Managing the Mars Science Laboratory Thermal Vacuum Test for Safety and Success

Jordan P. Evans
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, CA 91109
818-354-1358
Jordan.P.Evans@jpl.nasa.gov

Abstract—The Mars Science Laboratory is a NASA/JPL mission to send the next generation of rover to Mars. Originally slated for launch in 2009, development problems led to a delay in the project until the next launch opportunity in 2011. Amidst the delay process, the Launch/Cruise Solar Thermal Vacuum Test was undertaken as risk reduction for the project. With varying maturity and capabilities of the flight and ground systems, undertaking the test in a safe manner presented many challenges. This paper describes the technical and management challenges and the actions undertaken that led to the ultimate safe and successful execution of the test.[1 2]

TABLE OF CONTENTS

1. INTRODUCTION

Overview of the Mars Science Laboratory Project

The Mars Science Laboratory (MSL) will begin science operations soon after landing in the summer of 2012 [1]. The overall scientific goal of the mission is to explore and quantitatively assess a local region on Mars' surface as a potential habitat for life, past or present. The MSL rover is designed to carry ten scientific instruments and a sample acquisition, processing, and distribution system. The various payload elements will work together to detect and study potential sampling targets with remote and in situ measurements, to acquire samples of rock or soil and analyze them in onboard analytical instruments, and to observe the environment around the rover. The primary mission will last one Mars year (approximately two Earth years).

The MSL mission has four primary science objectives to meet the overall habitability assessment goal:

(1) The first is to assess the biological potential of at least one target environment by determining the nature and inventory of organic carbon compounds, searching for the chemical building blocks of life, and identifying features that may record the actions of biologically relevant processes.

(2) The second objective is to characterize the geology of the landing region at all appropriate spatial scales by investigating the chemical, isotopic, and mineralogical composition of surface and near-surface materials, and interpreting the processes that have formed rocks and soils.

(3) The third objective is to investigate planetary processes of relevance to past habitability (including the role of water) by assessing the long timescale atmospheric evolution and determining the present state, distribution, and cycling of water and CO_2.

(4) The fourth objective is to characterize the broad spectrum of surface radiation, including galactic cosmic radiation, solar proton events, and secondary neutrons.

The mission will be launched from Kennedy Space Center in the October 2011 time frame and will take approximately 11 months to reach Mars in a direct flight path (the cruise phase). The entry vehicle has a ballistic trajectory into the Martian atmosphere and is protected from large aerothermal loads by a heat shield and backshell. A Descent Stage (DS) is used to decelerate the rover prior to landing on the Martian surface. In the final moments of the Entry, Descent, and Landing (EDL) event, the rover descends below the DS on a tether. The Main Landing Engines (MLE's) fire to slow the descent velocity to 3 m/sec. When the rover touches down on the surface, the tether is cut and the DS flies away from the landing site. The rover lands with all 6 wheels on Martian soil. This EDL system does not need a lander. Figure 1 show the sequence from separation of the Cruise Stage (CS) at the end of the trip to Mars, through safe landing of the Rover on the surface.

[1] 978-1-4244-3888-4/10/$25.00 ©2010 IEEE
[2] IEEEAC paper #1633, Version 3, Updated 1/1/2010

The power source for the rover during surface operations is a Multi-Mission Radio-isotope Thermoelectric Generator (MMRTG). The MMRTG dissipates about 2000W of thermal energy and generates a much smaller amount of electrical energy. During the cruise phase of the mission, the excess thermal energy is rejected to space by using a liquid, pumped fluid loop called the Cruise Heat Rejection System (HRS).

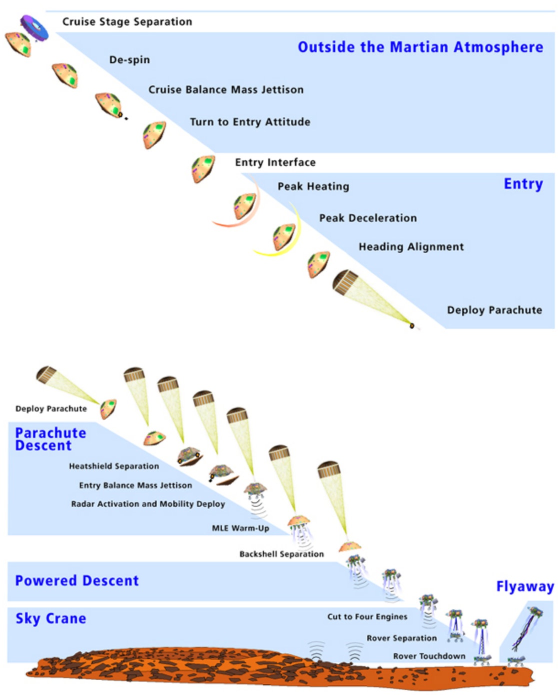

Figure 1 – Mars Science Laboratory from Cruise Stage separation through landing on the Martian surface

