

Thermal Performance of the Mars Science Laboratory Rover during Mars Surface Operations

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On November 26, 2011, NASA launched a large (900 kg) rover as part of the Mars Science Laboratory (MSL) mission to Mars. Eight months later, on August 5, 2012, the MSL rover (Curiosity) successfully touched down on the surface of Mars. As of the writing of this paper, the rover had completed over 200 Sols of Mars surface operations in the Gale Crater landing site (4.5°S latitude). This paper describes the thermal performance of the MSL Rover during the early part of its two Earth-year (670 Sols) prime surface mission. Curiosity landed in Gale Crater during early Spring (Ls=151) in the Southern Hemisphere of Mars. This paper discusses the thermal performance of the rover from landing day (Sol 0) through Summer Solstice (Sol 197) and out to Sol 204. The rover surface thermal design performance was very close to pre-landing predictions. The very successful thermal design allowed a high level of operational power dissipation immediately after landing without overheating and required a minimal amount of survival heating. Early morning operations of cameras and actuators were aided by successful heating activities. MSL rover surface operations thermal experiences are discussed in this paper. Conclusions about the rover surface operations thermal performance are also presented.

Nomenclature

<i>AFT</i>	= Allowable Flight Temperature
<i>APXS</i>	= Alpha Particle X-Ray Spectrometer
<i>CCBU</i>	= ChemCam Body Unit
<i>CCMU</i>	= ChemCam Mast Unit
<i>ChemCam</i>	= Chemistry and Camera Instrument
<i>CheMin</i>	= Chemistry and Mineralogy Instrument
<i>CHIMRA</i>	= Collection and Handling for In-situ Martian Rock Analysis
<i>CO₂</i>	= Carbon Dioxide Gas
<i>CFD</i>	= Computational Fluid Dynamics
<i>CTE</i>	= Coefficient of Thermal Expansion
<i>DAN</i>	= Dynamic Albedo of Neutrons Instrument
<i>DE</i>	= Detector Electronics (part of DAN instrument)
<i>DRT</i>	= Dust Removal Tool
<i>DTE</i>	= Direct-to-Earth
<i>EDL</i>	= Entry, Descent and Landing
<i>EVR</i>	= Event Record

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<i>FOD</i>	= Foreign Object Debris
<i>FSW</i>	= Flight Software
<i>FTA</i>	= First Time Activity
<i>GCM</i>	= Global Circulation Model
<i>Hazcam</i>	= Hazard Avoidance Cameras
<i>HGA</i>	= High Gain Antenna
<i>HRS</i>	= Heat Rejection System
<i>JPL</i>	= Jet Propulsion Laboratory
<i>LGA</i>	= Low Gain Antenna
<i>LMST</i>	= Local Mean Solar Time
<i>Ls</i>	= Solar Longitude
<i>MAHLI</i>	= Mars Hand Lens Imager
<i>MARDI</i>	= Mars Descent Imager
<i>Mastcam</i>	= Mast Camera
<i>MMRTG</i>	= Multi-Mission Radioisotope Thermoelectric Generator
<i>MSL</i>	= Mars Science Laboratory
<i>NASA</i>	= National Aeronautics and Space Administration
<i>Navcam</i>	= Navigation Camera
<i>PNG</i>	= Pulsed Neutron Generator (part of DAN instrument)
<i>PRT</i>	= Platinum Resistance Thermometer
<i>psia</i>	= pounds per square inch (absolute pressure)
<i>QMS</i>	= Quadrupole Mass Spectrometer (part of SAM instrument)
<i>RA</i>	= Robotic Arm
<i>RAD</i>	= Radiation Assessment Detector
<i>RAMP</i>	= Rover Avionics Mounting Panel
<i>RBAU</i>	= Rover Battery Assembly Unit
<i>RCE</i>	= Rover Compute Element
<i>REMS</i>	= Rover Environmental Monitoring Station
<i>RIMU</i>	= Rover Inertial Measurement Unit
<i>RIPA</i>	= Rover Integrated Pump Assembly
<i>RMCA</i>	= Rover Motor Controller Assembly
<i>RPA</i>	= Rover Power Assembly
<i>RPAM</i>	= Rover Power and Analog Assembly
<i>RPFA</i>	= Rover Pyro Firing Assembly
<i>RSM</i>	= Remote Sensing Mast
<i>RUHF</i>	= Rover Ultra-High Frequency Antenna
<i>SAM</i>	= Sample Analysis at Mars Instrument Suite
<i>SA-SPaH</i>	= Sample Acquisition - Sample Processing and Handling
<i>SDST</i>	= Small Deep Space Transponder
<i>SOC</i>	= State of Charge
<i>Sol</i>	= Day on Mars (duration is 24.66 Earth hours)
<i>SSPA</i>	= Solid State Power Amplifier
<i>STT</i>	= System Thermal Test
<i>THEMIS</i>	= Thermal Emission Imaging System
<i>UHF</i>	= Ultra-High Frequency

I. Introduction

NASA launched the Mars Science Laboratory (MSL) Rover to Mars on November 26, 2011. The MSL rover successfully touched down on the surface of Mars on August 5, 2012. The MSL rover has currently operated for more than 200 Sols during its quest to robotically explore the Gale Crater landing site (at 4.5°S latitude) and determine the planet's ability to support microbial life in the past or present. In order to investigate the question of Mars habitability, the rover is equipped with 10 science instruments. These science instruments are performing investigations to accomplish the 4 main science objectives of the MSL mission: 1) look for organic carbon compounds, 2) characterize the geology of the landing site, 3) investigate the processes that could have made Mars habitable in the past (including the influence of water) and 4) characterize the radiation environment of Mars.

The Rover landed on Sol 0 in early Spring (Ls=151) at the Gale Crater landing site and has recently completed Summer Solstice (Ls=270) operations on Sol 197. This paper describes the outstanding thermal performance the MSL Rover during the first 204 Sols of the planned (670 Sol) prime surface mission.

A. Brief Description of MSL Rover

When the rover is fully deployed on Mars, it has a wheelbase of 2.8 m long and 2.3 m wide, and a ground clearance of more than 60 cm. Engineering hardware, located on the outside of the Rover, is shown in Figure 1. The mobility system, which has 6 drive motors and 4 steer motors, allows the rover to traverse the Mars surface and access high value science targets. The Remote Sensing Mast (RSM), which supports Mastcam and ChemCam, stands 2.2 m above the ground. The Rover Pyro Firing Assembly (RPFA) was responsible for firing all rover launch locks and pyro release devices during Entry Descent and Landing (EDL) and after landing. There are 3 external telecommunications antennas, two operating in the X-band (the LGA and the HGA) and one in the UHF-band (the RUHF). Direct-to Earth (DTE) communications are done in the X-band and rover-to-Mars-orbiter communications are done in the UHF-band. The rover is powered by a nuclear power source, the MMRTG, which produces 110W of electrical power and 2000W of thermal waste heat. The Sample Acquisition-Sample Processing and Handling (SA-SPaH) subsystem is responsible for collecting, processing and delivering Mars soil and pulverized rock samples to the analytical science instruments (SAM and CheMin) located inside the rover chassis. The largest element of the SA-SPaH is a 5-degree-of-freedom Robotic Arm (RA). Two science instruments are mounted on the RA turret, APXS and MAHLI, along with 3 engineering mechanisms that are part of SA-SPaH: the percussive Drill, the Collection and Handling for Interior Martian Rock Analysis (CHIMRA) and the Dust Removal Tool (DRT). The percussive Drill penetrates and pulverizes rocks, creating powdered rock samples that are transferred to the CHIMRA. The CHIMRA has internal sieves that sort samples into fines and portions them before transfer into the analytical instruments. Inlet covers on the top deck of the rover open to allow sample to be deposited into the inlet funnels of SAM and CheMin. The DRT brushes surface dust off of rock targets to allow contact science on the rock external surfaces.

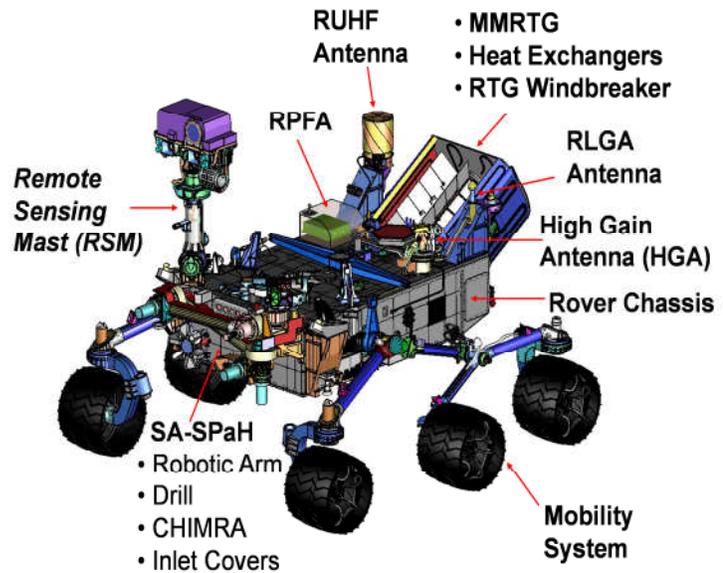


Figure 1. MSL Rover and External Engineering Hardware.

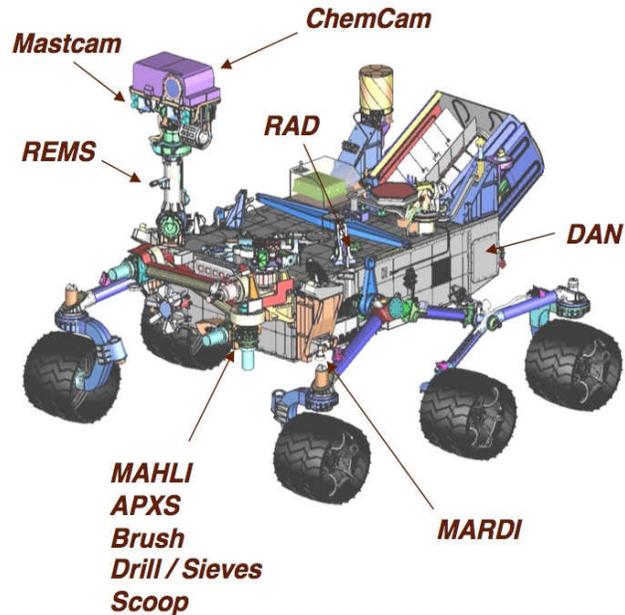


Figure 2. MSL Rover and External Science Instruments.

