Mars Exploration Rover Thermal Test Program Overview

M.T. Pauken, G.M. Kinsella, K.S. Novak, G.T. Tsuyuki
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA

ABSTRACT

In January 2004, two Mars Exploration Rovers (MER) landed on the surface of Mars to begin their mission as robotic geologists. A year prior to these historic landings, both rovers and the spacecraft that delivered them to Mars, were completing a series of environmental tests in facilities at the Jet Propulsion Laboratory. This paper describes the test program undertaken to validate the thermal design and verify the workmanship integrity of both rovers and the spacecraft.

The spacecraft, which contained the rover within the aeroshell, were tested in a 7.5 m diameter thermal vacuum chamber. Thermal balance was performed for the near earth (hot case) condition and for the near Mars (cold case) condition. A solar simulator was used to provide the solar boundary condition on the solar array. IR lamps were used to simulate the solar heat load on the aeroshell for the off-sun attitudes experienced by the spacecraft during its cruise to Mars.

Each rover was tested separately in a 3.0 m diameter thermal vacuum chamber over conditions simulating the warmest and coldest expected Mars diurnal temperature cycles. The environmental tests were conducted in a quiescent nitrogen atmosphere at a pressure of 8 to 10 Torr. In addition to thermal balance testing, the science instruments on board the rovers were tested successfully in the extreme environmental conditions anticipated for the mission. A solar simulator was not used in these tests.

INTRODUCTION

This paper focuses only on two of the four system level thermal vacuum tests performed for the MER spacecraft and rovers since similar tests were performed on each system. There is a wealth of background information about the mission publicly available on the Web at: http://jpl.nasa.gov/mer2004/index.html. Information about the rover thermal design has been published and presented at the 2003 Space Technologies and Applications International Forum (STAIF-03)[1]. Other papers have been published describing the Rover Heat Rejection System (HRS)[2], and the paraffin actuated heat switches used for the battery thermal control system[3,4].

CRUISE PHASE TESTING

The MER 1 Cruise System Thermal Test (STT) was conducted from November 9 to 21, 2002 in the JPL 25-Foot Space Simulator Facility. The focus was thermal balance testing of the cruise phase of the mission from Earth to Mars. The second spacecraft, MER 2 was tested in January 2003. Since the tests reported in this paper were nearly identical for both spacecraft, only the results for MER 1 will be presented and discussed.

The test article was predominantly flight hardware with several high-fidelity non-flight assemblies that included: batteries, hardware normally loaded with ordinance for flight, and the solar array.

The test was overwhelmingly successful since nearly all test objectives were satisfied although a few unrelated facility problems produced some early delays. Steady state and transient data of the integrated Rover HRS using the flight hardware were collected for the first time. This paper addresses thermal design validation, including thermal functional testing but excludes general spacecraft/rover functional testing results.

This test: (1) empirically validated the MER thermal design during the cruise phase, (2) demonstrated thermal h/w functionality (thermostats, heaters, PRTs, thermal valve, and heat switches), (3) verified flight software propellant line set point reset and HRS fault protection capabilities used to thermally control flight hardware, (4) reduced thermal design uncertainty, (5) provided an empirical basis to align resistance and thermal capacitance values in the analytical thermal model.

SURFACE PHASE TESTING

An eleven-day System Thermal Test of the flight MER 2 Rover and flight Lander Basepetal was conducted from December 11 to 23, 2002 in the JPL 10-Foot Space Simulator Facility.

Only the surface phase operations of the MER mission were simulated in this test. Steady state and transient data were collected to better understand the thermal performance of the Rover during surface operations. The test was a combination of thermal design validation, thermal hardware workmanship verification and rover functional test. This test was designed to reduce thermal design uncertainty, evaluate aerogel insulation thermal performance, and detect any potential thermal workmanship problems in the flight hardware. In addition, a number of functional tests were also done as a part of this test. Functional testing included: a stand-up and deployment verification, operation of the rover cameras, a Mini-TES calibration, and an Instrument Deployment Device (IDD) functional test.

The test article was a fully assembled flight rover sitting on a flight Lander Basepetal and was made up almost entirely of flight hardware. Notable exceptions include the rover solar array panels, the battery and RHU simulators. An external chiller was used to circulate Syltherm through a heat exchanger that cooled freon in the HRS loop inside the rover to accelerate the cooling of internal Warm Electronics Box (WEB) hardware.

The surface simulation included an 8 Torr GN_2 atmosphere to simulate the Martian 8 Torr CO_2 atmosphere. No attempt was made to simulate the Martian solar load during the test. Since it is difficult to precisely recreate the Martian environment in the chamber, thermally conservative tests were typically performed. The test data from the surface phase was used to align resistance and thermal capacitance values in an analytical thermal model of the rover to known chamber conditions. This permitted an extrapolation of the analytical model to the flight environment. This surface phase test could be characterized as a semi-empirical validation lying somewhere between a purely empirical validation and a verification by analysis.

