Paper Number

Development Testing of a Paraffin-Actuated Heat Switch for Mars Rover Applications

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ABSTRACT

A paraffin-actuated heat switch has been developed for thermal control of the batteries used on the 2003 Mars Exploration Rovers. The heat switch is used to reject heat from the rover battery to a radiator. This paper describes the development test program designed, in part, to measure the thermal conductance of the heat switch in an 8 Torr CO_2 environment over the expected operating temperature range of the battery. The switch has a closed conductance of about 0.6 W/C and an open conductance of 0.019 W/°C. The test program also included measuring the battery temperature profile over a hot case and a cold case Mars diurnal cycle. The test results confirm that the battery will remain well within the upper and lower allowable flight temperatures in both cases.

INTRODUCTION

Starsys Research Corporation has developed paraffin-actuated heat switches for thermal control several years ago[1] and has built the heat switches that will be used on the Mars Exploration Rover to control the rover battery temperature. They are passive, variable thermal conductance devices. The switches are bolted to Radioactive Heat Units (RHUs) at one end, and to radiators at the other as shown in Figure 1. The RHUs are mounted to the battery and provide a baseline heat load to keep the battery warm at night. But during daytime operations, the battery may overheat without rejecting heat through the switches. Above 18°C the paraffin wax inside the switches melts and expands, and mechanically closes the switch. This brings the battery into thermal contact with the radiators. Below 18°C the paraffin freezes and contracts, opening the switch. This isolates the battery thermally from the radiator panels. Development testing on the switches was conducted at the Jet Propulsion Laboratory in June and July 2001. This paper summarizes the test objectives, procedures and results.

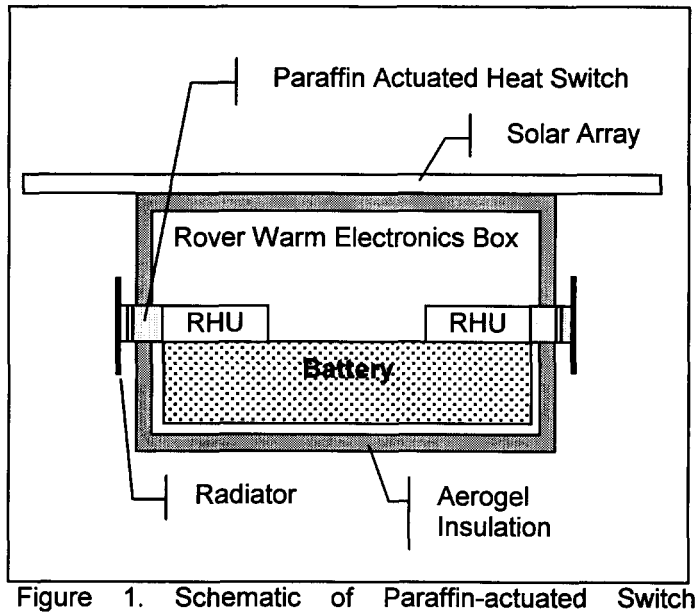


Figure 1. Schematic of Paraffin-actuated Switch Installation on Rover Battery Assembly seen from end view of the Rover

TEST OBJECTIVES

The development test program of the switches had four primary objectives.

1. Determine the thermal conductance of the switch over the operating range of the battery and the expected Mars ambient environment.
2. Characterize the switches in the hot case Martian diurnal cycle. This test case shows how the heat switches behave as part of the battery temperature control system in a simulated Martian environment on a warm day at the beginning of the mission.
3. Characterize the switches in the cold case Mars diurnal cycle. This is the same as test objective number 2, but the temperature profile simulates a cold Martian day at the end of the mission.
4. Characterize the system in the case of one switch failing in the open position. This test case determines if only one heat switch is sufficient to

maintain the battery within the allowable temperature limits. The test simulates one switch failing open (no conductive path from the battery to the radiator), which is the most plausible failure mode. The worst-case hot diurnal temperature profile was used in this test case. Removing the radiator panel from one of the switches simulated the failure mode.

EXPERIMENTAL APPARATUS AND PROCEDURE

The test apparatus was designed to simulate the rover components surrounding the battery as shown in Figure 2. The battery is adjacent to electronic components on two sides and next to the rover walls on all other sides. An aluminum thermal mass mock-up of the battery was used in place of an actual battery. Type-E Thermocouples were mounted on each face of the battery simulator and in four of the eight corners so that temperature gradients could be determined. A box, fabricated to enclose the battery, is shown in Figure 3. Thermocouples were attached to each face of the enclosure box. A heat exchanger was also attached to the enclosure box to regulate its temperature. This allowed the boundary conditions for the battery to be adjusted for each test. The heat exchanger was connected to a constant-temperature recirculating chiller, which had a temperature range of -35° to +35°C. This temperature range was adequate to cover the boundary conditions for the allowable flight temperatures around the battery. A LabView™ data acquisition program controlled the chiller set point.