There are 10 science instruments located on the rover. Figure 2 shows an external view of the MSL Rover highlighting the externally-mounted science instrument sensors. The science instruments cover a range of science investigation types:

- 1) Remote Sensing - (Mastcam and ChemCam),
- 2) Contact Science - (MAHLI and APXS),

- 3) Laboratory Sample Analysis - (SAM and CheMin, located inside the Rover body as shown in Figure 3), and
- 4) Environmental Sensing - (MARDI, REMS, RAD and DAN).

All of the temperature-sensitive science instruments and avionics are mounted inside the rover chassis as shown in Figure 3. This figure shows a view of the internal box configuration that one would see, looking up from the ground, after removing the rover belly pan. All of the boxes shown in Figure 3 are hard-mounted to the Rover Avionics Mounting Panel (RAMP) that serves as the main structural support inside the chassis. The RAMP is suspended below the rover top deck by a number of low thermal conductance flexures. Science instrument boxes bolted to the RAMP include: the SAM and CheMin instruments, electronics boxes for the APXS, REMS and RAD sensors, the ChemCam Body Unit (CCBU) that houses the ChemCam spectrometers, and the electronics for all of the science cameras (Mascam, MAHLI and MARDI). The DAN instrument has a Pulsed Neutron Generator (PNG) and Detector Electronics (DE) housed in the chassis compartments on either side of the MMRTG mounting struts. Engineering boxes that are mounted to the RAMP include: the telecommunications boxes (UHF Electra-Lite radio, the X-band power amplifier (SSPA) and transponder (SDST)), the rover avionics boxes (the redundant flight computers (RCEs), the power and switching boxes (the RPA and RPAMs), the Rover Motor Controller Assembly (RMCA) and the Rover Inertial Measurement Units (RIMUs)). Two 42-A-hr, Li-ion batteries, also mounted to the RAMP, make up the Rover Battery Assembly Unit (RBAU), used to store electrical energy produced by the MMRTG. The final major hardware element mounted to the RAMP is the Rover Integrated Pump Assembly (RIPA). The RIPA, at the heart of the Rover Heat Rejection System (HRS), pumps liquid Freon through tubing imbedded in the RAMP to remove or replace heat as needed. The MSL Rover HRS is described in more detail in the next section.

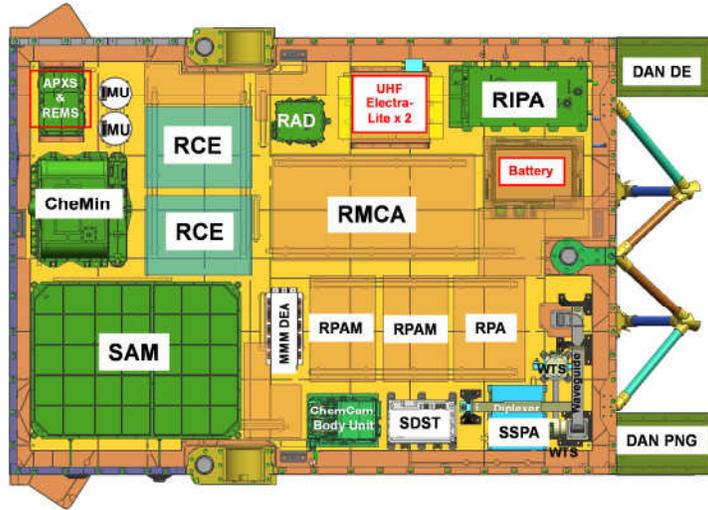


Figure 3. MSL Rover Science and Avionics Mounted on RAMP

B. Brief Description of MSL Rover Thermal Design

The rover internal hardware mounted on the Rover Avionics Mounting Plate (RAMP) has allowable flight temperature (AFT) limits of -40°C to $+50^{\circ}\text{C}$. RAMP-mounted boxes were qualified to operate over the wider temperature range of -55°C to $+70^{\circ}\text{C}$. In order to keep the RAMP mounted avionics and science boxes within their AFT limits during flight, heat must be provided to them when they are powered down and the environment is cold and heat must be removed from them when they are powered on and the environment is warm. The Rover HRS performs the functions of providing heat in the cold cases and rejecting heat in the hot cases. Papers describing the function of the Rover HRS in detail have been previously published.¹⁻⁸ Figures 7 and 8 are schematics showing the HRS system and its major components. In the cold case, the HRS pumps liquid Freon through tubes in hot plate heat exchangers, located on either side of the MMRTG, to pick up radiated waste heat from the MMRTG and bring it into the RAMP. In the hot case, the Freon flow is directed away from the HRS hot plates (using passively-actuated thermal control valves) and into heat rejection surfaces on the HRS cold plates and the rover top deck. The rover battery, having tighter AFT limits than the rest of the RAMP mounted hardware (-20°C to $+30^{\circ}\text{C}$) has additional survival and warm-up heaters that are controlled by mechanical thermostats. CO₂ gas-gap insulation is used inside the rover chassis to provide thermal resistance between the internal hardware and the rover chassis walls.⁹

There are a total of 221 PRTs read by the rover flight system. Most of these PRTs are redundant and nominally, only half of them can be read by the prime RPAM (A or B string) at one time. The backup RPAM can be commanded into an uninhibited mode in order to read the backup sensors. PRTs are used for temperature

monitoring and for control of FSW-controlled warm-up heaters on the actuators and cameras. Survival heaters must be able to operate when the rover flight computer is asleep, so they are all controlled by mechanical thermostats. There are a total of 24 mechanical thermostats on the rover. Sixteen of those thermostats control survival heaters (primary & backup) for the battery, Rover Pyro Firing Assembly (RPFA), ChemCam Mast Unit (CCMU) & ChemCam Body Unit (CCBU). An additional 4 thermostats control the battery warm-up heaters and 4 more thermostats are used for Rover HRS pump fault protection. If the primary HRS pump fails, and the RAMP exceeds its maximum or minimum Flight Acceptance temperature limits (+55°C or -45°C) the HRS fault protection thermostats will close and turn on the backup pump.

A majority of the hardware mounted on the outside of the rover has been designed and tested to survive the cold nighttime temperatures of Mars without any survival heating. Most of the external hardware has AFT limits of -128°C to +50°C. Notable exceptions to this rule are the RPFA, mounted to the top deck, and the CCMU, mounted at the top of the RSM which have AFT limits from -40°C to +50°C. Survival heaters are used to keep these external boxes warm at night.

There are a number of hardware mechanisms and cameras on the outside of the vehicle that must be warmed up prior to use. While they can survive non-operating cold temperatures (as low as -128°C), they have minimum operating temperatures between -55°C and -40°C. The four science cameras (2 Mastcam, 1 MARDI and 1 MAHLI) and twelve engineering cameras (4 front Hazcams, 4 rear Hazcams and 4 Navcams) have warm-up heaters to bring them up to operating temperature. The rover also employs 31 electric-motor driven rotary actuators to perform a variety of engineering and science functions including: mobility, camera pointing, telecommunications antenna steering, soil and rock sample acquisition and sample processing. When the Martian environment is cold, warm-up heaters are required to bring the actuators up to temperature (above -55°C) prior to use. A previously published paper describes the MSL actuator thermal design, testing and performance in detail.¹⁰ Actuator and camera warm-up heaters are controlled by Flight Software (FSW) running on the Rover Compute Element (RCE) boxes.

Prior to launch, the Rover was thermally tested in simulated cruise and surface environments during the Rover System Thermal Test (STT).¹¹ Analytical thermal models, correlated to STT test results, were subjected to the Gale Crater environments (solar loads, atmosphere, ground and sky temperature boundary conditions, assumed operational and sleep power profiles, with appropriate dust coverage and wind assumptions) to generate pre-landing, flight performance predictions.

II. Typical Environment and Power Profile

There are two main factors that influence the temperatures experienced on the inside and outside of the rover: the external Mars environment and the power dissipation profile of the hardware inside the rover. The REMS instrument was designed to measure atmosphere and ground temperatures as well as wind direction and wind speeds. During the landing event, a significant amount of soil and small rocks was excavated from the landing site, by exhaust from the Main Landing Engines, and subsequently re-deposited on the top deck of the rover. During that shower of soil and pebbles, two of the six REMS wind sensors were damaged and are not useable. Loss of these two sensors has necessitated a rework of the REMS software used to process wind data. Limited wind data has been available so far from the REMS instrument.

REMS atmosphere and ground temperature data is being made available to the engineering team on a daily basis. Figure 4 shows a typical plot of the ground and atmosphere temperature data on Sols 9 & 10 (blue and red data points) along with the predicted environment temperatures (solid lines in red, blue and purple) from a pre-landing run of the Mars Global Circulation Model (GCM). On this Sol, the measured ground temperature varied from a low of -85°C to a high of 9°C. The measured atmosphere temperature varied from a low of -75°C to a high of 0°C. Ground temperature data was found to be fairly close (within 10°C) to the predicted GCM profile. The measured atmosphere temperatures however, were found to be as much as 25°C warmer in the day and 10°C warmer at night than the predicted GCM environment. It is theorized that the higher atmosphere temperatures are due to the warming effect of the MMRTG (at 170°C) on the ambient atmosphere in the immediate vicinity of the rover. Thermal models used to predict rover temperatures were modified to use the latest REMS data for atmosphere temperatures.

