Mars Science Laboratory Rover System Thermal Test

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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. The MSL rover is scheduled to land on Mars on August 5, 2012. Prior to launch, the Rover was successfully operated in simulated mission extreme environments during a 16-day long Rover System Thermal Test (STT). This paper describes the MSL Rover STT, test planning, test execution, test results, thermal model correlation and flight predictions. The rover was tested in the JPL 25-Foot Diameter Space Simulator Facility at the Jet Propulsion Laboratory (JPL). The Rover operated in simulated Cruise (vacuum) and Mars Surface environments (8 Torr nitrogen gas) with mission extreme hot and cold boundary conditions. A Xenon lamp solar simulator was used to impose simulated solar loads on the rover during a bounding hot case and during a simulated Mars diurnal test case. All thermal hardware was exercised and performed nominally. The Rover Heat Rejection System, a liquid-phase fluid loop used to transport heat in and out of the electronics boxes inside the rover chassis, performed better than predicted. Steady state and transient data were collected to allow correlation of analytical thermal models. These thermal models were subsequently used to predict rover thermal performance for the MSL Gale Crater landing site. Models predict that critical hardware temperatures will be maintained within allowable flight limits over the entire 669 Sol surface mission.

Nomenclature

AFT	=	Allowable Flight Temperature
ATLO	=	Assembly, Test and Launch Operations
APXS	=	Alpha Particle X-Ray Spectrometer
BOL	=	Beginning of Life
CCBU	=	ChemCam Body Unit
CCMU	=	ChemCam Mast Unit
CFD	=	Computational Fluid Dynamics
ChemCam	=	Chemistry and Camera Instrument
CheMin	=	Chemistry and Mineralogy Instrument
CHIMRA	=	Collection and Handling for In-situ Martian Rock Analysis
CO2	=	Carbon Dioxide gas
CQCM	=	Cryogenic Quartz Crystal Microbalance
DAN	=	Dynamic Albedo of Neutrons Instrument
DE	=	Detector Electronics (part of DAN instrument)
DRT	=	Dust Removal Tool
DTE	=	Direct-to-Earth
EDL	=	Entry, Descent and Landing

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FSW = Flight Software
GN2 = Gaseous Nitrogen
GSE = Ground Support Equipment
GDS = Ground Data System
Hazcam = Hazard Avoidance Cameras
HGA = High Gain Antenna
HRS = Heat Rejection System
ILU = Integrating Lens Unit
JPL = Jet Propulsion Laboratory
k = Thermal Conductivity
LGA = Low Gain Antenna
MAHLI = Mars Hand Lens Imager
MARDI = Mars Descent Imager
Mastcam = Mast Camera
MMRTG = Multi-Mission Radioisotope Thermoelectric Generator
MSL = Mars Science Laboratory
NASA = National Aeronautics and Space Administration
Navcam = Navigation Camera
PNG = Pulsed Neutron Generator (part of DAN instrument)
PRT = Platinum Resistance Thermometer
psia = pounds per square inch (pressure)
psid = pounds per square inch differential (pressure difference)
RA = Robotic Arm
RAD = Radiation Assessment Detector
RAMP = Rover Avionics Mounting Panel
RBAU = Rover Battery Assembly Unit
RCE = Rover Compute Element
REMS = Rover Environmental Monitoring Station
RIMU = Rover Inertial Measurement Unit
RIPA = Rover Integrated Pump Assembly
RMCA = Rover Motor Controller Assembly
RPA = Rover Power Assembly
RPAM = Rover Power and Analog Assembly
RPFA = Rover Pyro Firing Assembly
RSM = Remote Sensing Mast
RUHF = Rover Ultra-High Frequency Antenna
SAM = Sample Analysis at Mars Instrument Suite
SA-SPaH = Sample Acquisition - Sample Processing and Handling
SDST = Small Deep Space Transponder
SLI = Single Layer Insulation
Sol = Day on Mars (duration is 24.66 Earth hours)
SSPA = Solid State Power Amplifier
STT = System Thermal Test
Tau = Optical Depth of the Atmosphere (a measure of dust load in the atmosphere)
TDAS = Thermal Data Acquisition System
TLYF = Test Like You Fly
UHF = Ultra-High Frequency
UPS = Un-interruptible Power Supply

I. Introduction

NASA launched the Mars Science Laboratory (MSL) Rover to Mars on November 26, 2011. The MSL rover will touch down on the surface of Mars on August 5, 2012. The MSL rover will robotically explore its Gale Crater landing site to 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 will perform 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.

Prior to launch, the flight MSL Rover was subjected to an environmental test called the Rover System Thermal Test (STT). During the Rover STT, the flight vehicle was thermally and functionally tested in environmental extremes that it would be exposed to during Mars surface operations. This paper describes the Rover STT test planning, execution and results.

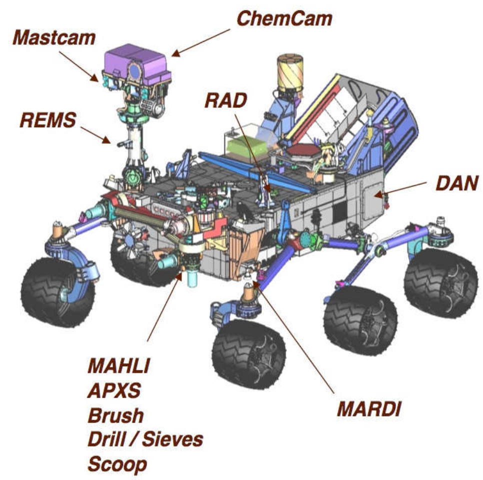

Figure 1. MSL Rover and External Science Instruments.

A. Description of MSL Rover

The MSL rover is designed to last an entire Martian year (669 Sols). The Rover is capable of landing and operating in a wide range of latitudes (± 30 degrees) on Mars. The Rover has been qualified to execute a long cumulative traverse (up to 20 km) over its lifetime. There are 10 science instruments located on the rover. Figure 1 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).

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. Additional engineering hardware is located on the outside of the Rover as shown in Figure 2. 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) is 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 RLGA 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 105W 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 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

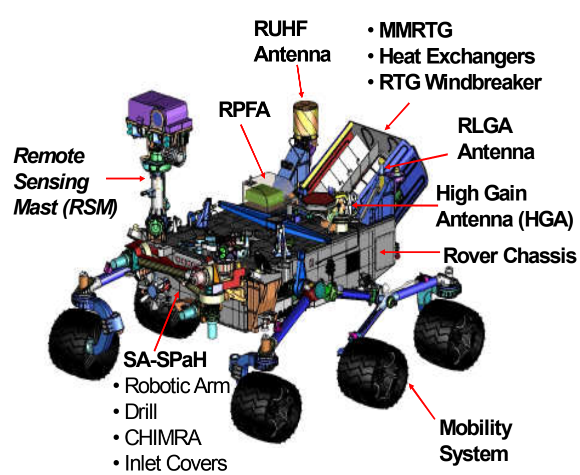

Figure 2. MSL Rover and External Engineering Hardware.

rock below.