MAIN SECTION

CRUISE PHASE TESTING

The cruise system thermal test consisted of eleven thermal tests shown in Table 1, cold and hot spacecraft baseline tests, and several special test requests (Attitude Control System, telecom). The eleven thermal tests included four steady state worst-case thermal balance cases, two thermal hardware functional tests, an Entry Descent and Landing (EDL) case with the HRS off, three thermal performance transient cases, and an HRS fault protection case.

Some flight system areas are at their steady state temperature extremes when the spacecraft is at its off-sun nominal orientation while other flight system areas reach their extremes with the spacecraft in a sun-pointed fault attitude. The thermal balance test cases bound the mission envelope for all flight system areas by simulating cold and hot conditions for both nominal and fault spacecraft attitudes.

Table 1. Test matrix for Cruise Phase

Test Case		Objectives
1	Pump-down and Accelerated Cooling	Draw vacuum, backfill to 300 Torr to accelerate cooling, pump-down to high vacuum.
Cold Cases		
2	Backshell worst case cold thermal balance	Thermal design verification at worst case cold condition for the backshell
3A	Flight software set-point test	Change propellant line set-point temperature
3B	SSPA Swap Test	Turn SSPA-A off and SSPA-B on
3C	Backup heater functional test	Disable primary heaters and test back up heaters
4	S/C functional test in cold environment	Run S/C baseline test to verify S/C functionality for cold simulated flight conditions
5	Propellant system worst case cold thermal balance	Thermal design verification at worst cold case for prop system
EDL Cases		
6	Final approach, Start of EDL, TCM 6 and cruise shunt radiator test	Perform TCM 6, fire thrusters, characterize warm up heaters for airbags, cat beds, lander battery, max allowable shunting power
7	EDL functional test	Run EDL at temperature, characterize gas generator heaters
8	HRS venting simulation and non-op test	Characterize how long can the S/C operate without HRS
Hot Cases		
9	Prop system worst hot case thermal balance	Thermal design verification at worst hot case for the prop system and solar array
10	Backshell worst hot case thermal balance	Thermal design verification at worst hot case for the backshell
11	WEB temperature fault protection test	Lower fault protection SSPA set-point, turn off Pump-A, let fault protection turn on Pump-B.
12	S/C functional test hot environment	Run S/C baseline test to verify S/C functionality for hot simulated flight conditions
13	Backfill and open chamber	Prepare S/C for removal from test chamber
☐ Cases repeated for 2nd Spacecraft		

The cruise simulation was performed under high-vacuum conditions with an LN2-cooled chamber shroud

simulating the sink of deep space. Xenon arc lamps illuminated the cruise stage solar array simulator. Separate arrays of quartz lamps independently lit the HRS radiators and backshell to simulate off-sun conditions. Two safety arrays of quartz lamps were present at the spacecraft top and bottom to protect flight hardware in the event of facility faults.

TEST ARTICLE CONFIGURATION

The spacecraft was suspended inside the vacuum chamber as shown in Figure 1 using three stainless steel cables attached to the Launch Vehicle Adapter MGSE ring. The estimated MER flight system mass for this test was 993 kg. This included about 23 kg of non-flight cabling (thermocouples and test heaters) and 16 kg for the LVA MGSE.

The spacecraft top was illuminated by xenon arc lamps during the entire test, except for short durations during the Kendall cone radiometer recalibration. These lamps simulate the solar flux that the spacecraft sees during flight. The simulated solar flux levels were reduced to match the removal of 300 W of electrical power by solar cells present for flight, but not present on the solar panel mock-ups used in the test.

The test article was surrounded by arrays of quartz lamps to simulate off-sun solar loads during cruise. The HRS radiators and backshell each had a dedicated array of lamps, and calorimeters were used to ensure proper flux levels. Two arrays of safety lamps at the spacecraft top and bottom were also used to safeguard flight hardware and shorten the test duration by accelerating warm-up.

The distance between the heat shield and chamber floor was 1.1 m. The chamber floor was bare without any MLI blankets, and reflections from the solar simulator were reduced by the MLI baffle above the test article. The suspension cables were cleaned to eliminate contamination concerns.

The X-band antennas (cruise LGA and MGA) had clip-on RF hats (anodized aluminum). These antennas and the UHF descent antenna were connected in a non-flight like manner with thick flexible coaxial cable routed from the antenna test ports to the chamber bulkheads. The connections of other antennas match flight identically. These include the rover LGA and UHF antennas.

SUMMARY OF TEST RESULTS

Case 2 Backshell Worst Cold Case

This was a steady state test that simulated a fault condition near Mars when the S/C returned to a safe sun-point orientation. The solar vector was perpendicular to the solar array. This was the worst-case cold condition for the backshell since it was not sunlit. It was also a worst-case cold thermal design validation for the star scanner, cruise electronics module, lander petals, airbags, and rover. This was a nominal cold case for the solar array, propulsion system, and the backshell interface plate.

