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Development of a Thermal Control Architecture for the Mars Exploration Rovers

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Abstract. In June and July of 2003, the U.S. will launch two roving science vehicles on their way to Mars. They will land on Mars in January and February of 2004 and carry out 90-Sol missions. This paper addresses the thermal design architecture employed in the Mars Exploration Rover (MER) surface design. The surface atmosphere temperature on Mars can vary from 0°C in the heat of the day to –100°C in the early morning, prior to sunrise. Heater energy usage at night must be minimized in order to conserve battery energy. The desire to minimize nighttime heater energy leads to a design in which all temperature sensitive electronics and the battery were placed inside a well-insulated (carbon-opacified aerogel lined) Warm Electronics Box (WEB). In addition, radioisotope heater units (RHU's) were mounted on the battery and electronics inside the WEB. During the Martian day, the electronics inside the WEB dissipate a large amount of energy (over 740 W*hrs). This heat energy raises the internal temperatures inside the WEB. Hardware items that have similar temperature limits were conductively coupled together to share heat and concentrate thermal mass. Thermal mass helped to minimize temperature increases in the hot case (with maximum internal dissipation) and minimize temperature decreases in the cold case (with minimum internal dissipation). In order to prevent the battery from exceeding its maximum allowable flight temperature, wax-actuated passive thermal switches were placed between the battery and an external radiator. This paper discusses the design philosophies and system requirements that resulted in a successful Mars rover thermal design.

INTRODUCTION

NASA's Mars Exploration Rover (MER) Project will launch 2 flight systems on their way to Mars in separate launches occurring in June and July of 2003. The MER A mission will deliver a lander and rover to Mars in early January of 2004 and the MER B mission will deliver an identical lander and rover to a different landing site on Mars in late January of 2004. The rovers have been designed to last at least 90 Sols (Martian days) on the surface of Mars. The rovers have a total traverse capability of up to 1 km and a single day driving capability of 100 m. The rovers carry five science instruments designed to perform in situ geological science data collection.

FLIGHT SYSTEM DESCRIPTION

The MER spacecraft is designed to take a rover and lander from the Earth to Mars (during the cruise phase), through the Mars atmosphere and onto the surface (during the entry descent and landing phase) where the rover will conduct science investigations of the Mars geology (during the surface phase). In order to accomplish these varied functions, the flight system (see Figure 1) consists of a cruise stage (used only during cruise it separates from the aeroshell prior to entry), an aeroshell entry vehicle (made up of a backshell and heatshield, used in the entry descent and landing phase), a tetrahedral lander structure and a rover (used in the surface phase).

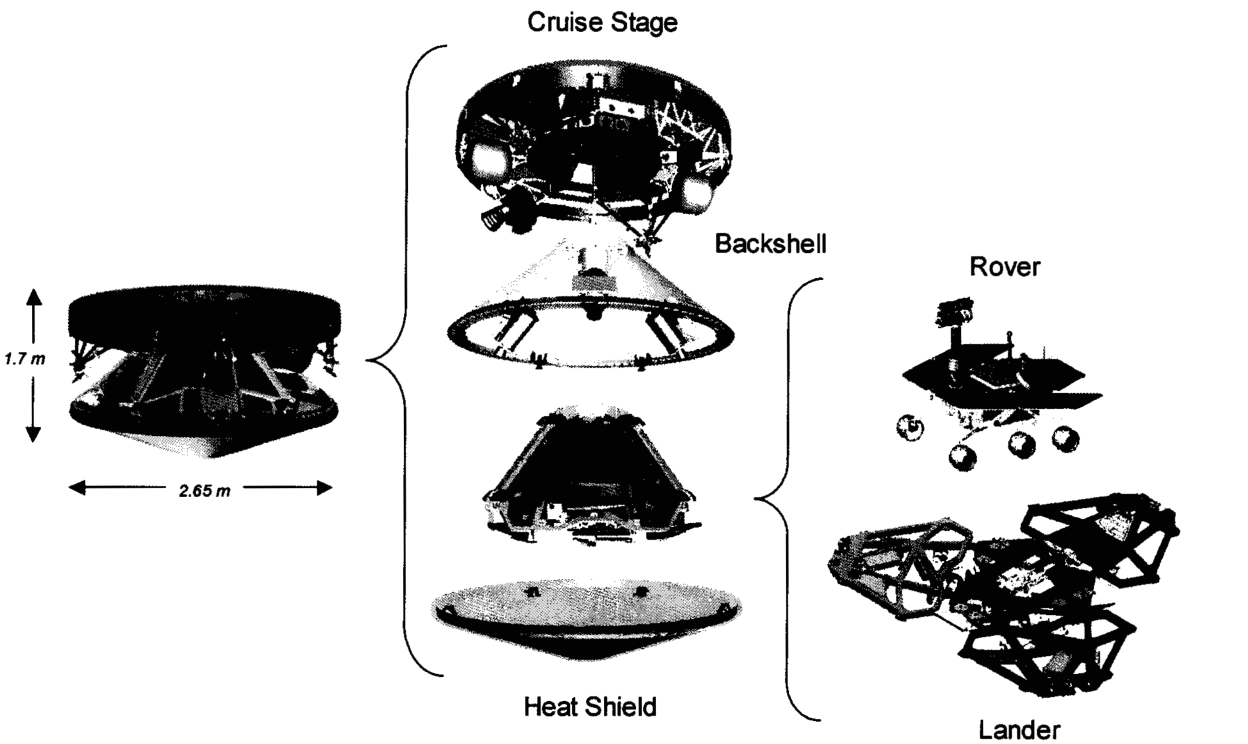

FIGURE 1. MER Flight Spacecraft Configuration

The cruise stage structure supports the cruise solar array on top and all of the propulsion and attitude control components needed to keep the S/C on the proper trajectory to Mars. The spacecraft is spin-stabilized during the cruise to Mars. X-band communication hardware located deep inside the rover and antennas on top of the cruise stage are used to communicate with the Earth during cruise. Thermal dissipation inside the rover is removed by a liquid, pumped-loop cooling system (Ganapathi & Awaya, 2002) known as the Heat Rejection System (HRS). The HRS consists of a fluid pump on the cruise stage that runs cold Freon into the rover electronics to pick up internal heat dissipation and transports the warmed fluid out to radiators on the cruise stage where it can be rejected to the environment. This HRS design was first developed for the Mars Pathfinder spacecraft (Birur & Bhandari, 1998) that successfully put a lander and smaller rover on the surface of Mars in July of 1997.

The entry descent and landing (EDL) phase of the mission is depicted in Figure 2. The EDL system is also based on the Mars Pathfinder design. Prior to entry, the cruise stage separates away from the aeroshell. The aeroshell utilizes a Viking-derived heatshield with SLA-561 ablative material to protect the lander and rover from the intense aero-heating environment during entry. A modified Viking/Mars Pathfinder-derived parachute deploys at 11.8 km above the surface. Shortly thereafter, the heatshield separates from the bottom of the backshell and the lander runs down a bridle underneath the open backshell. A radar altimeter senses the elevation of the lander above the ground. At an elevation of 355 m, airbags surrounding the lander are inflated. At approximately 150 m above the surface, solid rockets on the inside of the backshell are fired to slow the lander to zero vertical velocity. At an elevation of approximately 20 m, the bridle is cut allowing the airbag-

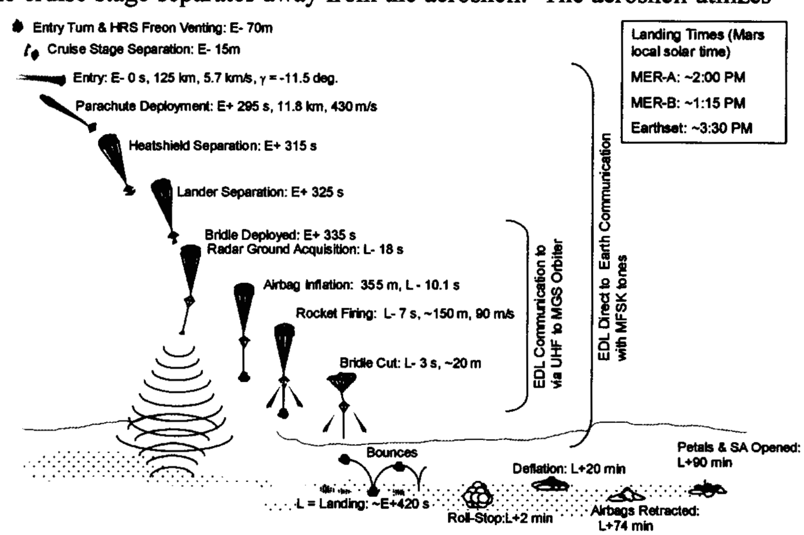

FIGURE 2. Entry, Descent and Landing

shrouded lander to drop onto the Martian surface. The backshell solid rocket motors continue to burn after the bridle is cut in order to move the backshell down range of the lander. The lander bounces for several minutes (at least a dozen times) before coming to rest on the Mars surface. The airbags are deflated and retracted toward the lander petals. One and a half hours after landing the lander petals are opened and the rover solar array panels are deployed.

