Mars Exploration Rover Surface Mission Flight Thermal Performance

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ABSTRACT

NASA launched two rovers in June and July of 2003 as a part of the Mars Exploration Rover (MER) project. MER-A (Spirit) landed on Mars in Gusev Crater at 15 degrees South latitude and 175 degree East longitude on January 4, 2004 (Squyres, et al., Dec. 2004)). MER-B (Opportunity) landed on Mars in Terra Meridiani at 2 degrees South latitude and 354 degrees East longitude on January 25, 2004 (Squyres, et al., August 2004) Both rovers have well exceeded their design lifetime (90 Sols) by more than a factor of 4. Spirit and Opportunity are still healthy and continue to execute their roving science missions at the time of this writing. This paper discusses rover flight thermal performance during the surface missions of both vehicles, covering roughly the time from the MER-A landing in late Southern Summer (Ls = 328, Sol 1A) through the Southern Winter solstice (Ls = 90, Sol 255A) to nearly Southern Vernal equinox (Ls = 160 , Sol 398A).

This paper describes the MER rover thermal design, its implementation and performance on Mars. The rover surface thermal design performance was better than pre-landing predictions. The very successful thermal design allowed a high level of communications immediately after landing without overheating and required a minimal amount of survival heating in the dead of winter.

An analytical thermal model developed for the rover was used to predict surface operations performance. A reduced-node version of this model was integrated into the mission planning tool to achieve the proper balance between: 1) desired science and communications operating profile, 2) available energy from the power system and 3) temperature limits prescribed for the hardware. One of the more challenging thermal problems during surface operations, predicting the performance of actuator and camera electronics warmup heaters, was automated by using heater lookup tables that were periodically updated based on flight telemetry.

Specific MER rover thermal flight experiences are discussed in this paper. Lessons learned and suggestions for improvement of future Mars surface vehicle designs are presented.

INTRODUCTION

The MER mission has been a resounding success, proving the versatility and robustness of a mobile science platform in planet surface exploration. A robust thermal design for the MER rovers has contributed significantly to their longevity and science productivity. The thermal design has successfully maintained hardware temperatures inside of allowable flight limits, minimized the depths of temperature cycles and minimized the energy load on the system from survival and warmup heaters.

DESCRIPTION OF THE MER ROVER

Figure 1 shows the rover in its fully deployed, surface operations configuration ready for Mars exploration. On top of the Rover Equipment Deck (RED), the Pancam Mast Assembly (PMA) supports 2 stereo pairs of cameras: one pair for navigation (the Navcams) and a second pair for panoramic science imaging (the Pancams). Actuators at the base of the mast control the mast deployment and the mast azimuth. One actuator at the top of the mast controls the camera bar elevation. Another actuator inside the mast controls a mirror that reflects IR energy from the Martian scene down the mast into another imaging science instrument, the Miniature Thermal Emission Spectrometer (Mini-TES). Mini-TES is housed inside the Warm Electronics Box (WEB), an insulated structure designed to keep temperature sensitive electronics from freezing in the Martian night. Three communications antennas are mounted to the top of the RED: the omnidirectional X-band Low Gain Antenna (LGA), the directional, 2-axis tracking, X-band High Gain Antenna (HGA) and the UHF Dipole antenna. The X-band antennas allow Direct-to-Earth communication while the UHF antenna is used to

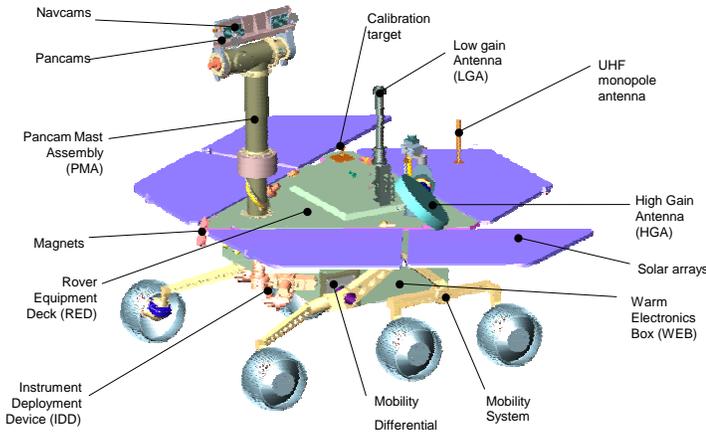communicate with Mars orbiting spacecraft. Solar cells on the RED and five deployable

Figure 1: MER Rover in Deployed Configuration Ready for Surface Operations

solar panels provide a daytime energy source. Energy is stored for nighttime and peak usage in a secondary battery located inside the WEB. The 6-wheel mobility system employs a rocker/bogie suspension and a differential. All 6 wheels have a drive motor, but only the front and rear wheel pairs have steer motors. The Instrument Deploy Device (IDD), a 5 degree-of-freedom robotic arm, is mounted under the solar panel on the front of the rover. The IDD has 4 science instruments located on a turret at the end of the arm. Two additional stereo camera pairs, the Hazcams (used for hazard avoidance), are mounted on the outside of the WEB on the front and back walls of the rover.

Figure 2 shows all the electronics that are mounted inside the WEB. The flight computer and much of the science, power and motor control electronics are housed on electronics boards inside the Rover Electronics Module (REM). Two X-Band telecommunications boxes, the Small Deep Space Transponder (SDST) and the Solid State Power Amplifier (SSPA) are mounted on the forward wall of the REM. An Inertial Measurement Unit (IMU) and the UHF radio are mounted on the rear wall of the REM. A rechargeable lithium ion battery is mounted to the bottom of the WEB, under the UHF radio and IMU.
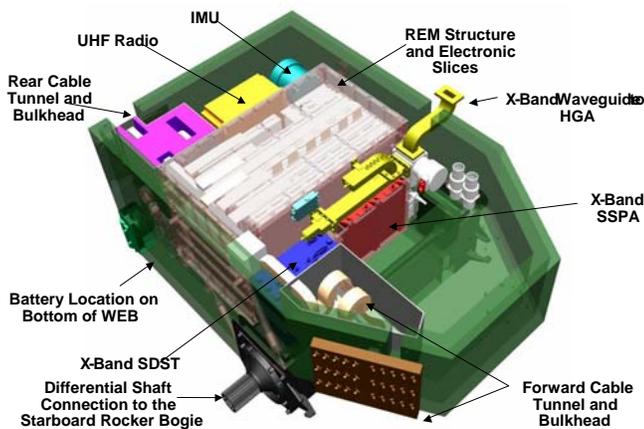

Figure 2: Rover Warm Electronics Box (WEB)

Cabling that passes from the inside of the WEB to external equipment is thermally insulated inside the forward and rear cable tunnels. External cable bulkheads are mounted on the outside walls of the rover.