All of the temperature-sensitive science electronics boxes 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 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 (Mastcam, 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.

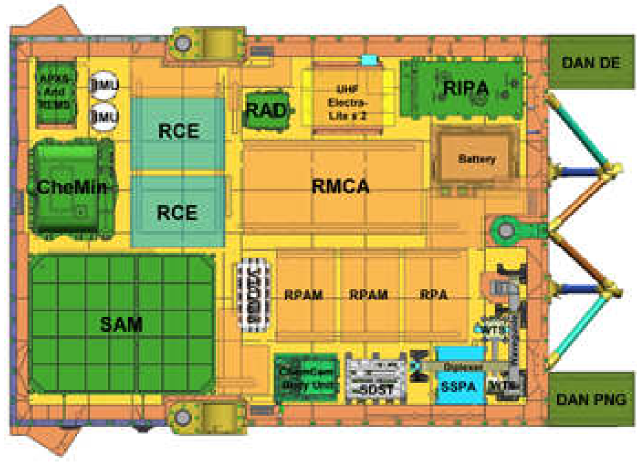

Figure 3. MSL Rover Science and Avionics Mounted on RAMP

B. MSL Rover Thermal Design

The MSL rover was designed to operate in latitudes between 30°N and 30°S. Across this latitude band and across the Mars seasons, a Mars rover would experience both the hottest and the nearly the coldest surface temperatures on the planet (ranging from a high of +38°C to a low of -123°C).

The rover internal hardware mounted on the Rover Avionics Mounting Plate (RAMP) has allowable flight temperature (AFT) limits of -40°C to +50°C. RAMP-mounted boxes were qualified to operate over the wider temperature range of -55°C to +70°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 function 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.[1-6] 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 (using passively-actuated thermal control valves) away from the HRS hot plates and into heat rejection surfaces, on the HRS cold plates and the rover top deck, so heat can be rejected to the Martian environment. The rover battery, having tighter AFT limits than the rest of the RAMP mounted hardware (-20°C to +30°C) has additional survival and warm-up heaters that are controlled by mechanical thermostats.

Most 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 Rover Pyro Firing Assembly (RPFA), mounted to the top deck, and the ChemCam Mast Unit (CCMU), mounted at the top of the RSM which have AFT limits from -40°C to +50°C. Survival heaters, controlled by mechanical thermostats, 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 -55ºC) prior to use. A previously published paper describes the MSL actuator thermal design, testing and performance in detail.[7] Actuator and camera warm-up heaters are controlled by Flight Software (FSW) running on the Rover Compute Element (RCE) boxes.

II. Rover STT Test Objectives

Prior to launch, the Rover was thermally tested in simulated cruise and surface environments during the Rover STT.

The primary STT objectives included the following:

- Gather sufficient data from multiple landed environments to permit an analytical thermal math model correlation.
- Validate that the Rover thermal design satisfies all AFT requirements. (done after the test with correlated thermal models in flight environment).
- Verify Rover HRS thermal performance and flight unit components functionality during Mars Surface steady state conditions over expected surface mission-extreme environments.
- Verify functionality of thermal hardware (heaters, thermostats, PRTs, SLI, rover HRS bypass and mixing thermal valves).

Other STT objectives included:

- Gather sufficient data to identify and correct potential thermal design deficiencies.
- Verify flight temperature sensor measurements via comparison to adjacent test thermocouples, where possible.
- Verify survival heater power and mechanical thermostatic operation during the cold test extremes.
- Verify that the FSW thermostatically controlled warm-up heater circuits function properly.
- Verify workmanship of thermal hardware (heaters, thermostats, PRTs, SLI).
- Verify integrity of thermal interfaces in vacuum and 8 Torr GN2 environments.

A. Why Can't We Empirically Validate the Rover Design in Test?

Due to the complex nature of the Mars surface thermal environment, it is extremely difficult, if not entirely impossible, to do a complete Mars thermal simulation inside a chamber. The following is a list of the elements of the Mars thermal environment that were not reproduced in the thermal chamber during the MSL Rover STT:

1) The Mars acceleration due to gravity is 3/8-g. Since the chamber experiences Earth's gravitational field at 1-g, free convection effects were higher in test than on Mars.
2) The Mars atmosphere is predominantly 8 Torr CO2 gas. In test, the chamber was backfilled with 8 Torr GN2, to prevent condensation, freezing and sublimation of the CO2 that would cause uncontrolled fluctuations in chamber pressure. GN2 ($k = 0.026$ W/m*K at 300K) has a 50% higher thermal conductivity than CO2 ($k=0.017$ W/m*K at 300K). Gas conduction and free convection effects in the chamber are higher than those on Mars. Using 8 torr GN2 results in a conservative cold test (i.e., higher heat losses than we would expect to see on Mars). In the cold case, there is a large temperature difference (70°C) between the RAMP-mounted electronics boxes and the rover chassis that results in a gas conduction heat loss that is about 20% of the total heat loss. In the hot case, the temperature difference between the RAMP-mounted boxes and the rover chassis is much smaller (10°C), so the gas conduction heat loss is small (about 3% of the total heat loss).Thus the use of GN2 in the hot test cases does not significantly alter the expected heat balance that will be experienced on the Mars. The rover thermal model must be correlated to test data assuming 8 Torr GN2 in the chamber. Prior to generating flight predicts, the gas conduction and convection conductances in the model must be modified to account for the 8 Torr CO2 atmosphere of Mars.

3) The Mars atmosphere is laden with statically-charged dust that deposits out on horizontal and vertical rover surfaces over time. Solar exposure also degrades thermo-optical properties of rover external surfaces over time. As installed in the chamber, the flight rover has pristine surface finishes with beginning-of-life properties. The solar absorptivities of rover surfaces in test were lower than those which will be experienced by the rover late in the mission.
4) During the Martian day, the sun tracks across the sky, in both azimuth and elevation, as dictated by the landing site location and the seasons. The solar load on the rover will have a direct and a diffuse component (driven by the amount of dust in the atmosphere). In the chamber, we imposed a solar load on the top of the vehicle; the solar beam did not track across the chamber and did not illuminate the sides of the rover. In addition, the chamber solar simulator created a collimated beam that had no diffuse component.
5) Mars has sustained winds up to 15 m/s. There was no wind simulation in the chamber.
6) Mars has three temperature sinks with specific diurnal profiles based on the ground, atmosphere and sky conditions at a particular landing site on a particular day. Ground and atmosphere temperature profiles are functions of the ground albedo and inertia of the landing site. Sky temperature is a function of the dust opacity of the sky. We controlled shrouds on the chamber walls and the chamber floor to a bounding ground temperature profile. We had no independent control over the effective sky or atmosphere temperatures. The atmosphere in the chamber interacted with the chamber floor and wall shrouds to create an atmosphere temperature that we measured but did not control.