Additional deployments that occur on Sol 1 include the solar array (with 3 primary panels and 2 secondary panels), the Pancam Mast Assembly (PMA) camera mast structure and the High Gain Antenna (HGA) steerable communications antenna. On Sols 2 and 3, the Rover Lift Actuator (RLA) lifts the Rover body up off the lander, the rocker deploy actuators (RDA's) rotate the front wheels out into position and the bogies are extended into their deployed configuration. On Sol 4 the rover cuts its umbilical cable interface with the lander and drives away onto the Martian soil.

Figure 3 shows the rover in its fully deployed, surface operations configuration ready for Mars exploration.

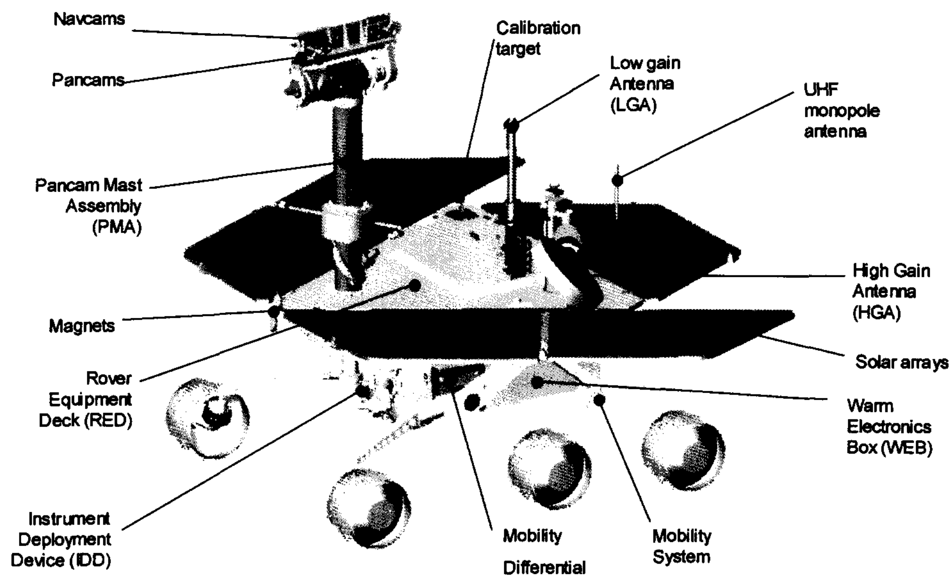

FIGURE 3. Deployed Surface Operations Configuration for MER Rover

On top of the Rover Equipment Deck (RED), the Pancam mast 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 known as 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. Mini-TES is attached to the bottom of the RED so that proper alignments can be made between the Pancam mast and the Mini-TES. Three communications antennas are also seen on 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 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. An Instrument Deploy Device (IDD) 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: the microscopic imager (MI), the Alpha Proton X-Ray Spectrometer (APXS), Moessbauer spectrometer and the Rock Abrasion Tool (RAT) used to grind away the top layer of rocks to analyze internal rock constituents. Two additional stereo camera pairs, used for hazard avoidance, are mounted on the outside of the WEB on the front and back walls of the rover.

Figure 4 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 X-Band Solid State Power Amplifier (SSPA) are mounted to 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. Cabling that passes from through the WEB wall is housed inside forward and rear cable tunnels. External cable bulkheads are mounted on the outside walls of the rover.

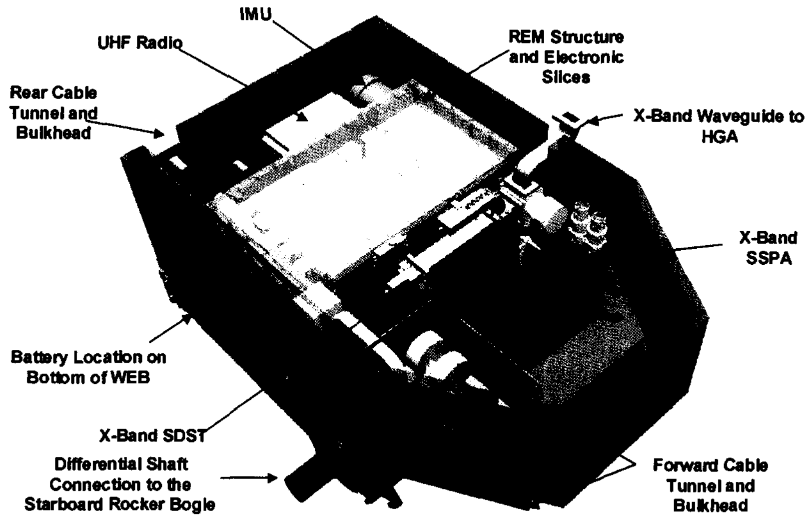

FIGURE 4. Rover Internal Hardware Isometric View

MARS SURFACE THERMAL DESIGN DRIVERS

The flight thermal design of the rover was driven by a number of factors. Primary thermal design drivers include: 1) the Mars external environment, 2) hardware temperature limits, 3) electrical energy usage limitations levied by the power system and 4) high and low energy operational scenarios devised by the mission planners.

Mars Surface Environment

The Mars surface thermal environment defines the ultimate thermal sink for the rover. The Mars surface environment is driven by such factors as landing site latitude, time of year (defined by the aereocentric longitude, L_S), ground characteristics (surface albedo and thermal inertia), the amount of dust in the atmosphere (defined by the atmosphere optical depth, Tau) and landing site elevation. Allowable landing site latitudes for MER were restricted to the band between 15°S to 10°N. Since the rover uses a solar array as its daytime power source, the latitude band near the equator where solar insolation is the highest was heavily favored. The earliest rover arrival date at Mars corresponded to an L_S of 328 (early autumn in the southern hemisphere). The beginning of the surface mission (Sol 0) defines the hottest thermal environment. Since the mission design lifetime is 90 Sols, the coldest thermal environment was defined as the latest landing date plus 90 Sols ($L_S = 16$).

Ground characteristics, albedo and thermal inertia, determine how much of the incident solar radiation is absorbed at the surface, how much of that heat is stored during the day and how much is released at night. Mars surface temperatures drive the atmosphere temperatures during the day and night. The amount of dust in the air affects the amount of solar insolation that reaches the surface (and the split between direct normal and diffuse components) as well as the effective sky radiation temperature. The worst-case hot and cold environments are defined by the low Tau (clear sky, low dust level) condition that maximizes the amount of solar insolation that reaches the surface during the day and minimizes the nighttime sky sink temperature. Landing site elevation was driven by the capabilities of the EDL system. The maximum allowable elevation for the MER landing system was –1.3 km based on the MOLA average Mars elevation measurements. Knowledge of landing site elevation helps to define the atmospheric pressure variations during the day.

The Mars General Circulation Model (Haberle, et al., 1999) was run with the appropriate input parameters to determine the worst-case hot and cold surface thermal environments for the MER rover. Figure 5 shows a typical curve for the predicted atmosphere, ground and sky temperatures on the worst-case hot day for the MER mission.

Figure 6 shows a typical curve for the predicted daytime solar insolation (total, diffuse and direct normal) on the worst-case hot design day.

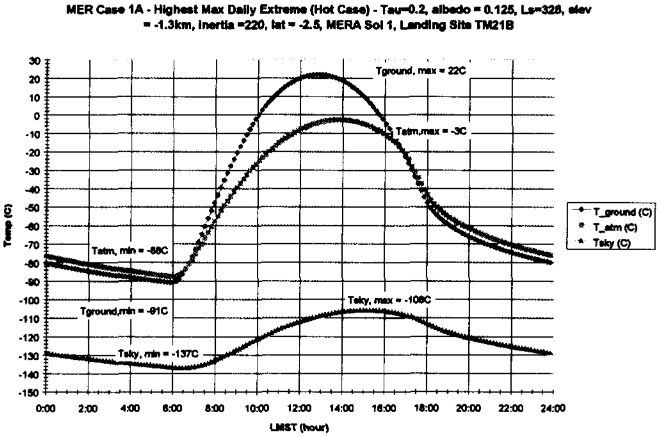

FIGURE 5. MER Surface Hot Environment Ground, Atmosphere & Sky Temperatures

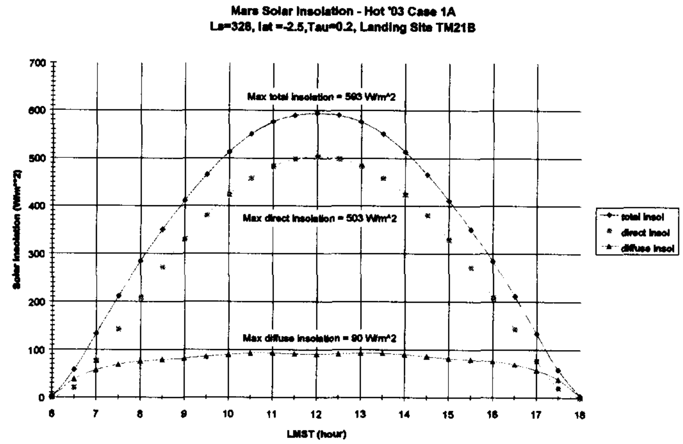

FIGURE 6. MER Surface Hot Environment Solar Insolation

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

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 4). The lithium ion rechargeable battery had the tightest temperature limits of any item on the entire rover (-20°C to +30°C). In addition, the battery must be at 0°C prior to charging to maximize charging efficiency. The remaining flight system electronics (REM and telecommunications hardware) had allowable flight temperature (AFT) limits of –40°C to +50°C. The MTES science instrument that was 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 (which include the solar arrays, visible cameras, telecommunications antennas, robotic arm and mobility system) are shown in Figure 3. 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 available energy to do so.

