Testing of the Mars Exploration Rovers to Survive the Extreme Thermal Environments

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Abstract

NASA's Mars Exploration Rover (MER) project involved delivering two mobile science laboratories (rovers) on the surface of Mars to remotely conduct geologic investigations, including characterization of a diversity of rocks and soils. The rovers were launched separately in 2003 and have been in operation on the surface of Mars since January 2004. The rovers underwent a comprehensive pre-launch environmental assurance program that included assembly/subsystem and system-level testing in the areas of dynamics, thermal, and electromagnetic (EMC), as well as venting/pressure, dust, radiation, and solid-particle (meteoroid, orbital debris) analyses. Due to the Martian diurnal cycles of extreme temperature swings, the susceptible hardware that were mounted outside of the thermal controlled zones also underwent thermal cycling qualification of their packaging designs and manufacturing processes. This paper summarizes the environmental assurance program for the MER project, with emphasis on the pre-launch thermal testing program for ensuring that the rover hardware would operate and survive the Mars surface temperature extremes. These test temperatures are compared with some of the Mars surface operational temperature measurements. Selected anomalies resulting from operating the rover hardware in the Mars extreme thermal environment are also presented.

Key Words

Dynamics Testing, EMC Testing, Environmental Assurance, Environmental Testing, Extreme Thermal Environments, Mars Environments, Mars Exploration Rover, Natural Space, Thermal Testing, Spacecraft Testing.

I. Introduction

The MER twin rovers (named "Spirit" and "Opportunity") were sent to the surface of Mars to remotely conduct geologic investigations, including characterization of a diversity of rocks and soils that may hold clues to past water activity [1], [2]. The first flight system, known as MER-A, "Spirit," was launched on June 10, 2003, from the Cape Canaveral Air Force Station in Florida using a Delta II 7925 launch vehicle. The second flight system, known as MER-B, "Opportunity," was launched on July 7, 2003, using a Delta II 7925H launch vehicle. Both rovers landed safely on the surface of Mars (MER-A at Gusev Crater and MER-B at Meridiani Planum) as scheduled on January 4 and 25, 2004, respectively.

II. Flight System Description

Each identical flight system (identified as MER-1 and MER-2 during ground testing), consisted of an Earth–Mars cruise spacecraft, an entry–descent–landing (EDL) system enclosed in an aeroshell (a heatshield/backshell combination), and a mobile science rover with an integrated instrument package stowed inside the lander (Fig. 1). This expanded view also shows some of the hardware that underwent environmental tests (or analyses) to ensure system reliability to accomplish the mission.

Fig. 2 shows the two rovers being assembled in the spacecraft assembly clean room. The Rover on the left shows all the wheels partially stowed toward the launch and cruise configuration. The wheels on the right rover are deployed as they would be for normal Mars surface operations. Each fully deployed rover is almost as tall as a person (standing at the back). The size of these rovers is in contrast with the much smaller 1997 Mars Pathfinder rover shown in the foreground of Fig. 2.

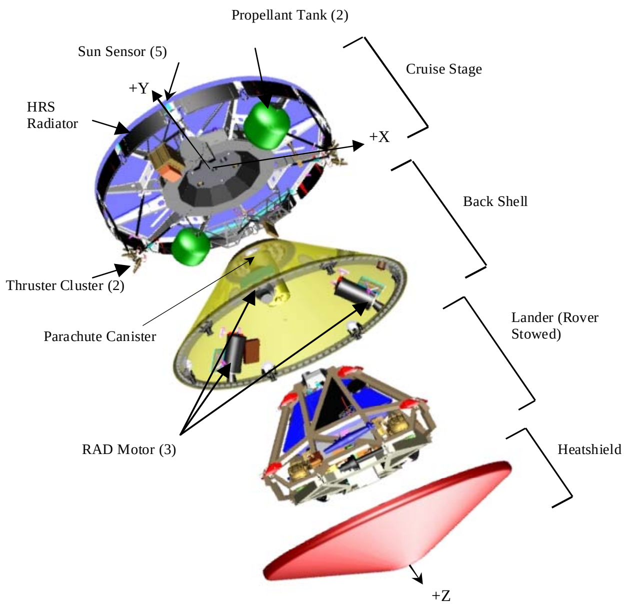

Fig. 1. MER flight system.

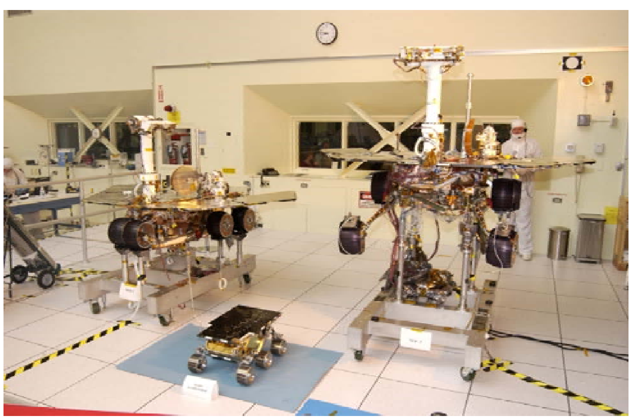

Fig 2. Picture of the two rovers being assembled.