The Rover uses a similar Surface HRS to capture excess MMRTG thermal energy during the cold Martian nights to keep electronics inside the rover warm. The Surface HRS is also used to reject heat during the Martian daytime when internal rover heat loads are at their peak. All of the rover internal hardware (Avionics, battery, telecom and science instruments) are mounted to the Rover Avionics Mounting Panel (RAMP), which has tubing attached to it to provide the heat exchange between the boxes and the HRS working fluid. Bypass valves in the system direct the working fluid to hot plates surrounding the MMRTG to pick up heat when the RAMP is cold. The valves redirect the flow to the cold plates and the top deck to reject heat when the RAMP is hot.

As described above, the MSL Flight System system consists of four major elements: the Cruise Stage, the Aeroshell (heatshield and backshell), the Descent Stage, and the Rover. The Entry, Descent, and Landing (EDL) system includes the aeroshell and Descent Stage. Figure 2 shows an expanded view of the MSL Flight System.

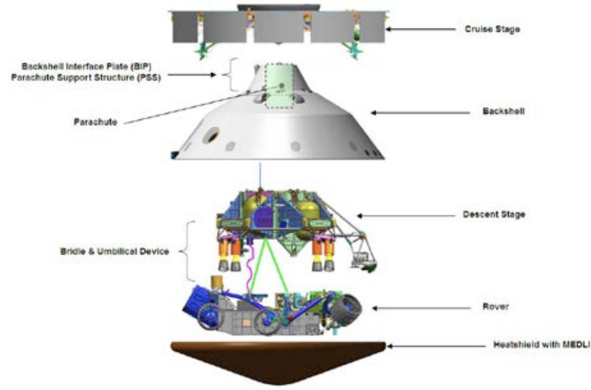

Figure 2 – Elements of the Mars Science Laboratory Flight System

On December 4, 2008, a press release was issued by NASA describing the technical challenges that forced a delay in the mission [2]. "NASA's Mars Science Laboratory will launch two years later than previously planned, in the fall of 2011…A launch date of October 2009 no longer is feasible because of testing and hardware challenges that must be addressed to ensure mission success. The window for a 2009 launch ends in late October. The relative positions of Earth and Mars are favorable for flights to Mars only a few weeks every two years. The next launch opportunity after 2009 is in 2011."

The release went on to state "The advanced rover is one of the most technologically challenging interplanetary missions ever designed. It will use new technologies to adjust its flight while descending through the Martian atmosphere, and to set the rover on the surface by lowering it on a tether from a hovering descent stage. Advanced research instruments make up a science payload 10 times the mass of instruments on NASA's Spirit and Opportunity Mars rovers. The Mars Science Laboratory is engineered to drive longer distances over rougher terrain than previous rovers…Rigorous testing of components and systems is essential to develop such a complex mission and prepare it for launch. Tests during the middle phases of development resulted in decisions to re-engineer key parts of the spacecraft…when it's all said and done, the passing grade is mission success."

Objectives of the Launch/Cruise Thermal Vacuum Test

Spacecraft undergo thermal vacuum testing to validate the thermal design in simulated environments representative of the expected extreme mission environments and to verify functional performance against specifications over temperature extremes.

The test validates that the flight hardware system thermal control design satisfies the Allowable Flight Temperature (AFT), thermal gradient, and thermal stability requirements under a combination of extreme simulated mission thermal environmental and operational conditions. The test is also designed to generate sufficient data to enable thermal math model correlation so that un-testable conditions can be validated by analysis. Verification of functional performance and system compatibility under the combination of extreme thermal conditions is also a significant part of the test., along with the workmanship of thermal hardware.

Travelling to the surface of Mars presents unique thermal environments that aren't found in Earth Orbit or cruising through deep space. The 8 torr CO_2 atmosphere of Mars introduces two additional heat transport mechanisms: an additional conduction path (gas conduction[3]) and convection (it can be windy on Mars). Additionally, the surface operations are performed by the Rover in a deployed, mobile configuration. During launch and the cruise to Mars, the Rover is stowed deep inside the Aeroshell with the Descent Stage and the Cruise Stage is provide the heat rejection to space. The configurational and environmental differences between Launch/Cruise and Surface operations drives the need for two separate system thermal tests. This paper focuses on the Launch/Cruise (L/C) thermal vacuum test.

The test cases developed to achieve the baseline objectives are captured in Table 1 and the key information about each element of the originally planned MSL L/C System Thermal Test (STT) [4].