THERMAL DESIGN DESCRIPTION

The MER rover thermal design architecture (Novak, 2003) was driven by: 1) the Mars surface thermal environment, 2) hardware temperature limits, 3) electrical energy use limitations imposed by the power subsystem and 4) high and low energy operational scenarios devised by the mission planners.

THERMAL DESIGN DRIVERS

The Mars surface thermal environment defines the ultimate thermal sink for the rover. The Mars General Circulation Model (GCM) was run with the appropriate input parameters to determine the worst-case hot and cold surface thermal environments for the MER rover (Haberle, et al., 1999). Figure 3 shows a typical curve for the predicted atmosphere, ground and sky temperatures on the worst-case hot day for the MER mission (Sol 1A). Figure 4 shows a typical curve for the predicted daytime solar insolation (total, diffuse and direct normal) on the worst-case hot design day.
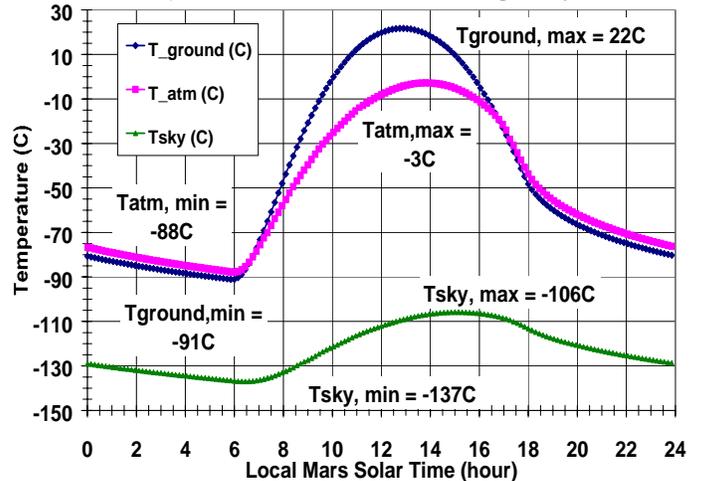

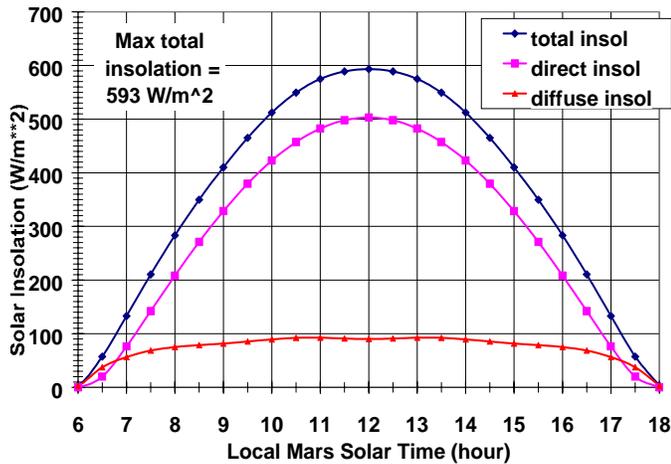**Figure 3 : MER Surface Hot Environment Temperatures.**

Figure 4 : MER Surface Hot Environment Solar Insolation

Excluding dust storm data, wind speeds recorded from the Viking 1 and Viking 2 landers reached levels as high as 10 to 20 m/sec (Kaplan, 1988). The MER rover was designed to survive a surface thermal environment in which the wind speed could vary anywhere in the range between 0 m/sec to 20 m/sec at any time of day or night. The surface wind speed determines the heat transfer coefficient on external surfaces of the rover. In the hot design case, a 0 m/sec wind speed was assumed (free convection on external surfaces) and in the cold design case a 20 m/sec wind speed was assumed (forced convection on external surfaces).

Hardware temperature limits play a major role in determining the appropriate rover thermal control design. Items that are highly sensitive to extreme cold Mars nighttime temperatures and to wide temperature swings (thermal cycling) must be shielded from the external Mars environment. These items on the MER rover were placed inside the insulated WEB (see Figure 2). The lithium ion rechargeable battery had the tightest temperature limits of any item on the entire rover (-20°C to +30°C). The remaining flight system electronics (REM and telecommunications hardware) had Allowable Flight Temperature (AFT) limits of –40°C to +50°C. The Mini-TES science instrument, located inside the WEB but mounted to the underside of the RED, had AFT limits of –40°C to +45°C.

Hardware items that were not highly temperature sensitive were mounted to the outside of the rover. Many of these items (including the solar arrays, visible cameras, telecommunications antennas, robotic arm and mobility system) are shown in Figure 1. All external rover hardware was designed to withstand Mars nighttime cold temperatures without needing survival heaters or thermal insulation. The non-operating AFT limits for external rover hardware were in the range of –105°C to +50°C. Minimum operational AFT limits for the camera electronics and for actuators were set at –55°C. Warmup heaters were installed on all camera electronics and actuators on the rover to allow nighttime and early

morning operations when there was enough energy available to do so. .