Fig. 3 shows an artist's rendition of a fully deployed rover on the surface of Mars in the operations mode. Some of the equipment that will be discussed later in this paper is identified in the picture. A comparison of the in-flight temperature measurements with the ground test temperatures for some of those assemblies will be made. The panoramic camera (pancam) and navigation camera (navcam) are mounted on top of the panoramic camera mast assembly (PMA). All of the antennas, including the high-gain antenna (a disc antenna), the low-gain antenna, and the ultra high frequency (UHF) antenna, are mounted on top of the rover deck, just above the solar arrays. A suite of instruments is mounted at the tip of the instrument deployment device (IDD) arm. It includes the microscopic imager (MI) and the rock abrasion tool (RAT), which is a rock grinder. The wheels and the rocker–bogie system comprise the mobility system. All the temperature-sensitive assemblies are mounted inside the temperature-controlled warm electronics box (WEB) just below the solar arrays, in the center of the rover.

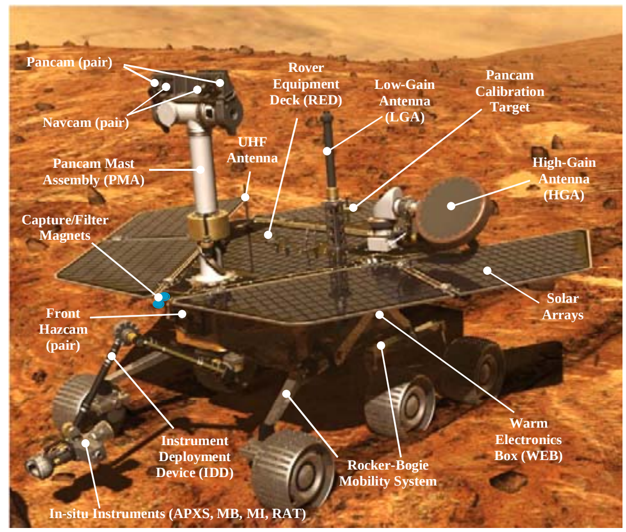

Fig. 3. Fully deployed rover.

Fig. 4 shows a diagram of the WEB, displaying some of the equipment inside. The rover electronics module (REM), with the flight computer in the form of electronics slices, is mounted in the middle of the WEB. The Mini-TES (thermal emission spectrometer) instrument is mounted at the front of the WEB.

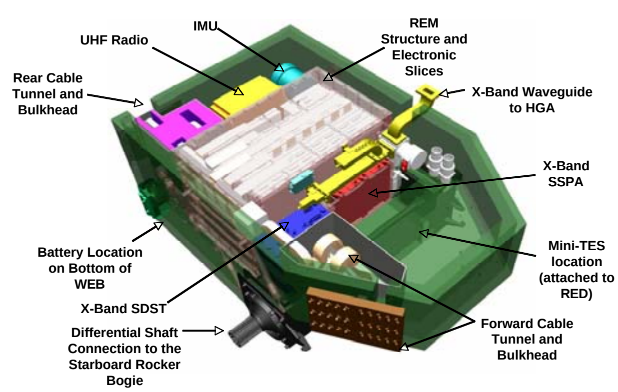

Fig. 4. Picture of the warm electronic box.

A. Landing Sites

Fig. 5 is a map of Mars showing the two rover landing sites. The one on the left is Meridiani (–2.06° latitude south and 354.01° longitude), used for Opportunity, and the one on the right is Gusev Crater (–14.64° latitude and 175.30° longitude), used for Spirit. Note that both landing sites are close to the equator. One of the reasons for landing near the equator is to minimize the coldest temperatures at night. In fact, the landing sites are on the opposite sides of Mars to investigate a diversity of geological features. The primary interest at Meridiani is to search for water-formed hematite and, at Gusev Crater, to study ancient lake sediments.

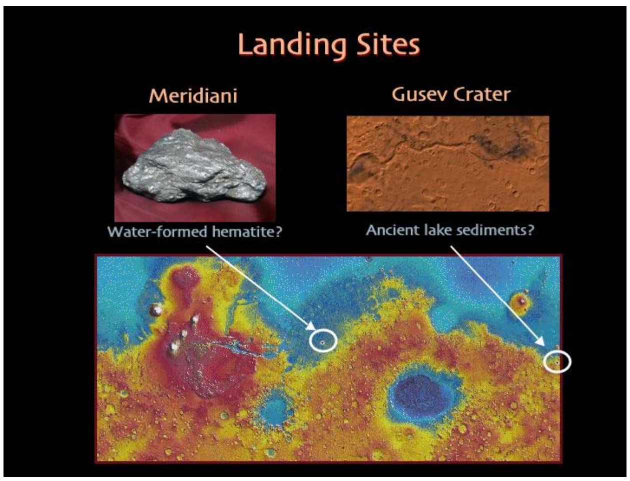

Fig. 5. Landing sites of the two rovers.

B. Environmental Assurance Program

The objective of the environmental assurance program was to assure that MER flight hardware was designed to survive and function during the extreme environments encountered during ground operations, launch, cruise, Mars EDL, and Mars surface operations [3]. It involved defining environmental requirements, supporting environmental tests and analyses, and verifying environmental compliance. The environmental testing and analysis program was applied at both the assembly/subsystem and system levels as well as to qualification of the packages.