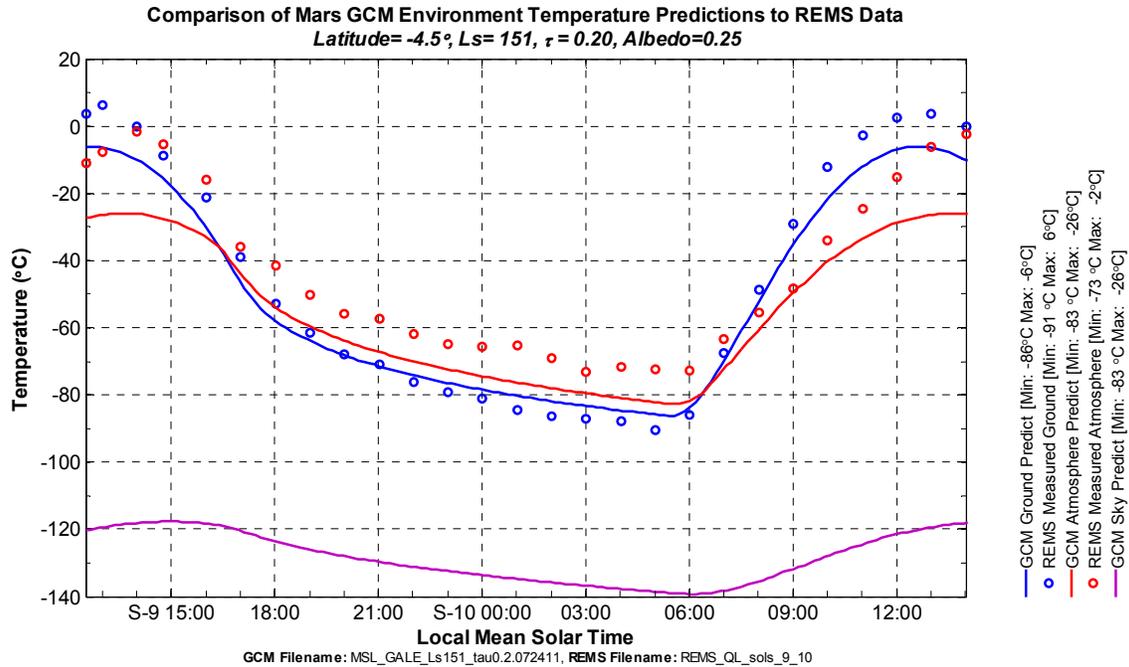


Figure 4. Atmosphere Ground and Sky Temperature Predictions Compared to REMS Flight Data for Sols 9 & 10

The other factor, which drives the internal rover temperatures, is the power profile. A typical daily profile for the rover consists of a daytime (from 09:00 to 16:00 Local Mean Solar Time, LMST) power load on the RAMP of 150W. At night, typically the rover goes to sleep in order to recharge the battery. There are normally 4 UHF downlink communication passes each Sol, two in the early morning around 03:00 LMST and two in the mid-afternoon, around 15:00 LMST. An X-band pass in the morning, around 10:00 LMST, is used to upload the commands to the Rover for the new Sol. Science instrument operations and movements of articulated joints (mobility, RA, RSM, etc.) result in a higher power dissipation inside and outside the rover. Flight experience has shown that the rover internal temperatures are almost the same every Sol. The environment temperatures have been quite repeatable and the HRS is very effective at controlling maximum and minimum temperatures in a fairly tight range (a diurnal variation of about 25°C to 30°C) regardless of the power profile. More detail about HRS performance is in the next section.

III. Mars Surface Flight Performance of HRS and Internal Electronics

The Rover HRS performance during the first 204 Sols of landed operations has been flawless. In the Spring/Summer environment experienced thus far during the mission, the HRS has maintained RAMP temperatures in a very benign temperature range. The RAMP is providing a mounting interface with at least 12°C of margin to the maximum interface AFT limit of 50°C and at least 45°C of margin to the minimum interface AFT limit of -40°C. Initial flight temperature telemetry from the rover internal hardware shortly after landing showed thermal performance that was within 2°C to 5°C of pre-landing predictions for most boxes. Figure 5 shows a comparison of the predicted RAMP temperatures (solid lines), from a pre-landing run of the analytical rover thermal model, and the corresponding flight telemetry (data points with symbols) from Sols 44 & 45. This plot also shows typical diurnal temperature swings on the RAMP, from minimum temperature range of 5°C to 10°C at night to a maximum temperature range of 30°C to 35°C during the day. Note that PRT temperature sensor accuracy was estimated to be +2°C to -3°C.

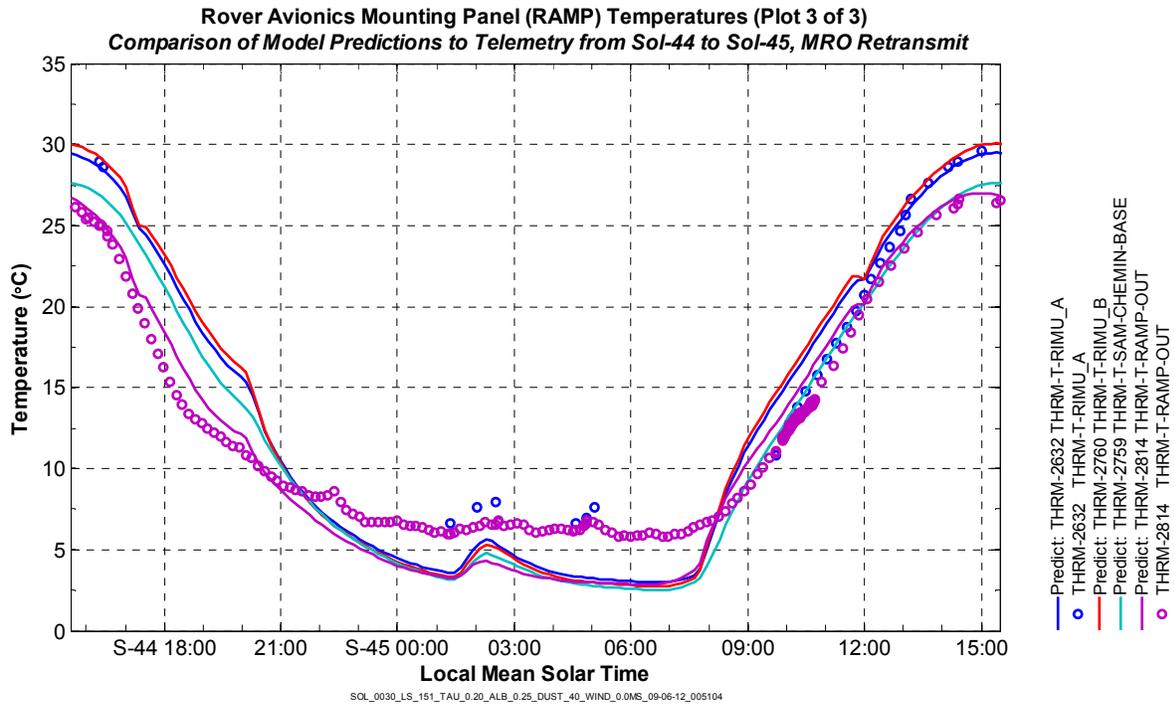


Figure 5. RAMP Temperature Predictions Compared to Flight Telemetry for Sols 44 & 45

The RAMP was nearly isothermal (only a 5°C to 6°C temperature gradient) at all times of day and under all varying power loads. Figure 6 shows the RAMP temperature distribution at the peak of the day (15:06 LMST) on

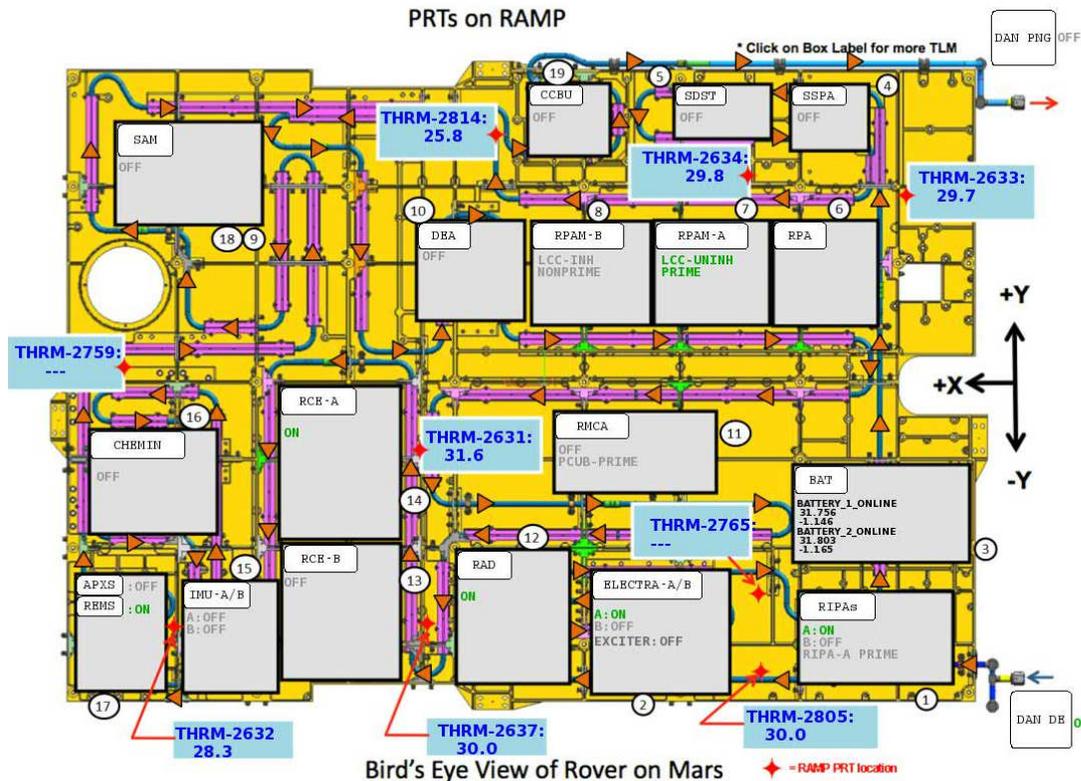


Figure 6. RAMP Temperature Distribution Flight Telemetry for Sol 199 at 15:06 LMST

Sol 199. The maximum temperature on the RAMP was 32°C near the operating flight computer (RCE-A) and the minimum temperature was 26°C near the quiescent CCBU science instrument. RAMP diurnal thermal performance is very repeatable (almost identical from Sol to Sol) in spite of the changing power dissipation profiles. This predictable RAMP performance has made it very easy for Rover planners to determine when to run certain science instruments (e.g., SAM & CheMin) at night to operate with the desired coldest RAMP interface temperatures. Battery and CCBU survival heaters have not turned on yet, since their close setpoints (-20°C for the battery and -45°C for the CCBU) are much lower than the minimum temperature that the RAMP is experiencing at night. In fact, predictions from the rover system analytical thermal model in the worst-case cold, Gale Crater winter environment show that these heaters will never cycle at all during the entire mission. All of the energy needed to keep the RAMP hardware above their minimum AFT limits is provided by the HRS (from MMRTG waste heat delivered to the RAMP); other than the 9W of electrical power needed to run the pump, no electrical heater power is needed to keep hardware warm on the RAMP.