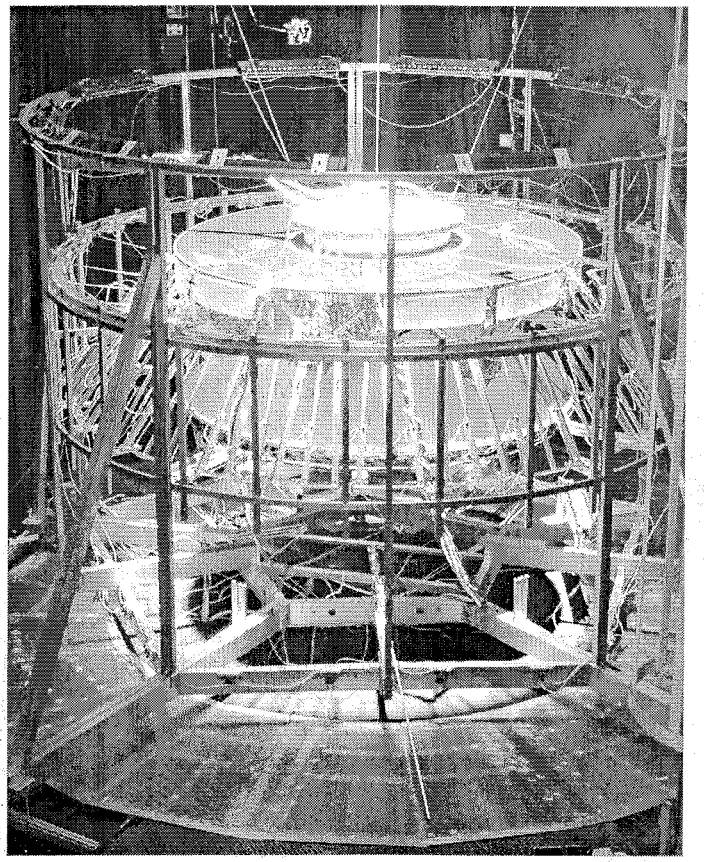

Figure 1. MER-1 Test Article in 25-ft Space Simulator.

The hardware attached to the lander were the pacing items since they were very insulated from the chamber environment by the aeroshell, airbags, and the lander MLI. Chamber control was fine (shroud temperature, pressure, and solar simulator) except for some short-term xenon lamp anomalies that had no lasting thermal effect.

The RHU simulator power for the battery and the Rover Electronics Module (REM) were turned on for the rest of the test. The quartz lamps were off, and there was zero power dissipation at the cruise shunt radiator.

Cruise stage hardware that was not thermostatically controlled typically had 20°C margins. Cruise stage hardware that was thermostatically controlled generally maintained positive temperature margins without using 100% duty cycles. Exceptions included the star scanner and propellant line zones 1 and 4 to 8 (had 100% duty cycles). The aeroshell hardware typically had 10°C to 20°C margins except for the Transverse Impulse Rocket motors (5°C). The backshell exterior temperature varied from –35°C nearest the cruise stage down to -76°C near the heat shield interface. The backshell interior ran 2°C to 5°C warmer than the exterior depending upon the vertical height.

Lander hardware that was not thermostatically controlled typically had large margins (≥20°C). Exceptions included the Radar Altimeter System (RAS) (4°C), lander petals (10°C to 14°C), and the lander pyro switch assembly (11°C). The smaller RAS thermal margin is positive and acceptable.

The HRS dominated the REM thermal performance as expected and afforded robust margins (39°C to 45°C). Although the rover battery is part of the HRS cooling loop, its narrower AFT limits result in a healthy 8°C AFT margin.

Case 5 Prop Line Worst Cold Case

This case simulated the outer cruise condition near Mars at the nominal spacecraft attitude. The simulated 46° off-sun orientation produced a nominal cold case for the star scanner, Cruise Electronics Module (CEM), backshell, lander petals, airbags, and rover. This was a worst-case cold condition for the solar array, propulsion system, and the Backshell Interface Plate (BIP).

The solar simulator flux from the xenon arc lamps was reduced from 522 W/m^2 to 344 W/m^2 for this case. This flux illuminated the S/C top (solar array substrate, cruise antennas, LVA, etc.) and simulated a nominal off-sun condition. The 344 W/m^2 flux included the effect of removing 300 W of electrical energy by solar cells not present in this test. The quartz lamps were turned on to illuminate the backshell corresponding to an in-flight 46° off-sun angle.

The digital sun sensor heads had the smallest thermal margin for this case. The ones mounted on the S/C side had 0°C and 5°C margins. The two mounted on top of the solar array mock-up had 4°C and 9°C margins. The next smallest thermal margins were the RAS and the rover battery (8°C for both). The remaining flight system hardware had large margins (>10°C) with much of it beyond 20°C.

The small margins for the digital sun sensor heads mounted to the S/C side were most likely a test limitation. The quartz lamp arrays were designed to illuminate the HRS radiators or backshell. These arrays likely illuminated these side-mounted sensor heads with a flux less than that expected for flight, causing them to run cooler than flight. The side-mounted sensor head margins are more likely closer to the top-mounted sensor head margins (4°C to 9°C).