Power System Constraints & Operational Scenarios

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 600 W*hrs of energy per Sol. Daytime energy is used as needed to run science, mobility and communications operations. Excess 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 120W*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. The power system bus voltage was controlled between 24V and 36V, with a nominal bus voltage of 28V.

Rover operational scenarios were defined by mission planners and translated into power profiles. A worst-case hot profile (maximum energy dissipated inside the WEB) corresponded to a day in which the rover spent 4 hours in a direct-to-Earth communications mode. The total internal energy dissipation inside the rover on the worst-case hot day was 742 W*hrs. This hot power profile would most likely occur near the beginning of the mission when the incident solar insolation was the highest and the environment was the warmest. A worst-case cold 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 428 W*hrs. This cold power profile would most likely occur near the end of the 90-Sol mission when the solar insolation was the lowest and the environment was the coldest.

THERMAL DESIGN STRATEGY

Once all the system level requirements and constraints had been defined, it was necessary to devise an overall thermal design strategy to meet them. The MER rover surface thermal design strategy will be discussed first for the temperature sensitive items inside the WEB and later for the more temperature robust items outside the rover.

WEB Internal Thermal Design

Since the items inside the WEB must 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 4, 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). These items all had similar temperature limits. Coupling together these hardware items tended to minimize temperature drops during cool-downs and temperature rises during warm-ups. It also allowed power sharing between boxes to minimize the number of survival heaters and thermostats. Mounting all of these items to the REM also helped to minimize the number of structural supports that were needed to secure the hardware to the external WEB structure. 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 mass (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. Aerogel is very fragile and quite difficult to machine and cut. The aerogel was securely held on the internal walls of the WEB with small "Z-spars" and protected from abrasion by thin glass-epoxy composite cover sheets. These cover sheets were coated with a low emissivity, co-cured goldized kapton surface that looked into the inside of the WEB. Requiring boxes inside the WEB to have low emissivity surface finishes also minimized radiation losses inside the WEB. The outside of the WEB structure also had a low emissivity, co-cured goldized kapton external surface to minimize the radiation directly to the external Mars environment. In general, the aerogel was 25mm thick on all of the WEB and RED internal walls except for the WEB floor where it was reduced to 12 mm in thickness. Significant cutouts in the aerogel were provided in areas where support strut mounted to the external WEB structure and where access was needed from the outside of the WEB to the inside of the WEB (e.g., RHU-insertion holes and cable feed through holes). As shown in Figure 7, thermal losses through the aerogel-lined walls of the WEB made up approximately 50% of the steady-state heat leak in the worst-case cold environment.

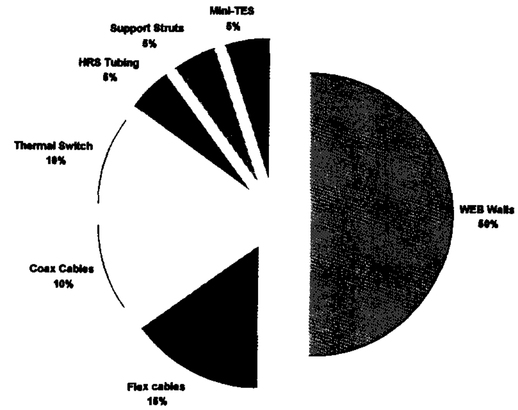

FIGURE 7. - Steady State Heat Losses from WEB

The heat leak from the inside of the WEB to the environment through the copper cables that exited the WEB structure was also minimized as much as possible. Instead of using conventional "round-wire" cables, the power and signal wires passing through the WEB wall were made of flexprint cabling (copper traces clad onto a polyimide base), to minimize the amount of copper conductors. In addition, the flex cables were run through cable tunnels, located in the front and rear of the rover, that kept the cabling insulated for a long length (approximately 0.5 m) inside the WEB prior to the egress. The cable tunnels were insulated with rigid polyurethane foam. Thermal losses through the flex cables accounted for about 15% of the total heat leak from the WEB.

Coax cables that ran from telecommunications equipment inside the WEB to antennas on the RED and lander also had a considerable amount of copper in them. The heat leak through the coax cables was limited by using the minimum diameter coax line that gave acceptable radio frequency (RF) performance. In addition, RF cables were also insulated inside the WEB for a long as possible, before the exited the WEB. Coax cable losses 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 switch closed and heat was rejected from the battery to a radiator on the outside of the rover. When the switch was below the paraffin melt point, it remained open with a gap between the hot and cold sides of the switch. The 1.3 mm gap was maximized to limit the amount of heat leak that could occur through the switch when it was in the open position. Gas conduction in the 10 torr $CO2$ 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 HRS cruise pumped loop cooling system required metal tubing to pass fluid from the radiators on the cruise stage into the electronics housed inside the rover. The tubing that was attached to heat transfer surfaces inside the WEB was made of aluminum. In an effort to minimize the heat leak through the HRS tubes that crossed the insulated WEB, that section of tubing was made of lower 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 tubular struts with Ti fittings to the external WEB and RED structure. The REM and battery struts were fabricated of high stiffness, low-conductivity Boron/Epoxy composite material and the Mini-TES struts were made of glass-epoxy material. Strut length was maximized and cross-sectional area minimized in an effort to reduce the thermal leak to the external WEB and RED structures. 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 telescope extended from the inside of the WEB up into the RED fitting that held the Pancam mast to the top of the rover. As such, 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. In addition, the battery had a warmup heater (also controlled by a mechanical thermostat) to allow the battery to warm up in the early morning prior to charging. Charging efficiency was improved when the battery was above 0°C. All heaters had primary and backup strings with series redundant thermostats. Thermostats had a dead band of approximately 3°C to 5°C. Mechanical thermostats were used in this application, instead of computer controlled thermostats for two main reasons: 1) computer-controlled thermostats would be inactivated when the computer was turned off during most of the night, leaving the hardware unprotected and 2) mechanical thermostats were considered to be more robust in case of a computer reset. 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, a non-electrical heat source was used to help keep the REM and battery warm at night. Two radioisotope heater units (RHUs) were mounted to the WEB 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 were also enough to overheat the battery during the day (depending on how much internal heat was dissipated inside the WEB form 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. The heat switch was a modified from a vacuum space application for use in the Mars 10 torr CO_2 atmosphere environment. Specifically, the gap between the hot side of the switch and the cold side of the switch was increased from 0.13 mm to 1.3 mm in an effort to reduce the gas gap conduction when the switch was in its open condition. When the battery was colder than the switch setpoint (<18°C), the switch remained open (conductance = 0.017 W/°C) and the RHU heat remained on the battery. When the battery was warmer than the setpoint (>18°C), the switch closed (conductance ramping up quickly to 1.0 W/°C with the hot side at 20°C) and the RHU heat was dumped outside the WEB to external radiators. The aluminum radiators were painted white and shielded from direct midday sun by the solar arrays.

Earlier designs of the rover had included a loop heat pipe attached to the SSPA (the highest heat dissipater inside the WEB) to allow daytime heat rejection from that unit to an external radiator (Birur, et al., 2002; Pauken, et al., 2002). The loop heat pipe would have enabled an unlimited amount of X-band communications downlink time without overheating the unit. The loop heat pipe was taken out of the design in an effort to reduce the complexity, mass and cost of the rover thermal design. The project was willing to accept limited downlink times (a maximum of 3 hours) based on the capability of the thermal mass in the WEB to absorb heat.

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 temp limits 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. Two stereo camera pairs are located at the top of the Pancam mast: a left and right Pancam science/panoramic camera pair and a left and right Navcam engineering/navigation camera pair (see Figure 3). There are 2 more stereo camera pairs attached to the front and back of the WEB structure under the solar arrays: a left and right forward Hazcam engineering/hazard camera pair and a left and right aft Hazcam engineering/hazard camera pair. The last camera, attached to the end of the robotic science arm known as the Instrument Deploy Device (IDD), is the microscopic imager. All of these cameras are identical in design except for their lens assemblies.

The camera electronics and CCD housings are covered in silvered Teflon tape to prevent them from overheating in the sun. The CCD housings are hard mounted directly to their interfaces. The camera electronics boards must be heated up to −55°C within one hour prior to early morning operation. In the interest of minimizing camera warmup heater size, the boards were isolated from the housings by low conductance G-10 washers and the electronics housings were isolated from their mounting interfaces with Ti standoffs. Warmup heaters consisted of wire-wound resistors mounted directly on the camera electronics boards. The Pancam and Navcam cameras up at the top of the Pancam mast (with a good view to the sky), had larger heaters than the cameras tucked under the solar array (with a poor view to the cold sky), the Hazcams and Microimager. Heaters were sized to allow warmup of the boards from –95°C to –55°C within an hour.

There are 34 actuators (gear/motors) on the flight rover. All actuators have a minimum operating AFT of –55°C. The viscosity of the "wet" Braycote lubricant, which increases dramatically at –70°C, drives the minimum temperature requirement. Since many of the actuators will be 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. Actuators that will get sun exposure were covered in silvered Teflon tape (low absorptivity/emissivity ratio material) to keep them cool in the sun. Actuators heaters were designed such that if they were left on continuously, they would not heat the actuators over the 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 –30°C.