One reason for the repeatability of RAMP temperatures over the Mars diurnal is the performance of the passive mixer and splitter valves in the HRS system.⁴ The mixer valve is responsible for determining the amount of flow in the hot plates and therefore the amount of heat addition into the HRS Freon fluid. At night, when the RAMP needs heat and the mixer valve goes below -10°C, the valve opens up to allow 97% of the flow to go through the hot plates. All indications thus far show that the mixer valve has not opened up much beyond its minimum setting of 55%, because the mixer valve has never gone below 10°C. Figure 7 shows the temperature distribution in the HRS system on a typical Martian night (in this case, at 03:20 LMST on Sol 199). Inlet fluid to the mixer valve is still above 10°C with the valve open to the hot plates at 55% flow. HRS fluid in the hot plates warms up from an inlet temperature of 18°C on the -Y Hot plate to an outlet temperature of 40°C on the +Y Hot plate. Even though the summertime ambient atmosphere temperature at night is -75°C, the HRS is able to maintain the RAMP temperature above 5°C for the entire night. The mixer valve is expected to open up (beyond the 55% flow level) to the hot plates later in the mission when the rover experiences the cold of the Martian winter (Winter Solstice will be on Sol 544).

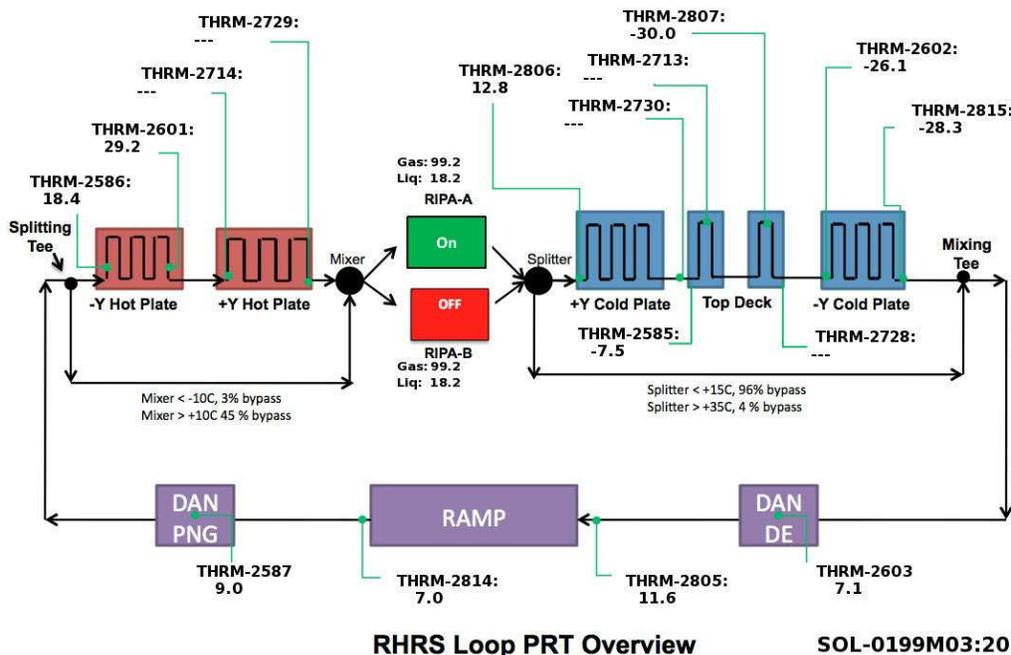


Figure 7. HRS System Temperature Telemetry for Sol 199 at 03:20 LMST (temperatures in °C)

The splitter valve is responsible for determining the amount of flow in the cold plates and top deck, and therefore the amount of heat rejection from the HRS Freon fluid. During the day, when ambient environment temperatures are warm and the total heat dissipation on the RAMP is high, the splitter valve goes above +35°C and the valve opens up to allow 97% of the fluid flow to go through the cold plates and top deck. The splitter valve has been operated

over its entire operating range of +15°C to +35°C so far during the mission. Figure 8 shows the temperature distribution throughout the HRS system on a typical Martian day (in this case, at 15:06 LMST on Sol 199). Inlet fluid to the splitter valve is above 35°C, so the valve is open to the cold plates at a maximum of 97% flow. HRS fluid in the cold plates cools down from an inlet temperature of 43°C on the +Y Cold plate to an outlet temperature of 24°C on the -Y Cold plate.

The diurnal pressure variation inside the HRS system (as measured by the pressure transducer on the gas side of the accumulator) followed the diurnal RAMP temperature profile. Minimum system pressure (between 95 and 100 psia) occurred around 06:00 LMST and maximum system pressure (between 125 and 145 psia) occurred around 15:00 LMST. Thus far, there have been no indications of a leak (which would be evidenced by a slow decrease in system pressure) in the HRS system. Minimum and maximum HRS system pressures between Sols 0 and 204 are shown later in Figure 12.

The repeatability of the HRS performance (and its insensitivity to power profile) has made it completely unnecessary for the thermal team to run the system level model on a daily basis. RAMP temperature predictions for a representative run of the thermal model have been within 5°C to 10°C of the actual temperatures on every Sol since landing.

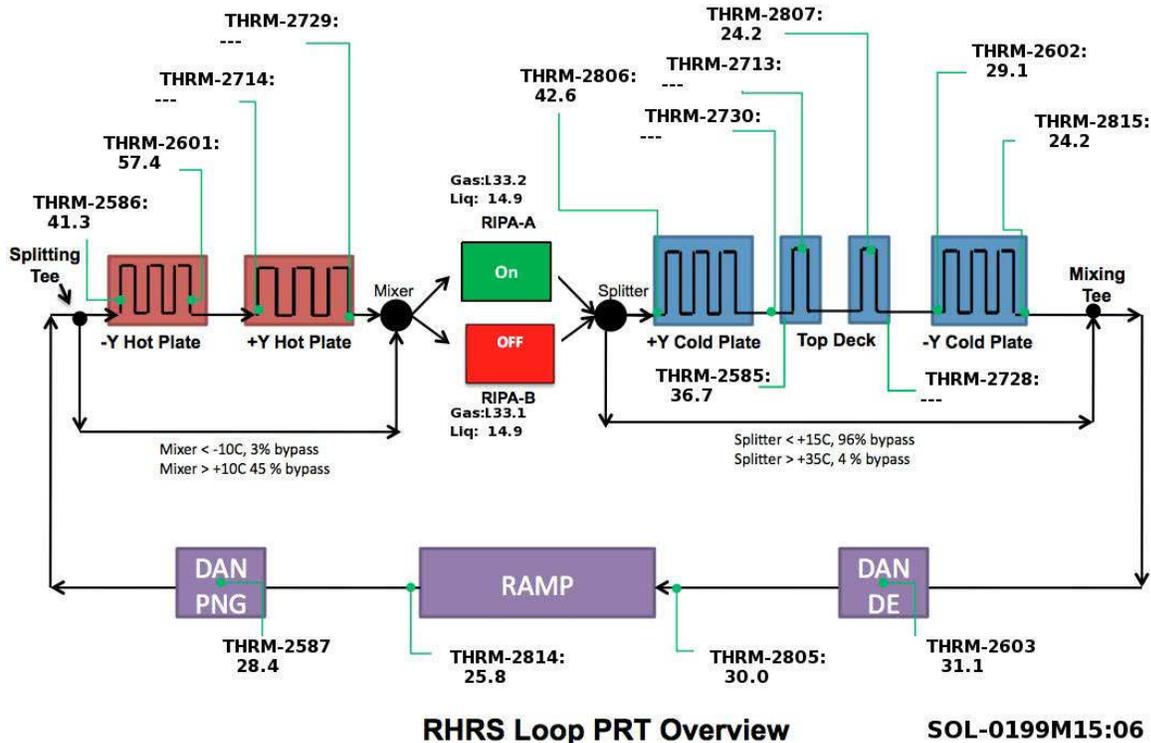


Figure 8. HRS System Temperature Telemetry for Sol 199 at 15:06 LMST (temperatures in °C)

IV. Mars Surface Flight Performance of External Hardware

Most externally mounted hardware on the outside of the rover was designed to survive the Martian night with no survival heat. Two notable exceptions are the RPFA (the pyro firing assembly on the top deck, which has AFT limits of $-40^{\circ}\text{C}/+55^{\circ}\text{C}$) and the CCMU (the science instrument at the top of the RSM, which has AFT limits of $-40^{\circ}\text{C}/+50^{\circ}\text{C}$). The RPFA survival heater was enabled, but never cycled during the mission. The minimum recorded temperature on the RPFA was -30°C and the mechanical thermostat which controlled its survival heater had a close setpoint of -40°C . After all pyros (launch lock releases) were fired and all articulated hardware had completed a First-Time-Activity (FTA), the RPFA was retired and the survival heater was disabled. The CCMU survival heater cycled on the night of Sol 0 and continues to cycle each night between the hours of 21:00 and 08:00 LMST (for about 11 hours each Sol). The CCMU survival heater dissipates 49W at 30.7V. The heater cycles at an average duty cycle of about 20%, consuming about 108 W*hrs of energy per Sol.

