Thermal Response of the Mars Science Laboratory Spacecraft during Entry, Descent and Landing

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NASA's Mars Science Laboratory (MSL) spacecraft successfully performed its Entry, Descent & Landing (EDL) phase on August 6, 2012. This paper presents the thermal response of the MSL spacecraft from EDL Initialization (5 days prior to Entry) to Rover touchdown on the surface of Mars. Temperature telemetry recorded during EDL is used to reconstruct the thermal response of the spacecraft to each EDL event. Temperature profiles for the Descent Stage and Rover hardware are presented and explained in the context of the changing EDL environments (aerothermal heating and convective cooling) and power states.

Nomenclature

AFT	=	Allowable Flight Temperature
AU	=	Astronomical Unit
BLRA	=	Base Load Resistor Assembly
BUD	=	Bridle Umbilical Device
CBM	=	Cruise Balance Mass
CCD	=	Charge Coupled Device
CHRS	=	Cruise Heat Rejection System
CPA	=	Cruise Power Assembly
CPAM	=	Cruise Power and Analog Module
CRCS	=	Cruise Reaction Control System
CS	=	Cruise Stage
CSS	=	Cruise Stage Separation
DIMU	=	Descent Inertial Measurement Unit
DMCA	=	Descent Motor Controller Assembly
DPA	=	Descent Power Assembly
DPAM	=	Descent Power and Analog Module
DRCS	=	Descent Reaction Control System
DRL	=	Descent Rate Limiter
DS	=	Descent Stage
E	=	Entry
EBM	=	Entry Balance Mass
EDL	=	Entry, Descent and Landing
FPA	=	Focal Plane Array
GCM	=	General Circulation Model
GNC	=	Guidance, Navigation and Control
H/S	=	Heatshield
Hazcam	=	Hazard Avoidance Cameras
HGA	=	High Gain Antenna

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HRS	=	Heat Rejection System
HX	=	Heat Exchanger
JPL	=	Jet Propulsion Laboratory
LGA	=	Low Gain Antenna
LMST	=	Local Mean Solar Time
L_S	=	Solar Longitude
LTST	=	Local True Solar Time
MARDI	=	Mars Descent Imager
MEDLI	=	Mars Entry Descent Landing Instrument
MLE	=	Mars Lander Engine
MLI	=	Multi-Layer Insulation
MMRTG	=	Multi-Mission Radioisotope Thermoelectric Generator
MOLA	=	Mars Observer Laser Altimeter
MRO	=	Mars Reconnaissance Orbiter
MSL	=	Mars Science Laboratory
NASA	=	National Aeronautics and Space Administration
Navcam	=	Navigation Camera
OWLT	=	One-Way Light Time
PDV	=	Powered Descent Vehicle (Descent Stage & Rover)
PRT	=	Platinum Resistance Thermometer
PUHF	=	Parachute UHF Antenna
PWTB	=	Power Thermal Battery
PYTB	=	Pyro Thermal Battery
RA	=	Robotic Arm
RAMP	=	Rover Avionics Mounting Panel
RBAU	=	Rover Battery Assembly Unit
RCE	=	Rover Compute Element
RCS	=	Reaction Control System
RHRS	=	Rover Heat Rejection System
RIPA	=	Rover Integrated Pump Assembly
RPA	=	Rover Power Assembly
RPFA	=	Rover Pyro Firing Assembly
RPM	=	Revolutions per Minute
RSM	=	Remote Sensing Mast
S/C	=	Spacecraft
SCET	=	Spacecraft Event Time
SDST	=	Small Deep Space Transponder
Sol	=	Day on Mars (duration is 24.66 Earth hours)
SSE	=	Star Scanner Electronics
STT	=	System Thermal Test
SUFR	=	Straighten Up and Fly Right
TCM	=	Trajectory Correction Maneuver
TDS	=	Terminal Descent Sensor
TLGA	=	Tilted Low Gain Antenna
TWTA	=	Traveling Wave Tube Amplifier
UHF	=	Ultra-High Frequency
UTC	=	Universal Time Constant

I. Introduction

THE MSL Rover, Curiosity, successfully landed in Gale Crater (at 137.4°E longitude and 4.5°S latitude) on Mars on August 6, 2012 at 05:17:57 UTC (SCET). Touchdown occurred at 15:03 LMST in Gale Crater. This paper documents the thermal response (as recorded by flight telemetry) of the MSL spacecraft (S/C) during the events leading up to and during the Entry Descent and Landing (EDL) portion of the mission. A previous paper,[1] discusses the Cruise thermal performance of the MSL spacecraft. Several other papers,[2,3] cover Rover thermal performance

on the surface of Mars. This paper fills the gap between the cruise and surface phases of the mission, covering the EDL phase from the EDL initialization segment (at E-5 days) all the way to Rover touchdown on the Mars surface.

This paper does not discuss thermal modeling that was done to design or predict S/C performance during EDL. A previous paper,[4] describes simplified analysis techniques that were used to generate worst-case bounding temperature predictions of S/C hardware during EDL. In this paper, there is no comparison between predicted performance and actual performance. This paper presents the thermal response of the MSL spacecraft from EDL Initialization (at Entry – 5 days) to Rover touchdown on the surface of Mars. Temperature profiles for the Descent Stage and Rover hardware are presented and explained to document the thermal response of the MSL spacecraft to the changing EDL environments (aerothermal heating and convective cooling) and hardware power states.

II. Spacecraft Description

Figure 1 shows an exploded view of the MSL S/C cruise configuration. The thermal design and testing of the MSL S/C in the cruise environment is documented in previous papers.[5-7] The fully-stacked S/C consisted of a Rover (with its Mobility, Robotic Arm, High Gain Antenna & Remote Sensing Mast subsystems stowed), attached to a Descent Stage (DS) inside an aeroshell (a backshell and heatshield) that was attached to a Cruise Stage (CS). The Cruise Stage contained the main power source (cruise solar array), propulsion and guidance systems that were used during the cruise from Earth to Mars. The CS also supported the Cruise Heat Rejection System (CHRS) pump, radiators and heat exchanger plates that helped to maintain thermal control of CS, DS and Rover hardware during cruise. There were pyro devices that allowed separation of the CS from the backshell, separation of the DS from the backshell and separation of the Rover from the DS. The aeroshell was the thermal protection system that shielded the Rover and DS from the high heat flux environment experienced during the aeroheating portion of EDL. After Cruise Stage Separation, the vehicle was in its entry configuration – just an aeroshell, DS and Rover. After heatshield and backshell separations, the vehicle was in its Powered Descent Vehicle (PDV) configuration – just a DS and Rover.

Figure 2 shows a top view of the Descent Stage configuration. The DS was the structure that housed the propulsion, power, avionics and guidance systems needed (after the aeroshell components were shed away) to bring the Rover to a safe touchdown on Mars. The PDV was tasked with reducing the Rover downward velocity from

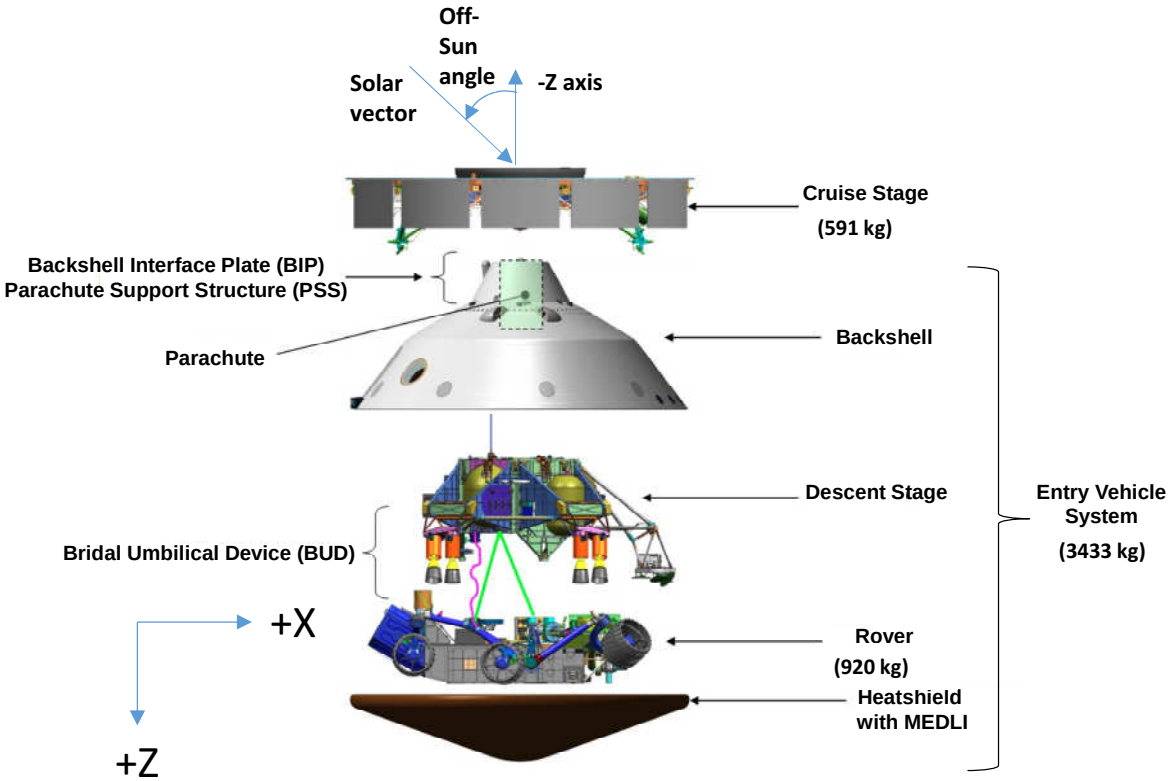

Figure 1. MSL Spacecraft Configuration (side view).