The graphite/epoxy composite PMA mast is bolted to a Ti fixture on the top of the RED. The bottom of the PMA is hollow to allow the Mini-TES instrument in the WEB to look up the mast, through two mirrors and out to the Mars scene. The inside of the mast is painted black to reduce stray IR emissions. The entire outside of the mast is painted white (S-13-GP/LO-1) to minimize the temperature gradients on the hardware.

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 PMA was designed to operate at any time during the day or night. Science desires requested the ability to take Mini-TES infrared images during the night and to take early morning (6AM) sunrise pictures with the visible wavelength cameras.

The HGA has 2 actuators, one for the azimuth and one for the elevation. Desire for early morning (7:30AM) 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 rover is capable of speeds up to 5 cm/sec and a maximum traverse of 100 m per day.

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 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 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 will be 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 are stowed to fit inside the tetrahedral lander. After landing, the launch restraints on the panels are cut and the panels are 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.

An additional consideration in the rover thermal design was the thermal control of the shunt radiator. The shunt radiator dissipates excess energy coming off the solar panels that is not being used by loads on the power bus or stored in the battery. The maximum power dissipation for the rover shunt heater is 105W. The shunt heater consists of 2 kapton film heaters mounted to the bottom facesheets of the left and right primary deployable solar panels. Each element or stage is capable of handling the entire 105W load, thus making the system functionally redundant. The graphite-epoxy solar array facesheets are very thin and have a low thermal conductivity. This results in the need for a heater that covers a large area to keep the resulting temperatures below the solar array structure maximum AFT of 90°C. The heater elements are covered with silvered Teflon tape (high emissivity) to allow thermal radiation to the ground and keep the panels from overheating.

ANALYTICAL THERMAL MODEL PERFORMANCE PREDICTIONS

Analytical thermal models of the rover and its external components were developed initially in the design stages of the project. As the design neared maturity, the analytical models increased in detail and complexity. For instance, the main rover model that included the WEB, internal WEB hardware and the solar array, grew in size to over 2000 nodes. After a high fidelity thermal characterization test of an engineering model version of the rover hardware, the model was reduced in size (to 100 nodes) and correlated to the test data.

Analytical thermal models are extremely important in the design development and verification of Mars surface operations performance. It is virtually impossible to precisely reproduce the Mars thermal environment in a thermal chamber here on Earth. It is much easier to correlate an analytical thermal model to known and controlled chamber conditions that come close to simulating the Mars environment and then analytically fill in the missing details to predict actual Mars surface performance. The key differences between the test chamber environment and the actual Mars surface environment are listed below:

1) Chamber atmosphere was 8 torr GN2 (to prevent chamber pressure problems associated with having CO2 condense, freeze out and sublimate on cold chamber shroud inlet lines) whereas the Mars atmosphere is 8 torr CO2. This difference increases gas conduction and free convection and decreases insulation performance during the test.
2) The acceleration due to gravity on Earth is 1 G, whereas the Mars gravitational constant is 3/8 G. This difference increases the free convection inside the chamber.
3) There was no solar simulation during the test. At best, the solar simulator could only illuminate the top of the rover and could not simulate the sweep of the sun across the sky at all sun angles.
4) The temperature of the shrouds drove the atmosphere temperatures inside the chamber. On Mars the rover has a view to the ground and a view to the sky that run at vastly different temperatures. Having to drive the atmosphere temperature inside the chamber with the shrouds results in differences in the radiative boundary condition for the rover between test and Mars operations.
5) No wind simulation was used in the chamber. Running fans inside a chamber at low pressures is difficult due to accelerated motor brush wear, motor overheating problems and an inability to accurately measure wind speed (Johnson, et al., 1996). Free convection control plates were used to understand the approximate free convection coefficients on the outside of the rover.

Because of these testing limitations, it is difficult to get a direct empirical validation of a Mars surface thermal design directly from chamber data. Instead the validation must come from a correlated analytical model that has the precise Mars environment details put back into the model.

A reduced-node SINDA/Fluint thermal model was used to correlate to the test data. Both TSS (Thermal Synthesizer System) and TAS (Thermal Analysis System) were used to create the model. Simplifying the geometry of the much larger system-level thermal model allowed the creation of a 100-node reduced model. Before the model correlation process began, analytical test cases were run to ensure that the 100-node model agreed well with the 2000-node, system-level thermal model. Running the 100-node model through both hot and cold transient Mars diurnal scenarios validated that both models agreed to within 5°C.

The analytical thermal model was correlated to test data by first adjusting conductances in the model so that it agreed with hot and cold steady state test data. Then, capacitances in the model were adjusted until the model predicts in the diurnal warmup and cooldown transient cases agreed with test data. After model correlation, test data and predicts for most major entities of the model agreed to within 5°C.

Figure 8 shows the temperature predicts from the correlated reduced model in the worst-case Mars cold environment with the low-energy (432 W*hrs) operational scenario. Note that the Mini-TES instrument runs much cooler than the rest of the hardware because of its low thermal mass, its thermal isolation to the rest of the hardware and its significant heat losses up the Pancam mast. All hardware is predicted to stay within AFT limits with margin. The only survival heater that comes on at night is that for the Mini-TES instrument. Additional heater energy is expended in the early morning to warm the battery up prior to charging. The nighttime energy expended to keep the WEB hardware from exceeding minimum temp limits is only 70 W*hrs (well under the nighttime maximum allowable allocation of 120 W*hrs).

Figure 9 shows the temperature predicts from the correlated reduced model in the worst-case Mars hot environment with the high-energy (742 W*hrs) operational scenario. This scenario includes two X-band downlink sessions of two hours each, from 8AM to 10AM and from 12:30PM to 2:30PM that result in a predicted peak SSPA temperature of 47°C. This is still 3°C under the max AFT of the SSPA, and exceeds the desired downlink duration capability by one hour. The battery temperature peaks at 25°C when the thermal switch closes and dumps excess heat to the Mars environment.

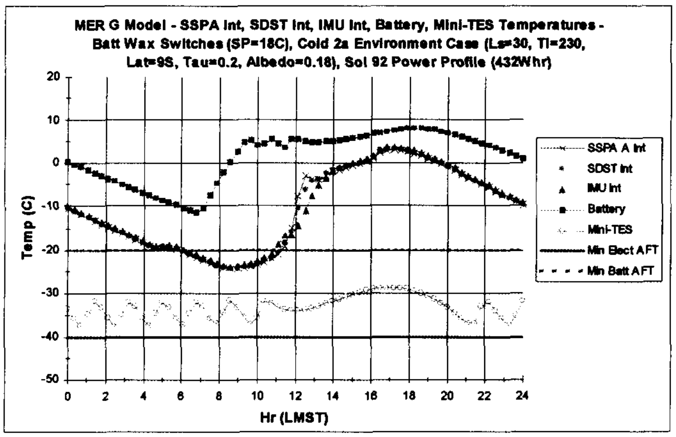

FIGURE 8. MER Internal Hardware Temperature Predicts from Correlated Model In Cold Environment Case

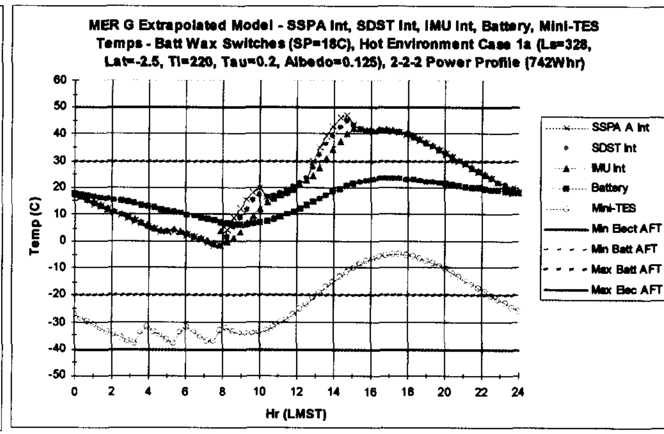

FIGURE 9. MER Internal Hardware Temperature Predicts from Correlated Model In Hot Environment Case

Analytical thermal model predicts for the external rover components were also completed with correlated thermal models. Camera and actuator warmup times met or exceeded requirements. In addition, no cameras or actuators were predicted to exceed maximum AFT limits during worst-case surface operations in the hottest design environment.

CONCLUSIONS

The thermal design strategies discussed above resulted in a highly successful rover thermal design that exceeded design requirements in both the hot and cold environments. An analytical thermal model was correlated to test data obtained from a highly flight-like engineering model rover. The analytical model was run in both hot and cold worst-case thermal environments. Results indicate that the rover will require only 60 % of the energy available for nighttime heating in the cold case environment. Hot case results indicate that 4 hours of direct-to-Earth communications are possible without exceeding maximum allowable temperature limits. This hot case performance provides a full hour of communications beyond the system requirement of 3 hours.

Additional thermal performance data will be obtained in November 2002 when the first flight rover thermal system test is performed. Results of that test are not expected to be significantly different from the results obtained in the engineering model test. The true test of the rover thermal design will occur in January of 2004 when the first MER rover drives off the lander to begin its primary mission for 90 days of Mars exploration.