All of the actuators and cameras on the outside of the vehicle experience a large diurnal variation in temperature each Sol. Figure 9 shows a typical diurnal cycle for the CHIMRA sample cavity. Symbols on the plot indicate flight data; the solid line shows conservative cold bounding predictions. The peak temperature of 12°C occurs at about 14:00 LMST and the minimum temperature of -70°C at about 05:00 LMST.

While all of the external hardware on the rover can survive a non-operating condition down to a min AFT limit of -128°C , the operating temperatures for cameras and actuators are typically above -55°C . Actuators have a wet lubricant in the gearboxes and bearings that needs to be warmed above -55°C to reduce the viscosity of the lubricant. Cameras have sensitive electronics that needs to be warmed above -55°C prior to use.

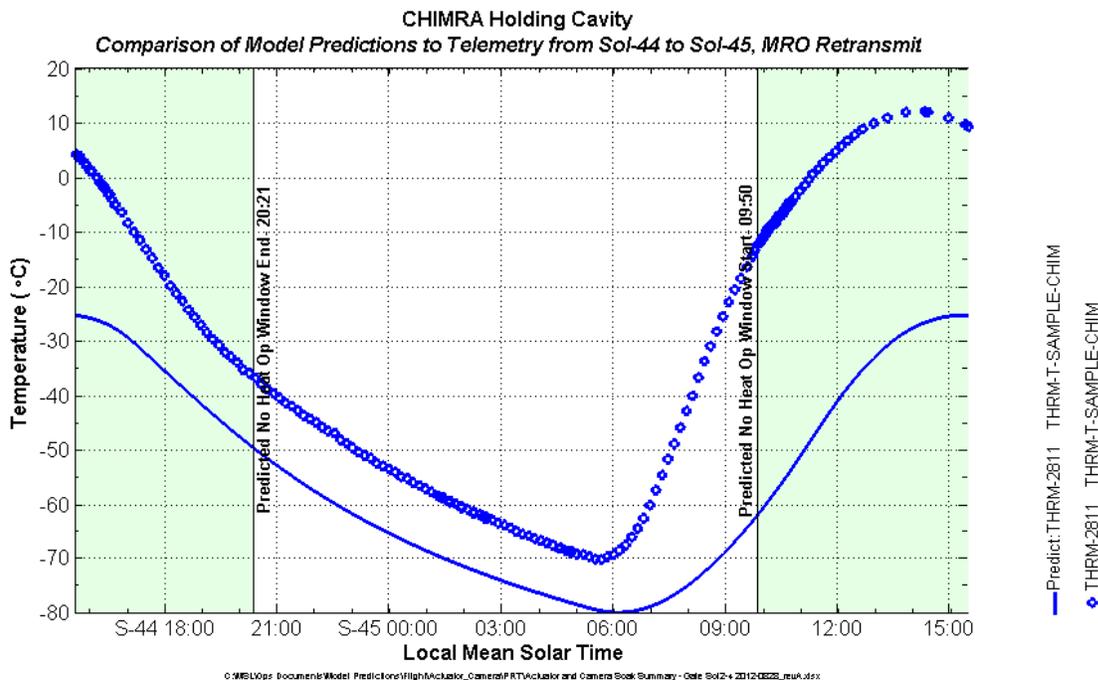


Figure 9. Diurnal Temperature profile for CHIMRA Sample Cavity During Sols 44 & 45

In many cases, rover planners would prefer to wait until hardware is naturally warmed above its minimum operating temperature by the environment. This eliminates the need for a heating command sequence and reduces the energy cost of the camera or actuator activity. However, there are many activities that must be done in the cold nighttime and early morning hours when the hardware is below its minimum operating temperature. In these cases, warm-up heaters must be used to bring the hardware up to operating temperature and hold it there during the operation. A typical warm-up and maintenance heating activity for the MastCam is shown in Figure 10. Prior to the

warm-up, the camera was at -63°C . The minimum operating AFT limit for the MastCam is -40°C . PRTs that are used to provide closed-loop heater control are located on the outside housing of the camera. There are temperature sensitive items inside the housing of the camera that lag in temperature behind the external PRT temperature during the warm-up. In order to account for this temperature lag between the internal and external components and get the fastest warm-up possible (which is also the most energy efficient warm-up), the target setpoint (-21°C) and control

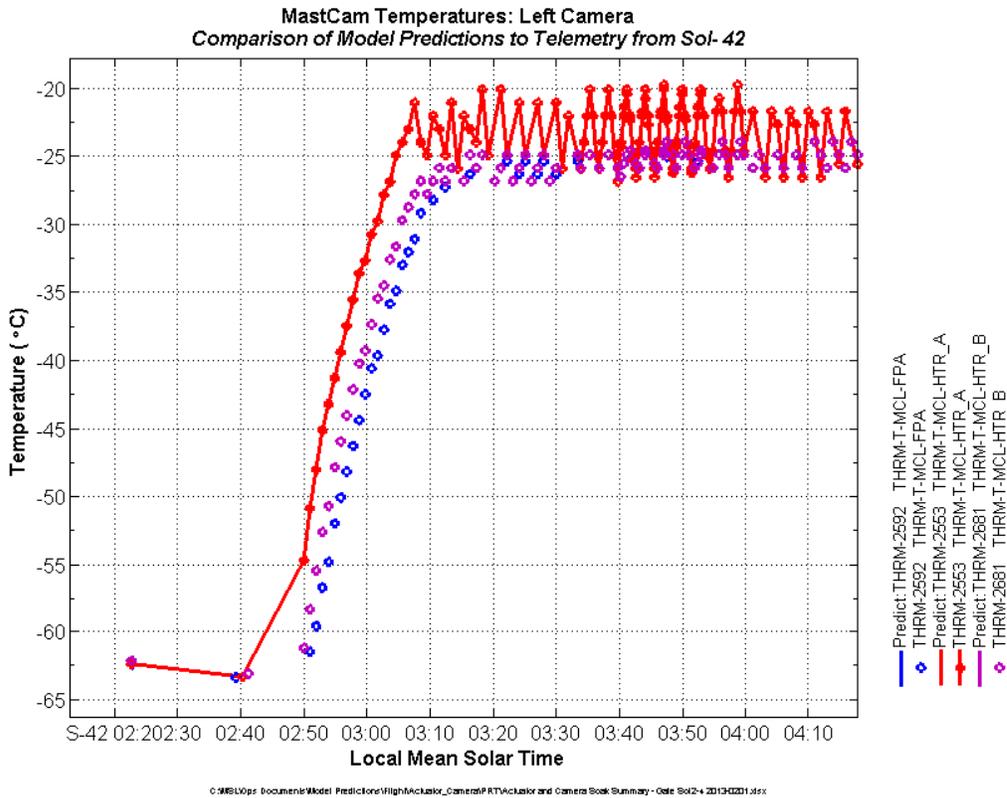


Figure 10. Warm-up of Left MastCam Camera on Sol 42

setpoints (-26°C to -21°C) are set well above the minimum operating limit of -40°C . Analytical thermal models are used to predict the proper target setpoints, warm-up durations and control setpoints. The Mastcam warm-up, starting at 02:49 LMST on Sol 42, raised the control PRT temperature from -63°C to -21°C in 19 minutes. The heater then went into maintenance mode with an approximate duty cycle of 30%.

Assumptions in the Rover STT-correlated, analytical thermal models of cameras and actuators were all biased cold in order to develop heating parameters that were conservative and would guarantee a successful warm-up regardless of rover orientation and bus voltage. Cold-biased assumptions in the analytical model included a worst-case orientation (maximum shade condition), a cold-biased environment, a target setpoint that is at the top of maintenance control range and a bus voltage of 28V. Typical bus voltage in flight was about 32V, so the heaters actually dissipate 30% more heat than the assumed dissipation at 28V. This meant that the pre-heat durations were shorter on the vehicle than they were in the predictions (consuming less energy) and that the maintenance duty cycle on the vehicle was less than predicted. Flight data shows that overall energy consumption for a typical warm-up (pre-heat and maintenance) was about 30% less than predicted. Note that the increased bus voltage (and heater power) has no effect on the maintenance energy consumption; a higher heater power results in a lower duty cycle, and the same overall maintenance energy consumption.

Thus far, no actuator or camera has exceeded its maximum operating AFT limit during surface operations. Actuator motors have maximum operating limits of 85°C . The hottest motor temperature recorded so far has been for the CHIMRA vibe actuator which rose from an initial temperature of -10°C to a peak temperature of 48°C during a 1.5-hour vibe activity on Sol 70. Even during the Deep Drill activity of Sol 182, the peak drill temperature was only 36°C on the Drill feed actuator motor (rose from 10°C to 36°C during the activity). The maximum

recorded science camera temperature (38°C) occurred for the MAHLI camera on Sol 94. The maximum recorded engineering camera temperature (37°C) occurred for the rear Hazcam on Sol 52. Image durations for the Rear Hazcam are usually quite short (about 1 minute), but the hot MMRTG on the rear of the vehicle has a significant heating effect on the rear Hazcam. Peak temperatures on the rear Hazcam (30°C) are typically 10°C warmer than the Front Hazcam (20°C). Minimum temperatures on the rear Hazcam (-40°C) are typically 20°C warmer than the minimum temperatures on the front Hazcam (-60°C). In fact, due to the influence of the MMRTG heat, the rear Hazcam never requires any warm-up heating for the entire Sol.

V. Long-Term Trending Plots of Temperature Telemetry

In addition to querying and plotting diurnal thermal telemetry on a daily basis (each Sol), the Thermal Flight Operations team stores all of the collected thermal telemetry from the vehicle in a database. Each week that database is used to produce long term trending plots, documenting the maximum and minimum temperatures for all hardware sensors each Sol. Long-term trending plots are very useful for: 1) Observing slow general temperature trends in the environment; there was a gradual warming trend from Sol 0 to Sol 200 as the seasons changed from early Spring to Summer, 2) determining repeatability and stability of the temperatures in the system, 3) identifying when collection of backup temperature sensor data had been done; certain temperature sensors are only read when the backup RPAM is uninhibited, 4) determining when the CCBU decontamination heaters came on; the thermostatically controlled decontamination heaters take the CCBU up to 48°C, which is well above its normal daily peak temperature of about 30°C, 5) observing effects of changes in rover orientations on peak temperatures; for example, hardware on the front chassis panel will register higher temperatures when the vehicle is facing west and receiving afternoon solar loads 6) identifying periods of low activity; internal RAMP temperatures were lower during low energy consumption Sols, 7) observing when SAM solid sample analyses were running; the SAM QMS temperature regularly exceeded 100°C during these science operations, 8) determining when the long CHIMRA vibrate activities occurred; vibrate motor temperatures went well above their normal soak temperatures and 9) identifying when changes in surface soil properties had an effect on vehicle temperatures.