The MER rover power system consists of a deployable solar array (with solar cells mounted on the RED deck, 3 primary and 2 secondary panels), two, 8 A-hr Li-ion rechargeable batteries and the necessary power conditioning and distribution hardware. The solar array covers an area of approximately 1.3 m^2 with triple-junction GaInP/GaAs/Ge cells capable of producing more than 700 W*hrs of energy per Sol. Daytime energy is used as needed to run science, mobility and communications hardware. Excess electrical energy is either stored in the Li-ion batteries or rejected to the environment through a shunt radiator resistor located on the bottom of one of the solar panels. Mission designers allocated a maximum of 120 W*hrs of nighttime heater energy (taken directly out of the battery) to use for survival heat inside the WEB. Because of the limited battery capacity, minimizing electrical heater energy usage at night was a high priority for the thermal design.

Rover operational scenarios were defined by mission planners and translated into hot and cold case design power profiles. A worst-case hot design profile (maximum energy dissipated inside the WEB) corresponded to a day in which the rover spends 4 hours in a direct-to-Earth communications mode. The total internal energy dissipation inside the rover on the worst-case hot day was 716 W*hrs. A worst-case cold design profile (minimum energy dissipated inside the WEB) corresponded to a day in which the rover would minimize its operations in an effort to recharge the battery. The total internal dissipation inside the rover on the worst-case cold day was 470 W*hrs.

WEB INTERNAL THERMAL DESIGN

Since the items inside the WEB had to survive thermal transients driven by internal power dissipation and the external environment, a primary focus of the internal WEB thermal design was to maximize its thermal time constant. The thermal time constant of a system is the product of its thermal resistance and thermal capacitance. Coupling as much thermal mass together as possible and maximizing the thermal resistance to the environment resulted in a large thermal time constant for items in the WEB.

As shown in Figure 2, the largest concentration of thermal mass inside the WEB (approximately 36 kg) was the coupling of all telecom hardware (the UHF radio, the SDST and the SSPA) with the attitude control hardware (IMU) to the main electronics housing (REM). Coupling together these hardware items tended to minimize temperature drops during cool-downs and minimize temperature rises during warm-ups. It also allowed power sharing between boxes, thus reducing the number of required survival heaters and thermostats. The battery mass (approximately 9 kg) was mounted to the floor of the WEB on its own support struts since its temperature limits were significantly tighter than those

for the REM. The Mini-TES (2.2 kg) was mounted to the bottom of the RED to allow proper alignment to be made between the IR instrument and the external Pancam mast that it looked through.

A considerable amount of effort was expended to maximize the thermal resistance of (i.e., minimize the heat leaks from) the WEB. The WEB structure was an "exoskeleton" design consisting of a stiff external box structure (made of aluminum honeycomb and carbon composite facesheets) lined on the inside with bricks of carbon-opacified silica aerogel insulation. The opacified aerogel has an extremely low density (0.02 g/cc) and a very low thermal conductivity (k = 0.012 W/m*K in 10 torr CO_2 at $0°C$). Carbon opacification was added to the aerogel in an effort to block the infrared thermal transmission through the material. To minimize radiative thermal losses, low emissivity surface finishes were applied to all of the internal boxes and to both the internal and external surfaces of the WEB structure.

Thermal losses through the aerogel-lined walls of the WEB made up approximately 50% of the steady-state heat leak to the external environment. Thermal losses through the flex cables running through insulated cable tunnels accounted for about 15% of the total heat leak from the WEB. Thermal losses through tele-communications coax cables (also run through insulated cable tunnels) represented about 10% of the total heat loss from the WEB.

The battery had two paraffin actuated thermal switches (Novak, et al., 2002; Lankford, 2002) that prevented the battery from overheating in the middle of the day. When the paraffin heated up to its melt point ($18°C$), the switches closed and heat was rejected from the battery to a pair of radiators on the outside of the rover. When the switches were below the paraffin melt point, they remained open with a gap between the hot and cold sides of the switches. The 1.3 mm gap was maximized to limit the amount of heat leak that could occur through the switches when they were in the open position. Gas conduction in the 10 torr CO_2 atmosphere of Mars was the mechanism for the switch heat leak. The thermal switch heat leak was approximately 10% of the total heat leak from the WEB.

The Heat Rejection System (HRS) pumped loop cooling system (used only during cruise) required metal tubing to circulate cold fluid from the radiators on the spacecraft cruise stage into the warm electronics housed inside the rover. In an effort to minimize heat leaks, the length of tubing that crossed through the insulated WEB was made of low thermal conductivity stainless steel. The heat leak through the HRS tubing was approximately 5% of the total heat leak from the WEB.

All three major mass items in the WEB (the REM with attached hardware, the battery and the Mini-TES) were supported on thin-walled, low-conductance tubular struts with Ti fittings to the external WEB and RED structure. Thermal losses through the support struts accounted for

approximately 5% of the entire heat leak to the external environment.

The Mini-TES instrument looked up the Pancam mast through two mirrors and out directly to the Martian scene. The Mini-TES instrument radiated and convected heat from its telescope up the cold Pancam mast at night. The Mini-TES heat leak was approximately 5% of the total heat leak from the WEB.

All hardware inside the WEB (the REM and attached hardware, the battery and the Mini-TES science instrument) was protected against an under-temperature condition by survival heaters that were switched on via mechanical thermostats. The flight computer was used to monitor the hardware for over-temperature conditions that were only likely during times when the flight computer was operating. Over-temperature fault responses turned the power off to the item that was in danger of overheating.

Since the nighttime electrical energy supply was limited by the size of the battery, non-electrical heat sources were used to help keep the REM and battery warm at night. Two radioisotope heater units (RHUs) were mounted to the REM and 6 RHUs were mounted on the top of the battery. The RHUs dissipated approximately 1.0W apiece. Six RHUs on the battery were enough to keep the battery warm at night, but would have overheated the battery during the day (depending on how much internal heat was dissipated inside the WEB from other sources). For this reason, paraffin actuated thermal switches were added to the battery to allow excess thermal energy from the RHUs to be shunted out of the WEB during the day. The Starsys Research Corporation developed these switches for the Jet Propulsion Laboratory.