Case 9 Prop Line Worst Hot Case

This case simulated an inner cruise fault condition near Earth when the S/C returns to a safe sun-point orientation. The solar array was hottest for this case since the solar vector was perpendicular to it. This was the worst-case hot thermal design validation for the propulsion system, solar array substrate, and BIP. The simulated 0° off-sun orientation produces a nominal hot case for the star scanner, CEM, backshell, lander petals, airbags, and rover since the backshell and HRS radiators are not sunlit.

The solar simulator flux from the xenon arc lamps was raised from 344 W/m^2 to 1300 W/m^2 for this case to simulate the fault attitude. The 1300 W/m^2 flux included the effect of removing 300 W of electrical energy by solar cells not present in this test. This corresponds to operating four of the eight solar array strings at perihelion. The quartz lamp array was off for this test case.

Test heaters were powered in a non-flight manner temporarily to accelerate the steady state convergence of this case. The solar flux was 1372 W/m^2 at the beginning of this case, which is the 1.0 AU flux before the 300 W of electrical energy is removed from the solar panel mock-up.

The Cruise Shunt Radiator (CSR) power varied between 240 W and 290 W for this test case. The CSR remained 28°C below its 100°C maximum AFT limit with the full 290 W at steady state.

The solar panel average temperature had no margin to the AFT limit and only 5°C margin to the FA limit.

The Propellant Distribution Module (PDM) violated its maximum AFT limit by 7°C and its FA limit 2°C in this case. The PDM temperature was sensitive to the hot solar panel temperatures and the warm environment created by it. Another MLI blanket was added to mitigate this problem (10 layer with low emittance exterior on both sides) and supply more isolation from the hot solar panel for the second STT for MER-2. This modification successfully eliminated the FA violation during the MER-2 STT.

The propellant line temperature for zones #1 and #6 violated their maximum AFT limits by 2°C, but that was due to the temporary set point selection for gathering additional thermal performance data.

Cruise hardware that was not thermostatically controlled had large margins (CEM: 20°C, LGA: 48°C, MGA: 57°C, Digital Sun Sensor (DSS) heads: 12°C to 22°C). The top DSS heads were covered with silver Teflon tape for this test since that was closer to the intended flight design. A bare DSS head was tested during the MER-2 STT and found to be acceptable for flight. Consequently, the expected top DSS head in-flight temperatures should run 15°C warmer than this test indicated.

Margins for aeroshell, lander, and rover hardware were also large for this case. The rover battery was the smallest margin of these, but still at a respectable 7°C.

Case 10 Backshell Worst Hot Case Thermal Balance

This case simulated the inner cruise condition near Earth at the nominal spacecraft attitude. The simulated 60° off-sun orientation produces a worst-case hot cruise

thermal design validation for the CEM, star scanner, backshell, lander petals, airbags, and rover. This was also a nominal cold case for the propulsion system, solar array substrate, and BIP.

The solar simulator flux from the xenon arc lamps was lowered from 1300 W/m^2 to 618 W/m^2 for this case to simulate the nominal off-sun attitude.

The quartz lamps were turned on to supply 1900 W to the backshell and 145 W/m^2 to the HRS radiators. The quartz lamp performance was generally good. The overall backshell heat load was approximately the same for test and flight. The spatial distribution along the backshell height differed somewhat from that expected in flight due to the inability to replicate a collimated solar source.

Cruise hardware that was not thermostatically controlled had even larger margins than the previous case except for the CEM. The CEM temperature remained the same. The off-sun illumination was offset by the solar panel temperature decrease from the reduced solar simulator flux. The PDM temperature decreased from 57°C to 32°C (19°C margin) in response to the average solar panel temperature decrease from 88°C to 39°C.

Aeroshell margins shrank by 2°C to 11°C for this case, but still remained well above 20°C. Lander and lander-attached hardware temperatures typically increased 7°C to 15°C for this case. The backshell illumination had little effect on the rover hardware temperature (typically < 2°C).

The infrared camera was used during this test to evaluate spatial gradients. Although this camera was fixed, it still afforded a good bird's-eye view of the top of the test article. The infrared camera spatial gradient information is shown in Figure 2. Dark areas are blanketed cable bundles and bare aluminum supports for cable bundles or calorimeters.

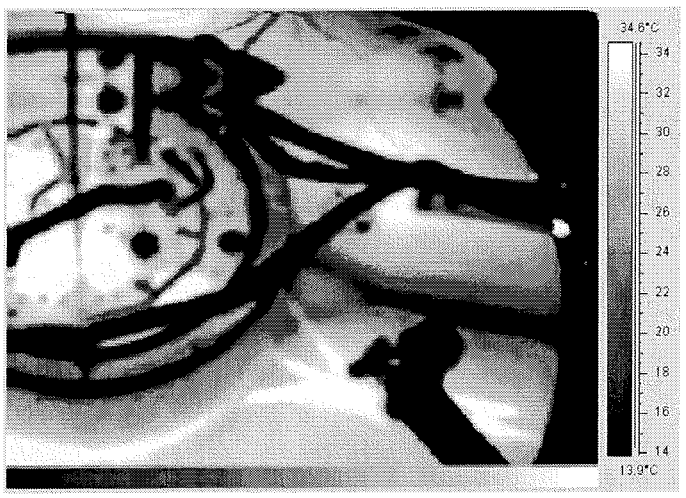

Figure 2. Infrared Camera View of MER 1 Solar Panel, Near Earth at Nominal Attitude Simulation (Case10).