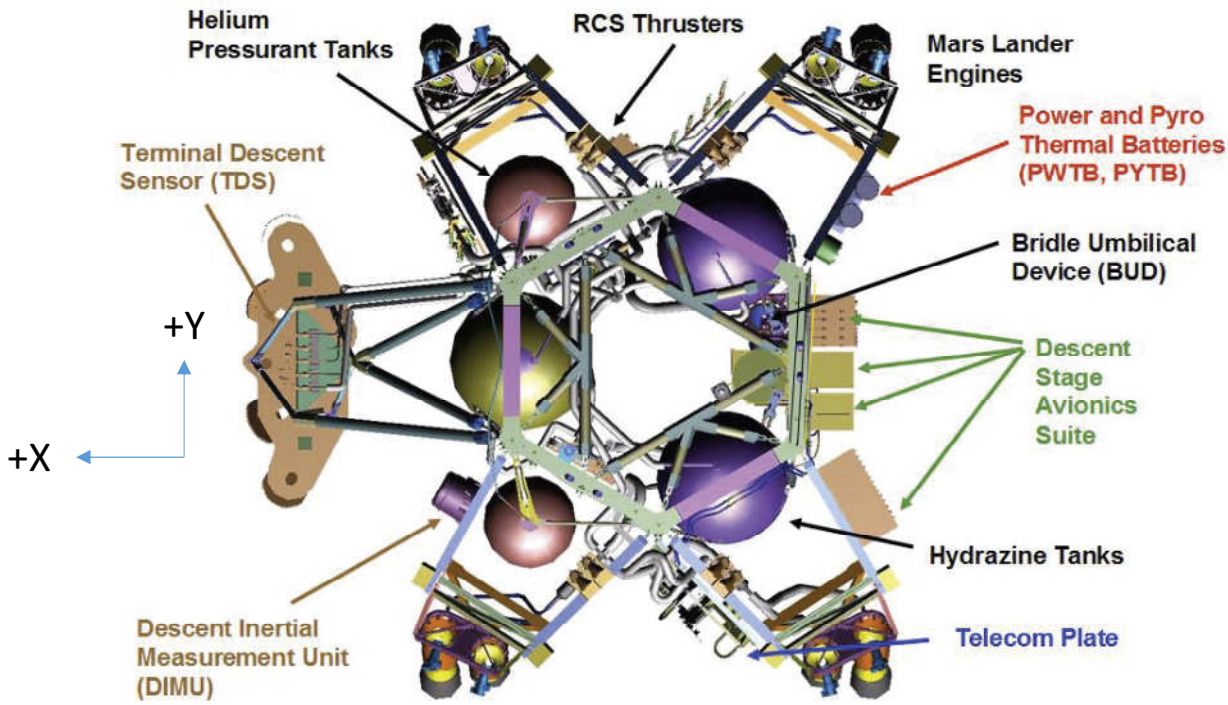

Figure 2. Descent Stage Configuration (top view).

about 79 m/sec, at backshell separation, down to 0.75 m/sec, at Rover touchdown. Thermal design of the PDV is documented in a previous paper.[4] Propulsion systems on the DS included a Reaction Control System (RCS) thruster system (used during guided entry) and an Main Landing Engine (MLE) system to provide downward thrust and slow the vehicle during the near-surface landing event. The Terminal Descent Sensor (TDS) was used determine the elevation of the vehicle above the ground.

Figure 3 shows a view of the deployed Rover configuration. All of the items normally stowed from launch to landing (Mobility, Robotic Arm, High Gain Antenna & Remote Sensing Mast), are shown in this image fully deployed. The power source for the Rover is the Multi-Mission Radioisotope Thermoelectric Generator (MMRTG). The MMRTG generates about 110W of electrical power, but dissipates about 2000W of thermal power. During late cruise, much of this thermal power (~1200W) is carried away by the CHRS fluid and rejected by the Cruise Stage radiators. The remaining ~800W is radiated directly to the backshell and heatshield. During Surface operations, the Rover HRS collects waste heat (when needed) from the MMRTG, via heat exchanger plates on either side of the MMRTG, and uses that heat to keep the avionics inside the Rover (e.g., the Rover battery, the Rover power avionics and the Rover Compute Element) warm at night. Engineering cameras are located on the Remote Sensing Mast (Navcam) and front and rear panels of the Rover chassis (Hazcam). The Mars Descent Imager (MARDI) camera is attached to the left front side of the Rover. The Rover Pyro Firing Assembly (RPFA) is located on the top deck of the Rover. The RPFA houses all of the electronics used to control firing of Rover pyro devices during EDL and at the beginning of the surface mission.

III. Entry, Descent and Landing Event Timeline

The EDL phase of the MSL Mission (see Figures 4, 5 & 6) was broken up into seven major segments: EDL initialization, exo-atmospheric, entry, parachute descent, powered descent, sky crane and flyaway. In the EDL initialization segment of the mission (from E-5 days to E-10 min), the S/C transitioned from a thermally-stable, late cruise mode and was readied for EDL. The exo-atmospheric segment began with Cruise Stage Separation (CSS) at E-10 minutes and ended with the S/C at the atmospheric entry interface point (E-0 min). The atmospheric entry interface point was defined as a location 3522.2 km from the center of Mars, at an altitude 131.1 km above ground level at the Gale Crater landing site. The One-Way-Light-Time (OWLT), the time that it would have taken for a signal from the Earth to reach the S/C at Mars, was about 13.8 minutes during EDL. Once EDL started, the S/C

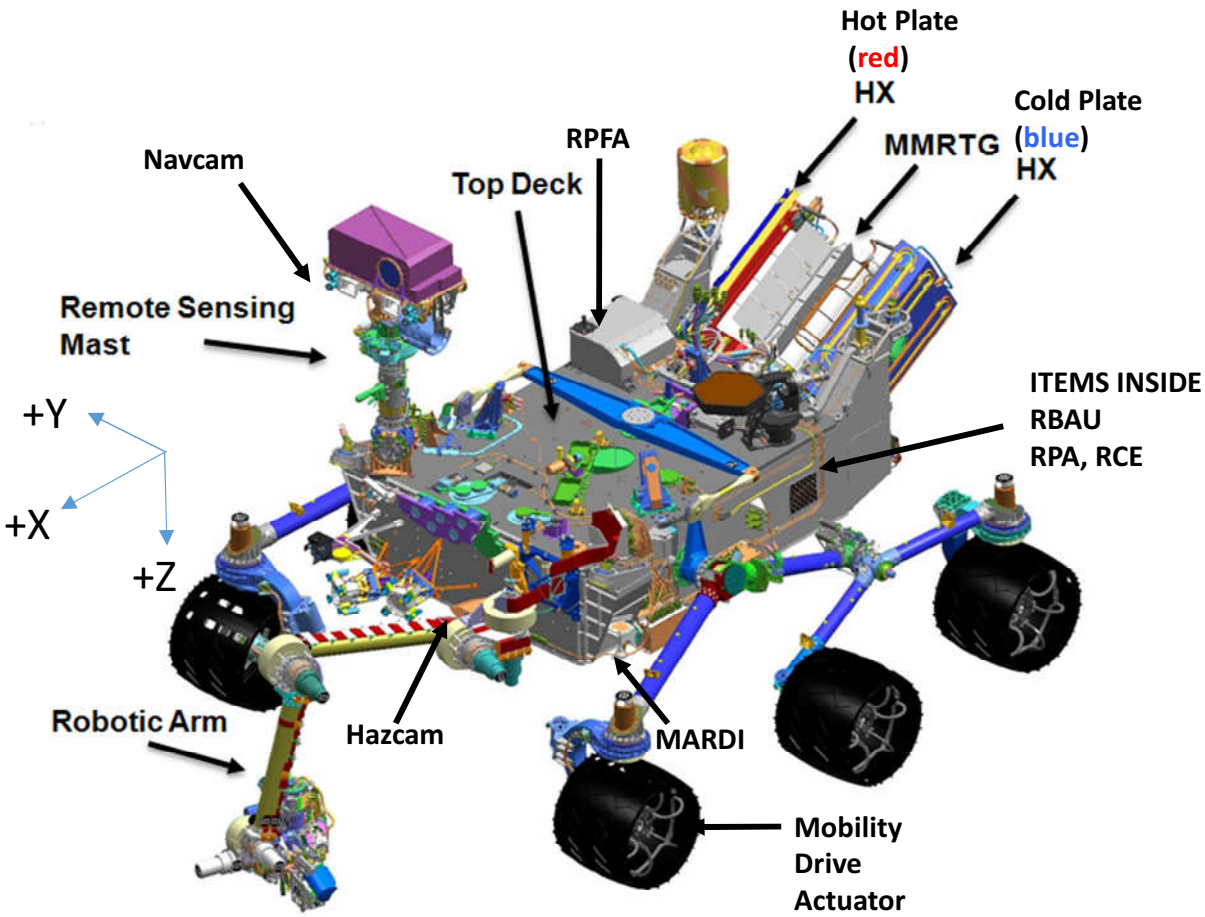

Figure 3. Deployed Rover Configuration (isometric view).

operated completely autonomously, with no intervention from the Earth-based ground control, until well after it had touched down on the surface of Mars. Thermally significant EDL events are shown in Table 1. More detailed descriptions of the EDL events are contained in previous papers.[8-12]

A. EDL Initialization Segment: E-5 days to E-10 minutes (see Figure 4)

In its pre-Entry configuration, the Spacecraft was at an off-Sun angle of about 35 degrees (see Figure 1) and spinning about the Z-axis at 2 RPM. At this point in the Mars orbit, the solar flux (at 1.51 AU) on a plate normal to the solar vector was about 600 W/m^2. Preparations for EDL were made in the EDL Initialization segment.

The EDL initialization segment is broken up into 2 sub-segments: Final Approach (from E-5 days to E-30 min) and EDL Start (from E-30 min to E-10 min). Ground commands were sent to the S/C to prepare it for EDL. The most notable thermal preparations during Final Approach involved turning on the MLE catbed heaters (at E-31 hours), turning on the RCS catbed heaters (at E-3 hours) and turning off the MARDI warmup heaters (at E-41 min). Use of catalyst bed heaters helps to extend catbed life and ensure more predictable hydrazine decomposition during initial thruster firing. The EDL Start sub-segment of the EDL Initialization segment picked up at E-30 minutes when the "DO EDL" command sequence was activated by the S/C.

The first major thermal event triggered by the EDL sequence was venting of the working fluid (Freon) from the cruise stage HRS. Before the CS could be separated away from the entry vehicle, the Freon needed to be evacuated from the CHRS in a controlled manner. Freon was vented through a valve at the top of the CS along a vector through the CS center of mass, so as to impart only a minimal nutation to the spinning vehicle. Venting of the Freon

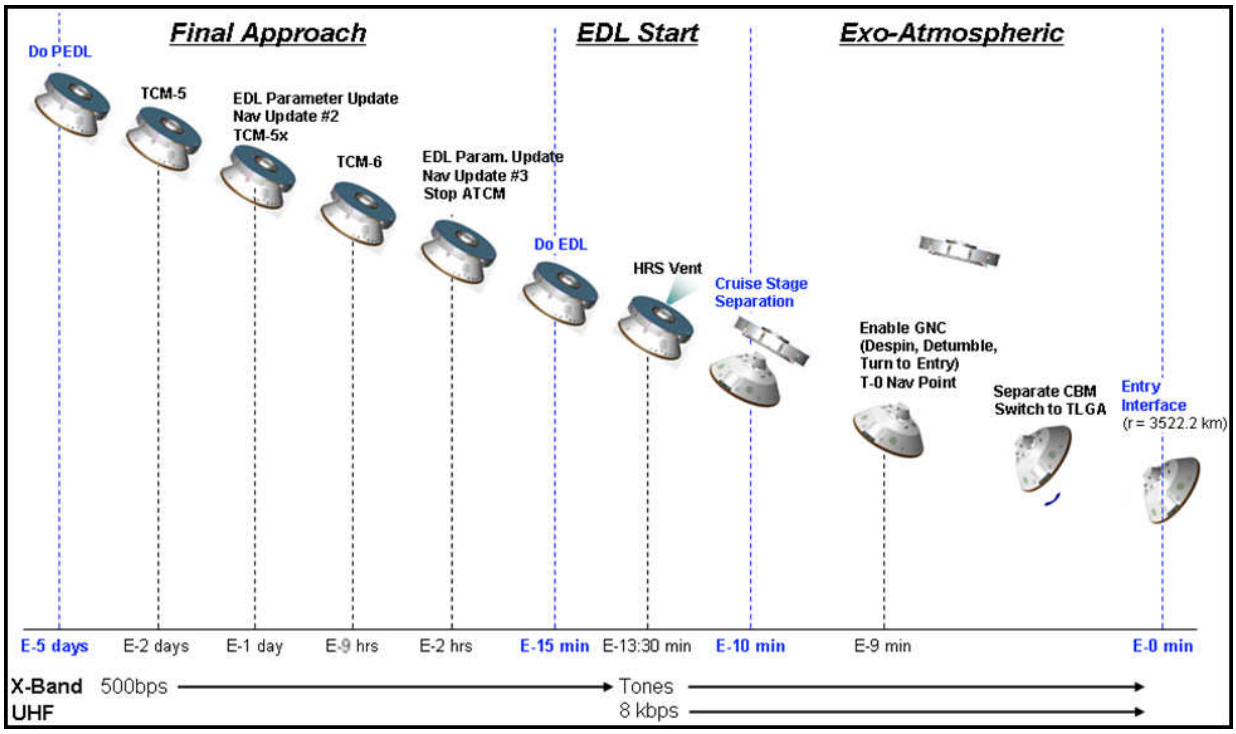

Figure 4. EDL Initialization (Final Approach & EDL Start sub-segments) and Exo-Atmospheric Segments.