Environmental testing was the preferred method of environmental design verification. Analyses were performed for mission environments that are impractical to verify by test or where analyses were more cost effective than testing, such as for meteoroid compatibility, venting, and radiation dosage compatibility.

Flight hardware environmental testing verification was accomplished using three approaches: (1) qualification (Qual) test of an engineering model (EM) followed by flight acceptance (FA) testing of the flight models (FM), used primarily on the payload instruments; (2) protoflight (PF) testing of all flight units, used primarily on payload instrument and selected inherited flight system hardware; and (3) a combination of PF and FA testing, used primarily on flight system hardware consisting of multiple units.

Qualification testing is normally performed on a dedicated qualification model or flight-like EM of the flight hardware, which is not intended to fly, in order to demonstrate the hardware functions within design specifications for the maximum expected flight environments plus margins.

Protoflight (PF) testing is performed on flight hardware, which is intended to be flown, and for which there is no or inadequate previous qualification heritage. Protoflight testing accomplishes the combined purposes of design qualification and flight acceptance.

Flight acceptance (FA) testing is typically performed on flight hardware and spares to verify flight workmanship quality when a previous design qualification test has been performed on an identical item.

C. Hardware Verification

To ensure that the flight hardware would survive the mission environments throughout their mission lives, all the hardware underwent a series of environmental tests or analyses. All MER hardware was required to demonstrate compatibility and survivability in the dynamics, thermal, EMC, and natural space mission environments. Table 1 shows a summary of the environmental verification requirements for the assembly/subsystem and spacecraft system. The environmental tests and analyses that were performed on the assemblies/subsystems are shown on the left, and those that were performed on the spacecraft system are shown on the right. In addition to the thermal tests, which will be discussed in more detail later, they include a set of dynamics and EMC tests, as well as a set of environmental analyses for the assemblies and for the spacecraft systems. This paper will focus only on thermal testing [4].

Table 1
Summary of MER environmental verification requirements.

Assembly/subsystem	Spacecraft system
Dynamics tests	
• Random vibration (including frequency survey) • Quasi-static loads (entry, landing) • Pyroshock • Acoustic noise (selected – large area/mass) • Sine sweep (grinding/drilling)	• Low-level random survey • Random vibration • Quasi-static loads (launch/entry) • Acoustic noise • Pyro firing
Thermal tests	
• Thermal vacuum (all hardware) • Thermal Mars atmosphere (landed hardware) • Thermal cycling life qual (selected hardware)	• Thermal vacuum (with thermal balance-critical hardware at FA limits during functional testing)
EMC tests	
• Conducted susceptibility/emission • Radiated susceptibility/emission • Grounding and isolation • Multipacting/ionization breakdown (corona)	• Radiated emission • Radiated susceptibility • Self-compatibility • Magnetic cleanliness
Environmental Analyses	
• Radiation (TID, DD, SEE) • Venting (pressurization and depressurization) • Meteoroid (done at system level)	• Orbital debris • Meteoroid (probability of survival and shielding) • ESD (touch down)

III. Thermal Test Program

The MER thermal test program consisted of three levels of testing:

1. Assembly level (also commonly known as the unit level);
2. System level (at the integrated spacecraft level); and
3. Packaging level, applicable to thermal cycling life qualification of electronic boards and cards.

Thermal testing was required to be performed in vacuum for all types of hardware, including cruise, Mars entry, and landed hardware. In addition, hardware that needed to operate on the surface of Mars and that was exposed to the Martian atmosphere was also tested in a simulated Mars atmosphere of 5–10 Torr of gaseous nitrogen or, in a few cases, in CO_2. At the spacecraft-system level, there was also a thermal balance test to verify the thermal model. During thermal testing, all hardware was powered-on to undergo the full set of performance tests to exercise all the functional modes.

In addition, for landed hardware that was not planned to be temperature controlled on the surface of Mars, thermal cycling life qualification testing was also performed to verify survival of the hardware over the Mars diurnal temperature cycle [5].

A. Test Temperature Definitions

To define the allowable flight temperatures (AFT) and the thermal test parameters, the Mars Global Circulation Model was used to predict the ground, atmosphere, and sky temperatures. Allowable flight temperatures (AFTs) typically include both operational and non-operational limits. Operational AFTs are the mission temperature limits (including allowance for prediction uncertainties) in a worst-case powered-on, operational (operating within functional specifications) mode that the thermal control system is designed to maintain for specified assemblies and subsystems (hot or cold). Non-operational AFTs are the corresponding mission temperature limits in a worst-case unpowered, non-operational mode that the thermal control system is designed to maintain. These temperatures are measured at the thermal control surfaces (e.g., mounting surfaces, radiator surfaces), as specified in the thermal design. The MER hardware was designed to within the design temperature limits, which are the temperature limits at the thermal control surface at which assemblies are designed to meet functional and performance specifications, normally equivalent to the qualification/protoflight limits.

Ground temperature is the temperature on the Mars surface; atmosphere temperature is the temperature at 1 m above ground; and sky temperature is the temperature seen when looking up into the sky.

Table 2 shows the four model cases that were run, covering a wide range of environmental conditions as defined by the different parameters.