SURFACE PHASE TESTING

This test was designed to allow an understanding of the Rover thermal and functional performance in a Mars surface environment. There were only two major pieces of assembled flight hardware in the test: the flight MER Rover 2 and the flight Lander Basepetal. All testing was be done in the chamber with an 8 Torr GN_2 atmosphere. The test covered only the surface environment, not the cruise or EDL environments. Thermal functional tests were performed to checkout heaters, thermostats and flight temperature sensors (PRT's). Cold and hot thermal balance tests, along with cold and hot diurnal tests were performed. In general, results from these tests were not meant to provide a direct empirical validation of the rover thermal design. The Mars surface thermal environment is much to complex to be directly simulated in a thermal chamber. Instead, data from these tests was used to correlate an analytical thermal model of the rover. The correlated analytical thermal model was then used to predict flight rover performance in the more complicated Mars environment. The correlated thermal model was also used for flight temperature predicts during surface operations.

In addition to thermal functional tests, there were general functional tests of rover hardware performed during the Rover 2 STT. These functional test included: 1) a rover standup and deploy verification, 2) functional testing of the cameras at four temperature levels 3) calibration tests of the cameras and Mini-TES and 4) functional testing of the Instrument Positioning System (IPS). The surface phase system thermal test consisted of eleven thermal test cases shown in Table 2 in addition to pump down and return to ambient cases. The most essential thermal tests included two steady state worst-case thermal balance cases, and two transient diurnal cycle test cases.

In general the primary test objectives were to:

- Improve the understanding of the flight Rover surface thermal design performance and empirically validate it when feasible.
- Reduce thermal design uncertainty.
- Gather sufficient data to enable mitigation of potential thermal design deficiencies.
- Identify problems to permit implementation of an acceptable repair on the flight hardware.
- Gather sufficient data to assist in analytical model correlation specifically to:
  - Align resistance and thermal capacitance values from steady state and transient test data, respectively.
  - Extrapolate a correlated analytical model to flight environment to validate Rover thermal design

Other specific test objectives included:

- Evaluate the WEB aerogel thermal performance.
- Verify that the thermal switches opened and closed at the proper temperatures.

- Verify that the survival heaters and warm up heaters were properly sized.
- Verify that the number of RHUs was sufficient.
- Verify that the rover can provide 3 hours of DTE communications in the worst-case hot environment without exceeding AFT limits on the SSPA.
- Verify that the Rover battery spatial temperature gradients were less than 5°C.

Table 2. Test matrix for Surface Phase

Test Case		Objectives
1	Pump-down and Accelerated Cooling	Draw vacuum, backfill to 400 Torr to accelerate cooling, pump-down to high vacuum.
Cold Cases		
2	Accelerated Cool down	Verify battery survival heater and thermostat circuit functionality
3	Functional Test of Rover Stand up and Deployments	Verify all rover deployments work in the cold steady state condition
4	REM and MiniTES Survival Heating	Verify survival heater and thermostat circuit for the REM and Mini-TES
5	Cold Thermal Balance Test	Gather steady-state data for thermal model correlation of conductors
6	Cold Case Diurnal Cycle Test	Gather transient data for thermal model correlation of capacitance values and survival heater duty cycles
7	Functional Test at -95°C	Verify Rover functionality at surface cold conditions with warm up heaters operating
8	Functional Test at -30°C	Verify Rover functionality at surface cold conditions without warm up heaters.
Hot Cases		
9	Hot case thermal balance	Gather steady state data for thermal model correlation
10	Functional Test at 0°C	Verify Rover functionality at surface hot conditions
11	Hot Case Diurnal Cycle Test	Gather transient data for thermal model correlation
12	Functional test of Mini-TES at 30°C	Perform radiometric calibration of MTES
13	Backfill and open chamber	Prepare Rover for removal from test chamber
☐ Cases NOT repeated for 2nd Rover		

TEST ARTICLE CONFIGURATION

The test article (see Figures 3 and 4) consisted of the complete flight rover including functional mobility and the flight Lander Base-Petal Assembly. The Base-Petal was supported off the floor heat exchanger by a number of aluminum struts with G10 stand-offs. The rover was initially tied down to the Lander base petal in a stowed configuration. During the test, the rover performed a "stand up" from the Base Petal. Other deployments included the solar arrays, Pancam Mast Assembly (PMA), High Gain Antenna Gimbal (HGAG), and the Instrument Deployment Device (IDD). The three remaining Lander side petals were not included in this test due to volumetric constraints in the 10ft space simulator. The removal of these petals did not significantly impact the thermal aspects of the test. The majority of Rover hardware was either flight hardware or flight like engineering model units.