2. Test Planning and Preparation

Early Test Planning

For a test of this magnitude, drawing together subsystem support, the test lab and instrumentation personnel, and the systems engineers to define the mechanical and electrical configuration and test execution details is a sizable task. The planning of the MSL Launch/Cruise STT started with weekly meetings approximately 12 months prior to the expected execution date. This provided the time necessary to define the configuration, design and fabricate the support equipment necessary, and develop the documentation to execute the test.

To ensure clear communication and a broad understanding of how the test configuration was maturing, a large distribution list was established for meeting announcements and post-meeting notes. The personnel included on the distribution were:

Test Case		Objectives	Flight Simulation		Estimated Duration [hrs]
			AU Distance	S/C Dissipation Profile	
Transitional Test Cases					
1	**Pumpdown and Transitional Cooling**	Draw vacuum at ambient temperature to drive off water vapor. Characterize warm-up of Descent Stage Telecom and Avionics with HRS pumps off. Flood chamber shrouds to transition S/C cold	N/A	pre-STT	30
Cold Cases					
2	**Descent Stage System Worst Case Cold Thermal Balance**	Thermal Design verification at WC cold condition for DS Prop System	1.63	late Cruise profile	40
3	**Final Approach Thermal Transient**	Verify CS Thruster, RCS, MLE catbed heaters and MARDI warmup heater	1.63	Final Approach profile	36
4a	**Flight Software Setpoint Test**	Raise Cruise and Descent Stage propellant line setpoint temperature	1.63	late Cruise profile	4
4b	**Backup Heater Functional Test**	Disable primary heaters and test backup heaters. Swap CHRS Pump A/B	1.63	late Cruise profile	4
5	**Spacecraft Cruise Functional Test--Cold Environment**	Run Flight system spacecraft ST-3 tests at cold simulated flight conditions	1.63	as needed	10
6	**Cruise Stage Prop System Worst Case Cold Thermal Balance**	Thermal Design verification at WC cold condition for Cruise Prop System and S/A	1.63	late Cruise profile	40
Hot Cases					
7	**EDL Worst Case Thermal Balance**	Pre-EDL Worst Case Hot Thermal Balance	1.5	late Cruise profile	36
8	**Spacecraft EDL Functional Test--Hot Environment**	Run Flight system spacecraft ST-3 tests at hot simulated flight conditions	1.5	as needed	10
9	**Spacecrat Worst Hot Case Thermal Balance**	Thermal Design verification at WC hot condition for Cruise Prop System and S/A	1	early Cruise profile	36
10	**Spacecraft Cruise Functional Test--Hot Environment**	Run Flight system spacecraft ST-3 tests at hot simulated flight conditions	1	as needed	10
11	**Backfill and Open Chamber**	Backfill and open chamber	N/A	minimum	25
				Total Test Time (hrs):	281
				(days):	11.7

Table 1 – Test Cases for the originally baselined Launch/Cruise System Thermal Test

[3] Gas conduction is important here because the CO_2 environment is at 8 torr (in a transition regime between the continuum regime (50 torr and above) and the Knudsen free molecular conduction regime (1 torr and below)) [3].

(1) Mechanical

a. Assembly, Test, and Launch Ops (ATLO) Mechanical Engineering

b. Mechanical Ground Support Equipment

(2) Electrical

a. ATLO Electrical and Systems Engineering

b. ATLO Cabling

(3) Thermal

a. Thermal Test Lead

b. Thermal Systems Engineering

(4) Systems Engineering

a. Power Systems Engineering

b. Telecom Systems Engineering

c. Flight System Systems Engineering

d. Avionics Systems Engineering

(5) Environmental Test Laboratory (ETL)

a. ETL Facility Test Lead

b. Instrumentation Lead

The planning meetings were structured to first define the physical configuration (mechanical, electrical, and RF) and then focus on details of the implementation (tactical schedules, staffing, etc.). There are many factors that drive the physical configuration: geometry of the flight hardware, limitations/features of the thermal chamber, desired thermal cases, specific functional tests planned, and responses necessary for hardware safety. Each week, an area of focus was chosen to develop the requirements and arrive at an early configuration concept that could be matured. One example of this is the need for infrared (IR) lamp arrays above and below the unit under test. The IR lamp need arose because the test utilized a solar simulator to provide the solar flux onto the vehicle, along with thermal shrouds to control the radiative boundary conditions. A loss of the solar simulator or problems with the lower shroud could allow the flight hardware flight temperature limits to be exceeded. A redundant source of heat was necessary and the implementation chosen was IR lamps (typically used at JPL). Figure 3 shows the final configuration of the hardware in the chamber.