Figure 11 shows the long-term trending plot of RAMP temperatures from Sol 0 to Sol 204. Maximum temperatures each Sol are plotted as open symbols. Minimum temperatures each Sol are plotted as solid symbols. The minimum temperatures are very repeatable from Sol to Sol. This repeatability is due to the functioning of the HRS mixer valve which pulls heat in from the MMRTG and keeps the RAMP from dropping below 5°C. There is

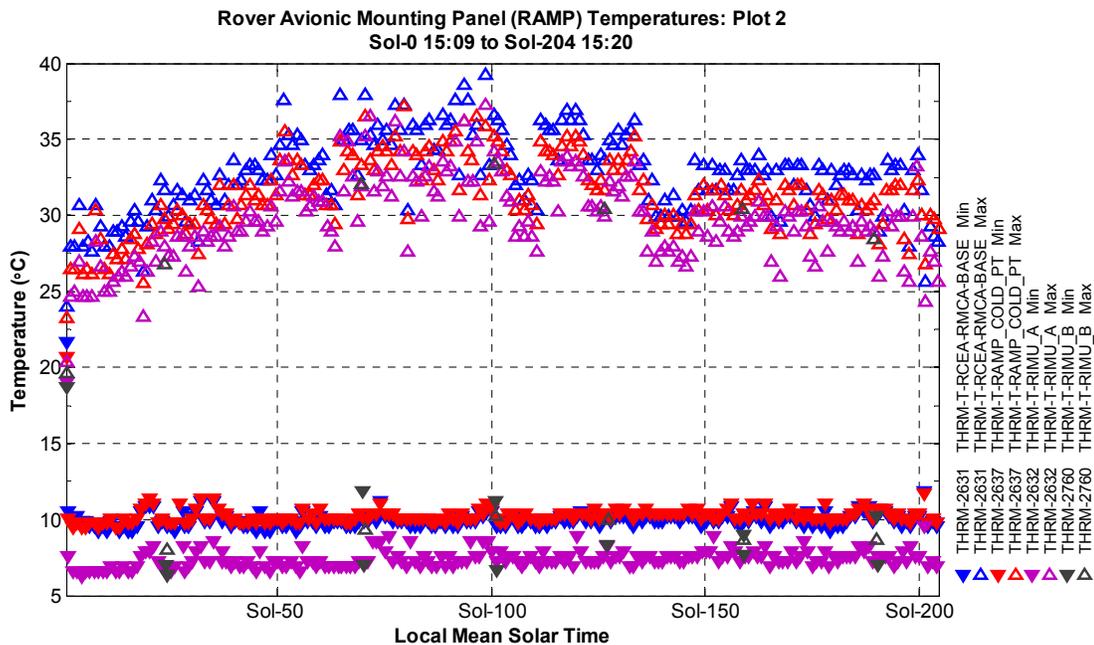


Figure 11. Long-Term Trending Plot of RAMP Temperatures from Sol 0 to Sol 204

much more scatter in the maximum temperature on the RAMP each Sol. Peak temperatures are driven more by the power profile on the RAMP which varies from Sol to Sol. A significant dip in the peak temperatures just prior to Sol 150 occurred when the Rover went on Winter Break for a week and activity levels were low. On a high-energy Sol, the rover consumes as much as 3200 W*hrs of energy; on a low-energy Sol the rover only consumes about 1500 W*hrs of energy. The long-term trending plot also shows how much temperature margin the system has to its maximum AFT limit of 50°C (there is 10°C of margin) and to its minimum AFT limit of -40°C (there is 45°C of margin). Note that the MSL Rover thermal subsystem (which landed at 4.5°S latitude) was designed to operate in a much more severe thermal environment at a 27°S latitude in which summer temperatures would have been warmer and winter temperatures would have been much colder.

Figure 12 shows a long-term trending plot of the RIPA accumulator gas-side pressures from Sol 0 to Sol 204. This plot follows a similar trend to that shown in the RAMP temperatures of Figure 11. This similar trend is to be

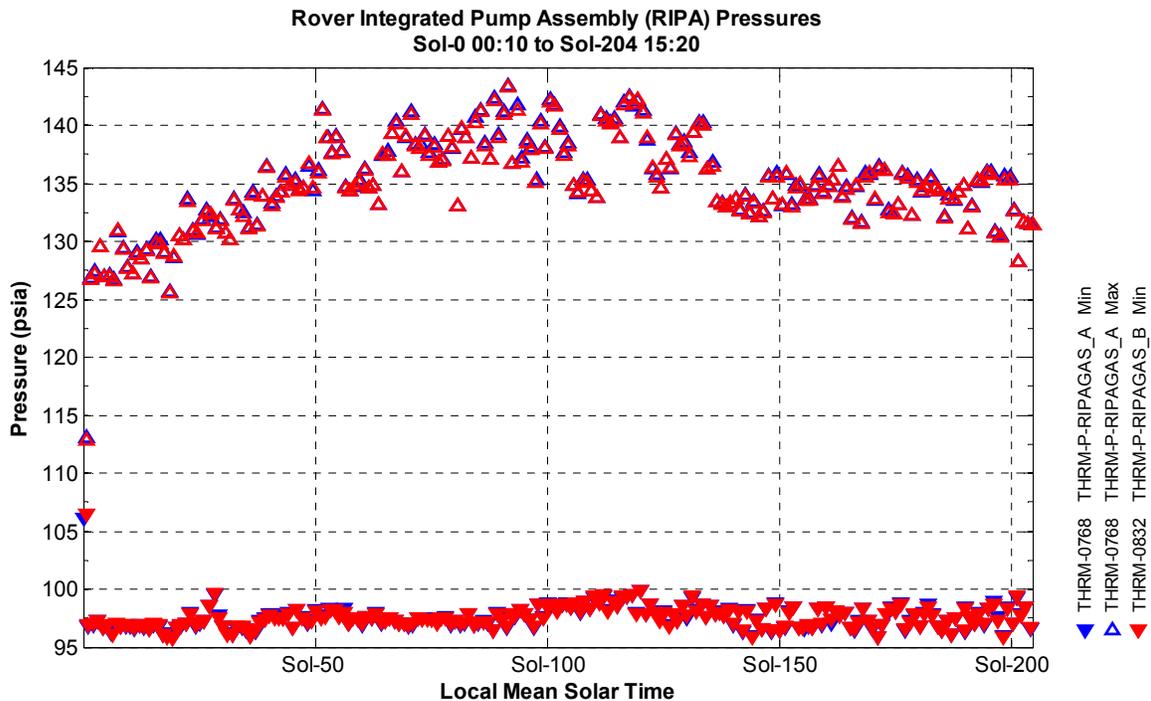


Figure 12. Long-Term Trending Plot of RIPA Pressures from Sol 0 to Sol 204

expected, because the HRS accumulator pressure is driven by the average fluid temperature of the Freon in the system. On days of higher power dissipation on the RAMP, the HRS fluid temperatures and pressure will be higher. There is at least 35 psia of margin between the measured maximum pressure (145 psia) and the maximum allowable pressure of 180 psia. There is at least 30 psia of margin between the measured minimum pressure (95 psia) and the minimum allowable pressure of 65 psia. The fact that the minimum pressures in the HRS system are repeatable each Sol indicates that the system does not have a gross leak.

Figure 13 shows a long-term trending plot of the Front Hazcam temperatures from Sol 0 to Sol 204. This plot shows a similar trend to all of the external hardware items for minimum temperature. Minimum temperatures each Sol are around -60°C, showing at least 68°C of margin to the minimum non-operating AFT limit of -128°C. Maximum temperatures show much more scatter (ranging from -10°C to as much as 32°C). The peak temperature scatter is due to differences in operational power profile and rover orientation. On Sols when the rover drive direction is pointing west, the front Hazcam (located on the rover chassis front panel) will get plenty of afternoon sun exposure that will drive camera soak temperatures higher. On Sols of high operational use, the Front Hazcam will also experience higher temperatures. With a peak temperature of 32°C, the Front Hazcam still has 18°C of margin to its maximum AFT limit of 50°C.

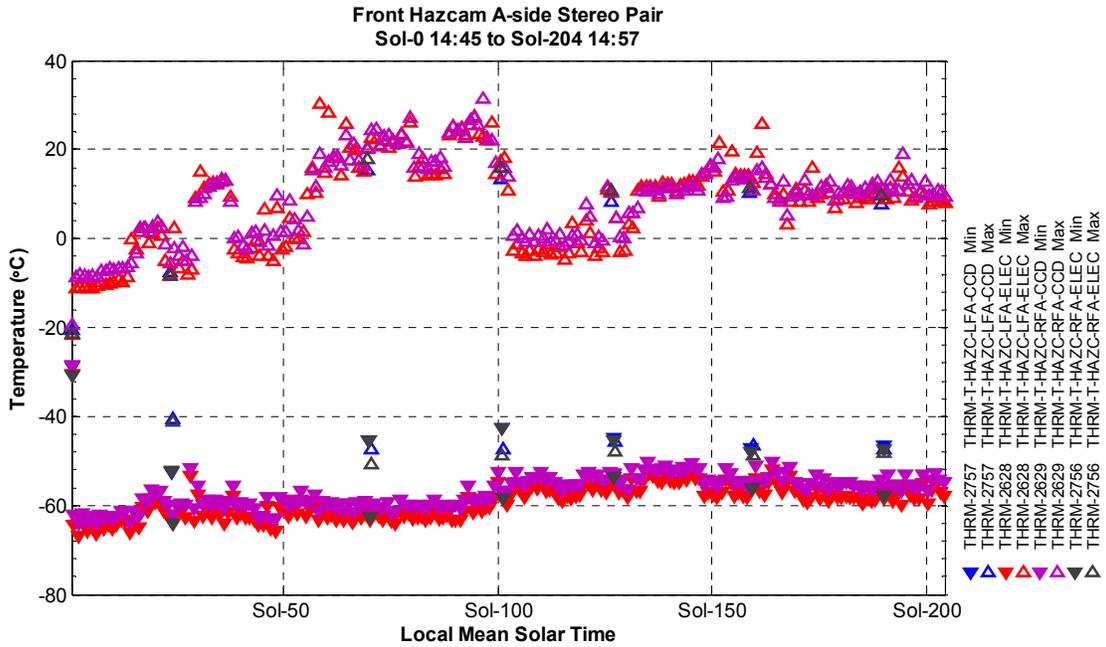


Figure 13. Long-Term Trending Plot of Front Hazcam Temperatures from Sol 0 to Sol 204