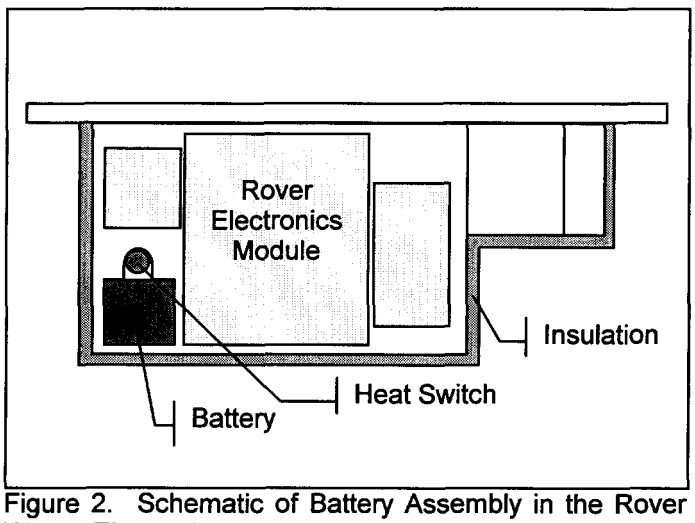


Figure 2. Schematic of Battery Assembly in the Rover Warm Electronics Box seen from a side view of the Rover.

The battery box was closed with one insulated wall, which was penetrated by the heat switches to simulate the flight design. However, the insulation was Styrofoam™ instead of aerogel. Thermocouples were attached to both faces of the insulated wall. The heat switch radiator panels were attached after the insulated wall was installed as shown in Figure 4. Thermocouples were attached to the radiator at the base of each switch and in the corners to determine temperature gradients. Thermocouples were attached to the ends of both heat switches. These thermocouples were used to determine the thermal conductance of the switches. A cold sink radiator plate was installed as close as possible to the heat switch radiators. This provided the boundary condition for the radiators. The cold sink was connected to another constant-temperature recirculating chiller, which had a temperature range of -80° to +60°C. This temperature range did not allow the radiator to get to the lowest allowable flight temperature of -90°C, but it was sufficiently low to adequately evaluate the operation of the heat switches. The data acquisition program also controlled the set point of this chiller. The cold sink and the heat switch radiators were surrounded by an insulated enclosure.

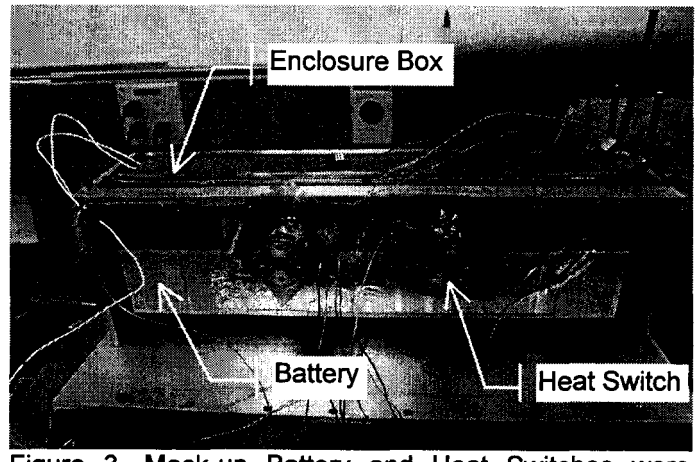


Figure 3. Mock-up Battery and Heat Switches were mounted first in the Test Chamber

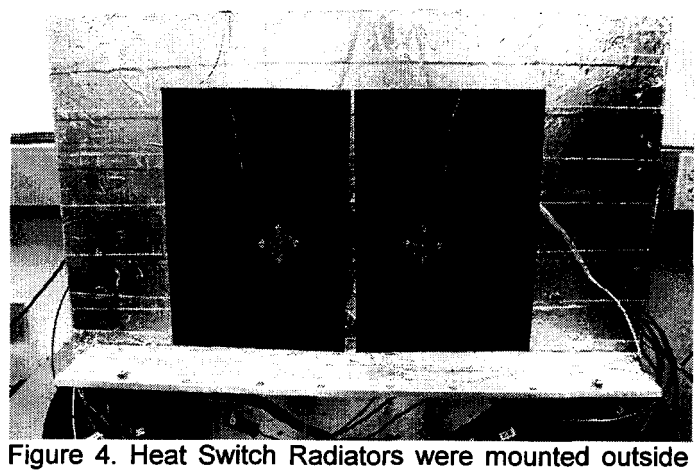


Figure 4. Heat Switch Radiators were mounted outside the Insulated Wall of Battery Box.

