Mars Exploration Rover (MER) Project Environmental Assurance Program

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ABSTRACT

A comprehensive prelaunch environmental assurance program was planned and implemented on NASA's Mars Exploration Rover (MER) project. This project consisted of two rovers/spacecraft launched on two separate launch vehicles. The environmental assurance program included assembly/subsystem and system-level testing in the areas of dynamics, thermal, and electromagnetic (EMC), as well as venting/pressure, dust, radiation, and micrometeoroid analyses. Due to the Martian diurnal cycles, the susceptible hardware also underwent thermal cycling qualification of their packaging designs and manufacturing processes.

This paper presents a comprehensive summary of the environmental assurance program for the MER project. A series of test and analysis metrics are generated. Selections of the numerous lessons that have been learned from implementation of the MER environmental assurance program are documented in this paper. They include both technical and programmatic lessons that would be helpful in improving implementation of the environmental program for future projects.

1. INTRODUCTION

The MER twin rovers (named "Spirit' and "Opportunity" after landing) were sent onto 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. The first flight system, known as MER-A, 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, was launched on July 7, 2003 using a Delta II 7925H launch vehicle. They both landed safely on the surface of Mars (Gusev Crater for MER-A and Meridiani for MER-B) as scheduled on January 4, 2004 and January 25, 2004 respectively.

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 heat shield/backshell combination), and a mobile science rover with an integrated instrument package inside the lander, is shown in Fig.1. This exploded view also shows some of the hardware that has undergone environmental tests (or analyses) to ensure system reliability to accomplish the mission. A more detailed description of the spacecraft configuration is given in [1].

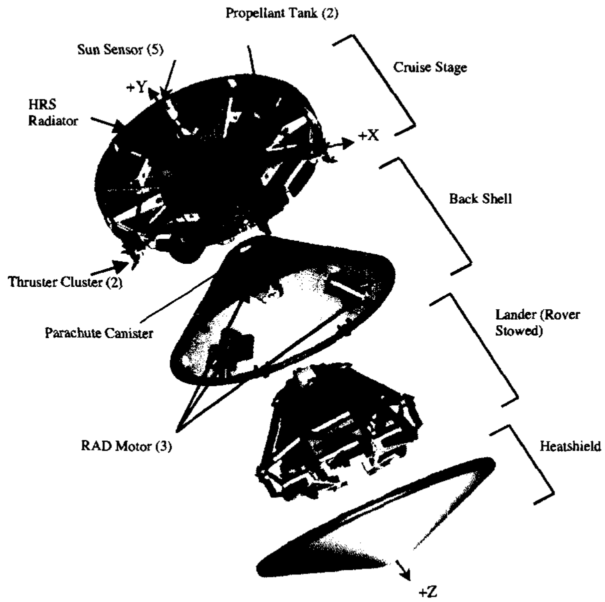

Fig. 1. MER Flight System

2. ENVIRONMENTAL ASSURANCE PROGRAM

The objective of the environmental assurance program was to assure that MER hardware was designed to survive and function during the extreme environments encountered during ground operations, launch, cruise, Mars entry, descent and landing, and Mars surface operations. It involved defining environmental requirements, supporting environmental testing and analyses, and verifying environmental compliance. From the beginning, the Project adopted a rigorous environmental testing and analysis program at both the assembly/subsystem and system levels. Environmental testing was the preferred method for environmental design verification. Analyses were performed for those mission environments that might be impractical to verify by test or that were more cost effective than testing, such as micrometeoroid compatibility, venting, and radiation dosage compatibility.

Flight hardware environmental testing verification was accomplished using one of two approaches: 1) qualification (Qual) test of an engineering model (EM) followed by flight acceptance (FA) test of the flight models (FM); or 2) protoflight (PF) testing of all the flight 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 design functions within specification 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.

3. ASSEMBLY ENVIRONMENTAL PROGRAM

The MER assembly environmental program requirements were similar to other major interplanetary missions. However, there were some additional, unique requirements derived from the Mars landing and surface events that posed the greatest design and test challenges. Examples include:

1. UHF compatibility issues due to the rover UHF antenna being in close proximity to other Rover equipment.
2. Numerous deep thermal cycles due to Mars diurnal and power cycling inside the Rover.
3. Mars landing load.
4. High pyroshock environment due to numerous pyro-mechanisms on the Lander and Rover.
5. Extreme cold temperatures, especially for externally mounted rover equipment, to -95°C.
6. RF/Ionization Breakdown concerns for telecom equipment due to Mars surface and EDL pressure environments.
7. Mars dust environment.