Table 2 Parameters for the four thermal model cases.							
	Daily temperatures	**Optical depth (tau)**	**Surface albedo**	**Thermal inertia ($J\ m^{-2}\ K^{-1}\ s^{-1/2}$)**	**Pressure (mbar)**	**Latitude (degrees north)**	**L_s (degrees)**
Case 1	**Highest max.**	**0.2**	**0.125**	**220**	**6.5**	**–2.5**	**328**
Case 2	**Lowest min.**	**0.2**	**0.18**	**230**	**7.8**	**–9.0**	**29.5**
Case 3a	**Lowest max. (dusty; tau = 2)**	**2**	**0.136**	**710**	**6.5**	**–13.1**	**16**
Case 3b	**Lowest max. (dusty; tau = 1)**	**1**	**0.136**	**710**	**6.5**	**–13.1**	**16**

Case 1 is the highest maximum daily temperature case, which is the highest temperature during the day. Case 2 is the lowest minimum daily temperature case, which is the lowest temperature during the night. Cases 3a and 3b are for the lowest maximum daily temperature cases, corresponding to two dust levels. The parameters were selected to provide the specified environmental conditions and are defined below.

1) Surface albedo is the reflectivity of the Martian surface. It is a measure of the shininess or reflectivity of the soil.
2) Thermal inertia is a measure of the thermal properties of the soil and the capacity of the soil to adsorb heat. It can indicate the material density or rockiness of the soil.
3) Pressure is the pressure at the location.
4) Latitude is a measure of how far north or south a location is from the Martian equator, a measure that affects the temperature.
5) Solar longitude, Ls, is basically the Mars season, which also affects the temperature.
6) Optical depth, tau, is the atmospheric opacity. It is a measure of how clear or dusty the Mars atmosphere is. The value of tau can sometimes be critical to the mission since it affects the maintenance of the temperature control as well as the power generation capability. A value of tau = 0.2 represents a clear day and a value of tau = 1 or tau = 2 represents a typical dusty day.

1) Effects of Dust Storms:
During a severe dusty storm, tau can be many times larger, as occurred on Sol 1236 at the Meridiani site for Opportunity, when tau reached greater than 5. A prolonged dust storm created dust levels in the Martian atmosphere that blocked 99% of direct sunlight to the rover, leaving only a limited diffuse sky light to power it. Fig. 6 shows a contrast of the views between a normal day and dusty days of different tau values. The high dust level affected the generation of power needed to keep the electric heaters operating to increase the temperature of the rover vital core electronics above the minimum survival cold temperature to enable the rover equipment to be operational, even in a near-dormant state. Consequently all the rover driving and science investigations were suspended, including use of the robotic arm, cameras, and spectrometers. Before the dust storms began blocking sunlight a month earlier, Opportunity's solar panels had been producing about 700 watt-hours of electrical energy per day. When dust increased in the air, it reduced the panels' daily output to 128 watt-hours from Opportunity's solar panels, the lowest point ever recorded and barely sufficient to prevent the essential electronics from becoming too cold. Opportunity was even programmed to refrain from communicating with Earth for a few days to conserve energy.

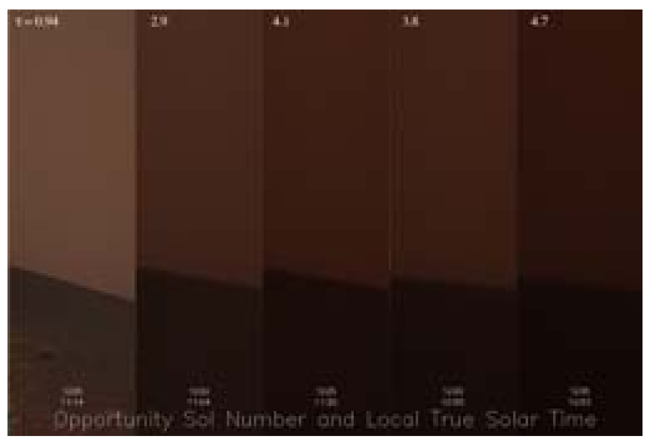

Fig. 6. Plot of different taus (dust levels).

2) Case 1 Results:
The results from the model for Case 1, the highest maximum daily temperature, are shown in Fig. 7. The vertical axis shows the predicted temperatures and the horizontal axis is the time of day. The blue (top) curve shows that the maximum predicted ground temperature could be as high as 22°C at 1 PM and as low as –91°C at 6 AM. The red curve shows the predicted atmospheric temperatures, which are generally less extreme than the ground temperature. The green curve shows the sky temperature, which could be as low as –137°C at dawn. The shape of the curves for Case 2, the lowest minimum daily temperature, look similar to the curves for Case 1, except that the temperatures are somewhat lower at all

times of day and the predicted lowest temperature is approximately –100°C.

3) Allowable Flight Temperatures:
Using the minimum and maximum predicted temperatures from the model shown in Fig. 7 and from the thermal model, the thermal control team was able to define the allowable flight temperatures (AFTs) for each piece of hardware. The AFTs for the flight system electronics, which were located inside the warm electronics box (WEB), were specified to be –40°C to +50°C. The Mini-TES instrument and lithium-ion batteries, which were also inside the WEB, had narrower temperature ranges of –40°C to +45°C and –20°C to +30°C, respectively. However, for the hardware that was mounted outside of the WEB, the AFTs were –105°C to +50°C. This hardware included the nine (9) cameras, 34 actuators, and a list of other hardware, such as the deployable solar arrays, telecommunications antennas (high gain, low gain, UHF), robotic arm, pancam mast assembly, and the mobility system.