The inability to precisely recreate the Mars thermal environment in the thermal chamber makes an empirical validation of the rover design not possible. Instead we must subject the rover to a number of simplified bounding environmental conditions (both steady state and transient) and correlate a thermal model to the test results. Then we can use the test-correlated analytical thermal model (which can simulate the Mars environment with all its complexities) to fully validate the thermal design and certify it as ready for launch.

B. Rover Hardware Thermal Characterization

Some of the key Rover STT test objectives were to verify functionality, performance and workmanship of all the thermal hardware elements on the rover. There are 92 power switches that control heaters on the rover. All of the heaters are custom-designed, Tayco Kapton film heaters. In general, each hardware element has a primary and a redundant heater circuit. Ten of these rover heater circuits are controlled by Honeywell mechanical thermostats: the battery warm-up and survival heaters, the CCBU survival heaters, the CCMU survival heaters and the RPFA survival heaters. These heaters must be controllable even when the flight computer is off. All of the remaining 82 heaters are FSW-controlled heater circuits. These FSW-controlled heaters include: 6 CCBU decontamination heaters, 20 camera warm-up heaters and 56 actuator warm-up heaters. Each of these heater circuits was energized during the test at different temperature levels to confirm functionality and performance of the switches, thermostats and control PRTs. Heater warm-ups were also performed in functional tests of the rover mechanisms and cameras to confirm that heaters could bring the hardware up to operating temperature in a worst-case cold environment.

There are an additional 4 mechanical thermostats in the rover that are used for HRS fault protection. If a pump were to fail when the flight computer was off, the thermostats are designed to cycle on the backup pump and prevent RAMP temperatures from reaching the minimum (-55°C) or maximum (+70°C) qualification limits. If the pump failed during the day, when there was high power on the RAMP, the RAMP-too-hot thermostat would close at +55°C and turn on the backup pump. If the pump failed at night, when there was low power on the RAMP, the RAMP-too-cold thermostat would close at -45°C and turn on the backup pump. Neither of these circuits could be tested in Rover STT without endangering flight hardware. The other low temperature thermostat that was left untested in Rover STT was the CCBU survival heater; this thermostat also closes at a temperature (-48°C) lower than the min AFT limit (-40°C) of the hardware. In lieu of testing at the system level, a careful review of the thermostat hardware installation paperwork and digital images taken during installation was done to confirm the serial numbers, placement locations and manufacturer's tested close and open setpoints for these thermostats.

The Rover flight system has 221 Honeywell, 1000-Ohm, 2-wire PRTs. Some of these PRTs are used to control warm-up heaters on the actuators and cameras, while others are used to control the decontamination heaters on the CCBU. The remaining PRTs are used to monitor rover thermal system performance and health. In test, thermocouples were placed next to each PRT to check PRT accuracy.

The Rover HRS was also thermally characterized during Rover STT. All of the flight HRS elements (RAMP, Hot and Cold Plates, RIPA and bypass valves) were present in the test. The HRS was exercised over all extreme rover thermal environments and power conditions.

III. Rover STT Test Matrix and Test Profile

The as-planned MSL Rover STT Thermal profile plot is shown in Figure 4. There were a total of 18 individual cases defined for the test. Each test case had its own objectives that supported the main objectives of the test. Figure 4 identifies 15 individual cases; cases not shown in this plot are transition cases (Case 2 – Cooldown to -55°C, Case 4 – Cooldown to -105°C, Case 9 – Warm-up to -80°C), and Cases 14 and 15, which were cancelled. Figure 4 shows the as-planned profiles for the thermal chamber shroud temperature, the prescribed MMRTG power dissipation and the expected average RAMP temperature for each case. Note that MMRTG power dissipation was at a maximum (1821W) in the hot cases (simulating no wind) and lower (1315W) in the cold cases (simulating the cooling effects of a 15 m/s wind). The general test flow was as follows:

1) <u>Cases 1A and 1B</u>: Pump down to vacuum conditions with warm shrouds (at 20°C) and a warm RAMP (at 40°C) to promote outgassing of the rover and to establish a baseline CQCM contamination measurement.
2) <u>Cases 2 and 3</u>: Backfill chamber with 8-Torr GN2 and cool down shrouds to a soak temperature of -55°C. Perform the first functional test by firing all rover pyros and doing initial deployments of all rover mechanisms.
3) <u>Cases 4, 5, 6A, 6B, 7, and 8</u>: Cooldown to minimum shroud temperature of -105°C to perform a Cold thermal balance, cold functional testing in GN2, thermal characterization tests of camera and actuator warm-up heaters, a cold thermal balance in a vacuum environment and lastly, an instrument checkout functional test in a simulated Cruise vacuum environment. Performing the Cruise simulation test after rover deployments was not an issue for the gathering the type of data that was desired from that test case. Extensive vacuum testing had been done with the entire spacecraft (Rover, Descent Stage and Cruise Stage) during the Cruise Phase System Thermal Vacuum Test.[9] Vacuum testing in the Rover STT was done to check integrity of the box-to-RAMP mounting interfaces (a workmanship check) and to derive test data for model correlation in which the gas conduction and free convection effects inside the rover chassis were negated.