3.1 Assembly Environmental Analyses

The three main types of environmental compatibility analyses required at the assembly-level were pressure decay, Mars dust, and radiation. (Micrometeoroid survivability and shielding analyses were performed as system analyses.)

The verification to survive launch depressurization and Mars atmospheric entry repressurization was a simple venting analysis to ensure the vent holes were large enough to avoid trapped volumes.

Due to the difficulty in performing an analysis for dust, the dust analysis, in reality, was an assessment function to check that design mitigations were in place to prevent dust contamination. To gain confidence in those design mitigations a rover Dynamic Test Model (DTM) performed many maneuvers in a dusty environment in a Mars surface simulation laboratory. One particular assembly, the Rover Lift Actuator, had to be augmented late in the program with a dust seal (in the form of a wire brush) to prevent dust from jamming the lead screw mechanism.

Radiation analyses for total ionization dose (TID), displacement damage (DD), and single event effects (SEE) were performed. Although the radiation environment for MER was fairly benign, a number of SEE events were observed during flight, as expected.

No formal Electrostatic Discharge analyses were required for MER because the mission did not involve trapped radiation belts. However, a tribo-electric charging evaluation was performed for the EDL event to verify that static charge would not build up on the bridle cable during descent.

Table 1. Typical Suite of Assembly Environmental Tests

	Qual or 1st PF unit:		FA or PF (subsequent units):	
	Landed Assembly	Cruise Assembly	Landed Assembly	Cruise Assembly
Random Vibration	✓	✓	✓	✓
Landing Load	✓		[✓][1]	
Pyroshock	✓[3]	✓[3]		
Acoustics			✓[4]	✓[4]
Thermal vacuum		✓		✓
Thermal vacuum + Mars atmosphere (5 to 10 Torr GN_2)	✓		✓	
Multipaction/ Ion. Breakdown	✓[2]	✓[2]		
EMC	✓[3]	✓[3]		

1) Landing Load was required on flight units on a case-by-case basis.
2) Required on RF assemblies only.
3) Required of selected assemblies with sensitivity to these environments.
4) Required on solar arrays only.

3.2 Assembly Environmental Testing

The engineering models or dedicated Qual models were usually subjected to the entire suite of qualification tests and the flight units to thermal and random vibration. The exact tests performed depended on whether the hardware was on the lander or on the cruise stage. Table 1 shows a typical suite of assembly Qual/PF and FA tests.

Due to the Mars deep diurnal cycling of rover hardware, thermal cycling exposure was required for selected assemblies and they were usually verified separately at the electronic packaging level, although some testing was performed at the assembly level using engineering models.

Ideally, the qualification tests to prove out the design should occur before the flight FA tests. However, because of the project's tight development schedule and the need to deliver the flight units for system integration, sometimes the environmental testing sequence was performed out of order.

3.2.1 Assembly Dynamics Testing

A brief description of dynamics testing is given in this section. A more detailed description of dynamics testing and test facilities are given in [1,2].

The dynamics tests included random vibration, landing load, pyrotechnic shock, and acoustic noise. Several instruments that were mounted on the tip of the instrument deployment arm also underwent the Sine sweep test to simulate the vibration induced by the drilling motions of the Rock Abrasion Tool.

3.2.1.1 Assembly Random Vibration Testing

Random vibration was performed on every piece of hardware, except the solar arrays that underwent acoustics testing instead. Force limiting was allowed for random vibration and it was taken advantage of on selected assemblies. Powered-on vibration was required for all assemblies that were powered on during either the launch or Mars descent phases.

3.2.1.2 Assembly Landing Load Testing

The landing load test was devised to make sure all assemblies located on the landed system would be able to withstand the landing event. Since the fundamental frequency of the airbag-cushioned landing is less than 10 Hz, the landing load test could be conducted using either 1) a centrifuge, 2) a shaker with a relatively low frequency input, or 3) a drop test. In most cases the landing load test was conducted on a shaker using the Sine pulse method. This was a fairly easy test to perform since the hardware was already on the shaker table for random vibration testing.