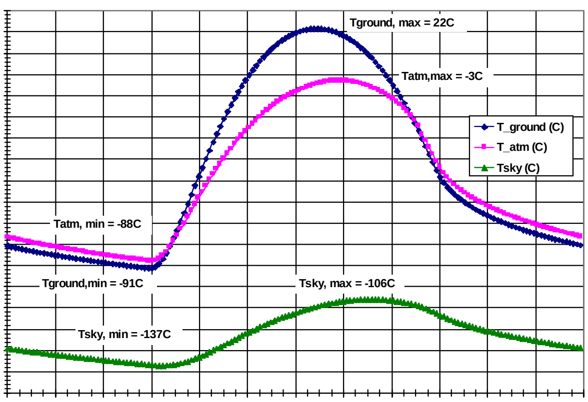

Fig. 7. Plot of Case 1, highest maximum daily temperature.

B. Thermal Test Requirements
From the allowable flight temperatures, the thermal test requirements were then defined. Table 3 shows a summary of the thermal test requirements for the assemblies. It specifies the thermal test levels, test durations, number of cycles, and test media for both electronics and nonelectronics equipment, and for both qualification (Qual) or protoflight (PF) testing and for flight acceptance (FA) testing. In general, the FA test levels and durations were lower than those for Qual and PF testing. In addition to these parameters, the ramp rate was restricted to 5°C per minute. There were three on/off cycles and three non-op cold startups exercised during the thermal tests. Functional verification was also performed during the extreme hot and cold temperatures.

Table 3
Thermal test requirements for assemblies.*,†

	Qualification (Qual) or protoflight (PF) test		Flight acceptance (FA) test	
Assembly type	**Temp. levels (margins, °C)‡**	**Test duration operational (h)**	**Temp. levels (margins, °C)‡**	**Test duration operational (h)**
Electronics				
Cold	–15	24	–5	24
Hot	+20 or +70 (whichever is higher)	144	+5 or +55 (whichever is higher)	50
Nonelectronics				
Cold	–15	24	–5	24
Hot	+20	50	+5	50

*Test media for all conditions were the same: vacuum (plus 5–10 Torr CO_2 or GN_2 gas for landed h/w).
†All test conditions employed 3–10 thermal cycles.
‡Relative to AFTs (allowable flight temperatures).

IV. System Thermal Testing

In addition to thermal testing at the assembly level, thermal testing was also performed at the system level (for the cruise configuration), as shown in Fig. 8, and for the rovers, as shown in Fig. 9. Thermal balance testing was also performed to verify the thermal model.

Fig 8. System thermal testing; cruise configuration.

A. Thermal Cycling Life Qualification Testing
In addition, for landed hardware that was mounted outside the WEB and was not temperature controlled on the surface of Mars, thermal cycling life qualification testing was also performed to verify survival of the hardware for Mars diurnal temperature cycling. These tests were performed using flight-like packaging samples (or coupons) or non-flight engineering units. Life qualification testing was not performed using the actual flight models to avoid reducing their lives via fatigue mechanisms. This hardware was required to demonstrate three times the primary mission diurnal cycles. The MER

primary mission design lifetime was 90 days. Thus, packaging coupons were required to be tested for 270 cycles. A total of 39 life qualification tests were performed on various electronic packaging and device types.

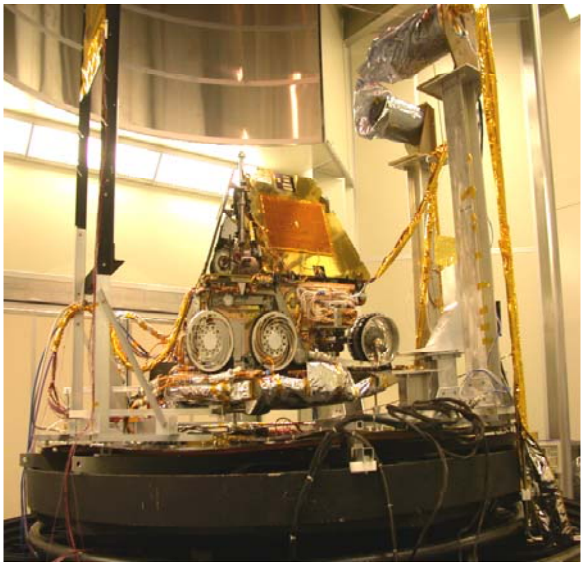

Fig. 9. System thermal testing; rover.

Fig. 10 shows an example of a thermal cycling life testing profile. This plot shows the test profile that was specifically applicable to the motors. The qualification temperatures for these motors were –120 to +85°C. The dwell time at the hot temperature was 45 minutes, and that at the cold temperature was 10 minutes. The ramp rate was restricted to a maximum of 5°C per minute. The profile continued for 270 cycles to satisfy three times the primary mission life cycles.

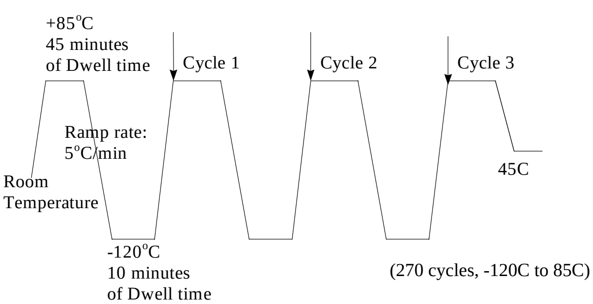

Fig. 10. Typical thermal cycling life testing profile.