The heat switches were tested in a vacuum chamber that was initially evacuated for 24 hours to allow for out-gassing and then back-filled with 8 to 10 Torr CO_2 to mimic the Mars atmosphere. The pressure of the system was continuously monitored by the data acquisition system. The complete assembly of the test article just prior to closing the chamber is shown in Figure 5.

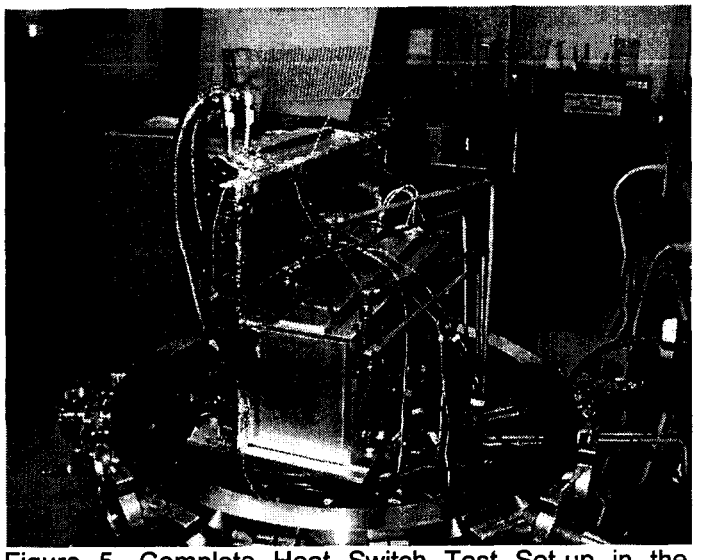


Figure 5. Complete Heat Switch Test Set-up in the Vacuum Chamber.

TEST PROCEDURES

The four objectives of the test program were accomplished using the following test matrix:

Test Case #1: Switch Conductance Measurement

The thermal conductance of the heat switches was measured in both the open and closed positions. In the closed position, the switches were required to remove 6.5 watts of heat from the battery. This is the heat load from the RHUs on the flight unit. The sink temperature for the radiators was set at 30°, 15°, 0° and -15°C and the system was allowed to reach steady state temperatures. These temperatures are representative of the environment temperatures for the radiators while operating during the warm part of the day at Mars. The temperature of the battery enclosure box was set to equal the temperature of the battery to reduce parasitic losses.

In the open position, the switches transfer only a parasitic heat load. The heat load on the battery was set to 2.5 watts and the sink temperature was set to -80°C. These conditions kept the battery and switch temperatures below the melting point of the paraffin 18°C.

Test Case #2: Mars Diurnal Cycle Hot Case

The Mars diurnal temperature profile at the *beginning* of the mission was imposed on the heat switch radiators to characterize the performance of the switches while keeping the battery within allowable flight temperatures. The characterization would verify assumptions used in modeling the transient behavior of the heat switches. The battery enclosure box also tracked a diurnal temperature profile based on thermal model predictions for the components surrounding the battery. The temperature profiles are shown in Figure 6. The test ran for two consecutive diurnal cycles, lasting 48 hours. A parasitic heat load of 1.5 watts was added to the battery for eight hours during each cycle to simulate daytime operations on the rover.

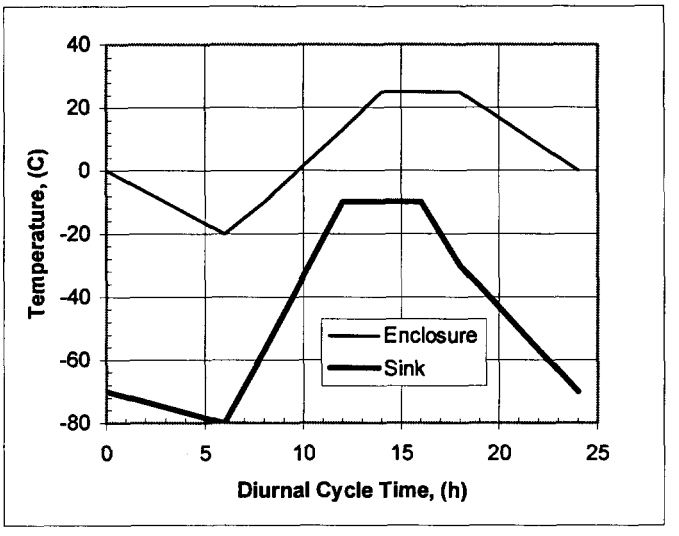


Figure 6. Diurnal Temperature Profile of the enclosure box and the heat sink used in the hot case test.

Test Case #3: Mars Diurnal Cycle Cold Case

The Mars diurnal temperature profile at the *end* of the mission was used on the radiators, with some limitations, in this test. The low temperature limit of the chiller was -80°C. The sink temperature on Mars could reach as low as -105°C near the end of the planned mission. Thus the low end of the temperature profile was truncated, but this was deemed an acceptable limitation for this test. The temperature profiles for this case are shown in Figure 7. The battery heat load profile included operating a 20-watt heater beginning at the sixth hour of the cycle. The heat load simulates operation of a warm-up heater used to heat the battery above 0°C before daytime charging begins.

