A Curious Year on Mars—Long-Term Thermal Trends for Mars Science Laboratory Rover's First Martian Year.

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By the time of this writing, Curiosity, the Mars Science Laboratory (MSL) Rover, has weathered four seasons in Gale Crater, just south of and approaching the foothills of the 5-km high Aeolis Mons, known as "Mount Sharp," at 4.59º south latitude. The mission design included a much broader latitude range of 30º north to 30º south constraining some of the Rover environmental requirements and operations. To date, Curiosity has relayed over 150 MB of thermal telemetry. Curiosity has relayed over 150 MB of thermal telemetry through four seasons. The trends and idiosyncrasies revealed through four seasons of telemetry from Mars are discussed. The better-characterized thermal environment allows for less conservatism in operational models and increases the amount of science data collection. Examples include: the elimination of overheating concerns for some cameras and the use of the previous sol's temperature telemetry along with the conservative soak temperature curve from the winter thermal model, to produce a custom heating prescription for the upcoming weeks thus increasing operation time and reducing heating times. This paper discusses the lessons learned for Rover operation as well as general idiosyncrasies discovered about the local environment—such as the effect of orientation on subsystem temperature variation, a regular morning and afternoon wind, ground and air microclimates with distinct temperature differences from other terrain, and how the Rover affects the local environment. This paper further documents and explains some of the interesting highs and lows of the temperature telemetry data as well as offers explanations for sudden temperature changes on board the Rover.

Nomenclature

AFT = Allowable Flight Temperature
ATLO = Assembly, Test, and Launch Operations
APXS = Alpha Particle X-Ray Spectrometer
CCBU = ChemCam Body Unit
CCMU = ChemCam Mast Unit
CFC-11 = Trichloromonofluoromethane (Refrigerant 11)
ChemCam = Chemistry and Camera Instrument
CheMin = Chemistry and Mineralogy Instrument
CHIMRA = Collection and Handling for In-situ Martian Rock Analysis
CO2 = Carbon Dioxide Gas
CTE = Coefficient of Thermal Expansion
DAN = Dynamic Albedo of Neutrons Instrument
DRT = Dirt Removal Tool
d*t* = Time Step
DTE = Direct to Earth
HRS = Heat Rejection System

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IT = Information Technology
FSW = Flight Software
GCM = Global Circulation Model
LMST = Local Mean Solar Time
Ls = aerocentric solar longitude, indication of season (Ls 90 is winter in the southern hemisphere)
LST = Local Solar Time
MAHLI = Mars Hand Lens Imager
MastCam = Mast Camera
MMRTG = Multi-Mission Radioisotope Thermoelectric Generator
MPFL = Mechanically Pumped Fluid Loop
MSL = Mars Science Laboratory
OCIO = Information Technology
PRT = Platinum Resistor Thermometer
PU^{238} = Plutonium 238
RA = Robotic Arm
RAMP = Rover Avionics Mounting Panel
REMS = Rover Environmental Monitoring Station
RLGA = Rover Low Gain Antenna
RSM = Remote Sensing Mast
RTG = Radio-isotope Thermo-elecric Generator
RWEB = Remote Warm Electronics Box
SASPAH = Sample Acquisition, Processing and Handling
Sol = Mars solar day, 24h 39m 35s
W = Watts

I. Introduction

THE CURIOSITY Rover has weathered four Martian seasons roving Gale Crater just northeast of and driving toward the 5-km high Mount Sharp at 4.5º South of the equator on June 23, 2014 just 668 Sols since landing on August 6, 2012. Over the past two Earth years the Mars Science Laboratory (MSL) Rover thermal team has discovered what 'normal' means for Curiosity. This paper captures a complete cycle of a Martian year's worth of activity from a thermal perspective of the Curiosity Rover on Mars. An earlier paper[1] presented the thermal performance of the MSL rover over the first 200 Sols of the landed mission.

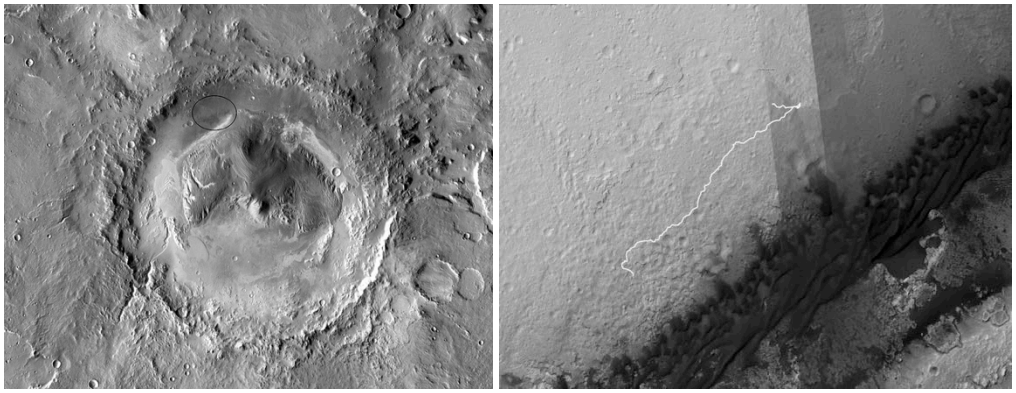

Figure 1. Gale Crater (left) with landing ellipse (near 11:00 around the crater cicle). Extent of MSL's 6.317 km traverse as of Sol-609 one the way to the base of Mt. Sharp (dark band of sand near the bottom right of image). Odometry as of the writing of this paper (sol 627) is just over 6.4 km.

Following a brief overview of the MSL mission, Rover system and thermal design, this paper will address some of the interesting thermal telemetry and system behavior noted by thermal ground operations engineers over the past Martian year. In particular the thermal system behavior has been influenced by the long term season trends and system performance, the effects of local terrain, weather, and orientation, performance of air-gap insulated hardware, and the heater system efficiency. Finally we'll look at the challenges facing MSL operations as the rover transitions into the extend mission phase and drives into the foothills of Mt. Sharp.

Figure 2. MSL "selfie" produced from multiple MAHLI images stitched together (Sol-613).

From telemetry, the team has learned more about Rover operations, thermal hardware on-board the Rover, and the environment near the Martian equator. The team has been able to relax some of the original operations plans that were overly concerned with overheating engineering cameras, a concern that telemetry suggests is not possible in the current local environment at Gale and camera operational modes. Unlike our previous Rovers which experienced multiple PRT failures immediately following landing, Curiosity has endured 668 Sols without a single PRT failure or debonding, with each external PRT subjected to 80ºC temperature swings each Sol.

We have witnessed the effectiveness of Curiosity's Heat Rejection System (HRS). In addition to health assessments, the team has learned further detail about the local environment, such as regular morning and afternoon winds and differences in terrain-induced microclimates. All of these lessons lead to a more efficient operation of Curiosity as well as impact the design of future missions.

A. Description of the Mars Science Laboratory Rover Mission

Curiosity's primary mission is to investigate the habitability of Mars, and the 10-instrument, remote geology science suite is specifically engineered to "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."[1] The science payload tool suite is shown in Figure 3 below. For more details on the science instruments and their recent investigations, please refer to the JPL or NASA MSL public website.[2]

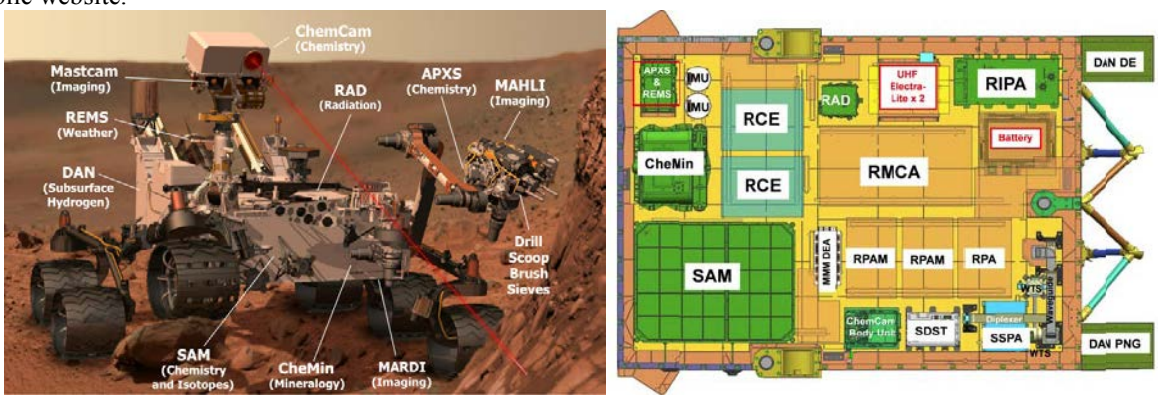

Figure 3. MSL Rover (left) science suite with internally mounted RAMP payload (right). The RAMP is an enclosed plate that is suspended from the top deck of the Rover. Imbedded with the structure of the RAMP is the heat rejection system (HRS) fluid loop. The top deck of the Rover also contains a fluid loop for rejecting heat from the interior of the Rover.