Landing load design and workmanship testing was originally required of all landed assemblies. As the program progressed, it was determined in most cases that landing load qualification testing of only one unit was sufficient. Upon review of the landing load qualification data, dynamics environments engineers usually determined that FA tests of subsequent flight units were unnecessary as long as there were no unusually high responses, and random vibration testing was deemed sufficient for workmanship screening.

3.2.1.3 Assembly Pyroshock Testing

Pyroshock testing was required for assemblies exposed to pyrotechnic shock loading, whether the loading was self-generated or induced by external sources. In almost all cases assembly-level pyrotechnic shock testing was performed on an Engineering Model (EM) or a Flight Spare (FS).

The MER pyroshock test requirements ranged from 500g (Shock Response Spectrum, SRS) up to 8000g. Assembly-level shock tests were performed at levels up to 4000g. No sensitive hardware was located in the highest shock zones, which were verified from testing using a Dynamic Test Model and at the system level.

Assembly pyroshock testing was waived for a few pieces of hardware that did not have an EM or Flight Spare, due to concerns that the levels were unrealistically high and fear of damage to the flight hardware.

There were two very significant shock-related issues on MER, one related to the broken brushes in the numerous brushed motors used and, the other, to relay transfers in the different types of relays. An extraordinary amount of effort was expended to resolve these problems.

3.2.1.4 Assembly Acoustics Testing

Acoustic noise testing was only required for assemblies with large area to mass ratio, such as antennas and solar panels, or assemblies with thin diaphragms. For MER, only the cruise and rover solar array flight panels underwent PF acoustics testing.

3.2.2 Assembly Thermal Testing

A brief description of thermal testing is given in this section. A more detailed description of thermal testing and test facilities are given in [1,2].

The MER assembly-level thermal test requirements varied depending on the types of assembly: electronics versus non-electronics (mechanism). The main differences were that there was no minimum hot temperature for non-electronics and the hot test dwell time for non-electronics was less. The PF and FA test temperature limits for each assembly were specified in detail in the MER Temperature Table, which also contained all the allowable flight temperatures. Waivers were generated for all assemblies (nine total) that did not meet the required test margins. All the landed assemblies also required thermal testing in a low-pressure environment of CO_2 or GN_2 (6-10 Torr) to simulate the Mars surface pressure.

Tailoring of the thermal test requirements was frequently made for individual assemblies in order to optimize testing. The following describes some deviations from the standard requirements:

1. Temperature atmosphere dynamometer testing was frequently substituted for thermal vacuum testing of actuators (to improve performance characterization).
2. The verification focus for mechanical assemblies was on the fidelity of functional testing during environmental exposure rather than subjecting the mechanism to the standard 24/50 hours cold/hot durations typically applied to electronic hardware.
3. Non-operational PF test limits were augmented to encompass the planetary protection (PP) bake-out requirement (110°C or 125°C) for assemblies that were required to undergo PP bake-out prior to system integration. This was important to make sure the assemblies would survive and be able to perform after bake-out.
4. RF assemblies were required to operate during GN_2 back-fill in order to demonstrate resistance to Corona breakdown, otherwise this requirement was not strictly imposed on other assemblies. For critical RF hardware, CO_2 testing was performed in a small bell jar at ambient temperature. Only the descent and rover antennas were subjected to Corona breakdown testing in CO_2 while at extreme temperatures.
5. Some tailoring was also allowed for the hot dwell qualification duration requirement (144 hours) for electronics. As the program got underway and the schedule became critical, some compromises were made in order to optimize functional testing and achieve a balance of hot and cold exposure.
6. Temperature atmosphere testing in lieu of thermal vacuum testing was authorized for a few assemblies because of the tight schedule.

