# Mars Exploration Rover Entry, Descent, & Landing: A Thermal Perspective

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## ABSTRACT

Perhaps the most challenging mission phase for the Mars Exploration Rovers was the Entry, Descent, and Landing (EDL). During this phase, the entry vehicle attached to its cruise stage was transformed into a stowed tetrahedral Lander that was surrounded by inflated airbags through a series of complex events. There was only one opportunity to successfully execute an automated command sequence without any possible ground intervention. The success of EDL was reliant upon the system thermal design: 1) to thermally condition EDL hardware from cruise storage temperatures to operating temperature ranges; 2) to maintain the Rover electronics within operating temperature ranges without the benefit of the cruise single phase cooling loop, which had been evacuated in preparation for EDL; and 3) to maintain the cruise stage propulsion components for the critical turn to entry attitude. Since the EDL architecture was inherited from Mars Pathfinder (MPF), the initial EDL thermal design would be inherited from MPF. However, hardware and implementation differences from MPF ultimately changed the MPF inheritance approach for the EDL thermal design. With the lack of full inheritance, the verification and validation of the EDL thermal design took on increased significance. This paper will summarize the verification and validation approach for the EDL thermal design along with applicable system level thermal testing results as well as appropriate thermal analyses. In addition, the lessons learned during the system-level testing will be discussed. Finally, the in-flight EDL experiences of both MER-A &-B missions (Spirit and Opportunity, respectively) will be presented, demonstrating how lessons learned from Spirit were applied to Opportunity.

## INTRODUCTION

In July 2000, with a little less than three years to launch, NASA formally approved a dual rover mission to Mars, known as the Mars Exploration Rover (MER) Project. The primary mission objectives were to determine the aqueous, climatic, and geologic history of a pair of sites on Mars where the conditions may have been favorable to the preservation of evidence of pre-biotic or biotic processes. The primary missions requirements sought to deliver two identical rovers to the surface of Mars in order to conduct geologic and atmospheric investigations for at least 90 Sols (approximately 93 Earth days) after landing and to demonstrate a total traverse distance of at least 600 m, with a goal of 1000 m[1].

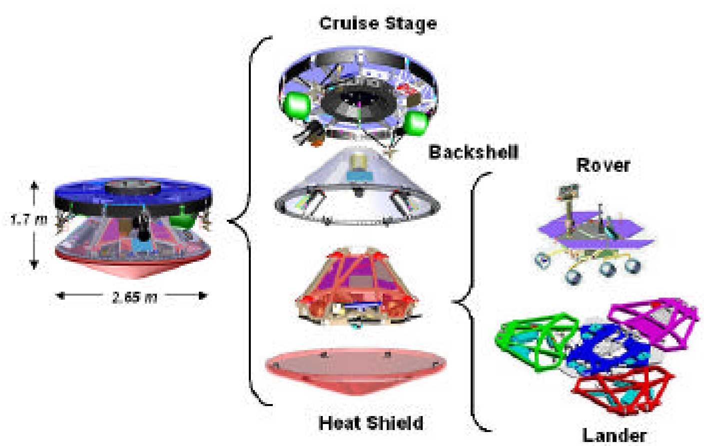
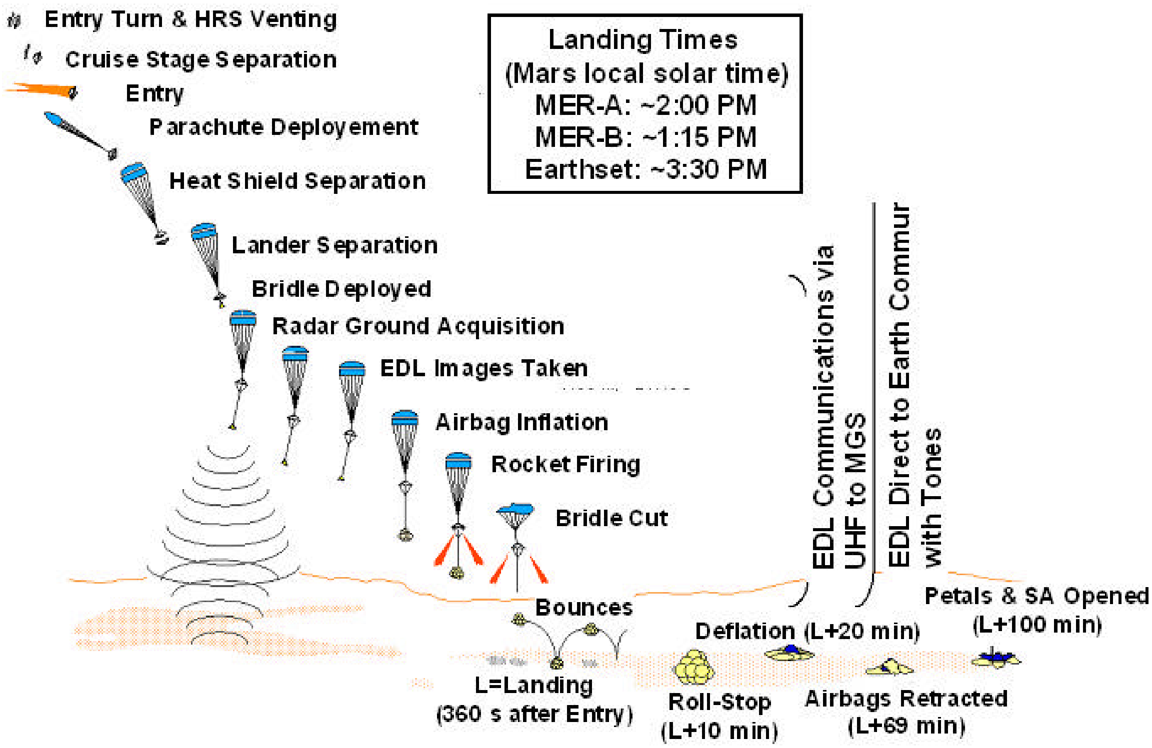



**Figure 1 - MER Flight System Configuration**

The MER flight system design adapted many successful features of the MPF spacecraft design that was launched in 1996 and landed on Mars on July 4, 1997. During cruise, MER was a spin-stabilized spacecraft with a nominal spin rate of 2 revolutions per minute. The MER flight system consists of four major components: cruise stage, entry, EDL system, Lander structure, and the Rover. The mass allocation for the entire flight system (including propellant load) was 1065 kg. The cruise configuration is shown in Figure 1. The two MER missions were designated as MER-A (Spirit) and MER-B (Opportunity). The first spacecraft (MER-A) was launched on June 10, 2003 atop a Boeing Delta II 7925 launch vehicle from Kennedy Space Center (KSC). The second spacecraft (MER-B) was launched on July 8, 2003 on a Boeing Delta II 7925H. Approximately 7 months after each launch, each spacecraft entered the Martian atmosphere directly from their interplanetary trajectories. Similar to the MPF mission, the MER entry trajectory followed an unguided, ballistic descent. The entry vehicle, consisting of the backshell, heat shield, stowed tetrahedral lander with the Rover (see Figure 1), separated from the cruise stage just prior to Mars Entry. The entry vehicle relied upon a heat shield and parachute to slow its descent through the Martian atmosphere, deployed a tether to provide separation distance between the lander and backshell, fired retro-rockets to reduce its vertical and transverse landing velocities, and finally deployed airbags to cushion its impact with the surface after the tether (known as the bridle) was severed. After the airbag assembly rolled to a stop, the lander retracted the airbags, uprighted itself, and deployed the lander side petals, thus completing lander deployment. Then, the rover deployed its solar panels, panorama camera mast, and high gain antenna completing EDL phase of the mission. A sequence of the EDL events is shown in Figure 2. From this point, the egress phase began with the imaging of the landing site, pryo-release of the rover from the lander, pyro-cutting of the lander cabling, and the stand-up of the rover. Once these actions were completed, the rover was able to drive away from the lander.