B. Description of the Mars Science Laboratory Rover Thermal Design

The two Rover thermal control systems described herein consist of an active fluid loop heat rejection system (HRS) and heater controlled hardware (warm-up and survival). The HRS minimizes the electrical survival heat required and allows the available electrical power produced by MMRTG to be utilized by the instruments and the avionics.

The overall HRS approach is to utilize a single-phase, mechanically pumped, Freon (CFC-11) fluid loop for the majority of the thermal control of the Rover. Passively activated temperature control valves (consisting of a mixing valve and a splitting valve) control the HRS fluid flow to maintain RAMP temperatures within AFT bounds. For the cold case, the HRS radiatively collects waste heat from a radio-isotope thermo-electric generator MMRTG via 'hot plates" to maintain certain science and avionics boxes mounted to the Rover avionics mounting panel (RAMP) above their minimum allowable flight temperatures (AFT).

For the hot case when the RAMP electronics temperatures approach maximum AFTs, the HRS rejects heat to the environment via the 'cold plates' and top deck radiators to maintain safe interface temperatures (see Figure 4 and 5). A passive thermal control valve (actuated by DC-200 fluid silicone) automatically directs flow from the hot plates to the RAMP (in cold conditions) or to the cold plate radiators (in hot conditions).

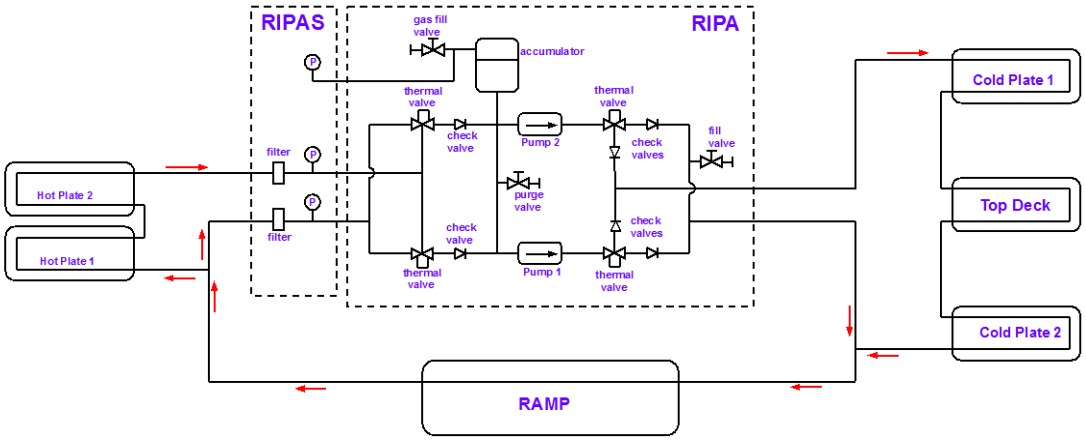

Figure 4. Rover HRS flow diagram.

The science instruments SAM, DAN, CheMin, and the ChemCam body unit all rely on the RAMP, as well as many of the engineering avionics boxes such as the telecom system, the Rover computer, and power and data handling systems. So far all the pumps and fluid loops have performed flawlessly ever since landing and have experienced not a single anomaly for over one Mars year (670 Sols). A more detailed description of Curiosity's HRS can be found in References 2-4.

Two types of heaters are employed in the thermal design: survival heaters are used to maintain a subsystem above its minimum non-operation AFTs and warm-up heaters are used to get a subsystem above its minimum operational AFTs. Survival heaters use mechanical thermostats to autonomously maintain subytems, such as the ChemCam Mast Unit, above their minimum survival temperatures. Warm-up heater target temperatures, durations, and min/max maintenance control temperatures are commanded via ground command sequences and controlled onboard by flight software. The warm-up heaters heat actuators (used in the mobility subsystem, the remote sensing mast, inlet covers for the SAM and Chemin science instruments, and the robotic arm) as well as MSL's cameras, drill, and sampling subsystems (see Figure 6). Due to the seasonal and diurnal variation of the Mars surface thermal environment, heater prescriptions (duration and control set points) are prescribed for a particular Sol's plan by the thermal engineering team.

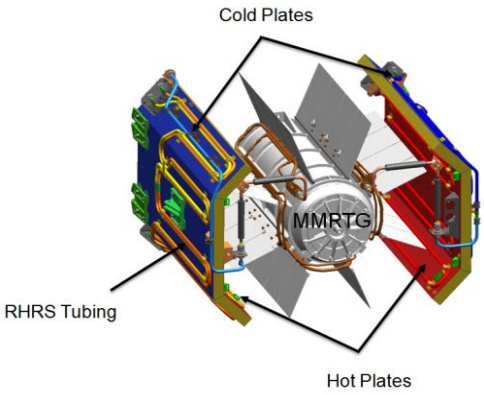

Figure 5. HRS hot and cold plates about the MMRTG.

The RSM is located above the Rover top deck but is not serviced by the fluid loop. It consists of a almost rectangular shaped housing defined as the remote web (RWEB) which houses the ChemCAM instrument inside. Other cameras like NavCam are mounted on the underside of the enclosure. For ChemCAM, its thermal design relies on thermal isolation of the unit from the RWEB using Titanium flexures and Carbon Dioxide gaps. The external surface is white painted to reduce solar loadings and interior surface is low-e surface to further reduce radiative heat loss from the housing. Also, a mechanical thermostat controlled, survival heater keeps the ChemCAM unit above its minimum non-operational AFTs at night. Figure 6 shows the various Rover subsystems referenced in this paper. For more details about the system and thermal design, please see References 1-4.

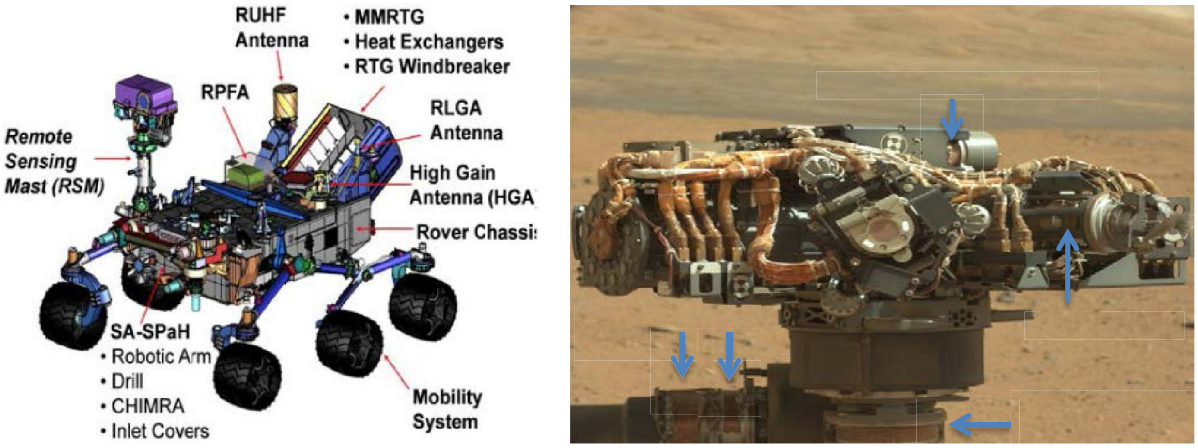

Figure 6. Mars Science Laboratory Rover main engineering subsystems (left). At right, the turret at the end of MSL's robotic arm. Directly in front is the MAHLI instrument, the DRT can be seen to the right, and the back end of the drill is to the left. The robotic arm wrist and turret actuators are visible as well, with Kapton film heaters and temperature sensors (blue arrows).

II. Long term Seasonal Trends and System Performance

MSL has completed one full Martian year on the surface of Mars. This paper documents some of the noteworthy long-term trends in thermal system performance as of this milestone. For refence, Table 1 shows the relationship between landing sols elapsed since landing, aerocentric solar longitude, to the current season.