Rescoping the Test in Light of the Launch Slip

As the decision came down to delay the launch of MSL until the next opportunity (fall of 2011), the ATLO team was busily pressing forward to try and maintain the schedule towards a 2009 launch. The hardware was still immature

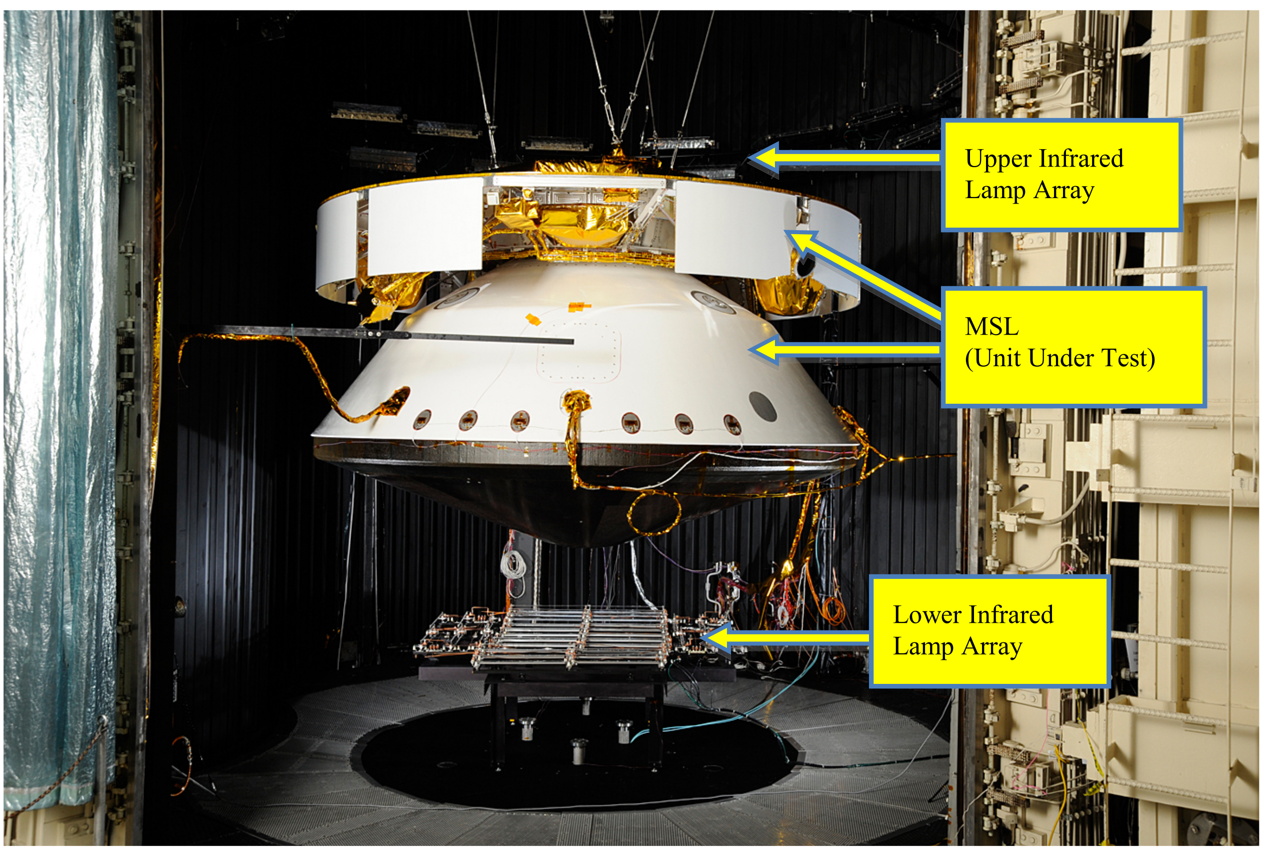

Figure 3 – Mars Science Laboratory in the 25 foot Space Simulator at JPL, ready for pumpdown

and the flight software and ground data systems were still in their early release states. As with any integration and test effort on complex one-of-a-kind spacecraft, the hardware and software initially required workarounds to get the desired functionality out. With the schedule pressure now relieved, the project took a step back to examine the upcoming L/C STT. Should it be delayed until we resume for 2011? Should it press on as is so we won't have to perform the test again prior to launch?

A series of meetings were held to revisit the test objectives and trade the test execution as planned versus the cost versus some intermediate position (shorter test focused on risk reduction). The group (flight system management, systems engineering, thermal, ATLO, and the JPL line organization) discussed where the mission risks in the design are and what could be done to buy down those risks in the near term instead of waiting to uncover potential problems a year and a half later.