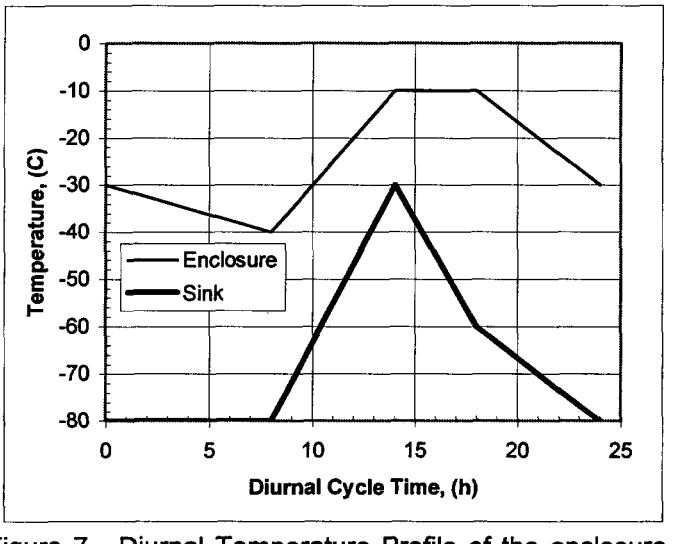


Figure 7. Diurnal Temperature Profile of the enclosure box and the heat sink used in the cold case test.

Test Case #4: One Heat Switch Failed Open

This test characterizes the system performance in the case of one switch failing in the open position, which is the most plausible failure mode. The hot case diurnal temperature profile was used. Removing the radiator of one switch simulates the failure.

EXPERIMENTAL RESULTS

THERMAL CONDUCTANCE MEASUREMENTS

The results of the heat switch conductance measurement tests at Starsys Research and JPL are shown in Figure 8. There is agreement between both data sets, which came from different test configurations. The measurements from Starsys were taken on individual switches. The measurements from JPL were calculated for individual switches assuming that half of the applied heat load on the RHU mock-up went through each switch. The conductance of the switches increases when the warm side is above 20°C. The conductance does not increase at the paraffin melt temperature because there is a 1 mm gap between the switch sides when it is open.

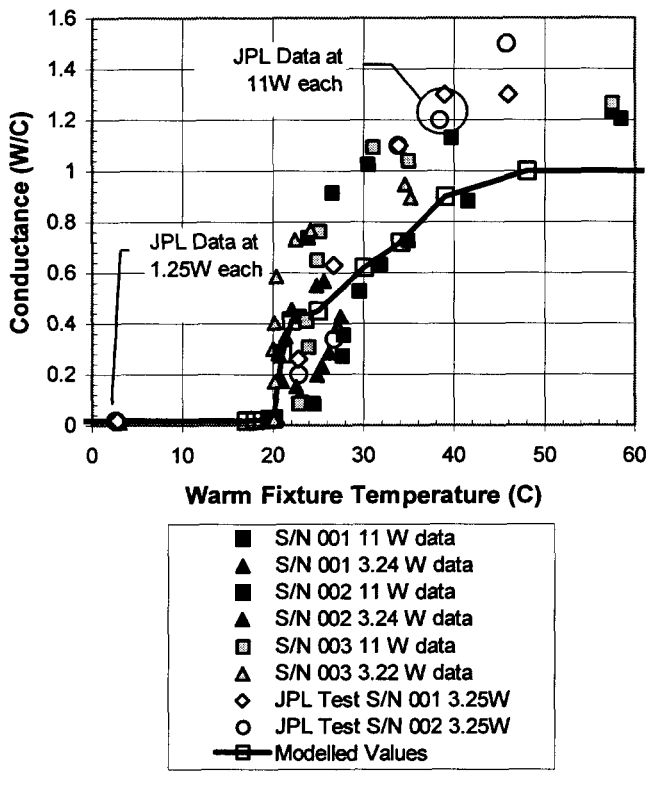


Figure 8. Heat Switch Conductance values measured at JPL and at Starsys Research Corp.

The open switch conductance was 0.019 ±0.001 W/°C for each switch. This value stays constant once the switch is opened. The closed switch conductance varies as the pressure between the contact-surfaces increases. Above 50°C the conductance reaches a constant value of about 1.2 W/°C. At the battery AFT limit of 30°C, the switch conductance is about 0.6 W/°C. A thermal model of the switches uses conductance values as shown in the line drawn over the data in Figure 8.

MARS DIURNAL CYCLE: HOT CASE

The results of the Mars Diurnal Cycle Hot Case Test are shown in Figures 9-12. The temperature of the switches on the battery side and the radiator side are shown in Figure 9. There was a noticeable difference in temperature of the cold side of switches when the switches were closed, which could be attributed to differences in the paraffin fill volume or mechanical adjustments to the heat switch assembly. Since these results were from the first two units produced, the data reflects some expected variation until the assembly process is finalized.