Table 1. Landing Sol, Aerocentric Solar Longitude (Ls), and Southern Hemisphere Season

Sol	Ls	Season
0	151	Early Spring
55	180	Spring Equinox
197	270	Summer Solstice
350	0	Fall Equinox
544	90	Winter Solstice

A. Long-Term Seasonal Trends

The complete annual change of seasons (air/ground temperatuers) can be detected in nearly all of the thermal max/min trending plots (see Figure 7), though due to self-heating and warm-up heating, this trend is most clear in non-heated or inactive subsytems such as the RSM deploy actuator. The RSM deploy actuator was used once and not heated. A comparison of Figure 8 to Figure 9 shows that the seasonal ground temperature predictions for Gale Crater were accurate.

All of the temperature telemetry for the primary mission have been within the predicted bounds. The hottest temperatures recorded on the rover occur due to self-heating, such as on the MMRTG (T=198ºC), SAM when performing its own volatiles experiement (T=105ºC), HRS Hot Plates (T=72ºC), HRS Cold Plates(T=50ºC), Top Deck HRS radiator, and CCBU during decontamination mode. Under all these conditions they generate more heat than nominal operation.

Meanwhile the coldest temperature recorded was -95.2ºC on Sol 559 on the robotic arm (to be discussed in detail below in section III.D.).

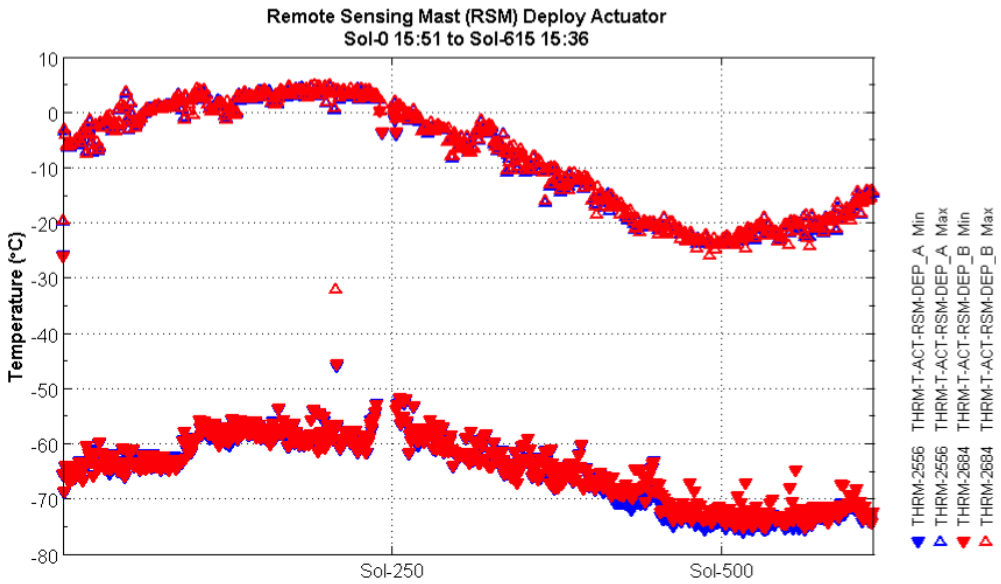

Figure 7. Long-term min/max temperatures for the landed Rover mission for the RSM Deploy Actuator demonstrate the Martian seasonal variation as sensed from PRTs on the top deck and Rover turret, respectively. Regarding the outliers: the Sol-0 telemetry, immediately on the Y-axis, occurred during EDL; the Sol-200 outliers correspond to an onboard anomaly in which data was lost for the remainder of the Sol; and the gap in data just prior to Sol 250 correspond to solar conjunction.

Figure 8 shows the long-term trending for the mobility system. As the Rover entered fall, the drive campaign geared up, and the seasonally dominated temperature trending is broken up as the warm-up heating dominates the maximum temperatures starting near Sol-340 (indicated by a dashed blue line in Figure 8). It should be noted that drive sols in the summer months do not require as much heating, so self-heating and the local environment dominated maximum recorded temperatures prior to Sol-340. Two definitive curves can be seen in maximum temperature telemetry data following Sol-340. For instance the pink points (corresponding to the left front drive actuator) have one curve corresponding to warm-up heating, and another from non-drive sols in which the actuators followed the local environment.

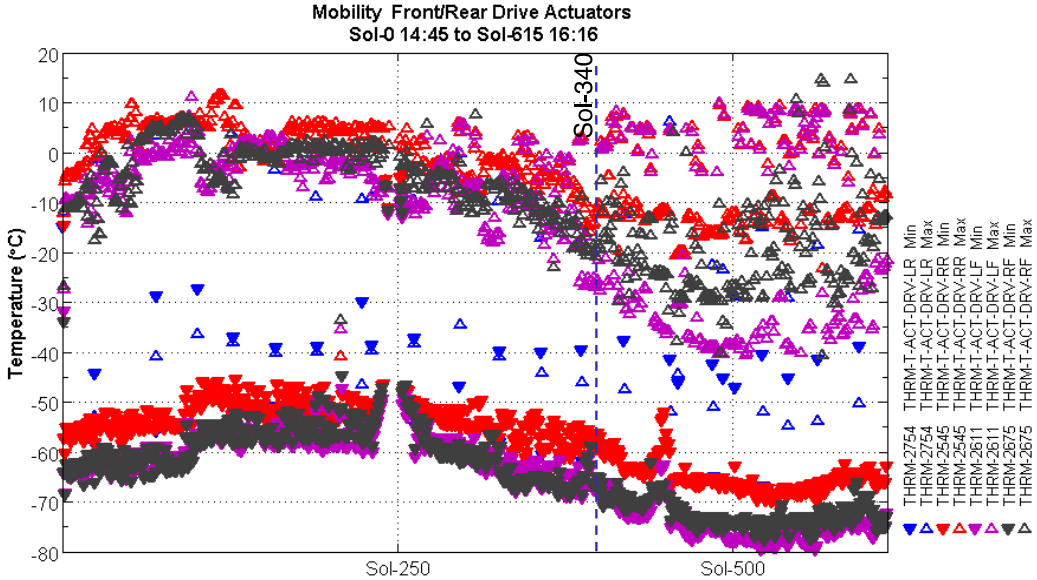

Figure 8. Long term temperature trending for the mobility drive actuators. The minimum temperatures follow the local environment (ground) temperatures, whereas the maximum temperatures are dominated by preheating for drive Sols particularly following Sol-340 (vertical dashed line).

B. Heater performance—hybrid heating tables and custom prescriptions

The ground-command, FSW-controlled heaters perform warm-up and maintenance heating duties. Due to the diurnal temperature variations on a particular Sol, there are defined periods for which warm-up heating is required (evening through morning), no heating is required (generally in the middle of the Sol), or only maintenance heating is required (end of the afternoon). Within the no-heat windows, planners are free to turn on a subsystem without any pre-heating. For activities that fall outside of these no-heat windows, a unique heater prescription detailing warm-up duration, target temperature, maintenance heating duration, and high/low set point temperatures is required.

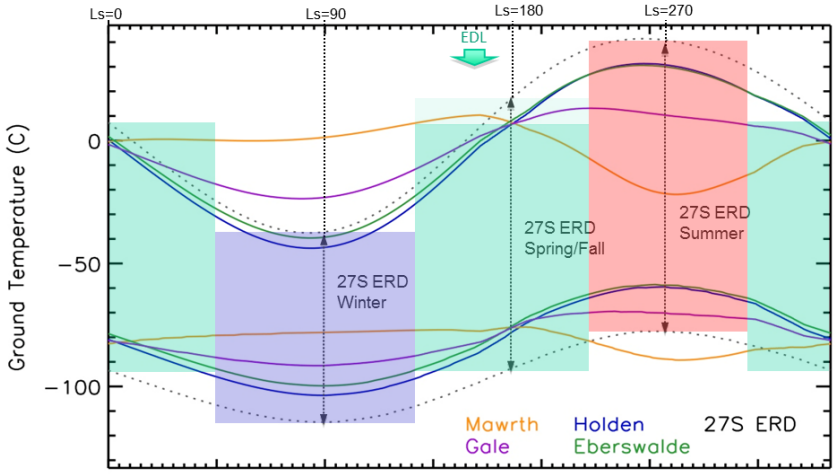

Figure 9. Temperature versus season (Ls) showing a relatively flat ground temperature.