**Figure 2- EDL Sequence of Events**



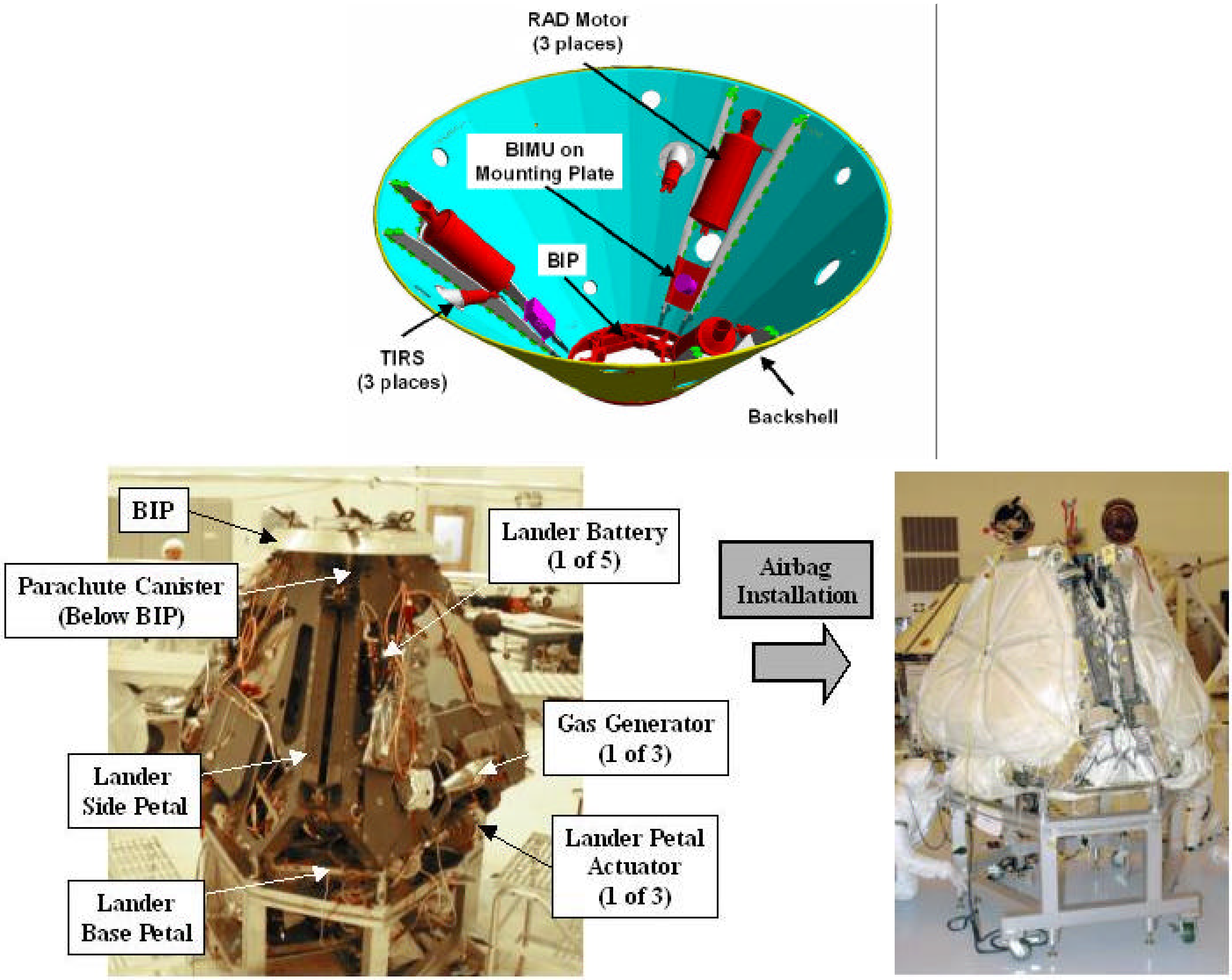

## EDL THERMAL DESIGN DESCRIPTION

The primary EDL hardware on the aeroshell consisted of: BIMU (entry vehicle attitude), thermal battery (EDL power source), BPSA (pryo switching), RAD motors (vertical velocity nulling), TIRS motors (transverse velocity nulling), gas generators (airbag inflation), and airbags. The primary EDL hardware on the lander consisted of: parachute canister, descent rate limiter (controls the deployment rate of the bridle), and lander batteries (EDL power source). The EDL hardware is shown in Figure 3. The allowable flight temperature limits for cruise and EDL are shown in Table 1. This complement of hardware was maintained at non-operational temperature levels during cruise. The BIMU, thermal battery, BPSA, RAD motors, and TIRS motors were actively controlled at non-operational temperature limits through the use of electrical heaters with bimetallic thermostats. Table 1 also shows the bimetallic thermostat open and close set points. The remaining hardware relied on wide allowable flight temperature limits so that active control was unnecessary.

As part of the EDL phase, thermal conditioning of the lander thermal batteries and the gas generators was performed. The lander battery temperatures were elevated from about -30$^o$C to 0$^o$C in about 5 hours with Kapton film heaters with bimetallic thermostats. The gas generators were warmed from about –33$^o$C to no greater than 0$^o$C in 1 hour through a command sequence. The remaining EDL hardware such as the parachute canister, descent rate limiter, RAD motors, TIRS motors, thermal battery, BPSA, BIMU, ARAs, and LPAs had non-operational levels that significantly overlapped the operational temperature ranges so no thermal conditioning was needed.

During the relatively quiescent flight from Earth to Mars, the cruise stage provided attitude control, propulsion, and power generation. The rover, nestled within the entry vehicle, provided flight computer processing and telecommunication functions. The cornerstone of the cruise thermal design was the Heat Rejection System (HRS). This was a single-phase, mechanically pumped fluid loop. The redundant integrated pump assembly, located on the cruise stage, circulated the working fluid, CFC-11, throughout the cruise stage, lander, and Rover. The primary cruise heat sources were the telecommunications hardware and the electronics located within the Rover warm electronics box. The fluid loop shuttled the Rover waste heat to radiators located on the periphery of the cruise stage. The design and performance of this system has been well documented.[2,3] Prior to Mars entry and cruise stage separation, the HRS working fluid was vented, and for approximately 2.5 hours (from HRS venting to landing with the lander side petals deployed) the Rover battery, REM, and telecommunication hardware attached to the REM, relied on thermal capacitance to maintain allowable flight temperatures.