ROVER EXTERNAL THERMAL DESIGN

The principal hardware items located outside the WEB that needed thermal control were the cameras and the mechanisms (actuators and bearings). In general all of the rover external hardware can survive in a non-operating condition during the Martian night without any survival heat and with no thermal insulation. All external rover hardware had non-operating minimum AFT limits of $−105°C$. Upper temperature limits vary and were based on the capability of the hardware during daytime operations.

There are 9 cameras on the rover, each having a charge-coupled device (CCD) housing and a camera electronics box. The camera electronics and CCD housings are covered in second-surface, silvered Teflon tape to prevent them from overheating in the sun. The CCD housings are hard mounted directly to their interfaces, but the camera electronics housings are thermally isolated on Ti standoffs from their mounting interfaces. The camera electronics boards must be heated up with commandable warmup heaters to –55°C within one hour prior to early morning operation.

There are 34 actuators (gear/motors) on the flight rover. All actuators have a minimum operating AFT of –55°C. Since many of the actuators are used in the early morning (before the ambient atmosphere temperature reaches –55°C), all actuators were equipped with warmup heaters. Warmup heaters were sized to bring the actuators up to operating temperatures within one hour after heater activation. Warmup heaters were designed such that if they were left on continuously, they would not heat the actuators over their maximum qualification non-operating temperature limit of 110°C. Actuator heater circuits that were in danger of overheating hardware were run through a thermostat box that opened those circuits (turning off the heater) when the atmosphere temperature went above approximately –30°C.

There are 4 actuators on the PMA mast: the mast deploy drive, the azimuth drive, the Mini-TES elevation drive and the camera bar elevation drive. All of the PMA actuators have Kapton film heaters on the motors and gearheads. The PMA also has heaters on critical bearings inside the mast: the azimuth bearing, and the camera drive follower bearings. The Pancam camera CCD housings, mounted to the top of the camera bar, have 2 more actuators (one for each CCD housing) on the filter wheel mechanisms. The filter wheel motors are equipped with warmup heaters. The HGA has 2 actuators, one for the azimuth and one for the elevation. Desire for early morning (7:30 AM LST) communications drove the need for actuator and bearing warmup heaters inside the HGA. The mobility subsystem contains 2 rocker deploy mechanisms, 6 drive actuators and 4 steer actuators. The IDD is a five degree-of-freedom robotic arm mounted on the front of the rover. Actuators controlling the azimuth, elevation, elbow, wrist and turret joints enable each degree of freedom. Four science instruments are attached to the end of the arm on a turret actuator: the Alfa Proton X-Ray Spectrometer (APXS), the Moessbauer Spectrometer, the Microscopic Imager (MI), and the Rock Abrasion Tool (RAT). The RAT, a tool for grinding away the top layer of a rock for inspection by the spectrometers, has 3 motors inside its housing. The microimager has an actuated dust cover to protect the camera from dust and debris generated by the RAT. This is the only motor on the entire rover that does not have a heater. Operations of the dust cover are restricted to daytime hours when the atmosphere temperature is above -55°C. The remaining 5 actuators are located on the deployable solar array panels. There are 3 primary and 2 secondary solar array panels on the rover. During cruise, the panels were stowed to fit inside the tetrahedral lander. After landing, the launch restraints on the panels were cut and the panels were deployed.

In general, power dissipations and duty cycles are so low inside the actuator motors that the motors are in no danger of overheating during normal operations. Onboard fault-protection software will detect a motor stall or overcurrent condition and immediately shut down the motor. In addition, an onboard thermal model predicts real-time motor rotor temperatures and shuts down an actuator when its predicted rotor temperature exceeds 105°C.

ROVER ANALYTICAL THERMAL MODEL

The rover analytical thermal model that was carried into the mission operations campaign was a simplified (375-node) version of the more complex (2000-node) model that had been used in the latter stages of the rover development. The mission operations model was correlated to data obtained in thermal vacuum testing of the flight vehicles (Pauken, et al., 2004).

The system-level thermal model was built using TAS (Thermal Analysis System). Radiation conductors and diurnal heat rates were calculated using TSS (Thermal Synthesizer System). Model translations between these two software packages were accomplished using a 3rd party FORTRAN program developed by J. Abott (Composite Optics). The system-level thermal model is solved using SINDA/FLUINT. Figure 5 is a view of the TSS model of the rover.
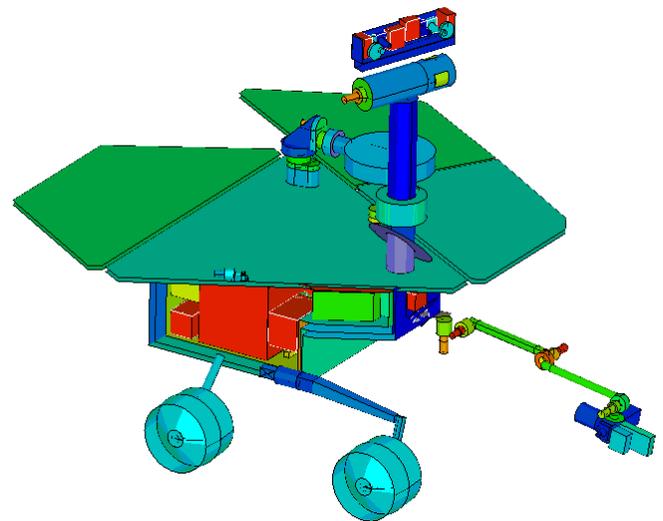

Figure 5: TSS Model of MER Rover

After thermal vacuum testing of the rovers, a system-level thermal model correlation effort was undertaken. Two steady state test cases (worst case cold/hot) were used to characterize the magnitude of all of the thermal links in the model. Transient diurnal test cases were used to correlate internal rover heating due to electronics operation as well as external actuator temperature rises due to the use of warm-up heaters. The goal of the correlation was to be able to predict all rover temperatures to within 5C. After model correlations activities were completed, the model was extrapolated to a true Mars environment, substituting 10Torr CO_2 (Mars environment) for 10Torr N_2 (test environment).