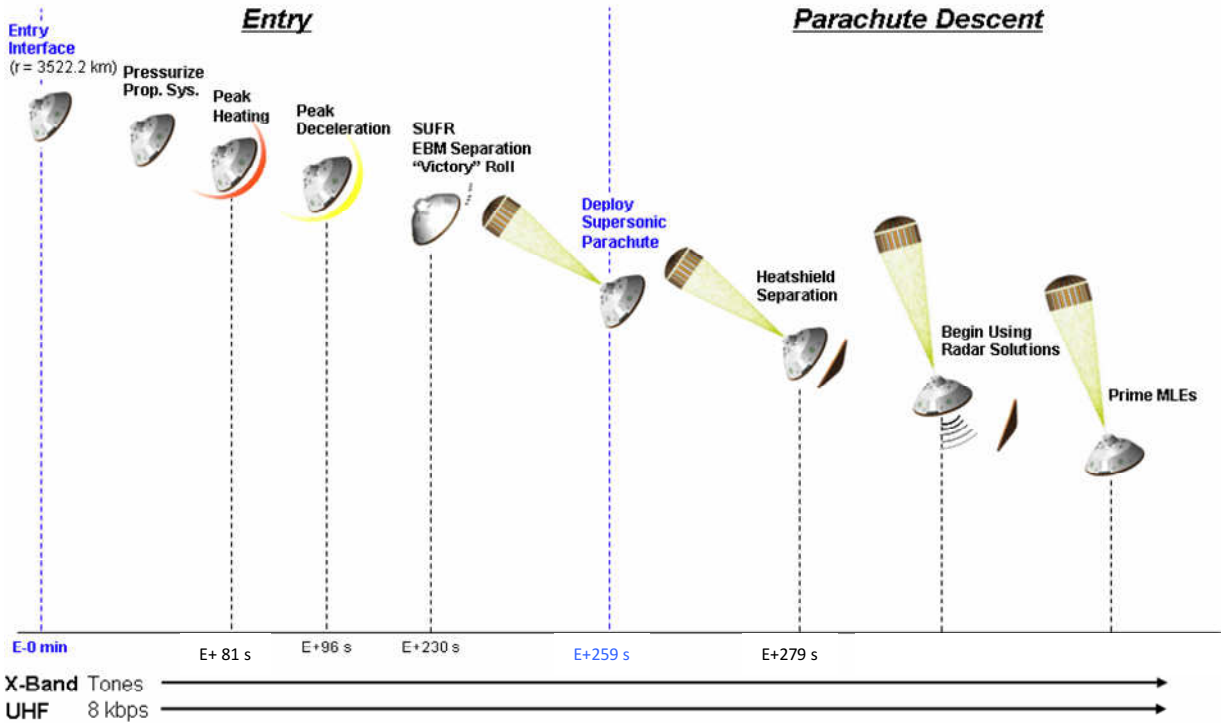

Figure 5. Entry and Parachute Descent Segments.

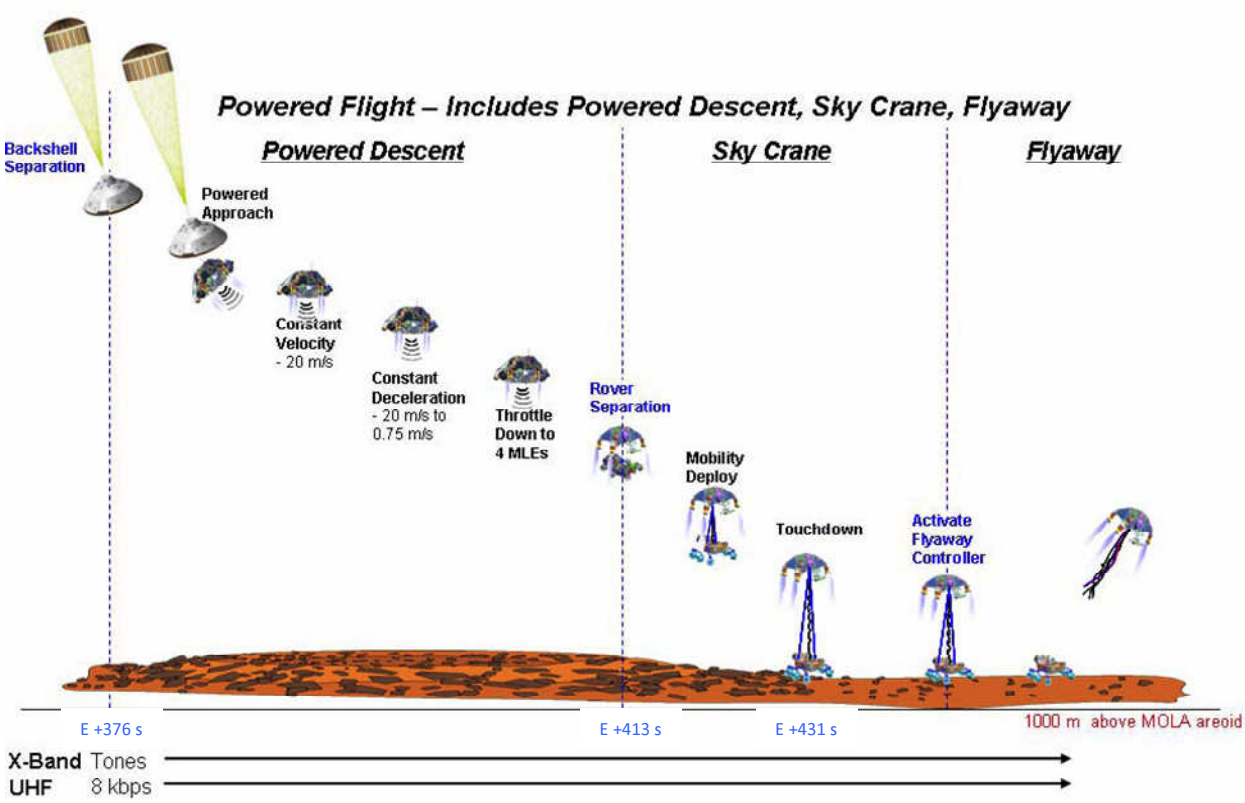

Figure 6. Powered Descent, Sky Crane and Flyaway Segments.

Table 1. Thermally Significant EDL Events

No	Event Name	Time Relative to Entry	Altitude AGL (m)	Mars Relative Velocity (m/sec)	SCET Date (UTC)	SCET DOY (UTC)	SCET Time in UTC (HH:MM:SS)
1	Turn ON MLE Catbed heaters	E - 31 hr			8/4/2012	217	22:00:00
2	Turn ON RCS Catbed heaters	E - 3 hr			8/6/2012	219	2:15:00
3	Turn OFF MARDI warmup heater	E - 41 min			"	"	4:29:29
4	Activate EDL sequence	E - 30 min			"	"	4:40:46
5	HRS Vent (end CHRS control)	E - 13.5 min			"	"	4:57:00
6	Cruise Stage Sep (TDS power ON)	E - 10 min			"	"	5:00:46
7	ENTRY INTERFACE POINT	E - 0 sec	124,994	5,845.4	"	"	5:10:46
8	Peak Heating	E + 81 sec			"	"	5:12:07
9	Parachute Deploy	E + 259 sec	12,147	406.4	"	"	5:15:05
10	Heatshield Separation (start forced conv. on DS & Rover)	E + 279 sec	9,997	146.0	"	"	5:15:25
11	Backshell Separation (start of Powered Descent)	E + 376 sec	1,671	78.9	"	"	5:17:02
12	Rover Separation (down on bridle)	E + 413 sec	22	0.7	"	"	5:17:39
13	TOUCHDOWN	E + 431 sec	9	0.6	"	"	5:17:57

from the CHRS meant that all items on the CS, DS and Rover, with power dissipations that were thermally regulated by the CHRS in the cruise phase, were now free to transiently increase in temperature. The degree to which these items increased in temperature was limited by their power dissipations, local thermal environments and thermal masses. As shown in Figure 7, the CHRS controlled the Cruise Power & Analog Modules (CPAMs), Cruise Power Assembly (CPA) and Star Scanner Electronics (SSE) on the CS Avionics plate, the Descent Power & Analog Modules (DPAMs) & Descent Power Assembly (DPA) on the DS Avionics plate, the Traveling Wave Tube

