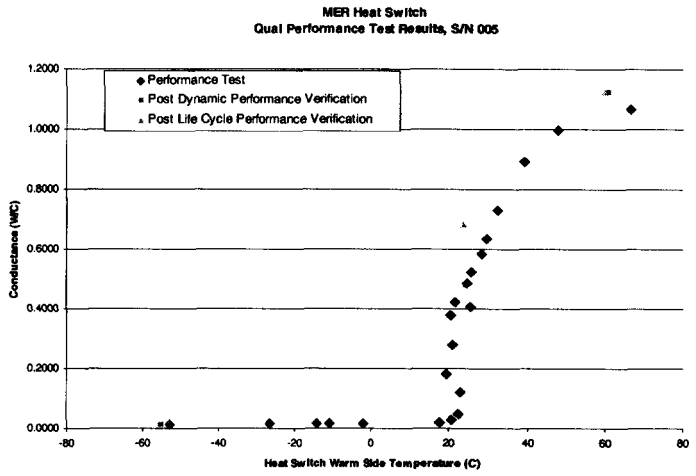

Figure 4. The switch closed to open conductance ratio exceeds 60:1 at extreme temperatures. The test data shown was taken in an 8 torr CO2 environment.

The heat switch design was also qualified to meet the structural requirements. After undergoing random vibration, pyrotechnic shock, and landing loads tests the switch showed no signs of visible damage and no degradation in thermal performance. All structural tests were performed with a flight-like radiator cantilevered off of the heat switch in the switch-open configuration. Since the switch is predicted to be closed during launch, the random vibration tests were also conducted in the switch-closed configuration.

Life tests were also conducted on the heat switch. The seal boot containing the paraffin wax was hydro-mechanically cycled more than 20,000 times. The entire assembly was also subjected to 100 cycles across the acceptance temperature range and 250 cycles over a temperature range sufficient to achieve the full stroke. Performance verification tests showed no signs of significant wear and no degradation in thermal performance.

MER ROVER BATTERY THERMAL PERFORMANCE

The thermal control system of the Rover battery consisted of the heat switches as well as survival and warm-up heaters. Because night time heater power is scarce, the goal of the design was to sufficiently hot bias the system to minimize the use of these heaters. Figures 5 and 6 show the predicted worst case hot and cold battery temperatures over the Mars diurnal.

The most plausible failure mode of the heat switch is for it to fail in the open condition. The thermal model was also run for this condition, the results of which are shown in Figure 7. Because the remaining heat switch thermal conductance continues to increase with temperature, the effect of the open-switch failure is minimized: the battery is held near its upper allowable temperature limit.

CONCLUSION

The MER mission requires unique thermal control techniques to deal with the extreme Martian environment. And the Rover battery, with one of the narrowest allowable temperature ranges, is a mission critical component. It must be kept above its survival temperature at night, while not overheating during the day. A successful thermal control system must not only meet these requirements, but should also minimize the amount of heater power required for survival and warm-up. The heat switch is a key component in the design to help meet these requirements and goals. The switch itself requires no power and runs autonomously. Its variable thermal conductance also makes it tolerant to failure. The MER battery design currently has two switches baselined, each with its own external radiator. If one switch were to fail open, the other would respond to the resulting increase in temperature by increasing its thermal conductance to nearly twice its value from 25 °C to 40 °C, the upper qualification temperature limit. The design is fully flight qualified. Flight units have also been acceptance tested and delivered to JLP. The heat switches are baselined on the MER mission which is scheduled to be launched in 2003.

Figs 5, 6 & 7 missing

ACKNOWLEDGMENTS

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