The flight analytical thermal model consists of approximately 375 nodes and 18300 conductors (800 linear, 17500 radiation). A typical 1-Sol simulation takes

one minute to solve (20 second time step, five minute output interval). Solution speed was critical during flight operations since the model was called upon often to answer "what-if" scenarios in a timely manner. Ease of use was also very important given that thermal engineers not familiar with the model would be operating it every Sol under stressful work conditions. The model was broken down into separate modules using INCLUDE and INSERT statements. This ensured that the user only had to look at a front-end input deck where run parameters could be changed. Model revisions could be made to separate modules. An Excel spreadsheet was developed to aid in plotting standard telemetry queries on top of thermal model predicts (see Figures 6, 7 & 8). Plots from this Excel spreadsheet were included in downlink reports to aid rover planners and uplink leads since rover activity planning occurred when thermal subsystem engineers were not on station.

One of the critical functions of the flight rover thermal model was to predict how long external mechanisms would need to be heated prior to use. This duration is highly dependent on time of day. To aid the rover activity planners, a spreadsheet tool was developed containing heating tables for each mechanism. A front-end worksheet allowed the planner to enter the time of day (LST) for desired actuator use. The spreadsheet would then interpolate over a specific table to show the correct amount of heating required prior to operation or would signal the operator that heating was not possible at that time. These tables were updated every 20 sols to ensure the latest model correlation was being used. A variant of the flight thermal model is used to construct these tables. An AFT and dwell time above AFT was entered into this model and it would iteratively solve for the required heating duration at one-hour intervals. Another output of the heating tables was a column delimited file that the activity planning software APGEN (Activity Plan Generator) would use to signal the operator when heating was required. This file was uploaded by the thermal engineer into individual sol directories that the activity planning software would automatically access.

One hardware complication that the thermal model addressed was in the prediction of actuator temperatures at turn-on in the absence of motor temperature telemetry. The actuator current limiting software included an internal thermal model of the motor rotor whose electrical resistance was a function of temperature. In the event of a motor stall or an anomalous current draw the software would shut down the motor. If warm-up heating occurred before actuator movement, the predicted actuator temperature at turn-on was uploaded as part of the actuator movement sequence. When heating did not occur before actuator movement, the current limiter would query and interpolate over an onboard diurnal temperature profile table called a T-environment table (Tenv). This table consisted of eight temperature points vs. time of day (LST) and was different for each actuator. These tables

needed to be adjusted frequently and uploaded to each rover during the mission to ensure actuator health.

A simple 10-node thermal model of the rover internals was also programmed into the power analysis tool MMPAT (Multi-Mission Power Analysis Tool). This thermal model shared the same time step as the power model. This thermal model helped to manage the rover's energy budget by predicting how much energy was expended by thermostatically-controlled survival heaters. These heaters would often operate while the rover was in "sleep" mode. During this time, very little telemetry was recorded. Even when telemetry was being recorded, the power engineers had no knowledge into the on/off state of the mechanical thermostats other than temperature data. This simple thermal model was adjusted approximately every 20 Sols to ensure the energy predictions were in line with the actual temperature telemetry.

During the course of the mission, the flight system-level thermal model was re-correlated approximately every 20 Sols. Based on GCM predicts, the environmental atmospheric temperatures at the MER landing sites changed approximately 2.5C per every 20 Sols (up until Southern Winter Solstice). There was no meteorology science instrument on the MER rovers that could be used to determine actual atmosphere temperatures during the surface mission. Based on thermal vacuum test data, no rover temperature sensors were found to be very reliable indicators of atmosphere temperature. Diurnal solar heating also changed enough over the course of the mission to warrant re-correlation. The entire model was parameterized using registers in SINDA/FLUINT. Every boundary temperature, heat transfer coefficient, and environmental heat load was assigned a multiplying factor. Most factors were made to be time of day dependent. A correlation activity would typically look at the past 10 Sols. For conservatism, the model was always correlated to the minimum telemetry temperature over that 10 Sol range. As long as all model-predicted temperatures were from 0C to 5C below these minimum telemetry temperatures, the model was considered correlated. The internal WEB model never needed re-correlation. Only the external model entities (most influenced by the changing environment) required periodic re-correlation. Once the correlation was completed, the heater tables and Tenv tables would be updated. A new baseline model would be delivered to the thermal engineer on station. Model correlation typically took 1 day of effort. Table updates typically took 4 days of effort.

The system-level rover thermal model had a profound impact on rover operations. Activities such as DTE (Direct to Earth) communications and nighttime actuator warm-ups were often constrained depending on how much temperature margin was being held in the thermal model. At the beginning of the mission, 5C of margin was held in heating estimates and temperature predictions. While predictions were often better than

this, there were limitations in how well the thermal model could ensure the thermal safety of the hardware.

One major limitation of the flight thermal model was that it could not accurately predict external rover temperatures versus a specific rover orientation. All diurnal heat rates were calculated with the Rover facing due east. There would never be time on station to re-calculate diurnal heat rates depending on rover clock angle and tilt. Even if pre-calculated tables had been available, it would have been difficult to accurately model shadowing given the model's geometric fidelity. On several occasion, the HGA was in the shadow of the PMA at the time of articulation. When this happened, the HGA actuators would be 15C cooler than expected and the HGA actuators were in danger of stalling. Also, the mobility actuators were constantly in shadow. Care was taken to always correlate the thermal model's mobility actuators to shadowed conditions. The IDD robotic arm position (stowed or extended) also made it difficult to correlate the IDD temperatures accurately. Although the thermal model did allow for specifying whether the IDD was stowed or deployed, the IDD was always correlated in the stowed condition, which usually yielded the coldest temperatures.

The system-level Rover thermal model proved to be a valuable asset during operations. For future rover missions, it is recommended that the thermal models remain as simple as possible. Also, it is recommended that the thermal design be robust enough such that model predictions with 5C are sufficient for safe and reliable operations.

SURFACE OPERATIONS FLIGHT EXPERIENCE

MER-A touched down on Mars in Gusev Crater on January 4, 2004. The rover successfully egressed from the lander on Sol 12. Comparisons of temperature telemetry for external rover hardware before and after egress revealed an unexpected "lander effect." External rover hardware ran about 10C warmer than model predictions because the lander carbon composite structure retained heat and ran warmer than the Martian surface at night. A similar "lander effect" was observed in the MER-B temperature telemetry.