B. In-Flight Temperature Measurements

In-flight temperature measurements were made throughout the mission and particularly on the surface of Mars [6], [7]. Some examples of actual in-flight temperature measurements during the surface mission are shown in Figs. 11, 12, and 13.

Fig. 11 shows the temperature measurements for the rover electronics module. As noted earlier, the REM was mounted inside the warm electronics box and the AFTs were –40 to +50°C. The measured temperature is plotted as a function of sol. The upper blue curve shows the maximum hot temperatures, whereas the lower red curve shows the minimum cold temperatures. As shown in the plot, the measured temperatures for the REM were essentially kept within the AFTs except for a slight exceedence at the beginning of the mission by less than two degrees. At the cold end, the measured temperature was always kept within the AFT range.

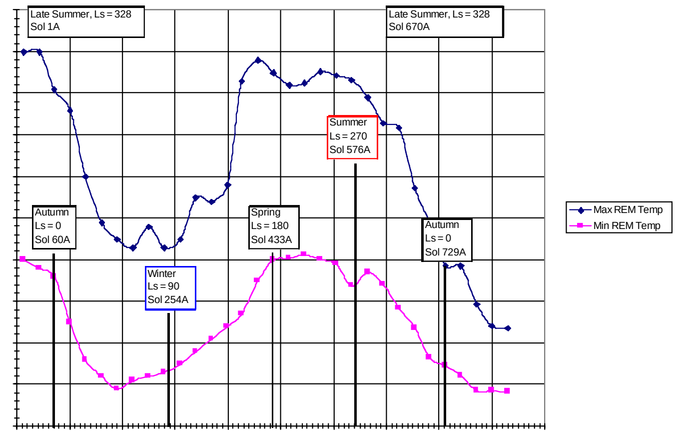

Fig. 11. In-flight temperature measurements for the REM.

Fig. 12 shows the temperature measurements for the Mini-TES instrument. This instrument was also mounted inside the WEB, and AFTs were –40 to +45°C. As shown in the plot, the measured temperatures were all within the AFTs.

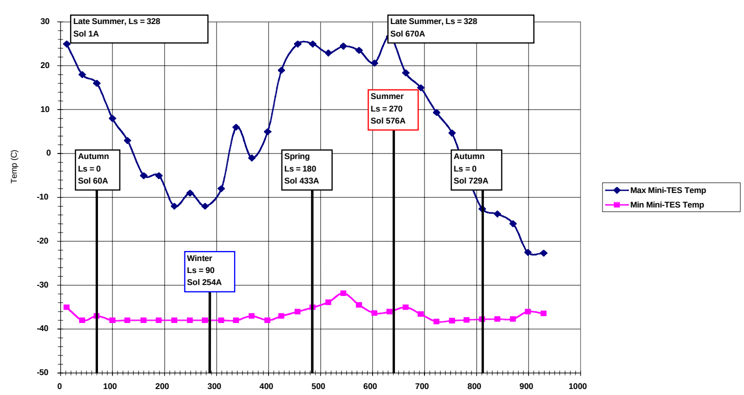

Fig. 12. In-flight temperature measurements for the Mini-TES instrument.

Fig. 13 shows the temperature measurements for the panoramic camera electronics, which were mounted outside the WEB, without temperature control; the AFTs were –105 to +50°C. As shown in the plot, the temperatures were much higher than the AFTs at the beginning of the mission, reaching nearly +65°C, but they were still within the qualification temperature limit of +70°C. The cold temperatures were all within the AFTs.

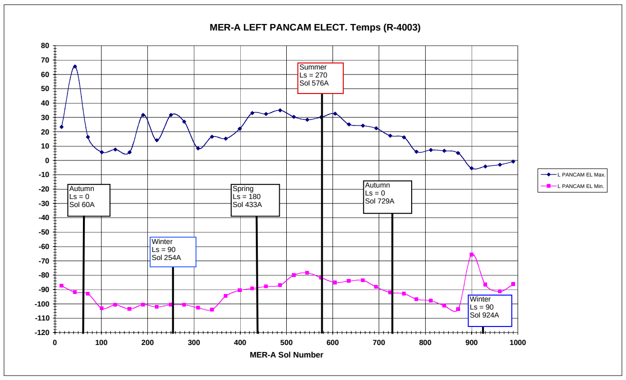

Fig. 13. In-flight temperature measurements for the panoramic camera electronics.

C. Comparison of in-Flight Measurements with As-Tested Temperatures

Comparisons of the measured temperatures with the ground test data are made for some of the hardware. For Figs. 14, 15, and 16, the white boxes are the AFT limits, the boxes with blue hash marks depict the flight acceptance (FA) test temperature limits, and the green boxes are the qualification or protoflight (Qual/PF) test temperature limits. The boxes with red hash marks depict measurements during the primary mission; the solid red boxes depict the temperature measurements during the extended mission, beyond the first 90 days; and the thin lines depict the actual temperatures measured at the rover system during thermal testing.