The resulting plan was to execute a shorter/less expensive (5.5 day versus 11.7 day) test that exercised the Heat Rejection System (HRS) over many of its extreme environments. Given the launch/cruise architecture of a 2000W Multi-Mission Radioisotope Thermal Generator (MMRTG) buried deep inside the entry capsule, the effectiveness of the HRS to pull that heat out and reject it was critical to the mission and no suite of prior testing could verify that the system performed. An additional test would be planned as part of the resumption of ATLO for the 2011 launch.

The table of test cases below (Table 2) reflects the reduced "risk reduction" version of the L/C STT that was executed to satisfy the risk reduction objectives [5]. Key changes include a focus on thermal balance only (no transients) and a focus on Cruise Stage extremes only (worst-case hot and cold) and not on the Descent Stage extremes because the DS was deemed lower risk. The case numbers were maintained to tie back to the original plan.

The Test Readiness Review (TRR)

JPL and NASA practices require a Test Readiness Review (TRR) be performed prior to conducting any significant test that will place the hardware at risk [6]. The TRR evaluates the readiness of flight hardware items to be tested along with the readiness of personnel, test procedures, test equipment, and test facilities.

The content of the review must include the test requirements and pass/fail criteria and a detailed description of the test plans and procedures sufficient to ensure the board can penetrate and truly assess the readiness and safety of the test. Instrumentation, facility status/procedures, and personnel qualifications are reviewed along with the configuration of and status of the hardware items to be tested, including calibrations, alignments, etc. A thorough assessment of personnel safety and the safety of the flight hardware items, including risk-reduction actions taken, is included. The review also covers the compliance with applicable institutional test policies, requirements, practices, and principles and the status of approvals for the start of testing.

The review board consisted of senior engineers and managers with test experience and backgrounds or active assignments in thermal engineering, ATLO, mission assurance, environmental requirements engineering, test facilities, and flight system engineering.

The timing of the TRR must be sufficiently in advance of start of testing to allow time for correction of deficiencies apparent from the review. For MSL, we chose to enforce the closure of the TRR actions by including a mandatory, QA-verified step at the start of the test procedure that verified the closure of TRR actions. This ensured a closed-loop process and is recommended for future projects.

"Gremlin" Sessions

The transition from electrical integration and functional testing to the environmental test campaign (dynamic and thermal vacuum testing) represents a significant change in the physical configuration of the flight hardware and an

Test Case		Objectives	Flight Simulation		Estimated Duration [hrs]
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1	**Pumpdown and Transitional Cooling**	Draw vacuum at ambient temperature to drive off water vapor. Characterize warm-up of Descent Stage Telecom and Avionics with HRS pumps off. Flood chamber shrouds to transition S/C cold	N/A	pre-STT	30
Cold Cases					
2	**Descent Stage System Worst Case Cold Thermal Balance**	Thermal Design verification at WC cold condition for DS Prop System	1.63	late Cruise profile	40
5	**Spacecraft Cruise Functional Test--Cold Environment**	Power subsystem testing at cold simulated flight conditions	1.63	as needed	10
Hot Cases					
9	**Spacecrat Worst Hot Case Thermal Balance**	Thermal Design verification at WC hot condition for Cruise Prop System and S/A	1	early Cruise profile	36
10	**Spacecraft Cruise Functional Test--Hot Environment**	Power subsystem testing at hot simulated flight conditions	1	as needed	10
11	**Backfill and Open Chamber**	Backfill and open chamber	N/A	minimum	25
				Total Test Time (hrs):	137
				(days):	5.7

Table 2 – Test cases for the "Abbreviated" L/C STT, focused on risk reduction

increase in the risk to that flight hardware and personnel. This transition, coupled with the typical diversity in test experience of the ATLO team, presents a management challenge in terms of maintaining the same level of hardware and personnel safety and schedule tempo that was established in the gradual buildup of the hardware and test capabilities. This "step increase" in risk is dramatic and not necessarily noticeable to the team that is responsible for executing the environmental test program.

In an effort to educate the team, wring out the procedures (particularly the contingency procedures and decision trees), ensure the communications paths were functioning, and to look for hardware and facility infrastructure issues, we set up a series of training sessions.

These training sessions, which became known as "Gremlin Sessions" were designed to essentially build the "mental model" of the physical configuration and the set of "knobs" available to the ATLO team, thermal team, and facility team while ensuring the hardware and software tools necessary for test execution were functioning as intended. A set of scenarios, designed to serve the training objectives were developed. These scenarios, each presenting a unique issue that could arise during the test, were the "Gremlins." As the manager responsible for defining and communicating these Gremlins over the communications network to the team, I became known as "Gremlin One."

To generate the Gremlins list, the author enlisted the help of the ATLO Manager and Flight Systems Engineer. Additionally, several team members with unique depth in elements of the flight hardware or ground data system offered up additional ideas without getting full insight into the complete list (since they were part of the training).