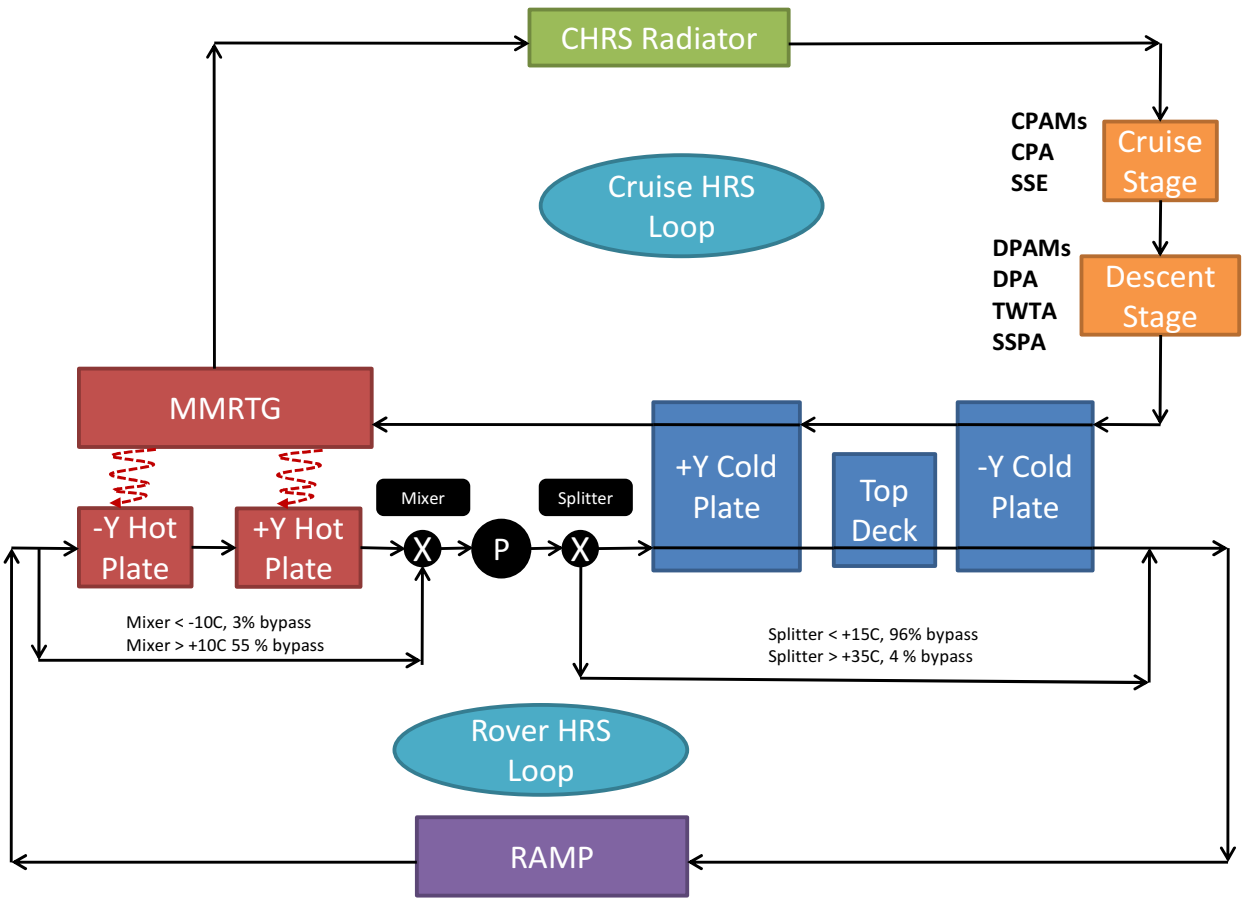

Figure 7. Cruise & Rover HRS Loops.

Amplifier (TWTA) & Small Deep Space Transponder (SDST) on the DS Telecom plate and the MMRTG on the Rover. There was also a link between the CHRS and RHRS at the Rover cold plates. However, this link was not really critical during the near-Mars, cruise cold condition since the Rover rejected most of its own heat through the Rover heat exchanger cold plates directly to the backshell. The CHRS system was vented at 04:57 UTC SCET on August 6, 2012. After CHRS venting, the electrical cables and HRS tubes across the CS-to-DS interface were severed using pyro-activated cable cutters. Many papers have been written to document the design, testing and performance of both the CHRS and RHRS systems. [13-20]

B. Exo-Atmospheric Segment: E-10 min to E-0 min (see Figure 4)

The CS was mechanically separated away (at E-10 min) and left to burn up in the Mars atmosphere. The Terminal Descent Sensor (TDS) and the Mars Entry Descent Landing Instrument (MEDLI) were turned on shortly after CS separation. The TDS was used to measure the velocity and distance to the ground of the PDV during EDL, after separation of the heatshield. MEDLI recorded atmospheric data and heatshield performance during descent. After CSS, the S/C was despun (from 2 RPM to 0 RPM) and turned to the entry attitude (see Figure 4). The cruise balance masses were then ejected to move the center of mass of the entry vehicle and establish the proper angle of attack for creating aerodynamic lift during the entry segment of EDL.

C. Entry Segment: E-0 min to E+259 sec (see Figure 5)

After the S/C reached the entry interface, at 3522.2 km from the center of Mars, the entry segment began. The DS RCS propulsion system was pressurized to enable thrusters to control the entry vehicle orientation. Entry guidance became active to allow control of the lift vector and targeting of the landing site in both down-range and cross-range directions. Peak aeroheating and deceleration were experienced during entry as friction between the Mars atmosphere and the aeroshell drove external heatshield temperatures up to about 1400°C. The entry vehicle

was slowed from 5845 m/sec to 406 m/sec in this segment, dissipating 99% of its total kinetic energy. Before parachute deploy, the Entry Balance masses were ejected to allow the vehicle to rotate into a position for the TDS sensors to point at the ground. Once the vehicle slowed enough to get into the deploy envelope for the supersonic parachute, the parachute deploy command was issued and the entry segment was completed.

D. Parachute Descent Segment: E+259 sec to E+376 sec (see Figure 5)

The MSL spacecraft utilized a 21.35 m diameter parachute decelerator derived from the Viking mission, but with a 50% larger reference area. The parachute was mortar-deployed from the backshell when the vehicle was moving at a velocity of approximately Mach 1.75 (406 m/sec). Full inflation of the parachute took about 2 seconds. At E + 279 sec, when the vehicle was moving at about Mach 0.62 (146 m/sec), the heatshield was released and jettisoned by push-off springs. Heatshield separation was recorded by the Mars Descent Imager (MARDI) camera located on the left front side of the Rover. Once the heatshield separated, the Rover and DS were exposed to the convective environment of the Mars atmosphere. With the heatshield removed, the TDS located the ground and computed a radar-based landing solution. At the end of the parachute descent segment, the Main Landing Engines (MLEs) were primed with fuel. The aerodynamic drag of the parachute slowed the entry vehicle down from about 406 m/sec to 79 m/sec. The parachute descent segment ended with backshell separation at E+376 sec.

E. Powered Descent Segment: E+376 sec to E+413 (see Figure 6)

The Powered Descent segment began with backshell separation. At backshell separation, the DS & Rover were separated away from the backshell and free fell for about 0.8 seconds to provide distance and avoid a re-contact between the Powered Descent Vehicle (PDV) and backshell, prior to firing the MLEs. Control of the PDV was provided by eight independently-throttled MLEs. The MLEs were warmed up by running them at a 20% throttle setting for about 0.2 sec. The first function of the PDV was to perform a backshell avoidance maneuver. Next, the PDV brought the vehicle into a vertical flight mode at a constant downward velocity of about 32 m/sec to allow improved altitude measurements to be made by the TDS. In the final phase of powered descent, the PDV went into a constant deceleration mode that reduced its vertical velocity to 0.7 m/sec and its horizontal velocity to 0 m/sec. The PDV then throttled down to 4 MLEs running at about 50% thrust level. The Powered Descent segment ended with Rover separation from the DS.

F. Sky Crane Segment: E+413 sec to E+431 sec (see Figure 6)

The Sky Crane segment began with the separation of the Rover from the DS at an altitude of about 22 m from the ground. The Rover was lowered away from the DS on an umbilical cable played out by the Descent Rate Limiter (DRL) and Bridle Umbilical Device (BUD). The 7.5 m long umbilical cable, connected the DS to the Rover, allowing communication between DS and Rover flight computers as well as communication using the DS UHF antenna and the Rover UHF radio. The Rover Mobility system was deployed and readied for touchdown, while the Rover was being lowered on the BUD. The Rover touched down at a vertical velocity of 0.6 m/sec. Shortly after Rover touchdown, bridle offload was detected by reduced MLE throttle commands and the bridle lines were separated from the Rover. The Sky Crane segment ended with bridle cut. During the Sky Crane segment, the vehicle slowed from 0.6 to 0.0 m/sec.

G. Flyaway Segment: at E+431 sec (see Figure 6)

After the Bridle was cut, control of the DS was transferred to the DMCA. The DS traveled straight up above the Rover, before turning 45 degrees and thrusting away from the landing site. The DS flew away and impacted the Mars surface, as planned, at a safe distance (650m) away from the Rover. After touchdown, the Rover's computer switched from EDL mode into surface operations mode and began autonomous execution of Rover activities for Sol 0. At Rover touchdown, the local time in Gale Crater was 15:03 LMST.

IV. Thermal Response of MSL Spacecraft Hardware

The most dramatic temperature changes that occurred during EDL occurred on the outside of the aeroshell due to aerothermal heating during the Entry phase. The effects of aerothermal heating on the heatshield were recorded by the MEDLI instrument[18] and are not discussed in any detail in this paper. Suffice to say, the aeroshell served as a very effective barrier between the high external environmental heat flux during entry and the thermally-sensitive DS & Rover hardware inside it. Peak temperatures measured by thermocouples on the heatshield plugs, at a depth of 2.7 mm into the heatshield material, reached as high as 1050°C. Heatshield temperatures measured at a depth of about 17.8 mm into the heatshield material were less than 200°C. The effectiveness of the heatshield material as an

insulator, coupled with the short duration of the aerothermal heat flux pulse (the aeroheating only lasts about 70 seconds) meant that the aerothermal heat pulse during entry is barely detected by temperature changes on the massive (long time constant) DS and Rover. In fact, at the time of heatshield separation, images from the MARDI camera show that water ice & organic volatiles were still present in small patches along the heatshield interior MLI blanket seams.

The most significant temperature changes on the MSL PDV occurred due to deliberate actions (commands executed by the S/C) such as: 1) turning on or off of an electrical resistance heater, 2) venting of the working fluid (Freon) from the CHRS system, 3) firing of MLEs or RCS thrusters, 4) turning on or off of an electronics box, and 5) initiating a pyro thermal battery. This paper documents some of the more interesting and dramatic temperature changes on the entry vehicle during EDL. It is not an exhaustive study, but it does cover a wide range of hardware temperature responses seen on the DS and Rover during the MSL EDL.

A. Descent Stage Propulsion Subsystem

Figure 8 shows the thermal response of the Descent Stage propulsion hardware during EDL. During the Final Approach segment (at E-31 hours; at 22:00 UTC on August 4) the MLE catbed heaters were turned on. The MLE catbeds warmed from their late cruise, non-operating condition temperature of -6.5°C to 25°C in about 2 hours (at 00:00 UTC on August 5). The MLE catbeds continued to warm and reached a steady state temperature of about 57°C, 16 hours later (at 16:00 UTC on August 5). MLE thruster valve temperatures were not affected by catbed heater warmup; they continued to cycle between 30°C and 35°C (the valve survival heater control range) for most of EDL.

The DS RCS thruster catbeds heaters were turned on at 02:15:46 UTC on March 6 (E-3 hours) and warmed the catbeds for about 2 hours and 45 minutes. The catbed temperatures ranged from 72°C to 114°C after the warmup. DS RCS thruster valve temperatures cycled in their heater control range (between 27°C and 33°C) prior to catbed heater turn on. After the RCS catbeds had reached a steady state temperature above 72°C, the valve survival heaters stopped cycling, since there was enough heat coming from the catbeds to maintain the valves above the lower control setpoint of the survival heater.