**Figure 3 - EDL Hardware Locations**




## EDL DESIGN IMPLEMENTATION

### INHERITED MPF DESIGN IMPLEMENTATION

Much of the thermal design approach for the EDL hardware was very similar to MPF. For the thermal battery, BPSA, and RAD motors, thermostatically controlled electrical survival heaters were employed. In the case of the gas generators, and airbags, conditioning heaters controlled by the on-board EDL sequence dictated the warm-up duration. Since thermostat set points are dictated by allowable flight temperature requirements, thermal analyses were used to size the heater power. Fault protection requirements led to the use of block redundant survival heaters. Although both sides were enabled during flight, simultaneously operation of the “A” and “B” survival heater sides were avoided by staggering open and close thermostat set points for each side.

**Table 1 - Allowable Flight Temperature Limits for EDL Hardware in °C**

| Hardware Item | Cruise, Non-operating | EDL, Operating | "A" String Thermostat Set Points Close | "A" String Thermostat Set Points Open (max) |
|---|---|---|---|---|
| BACKSHELL | | | | |
| Airbag | -80 to 80 | -45 to -25 | N/A† | N/A† |
| Gas Generators | -50 to 50 | -30 to 0 | N/A† | N/A† |
| RAD Motors | -40 to 40 | -40 to -20 | -27.6 (min) | -22.0 |
| TIRS Motors | -40 to 40 | -40 to 0 | -27.6 (min) | -22.0 |
| BIMU | -47 to 65 | -39 to 51 | -28.8 ± 1.7 | -23.2 |
| BPSA | -40 to 50 | -40 to 50 | -28.8 ± 1.7 | -23.2 |
| Thermal Battery | -40 to 35 | -40 to 35 | -28.8 ± 1.7 | -23.2 |
| LANDER | | | | |
| DRL | -55 to 40 | -55 to 0 | N/A‡ | N/A‡ |
| Parachute Canister | -45 to 45 | -45 to 45 | N/A‡ | N/A‡ |
| Lander Battery | -40 to 10 | 0 to 60 | 0.0 ± 1.7 | 6.0 |
| ARAs | -105 to 85 | -45 to 15 | N/A† | N/A† |
| LPAs | -105 to 40 | -55 to 15 | N/A† | N/A† |
| ROVER ELECTRONICS MODULE | | | | |
| SSPA | -25 to 50* | -25 to 50 | N/A‡ | N/A‡ |
| SDST | -25 to 50* | -25 to 50 | N/A‡ | N/A‡ |

* Operating limits shown since hardware operates during cruise

† Commandable warm-up heater

‡ No heater on this hardware

## NEW EDL HARDWARE DESIGN IMPLEMENTATION

The BIMU thermal design approach was similar to the other backshell-mounted equipment (i.e., thermostatically controlled electrical heater) for maintaining non-operating allowable flight temperature limits. The BIMU thermal design for cruise presented interesting challenges.[4] It had significant operational power and was thermally isolated from its local environment. However, when the BIMU operated during the final approach and EDL sequences, it was expected to attain a steady-state temperature between 15°C and 17°C, well below its maximum operating allowable flight temperature limit of 51°C.

The TIRS motors were added to the EDL architecture to ensure a safe landing by nulling transverse terminal velocity (i.e., swinging back and forth on the bridle). Again, thermostatically controlled electrical heaters were employed, similar to the RAD motors.

Lander batteries were added to meet high electrical energy demands from pyrotechnic events. These batteries were thermally conditioned and maintained at operational temperatures well before their EDL use. In this case a single string survival heater was used due to the lack of area to locate a block redundant heater circuit. Fault protection engineers deemed this risk was acceptable, because EDL could be performed with the entire loss of a single lander battery assembly. The sulfur dioxide battery chemistry posed a challenge similar to the thermal battery where significant internal heat generation occurs during use. A calorimetric design approach was employed where the battery and surrounding structure thermal capacitances were used to maintain battery temperature during the EDL operational window.

## REM EDL THERMAL DESIGN & ANALYSIS

The Rover electronics consists of a core chassis (known as the Rover Electronics Module [REM]) with telecommunications and attitude control equipment (solid state amplifier [SSPA], small deep space transponder [SDST], UHF transceiver, and the rover inertial measurement unit) mounted to it. A thermal math model of the REM including the HRS fluid flow was developed for the EDL phase. Fluid flow modeling was included although it would not be germane to this particular analysis. A number of hot-biased assumptions were made to render the model as "worst-hot." The total REM thermal capacitance was intentionally under-estimated, and heat transfer paths from the high heat generating equipment (i.e., telecommunications hardware such as the SDST and SSPA) to the REM were assumed to flow through mounting bolts only. Analysis results indicated that the SSPA and SDST would reach 46°C and 24°C, respectively, at roll-stop (Mars landing), within the maximum allowable flight temperature limits.[2]

## EDL THERMAL DESIGN VERIFICATION & VALIDATION

### ROVER-HRS THERMAL CHARACTERIZATION TEST

A thermal design characterization test was performed late in the design development (approximately one year before launch).[5] While it was primarily focused on quantifying the HRS thermal performance during cruise, this test also targeted EDL thermal performance. There were two specific EDL test cases: 1) thermal conditioning of EDL hardware prior to Mars entry, and 2) Mars entry simulation for the REM. The test article was an assembly of non-flight or mocked-up hardware (see Figure 4). Aeroheating loads were not simulated for the EDL test, but they only slightly affected temperatures of the stowed lander.