Figure 14 shows a long-term trending plot of the MMRTG temperatures from Sol 0 to Sol 204. Peak temperatures indicate a very slight warming trend from Sol 0 to Sol 204 as the rover experiences warmer environment temperatures closer to summer solstice (Sol 197). The maximum temperatures are quite repeatable because the power dissipation of the MMRTG is constant and the early afternoon winds (which could cause significant temperature decreases) are light. The maximum recorded MMRTG temperature was 196°C which is 4°C cooler than the maximum op AFT limit of 200°C. The MMRTG is the hottest hardware element on the entire

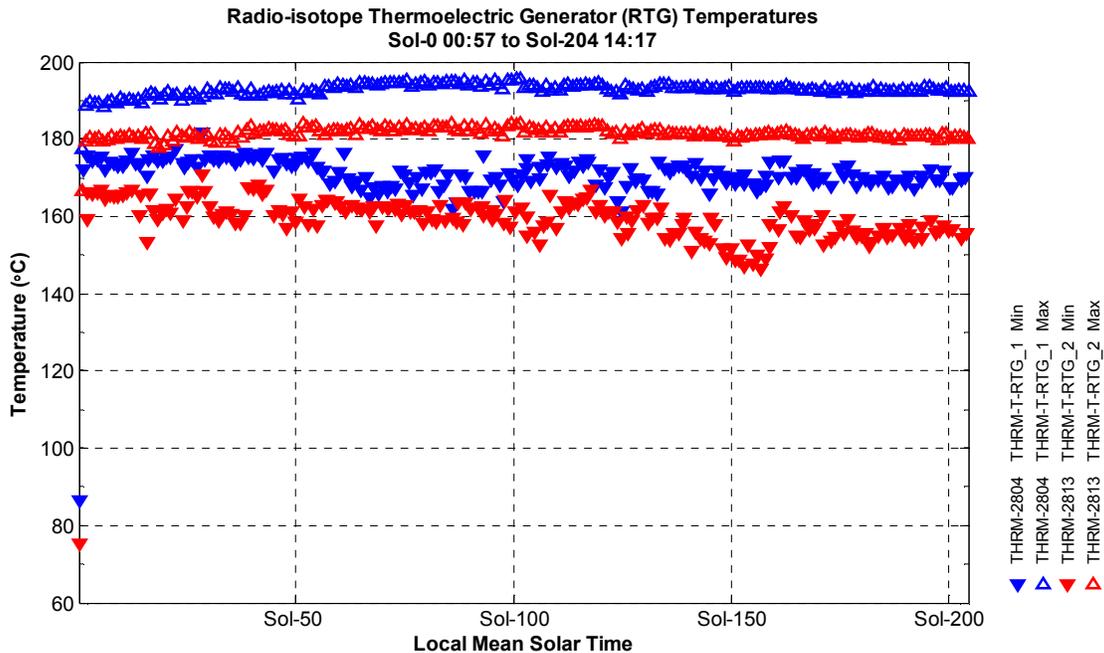


Figure 14. Long-Term Trending Plot of MMRTG Temperatures from Sol 0 to Sol 204

vehicle. The minimum temperatures of the MMRTG show much more scatter. Nighttime minimum temperatures are more influenced by cold winds which can drop the MMRTG by 10°C in an hour at certain times of night. The minimum recorded MMRTG temperature during surface operations was 150°C which is 85°C warmer than the minimum AFT limit of 65°C. The two minimum temperature data points on Sol 0 are from the late cruise, pre-EDL telemetry.

VI. Standard Thermal Activities on the Rover During Surface Operations

There are a number of standard thermal activities that were performed during MSL Flight operations including: 1) HRS Backup Pump maintenance, 2) Nighttime wakeups to gather temperature telemetry, 3) an electrical heater checkout, 4) a DRT heater thermal characterization and 5) a Drill preheat checkout. Some of these activities are performed on a regular basis and others were one-time activities.

HRS backup pump maintenance is required to be performed every 28 Sols \pm 2 Sols. Pump maintenance is done by running the backup pump for 1 hour (with the primary pump left on) and then turning it back off. The goal of pump maintenance is to flush out any particulates that may have accumulated inside the backup pump Freon fluid lines and prevent seizing of the hydro-dynamically lubricated HRS pump impeller bearings. Successful pump maintenance is verified by: 1) confirming electrical switch states (on and off at the proper times), 2) observing expected changes in temperature on the HRS hot plates (increased flow from the backup pump causes a 4°C drop in the hot inlet temperature which recovers after the pump is turned back off), 3) verifying a nominal increase in current draw (0.25A) when the backup pump is turned on and the corresponding reduction in current draw when the pump is turned off and 4) expected event records (EVRs) generated by the command sequence that turns the backup pump on and off.

The rover spends about 17 hours each Sol (typically from 17:00 LMST to 10:00 LMST) in a sleep mode to limit overall power consumption. Sleep mode reduces the energy load on the system and allows the MMRTG to recharge the battery back as close as possible to a full state of charge (SOC). In sleep mode, the Flight Computer is off and will not record and store telemetry. In order to recoup some of the temperature telemetry that is not being recorded when the rover is in sleep mode, a sequence was written to wake up the rover for 15 minutes every 3 hours between 18:00 LMST and 09:00 LMST on specific Sols. This sequence is run for the Prime RPAM every 10 Sols. This sequence is run with the backup RPAM uninhibited (collecting data on all of the temperature sensors on the vehicle) every 30 Sols. Complete sets of temperature telemetry are essential to assessing sensor health and for doing analytical thermal model correlation to nighttime temperature data.

The discovery of Foreign Object Debris (FOD), on the Mars surface on Sol 62, that could have been epoxy from one of the heater or PRT installations, raised concerns about the health of the rover actuator and camera warm-up heaters. (The FOD was later determined to be a small piece of shrink tubing that had fallen off the rover.) On Sol 90, an electrical heater checkout was performed to test the electrical continuity of the heaters. Each of the A-side heaters was cycled on for 10 seconds and then turned off. This was not long enough to see a temperature rise on the hardware, but it was long enough to register a rise in current draw and confirm that the heater was still healthy. All 30 A-side heaters were confirmed to be operating nominally, drawing the proper currents based on the bus voltage and the pre-launch measured heater circuit resistances.

The DRT was not ready to be integrated on the rover prior to Rover STT. For this reason, none of the standard thermal characterization warm-ups could be performed on the DRT heaters during STT. In fact, the DRT was delivered directly to the launch site for integration into the flight rover. Some thermal testing was done with the flight heaters prior to launch, but that testing was rather low fidelity. In order to generate some model correlation data on the DRT warm-up heater, a thermal characterization test was performed on Sol 50. The DRT heater was turned on at 02:00 LMST and left on for 1.5 hours, until it reached a steady state temperature. The DRT rose 61°C, from -56°C to +5°C, and then the heater was turned off to get a transient cooldown characterization. The test was useful in determining the true capability of the heater and for warm-up heater thermal model correlation.

Concerns about the impact of CTE mismatch on internal hardware in the Drill (especially an epoxied Teflon bushing) led to a change in the Drill operating temperature limits during surface operations. Around Sol 31, the Drill team determined that the stresses could be minimized at the bushing interface if the drill percussion motor were

heated up above 0°C prior to start of operation. So, heaters that were originally designed to bring drill components up to -55°C were now required to cycle between 15°C and 20°C, before the Drill could be used. Thermal analysis of the Drill heaters showed that they were so robustly designed that even in the worst-case cold Winter environment, the Drill heaters were capable of maintaining the voice coil well above 20°C for the entire Sol. Heating tables for the Drill were revised to reflect the new temperature limit. All Drill heater zones were required to cycle between 15°C and 20°C. On Sol 101, a successful Drill pre-heat characterization activity was performed on the flight Drill. The test confirmed that the Drill could be pre-heated to and maintained at the new temperature limit. For all future Drill activities, it would need to be pre-heated; there is no time of day on any Sol in which the percuss motor would be naturally heated above its minimum op AFT limit of 0°C. Successful heating of the Drill on Sol 180 enabled the historic Deep Drill activity in which the Drill bored 6.4 cm into a rock known as “John Klein” to reveal an un-oxidized gray rock material inside.

VII. Interesting Surprises in the Rover Thermal Performance

There were a number of interesting and surprising thermally-related events that occurred in the first 200 Sols of the mission. Several of these surprises were related to the Martian thermal environment and some were more hardware related.

Immediately after landing, the Thermal team realized that the assumed atmosphere temperature profile was under-predicting the actual measured atmosphere temperatures by as much as 25°C (see Figure 4). This apparent warmer environment around the rover was attributed to the local effects of MMRTG heating on the atmosphere. Since the rover external equipment sees this micro-climate, the analytical thermal models were adjusted to run with the actual atmosphere temperature profiles that were reported from the REMS instrument.