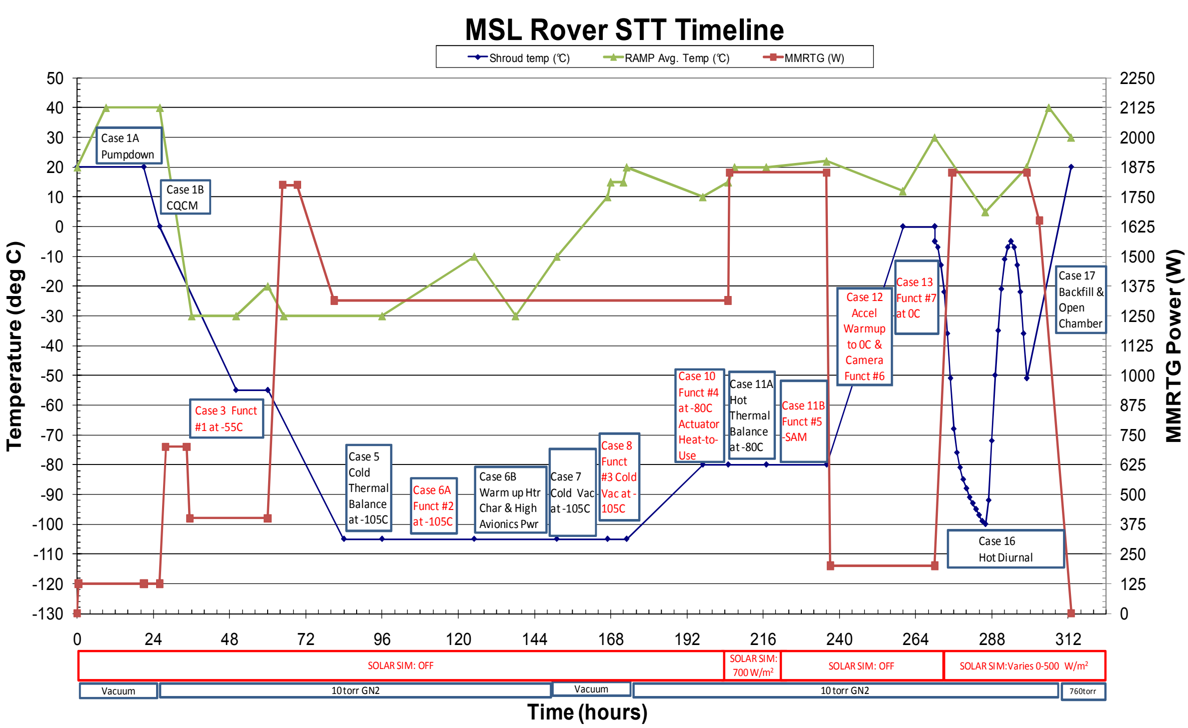

Figure 4. As-Planned MSL Rover STT Thermal Profile Plot

4) Cases 9, 10, 11A and 11B: Backfill chamber with 8-Torr GN2 and warm up shrouds to a temperature of -80°C. Perform functional testing in conjunction with actuator warm-up heating activities, a hot thermal balance with the solar simulator on (at a high solar flux of 700 W/m^2), and a high power functional case with the SAM instrument operating. Note that the hot thermal balance (of Case 11A) was done with colder shrouds (-80°C) to prevent the rover from overheating in this steady-state hot case. The environmental temperatures (atmosphere, ground and sky) on Mars change continuously on a diurnal basis. On Mars, there is never a "steady-state" hot (or cold) condition. The Rover thermal design relies on long time constants and large thermal masses to keep temperatures inside the rover from exceeding maximum AFT limits. If we were to run a worst-case (stacked up) hot case with maximum power on the RAMP, maximum solar flux and maximum environmental temperatures, the rover would surely overheat. Running a steady-state hot case with colder shrouds allows us to maximize most of the effects without overheating the vehicle.
5) Cases 12 and 13: Warm up to shroud temperature of 0°C, perform functional testing of the engineering cameras during the transition, perform rover functional testing with the shrouds soaked to 0°C
6) Cases 14 and 15: cancelled. Case 14 (hot RAMP test) was already performed earlier in the test (see Case 11A) and case 15 was an unneeded transition case.
7) Case 16: Hot diurnal case was a more realistic functional/thermal case in which the rover was operated in a flightlike manner while the environment (shroud temperatures and solar simulator) ramped up and down on an hourly basis to approximate a Mars diurnal profile.
8) Case 17: Warm test article back to ambient, backfill with ambient filtered air and open chamber.

One of the main purposes of this test, from a thermal design standpoint, was to generate enough data so that analytical thermal models of the rover could be correlated with confidence. This meant that test cases had to be devised so that thermally-significant parameters could be exercised over the range of expected values. Model correlation cases were both steady state and transient. Steady state cases allow a thermal model to be correlated by adjusting only conductances in the model. Transient cases introduce the effects of thermal mass and allow capacitances in a model to be correlated.

C. Thermal Sensitivity Variables Exercised in Rover STT

A number of thermal sensitivity variables were exercised over expected ranges in order to get a good thermal characterization of the rover thermal performance in multiple environments. The following sensitivities were investigated:

1) Effect of GN2 atmosphere versus vacuum - Compare case #5 (Cold Thermal Balance at -105°C) and case #7 (Cold Vacuum Test at -105°C). Note that the cold thermal balance in the vacuum environment was not a flightlike condition, but was added to the test matrix to produce a model correlation case that had no gas conduction or free convection effects. Extensive testing was done previously to characterize gas conduction and free convection effects in gas gaps (from 3.8 cm to 12.7 cm) filled with GN2 and CO2.[8]

2) Effect of MMRTG Power (Q = 1315 W to 1821 W) - Compare case #5 (Cold Thermal Balance at -105°C) to case #11B (Functional #5 at -80°C). Note that the minimum MMRTG power dissipation case (Q=1315W) simulated the MMRTG performance in a forced convection (15 m/s wind) environment, while the maximum MMRTG power dissipation case (Q=1821W) simulated the MMRTG performance in a free convection environment (no wind). Less heat is available for pickup by the HRS hot plates, when the wind is blowing on Mars. Wind was not explicitly simulated in the chamber (e.g., with a fan), but was accounted for by reducing the MMRTG dissipation. The Rover HRS performance in the cold case is particularly sensitive to wind. In the worst-case cold environment, the difference in predicted RAMP temperatures between a case with no wind and a case with 15 m/s wind can be as much as 30°C.

3) Effect of Solar Flux (Q" = 0 W/m^2 to 700 W/m^2) - Compare case #10 (Functional Test #4 Environment at -80°C) and Case #11A (Hot Thermal Balance at -80°C). The maximum solar flux over the landing site latitude range for MSL is approximately 700 W/m^2.

4) Effect of Shroud Temperature (+20°C to -105°C) - Multiple cases. Predicted atmosphere temperatures at the Gale Crater (4.5° S latitude) landing site for MSL range from -11°C to -91°C.

5) Effect of Power Dissipation on the RAMP (30W to 290W) - Multiple Cases. The minimum sleep power of the rover is 30W. The maximum sustained power on the RAMP is about 200W. Peak transient powers can be as high as 290W.

D. Functional Testing in Rover STT

Seven functional tests (indicated by the red text boxes in Figure 4) were performed during the Rover STT. These functional tests are not discussed here in any great detail since they were not considered to be thermal model correlation cases and as such did not have controlled power dissipation profiles. The following types of rover activities were performed in the chamber during functional test cases: nine pyro firings to release launch locks, all rover deployments, range of motion tests on all articulated hardware, drill bit exchange, RA positioning and preloading, RSM pointing, imaging of calibration targets with all science and engineering cameras, science instrument checkouts and calibrations at varying RAMP temperatures, and actuator and camera heat-to-use warm-ups followed by mechanism and camera functional testing. The effects of ambient temperature changes on the RA preload onto a simulated rock target were investigated during the diurnal simulation of Case 16.

IV. Test Article Description

With only a few exceptions (described in the paragraph at the end of this section), the test article Rover consisted entirely of flight hardware. All of the following items were included in the test:

1) All Rover structures, and mechanisms: chassis, RAMP, mobility, actuators.
2) The entire Surface HRS thermal system: RIPA, Heat Exchanger Plates, RAMP.
3) All Avionics components: flight Computer, power boxes, battery, telecommunications boxes.
4) All engineering cameras: Hazcams, Navcams.
5) All Science instruments: MAHLI, Mastcams, ChemCam, APXS, REMS, RAD, CheMin, SAM, DAN.
6) All Sample Acquisition/Sample Processing and Handling (SA-SPaH) hardware: Robotic Arm, Drill, CHIMRA, 3 Sample Inlet Covers, 2 Contact Sensors, 2 Drill Bit Boxes.