3.2.3 Assembly EMC Testing

EMC tests on the assemblies/subsystems were selected based on an assembly's sensitivity to electrical noise or its potential for being a noise generator. Due in part to their small sizes, most of the selected hardware was individually tested in a small shield room. A detailed test procedure, consistent with the assembly's needs and functions, was written for each test. The tests consisted of five basic components:

1. Grounding/Bonding/Isolation
2. Radiated Emissions (RE)
   - General radiated emissions 14 kHz to 10 GHz
   - Specific receiver band emissions at UHF, S-Band, C-Band, and X-Band
3. Radiated Susceptibility (RS)
   - General radiated susceptibility 14 kHz to 10 GHz
   - Specific transmitter frequencies simulating Cape (KSC) radars, launch vehicle transmitters as well as spacecraft transmitters
4. Conducted Emissions (CE)
   - Power line emissions from 30 Hz to 50 MHz
   - Power line inrush current limits
5. Conducted Susceptibility (CS)
   - Power line ripple noise injection 30 Hz to 50 MHz
   - Power line common mode transients
   - Power line differential mode transients
   - Voltage surge test

Table 2. A Summary of Assembly EMC Tests

	EMC Tests performed												
MER Assmblies	**Conducted Emissions CE01/ CE03 Power Line Freq Domain**	**Conducted Emissions Power Line Inrush Current Time Domain**	**Radiated Emissions RE02**	**Radiated emission, S/C, Launch Vehicle Receivers**	**Radiated Susceptibility RS03**	**Radiated susceptibility, S/C, Launch, Cape Transmitters**	**Conducted Susceptibility CS01/CS02 Power Line Ripple**	**Conducted Susceptibility, Surge Voltage**	**Conducted Susceptibility CS06, Common Mode Transients**	**Conducted Susceptibility CS06, Differential Mode Transients**	**Grounding/Isolation**	**Number of PFRs**	**Number of Waivers**
Telecommunication													
Radar Altimeter	-	-	P	F	F	F	-	-	-	-	P	1	1
X-band RFS	P	P	P	F	F	F	P	P	P	P	P	1	1
X-RFS FM Unit	-	-	-	F	-	P	-	-	-	-	P	1	1
UHF Transceiver	F	P	P	P	P	P	P	P	P	P	P	1	1
Power and Pyro													
Pyro Switch	F	F	P	P	P	P	P	P	P	P	F	1	1
Propulsion													
Press Transducer	Htg	Htg	Htg	Htg	Htg	Htg	Htg	Htg	Htg	Htg	Htg	-	-
Avionics													
CEM Assembly	F	F	P	P	P	P	P	P	P	P	F	2	2
Power-LEM	P	P	P	F	P	P	P	P	P	P	P	1	1
Avionics-LEM	P	F	P	F	P	P	F	P	P	P	F	3	1
Rover REM	-	-	-	-	-	-	-	-	-	-	-	-	1
Attitude Management													
Star Scanner	Htg	Htg	Htg	Htg	Htg	Htg	Htg	Htg	Htg	Htg	Htg	-	-
Sun Sensor	P	P	P	P	P	P	P	P	P	P	P	-	-
IMU	-	-	P	P	P	P	P	-	-	-	P	-	-
Engineering Cameras													
Haz Cameras	-	-	P	P	P	P	-	-	-	-	P	-	-
Descent Camera	-	-	-	-	-	P	-	-	-	-	-	-	-
Navigation Cameras	-	-	P	P	P	P	-	-	-	-	P	-	-
Mechanical - Devices													
Lander Petal Actuator	F	F	P	F	-	-	-	-	-	-	P	1	1
Rover Lift Actuator	F	P	P	P	P	P	P	P	P	P	P	1	1
Maxon Motors	-	-	P	P	P	P	-	-	-	-	-	-	-
Thermal Control													
Integ. Pump Ass'y	Htg	Htg	P	F	P	F	Htg	Htg	Htg	Htg	P	?	1
Science Payloads													
APXS	P	F	P	P	F	F	P	P	P	P	P	?	FR
Mini-TES	Htg	Htg	Htg	P	Htg	P	Htg	Htg	Htg	Htg	P	-	-
PanCam/MicroImager	-	-	P	P	P	P	-	-	-	-	P	-	-
Mossbauer Spect.	Htg	Htg	Htg	P	Htg	F	Htg	Htg	P	P	P	?	FR

Legend:
- = Not Applicable/ not required
P = PASS
F = FAIL
Htg = Heritage
? = *Missing Document*
FR = Flight Rule

Where an assembly had previous heritage qualification data from prior missions, no EMC qualification testing was required. If the heritage data did not include or was not consistent with MER EMC specification limits, an abbreviated test was performed. In cases where multiple MER subsystems contained the same design, only a representative unit was fully tested. This was the case with the different types of cameras, and Microscopic Imager. In the case of the actuators, only two representative brushed motors were tested.