We had anticipated that the Rover system-level analytical thermal model would need to be adjusted and re-correlated to flight data after the Rover reached Mars. We had reserved a week for re-correlation of the model. As it turned out, the STT-correlated model was quite accurate; it predicted RAMP temperatures within $\pm 5^\circ\text{C}$ for the entire Sol. The one exception was for the Rover battery, which was running as much as 10°C warmer than expected. Pre-launch predictions showed a diurnal temperature swing of 3°C to 6°C; flight telemetry showed a diurnal swing from 6°C to 16°C. It was later determined that the flight battery had been installed such that the flight cable thermally coupled the battery (much more strongly than expected) to nearby avionics boxes that routinely reached 35°C. This larger thermal coupling to a warmer source led to elevated battery temperatures and a wider diurnal variation in temperature. Increased battery thermal coupling was the only post-landing adjustment that needed to be made to the rover system model.

The dust, soil and rock deposition that occurred during the landing event was a surprise to the Thermal team. Images of the top deck taken shortly after landing revealed that the top deck had been showered with dust, soil and small rocks when the descent stage engines fired during the final stages of the EDL sky-crane maneuver. While dust deposition level was difficult to assess, the thermal team already had models ready to run with an assumption of 40% dust coverage.

Transient temperature variations seen on the MMRTG were quite unexpected. Given the facts that the MMRTG is rather massive (45 kg) and that it has a constant power dissipation (around 2000W thermal), we expected to see smooth temperature profiles for the MMRTG, just as we had seen on the MMRTG simulator in the Rover STT. Figure 15 illustrates the typical diurnal temperature response experienced by the MMRTG each Sol. There is a very significant drop (about 15°C) in the MMRTG end cap temperature (the blue data points in Figure 15) between 18:00 and 21:00 LMST. It was discovered that this temperature drop was not due to any change in MMRTG power

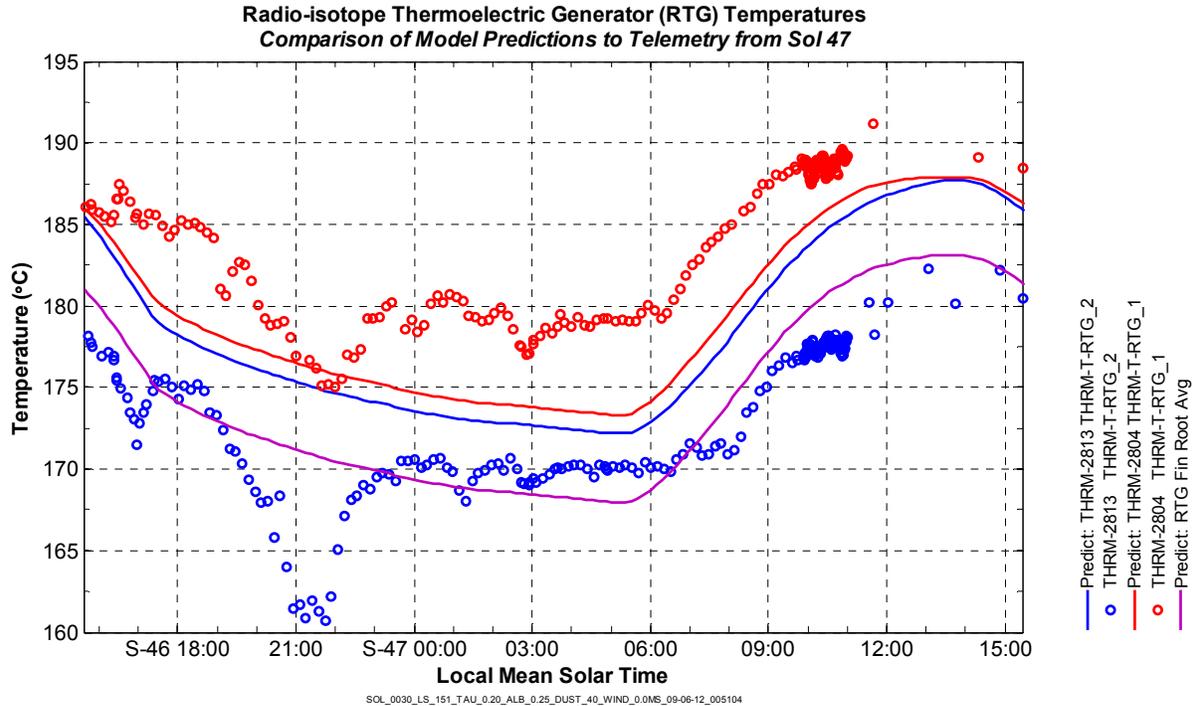


Figure 15. RTG Temperatures during Sols 46 & 47

dissipation, but was due to a sudden increase in the wind speed at that time of night. In fact on almost every Sol, we saw a similar drop in MMRTG temperatures at the same time in the evening. Not only are the environment temperatures in Gale Crater repeatable each Sol, the wind patterns are also repeatable. Thermal modeling of the MMRTG confirmed that indeed, with a -70°C atmosphere, a sustained wind gust of 15 m/sec for 3 hours would be more than enough to result in a 25°C drop in MMRTG temperature. REMS wind data (relative magnitude data only) confirmed that elevated wind speeds do occur in the 18:00 to 21:00 LMST time period each Sol. REMS CFD modeling of the Gale landing site also showed that the winds are expected to peak at 21:00 LMST.

The final surprise that the Gale Crater landing site had for the MSL thermal team was an unexpected change in environment temperatures within the Gale Crater landing site. Figure 16 is a long-term trending plot of the ground temperatures as measured by the REMS instrument between Sol 9 and Sol 198. There is a dramatic change in the maximum and minimum ground temperatures that occurs between Sol 120 and Sol 121. The peak ground temperature during the day dropped 16°C and the minimum ground temperature at night rose by 8°C. Until that point in the mission, the ground temperatures were showing a monotonic rise, as expected with the seasonal transition from Spring to Summer. By Sol 120, the rover had traversed more than 550 meters away from its initial landing site. The Bradbury landing site was characterized as having small rocks and loose, sandy soil. On Sol 121, we had moved away from this low thermal inertia material to an area named Yellowknife Bay, which was characterized as having more exposed sedimentary bedrock. This higher thermal inertia bedrock had a dramatic effect on ground temperature, reducing the daytime peak temperature (absorbing the solar load into the thermal mass of the rock) and increasing the nighttime low temperature (slowly dissipating the thermal energy gained during the day). Ground thermal inertia maps of the MSL landing site were derived using data taken by the THEMIS instrument flying on the Mars Odyssey orbiter.¹² These thermal inertia maps confirmed that the rover had driven from an area with a thermal inertia of about 350 SI inertia units to one with a thermal inertia of about 530 SI inertia

units. We expect to see more changes in the Mars surface temperatures, measured by REMS, as the rover traverses across low thermal inertia sand dunes on its way to the base of Mount Sharp, later this year.

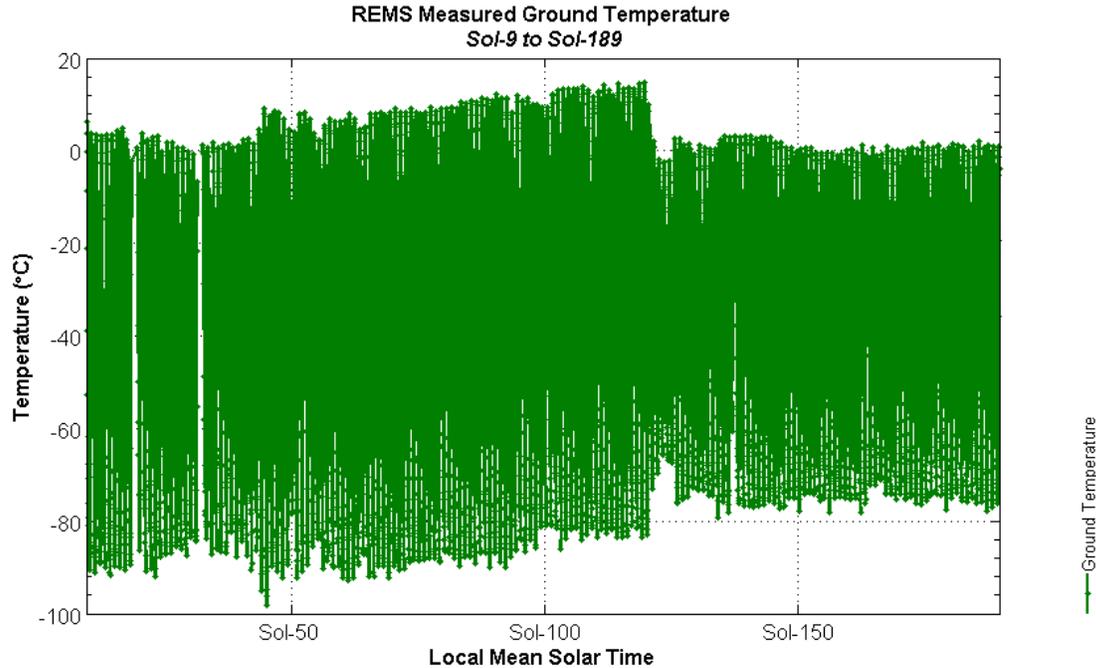


Figure 16. Long-Term Trending Plot of REMS Ground Temperature Measurements from Sol 9 to Sol 189

VIII. Conclusion

The following conclusions are made about the thermal performance of the MSL Rover during the first 204 Sols of the 670-Sol mission:

1. Thermal performance of all the rover subsystems has been excellent. All hardware has been maintained within its AFT temperature range with margin. The rover easily handles a high-energy Sol without overheating the RAMP mounted hardware and requires no RAMP survival heating on a low-energy Sol.
2. The HRS performance has been superb. It provides the RAMP mounted equipment with a stable and repeatable thermal interface each Sol, generally running at 5°C at night and peaking at 35°C during the day. The repeatability of the RAMP temperatures, due to the passively-controlled HRS bypass valves, has made it unnecessary to run thermal predictions on a per-Sol basis. The repeatability has also allowed the planning of science instrument activities to be done without detailed thermal modeling.

The MSL Rover thermal subsystem has proven itself to be very robust during the first 200 Sols of Mars surface operations in Gale Crater. The thermal subsystem has enabled high power dissipation science operations and actuator and camera warm-ups that have contributed to the science discoveries accomplished thus far in the mission. Thermal performance of the rover will be evaluated further as the rover moves into the Fall and Winter seasons on its way to the base of Mount Sharp.

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