ACKNOWLEDGMENTS

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Development of a Thermal Control Architecture for the Mars Exploration Rovers

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Abstract. In June and July of 2003, the U.S. will launch two roving science vehicles on their way to Mars. They will land on Mars in January and February of 2004 and carry out 90-Sol missions. This paper addresses the thermal design architecture employed in the Mars Exploration Rover (MER) surface design. The surface atmosphere temperature on Mars can vary from 0°C in the heat of the day to –100°C in the early morning, prior to sunrise. Heater energy usage at night must be minimized in order to conserve battery energy. The desire to minimize nighttime heater energy leads to a design in which all temperature sensitive electronics and the battery were placed inside a well-insulated (carbon-opacified aerogel lined) Warm Electronics Box (WEB). In addition, radioisotope heater units (RHU's) were mounted on the battery and electronics inside the WEB. During the Martian day, the electronics inside the WEB dissipate a large amount of energy (over 740 W*hrs). This heat energy raises the internal temperatures inside the WEB. Hardware items that have similar temperature limits were conductively coupled together to share heat and concentrate thermal mass. Thermal mass helped to minimize temperature increases in the hot case (with maximum internal dissipation) and minimize temperature decreases in the cold case (with minimum internal dissipation). In order to prevent the battery from exceeding its maximum allowable flight temperature, wax-actuated passive thermal switches were placed between the battery and an external radiator. This paper discusses the design philosophies and system requirements that resulted in a successful Mars rover thermal design.

INTRODUCTION

NASA's Mars Exploration Rover (MER) Project will launch 2 flight systems on their way to Mars in separate launches occurring in June and July of 2003. The MER A mission will deliver a lander and rover to Mars in early January of 2004 and the MER B mission will deliver an identical lander and rover to a different landing site on Mars in late January of 2004. The rovers have been designed to last at least 90 Sols (Martian days) on the surface of Mars. The rovers have a total traverse capability of up to 1 km and a single day driving capability of 100 m. The rovers carry five science instruments designed to perform in situ geological science data collection.

FLIGHT SYSTEM DESCRIPTION

The MER spacecraft is designed to take a rover and lander from the Earth to Mars (during the cruise phase), through the Mars atmosphere and onto the surface (during the entry descent and landing phase) where the rover will conduct science investigations of the Mars geology (during the surface phase). In order to accomplish these varied functions, the flight system (see Figure 1) consists of a cruise stage (used only during cruise it separates from the aeroshell prior to entry), an aeroshell entry vehicle (made up of a backshell and heatshield, used in the entry descent and landing phase), a tetrahedral lander structure and a rover (used in the surface phase).

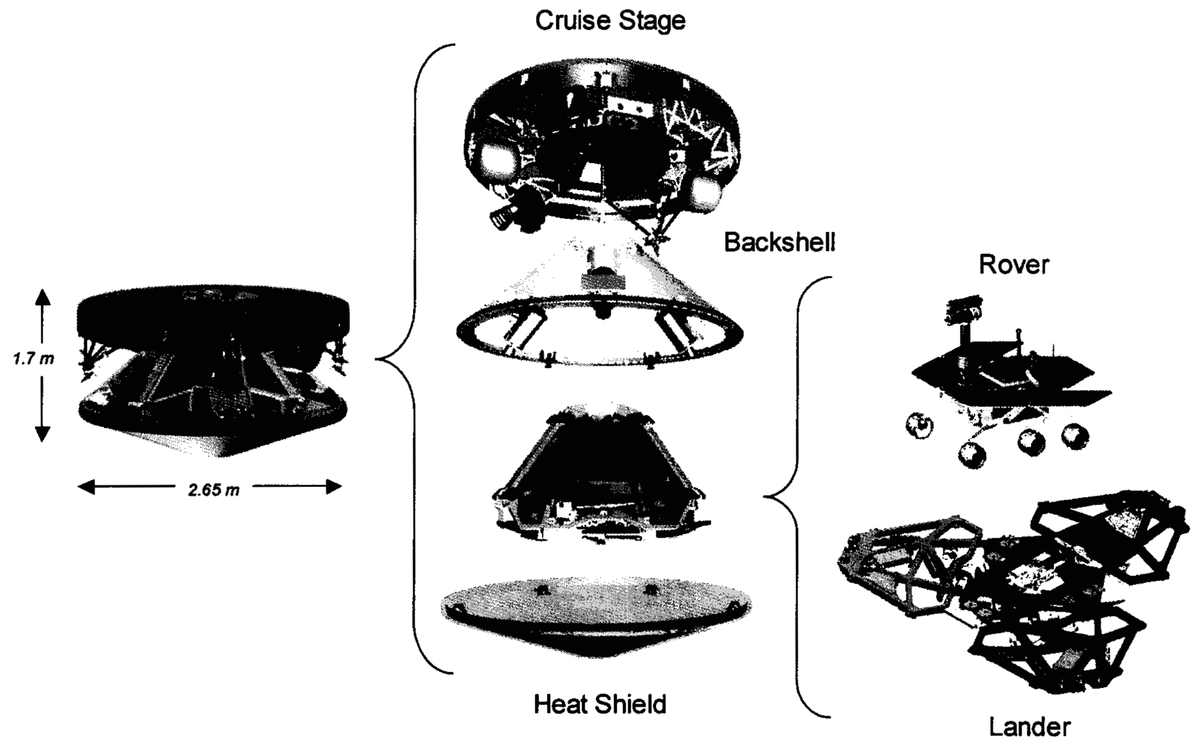

FIGURE 1. MER Flight Spacecraft Configuration

The cruise stage structure supports the cruise solar array on top and all of the propulsion and attitude control components needed to keep the S/C on the proper trajectory to Mars. The spacecraft is spin-stabilized during the cruise to Mars. X-band communication hardware located deep inside the rover and antennas on top of the cruise stage are used to communicate with the Earth during cruise. Thermal dissipation inside the rover is removed by a liquid, pumped-loop cooling system (Ganapathi & Awaya, 2002) known as the Heat Rejection System (HRS). The HRS consists of a fluid pump on the cruise stage that runs cold Freon into the rover electronics to pick up internal heat dissipation and transports the warmed fluid out to radiators on the cruise stage where it can be rejected to the environment. This HRS design was first developed for the Mars Pathfinder spacecraft (Birur & Bhandari, 1998) that successfully put a lander and smaller rover on the surface of Mars in July of 1997.

The entry descent and landing (EDL) phase of the mission is depicted in Figure 2. The EDL system is also based on the Mars Pathfinder design. Prior to entry, the cruise stage separates away from the aeroshell. The aeroshell utilizes a Viking-derived heatshield with SLA-561 ablative material to protect the lander and rover from the intense aero-heating environment during entry. A modified Viking/Mars Pathfinder-derived parachute deploys at 11.8 km above the surface. Shortly thereafter, the heatshield separates from the bottom of the backshell and the lander runs down a bridle underneath the open backshell. A radar altimeter senses the elevation of the lander above the ground. At an elevation of 355 m, airbags surrounding the lander are inflated. At approximately 150 m above the surface, solid rockets on the inside of the backshell are fired to slow the lander to zero vertical velocity. At an elevation of approximately 20 m, the bridle is cut allowing the airbag-

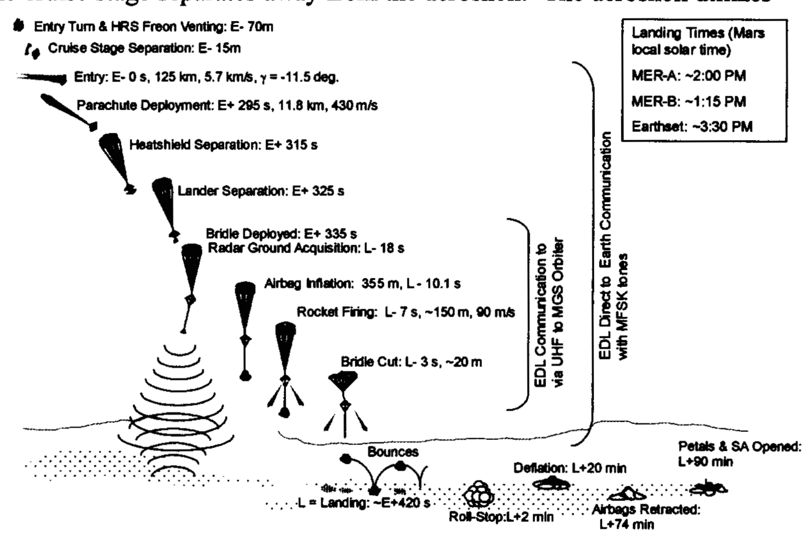

FIGURE 2. Entry, Descent and Landing

shrouded lander to drop onto the Martian surface. The backshell solid rocket motors continue to burn after the bridle is cut in order to move the backshell down range of the lander. The lander bounces for several minutes (at least a dozen times) before coming to rest on the Mars surface. The airbags are deflated and retracted toward the lander petals. One and a half hours after landing the lander petals are opened and the rover solar array panels are deployed.

Additional deployments that occur on Sol 1 include the solar array (with 3 primary panels and 2 secondary panels), the Pancam Mast Assembly (PMA) camera mast structure and the High Gain Antenna (HGA) steerable communications antenna. On Sols 2 and 3, the Rover Lift Actuator (RLA) lifts the Rover body up off the lander, the rocker deploy actuators (RDA's) rotate the front wheels out into position and the bogies are extended into their deployed configuration. On Sol 4 the rover cuts its umbilical cable interface with the lander and drives away onto the Martian soil.

Figure 3 shows the rover in its fully deployed, surface operations configuration ready for Mars exploration.