The Gremlin sessions were conducted between the time the Electrical Ground Support Equipment (EGSE) was moved to the test area outside the thermal vacuum chamber and the time the spacecraft was ready for pre-test electrical checkout (this is the period of time when the mechanical ATLO team is getting the spacecraft into the chamber and making the necessary preparations). Since part of the objective of the sessions is to wring out the support equipment used in emergencies, the EGSE was powered on and configured using the planned test procedures. The sessions were typically 2 hours long and the ATLO, thermal, and facility personnel were divided into two teams. Each team got to sit on console for half the session and observe the other team during the remaining half of the session.

Wherever feasible, we devised Gremlins to test the emergency response equipment. One example of this was a power failure "gremlin." We arranged to have the electrical power facilities contractor for JPL come and kill power to the building that houses the thermal vacuum chamber. This would allow us to verify we had the proper equipment on Uniterruptable Power Supplies (UPS) and also to test the emergency diesel generators and verify the circuits that they feed. The UPSs were in place to bridge the time between power failure and switchover to the backup generators. As we found with many of our gremlins, doing this proved to be very beneficial. We were able to track down workstations that should have been on UPS but weren't and printers that didn't need to be on UPS but were! Additionally, switching over to the backup generators requires the test facility personnel to manually throw a switch. The switch was faulty and sent a billow of smoke into the control room. At the conclusion of this Gremlin Session, we were able to replace the facility switch and correct the items supported by UPS. We later re-introduced this power outage gremlin to verify the fixes worked, since the time constants of some of the flight hardware would necessitate that this switchover happen in a matter of minutes if it happened during the actual test.

Getting the team to have a thorough mental model of the test setup is critical to their ability to exercise proper engineering judgment if something goes wrong. How is power introduced into the vehicle in this configuration? What sensors do the facilities folks have to help diagnose issues? How much time do we have if we get a Power-On Reset (POR) of the flight computer before we run into temperature trouble? What could go wrong if the facility reports a loss of pressure? How do we warm up that low mass piece of hardware quickly when the thermal team radios that there is an issue? What is a CQCM? The gremlins were designed to introduce new concepts, configurations, and capabilities to the team that they may not have come across before and certainly had not yet seen on MSL. This introduction is critical and too often neglected at this phase of a flight project. Table 3, below, provides a partial list of some of the gremlins presented to the team. As you can see, there was some humor inserted to keep the learning fun. The team comments following these sessions were all very positive in terms of provide them with a way to learn the upcoming test in a meaningful, expeditious, and hands-on manner.

Examples of "Gremlins" Introduced During Training

Scenario Presented	Concept Taught
Vacuum interlock kicks in. Pressure in chamber appears to be 5x10-3 torr. Results in vehicle Emergency Power Off (EPO). Later, RGA shows water in chamber.	Ensure it's not the flight hardware and then bring power back to spacecraft quickly to get heaters going again. Introduce the radiometer water chiller
Fairly significant earthquake, magnitude 5.0	Personnel safety first
Comm Net stops working…no direct communications.	Telephones work too! Make sure you've got a phone list for every station and an emergency "meet-me" line

On a routine check of the data by CC, the CQCM reading on one of the units looking inside the aeroshell is reading very high rates.	Learn what can cause changes in outgassing rate and what to check to identify root cause
During Cold balance, the Rover computer stops responding. No 1553 bus traffic. No telemetry from any of the Rover avionics.	This exercised some written contingency procedures and decision trees to wring them out.
Batteries inside the Rover start draining.	Understand the power block diagram for this test and be prepared to hook in the backup power supplies.
Person in the "Command" chair ate bad kimchee and vomits all over himself and workstation.	Ensure team knows how to bring up commanding on different workstation. Ensure we continue to poll thermal for HW safety.

Table 3 – Each "Gremlin" was devised to present a teachable moment related to some element of the upcoming thermal vacuum test.

3. TEST EXECUTION

So What Did Happen?

Not surprisingly, several of the gremlins that the team trained for showed up during the test. It is not uncommon for tests of this complexity to present the test team with these types of events/eventualities. This under-acknowledged reality is one of the motivations for writing this paper.

As the final preparations were being made for pumpdown, Southern California experienced an earthquake. The vehicle hung suspended in the chamber, the test teams were on console, and the building shook. The team was prepared and remained calm. As the author writes this, pondering the questions that might have gone through the team's minds as this event occurred with limited knowledge of the test configuration, and perhaps differing opinions on how to respond, the notion that the Gremlin Sessions were vital to our success is further reinforced.