Figure 9 shows a "zoomed in" version of the flight temperature telemetry from Figure 8, focused on the late EDL time period between HRS vent (during the EDL Initialization segment) and touchdown (in the Sky Crane segment). After Backshell separation, the MLEs commenced firing and continued to operate through the Powered Descent, Sky Crane and Flyaway segments. No DS telemetry is available from the Flyaway segment, since there was no communication between the DS and the Rover after the Bridle cut. The MLE catbeds rose in temperature from 59°C, just prior to backshell separation, to 352°C, at Rover touchdown. The MLE valves rose from 30°C to 53°C during the same time period.

The DS RCS thrusters were used immediately after CS separation during despin, detumble and turn-to-entry maneuvers in the Exo-Atmospheric segment and for attitude control during guided-entry. As shown in Figure 9, the thruster catbeds warmed from 103°C to 363°C during the post CS separation maneuvers, cooled down to 306°C after entry interface, warmed back up to 516°C during guided entry, and then cooled back down to 366°C by touchdown (at 05:18 UTC). The DS RCS valves rose slowly during the time period from CS separation to touchdown, starting at 31°C and rising to 47°C during last usage before parachute deploy and soaking back up to 53C by Touchdown. Another DS propulsion component that showed an interesting thermal signature during EDL was the DS gas regulator. The DS propulsion tanks were pressurized with He gas, prior to launch, at a relatively low pressure (300 psia). These tanks were fully pressurized (to 700 psia) just before entry. Figure 9 includes a curve of the DS gas regulator temperatures, which shows a temperature drop (due to gas expansion) from 23°C just after entry interface to -12°C at touchdown (at 05:18 UTC).

B. Thermal Subsystem – HRS-controlled hardware

One of the major thermal changes made to the S/C during EDL was the venting of the Cruise HRS thermal system, just prior to Cruise Stage Separation. The CHRS controlled the temperatures of items on the CS, DS and Rover during cruise. This section of the paper addresses only the effects of CHRS venting on the Rover. Subsequent sections will discuss the effect of CHRS venting on the DS components.

Figure 10 shows some of the Rover HRS-related temperatures between CHRS vent and touchdown. The +Y Cold Plate outgoing fluid temperature rose from -2°C to 18°C during EDL. Before CHRS vent, the CHRS system controlled the Cold Plate temperatures. When the CHRS fluid was vented, the cold plates were no longer cooled by that fluid and consequently they rose in temperature, closer to the Rover Avionics Mounting Panel (RAMP) outlet fluid temperature. The +Y Hot Plate temperature rose from 25°C to 34°C as it reacted to the temperature rise of the

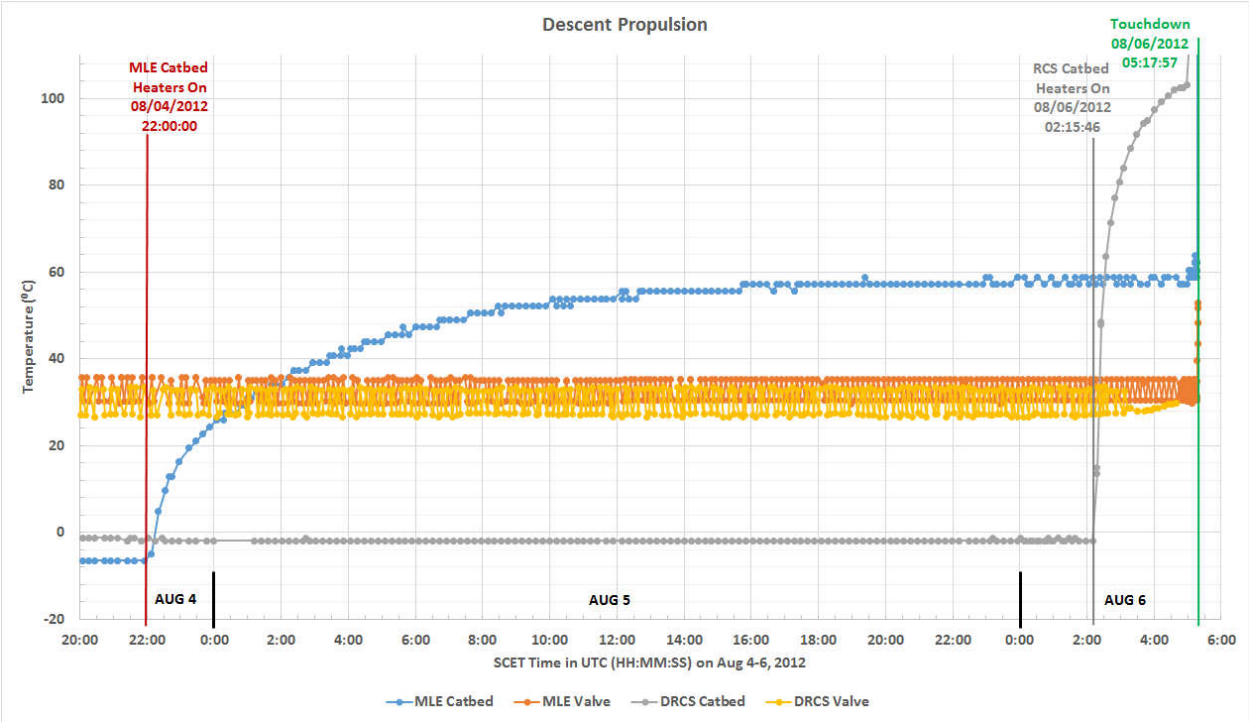

Figure 8. DS Propulsion Temperatures: EDL initialization to Touchdown.

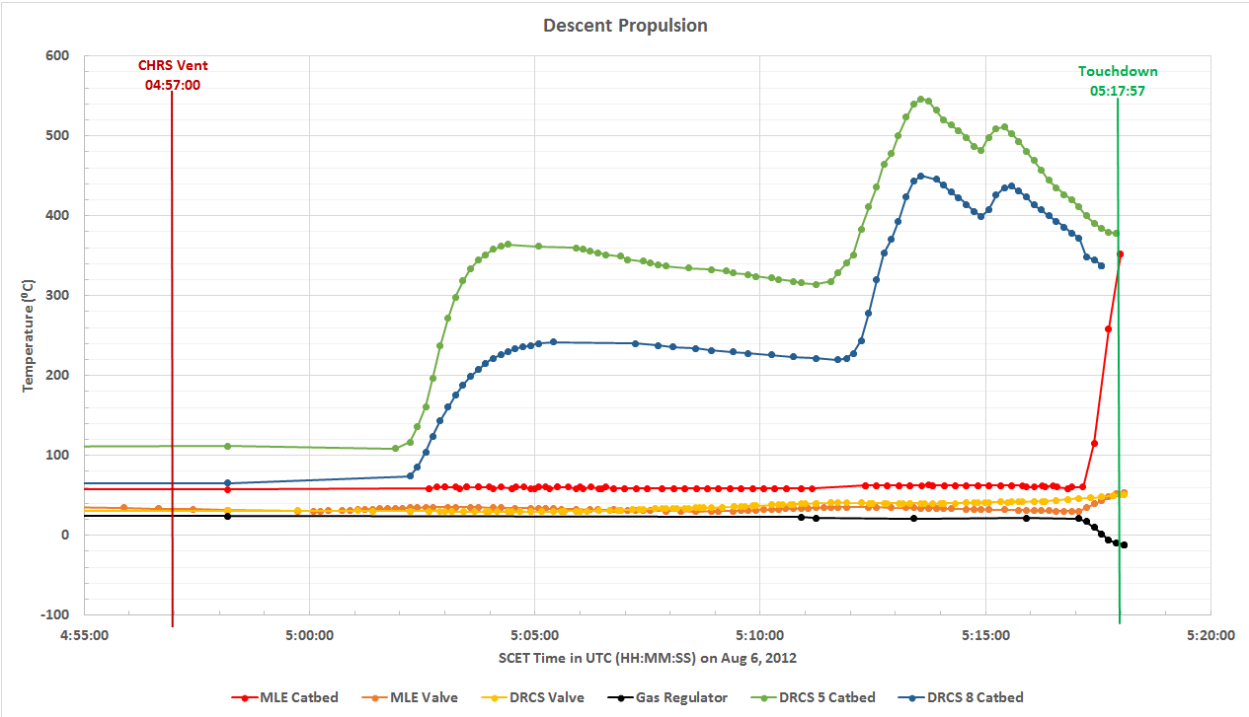

Figure 9. DS Propulsion Temperatures: CHRS Vent to Touchdown.

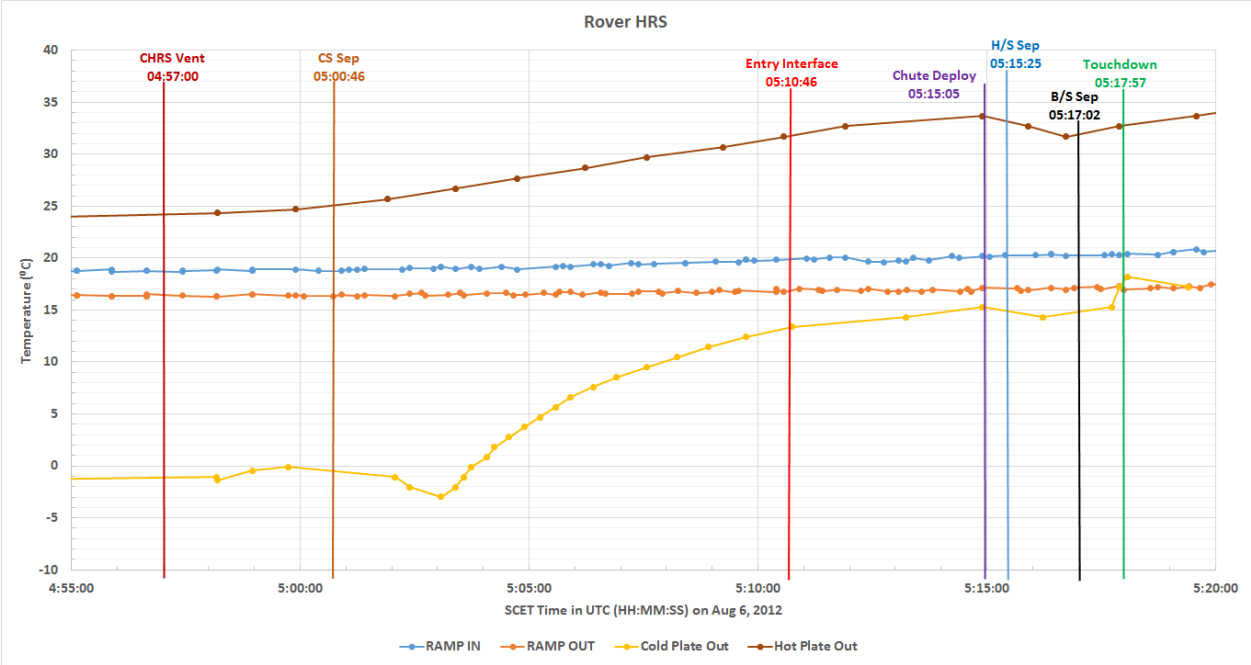

Figure 10. Rover HRS Temperatures: CHRS Vent to Touchdown.