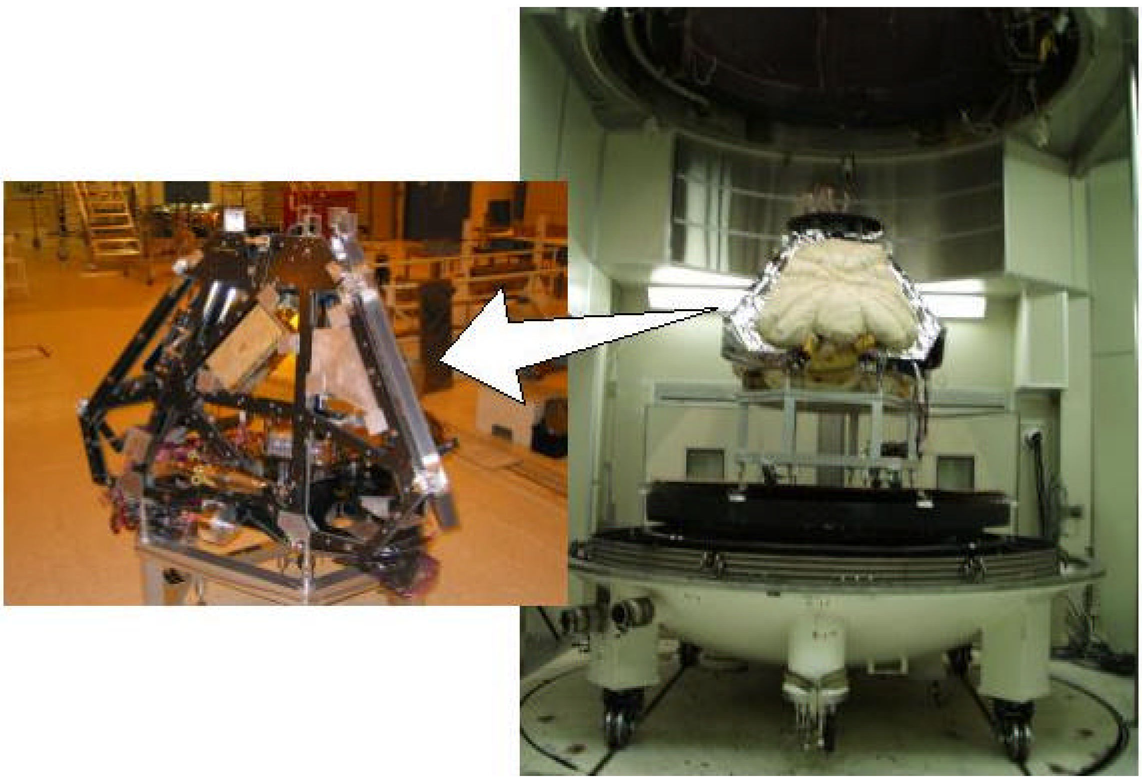


**Figure 4 - Rover-HRS Thermal Characterization Test Setup**

<u>EDL Thermal Conditioning</u>

At the time of this test, the flight thermal conditioning of the base petal airbag prescribed a 16-hour cycle based on MPF, where the warm-up heater is turned on for 8 hours and then powered off. Airbag temperatures are allowed to equilibrate for 8 hours, immediately followed by airbag inflation. The tightly compacted airbag layers thermally represented an excellent insulator, thus the applied heat on the airbag outer-most layer required time to diffuse to the inner-most layer. When this warm-up scenario was simulated, the outer layer of the base petal airbag warmed from -47°C to 20°C during the first 8 hours. The airbag outer layer cooled to -29°C during the latter 8 hours. The inner layer only warmed from -47°C to -46°C during the warm-up period, but continued to warm to -43°C 8 hours after the warm-up heater was turned off. This behavior was totally consistent with MPF flight data, which indicated that the base petal airbag outer layer warmed from -36°C to 10°C, and then cooled to -24°C over the next 15 hours after the heater was turned off. Since the "at-inflation" allowable flight temperature range was -45°C to -25°C, the planned conditioning strategy was deemed feasible. The near Mars entry base petal airbag temperature (-47°C) was very close to the minimum "at-inflation" allowable flight temperature limit of -45°C. Since the simulation of the backshell thermal boundary condition (the chamber shroud) was based on a worst-cold analysis, the near Mars base petal airbag temperature for this test might be conservatively low. EDL sequence planning proceeded assuming the need for base petal airbag thermal conditioning, however, a final decision would be deferred until system-level thermal balance testing.

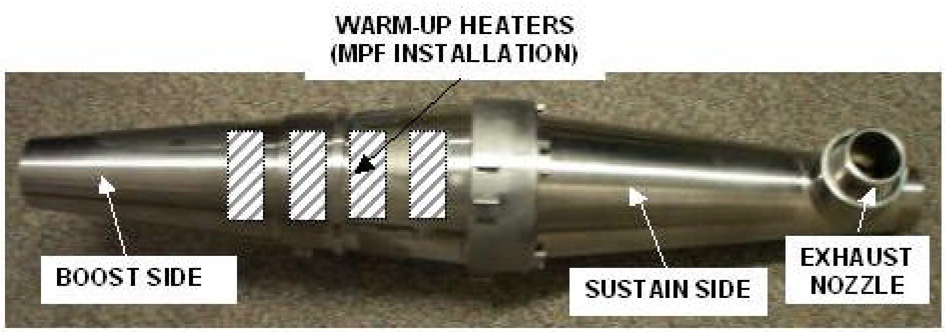
The gas generator has two distinct charges: one is used for the initial airbag inflation known as the boost grain and the other is used to maintain the inflation rate known as the sustain grain (see Figure 5). The “at-ignition” allowable flight temperature limits of $-30^{o}C$ to $0^{o}C$ apply to the boost grain most importantly. The planned flight gas generator thermal conditioning dictated a 1-hour warm-up, a 0.5-hour stabilization without the heater, and then gas generator firing. No gas generator firing was planned in this test. During the 1-hour warm-up for the gas generators, the boost grain warmed by $6^{o}C$ (from $-45^{o}C$ to $-39^{o}C$ for the test thermocouple that was most representative of the boost grain). Since the minimum “at-ignition” allowable flight temperature limit of $-30^{o}C$ was not achieved, the warm-up period was recommended to be extended to at least 2.5 hours to meet the “at-ignition” requirement.

The planned flight lander battery thermal conditioning was expected to be initiated approximately 24 hours prior to Mars entry. When the warm-up heater was activated for 4 hours, lander battery temperature increased $25^{o}C$ from $-31^{o}C$ to $-6^{o}C$. The heater was manually turned off before the thermostat was permitted to open at $6^{o}C$ for unknown reasons. However, the empirical test data strongly indicated that the lander battery would achieve thermostatic heater control (i.e., warm-up heater would cycle lander battery temperatures between the thermostat close and open set points of approximately $0^{o}C$ and approximately $6^{o}C$, respectively.

Mars Entry for the REM

Given the configuration of the cruise test article, the thermal simulation of the events between cruise stage separation to Mars landing to successful lander deployment was extremely simple. The HRS loop was deactivated for this case. The chamber shroud temperature, representing the backshell, was left in its previous state (cruise near Mars entry). Since the REM is thermally isolated from the backshell, the REM EDL response is essentially calorimetric (i.e., all the internal power dissipation goes into the REM thermal capacitance). After 1 hour of EDL simulation, REM temperatures increased between 10°C to 15°C with the SSPA and SDST at $26^{o}C$ and $12^{o}C$, respectively. At the start of the second hour of the EDL simulation, $GN_2$ at 1333 Pa (10 torr) was introduced into the chamber to simulate the Mars surface pressure. By the end of the lander deployment (approximately 3 hours after the HRS is turned off), the SSPA and SDST reached $26^{o}C$ and $28^{o}C$, respectively. These results demonstrated that the REM would be maintained well below its maximum allowable flight temperature limit of $50^{o}C$ during EDL, and the analysis was conservative (i.e., hot biased).

**Figure 5 - Gas Generator Description**




Other EDL Hardware Temperatures at Mars Entry

The other EDL hardware did not require thermal conditioning prior to Mars entry. The thermostatically controlled survival heaters maintained allowable flight temperature limits for BIMU, thermal battery, BPSA, RAD motors, and TIRS motors, while the parachute canister, descent rate limiter, ARAs, and LPAs were passively maintained above minimum allowable flight temperature limits and driven by the backshell/heat shield environment.