HOT CASE PERFORMANCE

The MER-A landing site, at the time of landing, was predicted to have the hottest ambient environment for the 90-Sol primary mission. In addition, high internal power dissipations inside the WEB at the beginning of the mission (driven by a desire to acquire a maximum amount of science and transmit it back to the Earth) served to push temperatures inside the WEB close to their maximum limits. On Sol 14A the total energy expended by the vehicle was 767 W*hrs. Figure 6 shows a diurnal temperature plot for the REM on Sol 14A. In Figures 6, 7, and 8, flight telemetry is shown as data points and model predictions are shown as curves. On a typical, hot early-mission day the REM

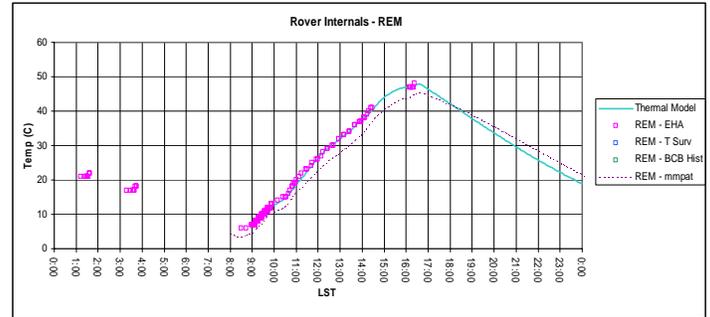experienced a diurnal temperature change of about 50C (from 0C to 50C).

Figure 6: REM Temperature on Sol 14A

Figure 7 shows a diurnal temperature plot for the rover secondary battery on Sol 14A. The battery temperature holds constant at 20C between the hours of 1400 and 1700 LST when the wax actuated switch closed and rejected excess battery heat to the external radiators.
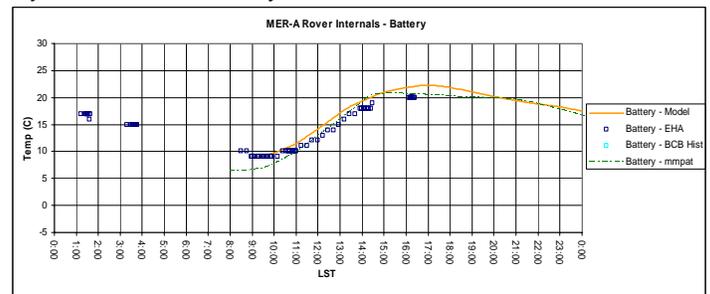

Figure 7: Battery Temperature on Sol 14A

Figure 8 shows the diurnal temperature profile for the rover solar arrays on Sol 14A. Each Sol, the solar arrays experience the widest temperature swings of any hardware on the vehicle each Sol. Because the arrays have a high solar absorptivity, they get very warm during peak solar day light hours (as high as 30C on Sol 14A). Since the arrays have a high IR emissivity and a good clear look at the cold night sky they get very cold at night (as low as -90C on Sol 14A).
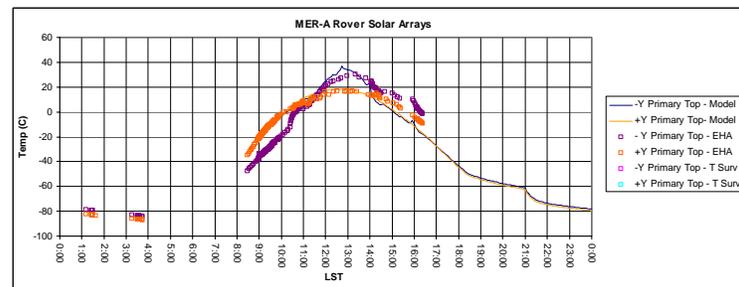

Figure 8: Rover Solar Array Temperatures on Sol 14A

COLD CASE PERFORMANCE

The MER-A landing site around Sol 254A (at the Winter Solstice in the Southern Hemisphere) was predicted to have the coldest environment during the mission. The minimum amount of solar insolation was recorded at about the same time, resulting in the lowest available energy generated by the solar arrays and the lowest energy expended by the vehicle (as low as 300 W*hrs). Figure 9 shows a plot of the minimum and maximum REM temperatures recorded on a monthly basis for Sols 1A through 400A. The minimum REM temperature recorded during the mission was -31C on Sol 190A. The REM survival heater, controlled by a mechanical thermostat with a closed setpoint of -40C, never came on during the entire mission.
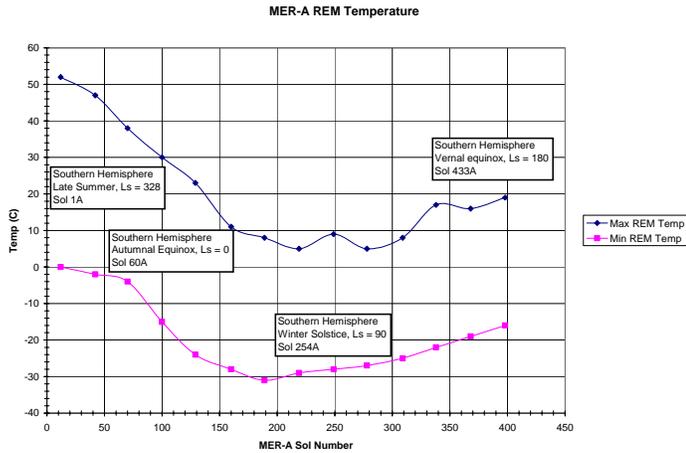
Figure 9: MER-A Max & Min REM Temperatures from Sol 1A and Sol 400A