MMRTG. There was a slight drop (1°C) in the hot plate temperature after Heatshield separation, caused by exposure to a cool (about -27°C) convective flow of Mars atmosphere prior to touchdown.

C. Decent Stage Telecommunications Subsystem

The Descent Stage telecommunications system was used to transmit critical tones and EDL telemetry to the Mars Reconnaissance Orbiter, Odyssey and Mars Express orbiters (via a UHF link) and directly to the ground (via an X-Band link). The UHF radio, located inside the Rover (on the HRS-controlled RAMP), experienced only a 1°C temperature rise (from 17°C to 18°C) during EDL. Figure 11 shows the temperature changes on some of the Descent Stage Telecom hardware during EDL. The Parachute UHF antenna, located on the parachute closeout cone, near the top of the backshell, rose in temperature from -18°C, at entry interface, to -7°C, at Backshell Separation. The TWTA and DS SDST were part of the Descent Stage X-Band communications system. The TWTA, an especially high-powered device, dissipated 85W of power when operating during EDL. Both the TWTA and the DS SDST were bolted to the CHRS-controlled Telecom plate in the Descent Stage. During late cruise and prior to CHRS venting, this plate was maintained at a nominal temperature near 0°C. Immediately after CHRS vent, these two telecom hardware units started to rise in temperature. The Telecom Plate, under the TWTA, started EDL (prior to CHRS vent) at 0°C and rose 15°C, to a peak of 15°C after Heatshield Separation. The lower power SDST, attached to the same DS Telecom plate started EDL (prior to CHRS vent) at 0°C and rose to 12°C at Parachute Deploy.

D. Power and Avionics Subsystem

The MMRTG (the Rover power source) dissipated about 2000W of thermal power (while producing about 110W of electrical power) at the beginning of the surface mission. Figure 12 shows the temperature rise experienced by the MMRTG during EDL. Prior to HRS vent, the MMRTG was maintained at 87°C by running cool HRS fluid in tubing mounted directly to the MMRTG outer housing. When the HRS fluid was vented away (at 04:57 UTC), the MMRTG temperature started to rise. By touchdown (05:18 UTC), the MMRTG temperature had risen by 51°C to 138°C.

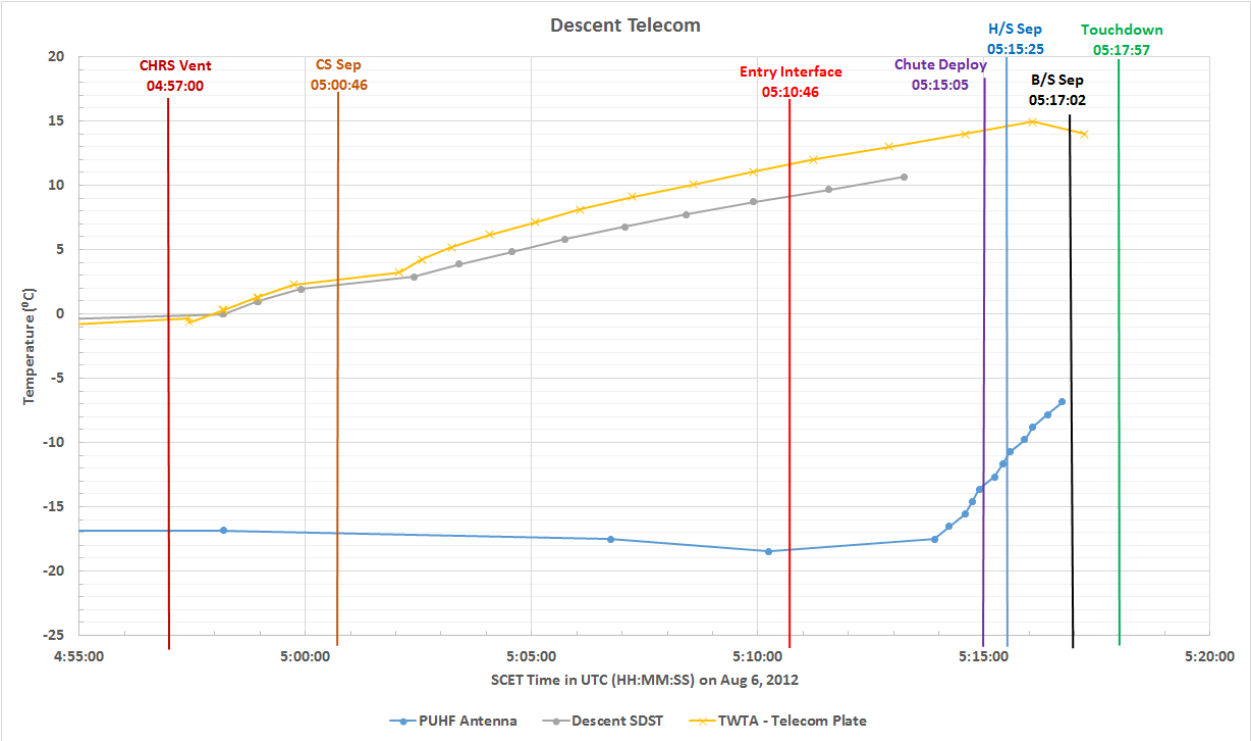

Figure 11. DS Telecom Temperatures: CHRS Vent to Touchdown.

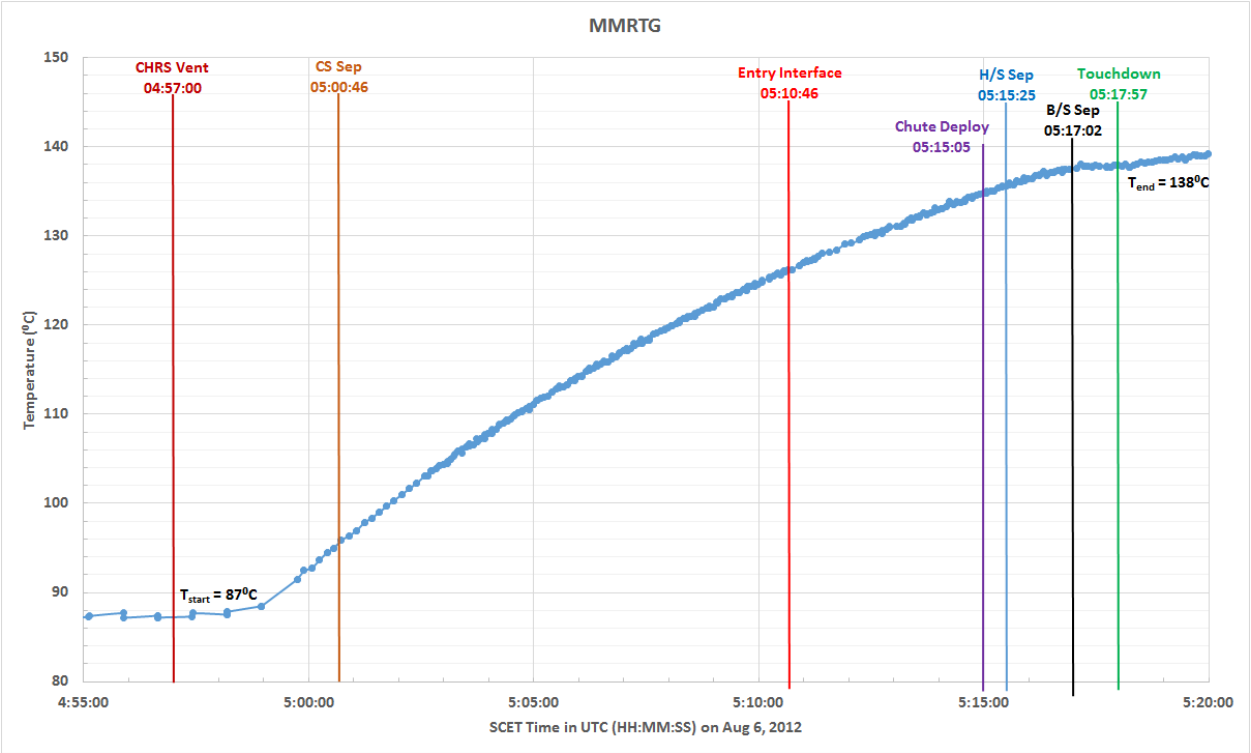

Figure 12. MMRTG Temperature: CHRS Vent to Touchdown.

The Descent Stage Power and Avionics subsystem hardware temperature responses during EDL are shown in Figure 13. The Base Load Resistor Assembly (BLRA) dissipated power after the initialization of the S/C pyro power bus during EDL. The BLRA, attached to one of the DS structure panels used to hold the MLEs, had a peak power dissipation of 105W during EDL. The BLRA started EDL (prior to CHRS vent) at a temperature of -12°C. By the end of EDL (at touchdown), the BLRA had risen 18°C, to a temperature of 6°C. The Descent Motor Controller Assembly (DMCA), used to control the MLE's during the powered descent phase of EDL, was attached to one of the DS structure panels. The DMCA, dissipating about 48W during EDL, started EDL (at CHRS vent) at 3°C and reached a final temperature (at touchdown) of only 7°C.

Once the Cruise Stage solar array was jettisoned from the entry vehicle, this power source was no longer available. The MMRTG on the Rover is a primary power source, but it only generated about 110W of electrical power. This was not enough power to run all of the EDL systems, so additional power was generated by thermal batteries. The Pyro Thermal Battery (PYTB) was used to fire pyrotechnic devices, and the Power Thermal Battery (PWTB) was used to power DS components, during EDL. These thermal batteries were attached to an outrigger structure on the DS stage. The thermal batteries stayed dormant during the entire cruise and were activated just prior to Cruise Stage separation. Temperature rise rate curves for the PYTB and PWTB are shown in Figure 13. The PYTB rose 118°C (from -3°C to 115°C) and the PWTB rose 101°C (from -7°C to 94°C) in the time period from CSS to Touchdown. The thermal batteries had no maximum operating temperature limits.

The Rover Power and Avionics subsystem hardware temperature responses during EDL are shown in Figure 14. As expected, the power and avionics hardware inside the Rover (Rover Battery, Rover Power Assembly (RPA) and Rover Compute Element(RCE)) attached to the RHRS-controlled RAMP, showed very little temperature rise (only about 1°C) during EDL. The RAMP experienced very stable and benign temperatures during EDL (steady at less than 25°C).

The RPFA, the box that fired all of the EDL and post-EDL pyros on the Rover, was mounted to the top deck of the Rover. The RPFA was thermally isolated from the top deck and from the environment. The RPFA dissipated about 15W. The RPFA rose about 5°C (from -3°C to 2°C) during the time it operated during EDL (from CHRS vent to touchdown).