OPPORTUNITY SYSTEM THERMAL TEST

The flight lander and Rover hardware were integrated and tested for the MER-B cruise system thermal test only. Schedule challenges precluded the presence of the flight lander and Rover hardware for the MER-A cruise system thermal test. Empirical validation of the cruise thermal design represented the primary objective of the MER-B cruise system thermal test. To this end, there were three test cases related specifically to EDL, and were similar to those in the Rover-HRS thermal characterization test.[6] One test case involved the conditioning of the airbags and lander batteries approximately 24 hours prior to EDL. The second case dealt specifically with thermal conditioning of the EDL hardware including the gas generators during EDL itself. Finally, the last case addressed the REM thermal response during EDL through lander deployment. This system thermal balance test was conducted in JPL’s 25-foot Space Simulator System between November 9 and 22, 2003 (see Figure 6). Solar simulation was accomplished through a combination of the facility’s Xenon lamp system and portable IR quartz lamps.

The MPF heater location approach had been adopted for the MER gas generators. This involved wrapping the heater element over half the circumference of the boost grain. The gas generator vendor, Alliant Techsystems, conducted detailed thermal analyses on this approach during the time between the Rover-HRS thermal characterization test and the MER-B cruise system thermal test. They concluded that the asymmetric warm-up heating would result in an adverse spatial temperature difference for the boost grain, and recommended that the heater elements be placed over the entire circumference of the boost grain. Since the JPL team was in midst of preparing for the MER-B cruise system thermal test, a hybrid validation strategy was undertaken. Two of the three gas generators would have the MPF heater installation and wired into the flight harness while one would use the vendor's recommended heater installation that would be wired into a test power supply. This provided test flexibility in characterizing the vendor's heater installation.

Airbag and Lander Battery Thermal Conditioning

This case lasted 14 hours and simulated transient events directly preceding EDL including base petal airbag and lander primary battery warm-ups. All chamber conditions and spacecraft state represented late cruise near Mars.

Both the primary and secondary airbag heater strings were turned on 3 hours after this case started. The dual string heater activations were so effective that the airbag heater was turned off after 3.3 hours of operation to prevent overheating of the outer layer. The airbag outer layer temperature reached 76$^{o}$C, which was 4$^{o}$C below its 80$^{o}$C maximum non-operating allowable flight temperature limit. The airbag innermost layer temperature increased 8$^{o}$C from -32$^{o}$C to -24$^{o}$C several hours later. At the time of planned airbag inflation, the airbag temperatures ranged between –20$^{o}$C and –14$^{o}$C; this was 5$^{o}$C to 11$^{o}$C above the maximum at-ignition allowable flight

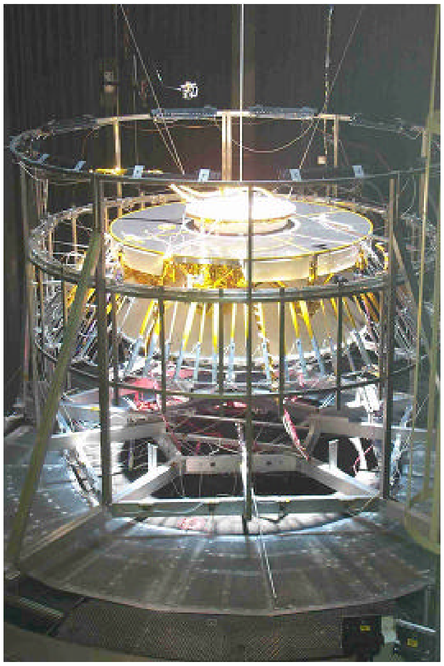


**Figure 6 - MER-B Cruise System Thermal Test Setup**

temperature limit (although airbag inflation was not conducted during this test). Prior to the initiation of airbag conditioning and during the cruise near Mars test case, the airbag temperatures were within the at-ignition allowable flight temperature range between -45$^{o}$C and -25$^{o}$C. This was significantly warmer than the Rover-HRS thermal characterization test. However, the MER-B cruise system thermal test simulated the near Mars thermal environment more accurately, thus a decision was made to forego airbag thermal conditioning in flight. The conditioning of the airbag created a dramatic yet transient spatial temperature difference across the airbag layers. EDL design engineers strongly preferred a uniform airbag temperature prior to inflation. If the flight experience yielded airbag temperatures below –45$^{o}$C, then the airbag conditioning could be reinstated.

The lander primary battery warm-up heater circuit was functionally verified during this test case.. Approximately 4 hours was required for the battery temperature to rise from –25$^{o}$C to the thermostat open set point of 6$^{o}$C. A few heater control cycles was permitted to further validate the heater circuit. These results were consistent with the Rover-HRS thermal characterization test. Since the lander battery thermal conditioning was initiated 24 hours prior to Mars entry, the lander battery should be comfortably within its operating allowable flight temperature range for EDL during flight.

Thermal Conditioning and Performance During EDL

The EDL test case lasted 4.2 hours. No attempt was made to simulate environmental loads from aerodynamic heating since it was beyond the scope of this test. However, these heat loads were expected to only produce minor temperature changes inside the stowed lander. This test case was performed under high-vacuum conditions with the CFC-11working fluid in the HRS lines at all times.

At the time of this test case, the flight gas generator warm-up strategy would activate both "A' and "B" heater strings for 1.3 hours followed by 0.4 hour of equilibration time with the heaters off. Then, gas generator firing would immediate follow the equilibration period, but again firing was not performed during this test. Test data suggested that the flight gas generator warm-up heaters (two of the three gas generators) were only turned for roughly 1.25 hours, which was close to the planned flight duration. These gas generator boost grain temperatures increased 17°C from -31°C to -14°C. The gas generator with the Alliant Techsystem's recommended heater installation experienced a rise in temperature from –30°C to –16°C in 1.3 hours of conditioning. Since this warm-up heater was wired to a test power supply rather than the spacecraft, JPL test engineers were able to control the warm-up duration independently from the spacecraft. Test data indicated that the gas generators would only decrease about 0.5°C during the equilibration period due to its large thermal capacitance. These results were in direct contrast to the Rover–HRS thermal characterization test. The planned 1.3 hour warm-up followed by 0.4 hour of equilibration would be sufficient to bring the gas generators within their "at-ignition" temperature range. In addition, the vendor's recommended heater installation approach was adopted for the flight application. The gas generators used in this test were high fidelity models that were devoid of live ordinance. The flight gas generators were delivered directly to KSC for proper handling, and the flight warm-up heaters would be installed later in the KSC integration and test flow.