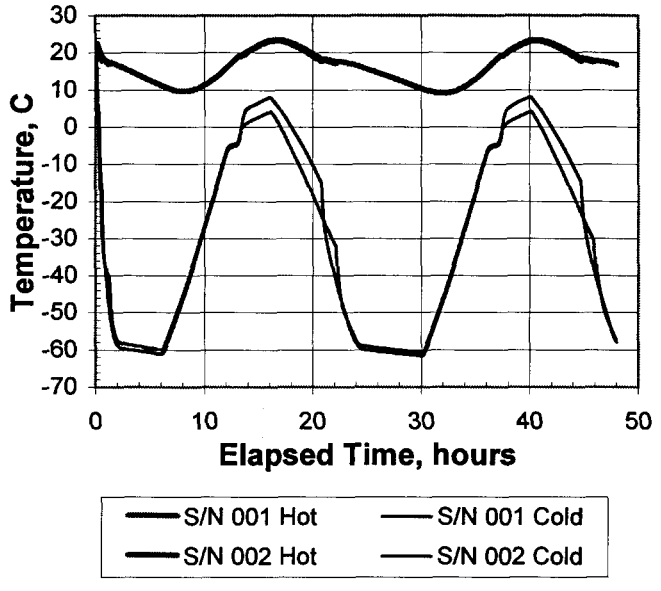


Figure 9. Heat switch face temperatures during the Mars diurnal cycle hot case.

The temperature of the battery is the primary concern in these tests. Figure 10 shows that the battery temperature was below the expected values in the model. This is because the thermal conductance of the heat switches is actually higher than that used in the model, which built in conservative conduction values. Furthermore, the model simulated the actual rover design whereas the test apparatus was only an approximation of the rover design. A thermal model of the test article was not within the scope of the work plan. The temperature variation in the battery is very small as indicated by the maximum and minimum battery temperatures in Figure 10. The heat load profile on the battery in Figure 10 shows the parasitic heat load placement in each cycle.

The temperature profile of the radiators is compared to the model predictions of the flight radiators in Figure 11. The thermal model used a simple on/off conductance scheme at this point in the development program so the predicted radiator temperature shows some oscillations

when the warm side of the switch approached the paraffin melting temperature. The maximum and minimum radiator temperatures were plotted along with the average and no large temperature gradients on the radiators were observed. The radiator temperatures were within a few degrees Celsius of each other when they were rejecting heat to the sink; confirming that both switches operated nearly identical to each other.

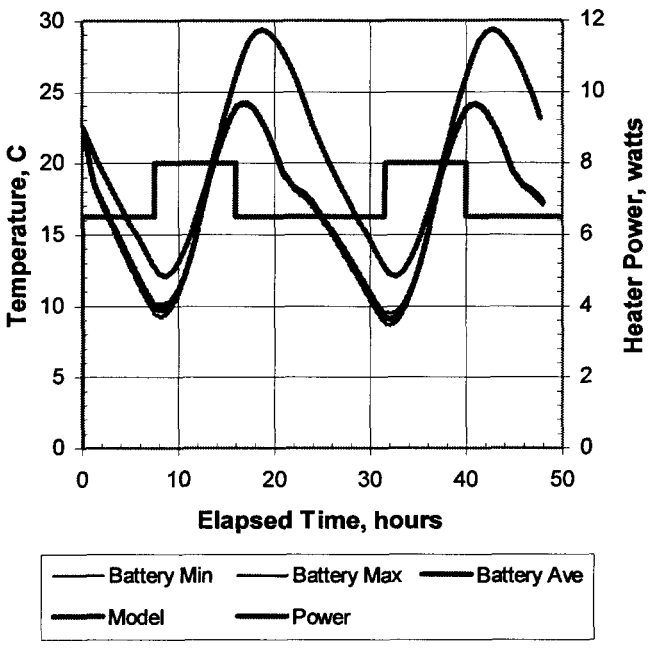


Figure 10. Battery temperature compared to model predictions for the Mars Diurnal cycle hot case test.