Table 2 shows a full summary of all assembly or subsystem-level EMC tests performed. There were 24 entries on the list with 23 tests performed (EMC testing for the Rover Electronic Module was deferred until the system level with a waiver). It shows the pass/fail status of each test and any Problem Failure Report (PFR) generated. A waiver was submitted only in cases where such a failure was a minor nonconformance and it did not affect its function. Where a failure posed a threat to other subsystems, fixes were implemented. (See Table 5 for EMC anomaly resolutions.)

Table 3. The Number of Assembly/Subsystem Tests

Subsystem	Telecom	Propulsion	Thermal	Power/ Pyro	Avionics/ ACS	Camera	Payload	Mechanical	Total #
Assemblies	28	8	10	13	14	19	11	61	164
Tests									**802**
Random Vibration	48	6	11	23	27	16	26	97	254
Landing Load	28	0	2	10	5	2	22	42	111
Pyroshock	11	0	4	11	6	1	12	30	75
Acoustics	0	0	0	3	0	0	0	0	3
Sine Sweep	0	0	0	0	0	1	4	0	5
Thermal	54	5	15	25	30	14	21	129	293
Multipacting/Ion. Breakdown	38	0	0	0	0	0	0	0	38
EMC	7	1	1	1	5	1	5	2	23
Re-tests									**47**
Dynamics	4	0	2	1	1	1	9	2	20
Thermal	3	0	2	4	5	1	4	7	26
EMC	0	0	0	0	0	0	1	0	1
Analyses									**86**
Pressure/Venting	15	1	1	10	5	4	3	16	55
Dust	0	0	0	0	0	4	2	19	25
EMC	0	0	0	0	0	0	0	2	2
Multipacting/Ion. Breakdown	4	0	0	0	0	0	0	0	4

3.2.4 Assembly Test and Analysis Metrics

Table 3 shows the number of different tests and analyses that have been performed on a total of 164 MER assemblies. These assemblies were essentially testable units predominantly at the assembly level, but a few of them, if appropriate, were also at the multi-assembly level (a functional unit consisting of several assemblies). Sometimes one analysis was performed for more than one similar assembly. The number of tests included testing for Qual, PF, and FA. Different dynamics tests were frequently performed at the same time using the same shaker table. The thermal tests included testing in vacuum, in atmospheric ambient, and in GN_2 or CO_2.

Random vibration and thermal vacuum/atmosphere tests had the most number of tests. Venting analysis was the most abundant analysis. The retests were performed as a result of a previous failed test.

The only two EMC radiated susceptibility analyses performed were for the two rockets inside the aeroshell to ensure that the rockets were not prematurely triggered on by external electromagnetic signals (a pyro firing analysis).

4. SYSTEM ENVIRONMENTAL PROGRAM

The objective of system-level environmental testing for MER-1 (MER-B, "Opportunity") and for MER-2 (MER-A, "Spirit") was to verify that the spacecraft in the cruise, entry/descent, and landed configurations would perform within acceptable limits during and after exposure to the launch, cruise, EDL, and Mars surface environments.

Table 4. System Environmental Program Summary

	Environment							
System Configuration	Acoustic Noise	Random Vibration	Landing Load	Pyroshock	Cruise Thermal Vacuum	EDL Atmosphere	Mars Surface Thermal	EMC (RE, RS)
MER-1 "Opportunity"								
Launch/Cruise S/C	T	T	-	T^5	T+A	-	-	T
Entry/Descent Vehicle	-	-	-	T^5	-	A	-	T^1
Landed System	-	-	A	T^5	-	-	A	-
Rover (on basepetal)	-	T	T^3	T^5	-	-	T+A	T^1
MER-2 "Spirit"								
Launch/Cruise S/C	-	-	-	-	-	-	-	T^4
Cruise Stage Aerosehell (CSAS), without Lander/Rover	T	-	-	T^5	T^2	-	-	-
Entry/Descent Vehicle	-	-	-	-	-	A	-	-
Landed System	-	-	A	T^5	-	-	A	-
Rover (on basepetal)	-	T	T^3	T^5	-	-	T+A	T^1

A = Analysis.
T^1 = EMC self compatibility test.
T^2 = Thermal design workmanship only.
T^3 = 12-20g only Sine burst test (limited by shaker capability).
T^4 = Abbreviated test at KSC.
T^5 = Actual firing of flight-like pyrotechnic devices.