Note that the very stable ground temperature assumed was the original justification for only using two heater tables (Ls-90 and Ls-151) going into the landed mission (this can be seen in Figure 9). (As will be discussed later, the heater tables are used to prescribe a heating duration and target temperature for warm-up operations.) As the mission progressed however, the desire for greater efficiency resulted in the eventual production of another set of heater tables (Ls-130).

Once the science and uplink engineering teams determine the activities for a particular Sol, the thermal engineering team then verifies that the target temperature for the heater control, the warm-up duration, as well as any maintenance heating (on/off temperatures and duration) required to maintain safe operating temperatures for the subsystem are properly prescribed. Heater prescriptions are based on local solar time (LST, time of day) and Martian season (time of year). and determined from thermal model runs.

Partly complicating the MSL heating approach with respect to the actuators, is that the interior gear box bearings require the heat, but the heaters and sensors are located on the actuator housing exteriors. Thus the outside temperature of an actuator can be well above its minimum AFT, but the interior might still be too cold to operate. According to our thermal models, the delta-T can be up to 76ºC, but varies based on LST.

Since landing, the team has used two seasonal models to determine the heater prescription. One is based upon late spring landing day (Ls-151), and the other is the middle of Martian winter (LS-90). The Ls-151 tables were used from landing, through the summer into fall, until Sol-434 (see Table 1). Thus during much of the summer, the heater prescription tended to be overly restrictive in that the heater prescription was longer than required if required at all. Note that additional model runs required to produce new tables takes on the order of 6-months, so alleviating the time and energy constraints by building additional heater tables is not an easy solution.

1. Martian Fall, Ls-0 and Hybrid Heating Approach: increasing available drive time

As Martian fall approached, the team compared the daily downlinked telemetry to the model-predicted environmental soak temperatures curves. A soak curve is the modeled, non-operating temperature profile for a particular device based upon the influence of the local environment (ground, air, sky temperature). Once any of the diurnal temperature telemetry channels for thermally controlled hardware touched its soak curve, this was an indication that Ls-151 models were no longer valid since these curves act as the bouding conditions for each device. Once this occurred, it indicates that the winter (Ls-90) tables were required to properly protect MSL (Figure 10).

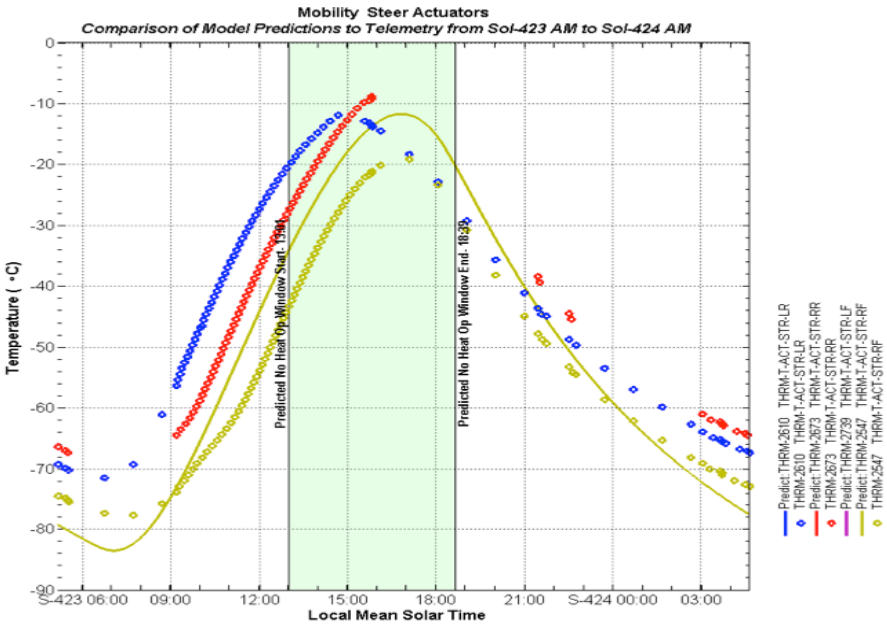

Figure 10. The right front actuator violates the Ls-151 soak temperature curves, causing the thermal team to begin using the Ls-90 and hybrid heater tables. (The solid line is the modeled environmental soak curve, and the dots are thermal telemetry.)

Unfortunately, at Ls-0 (fall), the Ls-90 (winter) tables were very conservative in their prescribed duration and energy use, and greatly restricted activities just as the planning team attempted to exercise a series of long traverses towards base of Mt. Sharp. The decrease in the no-heat window available for operations caused by moving from Ls-151 to Ls-90 tables was between 2.9 hours to 8.1 hours (depending upon the subsystem). Additionally the change in heater tables increased the heating time required for larger subsystems such as mobility, arm, and RSM actuators by up to 1-hour (based on the same type of activity starting at 9:00 LMST on Sol 415). This increased heater time and diminished no-heat windows greatly reduced the available time for driving and science, reduced the available power, and complicated the daily planning and uplink activities. For instance, in order to complete certain activities such as uplink, heating had to occur in the previous Sol's plan, across the daily plan boundary (referred to as the handover). Thus planners now had to make more detailed plans 2-days prior to execution or greatly simplify their goals for a particular sol to avoid handover activities.

The original thermal operations plan was to swap over the entire suite of heater control from Ls-151 to Ls-90. However, since only the mobility subsystem had violated its soak curves, the team implemented a hybrid heating approach in which we used a mixture of Ls-90 and Ls-151 heater tables to allow the science and engineering teams more time to complete activities. Ls-90 tables were applied to subsystems that were at or about to violate their model assumptions, but Ls-151 tables were used for devices safely above their Ls-151 soak curves. This greatly increased the complexity of both the thermal uplink planning and downlink analysis activities. The team needed to compare downlink telemetry to two different soak environments to properly monitor performance and to ensure that no system was now violating its Ls151 curves, and vice versa.

Ultimately, the project opted to produce an additional set of early-spring (late fall) heater tables to alleviate the inefficiency of the binary spring-winter heater tables and somewhat reduce operational complexity of using the hybrid table approach. The hybrid approach is not eliminated, but the need for it is perhaps alleviated by having a mid-range heater table. At this time the thermal team is finalizing the new intermediate heating table designated as Ls130 to bridge the gap between Ls90 and Ls151.

2. Martian Winter, Ls-90 and Custom Heating Approach

In addition to the hybrid heater table development, conditions required some custom heating prescriptions as well. On Sol 455 a change in orientation of the Rover after consistent end of drive pointing caused an overnight drop in temperature of 7ºC and caused a violation of soak curves for the left front mobility actuator. The device had not been planned for use on that day, but this was the trigger to move the entire system to the winter heating prescription

from the hybrid tables, and more routine activities for the thermal team in terms of uplink and downlink analysis. Subsequently by Sol-463 we moved the entire system to winter tables (Ls-90).

Just over two weeks later, on Sol-478 (see Figure 11, below), telemetry indicated that MSL had violated the winter model soak curves on which our heater prescriptions were based. From this we needed to develop a custom heating approach. The temperatures did not violate the coldest temperatures predicted, but rather violated the temperature profile predicted. This meant however, that the heater table prescription at that time would not be sufficient. Therefore we performed a custom heating solution for mobility—to assist driving and activities.