Flight hardware that was not in the test includes the DRT (was still in test at the vendor) and the MARDI science camera (attached to the rover during flight, but only planned to be used during EDL). The DRT was represented by a mass model bolted to the turret. MARDI had temperature limits compatible with EDL, but its minimum non-op AFT limit (-40°C) was not compatible with the planned minimum shroud temperature during the test (-105°C). The MARDI is thermally isolated from the rover and its omission from the test had no effect on the thermal performance of nearby hardware. The flight MMRTG was replaced by the MMRTG qualification unit which had internal heaters to simulate the power dissipation of the flight nuclear source. The high-fidelity MMRTG qualification unit did have thermoelectrics installed inside it and did generate electrical power, but that power was kept on the MMRTG via a shorting plug. All rover power during the test was supplied by external power supplies through an umbilical cable. The ATLO battery was used during STT in order to save lifetime on the flight battery. The flight battery was installed in the rover at Cape Kennedy, shortly before launch. Electrical testing verified function of the flight battery heater circuits shortly after installation.

V. Chamber and Test Article Instrumentation

The MSL Rover was tested in the 25-Foot Space Simulator Facility at JPL. Figure 5 shows a picture of the flight MSL Rover installed in the chamber. This vacuum chamber is 25.9 m (85 ft) high and has a carbon-steel pressure vessel lined with black-painted aluminum shrouds on the floor and walls. The chamber internal diameter (shroud-to-shroud distance) is 7.5 m (24.5 ft). The 25-Foot Space Simulator has a solar simulator system that includes an array of xenon arc lamps, a focusing component called an ILU (Integrating Lens Unit), a penetration window, and a collimating mirror mounted at the chamber top to redirect the simulated solar flux and illuminate the test article below. For this test, a lens was used to illuminate the rover at a flux level of 700 W/m^2 over a 4.6m (15 ft) wide hexagonal spot. Solar simulator flux levels were checked during the test with a Kendall cone radiometer. There are over 150 thermocouples mounted in different locations inside the chamber to monitor and control shroud and solar simulator temperatures.

There were 357 Type E, 26-gage thermocouples installed on rover hardware in the test. An additional 11 thermocouples were used to measure chamber atmosphere temperatures, and 18 more were installed on GSE structure and camera calibration targets. These temperature sensors were used for temperature monitoring and PRT

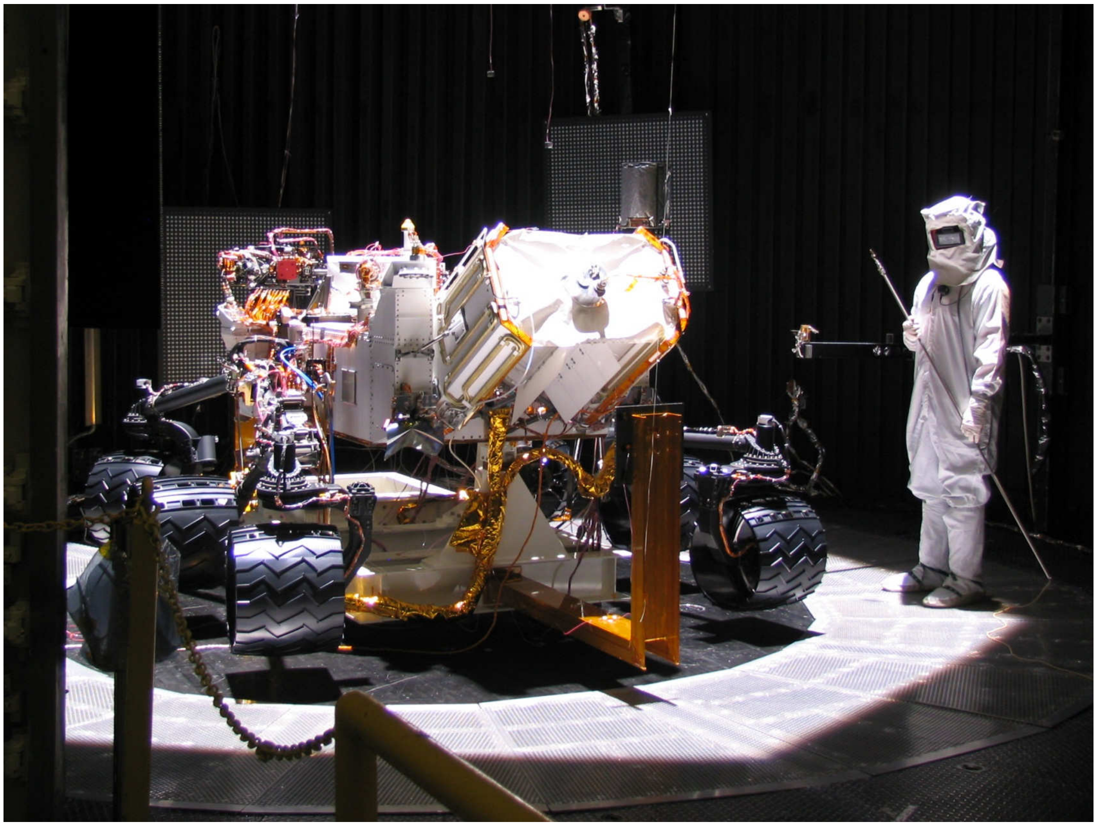

Figure 5. MSL Flight Rover Installed in 25-Foot Space Simulator Facility – Solar Spot Mapping

flight sensor verification. Thermocouples were mounted next to all flight thermostats and heaters, in locations needed to determine temperature gradients across interfaces and in locations where temperature data was needed to facilitate analytical thermal model correlation.

All test data was collected and stored by the JPL Thermal Data Acquisition System (TDAS) a LabView-based data-acquisition system. All data (time, date, temperature, power, voltage and current) was monitored and automatically recorded at one-minute intervals. In addition, the TDAS was able to intercept and record all flight system PRT temperature telemetry that was flowing into the flight Ground Data System (GDS). This was a very powerful function of the TDAS that facilitated comparison of thermocouple data and PRT telemetry within the same database. The TDAS was connected to an Un-interruptible Power Supply (UPS) and a backup electric generator. The TDAS was also used to control test heaters (for the rover shunts, CCBU decontamination heaters and RIPA fault protection) using software control of dedicated GSE power supplies.

The rover was mounted in the chamber on top of an I-beam support frame that stood 15 cm above the chamber floor shroud. Thermal isolators were used between the rover chassis and the support frame to limit local heat leaks from the rover to the support frame. The mobility wheels were suspended off the floor (i.e., did not contact the floor shroud) and thus were free-wheeling. This allowed the wheels to be rotated and functionally tested without having to deal with dragging umbilical cables across the floor or the resulting repositioning of the rover relative to calibration targets in the chamber.

VI. Test Results

The following items are the major test results and findings:

1) The thermal test was highly successful. All of the major thermal test objectives were completed. The rover thermal design performed extremely well during the test, and no violations of AFT limits were observed.

No thermal design deficiencies discovered. The full functionality and workmanship of thermal hardware was confirmed.

2) All thermal balance and transient test cases were completed. Sufficient data for thermal model correlation was generated.
3) Thermal performance of the rover in the steady-state cold condition was better than pre-test predictions. Thermal performance of the rover in the steady-state hot case was very similar to pre-test predictions.