The environmental verification program leveraged the advantage of having Development Test Model (DTM) hardware and two flight spacecraft, and was consistent with the approach applied on previous successful two-spacecraft development efforts, such as Mariner '71, Viking Orbiter, and Voyager. Where necessary, special environmental testing at the rover, lander, or assembly level were performed on DTM hardware or on lower levels of integration for flight hardware not included in the system environmental test program.

Table 4 shows the overall system-level environmental test and analysis program that was implemented.

4.1 System Dynamics Testing

The system dynamics testing was performed in three configurations [1]: (i) cruise configuration (cruise stage, lander, and rover), (ii) CSAS configuration (cruise stage and aeroshell, without the lander and rover), and (iii) surface configuration (rover on basepetal, no side petals). The purpose of these tests was to validate the dynamics design in the launch, landing, and landed configurations to verify system functional tolerance to dynamics events, and to verify workmanship of the systems. Functional checkouts were performed before and after the environmental testing. Force limiting was used during the random vibration testing. All the test objectives were met. There were a number of test anomalies that were documented as problem failure reports (PFRs) and appropriately resolved before launch.

4.2 System Thermal Testing

The system thermal testing was performed in two basic configurations[1]: Cruise and Mars surface. The purpose of these tests were (i) to validate the thermal design in the cruise and landed configurations, (ii) to verify system functional performance at temperatures at worst-case hot and cold extremes, and (iii) to verify workmanship of the systems. All the test objectives were met. There were a number of test anomalies documented as problem failure reports (PFRs) and appropriately resolved before launch.

4.3 System EMC Testing

The purposes of system EMC testing were to confirm the self-compatibility of the integrated system and its compatibility with the launch, cruise, EDL, and surface operation electromagnetic environments. It was also to qualify the pyrotechnic mechanisms and wiring for the RF susceptibility safety.

The MER system EMC test program had the following specific objectives:

1. Demonstrate total functional performance for self-compatibility of the integrated system, including the interface cabling.
2. Demonstrate total functional performance of the integrated system for compatibility with the intended environment, including the transmitter sources.
3. Demonstrate functional performance of the assemblies and their functions that were not tested in the assembly-level qualification testing.

System EMC testing for the launch/cruise and EDL modes were performed only on MER-1. Both tests were successfully completed and the test objectives met.

In addition, both rovers were separately tested for self-compatibility under surface operations. The rovers were located in the center of the room to minimize wall reflections and noise pick up from the air vents. The EMC test receiver and transmitter antennas were located approximately 1 meter from the rover edges. The test antennas were connected to the RF and UHF electronics via coaxial cabling routed though a feedthrough pipe. Fig. 2 shows the rover test setup.

Fig. 2. Rover EMC Test Setup

In order to perform the tests in a timely manner, a significant pre-test planning and assessment effort was conducted. Testing every rover function against every other rover function would have required an enormous amount of time. Since testing time was limited due to tight delivery schedules, it was decided to test the most critical rover functions. To this end, all assembly/subsystem-level EMC test data was gathered and thoroughly reviewed, and all over-spec test incidents were identified. From this information a test matrix was developed, identifying all potential sources and victims. Where a victim and source function intersected on the matrix, the box was then labeled in the order of importance based on subsystem data, from high priority to medium priority, then to low priority. Of utmost importance were all combinations involving the UHF and X-Band telecom subsystems. The matrix served as a guide for planning test details, generating the test procedures, and analyzing the results.

The rover surface compatibility testing was successfully completed and test objectives achieved. The X-Band receiver did not show any degradation in performance due to the operation of instruments (MB, APXS, Mini-TES, cameras), motors (i.e. Rock Abrasion Tool) and the UHF in transmit mode. For these tests, the High Gain Antenna was positioned in a worst-case noise pick-up configuration (antenna perpendicular to RED and pointed towards the PMA/IDD instruments). Likewise, the UHF receiver sensitivity was not significantly degraded by Rover spurious emissions except when the Rock Abrasion Tool and Microscopic Imaging instruments were operated. A noticeable degradation of performance was experienced when the Rock Abrasion Tool was operated, and loss of lock was experienced when the Microscopic Imager was powered on. Table 5 shows the resolutions of the incompatibilities uncovered during the rover surface operation tests.