**Table 2 - MER-B Cruise System Thermal Test Results (°C): EDL Test Cases**

| Hardware Item | Cruise, Prior to EDL | EDL, Prior to Use | Post-Landing, Prior to Use | Operating AFT Limits |
|---|---|---|---|---|
| BACKSHELL | | | | |
| Airbag | -36 to -32 | -20 to -14 | N/A† | -45 to -25 |
| Gas Generators | -32 to -27 | -18 to-16 | N/A† | -30 to 0 |
| RAD Motors | -29 to -26 | -29 to -26 | N/A† | -40 to -20 |
| TIRS Motors | -31 to -29 | -36 to -33 | N/A† | -40 to 0 |
| BIMU | -29 to -27 | -28 | N/A† | -39 to 51 |
| BPSA | -29 to -27 | -29 to -27 | N/A† | -40 to 50 |
| Thermal Battery | -29 | -29 | N/A† | -40 to 35 |
| LANDER | | | | |
| DRL | -30 | 1 to 5 | N/A† | -55 to 0 |
| Parachute Canister | -29 | -27 | N/A† | -45 to 45 |
| Lander Battery | -28 to -25 | 1 to 5 | N/A† | 0 to 60 |
| ARAs | -32 to -27 | N/A* | -27 to -24 | -45 to 15 |
| LPAs | -29 to -25 | N/A* | -26 to -23 | -55 to 15 |
| ROVER ELECTRONICS MODULE | | | | |
| SSPA | 10 | 30 | 38 | -25 to 50 |
| SDST | 2 | 27 | 33 | -25 to 50 |

* Does not operate during EDL

† Test result does not apply to flight condition

Just prior to cruise stage separation, the EDL hardware heaters were disabled to permit cabling cutting events via dead-facing. Thus there was a 2-hour window prior to landing where EDL hardware was not heater-controlled. However, changes in temperature were moderated by the large thermal capacitance of the hardware. Table 2 summarizes the EDL hardware temperatures just prior to the start of EDL and the end of the EDL sequence (landing in this test case). The RAD and TIRS motors each had a maximum temperature difference of 3$^{o}$C between any of three like motors. This was well within the maximum allowable flight temperature difference requirement of 7.2$^{o}$C.

Mars Entry to Landing for the REM

SSPA was the pacing item, and it reached 50$^{o}$C about 3.7 hours after the HRS was turned off. Similarly, the SDST had reached 44$^{o}$C in this time frame. During the flight EDL sequence, the REM must tolerate termination of HRS functionality for approximately 2.5 hours (0.8 hour from HRS venting to Mars landing and 1.7 hours from Mars landing to full lander deployment). The test data indicated that the SSPA and SDST temperatures were 38$^{o}$C and 33$^{o}$C, respectively, 2.5 hours from HRS deactivation. With the maximum allowable flight temperature limit for both the SSPA and SDST being 50$^{o}$C, there was adequate thermal margin demonstrated. These results were higher than the Rover-HRS thermal characterization test. For the Rover-HRS thermal characterization test, $GN_2$ had been introduced into the test chamber while this was not performed for the MER-B system thermal test. This would possibly explain the warmer temperatures for the system thermal test.

## IN-FLIGHT EXPERIENCE

SPIRIT (MER-A) EDL

The thermally significant EDL events are summarized in Table 3. The final approach phase commenced 11 days prior to Mars entry. From a thermal standpoint, most of the final approach was relatively routine with a few trajectory correction maneuvers for final targeting. At 32 hours prior to Mars entry, the lander battery warm-up heaters were activated and warmed as expected. This thermal conditioning had a beneficial effect on gas generator temperatures. Gas generator temperatures increased about 2$^{o}$C from -31$^{o}$C (prior to thermal conditioning) to –30$^{o}$C (after lander battery warm-up heaters had established control). However, the base petal airbag temperature remained at –34$^{o}$C. Given that the base petal air bag temperature was sufficiently above the minimum at-inflation allowable flight temperature of –45$^{o}$C, airbag thermal conditioning was cancelled. In preparation for cruise stage separation, the RAD motors, TIRS motors, thermal battery, BPSA, and BIMU survival heaters were deactivated 1.9 hours from Mars entry. The spacecraft performed a turn to orient the heat shield in the ram direction at 1.4 hours from Mars entry. Shortly before the turn-to-entry is completed (1.3 hours from Mars entry), the gas generator warm-up heaters were activated. The flight EDL sequence prescribed 1.0 hour of warm-up heating followed by 0.4 hour of equilibration. Initial flight temperature telemetry indicated that gas generator temperature rate of change was approximately 30$^{o}$C/hr. The extrapolated gas generator temperature at ignition was estimated at 4$^{o}$C. This was 4$^{o}$C ABOVE the maximum allowable flight at-ignition limit of 0$^{o}$C. The gas generator at-ignition temperature range was relatively tight to ensure proper airbag inflation. Gas generator temperatures outside this range could result in over- or under-inflation of the airbags, either which would present a liability for successful landing. The EDL Flight Director was notified of this finding. The MER temperature requirements document stated that hot protoflight environmental testing had not been conducted since analysis demonstrated that performance was insensitive to higher temperatures (greater than allowable flight temperatures). EDL engineers were consulted, and they determined 25$^{o}$C was the upper ceiling of the “higher temperatures” that were cited. Therefore, there was no technical issue with gas generators firing at 4$^{o}$C. Shortly after this assessment, another EDL telemetry packet was received and the revised estimate for gas generator temperature upon firing was –1$^{o}$C. Post-EDL telemetry reconstruction revealed that the gas generators were between –7$^{o}$C and –4$^{o}$C at ignition, just within the –30$^{o}$C to 0$^{o}$C allowable flight at-ignition temperature range. The parachute mortar was fired about 95 seconds from Mars landing (initial impact) with the parachute canister at -14$^{o}$C. Following parachute deployment, the lander bridle was unfurled via the descent rate limiter. This started approximately 83 seconds from Mars landing with the descent rate limiter at –24$^{o}$C. The RAD motors fired approximately 7 seconds prior to Mars landing and EDL telemetry was only available for RAD motor #2, which was at -27$^{o}$C when fired. The RAD motor #2 temperature did not appreciably decrease between survival heater disabling and RAD firing. This coupled with the final approach flight data suggested that the temperature difference between all the RAD motors was within 4$^{o}$C at firing (maximum allowable flight temperature difference was 7.2$^{o}$C). Two of the three TIRS motors fired about 6 seconds prior to Mars landing, and again only TIRS motor #1 telemetry (-33$^{o}$C at ignition) was available. This TIRS motor cooled 5$^{o}$C between survival heater disabling and TIRS firing. Using a similar approach for the RAD motors, the maximum temperature between all TIRS motors was within 4$^{o}$C at firing (maximum allowable flight temperature difference was 7.2$^{o}$C). Table 4 summarizes the backshell and lander EDL hardware temperatures prior to Mars entry and prior to use during EDL. Note that all EDL hardware was within the operating allowable flight temperature ranges prior to use.

Upon Mars landing (initial impact), the SSPA and SDST temperatures were 19$^{o}$C and 12$^{o}$C respectively, with temperature rates of change of 13$^{o}$C/hr and 11$^{o}$C/hr, respectively. The peak SSPA and SDST temperatures between Mars landing and lander deployment were 23$^{o}$C and 28$^{o}$C, respectively. This was well within the maximum operating allowable flight temperature limits for this set of hardware (50$^{o}$C for both). This response was significantly different than cruise system thermal test, and differences were attributed to the changes in the telecommunication equipment operational profile during EDL.