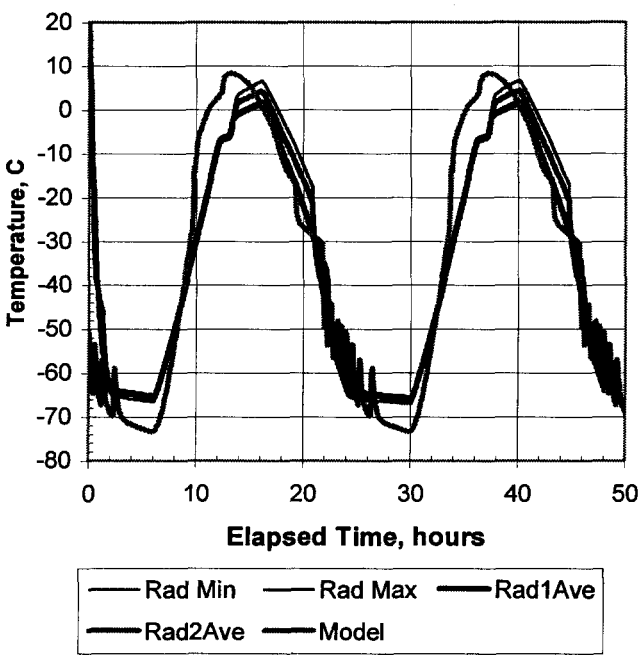


Figure 11. Radiator temperatures compared to model predictions for the Mars Diurnal cycle hot case.

A comparison between the battery enclosure box temperatures and the model boundary conditions is shown in Figure 12. The enclosure box is generally held to the average temperature of the model predictions. The highest temperature boundary condition is in the +X coordinate direction. The electronics module adjacent to the battery generates this boundary condition. The effect of the high temperature boundary condition was accounted for by using an artificial parasitic heat load on the battery since it was not possible to create the actual boundary condition using this simple test apparatus. The insulated walls surrounding the battery created the group of cold boundary conditions shown in Figure 12.

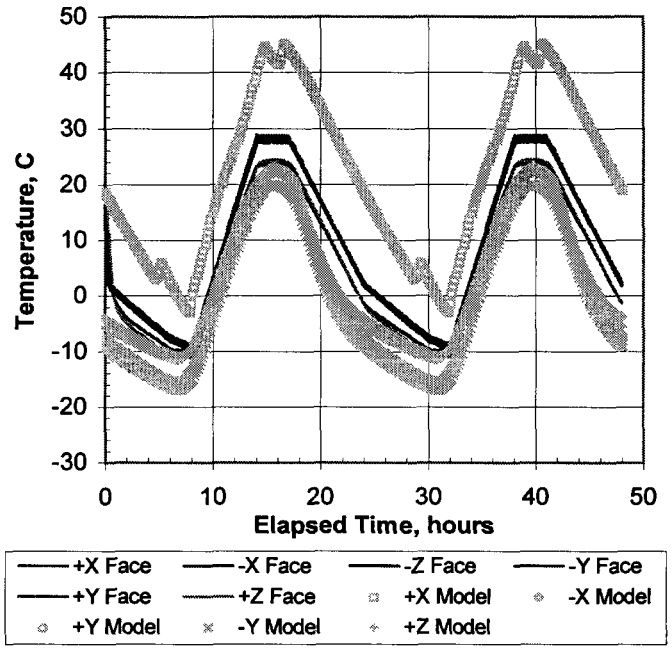


Figure 12. Battery enclosure box temperatures compared to model predictions for the Mars Diurnal cycle hot case.

MARS DIURNAL CYCLE: COLD CASE

The results of the Mars Diurnal Cycle Cold Case Test are shown in Figures 13-16. The temperature of the switches on the battery side and the radiator side are shown in Figure 13. The temperature of the hot side of the switches was not symmetrical in both cycles because of faulty logic in the data acquisition program that failed to turn on the 20-watt battery warm-up heater during the second diurnal cycle. The logic also failed to keep the warm-up heater on whenever the battery temperature dropped below 0°C after the initial warm-up. These deviations from intended results were deemed insufficient for correcting the logic and repeating the test. It was also observed that the temperature of the radiator side of the switches were about 4°C different from each other, indicating that one switch had a slightly higher heat loss than the other. The difference in open conductance is not readily apparent in Figure 8 because the conductance values are so small. Switch S/N 002 had a conductance that was about 10% higher than S/N 001. It should be pointed out, that the heat switches remained open during the cold diurnal cycle because the battery temperature was always below 18°C.

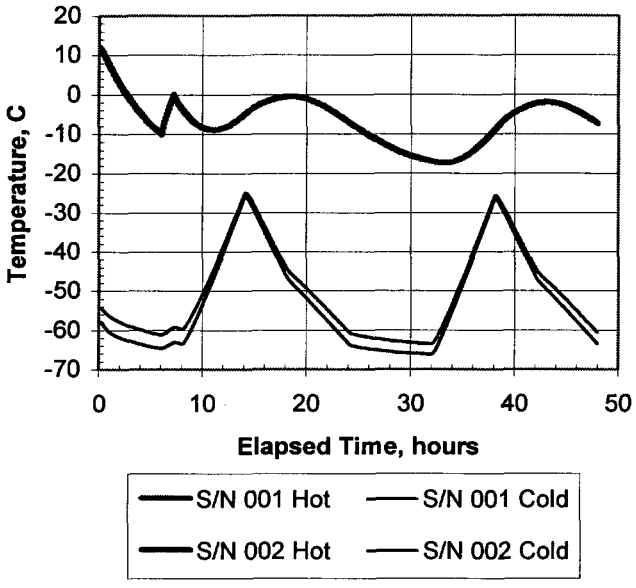


Figure 13. Heat switch face temperatures during the Mars diurnal cycle cold case.