In general, the rover STT was designed to subject the rover to representative surface flight environments that would exercise all of the thermal functions of the design in a flight-like manner. This type of test philosophy is known as Test-Like-You-Fly (TLYF). One notable exception to the TLYF rule (that was accepted by the project management) was the lack of RIPA fault protection testing. The HRS backup pump fault protection schemes, for both RAMP-too-hot and RAMP-too-cold conditions, were not tested in STT. Unsuccessful attempts were made to warm up and trigger the RAMP-too-hot thermostats (close setpoint = +55°C) using local GSE heaters, but the power levels were not large enough to heat the RAMP above 50°C. No attempt was made to test the under-temperature thermostats (close setpoint = -45°C), as this was not a pre-test objective.

All flight temperature sensor measurements (from PRTs) were checked against measurements from adjacent thermocouples in all of the steady state cases. Results show that in flight (after adjustments to the autozero calibration and fixes to the analog-to-digital conversion coefficients) the PRTs will be accurate to within -2°C to +3°C over their full temperature range. All FSW and mechanical thermostat controlled heater circuits were verified to function properly during the test. When survival heater performance was extrapolated from the test bus voltage of 29.5V to the worst-case minimum flight bus voltage of 22V, all predicted heater duty cycles were under 80%.

The integrity of the thermal interfaces from the electronics boxes to the RAMP was verified in both vacuum and 8 Torr GN2 atmosphere cases. Box-to-RAMP temperature gradients were nearly the same in both cases. The largest Box-to-RAMP temperature difference was 7°C for the UHF radio, which has a large thermal dissipation (61W) and a small box footprint (200 cm^2). All Box-to-RAMP temperature gradients were within expected ranges.

A. Rover HRS Thermal Performance

The rover HRS performed exceptionally well during Rover STT. As shown in Figure 6, RAMP temperatures

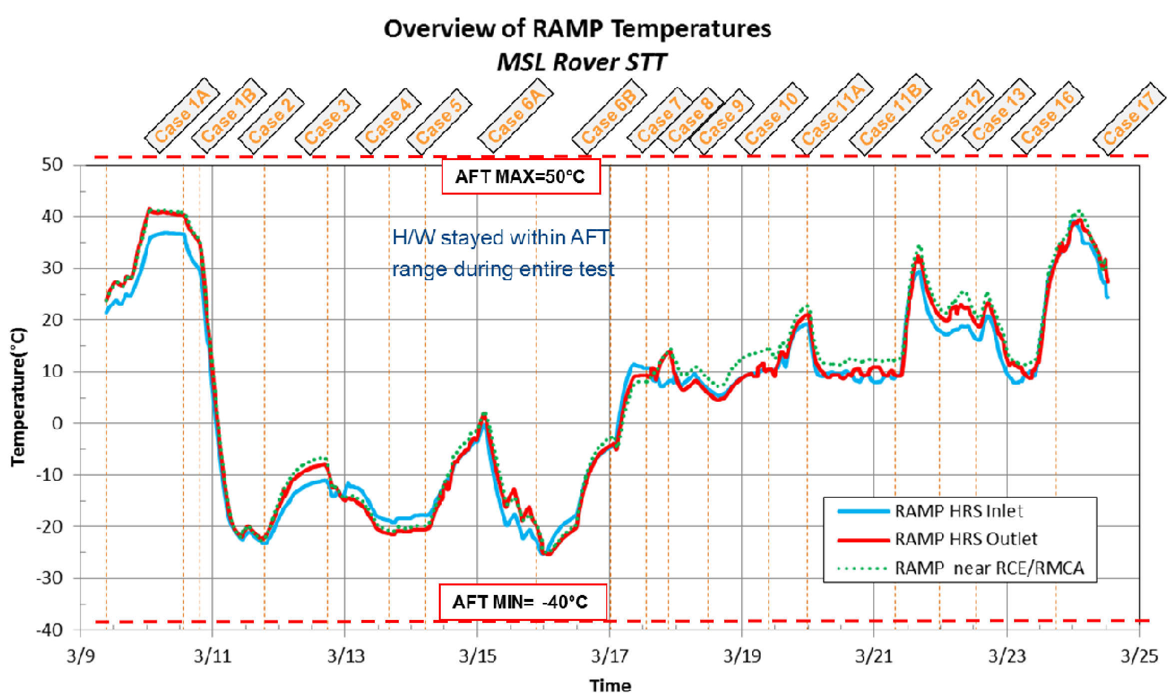

Figure 6. RAMP Temperatures during Entire Test

stayed within AFT limits (-40°C/+50°C) over the entire test.

In the worst-case cold test conditions, the RAMP component interfaces were ~3°C to 10°C warmer than predicted. Actual heat leaks from the rover boxes mounted to the RAMP were about 20% less than the cold-case conservative design model. The temperature drop from the inlet fluid to the exit fluid was less than predicted, indicating again that heat losses were less than expected.

In the hot thermal balance test conditions, the hottest RAMP component interface was ~0.2°C cooler than predicted. Hot case performance was very close to the predicted performance. In the steady-state hot case, the RAMP temperature distribution was very uniform (~ 2°C temperature gradient in STT vs. ~7°C predicted). This indicates better heat spreading on the RAMP than was predicted in the model.

Operating pressures in the HRS were maintained within the nominal expected range throughout the test. The minimum pressure recorded during STT was 67 psia (Min Yellow Alarm = 55 psia). The maximum system pressure recorded during STT was 153 psia (Max Yellow Alarm = 180 psia). No Freon leaks were observed. There was no evidence of accumulator bellows sticking; all gas-to-liquid pressure gradients inside the accumulator were less than 3 psid.

B. Battery Thermal Performance

Two battery warm-up heaters were able to warm the battery from its minimum AFT limit of -20°C to its optimal charging temperature of 0°C in 3.5 hours, using 224 W-hrs of energy. Test data from the worst-case cold steady state case shows that the battery can be maintained at 0°C with one warm-up heater on. The maximum temperature gradient observed across the battery with 3 heaters on simultaneously (the primary survival, the primary warm-up, and the back-up warm-up heaters) was less than 3°C. This worst-case test showed that the battery will never exceed its maximum allowable spatial gradient requirement of 5°C.

C. Actuator and Camera Warm-up Heater Thermal Performance

Test results show that actuator and camera warm-up heaters have been adequately sized. All warm-up heaters are capable of warming up actuators and cameras above their minimum operating AFT limits in the worst-case cold environment (-105°C shroud, no solar) within the expected time duration. In addition, the warm-up heaters are capable of maintaining the actuators and cameras in the operating temperature range with a reasonable duty cycle (< 80%). Pre-heat durations and maintenance heater duty cycles were consistent with pre-STT predictions.

Sufficient data was obtained in the test to allow thermal model correlation of the following actuators and cameras:

Actuators: Mobility, HGA, and Inlet Covers.
Cameras: MAHLI and Mastcams.