Table 5. Resolution of EMC Incompatibilities

	SOURCES																			
VICTIMS	X-Band Rx	X-Band Tx	UHF Rx	UHF Tx	Av/Power	IMU	APXS	Mossbauer	Mini-TES	PanCams	Micro-Imager	HazCams	NavCams	IDD	RAT	wheels	steering	HGA Gimbal	PMA	Filter wheel
X-Band Rx	-	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
X-Band Tx	0	-	0	0	0	0	0	0	0	0	0	0	[illegible]	0	[illegible]	[illegible]	[illegible]	0	[illegible]	0
UHF Rx	0	0	-	0	0	[illegible]	[illegible]	0	0	[illegible]	[illegible]	0	[illegible]	Cn	[illegible]	[illegible]	0	Cn	Cn	Cn
UHF Tx	0	0	0	-	0	0	0	0	[illegible]	0	0	[illegible]	0	[illegible]	[illegible]	0	0	0	0	0
Av/Power	[illegible]	0	0	[illegible]	-	0	0	[illegible]	[illegible]	0	0	[illegible]	[illegible]	0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0
IMU	0	0	0	0	0	-	0	0	0	0	0	0	0	[illegible]	[illegible]	0	0	0	0	0
APXS	0	0	0	[illegible]	0	[illegible]	-	-	0	-	-	-	-	-	-	-	-	-	-	-
Mossbauer	0	0	[illegible]	[illegible]	[illegible]	Cn	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Mini-TES	0	0	0	0	0	0	0	-	-	-	-	-	-	0	-	-	-	-	-	-
PanCams	0	0	0	0	0	0	-	-	-	-	-	-	-	0	-	-	-	-	-	-
Micro-Imager	0	0	0	0	0	0	-	-	-	-	-	-	-	-	-	-	-	-	-	-
HazCams	0	0	0	0	0	0	-	-	-	-	-	-	-	-	-	-	-	-	-	-
NavCams	0	0	0	0	0	0	-	-	-	-	-	-	-	-	-	-	-	-	-	-
IDD	0	0	0	0	0	0	0	-	0	0	-	-	-	-	-	-	-	-	-	-
RAT	0	0	[illegible]	0	0	0	-	-	-	-	-	-	-	-	-	-	-	-	-	-
wheels	[illegible]	[illegible]	[illegible]	-	[illegible]	[illegible]	-	-	-	-	-	0	0	-	-	-	-	-	-	-
steering	[illegible]	0	[illegible]	-	0	0	-	-	-	-	-	0	0	-	-	-	-	-	-	-
HGA Gimbal	[illegible]	0	0	0	0	0	0	-	0	0	-	-	-	0	-	-	-	-	-	-
PMA	0	0	[illegible]	[illegible]	0	0	-	-	0	0	-	-	-	-	-	-	-	-	-	-
Filter wheel	0	0	0	0	0	0	-	-	-	0	-	-	-	-	-	-	-	-	-	-

- = not applicable
0 - No EMI Concern - not tested
[illegible]
[illegible]
[illegible]
Cn - Medium EMI Concern - no fix required

5. PROBLEM FAILURE REPORTS

Whenever a test problem, failure, or anomaly occurred, a problem failure report (PFR) was generated. The PFR was risk rated and a resolution implemented to correct the problem.

There were 3,355 PFRs generated over the course of the MER development cycle. Of those, 294 were found to have occurred in either system or assembly-level environmental testing, roughly 10% of the total number. About one third (99 of 294) of the environmentally related PFRs occurred during system-level environmental testing. A significant number of anomalies occurring during system testing were anticipated since there was a rush to deliver assembly or subsystem flight hardware to system integration, at times even before the qualification testing had been completed.

Table 6 shows the numbers and percentages of assembly environmental test PFRs during the different types of environmental tests. By far the most PFRs occurred during thermal testing. However, as a percentage of the total number of tests run, EMC was highest; but most of them were minor out-of-spec conditions.