As shown in Fig. 14, the measured temperatures for the mobility drive actuators and the hazard camera head were both within the AFT limits during the primary and extended missions. The measured temperature range during rover system thermal testing was also within the AFT limits. All temperature measurements were within design limits.

Fig. 15 shows comparisons of the measured temperatures with the ground test data for the rock abrasion tool (RAT) assembly, microscopic imager (MI) electronics, and panoramic camera head. For the RAT and the MI, the measured temperatures were all within the AFTs throughout the mission. However, for the panoramic camera head, the measured temperatures were colder than the AFTs during the extended mission by a few degrees, but they were still within the FA levels. The measured temperature ranges during the rover system thermal testing for these three pieces of hardware were also within the AFT limits.

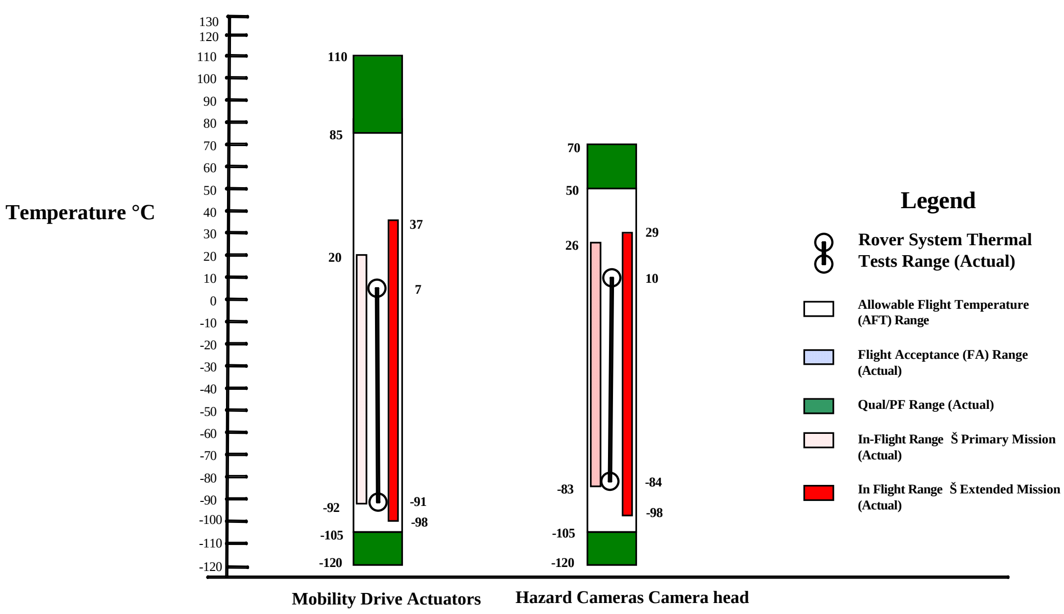

Fig. 14. Comparisons of the measured temperatures with the ground test data for the mobility drive actuators and the camera head.

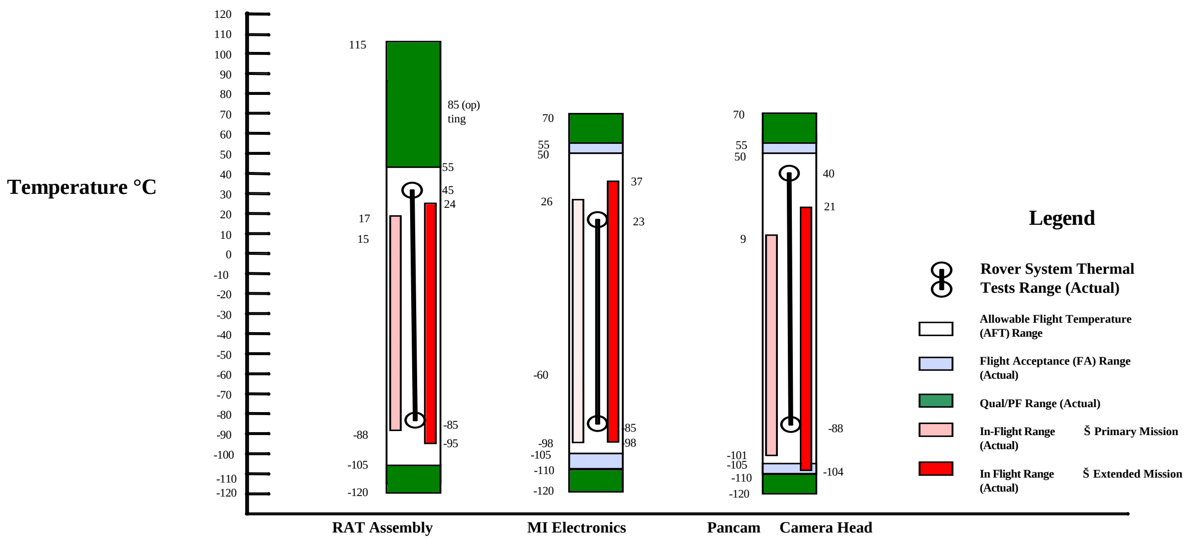

Fig. 15. Comparisons of the measured temperatures with the ground test data for RAT assembly, MI.