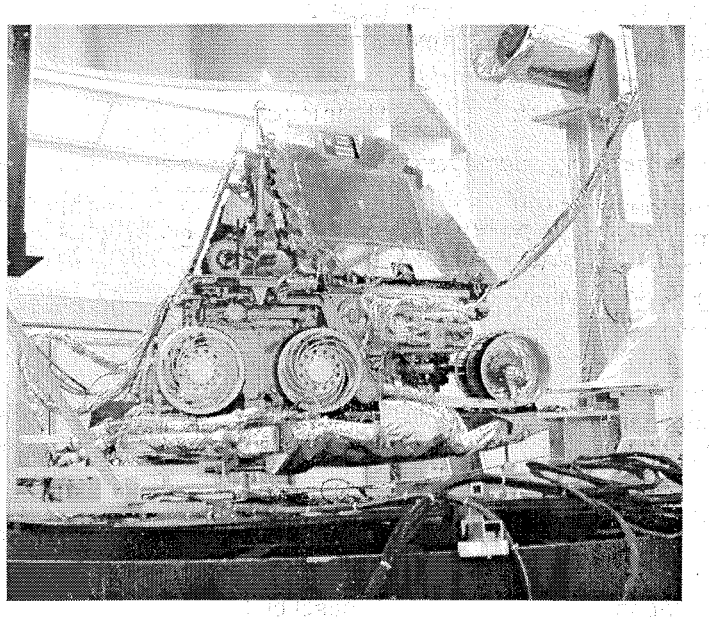

Figure 3. Rover in Stowed Configuration Prior to System Thermal Test.

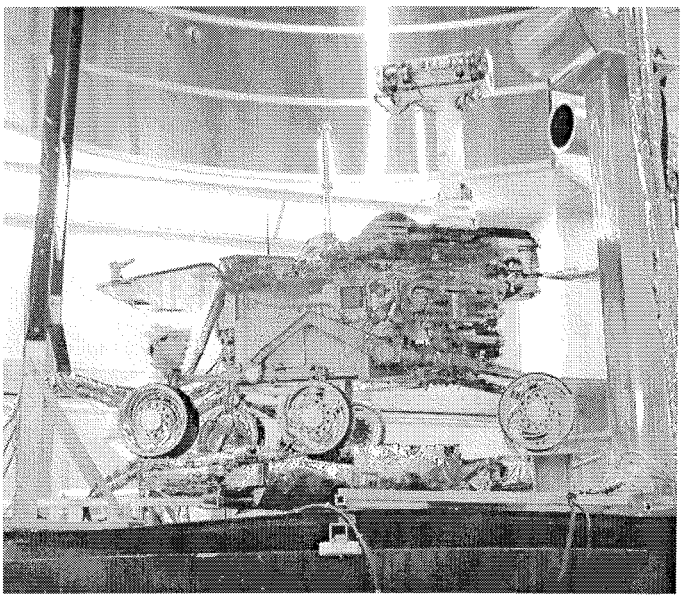

Figure 4. Rover in Deployed Configuration After the System Thermal Test.

SUMMARY OF TEST RESULTS

Case 5 Cold Thermal Balance Test

During Test Case 5, the test chamber shrouds and floor heat exchanger were held at a constant –95°C. During the second half of the test, the Rover was powered down, and the only power dissipations inside the Rover were supplied by test heaters. The thermal model temperature predictions and the actual test temperatures for the internal Web hardware, namely the REM, Mini-TES, and the battery were within ±2°C of each other. The predicted power dissipations needed to obtain the predicted temperatures and the actual test heater dissipations for those components agreed within only 1 Watt. A comparison between the predicted WEB internal/external temperatures and the actual test temperatures agreed within +20° to –9°C. The largest discrepancy existed for the Mini-TES porch internal WEB temperatures. Heat transfer from the Mini-TES to the internal WEB walls appeared to be less than predicted. It was believed that this was a result of the IDD being present on the hardware but not in the thermal model. The IDD increases the radiative and convective area from Mini-TES surface thus bringing that surface closer in temperature with the environmental boundaries. When the thermal models of the external hardware were integrated into the system level thermal model, this discrepancy was eliminated.

Case 9 Hot Thermal Balance Test

During Test Case 9 the chamber shrouds were held at a constant 0°C and the floor heat exchanger was held at a constant 20°C. The thermal model temperatures predictions and the actual test temperatures for the internal Web hardware, namely the REM, Mini-TES, and the battery were within ±1°C of each other. The predicted power dissipation needed to obtain the predicted temperatures and the actual test heater dissipations for those components agreed within only 1 Watt as in the cold case. A comparison between the predicted WEB internal/external temperatures and the actual test temperatures agreed within +11° to –4°C. Similar to the Cold Thermal Balance Test, the internal WEB walls of the Mini-TES porch seem to be running colder than predicted. This discrepancy was fixed in the thermal model.

Case 6 Cold Diurnal Test

In general, transient predictions for the internal Rover components correlated very well with the test results (within 5°C). Making a direct comparison was somewhat challenging given the operational nature of the Rover. Sometimes, items were turned on or off slightly before or after they were predicted to. There was also uncertainty in the thermal dissipation magnitude of some of the flight hardware. Thermal dissipations were operationally and temperature dependant. Figure 5 shows the internal Rover hardware Cold Case Diurnal temperature predictions as well as the test data. The only clear discrepancy occurs during the battery warm-up at the beginning of the test. This discrepancy was due to the operational use of the warm-up heater during the test. The time at which this heater was turned on was before it was predicted to be turned on.