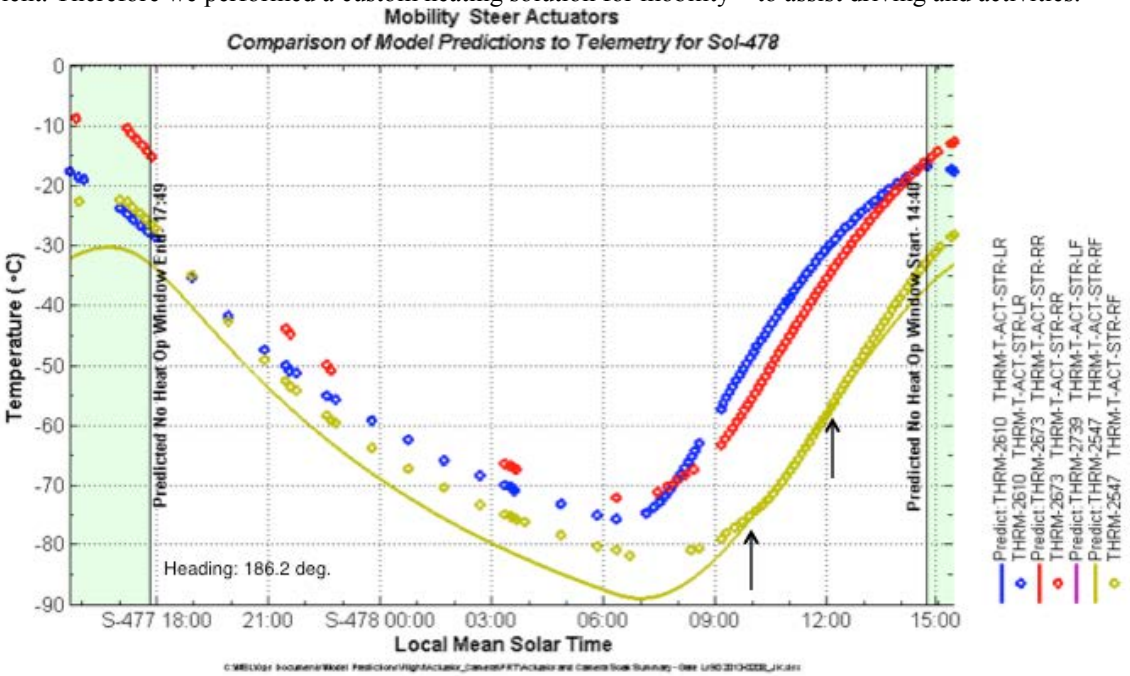

Figure 11. This image shows the flight temperature data from the right front steer actuator drop below the Ls-90 soak curves (arrows). The shaded green areas indicate the boundaries of the no-heat window for Sol-478. The heading on the Rover indicates that the drive direction pointed south, so that the right front steer actuator was shadowed during the violation. (The solid line is the modeled-predicted environmental soak curve, and the dots are telemetry.)

There was a real risk that our heater prescriptions would be insufficient to maintain cameras and actuators above their required temperature. In order to safely heat the hardware, the team developed a procedure to use the flight telemetry along with the modeled curve to extrapolate the proper prescription for the heating target temperature and duration. Each week, a thermal team member would develop a minimum duration/temperature for operations that occurred just after handover (generally around 9:30 LMST). While successful, the process was time-consuming, since we would need to review the previous two weeks of data, looking for worst case shading scenarios and terrain-induced low temperatures. To protect against an error, we would bias the prescription up by 5ºC.

C. Heater System Efficiency

As described in the previous section, usage of any actuator or instrument outside of its no-heat window requires a custom heating prescription that is generated from model predictions. The built-in conservatism of these model predictions, however, leads to a heating prescription that is overzealous in its energy usage as the modeled warm-up time takes longer than the actual warm-up times. Thus the model prediction may show 90-minutes to achieve warm-up, time that must be accounted for in the plan, but the target temperature onboard is achieved much quicker, using less energy than predicted. This problem is further compounded by the fact that the models are only truly valid for late-spring (Ls=151) and winter (Ls=90).

The heating tables are based upon worst-case orientations and the largest degree of shadowing because it is not feasible to accurately prescribe heating for every Rover orientation, terrain, and arm pose—or possible to accurately predict the end of Sol Rover orientation following an autonomous drive. Note too that it is impractical to re-run all actuator models for new orientations each Sol.

An additional inefficiency in heating arises due to the nature of the Rover's thermal architecture. Heating is defined for heater "zones" rather than individual heater circuits. In order to use the Rover's "wrist" to manipulate its sample acquisition instruments, for example, heating of the entire robotic arm is required – including actuators for the arm's shoulder, elbow, and aforementioned wrist joints – despite the fact that not all of these actuators will be used for the particular operation. The result is a set of heating commands that are often either excessive, or unnecessary, or both – and an over-budgeting of electrical power consumption that limits the science planners' ability to operate the rest of the vehicle to its full potential. This effect is most pronounced in planning activities around conservatively long, pre-heating activities. It also has a slight deleterious effect in battery usage; the battery is not being discharged to healthy levels due to over-predictions in energy usage. (Note that the thermal subsystem is not the only subsystem over-predicting its planned power requirements for a particular Sol's activities.)

An effort to characterize this inefficiency was conducted in late 2013. This study compared all heater prescriptions against the vehicle's reported heating durations, or "actuals," from late autumn through just before the implementation of the first hybrid heater table – a period spanning roughly Sols 315-400. The goal of this effort and its planned follow-up studies was to quantify, if possible, the degree of conservatism built into a typical heating prescription, and to answer several open questions about long-term trends in vehicle heating: Is the degree of overprescription repeatable from Sol to Sol? Does it vary between heater zones, or between distinct circuits in a single zone? Does the degree of conservatism built into the models vary from season to season? To analyze this issue, the executed duration for warm-up heating was compiled for all planned heating. An efficiency percentage was calculated by dividing the actual warm-up time by the planned duration, as shown in Figure 12.

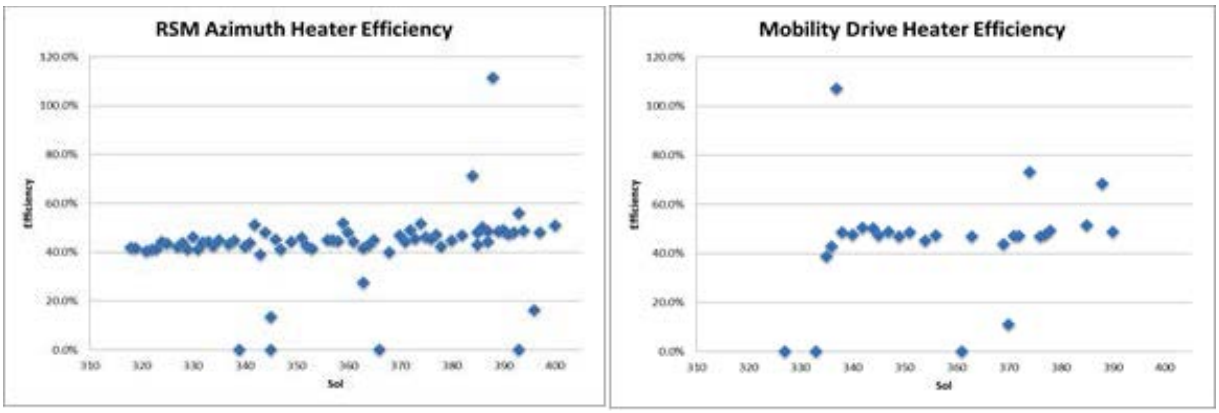

Figure 12. The left plot depicts the ratio of the actual to planned warm-up times (efficiency) for the RSM Azimuth actuator heater zone. The right plot depicts the efficiency of the Mobility drive actuator heater zone. Consistent ground temperatures on Mars makes this zone's efficiency predictable, though Rover orientation makes it less efficient than the RSM. operations.

For heater zones with near-constant thermal environments like the RSM Az actuator heater zone with a very predictable top deck and RAMP view and the Mobility actuators with a somewhat predictable ground temperature view, the observed trends were largely repeatable for a given zone. Orientation of the Rover affects the Mobility actuator zone's predictability more than the RSM Az actuator heater zone. This repeatable conservatism suggests that we can define a predicted power-usage "fudge factor." The power-usage factor for the RSM Az actuator zone and for the Mobility drive actuator zone allows science planners to "buy back" some of the budgeted power.

Other zones were found to be less predictable – of particular note is the Mastcam, whose structure is far removed from the tightly-controlled RAMP interface and whose orientation with respect to both the vehicle and the environment (particularly the Sun) make the heating performance less predictable.

This analysis is ongoing, and will increase both our understanding of the nuances of Curiosity's heater implementation, as well as our ability to accurately predict our power usage. While the process for generating heating prescriptions is unlikely to change, the way we plan and forecast subsystem performance can adapt to allow science planners more flexibility in pushing the vehicle to new limits and operating it to its fullest potential. Time saved in reducing heating times is power that can be used for Curiosity's ultimate purpose – science.

D. Heat Rejection System Performance

The MSL HRS system has provided a reliable minimum temperature. The minimum temperatures across the RAMP have varied by only ± 4.5ºC as measured between any two telemetry points across the RAMP. At any particular PRT, the change of the minimum temperature over the Martian year has been less than 5ºC.