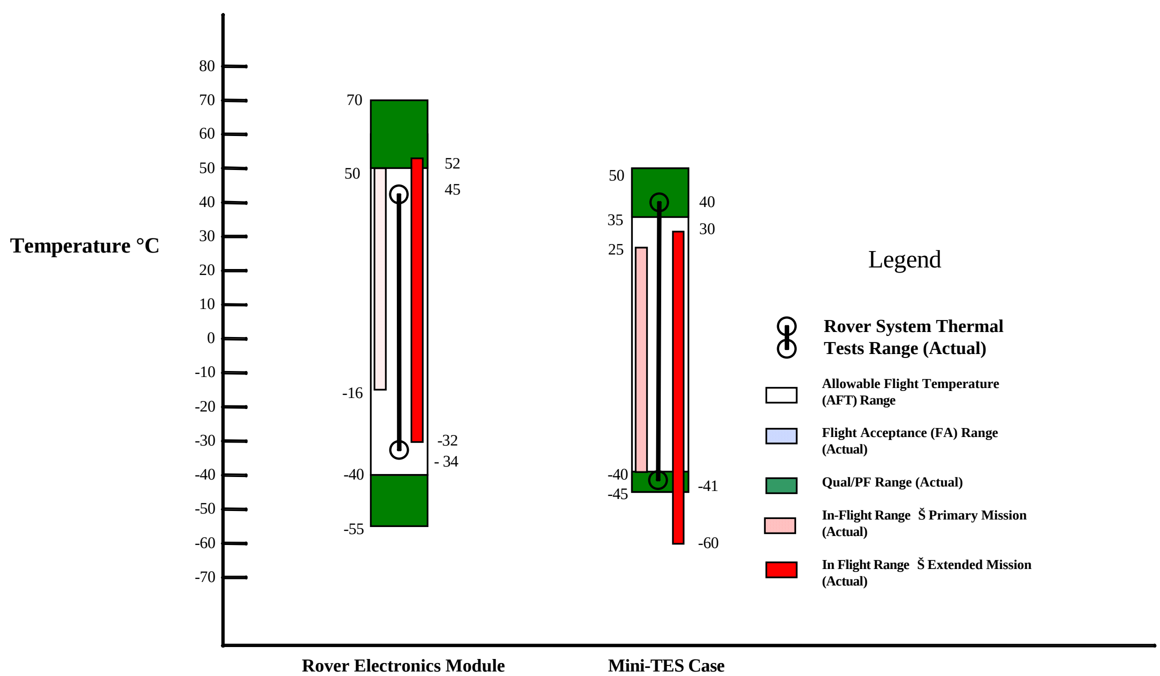

Fig. 16. Comparisons of the measured temperatures with the ground test data for the rover electronics module and the Mini-TES chassis.

Fig. 16 shows comparisons of the measured temperatures with the ground test data for the rover electronic modules and Mini-TES. The measured temperatures for the REM and the Mini-TES chassis were both within the AFTs during the primary mission. Although the measured temperatures for the REM were warmer than the AFTs during the extended mission, they were still within the qualification temperatures.

In the case of the Mini-TES, the measured temperature went well beyond even the qualification cold temperature limit during the extended mission, and this temperature exceedence occurred when the heaters were unpowered at certain times to conserve energy. Even during the rover system thermal testing, the measured temperature range of the Mini-TES was outside the AFT limits.

V. Conclusions

Both Spirit and Opportunity have been very successful and have performed for more than 12 times their design lives. The rigorous thermal test program and demonstrated margins have contributed to their long life and productivity in performing their robotic science missions during the primary and extended missions. Both vehicles have exceeded their thermal and operational expectations. Currently, both rovers are continuing to explore the surface of Mars and returning very valuable science data.

Acknowledgment

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References

[1] S.W. Squyres et al., "The Spirit Rover's Athena Science Investigation at Gusev Crater, Mars," *Science*, 2004; 305 (August 6).

[2] S.W. Squyres et al., "The Opportunity Rover's Athena Science Investigation at Meridiani Planum, Mars," *Science*, 2004; 306 (December 3).

[3] K.F. Man, C. Farguson, A.H. Hoffman, "Mars Exploration Rover (MER) Project Environmental Assurance Program," Proceedings of the 5th International Symposium on Environmental Testing for Space Programs, Noordwijk, The Netherlands, SP 558, pp. 59–66, August 2004.

[4] M. Pauken, G. Kinsella, K. Novak, G. Tsuyuki, "Mars Exploration Rover Thermal Test Program Overview," Proceedings of the International Conference on Environmental Systems, Paper 04ICES-036, Colorado Springs, CO, July 2004.

[5] K.F. Man, A.R. Hoffman, "Testing of the Mars Exploration Rovers to Survive the Extreme Thermal Environments," IMAP 2nd Advanced Technology Workshop on Reliability of Advanced Electronic Packages and Devices in Extreme Cold Environments, Embassy Suites Hotel, Arcadia, CA, February 27–March 1, 2007.

[6] K. Novak, C. Phillips, E. Sunada, G. Kinsella, "Mars Exploration Rover Surface Flight Thermal Performance," Paper 2005-01-2827, SAE, Transactions Journal of Aerospace, 2005.

[7] A.R. Hoffman, C.T. Farguson, K.F. Man, C.D. Porter, K.S. Novak, "Comparison of Surface Operation Temperatures to Prelaunch Testing Results for Mars Exploration Rovers," 24th Space Simulation Conference, Annapolis, Maryland, 7–9 November 2006.