The cold case battery temperature is compared to the model predictions in Figure 14. The battery deviation from the model is explained by the faulty logic operating the warm-up heater previously described. The figure shows the warm-up heater activating only once and then it remained off for the rest of the test.

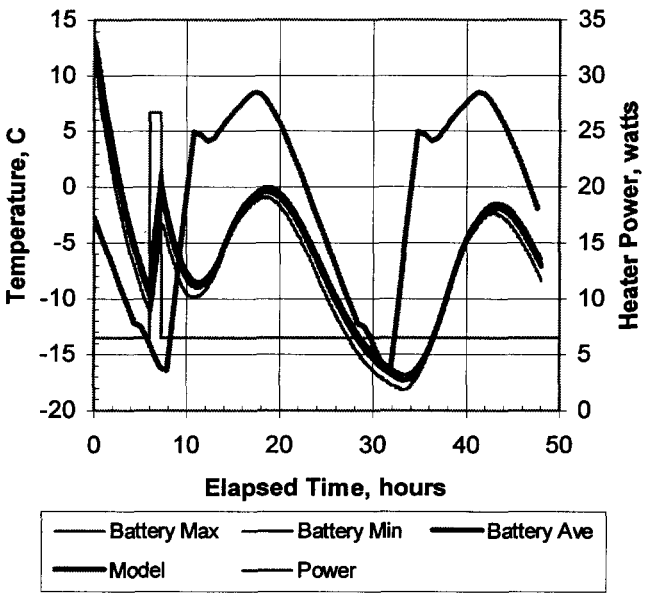
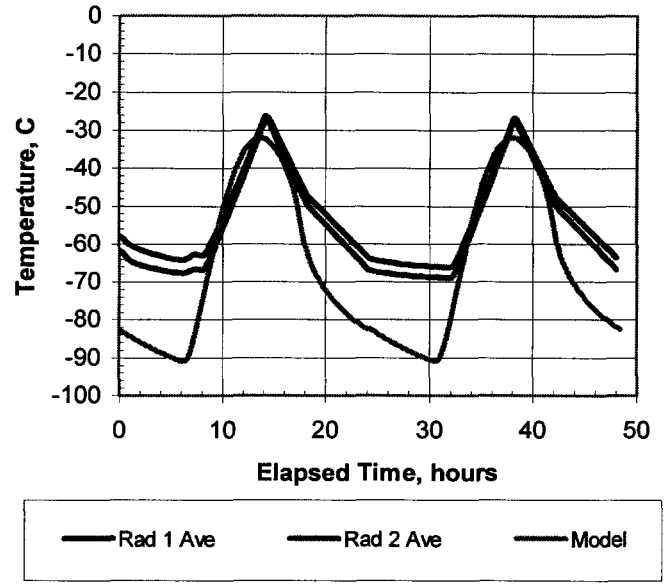


Figure 14. Battery temperature compared to model predictions for the Mars Diurnal cycle cold case test.

The temperature of the radiators compared to the model predictions are shown in Figure 15. The low temperature limit of the chiller was insufficient to cool the radiators to -90°C. Liquid nitrogen shrouds were not used because they produce frost and make it difficult to maintain the chamber pressure in a carbon dioxide atmosphere at this temperature range.

Figure 15. Radiator temperatures compared to model



predictions for the Mars Diurnal cycle cold case.

The temperature of the battery enclosure box is shown in Figure 16 with the model predictions for the battery boundary conditions. The chiller did not have sufficient capacity to cool the box to -40°C during the low temperature phase of the diurnal cycles. As in the hot case, the +X coordinate boundary condition is the warmest, while the insulated walls formed the coldest boundary conditions.

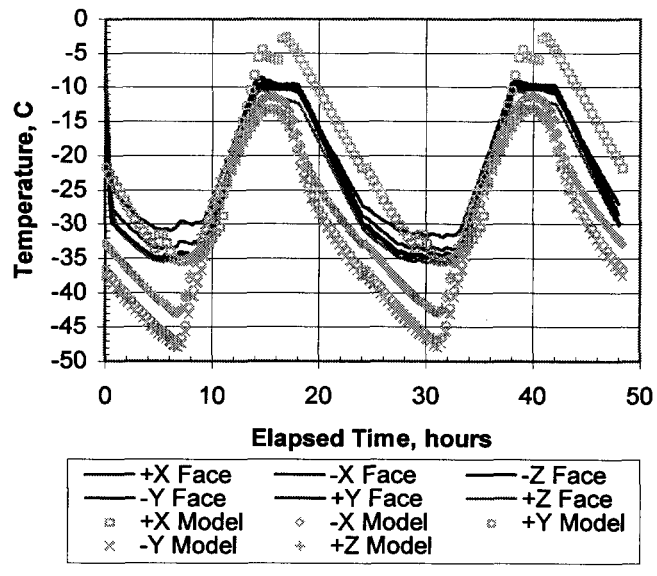


Figure 16. Battery enclosure box temperatures compared to model predictions for the Mars Diurnal cycle cold case.