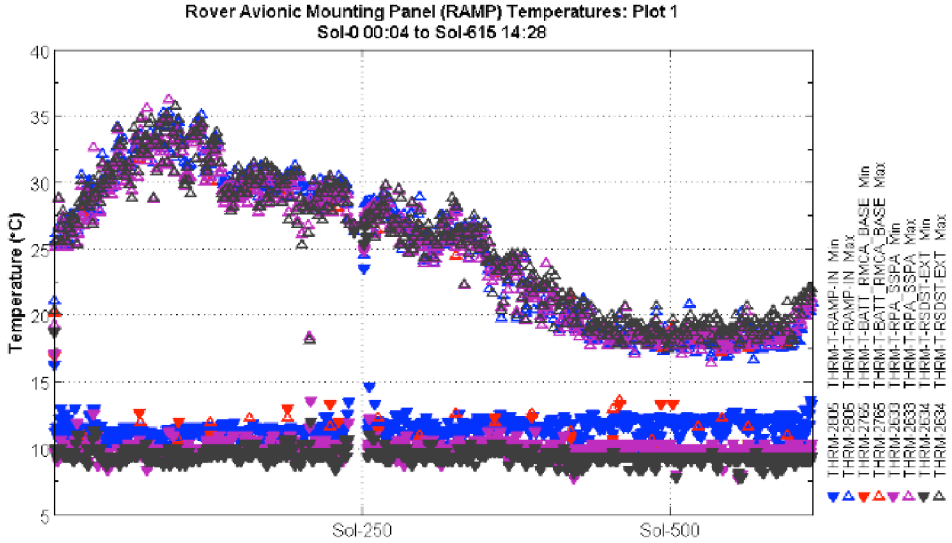

Figure 13. Long-Term Min/Max Temperature trending plot for the RAMP near the HRS inlet.

The maximum temperatures demonstrate the HRS capability to reject heat over an entire martian year, with a variation from +12ºC to +37ºC. The thermostat heaters on the RAMP-mounted CCBU and the warm-up and survival heaters on the Rover battery, which is mounted by stand-offs to the RAMP, have not and likely never will be necessary for the life of the mission.

For the battery this is due to the increased thermal coupling of the battery through the Rover battery cabling to neighboring avionics boxes as discussed by Novak previously.[1] As predicted in that paper, neither the CCBU nor the battery heaters turned on during the primary mission, nor will they likely ever turn on..

III. Local terrain, weather, and orientation effects on Rover temperatures

A. Shadowing & Temperature

An example of shadowing effects can be seen in this Sol-644 through 645 temperature plot in which the Rover was in a general north, north-west heading. The early morning winter sun rising in the north east casts a shadow from the RSM and mast over the inlet covers sequentially causing them to suddenly drop off, but then resume their rise (see Figure 14).

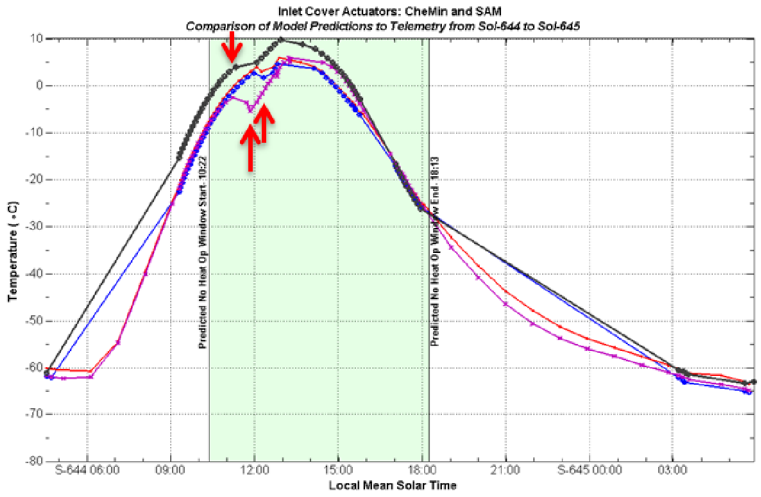

Figure 14. Shadowing affects inlet cover temperatures. (Chemin=blue/red, Sam-1=pink, Sam-2=dark-green)

B. Sand & Rock, how the Martian soil affects local temperatures

Ground temperature has a significant effect on MSL's thermal performance. The plot from the Drill Bit Boxes, which are mounted on the front end (+X) of the Rover show the suppression of diurnal ground temperature variation after driving over big, high-thermal-inertia rock versus the amplification of diurnal ground temperature variation after driving into low thermal inertia sand (see Figures 14, 15, and 16).

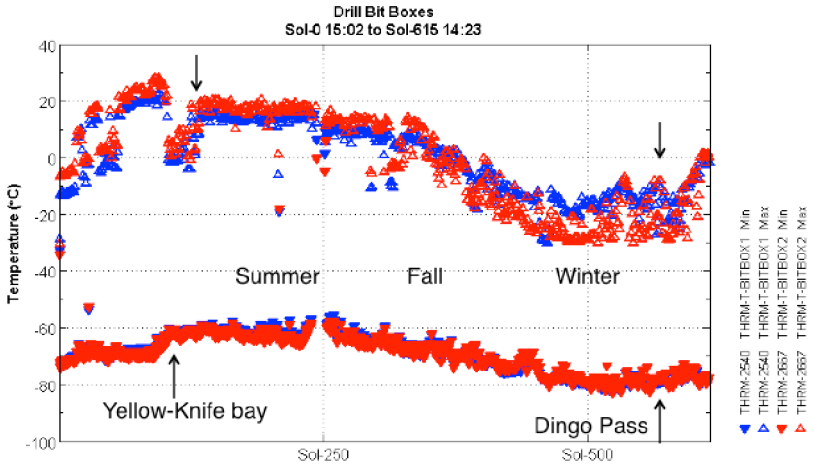

Figure 15. Long-term temperature plot of the drill bit boxes that show the suppression of summer temperatures due to rocky terrain (Yellow-Knife Bay, Shaler, and Glenelg), and the amplification of min/max temperatures in sandy terrain (Dingo Pass).

Most of this effect is seen in the peak ground temperatures. Rockier terrains have cooler peak temperatures and the sandier terrains have warmer terrains. The effect of the rockier terrain is noticeable as a flattening of the maximum temperatures starting around Sol-102 and persists for nearly 215 Sols to Sol 317, as Curiosity drove from an area called RockNest into rockier terrain named Shaler, Glenelg, and Yellow-Knife bay (though the effect is most pronounced from Sol-102 to about Sol-200, before seasonal effects cause the temperature to drop). Contrariwise, when Curiosity drove into the region named Dingo Pass (particularly Sols 527-538), the sandier terrain with its lower thermal inertia caused a very slight amplification of the maximum temperatures.

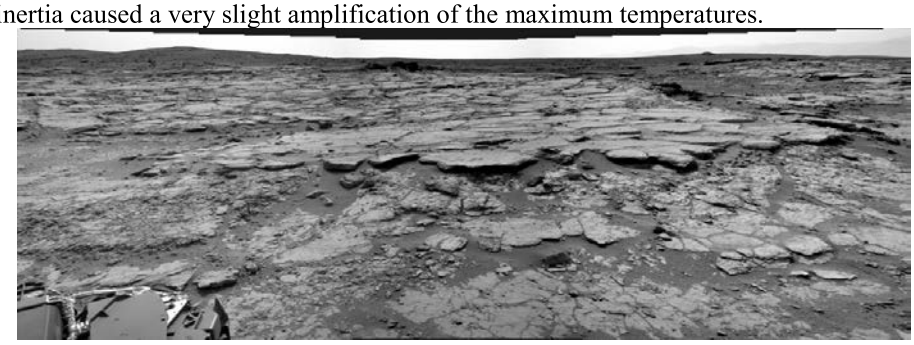

Figure 16. The thermal inertia of Yellow Knife bay's rocky terrain dimishes temperature extremes (Sol-125).

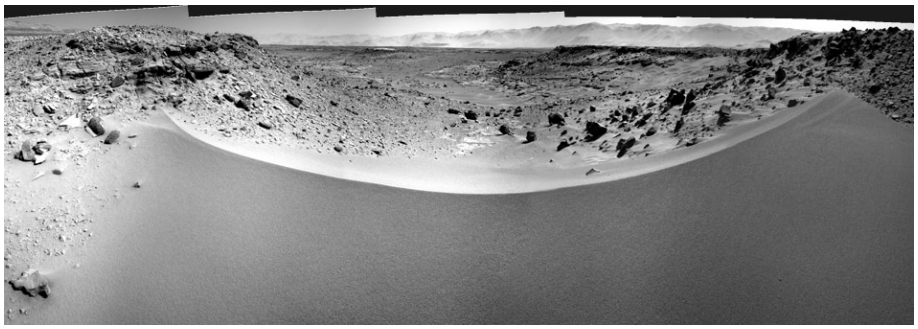

Figure 17. Sandy terrain at Dingo Pass which tended to amplify temperature extremes (Sol-528).