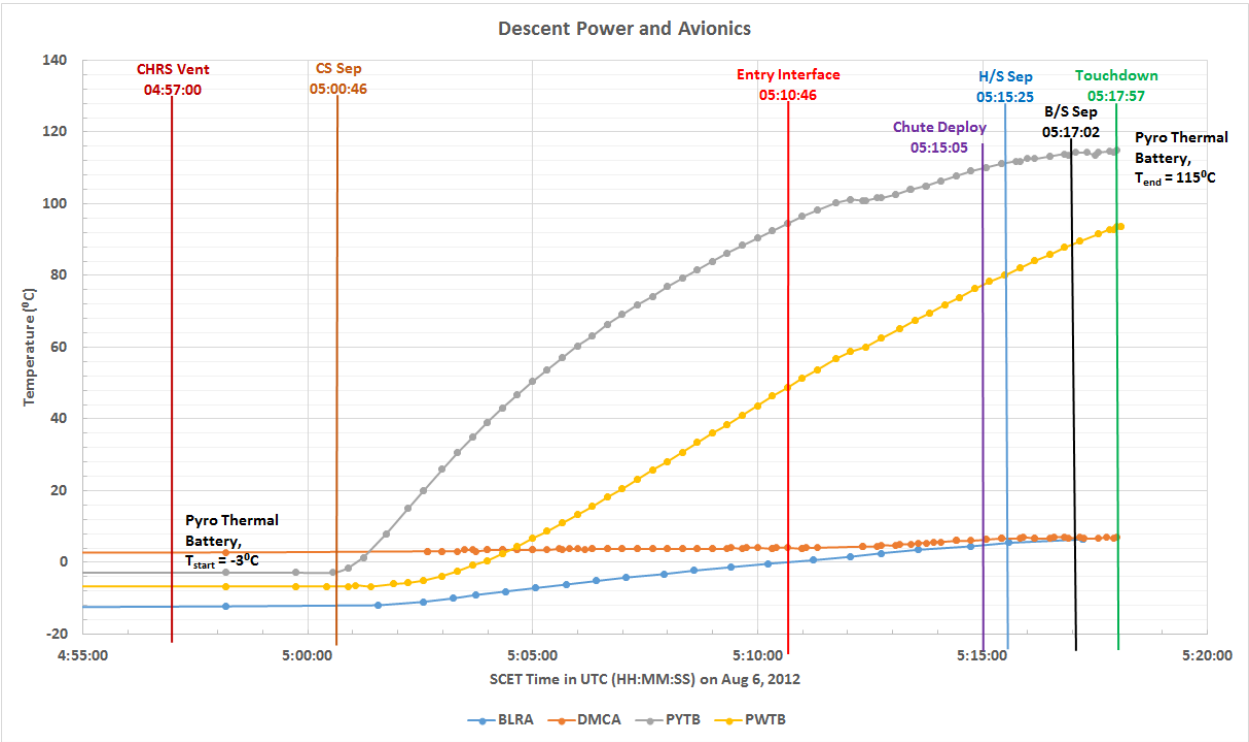

Figure 13. DS Power & Avionics Temperatures: CHRS Vent to Touchdown.

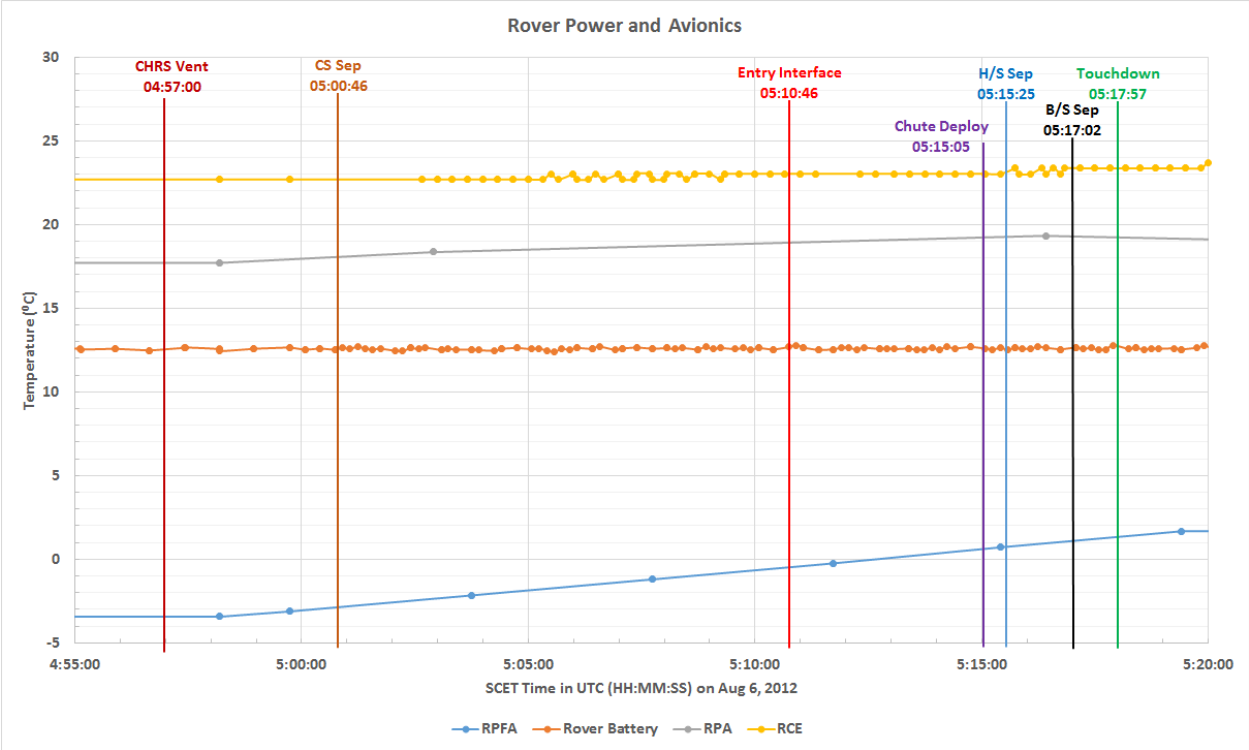

Figure 14. Rover Power & Avionics Temperatures: CHRS Vent to Touchdown.

E. Guidance, Navigation and Control (GNC) Subsystem

The thermal response of GNC hardware during EDL is shown in Figure 15. The Descent Stage had redundant inertial measurements units (DIMU-A & DIMU-B). DIMU-A, the primary unit, was mounted directly to a DS structure panel and was covered with a black kapton cover. As shown in Figure 16, the DIMU-A unit started EDL (at CHRS Vent) at 6°C and cooled nearly linearly down to 4°C (at a rate of 0.1°C/min). DIMU-B, however started at 1°C and fluctuated between 1°C and 6°C during EDL, experiencing a drop to 1°C at about the time of parachute deploy.

The Terminal Descent System (TDS) reported the elevation of the vehicle above the Mars surface, after H/S separation. The TDS had a digital electronics unit mounted to a proboscis, extended off the DS structure. Figure 15 shows the small temperature rise of the TDS Electronics during EDL. The TDS Electronics (dissipating 36W) started at -20°C just prior to CHRS vent and warmed up 5°C during EDL to -15°C.

F. External Rover Hardware

Figure 16 shows the temperature response of external Rover hardware during EDL. The MARDI camera, mounted to the left (-Y) side of the Rover, was used to image the heatshield and ground during EDL. MARDI was warmed up prior to HRS vent (cycling between -5°C and +1°C), but its Flight Software-controlled heater was turned off at 04:29:29 UTC. The MARDI housing cooled down from 1°C to -17°C during EDL. The MARDI optics saw a slight temperature rise (6°C), after H/S separation, during the time it was imaging. All of the engineering cameras (Hazcams & Navcams) were very stable in temperature during EDL. None of these engineering cameras operated until after landing. The right front Hazcam Optics held at a constant temperature of -28°C and the right Navcam Optics held at a constant temperature of -9°C during EDL. The front Hazcams have a good view to the cold heatshield prior to heatshield separation. The Navcams look directly at the warmer Rover top deck during the entire EDL, because the Remote Sensing Mast (RSM) is in its "stowed-for-launch" configuration. Figure 16 also shows that massive hardware, like the right front mobility drive actuator, did not change in temperature at all during EDL. The drive actuator temperature was steady at -34°C during the entire EDL. The Rover PRT that is mounted on the external hardware item with the shortest time constant is the Robotic Arm (RA) Upper Link PRT. This PRT is

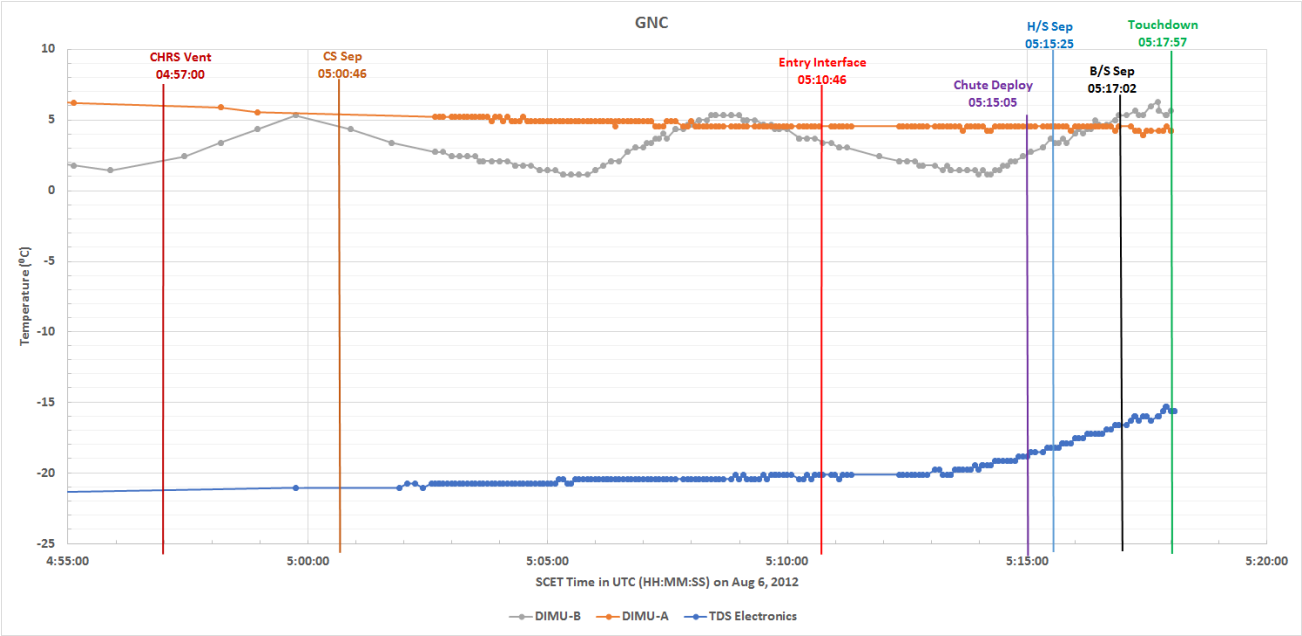

Figure 15. DS GNC Temperatures: CHRS Vent to Touchdown.