**Table 3 - Flight EDL Sequence Timeline**

| Spirit Event Time (Month-Day-Year, GMT) | Spirit Entry Relative Time (Day-Hr:Min:Sec) | Opportunity Event Time (Month-Day-Year, GMT) | Opportunity Entry Relative Time (Day-Hr:Min:Sec) | Event |
|---|---|---|---|---|
| **12-24-2003 4:19:53.363** | **E - 11-0:00:00.0** | **01-14-2004 4:48:42.418** | **E - 11-0:00:00.0** | **Final Approach** |
| 01-02-2004 20:19:51.991 | E - 1-8:00:00.0 | 01-23-2004 18:59:52.991 | E - 1-9:48:49.0 | Turn On Lander Primary Battery Heaters |
| 01-04-2004 2:28:51.811 | E - 1:51:00.0 | 01-25-2004 2:57:41.931 | E - 1:51:00.0 | Turn Off Backshell (RAD, TIRS & other equipment) Cruise Heaters |
| 01-04-2004 2:28:51.811 | E - 1:51:00.0 | 01-25-2004 2:57:41.931 | E - 1:51:00.0 | Turn Off Prop Tank Heaters |
| **01-04-2004 2:34:52.000** | **E - 1:45:00.0** | **01-25-2004 3:03:41.931** | **E - 1:45:00.0** | **Turn To Entry Attitude To Entry Phase** |
| 01-04-2004 2:54:51.809 | E - 1:25:00.0 | 01-25-2004 3:23:41.930 | E - 1:25:00.0 | Turn to Entry Attitude |
| 01-04-2004 3:02:51.808 | E - 1:17:00.0 | 01-25-2004 4:01:41.929 | E - 0:47:00.0 | Turn On Gas Generator Heaters |
| 01-04-2004 3:39:51.804 | E - 0:40:00.0 | 01-25-2004 4:08:41.929 | E - 0:41:00.0 | Fire HRS Venting Pyro Valves |
| 01-04-2004 3:39:51.804 | E - 0:40:00.0 | 01-25-2004 4:08:41.929 | E - 0:41:00.0 | HRS Venting |
| 01-04-2004 4:03:06.802 | E - 0:16:45.0 | 01-25-2004 4:31:56.928 | E - 0:16:45.0 | Lander Battery Heater Off. |
| 01-04-2004 4:03:06.802 | E - 0:16:45.0 | 01-25-2004 4:31:56.928 | E - 0:16:45.0 | Turn Off Gas Generator Heaters |
| 01-04-2004 4:04:51.802 | E - 0:15:00.0 | 01-25-2004 4:33:41.928 | E - 0:15:00.0 | Cruise Stage Separation |
| **01-04-2004 4:19:51.801** | **E - 0:00:00.0** | **01-25-2004 4:48:41.928** | **E - 0:00:00.0** | **Entry - Descent Phase** |
| 01-04-2004 4:23:55.802 | E + 0:04:04.0 | 01-25-2004 4:52:44.928 | E - 0:04:03.0 | Fire parachute mortor pyros |
| 01-04-2004 4:24:15.602 | E + 0:04:23.8 | 01-25-2004 4:53:04.728 | E - 0:04:22.8 | Fire heatshield separation nuts group #1 |
| 01-04-2004 4:24:15.727 | E + 0:04:23.9 | 01-25-2004 4:53:04.853 | E - 0:04:22.9 | Fire heatshield separation nuts group #2 |
| 01-04-2004 4:24:15.802 | **E + 0:04:24.0** | 01-25-2004 4:53:04.928 | **E - 0:04:23.0** | **Terminal Descent Phase** |
| 01-04-2004 4:24:25.802 | E + 0:04:34.0 | 01-25-2004 4:53:14.928 | E - 0:04:33.0 | Lander/Backshell Separation (LBS) |
| 01-04-2004 4:25:39.802 | E + 0:05:48.0 | 01-25-2004 4:54:24.928 | E - 0:05:43.0 | Fire Gas Generators |
| 01-04-2004 4:25:41.802 | E + 0:05:50.0 | 01-25-2004 4:54:26.928 | E - 0:05:45.0 | Fire RAD Rockets (Estimate) |
| 01-04-2004 4:25:42.002 | E + 0:05:50.2 | 01-25-2004 4:54:27.128 | E - 0:05:45.2 | Fire TIRS |
| 01-04-2004 4:25:44.802 | E + 0:05:53.0 | 01-25-2004 4:54:29.928 | E - 0:05:48.0 | Fire Bridle Cutter (Estimate) |
| 01-04-2004 4:25:48.052 | E + 0:05:56.3 | 01-25-2004 4:54:33.178 | E - 0:05:51.3 | Initial Impact (Estimate) |

**Table 4 - Flight EDL Temperature Telemetry (Format: Spirit Data/Opportunity Data) in $^{o}$C**

| Hardware Item | Cruise, Prior to EDL | EDL, Prior to Use | Post-Landing, Prior to Use | Operating AFT Limits |
|---|---|---|---|---|
| BACKSHELL | | | | |
| Airbag | -34 / -34 to -32 | -36 / -34 | N/A† | -45 to -25 |
| Gas Generators | -32 to -27 / -33 to -28 | -7 to -4 / -14 to -18 | N/A† | -30 to 0 |
| RAD Motors | -29 to -24 /-27 to -23 | -30 to -27 / -27 to -22 | N/A† | -40 to -20 |
| TIRS Motors | -31 to -28 / -32 to -27 | -36 to -33 / -38 to -33 | N/A† | -40 to 0 |
| BIMU | -28 to -25 /-28 to -26 | -28 to -25 /-28 to -26 | N/A† | -39 to 51 |
| BPSA | -30 to -28 / -28 to -27 | No Data | N/A† | -40 to 50 |
| Thermal Battery | -27 to -23 / -27 to -23 | -31 / -31 | N/A† | -40 to 35 |
| LANDER | | | | |
| DRL | -25 to -23 / -29 to -26 | -24 / -24 | N/A† | -55 to 0 |
| Parachute Canister | -14 to -10 / -13 to -11 | -12 / -13 | N/A† | -45 to 45 |
| Lander Battery | -21 to -27 / -25 to -28 | 1 to 9 / 0 to 11 | N/A† | 0 to 60 |
| ARAs | -31 to -24 / -32 to -24 | N/A* | -29 to -22 / No Data | -45 to 15 |
| LPAs | -28 to -24 / -28 to -24 | N/A* | -27 to -23 / No Data | -55 to 15 |
| ROVER ELECTRONICS MODULE | | | | |
| SSPA | 8 to 9 / 7 to 8 | 19 / 22 | 23 / 23 | -25 to 50 |
| SDST | 1 to 3 / 2 to 3 | 12 / 9 | 28 / 30 | -25 to 50 |