C. Wind Effects

The thermal team has seen indications of wind as previously noted by Novak et al[1], particularly from the RTG, which is a nearly constant heat source and acts as a crude anemometer. Time occurrences of wind activity over the year (sol by sol basis) – have been consistent and wind models have predicted two diurnal high wind events per sol (around 0600 and 2100 LMST), something we have been able to verify with telemetry (see Figure 18).

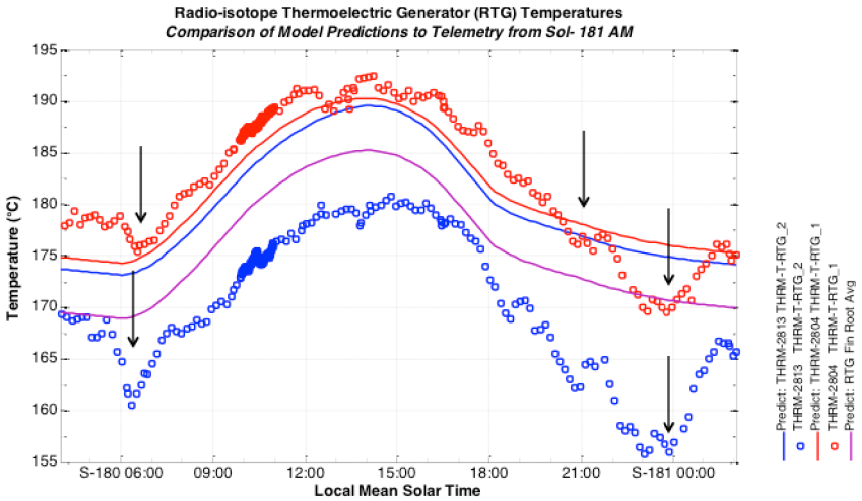

Figure 18. RTG temperatures over sol 181. Arrows highlight 5ºC to 10ºC drops likely due to increased wind activity (no solar load at that time).

D. Temperature Drops and Configuration

Overnight on Sol 323, in late Martian summer, the RA upper arm tube temperature sensor dropped 20ºC from the previous Sol, setting a new low temperature mark for the mission of -82.3ºC. The previous and following nights the same sensor had a minimum temperature -60ºC. All devices on the arm were still safely above their minimum flight allowable temperatures. There are no heaters on the upper arm tube. This behavior raised concerns for neighborhing hardware that could be at risk or that perhaps a temperature sensor was failing.

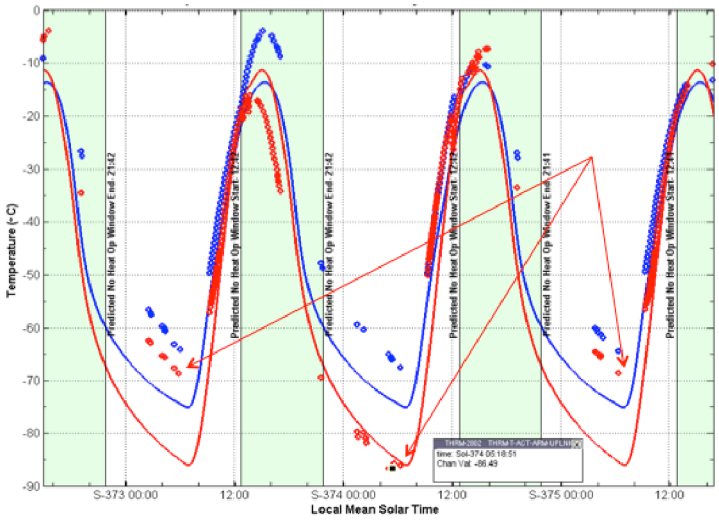

Figure 19. Minimum temperature on the upper arm temperature sensor over a 3-sol period showing the -20C drop on Sol-374 (0600 LMST). Arrows point out where the upper arm temperature was at -68 on Sols 373 and 375.

As would be expected, the low temperature occurred just before sol-break (morning, 0600 LMST), when the local environment had reached its lowest temperature. This definitely ruled out Rover shadowing as an explanation for the colder temperature. No other external hardware on the Rover showed a similar temperature drop—also eliminating wind as a possible explanation.

As it turns out, the APXS instrument was pressed against a rock, with the arm nearly fully extended 2 meters from the Rover chassis. The PRT is mounted on the forearm of the robotic arm. Based on kinematics, the fore arm PRT can either be sky-pointed (corresponding to a *shoulder-out* configuration) or ground-pointed (corresponding to a *shoulder-in* configuration). Because the PRT is mounted on a low thermal conductance, thin titanium tube with little thermal mass, it responds rapidly to the environment. See plot in Figure 19.

Figure 20. The PRT on the forearm of the Robotic Arm is midway down the white forearm (right). The arm can place the APXS sensor on the ground with either a sky-view or ground view for the PRT, causing significantly different temperatures. The sky view PRT configuration consistently produces the lowest temperatures. The right bottom and right top shows the *shoulder-out* configuration which corresponds to the colder, sky-view for the PRT (the elbow actuor is pointed inboard). The left bottom image shows the *shoulder-in* configuration which corresponds to the warmer, ground-view for the PRT (The elbow actuator is pointed outboard.)

This behavior was confirmed subsequently on sols 361 and 374, in which new low temperature records of -86°C and -87°C were established for Curiosity. In both instances, the arm was extended with the forearm PRT view to sky. The coldest temperature recorded to date was -95.2ºC on Sol-559, which was measured by this same PRT on the forearm during an overnight APXS integration.

IV. Looking Ahead

The Rover team is planning for the extended mission, and here are some of the anticipated challenges awaiting the thermal team.When looking at the terrain in Figure 21, two immediate challenges are notable. The canyons will mask the horizon and potentially create the need for a new set of custom heating solutions for large shadowed areas. Canyons also are known for wind effects due to differential peak and valley heating, and cold air upwelling in the mornings adding large scale convective effects.

The base of the foothills contains a dark band of black colored sand, which should give us a much different ground temperatures and potentially both hot and cold extremes. Current estimates put MSL in this region in the middle of summer (see Figure 21).

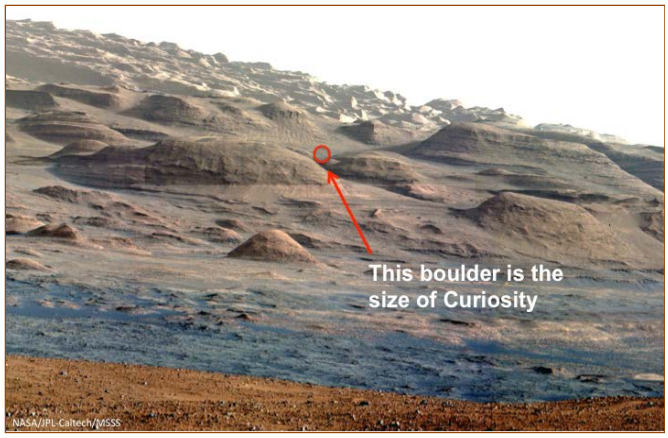

Figure 21. Black sands, canyons and buttes await Curiosity in the coming months as Curiosity drives into the foothills of Mt. Sharp. (Image created by JPL Mars Outreach from NASA/JPL-Caltech/MSSS.)

MSL has been getting bathed in red dirt. Compare the images in Figure 22 and Figure 23. The top deck is one of the radiators for the HRS sytem. Calculations indicate that the Rover is immune to a large degree in the surface paint, but clearly the Rover is no longer white. The vertical radiators on the HRS cold plates have little dust accumulation and from the telemetry appear to be compensating for any increase in the top deck absorptivity (and degradation of it as a radiator).