In addition, sufficient thermal data was obtained to allow checking of previously correlated models for the following actuators and cameras:

Actuators: RSM, CHIMRA, Drill, and RA.
Cameras: Hazcams and Navcam.

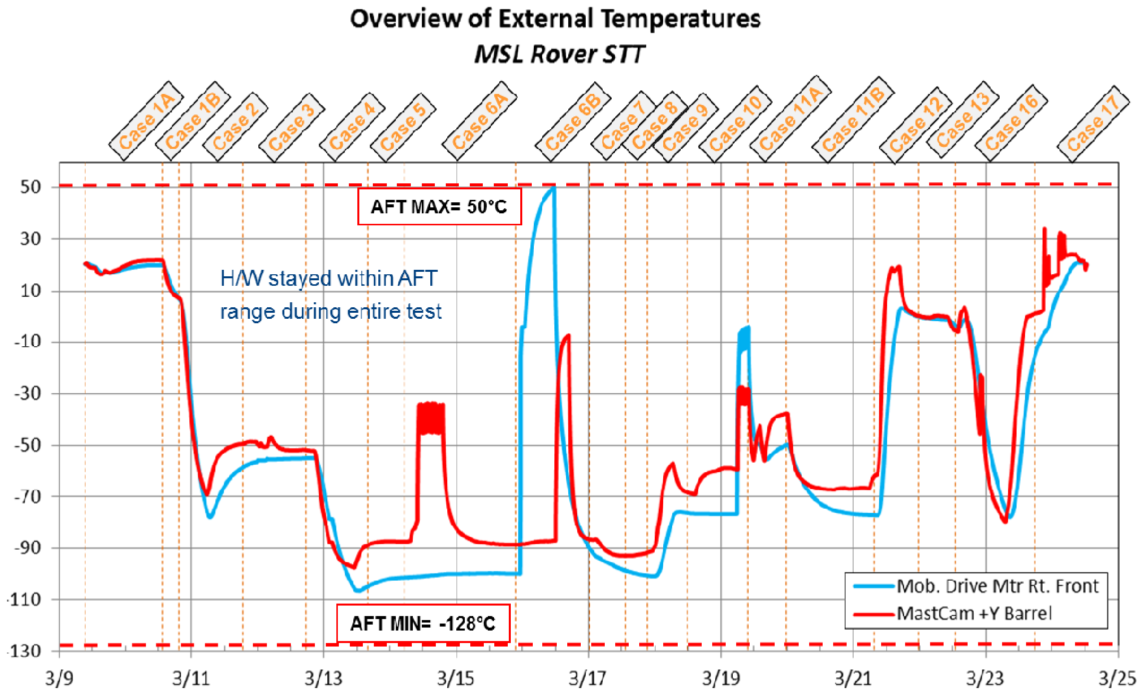

Figure 7. Mobility Actuator and Mastcam Camera Temperatures during Entire Test

Figure 7 shows representative actuator (mobility right front drive motor) and camera (Mastcam +Y) temperatures during the entire test. In case 6A, the Mastcam was warmed up and went into maintenance mode (see red curve around 3/14 on the timeline). Case 6A is the nominal use case of warm-up heaters for flight. In case 6B, both the Mobility and the Mastcam heaters were run to a steady state condition and allowed to cool back down. Case 6B is only a test case and is not representative of the manner in which the warm-up heaters would be used in flight. The transient warm-up, steady state and transient cooldown data generated in Case 6B was used to correlate the mobility and Mastcam analytical thermal models.

D. Rover Thermal Design Sensitivities

The effect of a chamber atmosphere on the temperature gradients from operating electronics boxes to the RAMP can be derived by comparing results from Case #5 (in 8 Torr GN2) to those from Case #7 (in a vacuum). There was very little difference in the box-to-RAMP temperature gradients from the case with GN2 to the vacuum case. The thermal interfaces perform very well in both a gas environment (on Mars) as well as in a vacuum (during cruise).As previously stated, the maximum box-to-RAMP temperature gradient was 7°C for the UHF radio.

The effects of MMRTG Power and shroud temperature on the RAMP temperatures can be derived by comparing the results from Case #5 (Cold Thermal Balance: Q_{MMRTG} = 1315 W, T_{shroud} = -105°C) to those from case #11B (Functional #5: Q_{MMRTG} = 1821 W, T_{shroud} = -80°C). These are the combined effects of 2 variables and they show a strong response in the RAMP temperature. An increase in the MMRTG power by 506W (from 1315W to 1821W) coupled with an increase in shroud temperature of 25°C (from -105°C to -80°C) results in a 30°C rise (from -20°C to +10°C) in RAMP temperature. Most of the 30°C increase in RAMP temperature is due to the increased MMRTG power, thus re-confirming that the Rover thermal design is sensitive to drops in collected MMRTG waste heat caused by forced convection of Mars surface winds. Extensive CFD analysis was done to characterize convection heat transfer coefficients on the fins and body of the MMRTG and on the HRS heat exchanger plates in free (no wind) and forced (15 m/s wind) convection environments. Results of the CFD analysis are used in the flight version of the correlated system-level thermal model of the rover.

The effect of solar flux on the RAMP temperatures can be derived by comparing the results from case #10 (Functional Test #4 Environment at -80°C, $Q_{solar} = 0\ W/m^2$) to those from Case #11A (Hot Thermal Balance at -80°C, $Q_{solar} = 700W/m^2$). Increasing the solar load on the top deck from 0 W/m^2 to 700 W/m^2 resulted in a 10°C increase in RAMP temperature (from 10°C to 20°C).

VII. Thermal Model Correlation and Flight Performance Predicts

The Rover STT test data was used to correlate analytical thermal models of the Rover System, actuators and cameras. The Rover system model runs in the IDEAS-TMG software package. Separate individual sub-models of the actuators and cameras were developed in SINDA-3D and TSS.

A. Rover System Thermal Model Correlation

A view of the Rover system-level analytical thermal model inside the thermal chamber is shown in Figure 8. Parameters which were modified to improve rover system-level model correlation with test results included:

- Thermo-optical Properties
  - Emissivity
  - Absorptivity
- Radiation Blockage
- Thermal Conductances
  - Interfaces
  - Cables
  - CO_2 thickness for Gas Conduction
- Convection Coefficients
- Effective Thermal Mass

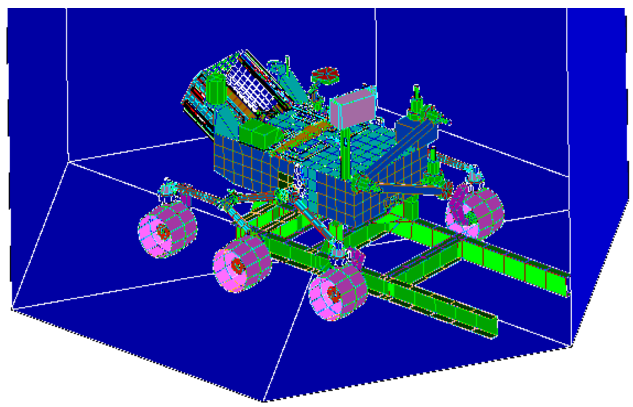

Figure 8. Rover System Thermal Model in STT Test Configuration

Many of these changes were a matter of removing conservatism from the thermal design model that was used to account for design uncertainty. Model correlation was within 5°C of test temperatures.