Once the test was underway, with the chamber at high vacuum and the thermal shrouds cooled to liquid nitrogen temperatures, the real gremlins came out to play. Below are excerpts from the status e-mails that were sent by the author of this paper as the test progressed…

<u>On 1/9/09 5:51 PM</u>:

"We commenced pumpdown last night at around 3am. We completed the pump/backfill cycles to drive water out of the chamber and are currently at 400 torr ready for the pump to high vac. Over the course of the night we ran into 3 issues that prevented us from going "cold wall" and truly starting the test. (1)Telemetry monitor displays not updating (fix implemented, retest in progress), (2)AE command sent to all 6 PAMs (troubleshooting still in work), and (3)Descent Stage temperatures exceed the FSW setpoints without turning the heater off (Understood by FSW, point build in progress)" – Immediately upon starting the test, Gremlin-like items appeared. With the training that was performed ahead of time, the team felt comfortable dealing with each issue as it arose.

<u>On 1/13/09 5:49 AM</u>:

"At approximately 8:50pm, we noticed a 0.75V increase in the rover bus voltage. The batteries started charging up to the new voltage. ATLO Systems investigated and it appears that isolation circuits to prevent charging of the thermal batteries kicked in. This results in no change in the DPJ power supply but does in the flight bus voltage. Given that these circuits can also turn off, we may see this behavior (in the other direction) again." – Hardware behaviors that don't get seen at ambient temperature and pressure.

<u>On 1/14/09 3:05 AM</u>:

"Now for some status...it was the night of the gremlins...

-Case 5 Power functional started a bit late and ran into problems with the Solar Array Simulator. This resulted in SAS1 going offline and somewhere in the process we ended up with the loss of commanding (for those of you who participated in the contingency training, this is a familiar gremlin).

-During section C.4 (Battery Charge Rate Limit), running on the DPJ Power Supply, we lost the Master/Slave configuration on the GSE PS likely due to a voltage setpoint issue (higher on master than slave) and needed to recycle the slave PS…It appears we did achieve the full charge rate limit…

-Over the course of the night, during a quiescent period between C.3 and C.4, we smelled some burning that was determined by ETL to likely be coming from the roof. The fire department investigated and did not find anything but did confirm that the smell was strongest on the roof. They called in the contractor to look at the HVAC, but did not find anything conclusive."

<u>On 1/14/09 5:17 PM</u>:

"-We're in the midst of Case 9 (Spacecraft Worst Hot Case Thermal Balance). The Sun is shining at 1372 W/m2 and we're on our way to thermal balance…

-Waiting for balance is not without excitement. One of the Solar Sim lamps that was not in use (already declared dead)

decided to spring a leak in the cooling water line. The ETL team was able to respond quickly and valve it off literally within seconds of pulling down the entire solar simulator...which would have resulted in our usage of the upper IR lamp array for vehicle safety and return to ambient." – This problem was part of our Gremlin Sessions and allowed the team to follow decision trees that they had already rehearsed.

On 1/15/09 8:19 AM:

"-The ETL team is continuing to aggressively monitor the Solar Lamp array. Following the leak in the water cooling line on one of the failed lamps yesterday, the lamp continues to periodically "spritz" water onto the adjacent lamps. We are ok for now and should be able to limp our way to a successful balance, at which time ETL will make adjustments by turning off some lamps and increasing the intensity on others."

On 1/16/09 6:52 AM:

"In terms of what happened overnight...

-At around 8:30pm last night, we lost 2 more bulbs in the solar sim...we should have plenty for the conclusion of this test.

-After slightly more than 4.5 days of continuous power on, and during our transition from hot balance back to ambient temperatures, we encountered a FSW reset on RCE-A." – Yet another gremlin that we practiced reared its head.

On 1/16/09 4:54pm:

"Greetings from Building 150,

I am pleased to report the conclusion of the MSL L/C "Early" STT. The test has ended at ~5:00pm. This puts the total test duration at ~5.5 days (and puts the total calories consumed at well over 100,000). The original predict by the Thermal team was 5.8 days (no predict on the calorie intake). This accuracy is a testament to the team that planned and executed this test and I want to thank all of you for your hard work, clear thinking, and dedication to making this test safe for the personnel and hardware. This test has reduced risk for our project and validated the bulk of the thermal design. It provided an opportunity for many folks to get to know each other better over the past year of planning and the recent round-the-clock execution. It also has been a great opportunity for the thermal team to see some closure on their hardware deliveries and analytical work."

The test concluded as planned, after 5.5 days at vacuum.

Sanity During an Around-the-Clock Test

As the excerpts from the status e-mails above reflect, humor was used as a means of keeping morale up during the long shifts. Regular communication to a large group was also critical to keeping everyone in synch as they came on shift and to give the team a sense of progress to further motivate them to the finish line.