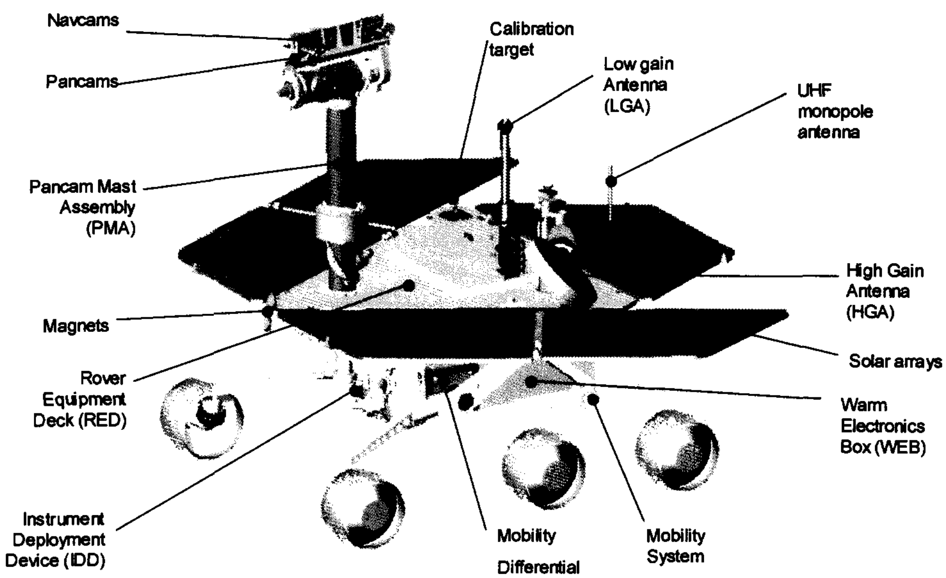

FIGURE 3. Deployed Surface Operations Configuration for MER Rover

On top of the Rover Equipment Deck (RED), the Pancam mast 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 known as 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. Mini-TES is attached to the bottom of the RED so that proper alignments can be made between the Pancam mast and the Mini-TES. Three communications antennas are also seen on 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 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. An Instrument Deploy Device (IDD) 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: the microscopic imager (MI), the Alpha Proton X-Ray Spectrometer (APXS), Moessbauer spectrometer and the Rock Abrasion Tool (RAT) used to grind away the top layer of rocks to analyze internal rock constituents. Two additional stereo camera pairs, used for hazard avoidance, are mounted on the outside of the WEB on the front and back walls of the rover.

Figure 4 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 X-Band Solid State Power Amplifier (SSPA) are mounted to 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. Cabling that passes from through the WEB wall is housed inside forward and rear cable tunnels. External cable bulkheads are mounted on the outside walls of the rover.

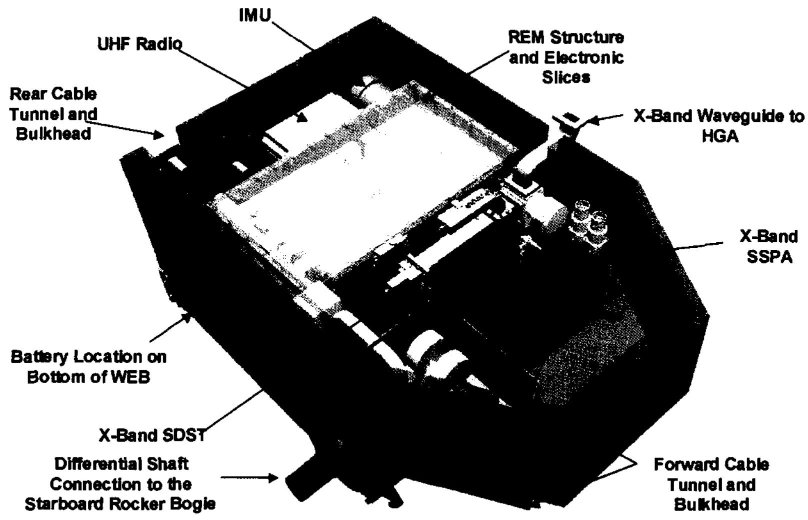

FIGURE 4. Rover Internal Hardware Isometric View

MARS SURFACE THERMAL DESIGN DRIVERS

The flight thermal design of the rover was driven by a number of factors. Primary thermal design drivers include: 1) the Mars external environment, 2) hardware temperature limits, 3) electrical energy usage limitations levied by the power system and 4) high and low energy operational scenarios devised by the mission planners.

Mars Surface Environment

The Mars surface thermal environment defines the ultimate thermal sink for the rover. The Mars surface environment is driven by such factors as landing site latitude, time of year (defined by the aereocentric longitude, L_S), ground characteristics (surface albedo and thermal inertia), the amount of dust in the atmosphere (defined by the atmosphere optical depth, Tau) and landing site elevation. Allowable landing site latitudes for MER were restricted to the band between 15°S to 10°N. Since the rover uses a solar array as its daytime power source, the latitude band near the equator where solar insolation is the highest was heavily favored. The earliest rover arrival date at Mars corresponded to an L_S of 328 (early autumn in the southern hemisphere). The beginning of the surface mission (Sol 0) defines the hottest thermal environment. Since the mission design lifetime is 90 Sols, the coldest thermal environment was defined as the latest landing date plus 90 Sols ($L_S = 16$).

Ground characteristics, albedo and thermal inertia, determine how much of the incident solar radiation is absorbed at the surface, how much of that heat is stored during the day and how much is released at night. Mars surface temperatures drive the atmosphere temperatures during the day and night. The amount of dust in the air affects the amount of solar insolation that reaches the surface (and the split between direct normal and diffuse components) as well as the effective sky radiation temperature. The worst-case hot and cold environments are defined by the low Tau (clear sky, low dust level) condition that maximizes the amount of solar insolation that reaches the surface during the day and minimizes the nighttime sky sink temperature. Landing site elevation was driven by the capabilities of the EDL system. The maximum allowable elevation for the MER landing system was –1.3 km based on the MOLA average Mars elevation measurements. Knowledge of landing site elevation helps to define the atmospheric pressure variations during the day.

The Mars General Circulation Model (Haberle, et al., 1999) was run with the appropriate input parameters to determine the worst-case hot and cold surface thermal environments for the MER rover. Figure 5 shows a typical curve for the predicted atmosphere, ground and sky temperatures on the worst-case hot day for the MER mission.

Figure 6 shows a typical curve for the predicted daytime solar insolation (total, diffuse and direct normal) on the worst-case hot design day.

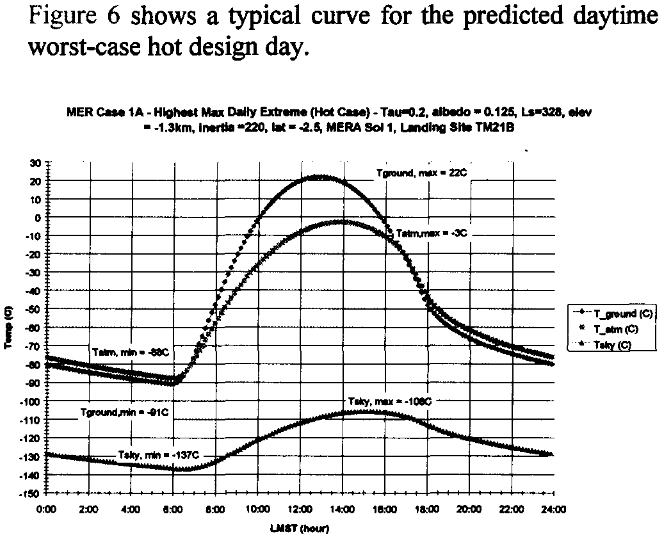

FIGURE 5. MER Surface Hot Environment Ground, Atmosphere & Sky Temperatures

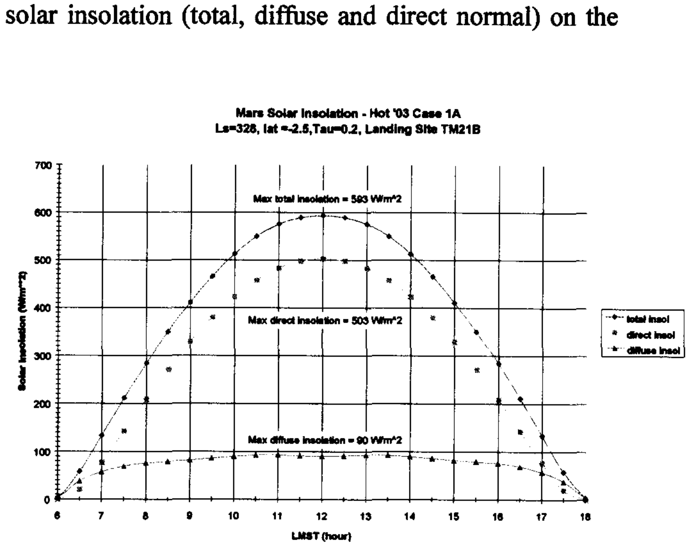

FIGURE 6. MER Surface Hot Environment Solar Insolation

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

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 4). The lithium ion rechargeable battery had the tightest temperature limits of any item on the entire rover (-20°C to +30°C). In addition, the battery must be at 0°C prior to charging to maximize charging efficiency. The remaining flight system electronics (REM and telecommunications hardware) had allowable flight temperature (AFT) limits of –40°C to +50°C. The MTES science instrument that was 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 (which include the solar arrays, visible cameras, telecommunications antennas, robotic arm and mobility system) are shown in Figure 3. 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 available energy to do so.