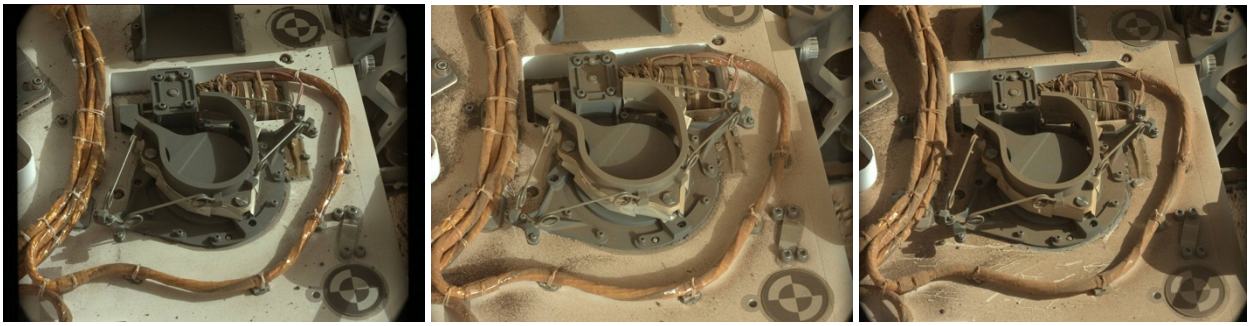

Figure 22. A comparison of the Rover top deck near the CheMin simple inlet on Sol 71 (left), Sol 282 (middle), and Sol 623 (right) as it gets progressively dustier.

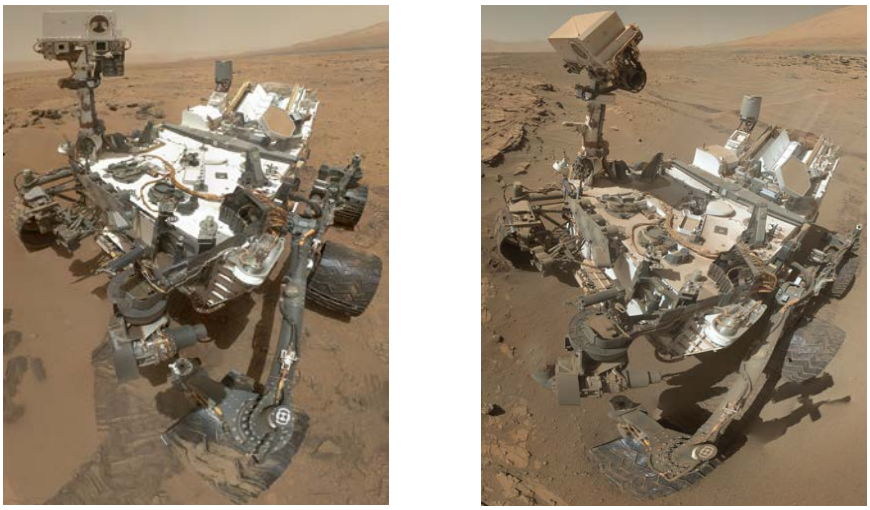

Figure 23. A dustier top deck from Sols 84 (left) and 613(right). Note that the considerable dust atop the remote sensing mast head (top left of Sol 613 image), despite that the head is stowed with the cameras down.

The daily downlink health assessment and reporting is stored on sol-specific web-pages akin to a daily journal. Results from the daily Matlab runs are exported into a powerpoint file that is then archived on the daily report page for the corresponding Sol. Our long term trending reports, which are the source for most of the figures in this paper, are run on a weekly basis and stored on the Sol corresponding to that weekly.

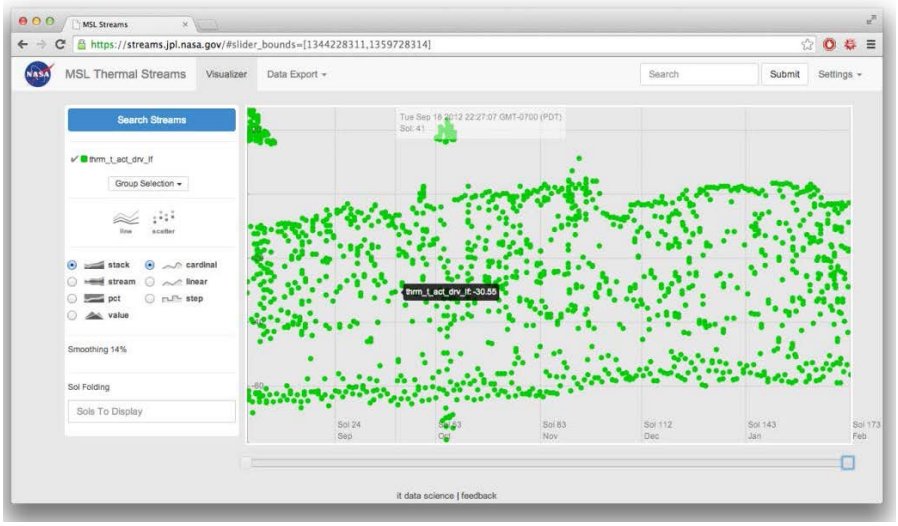

Figure 24. Screen shot of the Streams analytics tool which allows rapid searches and graphing of all thermal telemetry available, amongst other web-based features. Streams is based on open-source software packages.

These Sol-unique web-pages serve a necessary journaling function, but are not well suited for event/data-specific searches or long-term, trend analytics since the data is archived on unique web pages in CSV and powerpoint files. CSV data files are not easy to access, take time to format, and do not easily allow for multi-Sol analysis. The powerpoint fields are not interactive, and lose usefulness for data-mining and in-depth probes (though they are still useful for presentations and sharing).

With over 680 Sols under our belt, the team is now preparing to transform our tools from daily journaling based tools, which are essential in the early phase of the mission, to tools that can process and handle large data sets and are suited to analyze thousands of sols.

With the help of JPL's information technology data scientists, we have developed a web-based tool called Streams that can anyalyze trends and search for specific events.The Streams tool stores each data point as a text file. This allows less than split-second telemetry searches, quick loading, hover point data point discovery, and overlay of various sols for comparison. Each view has a uniquely defined URL (restful URLs), so that specific views can be shared with other engineers and remain interactive by the end user.

We are also in the process of creating other web based tools inconjunction with the MSL project for analytics that will allow us to analyze long-term, subsystem heating performance as well. All of these tools will aid our upcoming challenges as we drive into and up Mt. Sharp.

V. Conclusion

Curiosity's first full Martian year has been a huge success. In the process of operating this incredibly complex vehicle in such an extremely harsh environment using very conservative guidelines has led to a few interesting lessons about the local environment and how we can tailor our thermal operations to be more effective. We have seen the effects of orientation, shadowing, wind and terrain on rover telemetry, and learned how to adapt our tools to improve operational efficiency and adjust to conditions just outside of our plan. This completion of this Martian year has demonstrated the effectiveness of the new temperature sensor selection and the robustness of the HRS system. And finally, we have begun to transition to a long-term mission approach to data analysis, and develop tools to assist in Curiosity's planned drive into the foothills of Mount Sharp during the extended mission phase.

Acknowledgments

This paper hopefully compliments and bookends the papers previously presented at ICES on the thermal MSL design and flight results. In particular Gaj Birur, Josh Kempenaar, Yuanming Liu, Jen Miller, AJ Maestropietro, David Bame, CJ Lee, Juan Cepeda-Rizo, Pradeep Bhandari, and Jackie Lyra and a score of engineers and technicians, too many to list that were actively engaged in the design, fabrication, and operation of MSL have made this paper possible.

Mars images presented in this paper are all the product of NASA, JPL and MSSS from the Curiosity Rover.

Ls130 environments were based on GCM runs by Dr. Jim Murphy of New Mexico State University, the Rover boundary model produced by Joshua Kempenaar of JPL, and actuator and camera models produced Chern-Jiin Lee of Applied Sciences Laboratory. The heater table prescription concept was produced by Dr. Yuanming Liu of JPL. It is expected that the new Ls-130 table will be functional in June 2014.

The Streams tool development was a cooperative development effort between the MSL thermal operations team and the OCIO IT data scientists, Rob Wittoff, Andrew Hart, Dan Isla, and David Mace.

The thermal models used to predict the 76°C temperature differential across the actuators were produced (via a JPL study) and analyzed by Cern-Jiin Lee. Rich Welch and Robert Zimmerman produced Figure 9.

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[4]Birur, G., Bhandari, P., Bame, D., Karlmann, P., Mastropietro, A.J., Liu, Y.M., Miller, J., Pauken, M., and Lyra, J. "From Concept to Flight: An Active Fluid Loop Based Thermal Control System for Mars Science Laboratory Rover," 42nd International Conference on Environmental Systems, San Diego, CA, July 2012.