REMOVED RADIATOR TEST CASE

The battery temperature for the failed-open switch test case is shown in Figure 17. As the temperature of the battery rises, the thermal conductance of the switch increases. The maximum battery temperature was 32°C, which is slightly above the maximum allowable

flight temperature. This is not deemed a catastrophic failure but may reduce battery life or capacity.

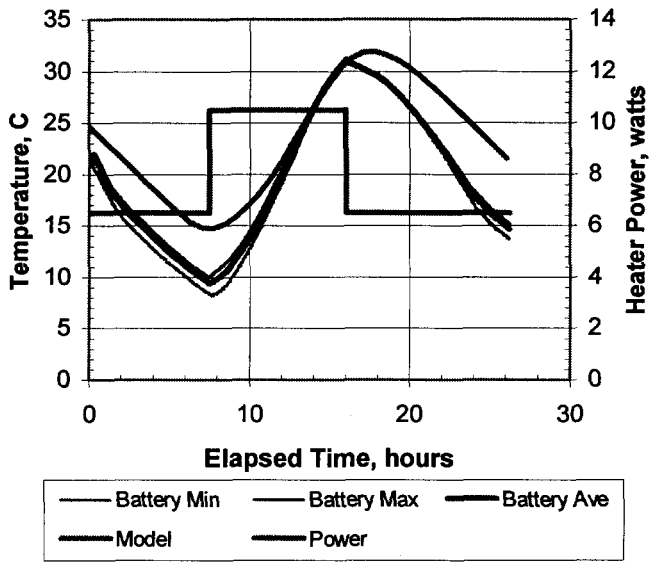


Figure 17. Battery temperature compared to model predictions for the Mars Diurnal cycle hot case test with one radiator removed.

CONCLUSION

The rover battery temperature control system utilizes a constant heat source of 6.5 watts from radioactive heat units to reduce electrical power consumption for keeping the battery warm at night. Electric heaters are used to provide warm-up heating prior to battery charging from the solar cells and to provide survival heating to maintain the battery above the lower AFT of -20°C. The role of the heat switches in the thermal design is to keep the battery from overheating during daytime operation near the beginning of the mission, which is the warmest part. The heat switches must provide adequate thermal isolation during the night and during the cold part of the mission, which occurs at the end of the planned 90-day mission. The results of the development test program for the paraffin-actuated heat switches indicate satisfactory thermal performance and mechanical operation for controlling the rover battery temperature. The heat switches have a closed/open conductance ratio exceeding 30, which provides excellent thermal transport at warm temperatures and good thermal isolation at cold temperatures.

Although the Mars diurnal cold case test had numerous problems and did not meet all the test requirements, the test provided sufficient information about thermal conductance at cold temperatures to improve the thermal model of battery temperature control system.

ACKNOWLEDGMENTS

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APPENDIX

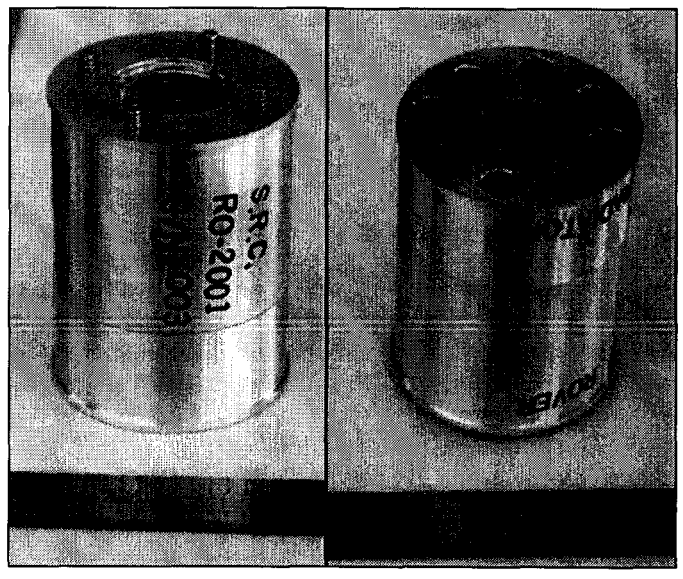

Figure 18. A photograph of heat switch S/N 003 shows the RHU connection side up on the left, and the radiator side up on the right. This is in the closed position; the paraffin is melted at this condition.