Power System Constraints & Operational Scenarios

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 600 W*hrs of energy per Sol. Daytime energy is used as needed to run science, mobility and communications operations. Excess 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 120W*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. The power system bus voltage was controlled between 24V and 36V, with a nominal bus voltage of 28V.

Rover operational scenarios were defined by mission planners and translated into power profiles. A worst-case hot profile (maximum energy dissipated inside the WEB) corresponded to a day in which the rover spent 4 hours in a direct-to-Earth communications mode. The total internal energy dissipation inside the rover on the worst-case hot day was 742 W*hrs. This hot power profile would most likely occur near the beginning of the mission when the incident solar insolation was the highest and the environment was the warmest. A worst-case cold 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 428 W*hrs. This cold power profile would most likely occur near the end of the 90-Sol mission when the solar insolation was the lowest and the environment was the coldest.

THERMAL DESIGN STRATEGY

Once all the system level requirements and constraints had been defined, it was necessary to devise an overall thermal design strategy to meet them. The MER rover surface thermal design strategy will be discussed first for the temperature sensitive items inside the WEB and later for the more temperature robust items outside the rover.

WEB Internal Thermal Design

Since the items inside the WEB must 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 4, 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). These items all had similar temperature limits. Coupling together these hardware items tended to minimize temperature drops during cool-downs and temperature rises during warm-ups. It also allowed power sharing between boxes to minimize the number of survival heaters and thermostats. Mounting all of these items to the REM also helped to minimize the number of structural supports that were needed to secure the hardware to the external WEB structure. 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 mass (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 $CO2$ at 0°C). Carbon opacification was added to the aerogel in an effort to block the infrared thermal transmission through the material. Aerogel is very fragile and quite difficult to machine and cut. The aerogel was securely held on the internal walls of the WEB with small "Z-spars" and protected from abrasion by thin glass-epoxy composite cover sheets. These cover sheets were coated with a low emissivity, co-cured goldized kapton surface that looked into the inside of the WEB. Requiring boxes inside the WEB to have low emissivity surface finishes also minimized radiation losses inside the WEB. The outside of the WEB structure also had a low emissivity, co-cured goldized kapton external surface to minimize the radiation directly to the external Mars environment. In general, the aerogel was 25mm thick on all of the WEB and RED internal walls except for the WEB floor where it was reduced to 12 mm in thickness. Significant cutouts in the aerogel were provided in areas where support strut mounted to the external WEB structure and where access was needed from the outside of the WEB to the inside of the WEB (e.g., RHU-insertion holes and cable feed through holes). As shown in Figure 7, thermal losses through the aerogel-lined walls of the WEB made up approximately 50% of the steady-state heat leak in the worst-case cold environment.

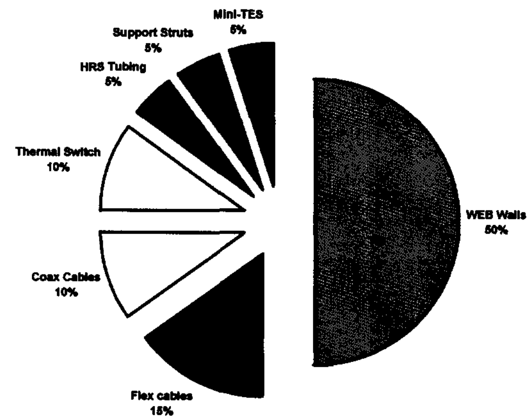

FIGURE 7. - Steady State Heat Losses from WEB

The heat leak from the inside of the WEB to the environment through the copper cables that exited the WEB structure was also minimized as much as possible. Instead of using conventional "round-wire" cables, the power and signal wires passing through the WEB wall were made of flexprint cabling (copper traces clad onto a polyimide base), to minimize the amount of copper conductors. In addition, the flex cables were run through cable tunnels, located in the front and rear of the rover, that kept the cabling insulated for a long length (approximately 0.5 m) inside the WEB prior to the egress. The cable tunnels were insulated with rigid polyurethane foam. Thermal losses through the flex cables accounted for about 15% of the total heat leak from the WEB.

Coax cables that ran from telecommunications equipment inside the WEB to antennas on the RED and lander also had a considerable amount of copper in them. The heat leak through the coax cables was limited by using the minimum diameter coax line that gave acceptable radio frequency (RF) performance. In addition, RF cables were also insulated inside the WEB for a long as possible, before the exited the WEB. Coax cable losses 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 switch closed and heat was rejected from the battery to a radiator on the outside of the rover. When the switch was below the paraffin melt point, it remained open with a gap between the hot and cold sides of the switch. The 1.3 mm gap was maximized to limit the amount of heat leak that could occur through the switch when it was in the open position. Gas conduction in the 10 torr $CO2$ 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 HRS cruise pumped loop cooling system required metal tubing to pass fluid from the radiators on the cruise stage into the electronics housed inside the rover. The tubing that was attached to heat transfer surfaces inside the WEB was made of aluminum. In an effort to minimize the heat leak through the HRS tubes that crossed the insulated WEB, that section of tubing was made of lower 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 tubular struts with Ti fittings to the external WEB and RED structure. The REM and battery struts were fabricated of high stiffness, low-conductivity Boron/Epoxy composite material and the Mini-TES struts were made of glass-epoxy material. Strut length was maximized and cross-sectional area minimized in an effort to reduce the thermal leak to the external WEB and RED structures. 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 telescope extended from the inside of the WEB up into the RED fitting that held the Pancam mast to the top of the rover. As such, 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. In addition, the battery had a warmup heater (also controlled by a mechanical thermostat) to allow the battery to warm up in the early morning prior to charging. Charging efficiency was improved when the battery was above 0°C. All heaters had primary and backup strings with series redundant thermostats. Thermostats had a dead band of approximately 3°C to 5°C. Mechanical thermostats were used in this application, instead of computer controlled thermostats for two main reasons: 1) computer-controlled thermostats would be inactivated when the computer was turned off during most of the night, leaving the hardware unprotected and 2) mechanical thermostats were considered to be more robust in case of a computer reset. 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, a non-electrical heat source was used to help keep the REM and battery warm at night. Two radioisotope heater units (RHUs) were mounted to the WEB 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 were also enough to overheat the battery during the day (depending on how much internal heat was dissipated inside the WEB form 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. The heat switch was a modified from a vacuum space application for use in the Mars 10 torr CO_2 atmosphere environment. Specifically, the gap between the hot side of the switch and the cold side of the switch was increased from 0.13 mm to 1.3 mm in an effort to reduce the gas gap conduction when the switch was in its open condition. When the battery was colder than the switch setpoint (<18°C), the switch remained open (conductance = 0.017 W/°C) and the RHU heat remained on the battery. When the battery was warmer than the setpoint (>18°C), the switch closed (conductance ramping up quickly to 1.0 W/°C with the hot side at 20°C) and the RHU heat was dumped outside the WEB to external radiators. The aluminum radiators were painted white and shielded from direct midday sun by the solar arrays.

Earlier designs of the rover had included a loop heat pipe attached to the SSPA (the highest heat dissipater inside the WEB) to allow daytime heat rejection from that unit to an external radiator (Birur, et al., 2002; Pauken, et al., 2002). The loop heat pipe would have enabled an unlimited amount of X-band communications downlink time without overheating the unit. The loop heat pipe was taken out of the design in an effort to reduce the complexity, mass and cost of the rover thermal design. The project was willing to accept limited downlink times (a maximum of 3 hours) based on the capability of the thermal mass in the WEB to absorb heat.

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 temp limits 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. Two stereo camera pairs are located at the top of the Pancam mast: a left and right Pancam science/panoramic camera pair and a left and right Navcam engineering/navigation camera pair (see Figure 3). There are 2 more stereo camera pairs attached to the front and back of the WEB structure under the solar arrays: a left and right forward Hazcam engineering/hazard camera pair and a left and right aft Hazcam engineering/hazard camera pair. The last camera, attached to the end of the robotic science arm known as the Instrument Deploy Device (IDD), is the microscopic imager. All of these cameras are identical in design except for their lens assemblies.

The camera electronics and CCD housings are covered in silvered Teflon tape to prevent them from overheating in the sun. The CCD housings are hard mounted directly to their interfaces. The camera electronics boards must be heated up to –55°C within one hour prior to early morning operation. In the interest of minimizing camera warmup heater size, the boards were isolated from the housings by low conductance G-10 washers and the electronics housings were isolated from their mounting interfaces with Ti standoffs. Warmup heaters consisted of wire-wound resistors mounted directly on the camera electronics boards. The Pancam and Navcam cameras up at the top of the Pancam mast (with a good view to the sky), had larger heaters than the cameras tucked under the solar array (with a poor view to the cold sky), the Hazcams and Microimager. Heaters were sized to allow warmup of the boards from –95°C to –55°C within an hour.

There are 34 actuators (gear/motors) on the flight rover. All actuators have a minimum operating AFT of –55°C. The viscosity of the "wet" Braycote lubricant, which increases dramatically at –70°C, drives the minimum temperature requirement. Since many of the actuators will be 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. Actuators that will get sun exposure were covered in silvered Teflon tape (low absorptivity/emissivity ratio material) to keep them cool in the sun. Actuators heaters were designed such that if they were left on continuously, they would not heat the actuators over the 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 –30°C.