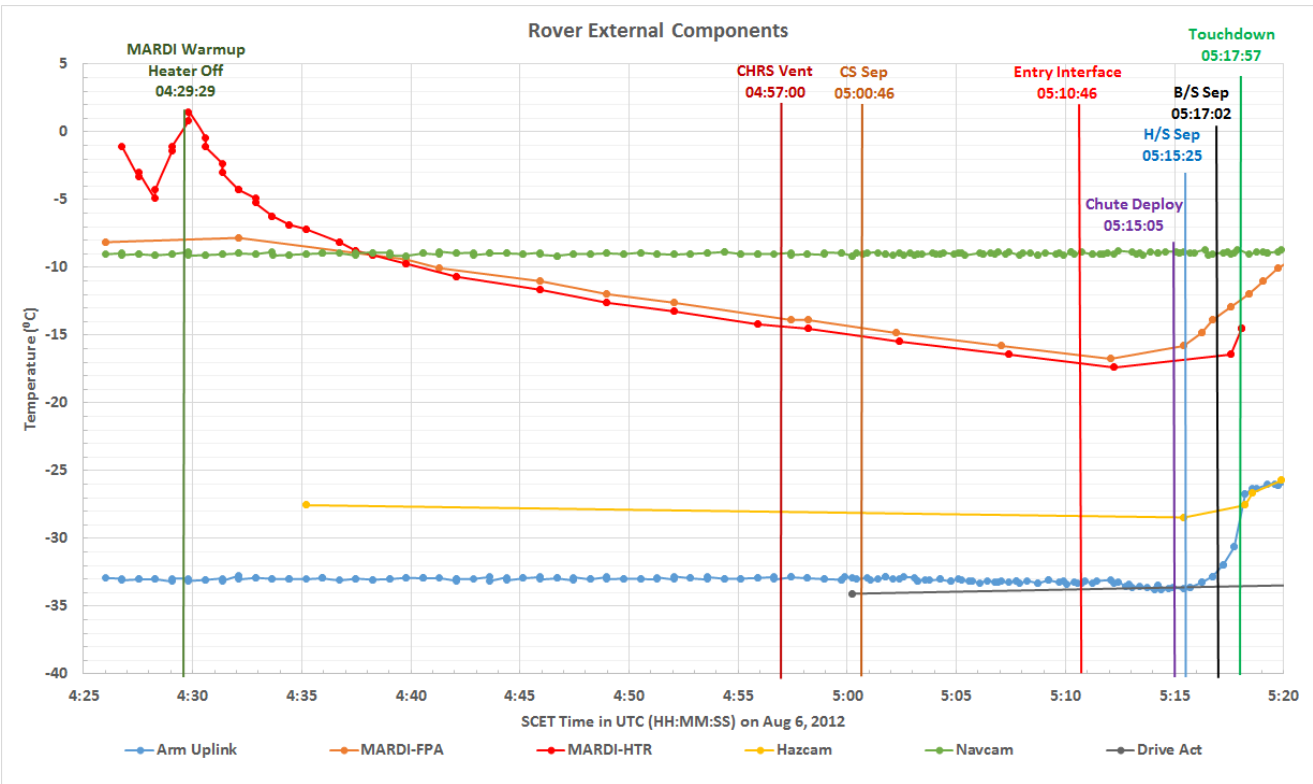

Figure 16. Rover External Components: MARDI Heater Turn-Off to Touchdown.

mounted on the titanium tube that links the RA shoulder joint (azimuth/elevation actuators) to the elbow joint. This PRT remained at a constant temperature of -33°C during most of EDL, until after H/S separation, when it rose 3°C (from -33°C to -30°C) after being exposed to forced convection of the Mars atmosphere. Based on this data, one could infer that the Mars atmosphere was near -30°C about the time of landing. Indeed, the predicted Mars atmosphere temperature from the Mars GCM at an elevation of 1.5m, for Gale Crater at Ls=151 degrees (Landing Day – Sol 0), at 15:03 LMST was about -27°C.

V. Discussion of MSL EDL Flight Temperature Telemetry & AFT Limits

Table 2 shows the EDL start and end temperatures for some representative hardware on the Descent Stage and Rover. The table also contains the hardware temperature change (either a warm-up or cooldown). Most hardware had healthy margins to Allowable Flight Temperature (AFT) limits. Temperatures for most of the items in Table 2 are shown in Figures 8 - 16.

There were three apparent temperature limit violations (see negative margin numbers shown in red in Table 3), on the DS propulsion system that deserve further explanation. The maximum temperature experienced by the DS MLE throttle valve was 53°C, which is 3°C above the maximum operating AFT limit of 50°C. While this is a violation of the maximum AFT limit, there was still 17°C of margin to the maximum operating qualification limit. Similarly, the DS RCS thruster valve experienced a maximum temperature of 51°C, violating the maximum operating AFT limit of 50°C by 1°C. Again, the maximum qualification limit for the DS RCS thruster valves is 70°C, so there was still 19°C of margin to the maximum qualification temperature limit. After the DS RCS catbed heater warmup, the minimum catbed temperature was only 72°C, which violated the minimum catbed operational AFT limit of 93°C by 21°C. However, it was known and accepted that the DS RCS thruster would need to fire once to pre-condition the catbeds for subsequent operation. After the first firing, the DS RCS thruster catbeds never dropped below 225°C, and thus did not violate the minimum operational AFT limit of 93°C.

Also of note in Table 2 are the MEDLI hardware temperatures. The MEDLI electronics box, mounted to (but thermally isolated from) the heatshield, located directly under the MMRTG, stayed well within its AFT limits, but rose 40°C (from 5°C to 45°C) during EDL. The MEDLI pressure transducers, imbedded in the heatshield, rose from -80°C to -65°C.

VI. Conclusion

This paper documents the thermal response of the MSL spacecraft during Entry Descent and Landing. The EDL sequence is relatively short in duration (approximately 7 minutes from entry interface to touchdown) and much of the spacecraft hardware has time constants considerably longer than 7 minutes. During atmospheric entry, aero-heating raised the external surfaces of the heatshield up to about 1400°C. However, items inside the aeroshell were effectively shielded from the aeroheating flux by the thermal protection systems on the heatshield and backshell. DS electronics that operated during EDL was kept from exceeding maximum AFT limits by utilizing the thermal mass of the hardware and limiting the duration of operation. Rover electronics was kept under thermal control by the Rover HRS. Convective cooling after H/S separation was minimal and in fact, in some cases, the atmosphere actually convectively warmed hardware. The near-ground atmosphere temperature at 15:03 LMST on landing day was about -27°C. All DS propulsion system hardware (RCS thrusters and MLEs) experienced nominal temperatures during EDL. By the end of the EDL sequence, the DS RCS thruster valves and the MLE throttle valves had a few minor maximum AFT limit violations (1°C to 3°C), but there was still plenty of margin to their maximum qualification temperature limits. The MMRTG power source warmed up to 140°C, but still had plenty of margin to its maximum AFT limit. The thermal performance of the MSL spacecraft during EDL was excellent and was a key element of the successful landing of the Curiosity Rover in Gale Crater on August 6, 2012. The Curiosity Rover is currently on Sol 1321 of its highly successful surface mission.

Table 2 – Hardware Temperatures during EDL

Hardware Components	EDL Flight Telemetry (°C)		
	T start	T end	change
TELECOMMUNICATION			
Backshell:			
Parachute UHF (PUHF) Antenna	-16.9	-6.9	10.0
Descent Stage:			
Traveling Wave Tube Amplifier (TWTA)	-0.7	15.0	15.7
Small Deep Space Transponder (SDST)	0.0	11.6	11.6
AVIONICS			
Descent Stage:			
Pyro Thermal Battery (PYTB)	-2.8	114.9	117.7
Power Thermal Battery (PWTB)	-6.7	93.6	100.3
Descent Motor Controller Assembly (DMCA)	2.8	7.0	4.2
Base Load Resistor Assembly (BLRA)	-12.3	6.4	18.7
Rover:			
Rover Pyro Firing Assembly (RPFA)	-3.4	1.7	5.1
Rover Power Assembly (RPA)	17.7	19.3	1.6
Rover Compute Element (RCE)	22.7	23.7	1.0
Rover Battery Assembly Unit (RBAU)	12.4	12.8	0.4
GUIDANCE, NAVIGATION, AND CONTROL (GNC)			
Descent Stage			
Terminal Descent Sensor (TDS) Electronics	-21.1	-15.4	5.7
Descent Inertial Measurement Unit (DIMU) A	6.2	3.9	-2.3
Descent Inertial Measurement Unit (DIMU) B	1.0	6.3	5.3
PROPULSION			
Descent Stage			
DS Regulator	23.8	-11.4	-35.2
DS Main Landing Engine (MLE) Valve	29.9	53.0	23.1
DS MLE Catbed	58.8	351.6	292.8
DS Reaction Control System (RCS) Valves	30.8	50.7	19.9
DS RCS Catbeds	71.9	445.0	373.1
ENGINEERING CAMERAS			
Rover:			
Hazcam	-28.4	-25.7	2.7
Navcam	-8.6	-9.5	-0.9
SURFACE STRUCTURES & MECHANISMS			
Mobility System			
Mobility Drive Actuator	-34.1	-33.1	1.0
Robotic Arm			
Robotic Arm (RA) Tube	-33.8	-25.9	7.9
MMRTG			
MMRTG	87.2	138.0	50.8
THERMAL CONTROL			
Rover			
Heat Rejection System (HRS) - surface			
Rover Avionics Mountin Panel (RAMP) Inlet Fluid	18.6	20.9	2.3
RAMP Outlet Fluid	16.3	17.5	1.2
RTG Heat Exchanger Hot Plate	24.4	33.7	9.3
RTG Heat Exchanger Cold Plate	-3.0	18.2	21.2
DESCENT STAGE PAYLOAD			
Mars Entry Descent Landing Instrument (MEDLI)			
Electronics	4.9	45.1	40.2
Pressure Transducers	-79.9	-64.6	15.3
Mars Descent Imager (MARDI) heater	1.5	-17.4	-18.9

Table 3 – Propulsion Component Temperature during EDL

Hardware Components	EDL Flight Telemetry (°C)			Operational AFT (°C)		Non-op (°C) AFT		Thermal Margins (°C)	
	T start	T end	change	min	max	min	max	min AFT	max AFT
PROPULSION									
Descent Stage									
DS High Flow Regulator	23.8	-11.4	-35.2	N/A	N/A	15	50	+9	+26
DS MLE Throttle Valve (liquid flow sections)	29.9	53.0	23.1	25	50	25	50	+5	-3
DS MLE Catalyst Bed	58.8	351.6	292.8	N/A	N/A	25	N/A	+34	
DS RCS Thruster Valves, Firing/Soakback	30.8	50.7	19.9	20	50	20	50	+11	-1
DS RCS Catalyst Beds, Firing/Soakback (min)	71.9	445.0	373.1	93	N/A	N/A	N/A	-21	
DS RCS Catalyst Beds, Firing/Soakback (max)	114.2	552.0	437.8	93	N/A	N/A	N/A	+21	

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