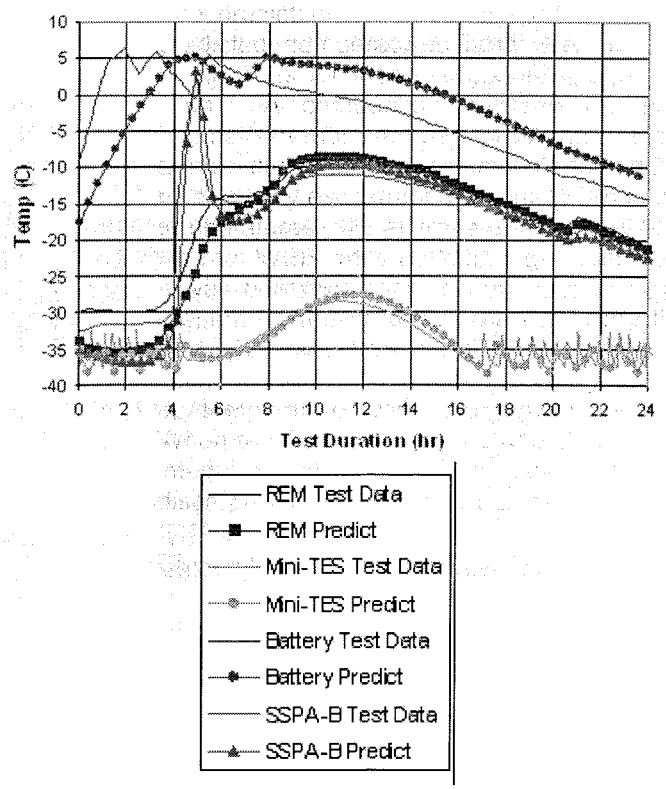

Figure 5. Internal Rover Hardware Cold Case Diurnal Temperature Predictions Compared to Test Data.

Case 11 Hot Diurnal Test

The internal Rover hardware Hot Case Diurnal temperature predictions as well as the test data are compared in Figure 6. The only discrepancy was with the Mini-TES. It was believed that the magnitude of the heat transfer modeled between the Mini-TES and the internal WEB walls of the Mini-TES porch is too large as explained above in Case 5. This discrepancy was fixed in the model although the predictions did not differ from test data significantly (8°C).

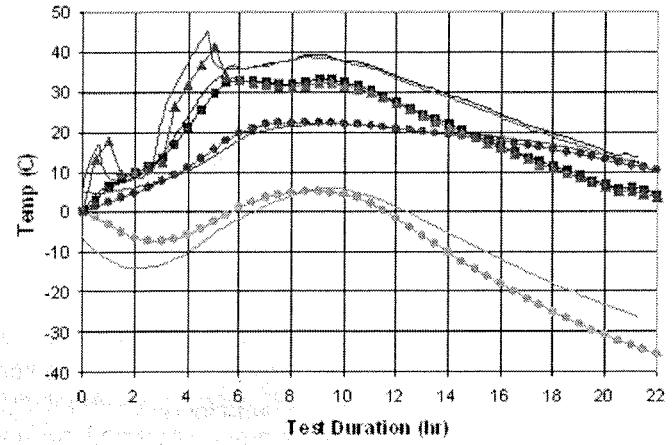

Figure 6. Internal Rover Hardware Hot Case Diurnal Temperature Predictions Compared to Test Data; legend from Figure 5 applies.

Assessment of Specific Objectives

WEB Aerogel Performance:

The steady state temperatures of the internal/external WEB were compared to the thermal model WEB wall temperatures predictions. The temperatures agreed within +5° to –2°C. No major changes to the WEB wall thermal conductivity values were deemed necessary for the thermal model.

Thermal Switch Performance:

The Rover Battery wax actuated thermal switches were tested during Test Case 11 (Hot Diurnal Test). The switches performed as expected. Both switches closed at approximately 19°C. The maximum Battery temperature during the Hot Diurnal test reached 22°C (30°C is max AFT). The battery switches remained closed for approximately 10hr 45min during the warmest part of the Diurnal profile. Both switches opened again at approximately 18°C.

Survival and Warm up heater performance:

Test Case 5 (Cold Thermal Balance Test) offered a chance to empirically validate that the survival heater sizing for the three thermal zones inside the rover (REM, Mini-TES and Rover Battery) was sufficient. By holding the Rover external WEB temperature at a constant worst case cold temperature and heating the inside of the Rover with test heaters to maintain minimum AFT temperatures, survival heater performance margin was measured. The most margin existed for the Mini-TES survival heater circuit. While there was little margin for the Rover Battery and REM, these survival heaters were not expected to operate while the Rover is on Mars given the transient nature of the boundary conditions on Mars.