The graphite/epoxy composite PMA mast is bolted to a Ti fixture on the top of the RED. The bottom of the PMA is hollow to allow the Mini-TES instrument in the WEB to look up the mast, through two mirrors and out to the Mars scene. The inside of the mast is painted black to reduce stray IR emissions. The entire outside of the mast is painted white (S-13-GP/LO-1) to minimize the temperature gradients on the hardware.

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 PMA was designed to operate at any time during the day or night. Science desires requested the ability to take Mini-TES infrared images during the night and to take early morning (6AM) sunrise pictures with the visible wavelength cameras.

The HGA has 2 actuators, one for the azimuth and one for the elevation. Desire for early morning (7:30AM) 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 rover is capable of speeds up to 5 cm/sec and a maximum traverse of 100 m per day.

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 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 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 will be 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 are stowed to fit inside the tetrahedral lander. After landing, the launch restraints on the panels are cut and the panels are 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.

An additional consideration in the rover thermal design was the thermal control of the shunt radiator. The shunt radiator dissipates excess energy coming off the solar panels that is not being used by loads on the power bus or stored in the battery. The maximum power dissipation for the rover shunt heater is 105W. The shunt heater consists of 2 kapton film heaters mounted to the bottom facesheets of the left and right primary deployable solar panels. Each element or stage is capable of handling the entire 105W load, thus making the system functionally redundant. The graphite-epoxy solar array facesheets are very thin and have a low thermal conductivity. This results in the need for a heater that covers a large area to keep the resulting temperatures below the solar array structure maximum AFT of 90°C. The heater elements are covered with silvered Teflon tape (high emissivity) to allow thermal radiation to the ground and keep the panels from overheating.

ANALYTICAL THERMAL MODEL PERFORMANCE PREDICTIONS

Analytical thermal models of the rover and its external components were developed initially in the design stages of the project. As the design neared maturity, the analytical models increased in detail and complexity. For instance, the main rover model that included the WEB, internal WEB hardware and the solar array, grew in size to over 2000 nodes. After a high fidelity thermal characterization test of an engineering model version of the rover hardware, the model was reduced in size (to 100 nodes) and correlated to the test data.

Analytical thermal models are extremely important in the design development and verification of Mars surface operations performance. It is virtually impossible to precisely reproduce the Mars thermal environment in a thermal chamber here on Earth. It is much easier to correlate an analytical thermal model to known and controlled chamber conditions that come close to simulating the Mars environment and then analytically fill in the missing details to predict actual Mars surface performance. The key differences between the test chamber environment and the actual Mars surface environment are listed below:

1) Chamber atmosphere was 8 torr GN2 (to prevent chamber pressure problems associated with having CO2 condense, freeze out and sublimate on cold chamber shroud inlet lines) whereas the Mars atmosphere is 8 torr CO2. This difference increases gas conduction and free convection and decreases insulation performance during the test.
2) The acceleration due to gravity on Earth is 1 G, whereas the Mars gravitational constant is 3/8 G. This difference increases the free convection inside the chamber.
3) There was no solar simulation during the test. At best, the solar simulator could only illuminate the top of the rover and could not simulate the sweep of the sun across the sky at all sun angles.
4) The temperature of the shrouds drove the atmosphere temperatures inside the chamber. On Mars the rover has a view to the ground and a view to the sky that run at vastly different temperatures. Having to drive the atmosphere temperature inside the chamber with the shrouds results in differences in the radiative boundary condition for the rover between test and Mars operations.
5) No wind simulation was used in the chamber. Running fans inside a chamber at low pressures is difficult due to accelerated motor brush wear, motor overheating problems and an inability to accurately measure wind speed (Johnson, et al., 1996). Free convection control plates were used to understand the approximate free convection coefficients on the outside of the rover.

Because of these testing limitations, it is difficult to get a direct empirical validation of a Mars surface thermal design directly from chamber data. Instead the validation must come from a correlated analytical model that has the precise Mars environment details put back into the model.

A reduced-node SINDA/Fluint thermal model was used to correlate to the test data. Both TSS (Thermal Synthesizer System) and TAS (Thermal Analysis System) were used to create the model. Simplifying the geometry of the much larger system-level thermal model allowed the creation of a 100-node reduced model. Before the model correlation process began, analytical test cases were run to ensure that the 100-node model agreed well with the 2000-node, system-level thermal model. Running the 100-node model through both hot and cold transient Mars diurnal scenarios validated that both models agreed to within 5°C.

The analytical thermal model was correlated to test data by first adjusting conductances in the model so that it agreed with hot and cold steady state test data. Then, capacitances in the model were adjusted until the model predicts in the diurnal warmup and cooldown transient cases agreed with test data. After model correlation, test data and predicts for most major entities of the model agreed to within 5°C.

Figure 8 shows the temperature predicts from the correlated reduced model in the worst-case Mars cold environment with the low-energy (432 W*hrs) operational scenario. Note that the Mini-TES instrument runs much cooler than the rest of the hardware because of its low thermal mass, its thermal isolation to the rest of the hardware and its significant heat losses up the Pancam mast. All hardware is predicted to stay within AFT limits with margin. The only survival heater that comes on at night is that for the Mini-TES instrument. Additional heater energy is expended in the early morning to warm the battery up prior to charging. The nighttime energy expended to keep the WEB hardware from exceeding minimum temp limits is only 70 W*hrs (well under the nighttime maximum allowable allocation of 120 W*hrs).

Figure 9 shows the temperature predicts from the correlated reduced model in the worst-case Mars hot environment with the high-energy (742 W*hrs) operational scenario. This scenario includes two X-band downlink sessions of two hours each, from 8AM to 10AM and from 12:30PM to 2:30PM that result in a predicted peak SSPA temperature of 47°C. This is still 3°C under the max AFT of the SSPA, and exceeds the desired downlink duration capability by one hour. The battery temperature peaks at 25°C when the thermal switch closes and dumps excess heat to the Mars environment.

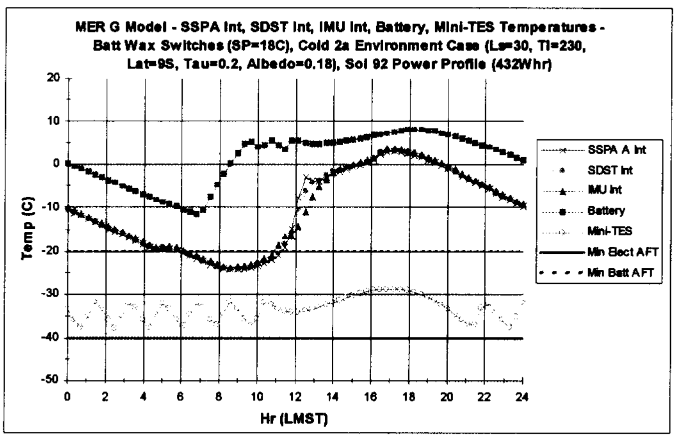

FIGURE 8. MER Internal Hardware Temperature Predicts from Correlated Model In Cold Environment Case

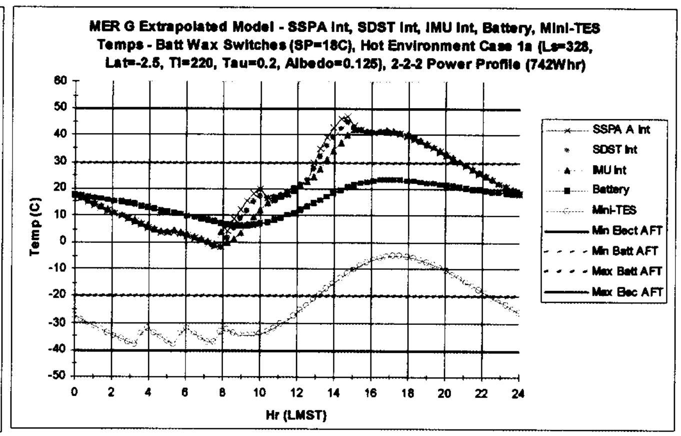

FIGURE 9. MER Internal Hardware Temperature Predicts from Correlated Model In Hot Environment Case

Analytical thermal model predicts for the external rover components were also completed with correlated thermal models. Camera and actuator warmup times met or exceeded requirements. In addition, no cameras or actuators were predicted to exceed maximum AFT limits during worst-case surface operations in the hottest design environment.

CONCLUSIONS

The thermal design strategies discussed above resulted in a highly successful rover thermal design that exceeded design requirements in both the hot and cold environments. An analytical thermal model was correlated to test data obtained from a highly flight-like engineering model rover. The analytical model was run in both hot and cold worst-case thermal environments. Results indicate that the rover will require only 60 % of the energy available for nighttime heating in the cold case environment. Hot case results indicate that 4 hours of direct-to–Earth communications are possible without exceeding maximum allowable temperature limits. This hot case performance provides a full hour of communications beyond the system requirement of 3 hours.

Additional thermal performance data will be obtained in November 2002 when the first flight rover thermal system test is performed. Results of that test are not expected to be significantly different from the results obtained in the engineering model test. The true test of the rover thermal design will occur in January of 2004 when the first MER rover drives off the lander to begin its primary mission for 90 days of Mars exploration.

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