B. Actuator and Camera Thermal Model Correlation

Uncorrelated thermal models of actuators and cameras were developed to aid in the design of the warm-up heaters. These design models were cold-biased and conservative. Through model correlation to the test data, we either validated the assumptions that had been built into the thermal models, or made the necessary model adjustments to take out some of the conservatism and better reflect reality.

The general correlation methodology for the actuator and camera thermal models is summarized briefly below:

- Use the uncorrelated flight models to correlate to the test data: Assume Sky temperature = mid/upper shroud temperature, and Ground temperature = floor shroud temperature.
- Use 8-Torr GN2 as the atmosphere for gas gap conduction and convection;
- Use measured Rover chassis test temperatures as boundary temperatures for external components (actuators and cameras);
- Assume cold BOL properties and free convection;
- Account for cable electrical resistance in heater power calculation;
- Use +/-5°C as correlation band;
- Correlate to both the steady-state and transient data;

Gas mixing inside the large volume thermal chamber effectively "isothermalized" the gas temperature in the chamber. Measured temperatures inside the chamber from the 12 gas thermocouples placed in different areas around the rover were within 10°C of each other during most of the test. The design is not sensitive to the spectral differences between the Xenon lamp solar simulator and the real solar spectrum that would be experienced on Mars and thus no such adjustments were made in the correlated flight thermal models.

C. Flight Predicts

The correlated test models were converted into correlated flight models by changing the 8-Torr GN2 atmosphere to 8-Torr CO2 and changing Earth gravity (1-g) to Martian gravity (3/8-g) in the convection coefficient calculations. Worst-case cold flight predicts were done assuming forced convection coefficients on external rover surfaces as calculated from forced convection correlation equations with 15 m/s wind. Worst-case hot flight predicts were done assuming free convection coefficients (no wind) on external rover surfaces. 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, appropriate dust coverage and wind assumptions) to generate flight performance predictions. The following are the major findings from flight predictions of the correlated thermal models:

1) Flight predictions from Rover system-level thermal model in the Gale Crater landing site (4.5°S latitude) extreme mission environments over all seasons show full compliance with all rover temperature limit requirements (see Figure 9). Worst-case flight predictions show more than adequate temperature margins:
    a. In the worst-case hot condition (maximum power on the RAMP, Summer Solstice environment, with 40% dust coverage and no wind) the predicted maximum RAMP temperature = 42°C (8°C margin to max AFT limit of 50°C)
    b. In the worst-case cold condition (minimum power on the RAMP, Winter Solstice environment, with 0% dust coverage and 15 m/s wind) the minimum predicted RAMP temperature = -13°C (27°C margin to min AFT of -40°C).

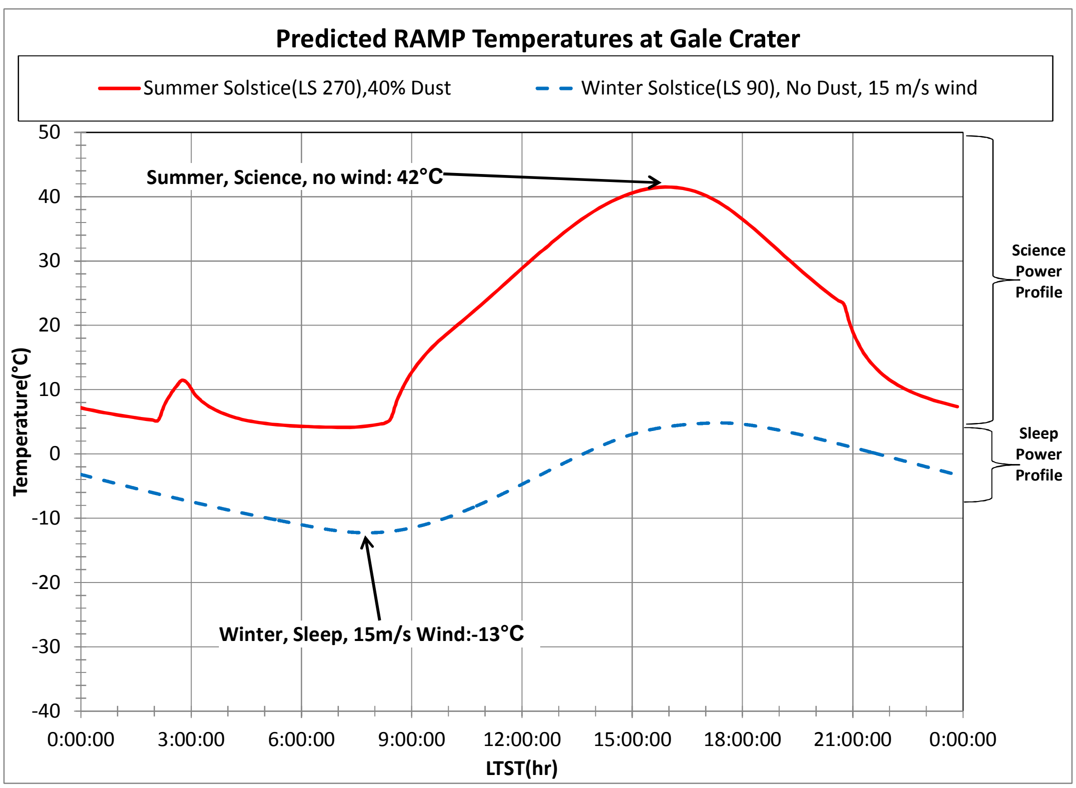

Figure 9. Test-Correlated Rover System Thermal Model RAMP Temperature Predicts for Gale Crater Flight Environments

2) Correlated camera and actuator thermal models were also run in the Gale Crater environments. All warm-up heaters meet the operational time-of-day requirements. In addition, the correlated models show faster warm-up times and slightly lower (7%) overall energy consumption (for warm-up and maintenance) than pre-test model predictions.

VIII. Conclusion

The following conclusions came out of the MSL Rover STT:

1. It was a very successful test.
2. All primary test objectives were met.
3. Rover thermal design performed well during this test and no violations of Allowable Flight Temperatures were observed.
4. The MSL Rover thermal design has been fully tested, and system level thermal models have been correlated to test data.
5. Flight temperature predictions have been formulated for all rover hardware components. Thermal performance predictions for Gale Crater Landing Site (4.5 degrees South latitude) are excellent.
6. All Rover component level thermal designs show adequate to robust temperature margins to AFT requirements in all Surface phase thermal environments.
7. The HRS performed extremely well and serves as an excellent backbone for the overall thermal control system. It created a highly isothermal and controlled interface for all RAMP-mounted hardware. HRS-controlled hardware had significant temperature margins against minimum AFT limits.

The MSL Rover has been successfully thermally tested and is certified to be ready for Mars surface operations in Gale Crater starting on August 5, 2012.

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