Sufficient RHU Capacity:

Six RHUs on the Rover Battery and 2 RHUs on the REM were found to be sufficient for acceptable thermal/power system performance. During the Test Case 6 (Cold Diurnal Test), 6 Battery RHUs (representing a thermal dissipation of approximately 6W) and 2 REM RHUs (representing a thermal dissipation of approximately 2W) were sufficient to prevent both the Rover Battery and REM survival heaters from coming on. The Battery reached a minimum of –16°C and the REM reached a minimum temperature of –33°C during the Cold Diurnal Test. Furthermore, two RHUs on the REM did not impede SSPA DTE performance significantly in Test Case 11 (Hot Diurnal Test).

Sufficient Time for DTE Communications:

Both Solid State Power Amplifiers (SSPA) performed as predicted during the test. The most relevant thermal characterization data was obtained during the Hot and Cold Diurnal tests. These tests simulated as closely as possible a low and high power flight scenario for the Rover during simulated worst-case hot and cold environmental boundary temperatures. Inability to exactly reproduce the Mars environment (solar heating, wind, CO_2, gravity) inside the test chamber makes a direct validation of SSPA performance during the test impossible. An extrapolated thermal model was used for a more refined prediction of SSPA performance while on the surface of Mars.

The SSPA-A (primary SSPA) was operated in a beginning of mission "flight-like" power scenario during Test case 11 (Hot Diurnal Test). During the Hot Diurnal test the rover executed high power scenario with 3 hours of total Direct-to-Earth (DTE) communication. This profile consisted of a 1hr DTE session beginning at 8am Local Mars Solar Time (LMST) followed by 2 hours of non-operation, and then a further 2 hours of DTE communication ending at 1pm LMST. During the test, the SSPA-A was operated for a total of 2hr 48min. The SSPA-A bracket interface temperature reached a maximum of 40.1°C (SSPA-A chassis was at 45.1°C). It was clear that 3 hours of diurnal communication is possible with about 6°C of margin on the SSPA-A bracket interface temperature.

Battery Temperature Gradients:

The largest battery cell-to-cell temperature gradients were observed during the Test Case 11 (Hot Diurnal Test). The battery cell to cell temperature gradient should not exceed 5°C. Worst-case gradients can be expected during the Hot Diurnal test since this is the only test in which the battery wax actuated heat switch reached a temperature high enough to actuate (dump battery heat to external battery radiator). The largest cell-to-cell temperature gradient for this test was 3.8°C, below the 5°C requirement. The time of this gradient

corresponds to when one paraffin actuated switch actuates slightly before the other thermal switch.

CONCLUSIONS

The MER 1 Cruise System Thermal Test was highly successful. Nearly all of test goals were accomplished. The MER thermal design was empirically validated, and nearly all thermal hardware was functionally verified. All residual hardware was thermally verified in subsequent rover system thermal tests.

This test uncovered several workmanship errors concerning thermostatically controlled heater circuits. Most problems were corrected prior to shipment to Kennedy Space Center, and the balance had no major flight operations implications. This test also detected some unexpected problems with the propellant thermal control although new set points eliminated the problem.

The HRS provided a robust thermal design during cruise. Most MER hardware had large thermal margins > 20°C during cruise, all AFT requirements were satisfied and no thermal problems were detected during the EDL simulation.

Only a single thermal design deficiency was identified during the entire system test. The PDM thermal design produced a 2°C FA limit violation at the simulated S/C fault attitude near Earth. This violation was eliminated with a post-test MLI blanket modification that was subsequently proven flight worthy in the MER-2 system thermal test.

The Rover-2 STT test was highly successful. Thermal data agreed very well with other rover development test data. No major modifications to the thermal design was needed to ensure mission success.

ACKNOWLEDGMENTS

This work was carried out for the 2003 Mars Exploration Rover Project at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

REFERENCES

1. Novak, K., Phillips, C., Birur, G., Sunada, E., Pauken, M., "Development of a Thermal control Architecture for Mars Exploration Rovers", STAIF-03, Albuquerque, NM, Feb 2003.
2. Ganapathi, G, Birur, G., Tsuyuki, G., McGrath, P., Patzold, J. "Active Heat Rejection System on Mars Exploration Rover – Design Changes from Mars Pathfinder", STAIF-03, Albuquerque, NM, Feb 2003.
3. Sunada, E., Pauken, M., Novak, K., Phillips, C., Birur, G., and Lankford, K., "Design and Flight Qualification of a Paraffin-Actuated Heat Switch for Mars Surface Applications, 32nd Int. Conf. On Environmental Systems, Paper no. 2002-01-2275 Proceedings San Antonio TX, July 15-18, 2002.
4. Pauken, M., Sunada, E., Novak, K., Phillips, C., Birur, G., and Lankford, K., "Development Testing of a Paraffin-Actuated Heat Switch for Mars Rover Applications", 32nd Int. Conf. On Environmental Systems, Paper no. 2002-01-2273 Proceedings San Antonio TX, July 15-18, 2002.

CONTACT

Dr. Michael Pauken
Jet Propulsion Laboratory
M/S 125-109
4800 Oak Grove Blvd
Pasadena, CA 91109
Phone: (818) 354-4242
E-mail: Michael.T.Pauken@jpl.nasa.gov