* Does not operate during EDL

† No data, no post-landing use

OPPORTUNITY (MER-B) EDL

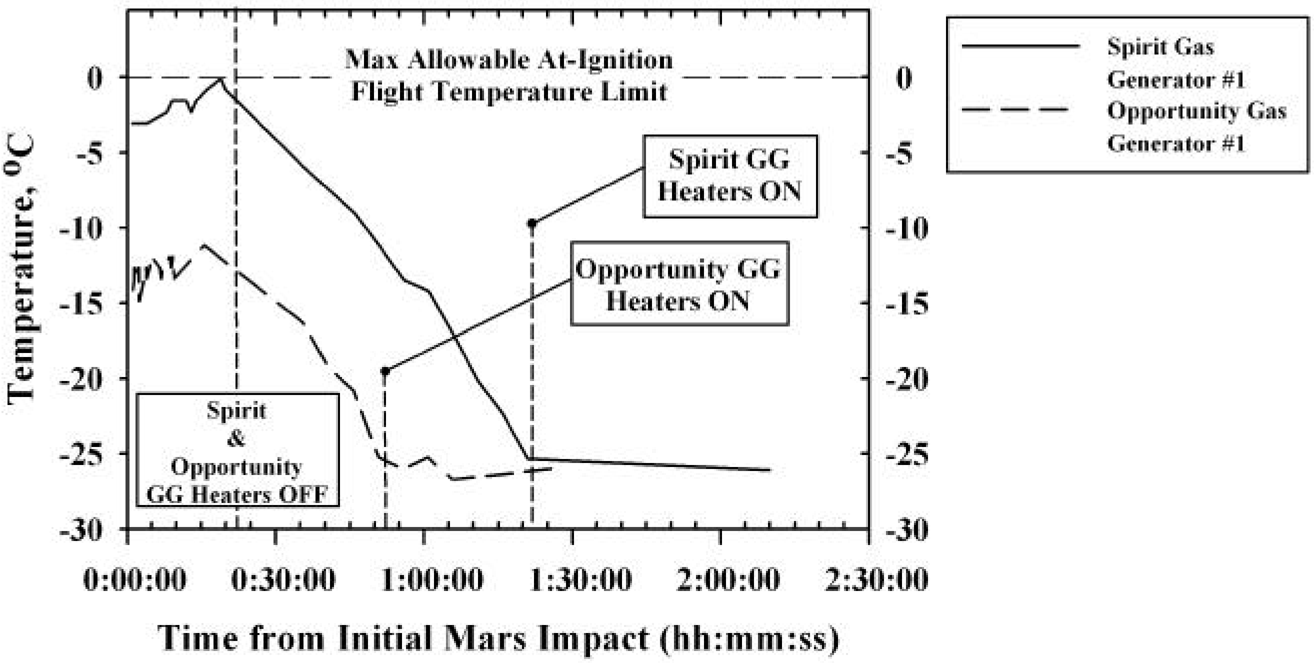
A day after the Spirit landing, an EDL reconstruction effort was initiated to capture the lessons learned that could be applied to Opportunity's EDL, which was less than three weeks away. In reviewing the Spirit gas generator thermal conditioning, JPL engineers found three root causes for the over-performance of the warm-up heaters: a) Gas generator temperatures were significantly affected by lander battery thermal conditioning thus leading to a higher initial warm-up temperature; b) there was an uncertainty in the gas generator thermal capacitance since mass models were used for the cruise system thermal test that could have led to a faster response than cruise system thermal testing; and c) the flight bus voltage was greater than that used in the cruise system thermal test, that led to higher power dissipation than cruise system thermal testing. JPL thermal engineers recommended that the gas generator warm-up heater window of operation be reduced from 1.3 hours to 0.5 hour. In addition, the gas generator equilibration duration of 0.4 hour would be retained. This warming strategy would place the gas generator temperature in midpoint of the allowable at-ignition flight temperature range (-30$^{o}$C to 0$^{o}$C). These recommendations were incorporated into the Opportunity EDL sequence.

The JPL thermal engineers confirmed that the decision to forego airbag thermal conditioning for Spirit was prudent. The Spirit airbag at-ignition temperature of –36$^{o}$C was in the middle of the allowable at-ignition flight temperature range (-25$^{o}$C to –45$^{o}$C). This approach would be continued for Opportunity.

The final approach EDL hardware temperatures were generally within 2$^{o}$C of corresponding Spirit temperatures. The only exceptions were the descent rate limiter and lander battery temperatures, which were within by 4$^{o}$C of Spirit flight data. Lander battery thermal conditioning commenced nearly 2 hours earlier than Spirit without significant consequence. Gas generator warm-up started 0.5 hour later than Spirit based on Spirit's EDL experience. Initial EDL telemetry indicated that the gas generator warm-up ramp rate was roughly the same as Spirit, 35°C/hr. The projected flight at-ignition temperature was estimated at –10°C. Post-EDL reconstruction demonstrated that the flight at-ignition temperatures for the gas generators ranged between -18°C to –14°C. Figure 7 shows the comparison between the Spirit and Opportunity gas generator thermal conditioning events. The at-ignition temperatures for the parachute mortar, descent rate limiter, RAD motors, and TIRS motors were generally within 2°C of corresponding Spirit temperatures. The inferred maximum temperature difference between the all 3 RAD motors (within 5.5°C) was slightly larger than Spirit. Likewise the inferred maximum temperature between all TIRS motors was within 5°C. Since mechanical thermostats have about 2°C variance in set points from unit to unit, this variance could be the most probable cause for difference from Spirit. Table 4 summarizes the backshell and lander EDL hardware temperatures prior to Mars entry and prior to use during EDL. Again, all EDL hardware was within the operating allowable flight temperature ranges prior to use.

The SSPA and SDST temperatures at landing were 22°C and 9°C, respectively, and this was within 3°C of corresponding Spirit flight data. Similarly, the SSPA and SDST temperatures peaked at 23°C and 30°C, respectively, between Mars landing and lander deployment. These responses were similar to Spirit and well below the maximum operating allowable flight temperature limits for this set of hardware (50°C for both).

**Figure 7 - Comparison of Spirit & Opportunity Gas Generator Warm-up**




## CONCLUSION

The MER EDL hardware thermal design was rooted with the MPF design approach with some incremental changes. The validation of this design used a methodical approach based on a combination of analyses and empirical testing (Rover-HRS thermal characterization and flight cruise system thermal tests). This approach was effective in demonstrating acceptable thermal performance under worst-case cold conditions. However, flight conditions were warmer than worst-case cold thus resulting in gas generator warm-up over-performance for Spirit. This lesson was readily applied to the Opportunity EDL, which was nearly flawless from a thermal standpoint.

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## DEFINITIONS, ACRONYMS, ABBREVIATIONS

**AFT:** Allowable flight temperature
**ARA:** Airbag Retraction Actuator
**BIMU:** Backshell Inertial Measurement Unit
**BIP:** Backshell Interface Plate
**BPSA:** Backshell Pyro Switching Assembly
**CFC-11**: Trichlorofluoromethane
**DRL:** Descent Rate Limiter
**EDL:** Entry, Descent, & Landing
**GG:** Gas Generator
**GMT:** Greenwich Mean Time
**$GN_2$:** Gaseous Nitrogen
**HRS:** Heat Rejection System
**IR:** Infra-red
**kg:** Kilogram
**KSC:** Kennedy Space Center
**LPA:** Lander Petal Actuator
**MER:** Mars Exploration Rover
**MER-A:** First MER mission launched; also known as "Spirit"
**MER-B:** Second MER mission launched; also known as "Opportunity"
**MPF:** Mars Pathfinder
**NASA:** National Aeronautics and Space Administration
**Pa:** Pascal, SI unit of pressure equal to 1 Newton per square meter
**RAD:** Rocket Assisted Deceleration
**REM:** Rover Electronics Module
**SDST:** Small Deep Space Transponder
**Sol:** A Martian day, about 24 hours and 40 minutes
**SSPA:** Solid-State Power Amplifier
**TIRS:** Transverse Impulse Rocket System
**torr:** Non-SI unit of pressure representing 1 mm of Mercury
**UHF**: Ultra-high frequency