The small things sometimes make a real difference in the attitudes of people and things that they remember going forward. Some small things that helped make a difference in the execution of this test include: the thermal team set up an amazing feast of snack food and drinks and opened it to the whole test team, the laboratory set up a freezer and stocked it with ice cream for the team (a JPL tradition), and the author of this paper stopped shaving prior to the test and vowed not to shave until the test was complete (an insignificant rallying cry).

Breaking Configuration and Giving Thanks

When the test procedure is completed and the test is considered "over" a critical meeting occurs called the "Break Config" meeting. This meeting occurs whenever a major configuration change is about to occur during ATLO and ensures the test objectives and problems encountered while in the configuration are sufficiently completed or understood to allow the configuration to change.

Break Config meetings require the presence of all stakeholders. It is too costly to move on and later discover that someone was sick and needed to maintain the configuration to obtain critical troubleshooting information for a problem that had been encountered. These meetings occur as soon after the test as is practical and typically include ATLO management and team leads, discipline leads for the tests undertaken in the current configuration, subsystem leads, payload engineers, QA, mission assurance, and systems engineering.

The content of the Break Config meeting is broken into three significant areas of focus. The first is a review of the test objectives to ensure there are no liens against them requiring the hardware to remain in the current configuration. The second is a review of all problem reports generated during the test. This problem review is necessary to obtain concurrence from the stakeholders that no additional testing or troubleshooting requires the current configuration. The third area of focus is liens against breaking the configuration. This is typically the list of post-test inspections that are requested/required.

When the Break Config meeting was successfully completed and it was clear the test was finished, it was time to thank the many individuals and organizations that supported the test. Thanks were owed to JPL Security for guarding the hardware prior to pumpdown so the team did not have to remain on 24-hour shifts. Thanks were also owed to upper management at JPL for providing the ice cream. Most importantly, thanks were owed to the ATLO, thermal, and facility teams that worked tirelessly to keep the flight hardware and each other safe.

Many e-mail messages were sent to broad distributions and some messages were conveyed to subsets of the teams that had particular focused roles. This paper is yet another way to give thanks to the MSL L/C STT team. The planning and execution process carried out by the MSL team is worthy of capturing to inform others of "something that worked." With MSL's delay there will be other tests and this team is not the team that will see the mission through to launch, but during those couple of weeks in January of 2009, they created the model of test execution and should be very proud.

4. CONCLUSIONS

For the MSL L/C System Thermal Vacuum Test, the success of the test was the result of a detailed planning effort, a thorough Test Readiness Review, fun and focused training sessions, a break config process that ensures opportunities are not lost and a dedicated team that was willing to perform each of these with the rigor necessary to ensure the safety of the hardware and the personnel.

Probably the single-most important addition to the practices of system thermal test planning that MSL has added is the Gremlin Sessions. The dramatically different physical configuration, interfaces with facility and thermal personnel, and the short time constants that require action are all aided by the Gremlin Sessions. Besides training the team and wringing out the procedures, the sessions offer an opportunity to review and question responses, hardware, and personnel that are otherwise taken for granted. This "questioning of everything" brings out learning in ways that are unexpected. An example of this is the IR lamps that are used for emergency heating in the chamber. The working assumption was that these lamps are evacuated (vacuum sealed). In reality, as we found by doing a checkout, they are pressurized. When they blow, they send ejecta. There is no substitute for getting the team to work with the hardware in a training and checkout mode before introducing the flight hardware into the test configuration.

This author has no doubt that the planning, in terms of procedures and configuration, along with the training for emergencies, were significant contributors to this test executing successfully.

ACKNOWLEDGEMENTS

The author wishes to thank the entire team that supported the planning and execution of the MSL L/C STT #1. Their work and focus on safety was tireless and, when coupled with their positive, humorous attitudes, made the test very rewarding for the author. The author also wishes to acknowledge his family for their support during the many long days and weekends involved in Assembly, Test, and Launch Operations of spacecraft.

The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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BIOGRAPHY

Jordan Evans *is the Assistant Division Manager for Flight Projects in the Mechanical Systems Division at the Jet Propulsion Laboratory. He has led the design and development of opto-mechanical subsystems, instruments, and spacecraft at Goddard Space Flight Center, Spectrum Astro, Inc., and the Jet Propulsion Laboratory. He previously served as the Deputy Assembly, Test, and Launch Operations Manager for the Mars Science Laboratory at JPL, where one of his duties was to lead the system-level Environmental Test efforts for the project. He has experience in all phases of the NASA Mission Lifecycle, with particular emphasis on system integration and test. He has a BSAE from San Diego State University and performed graduate study at the University of Maryland, College Park on the stability of composite structures.*