Table 6. Assembly Environmental Test PFRs

Tests	# of PFRs Generated	# of Tests Performed	% of Tests with PFRs
EMC	18	23	78%
Random Vibe	18	254	7%
Sine/Load/Static	6	111	5%
Pyroshock	6	75	8%
Acoustic	0	3	0%
Thermal Testing	137	293	47%
Ionization-breakdown	4	38	11%
Total:	189	797	24%

As for system environmental test PFRs (not shown), by far the most PFRs (83 out of 99) occurred in thermal testing. In terms of occurrence in subsystem, a large proportion occurred in flight software, which was actually part of Avionics (36 out of 83). There were also a large number of mechanical PFRs (13 out of 83). This was due to the rover performing many maneuvers in the surface thermal test that were not previously demonstrated in assembly-level environmental testing.

6. LESSONS LEARNED

Numerous lessons have been learned from the implementation of the environmental assurance program for this complex mission that had a very tight schedule. They include both technical and programmatic lessons. The following lists a small selection of lessons that are generic in nature, which would be helpful in improving implementation of the environmental program for future projects.

1. A static load test performed by a university was found to be the wrong profile. It was later determined that they did not have the capability to do the test. The hardware testing was eventually completed by an outside testing facility. There is a need to ensure that

test labs not familiar with delivering space hardware have the equipment and know how to run the tests properly to meet requirements. The bare test fixture test profiles and capabilities should be reviewed before testing of the flight hardware begins.

2. MER had a number of hardware inherited from past missions. Sometimes the qualification and flight acceptance testing history were not well understood. Significant efforts by the team members were expended into determining which requirements were met and which ones were not. If inherited hardware is to be used, there needs to be a complete set of documentation available to provide evidence of compliance with the current project requirements.
3. A high-temperature bake-out at 110°C or 125°C was required on most external rover hardware to reduce spore counts to meet NASA's Planetary Protection requirements. The bake-out was normally the last step before delivering the flight hardware for integration with the spacecraft. Since the bake-out temperatures were higher than the normal hot PF limit (+70C) and there was no functional test after the bake-out, there was no certainty that the hardware would function after the bake-out. Therefore in cases where bake-out is required, it should be coordinated with the thermal vacuum test as a requirement. The bake-out can be done as the final cycle of the thermal vacuum test before the final functional checkout to ensure the hardware will function after the bake-out.
4. There were more than 100 pyrotechnic devices (separation nuts, pin pullers, cable cutters) used in MER for separation and deployment and some were located very close to shock-sensitive hardware. Presently, the three categories of test methods to simulate an externally generated pyroshock environment are: (i) shaker shock simulation, (ii) impact-generated shock simulation, and (iii) ordnance-generated pyroshock simulation. All these methods can result in significant over-test and sometimes in significant under-test. There is a need to identify, develop, and implement improved assembly-level pyroshock test techniques to alleviate unrealistic test failures and avoid under-tests.
5. The presence of UHF transceiver (~400 MHz) has caused some EMC problems in all prior projects, including MER. If UHF transceiver is used, testing at the assembly level should be done early to properly test for compatibility with other hardware and to schedule additional time to resolve anticipated integration problems at the system level.
6. Some MER assemblies were not initially identified as requiring EMC testing, but later became problems during system integration. Early EMC testing at the assembly level and proper closure of any resulting PFRs are important in avoiding unforeseen problems during system testing.
7. Due to the Mars surface diurnal deep thermal cycling environment, the hardware that exposed to the Mars external surface environment required thermal cycling life testing. Several pieces of hardware were found to be marginal in meeting the thermal cycling life requirement. Initially the list of hardware for qualification was limited to electronic packaging, however, later critical Electro-Mechanical devices, such as motors, solenoids, thermal actuators, and platinum resistance thermocouples were determined to also require qualification.

7. CONCLUSIONS

A comprehensive prelaunch environmental assurance program was successfully implemented on the MER project. The rigorous environmental testing and analyses discovered a number of problems and anomalies, which were resolved before launch. Both MER spacecraft launched, cruised to its destination, landed, and operated almost flawlessly on the surface of Mars beyond their designed life. The rovers sent back stunning pictures of Mars and returned an unprecedented amount of science data. They confirmed past history of the presence of significant quantities of water that induced many geological processes. All mission objectives have been met beyond expectation. A rigorous environmental assurance program has contributed, in part, to the success of this mission. Both rovers are currently on extended mission.

8. ACKNOWLEDGEMENT

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