Figure 10 shows a plot of minimum and maximum battery temperatures recorded on a monthly basis for Sols 1A through 400A. The minimum battery temperature recorded during the mission was -17C on Sol 250A. The battery survival heater, controlled by a mechanical thermostat with a close setpoint of -20C, never came on during the entire mission.
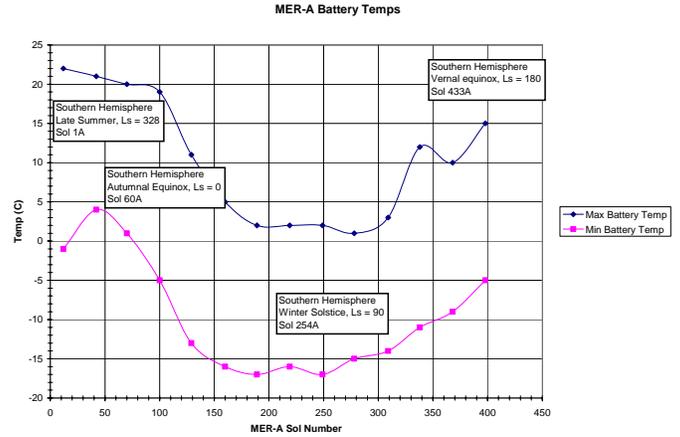

Figure 10 – MER-A Max & Min Battery Temps from Sol 1A to Sol 400A

In fact, the only survival heater that came on during the entire course of the mission (so far) was that for the Mini-TES instrument. The design allocation for energy usage by survival heaters had been set at 120 W*hrs. As shown in the plot of Figure 11, the actual survival heater energy consumption peaked at 48 W*hrs on Sol 186A (well below the allocation).
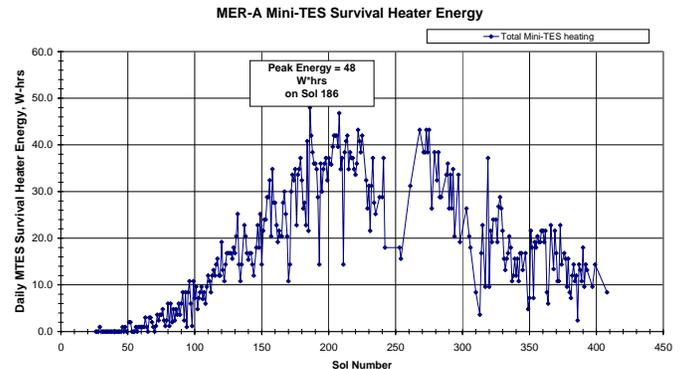

Figure 11: MER-A Mini-TES Survival Heater Energy from Sol 1A to Sol 400A

Figure 12 shows a plot of minimum and maximum solar array temperatures recorded on a monthly basis for Sols 1A through 400A. The minimum solar array temperature recorded during the mission was -115C on Sol 100A. This was below the expected minimum AFT of -105C, but still above the minimum qualification temperature for the solar arrays of -120C.
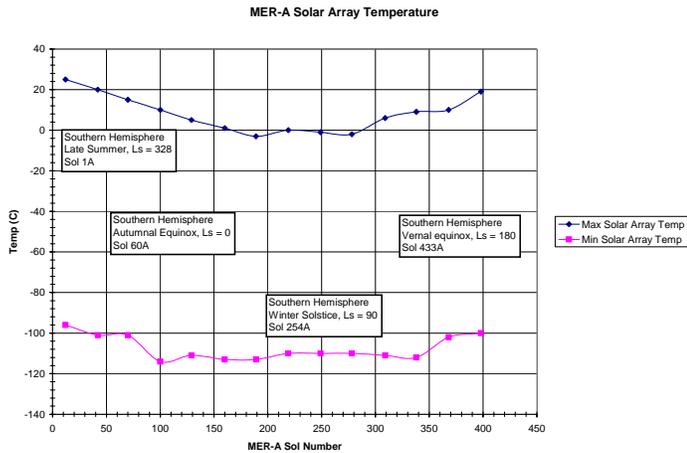
Figure 12: MER-A Max & Min Solar Array Temperatures between Sol 1A and Sol 400A

IDD HEATER ANOMALY

On January 24, 2004, MER-B touched down on Mars in Meridiani Planum, landing in an impact crater (20m in diameter) later named Eagle Crater. Power subsystem telemetry from the night of Sol 1B and morning of Sol 2B indicated an anomalous power draw that came on at 22:49 LST of Sol 1B and went back off at 09:50 LST of Sol 2B. Temperature telemetry was checked and no temperature sensors in the system showed a warmup over this time period. Heater resistance values were checked and it was determined that the IDD azimuth/elevation heater (IDD1) was the most likely culprit. The IDD1 heater had a resistance of 58.8 Ohms and drew 0.5A for a power draw of 14.7 W, exactly the anomalous power draw determined from power telemetry.

The IDD1 heater ran its circuits through a thermostat cutoff box, designed to open the heater circuit and turn off the heater when the atmosphere temperature went above approximately -30C. The analytical thermal model predicted close and open times for the IDD1 heater circuit (based on the thermostat setpoints) that were within 10 minutes of the actual power telemetry values. One piece of temperature telemetry that could have more easily diagnosed the problem, the temperature of the IDD azimuth motor, was not available on MER-B because the flight temperature sensor had been broken in thermal test and never replaced (due to accessibility problems).

The most probable cause for the stuck-on IDD1 heater was determined to be an electro-static discharge (ESD) related failure of the solid state power switch. Thermal modeling of the IDD heater predicted that the peak IDD azimuth/elevation motor temperatures of 80C would occur immediately before the heater was pulled offline by the thermostat at 09:50 LST. This was not a concern for the motors in a non-operating condition, since they had been
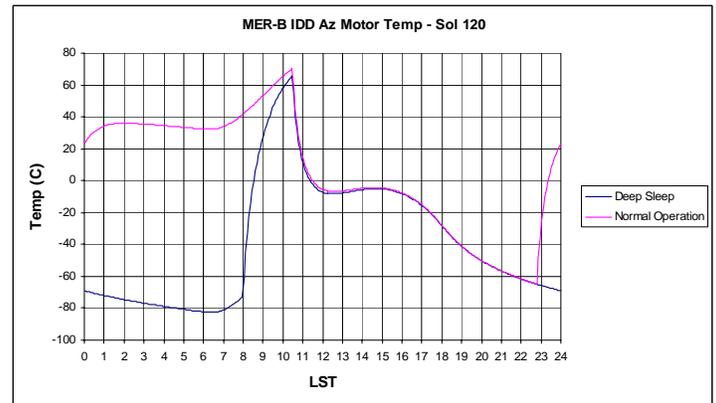

Figure 13: IDD Azimuth Motor Temp Predicts in Normal and Deep Sleep Modes for Sol 120B

qualified to 110C. However, the motors could not be safely operated above their maximum turn-on temperature of 45C. This concern led to operating time restrictions which allowed movement of the IDD only during the times of day when the motor was predicted to be well below 45C.

Another down side to the anomaly was the amount of energy that the 14.7W heater drew out of the battery at night when the heater was on. Over the 11 hour period that the heater stayed on each Sol, it drained 174 W*hrs of energy out of the power system, much of it coming directly out of the battery. To mitigate the energy consumption problem, a "deep sleep" power mode was constructed for the rover. This allowed the rover operators to command the rover to take the battery off-line at night (before 2200 LST) and come back to life in the morning (at 0800) when the current off the solar array was high enough to support early morning power loads. Figure 13 shows a plot of predicted IDD azimuth motor temperatures in the "deep sleep" and normal operations power modes. The disadvantage of the "deep sleep" power mode was that all of the survival heaters were taken off-line when the battery was disconnected. Luckily, the survival heaters on the REM and battery were never needed. However, the Mini-TES survival heater did cycle on regularly (drawing as much as 15 W*hrs of heater energy per Sol on MER-B) and disconnecting that heater did allow Mini-TES to slip below its minimum AFT limit of -40C by as much as 13C. As of Sol 400B, the Mini-TES instrument continues to function properly in spite of the numerous times that the vehicle has been put into deep sleep and the Mini-TES instrument has gone below its minimum AFT limit.

LESSONS LEARNED

The following lessons were learned during the surface thermal operations of the MER Rovers:

1. A Mars surface passive thermal design should be biased to protect against the cold environment (i.e., minimize heat leaks). Transient hot problems can usually be solved with a duration or time-of-day operations

constraint. Transient cold problems will need to be solved by survival heaters, costing valuable electrical energy that could be used for science or operations.

2. Testing hardware at qualification temperature limits having significant margin to AFT limits is extremely important. In numerous cases, AFT limits were exceeded when the MER mission was extended beyond the planned 90-Sol duration. Having hardware that was robust enough to handle temperatures beyond AFT limits was critical to surviving through the Martian winter.

3. Put flight temperature sensors on every motor. Implementation of the MER brush-motor, temperature-dependent current limiting scheme would have been greatly simplified if flight temperature telemetry was available for each motor. A great deal of effort was expended by the flight operations thermal team to produce and maintain temperature prediction tools necessary to seed the on-board current limiting software thermal model with temperature predicts simply because flight telemetry was not available.

4. Platinum Resistance Thermometer (PRT) temperature sensors are fragile and vulnerable to high coefficient of thermal expansion (CTE) mismatch stresses at cold temperatures. Avoid using epoxy adhesives for mounting PRT's. High strength epoxies transmit CTE mismatch stresses directly into the PRT package. Consider using more flexible adhesives such as RTV silicone to mount PRT's down on hardware.

5. The warmup heater thermostat cutoff box was a great idea, albeit an ad-hoc fault protection solution. Thermostats pulled heaters offline during warm daytime ambient hours. A thermostat in the cutoff box saved MER-B IDD azimuth/elevation motors, with a stuck-on warmup heater power switch, from overheating and wasting large amounts of energy.

CONCLUSION

The MER Rover thermal design has proven itself on the surface of Mars to be very robust. During the hottest times of the mission it allowed full functionality of the rover without overheating. During the coldest times of the mission, the rover was able to function with only a minimal amount of electrical survival heater power. The rover thermal design, by maximizing the thermal time constant for electronics inside the insulated WEB, has minimized potentially damaging depths of temperature cycles and minimized the amount energy needed to accomplish thermal control of the vehicle. These factors have contributed to the long life and productivity of the vehicles in performing their robotic science missions.

ACKNOWLEDGMENTS

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

AFT: Allowable Flight Temperature
APGEN: Activity Plan Generator
APXS: Alpha Proton X-Ray Spectrometer
CCD: Charge-Coupled Device
CTE: Coefficient of Thermal Expansion
DTE: Direct-To-Earth
GCM: General Circulation Model
Hazcam: Hazard Cameras
HGA: High Gain Antenna
HRS: Heat Rejection System
IDD: Instrument Deploy Device; robotic arm
IMU: Inertial Measurement Unit
IR: Infrared
Ls: aereocentric longitude
JPL: Jet Propulsion Laboratory
KSC: Kennedy Space Center

LGA: Low Gain Antenna
LST: Local Solar Time
MER: Mars Exploration Rover
MER-A: Spirit Rover
MER-B: Opportunity Rover
MI: Microscopic Imager
Mini-TES: Miniature Thermal Emission Spectrometer
MMPAT: Multi-Mission Power Analysis Tool
NASA: National Aeronautics and Space Administration
Navcam: Navigation Cameras
Pancam: Panoramic Cameras
PMA: Pancam Mast Assembly
PRT: Platinum Resistance Thermometer
RAT: Rock Abrasion Tool; rock grinder
RED: Rover Equipment Deck
REM: Rover Electronics Module
RHU: Radio-isotope Heater Unit
RTV: Room Temperature Vulcanizing silicone adhesive
SDST: Small Deep Space Transponder
SINDA/FLUINT: Finite Difference Thermal Analyzer
Sol: One Mars Day (24.66 Earth hours long)
SSPA: Solid State Power Amplifier
TAS: Thermal Analysis System
Tenv: Environment Temperature
TSS: Thermal Synthesizer System
UHF:
WEB: