Reliability and Qualification of Hardware to Enhance
The Mission Assurance of JPL/NASA Projects*

Rajeshuni Ramesham Ph.D.
Reliability Engineering, Office of Safety and Mission Success
Jet Propulsion Laboratory-NASA, California Institute of Technology
4800 Oak Grove Dr., 303-217C, Pasadena, CA 91109
e-mail: Rajeshuni.Ramesham@jpl.nasa.gov; Tel.: 818 354 7190

Key words: Extreme temperatures, qualification, reliability, solder joint failures, bonding failures, flip-chip failures, leadless chip carrier failures, life testing, PRTs, heaters, sensors, etc.

Abstract: Packaging Qualification and Verification (PQV) and life testing of advanced electronic packaging, mechanical assemblies (motors/actuators), and interconnect technologies (flip-chip), platinum temperature thermometer attachment processes, and various other types of hardware for Mars Exploration Rover (MER)/Mars Science Laboratory (MSL), and JUNO flight projects was performed to enhance the mission assurance. The qualification of hardware under extreme cold to hot temperatures was performed with reference to various project requirements. The flight like packages, assemblies, test coupons, and subassemblies were selected for the study to survive three times the total number of expected temperature cycles resulting from all environmental and operational exposures occurring over the life of the flight hardware including all relevant manufacturing, ground operations, and mission phases. Qualification/life testing was performed by subjecting flight-like qualification hardware to the environmental temperature extremes and assessing any structural failures, mechanical failures or degradation in electrical performance due to either overstress or thermal cycle fatigue. Experimental flight qualification test results will be described in this presentation.

*Copyright 2010 California Institute of Technology. Government sponsorship acknowledged.

Introduction

Figure 1 shows the family of rovers (Pathfinder, Spirit/Opportunity (MER), and Curiosity (MSL)), that were developed to explore Mars. Rover Spirit and rover Opportunity have been developed and qualified to explore Mars for longer duration (about 90 days). They were on Mars for over 6 earth years (2304 earth days) and over 3 Martian years. They were designed to survive for 90 earth days or 1 times the mission life. All the critical components were qualified for 270 earth days that is 3 times MER mission life to meet JPL design principles. Spirit and Opportunity are still providing scientific and technical data of the environments on Mars. [1]

The JPL/NASA is developing a 2011 Mars mission (Mars Science Laboratory, MSL) to set down a sophisticated, large, mobile laboratory using a precision landing on Mars. The objective is to investigate the past or present potential of Mars to support microbial life. MSL rover “Curiosity” will be launched in October 2011, arriving at Mars in summer 2012. The mobile laboratory will be about twice as long (about 2.8 meters or 9 feet) and four times as heavy as JPL/NASA's twin Mars Exploration Rovers (Spirit and Opportunity), which were launched in 2003 and landed on Mars in Jan 2004. MSL is being designed to carry equipment to
gather samples of rocks and soil, crush them and distribute them to on-board test chambers inside analytical instruments. The special power supplies to be employed could give the mission an operating lifespan on Mars' surface of a full Mars year (687 Earth days) or more. Certain critical hardware will be experiencing extremely wide temperatures during every Martian day (sol). This makes the reliability of the critical hardware very interesting and significantly challenging to demonstrate the hardware reliability for 3 times the mission life per JPL design principles. [2]

For example, the engineering cameras were designed and developed in parallel with the Pancam [3] and Microscopic Imager [4] science cameras during the early part of this decade. As a result, they share the same optical design heritage, electronics design, electrical interface, and data formats. The engineering camera performance properties (quantum efficiency, dark current, noise characteristics, etc.) are identical to those of the science cameras. [5] MER (Mars Exploration Rover) engineering cameras were, as part of the surface navigation process, contributing indirectly to the achievement of the MER and Mars Program scientific objectives by placing the rover at sites of interest and providing contextual support for the pointing and placement of the science instruments. [5] The need for higher reliability and ability to survive extreme temperature environments creates a stringent packaging requirement for deep space applications that include Mars missions, etc.

MSL is being designed to assess whether Mars ever had an environment capable of supporting microbial life. Determining past habitability of Mars gives NASA and the scientific community a better understanding of whether life could have existed on the red planet and, if it could have existed, an idea of where to look for it in the future. [6]

- Determine whether life ever arose on Mars
- Characterize the climate of Mars
- Characterize the geology of Mars
- Prepare for human exploration

The primary scientific goal of the JUNO mission is to significantly improve our understanding of the formation, evolution and structure of Jupiter. Juno will provide answers to critical science questions about Jupiter, as well as key information that will dramatically enhance present theories about the early formation of our own solar system. Juno will carry a color camera to give the public its first detailed look at Jupiter’s poles. In 2016, the spinning, solar-powered Juno spacecraft will reach Jupiter and enter into a highly elliptical polar orbit that skims only 5000 kilometers above the planet's atmosphere. Juno will seek these answers with instruments that can sense the hidden world beneath Jupiter's colorful clouds while other experiments investigate the external effects that world produces. [7]

The launch of the Juno mission in August 2011 begins a five-year journey back to Jupiter, to investigate the remaining unanswered questions beneath the surface of the mysterious gas giant. Some of the critical hardware will experience very extreme temperatures and we addressed some of the reliability issues of PRTs bonding. PRTs will be used to obtain the temperature telemetry of the hardware during the life of the mission.
Package Qualification and Verification

The main purpose of this electronics Packaging Qualification and Verification (PQV) is to minimize the likelihood of packaging related failures (interconnects, solder joints, adhesion/delamination, bonding, solder and other materials, advanced packaging technologies, new technologies, new materials, vias, etc.) occurring in flight hardware of JPL/NASA projects. Interconnects which serve as both the electrical and mechanical interconnects are known as consumables. Failure of these interconnects is commonly referred to as packaging related failures and most often manifest as either “packaging system design” failures related to low thermal cycle fatigue (i.e. thermal cycling), thermally induced brittle failures, or workmanship failures. Failure mechanisms occur at the lowest hardware level. However, the effects are often felt/realized at the system level. All failures are electrical failures eventually. However, the cause for the failures may be thermal, mechanical, electrical, chemical or combination of these. Successful implementation of the PQV plan/program is necessary to assure proper allocation of these limited life resources, resulting in packaging designs and fabrication processes that are qualified for the planned mission application. The failure mechanisms are categorized as overstress mechanisms and wear out mechanisms. Overstress mechanisms include mechanical (brittle failures, plastics, deformation, interfacial, delamination, etc.) and electrical (EMI, ESD, radiation, gate oxide, breakdown, interconnect, melting, etc.). The wear out mechanisms include mechanical (fatigue failure, creep, wear, stress-driven, voiding, interfacial, delamination, etc.), electrical (hillock formation, junction spiking, electromigration, etc.) and chemical (corrosion, diffusion, dendrite growth, etc.).

In this paper, we will discuss the engineering and navigation camera electronics, platinum resistance thermometers (PRT), heaters, flip-chips, ceramic column grid arrays (CCGA), force sensor packages, heaters for solar panels, motors/actuators, tin whiskers, encoders, and flex print cables. We will show the package qualification and verification test data associated with engineering/navigational/hazardous camera and platinum resistance thermometers for the MSL project/JUNO project and compare with MER data. Mars exploration rover mission was only a 90 sol (Mars solar day) mission whereas MSL is a 670 sol mission. The package requirements for the hardware are to survive 270 sols for MER and 2010 sols for MSL mission. The standard electronic packages are not generally built for low temperature applications down to -130°C or -150°C, they are built for military specification and others to survive in a temperature range of -65°C to +125°C for a certain duration. Therefore, the qualification of the electronics packages, surface mount devices (example: resistors, capacitors, leadless chip carrier (LCC) packages), motors/actuators, flip-chips, CCGAs, tin whiskers, heaters, PRTs, etc. has been attempted for low temperature applications to understand the survivability of the hardware and eventually to understand the reliability and the main purpose is to enhance the mission assurance.

A soldered connection on a printed circuit board is not well suited to withstanding a permanent mechanical load. The combination of low load-carrying capacity and sensitivity to cyclic stresses of the solder joint alloys used in electronics implies that the soldered joints have a finite life and, consequently, so does the electronic equipment in which they are used. The key consideration in design and manufacture is therefore to ensure that the expected lifetime of the soldered joints is adequate for the desired application. Properly designed and fabricated solder
joints are sufficiently reliable for most purposes. However, in practice, too many joints are potential failure sources as a result of insufficient design process. Three main causes of solder joint failure may be distinguished, although the mechanisms often work simultaneously, and other causes, such as corrosion, may play a role. These causes are:

- Overloading, causing a fracture or tensile rupture
- Long-lasting permanent loading such as dwelling at a certain temperature (creep)
- Cyclic loading due to thermal cycling (fatigue)

**Engineering Camera:**

**Qualification for MER Project**

The MER camera (Figure 2) was qualified for only 200 thermal cycles (-120°C to 85°C; ΔT: 205°C) to satisfy the 3x mission life per JPL design principles. The same camera should be qualified for 2010 thermal cycles (ΔT: 145°C) for MSL project to satisfy the JPL design principles. This test is a time consuming process and involves challenging qualification processes. Figure 3 shows the failure of a standard leadless chip carrier (LCC20) package only after 50 thermal cycles (-120°C to 115°C) test. This package does not meet the requirements of the MER project. The improvements for the LCC package mounting were made and retested to qualify for the MER mission for 200 thermal cycles with the high temperature limit reduced from +115°C to +85°C. Mars rovers are still functional even after more than 2304 sols (Spirit) and 2284 sols (Opportunity) since we have improved the package designs to enhance the mission assurance by qualifying the technologies for extreme low/hot temperatures.[8, 9, and10]

**Qualification for MSL Project**

The camera design that was used for MER will also be used for the MSL project. But, this design needs to be qualified for 2010 thermal cycles with reference to MSL project requirements and JPL design principles. This hardware doesn’t have a sufficient heritage not to perform the qualification process. Therefore, the qualification must be performed for 2010 thermal cycles with a desired temperature range based on the landing site on the Mars. Figure 4 and 5 show the temperature profiles corresponding to Mars summer and winter seasons for a given landing site. The worst hot and cold temperatures were determined using Ames GCM (Global Circulation Models) simulations performed by Jim Murphy [11] and Mars surface atmosphere models by Ashwin Vasavada [12]. Figure 6 shows the sequence of the seasons that correspond to the PQV testing of camera designs for MSL. Figure 7 shows the failure of the same leadless chip carrier package occurred only after 170 MSL thermal summer cycles with a small temperature ΔT when compared with the MER test. Figure 8 shows images of the test object and also the camera PQV team members taken after the completion of PQV engineering camera test of 2010 extreme temperature thermal cycles. The PQV tested camera is still functional even after 2010 thermal cycles test over the range of temperatures shown in figures 4-6).
It is very interesting to note that the same LCC package failed after 50 thermal cycles with a $\Delta T$ of 235°C for MER project and the same package failed after 170 cycles with a $\Delta T$ of 145°C for MSL project. These experimental test results and observations correlate well within the experimental error per reliability of solder joints principles. We have redesigned the package mounting and retested the LCC package for 2010 thermal cycles for MSL project with complete success. Table 1 shows the summary of MER and MSL test results of LCC packages. This test indicates that the engineering camera for the first time qualified successfully for MSL project to survive 3 Martian years (~6 earth years) on Mars. This test particularly enhances the mission assurance and reduces the risk, enhancing the confidence on this hardware and also meeting the JPL design principle.

**Platinum Resistance Thermometers (PRT) for MER, MSL, and JUNO:**

Figure 9 shows the optical photographs of the PRTs (Type X), which were bonded to the base material for thermal cycling testing to assess for their reliability (PRT and its bonding). PRTs are the temperature sensors that will be used to monitor the health of the hardware at a given time. They were subjected to qualification process (-110°C to 110°C) and results were negative and not encouraging. There were hard failures of PRT and were completely open whether it was hot or cold with all the PRTs after 22 thermal cycles. All the PRTs have hard failures after 22 thermal cycles whether are attached with adhesive 1 or adhesive 2. (Figure 10). Table 2 provides the summary of all the PRT test coupons which have failed after 22 thermal cycles.

The requirement for MER was 270 thermal cycles plus all ground operations equivalent thermal cycles and the qualification temperature range for certain PRTs was -105°C to 40°C. Only one PRT was chosen in this test due to unavailability of the test articles. Figure 11 shows the optical photograph of the PRT bonded with reduced bond line thickness and width. Aluminum block was pretreated appropriately prior to bonding. The adhesive bond line width was equal to ~10 mil. But, substantially lower bond line width was used in Figure 9 with adhesive 2. PRT (5000 Ohms, 4 leaded, mini-TES internal calibration target) has failed after 81 thermal cycles. It was also a hard failure and was completely open whether it was hot or cold temperature. The hard failure had occurred for the first time during the cold dwell. The integrity of the PRTs to the aluminum block substrate was checked. The bond (adhesive 2) integrity of this PRT is as it was originally. The PRT has survived for almost or close to one life cycle.

5400 Ohm PRT was attached to calibration target (for mini-TES) aluminum substrate coupon with 5 mil bond line of RTV566. Primer was used on aluminum substrate only. No primer was used on the PRT surface. Silverized Kapton tape has been used to enhance the adhesion of PRT to the aluminum substrate and it was present during the thermal cycling. Thermal cycling parameters are 270 thermal cycles in dry nitrogen, -105°C to 40°C. As per resistance characteristics PRT was functional for the complete duration of the thermal cycling test for 270 thermal cycles. PRT behavior was consistent throughout the test based on the analysis of the raw test data. But, there is no evidence to support the notion that the PRT became de-bonded during the test or after the thermal cycling test. However, the result was PRT has debonded from the aluminum block substrate. (Figure 12)
One PRT (type X) bonded as shown in figure 13 failed during qualification test for MSL project. The failure has occurred at 585th thermal cycle. Successfully completed 335 summer cycles (-105°C to 40°C) and 250th winter cycle (-130°C to 15°C). PRT became an open circuit such as very high resistance as shown in Figure 14 at or after 585th thermal cycle. This is close to one MSL life.

Figure 15 shows the optical photographs of the PRTs (Type Y), which will be used for MSL project. This is the first time these sensors will be used for Mars related projects. Different types of PRTs (Type X) were employed for MER project and several reliability issues were experienced even for a short duration mission like MER (Figures 9-14, Table 2) compared with MSL project. Therefore, the qualification process for the type Y PRT is needed for MSL project. Reliability of the PRT sensors and their bonding processes is a key element to understand the health of the hardware during all stages of the project and particularly during surface operations on the Mars. We finished three summer cycles plus three winter cycles (2010 cycles) and have not found any Type Y PRT failures associated with the bonding process. The reliability of the type Y PRT sensors is very critical since they allow us to monitor the health of the hardware during the mission life cycle on the Mars surface. Figure 16 shows the optical photograph of all the PRTs with various substrate materials and attached with various bonding materials. Type Y PRT has survived 2010 extreme temperature thermal cycles to meet the requirements of the MSL project requirements. Type Y PRT attachment was intact even after 2010 thermal cycles. Figure 16 shows the loss of cable staking material adhesion to the substrate after 2010 thermal cycles. This will not affect the performance of the PRT. 78 PRTs Type Y were bonded onto six different substrate materials using four different adhesives and thermally cycled for 2010 cycles which included a planetary protection cycle to 125°C for two hours, 3 protoflight/qual cycles (-135°C to 70°C), 1384 summer cycles (-105°C to 40°C), and 599 winter cycles (-130°C to 15°C). There were no observed changes in PRT resistances, bonding characteristics or no damage identified from the package evaluation as a result of the thermal cycling. The test data indicate that the PRTs (type Y) and bonding processes identified in these tests can survive the environmental conditions expected on Mars with margins meeting JPL design principles. [8, 9, and 10] Similar staking adhesion failure was observed when PRTs qualified to JUNO project as shown in Figure 16b.

Flip-chip reliability:

Advanced packaging interconnects technology such as flip-chip interconnect test boards (FB250 and FB500 in figure 17) have been subjected to various extreme temperature ranges that cover military specifications and extreme Mars and asteroid (Nereus) environments. The change in resistance of the daisy chained flip chip interconnects was measured as a function of increasing number of thermal cycles. No catastrophic failures were observed yet even after 481 extreme temperatures thermal cycles as per electrical resistance measurements and repeated the test for 311 thermal cycles to corroborate the test result for FB250. Failures were observed in FB500 board electrical based on resistance measurements during extreme temperature thermal cycling after 322 thermal cycles (Figure 17 and 18). Three daisy chains were open out of 10 daisy chains as per test data in FB500 board. Daisy chains are open during the cold cycle and recover during the hot cycle. [13]
**Tin Whiskers:**

Several experiments were performed to investigate the combined effects of temperature range, number of thermal cycles, and isothermal exposure in whisker initiation and growth. This work describes whisker growth on chip capacitors terminated with pure tin over a nickel barrier where some parts were tested “as is”, others exposed to solder heat, and some soldered to a printed circuit board. Similar chip capacitors were installed in flight assemblies of the Mars Exploration Rover’s (MER’s) Small Deep Space Transponder (SDST). The MER “landed” mission will experience 90 thermal diurnal cycles from –35°C to +50°C. Although 300 cycles equates to approximately 3-Mission lifetimes, the acceleration factors have not been determined yet. Uniform growth steps as seen in the figure 19, which appear analogous to fatigue striations, associated with some thermal cycling profiles have been observed. Each striation may be equivalent to one thermal cycle. The fastest growth steps were observed during the –15°C to +110°C thermal cycle profile yielding a growth rate of 0.125 µm per cycle. The longest tin whisker observed under this profile was 40 µm after 492 cycles. The average whisker length for the sample was 22 µm. The minimum conductor spacing in the SDST was 254 µm. With the average whisker length plus 3-sigma = 42 µm being less than 20% of 254 µm, shorting in SDST module due to whisker formation was appeared to be of low risk to SDST of MER mission. [14]

**Motors:**

The purpose of this reliability test of motor bare rotors and fully assembled motors of RE020, RE025 for space flight under extreme environments (-120°C to 115°C) and (-120°C to 85°C) in the MER project to survive 90 Mars days mission. The survivability of these motors was tested for 270 thermal cycles (3 times the mission length, 3 x 90) from -120°C to +85°C. This reliability test will consist of inspection of the bare rotors, RE020 and RE025 motors by optical techniques before and after thermal cycling under two extreme temperature ranges (a. -120°C to +115°C and b. -120°C to +85°C). Bare rotors were continuously monitored for resistance to look for any intermittent failures, especially at the temperature extremes. Assembled motors were tested at selected intervals, at the temperature extremes, to look for open circuit failures. Figure 20a show the optical photograph of the motors used in this reliability test. Figure 20b is an optical photograph of the encoder of the motor. Figure 20c is the x-ray image of the solder joint of the fully assembled encoder in the motor body. Very poor design of the solder joint between encoder and the power lead is seen. Therefore, this motor has been redesigned to improve the solder joint quality. RE25-041 and others were continuously electrically monitored to find out any intermittent failures in the windings. Figure 21 show the resistance of the windings vs., thermal cycling. (a) is the normal data of the windings as a function of thermal cycles, (b) one of the winding has failed around 89th thermal cycle, (c) second winding has failed around ~183rd cycle. Figure 4d is the enhancement of the second failure upon further thermal cycling. This motor design was able to survive one mission life cycle. Table 3 show the summary of the motors/rotors qualification tested for MER project.

**Heaters:**
Figure 22 shows the optical photograph of the heater that will be used during entry descent landing operation for MSL project on a certain type of hardware. At approximately 100°C some bubbling occurred on the Kapton heater. The size of the bubbles increased until the sample reached 220°C, at which point the bubbling remained relatively constant for 30 minutes. During the entirety of the test, the edges of the heater remained bonded to the titanium plate. During the test, no changes were noticed in the PRT or PRT adhesive. The test article was removed from the chamber after the hardware returned to room temperature. During the test, portions of the heater edge had lifted from the titanium plate while most of the heater edge remained bonded. This heater will be used only once during EDL operations. Figure 23 shows the optical photograph of the Kapton heater that was bonded to the backside of the solar panel after 270 thermal cycles of -120°C to +110°C. Significant portion of the Kapton heater was bubbled during the 270 thermal cycle test. There was no inspection data to draw the conclusion that when the heater started buckling-off of the substrate.

**Force sensor:**

A force sensor will be used for MSL project. We only completed 15 thermal cycles (-130°C to +40°C) to assess the workmanship. Several micro cracks have been observed in GageKoat material. Several bubbles have also been observed. Gradual change in resistance in one of the 700 ohm strain gauges was observed. Strain gauge started showing anomaly on the 15th cycle as shown in figure 24. Figure 25 shows the failure of the active components may be due to the cracks and bubble in the GageKoat material.

**Flex print cables:**

Figure 26 shows the optical photographs of the flex print cable prior to and after three protoflight thermal cycles for MSL project. There was adhesion failure at the bending of the flex print. No adhesion failure before the thermal cycling and adhesion failure was observed after thermal cycling. There are several approaches that are under development to mitigate the failure in the subsequent flex cable designs.

**Ceramic Column Grid Array (CCGA) packages:**

Advanced CCGA packaging interconnect technology test objects have been subjected to extreme temperature thermal cycles. The change in resistance of the daisy chained CCGA interconnects was measured as a function of increasing number of thermal cycles. Several catastrophic failures were observed after 137 extreme temperatures thermal cycles as per electrical resistance measurements and continued the test for 1058 thermal cycles to corroborate and understand the test results. Failures were observed based on electrical resistance measurements during extreme temperature thermal cycling after 137 thermal cycles. Six daisy chains were open out of 8 daisy chains as per experimental test data reported. Daisy chains are open during the cold cycle and recover during the hot cycle. CCGA packages have been tested from -185°C to +125°C. 63.2% failures were observed for ~664 thermal cycles. Thermal cycles are defined as the time at which 63.2% of the device population would have failed. A shape factor more than 1 indicates that this is related to constant failure rate during normal life or useful life of the package in a bathtub curve. Corner columns have failed first and dislodged.
Two failure mechanisms have been realized such as dislodging the column from the board/ceramic and failure of solder fillet. [15] Figure 27 shows the failure sign of the solder joint during thermal cycling of CCGA package via resistance monitoring of daisy chains. Figure 27 also shows the complete CCGA package and highly magnified view of solder joint failures of the columns. Figure 28 shows the unreliability vs. thermal cycles to failure data generated using experimental data.

Figure 29 shows the pressure sensors that were placed in the thermal chamber which have undergone NASA thermal cycles from -55°C to 100°C. These sensors were fabricated by New Jersey Institute of Technology for the Army. [16] A continuation of sample testing for the wired strain sensor that have completed the 200 thermal cycle of -55°C to 200°C. The samples are first etched via O₂ plasma with the RIE system to remove the top layer encapsulation of SiO₂, SiNₓ (top) + SiO₂ (bottom), and SiNₓ respectively. The sample’s resistivity has been measured with a digital multimeter probe. The average resistance of the sample, especially with SiO₂ top coat, is higher compare to the uncycled measurement. This resistance increase is due to the micro-fissures in the semiconductor thin films (active element).

Conclusions

Engineering camera packaging designs and PRT temperature sensors were successfully qualified for MER and MSL per JPL design principles under extreme temperatures. Package failures were observed during qualification processes and package redesigns were then made and tested to enhance the reliability and subsequently mission assurance. New PRT sensor (Type Y) design qualification has been successfully completed for the MSL project. These results show the technology is promising for MSL and especially for long term missions. Type X PRTs experienced some failures as shown in this paper as a result of extreme temperature thermal cycling.

During the first test all the PRTs with excess adhesive have failed for only 22 thermal cycles. All PRTs bonded with JPL process with adhesive 2 with no excess adhesive (bond line was more than 10 mil) have also failed within 22 thermal cycles. All PRTs bonded with JPL process with adhesive 2 with no excess adhesive (bond line was equal to 10 mil) have also failed only after 81 thermal cycles. JPL process with RTV 566 with no excess adhesive material beyond the PRT body (bond line was equal to 10 mil) has also been implemented in this study. As per resistance characteristics PRT was functional for the complete duration of thermal cycling test (270 thermal cycles). PRT behavior was consistent throughout the test based on analysis of the raw thermal cycling test data. But, there is no evidence to support the notion that the PRT became de-bonded during the test or after the thermal cycling test. However, the result was PRT has debonded from the aluminum block substrate. This process was adopted in reworked MER rover. Staking was also debonded in two different tests performed for Mars programs and JUNO project.

PQV Tests were completed for 275 thermal cycles (cumulative) from -120°C to 85°C. All RE025 Motors and Rotors have at least one failure during the qualification test. Additional failures can be detected in the bare rotors after first failure detection. They were redesigned and improved the life these motors for the project. Kapton thin film heaters showed bubbling at
approximately 100°C. The size of the bubbles increased until the heater reached 220°C, at which point the bubbling remained relatively constant for 30 minutes. This is one time use for entry descent landing operations and is considered as qualified for the project with a low risk. Kapton thin film heaters were qualified from -120°C to +110°C for Mars exploration program. We noticed the buckling of the heater from the base material and this design has been improved and implemented for the project. Growth of Tin whiskers has been studied on a particular hardware and assessed length the whiskers are substantially less than the distance between the components in the hardware and the assessed the risk with reference to complete project duration. A sensor was subjected to qualification and found that there are some failures in the coating materials that were employed. Mitigation process for this sensor is in progress. One of the sensors failed as a result of thermal cycling. Flex print cables were subjected to extreme temperature qualification for Mars programs and found that there are some adhesion issues and the process is in progress to mitigate this issue. Qualification via testing to meet the project requirements is a challenging one and this process certainly enhances the mission assurance by fixing the problems in advance. This will be a cost effective approach to meet the project schedules. All in all, this process will enhance the mission assurance for the project.

Acknowledgements

The research work described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA. This work is sponsored by the National Aeronautics and Space Administration’s (NASA) Mars Exploration Rover (MER), Mars Science Laboratory (MSL), MetCal NEMS task, and by the ARMY project on MEMS/flexible sensor package reliability at JPL. I would like to thank Mike Blakely, Steve Franklin, John Forgrave, Richard P. Brace, Christine Farguson, Gordy Cucullu, Justin Maki, Brett Kennedy, Kevin Burke, Don Noon, Wayne P. Bosze, Michael Hagman, Angel Garnica, Edwin Kan, Mark Schwochert, Eric Sunada, Amarit Kitiyakara, Richard Reddick, Frank Kelly, Anthony Parris, Rebecca L. Mikhaylov, Steven W. Lee, Jacqueline C. Lyra, Richard P. Kemski, Matthew T. Wallace, Richard Cook, Donald V. Schatzel, Ali M. Pourang, Tuyet T. Nguyen, Peter A. Kozb effic, Richard Paynter, Keith Novak, Ashwin Vasavada, etc., for their interest and support in various stages of this qualification effort. I want to particularly thank James Zunino (Army), H.C. Lim, J. Federici (NJIT) for providing me the sensors for thermal cycling to assess their reliability.

References

1. http://marsrover.nasa.gov/home/
8. R. Ramesham, “Extreme Temperature Thermal Cycling Tests and Results to Assess Reliability for Mars Rover Flight Qualification”
11. J. Murphy, New Mexico State University, Ames GCM (Global Circulation Model) Simulation data.
12. Ashwin Vasavada, Personal Communication (JPL)
**Figure 1:** Mars rover family, Pathfinder, Spirit/Opportunity, and Curiosity

**Figure 2:** Optical photograph of the engineering camera that was used in MER project

**Figure 3:** Optical photograph of a cracked interconnect in a package assembly after 50 cycles with a $\Delta T$ of 235°C. (-120°C to 115°C) for MER project
Figure 4: Temperature profile corresponding to summer season of MSL mission

Figure 5: Temperature profile corresponding to winter season of MSL mission

Figure 6: Sequence of thermal testing profile for MSL mission

Figure 7: Optical photograph of a cracked interconnect in a leadless package of camera assembly after 170 cycles with a ΔT of 145°C. (-105°C to 40°C) for MSL project
Figure 8: Images of the test object after complete PQV test and Picture of PQV team that was taken using the PQV tested camera after completing the package qualification and verification test.

<table>
<thead>
<tr>
<th>MSL PQV Range</th>
<th>MER Delta T</th>
<th>Tested for MER No. of Cycles</th>
<th>MSL Equivalent Cycles Estimated</th>
</tr>
</thead>
<tbody>
<tr>
<td>145</td>
<td>235</td>
<td>50 (SMT)</td>
<td>131</td>
</tr>
<tr>
<td>145</td>
<td>205</td>
<td>121 (L-shaped)</td>
<td>241</td>
</tr>
<tr>
<td>145</td>
<td>205</td>
<td>200 (Looped haywire)</td>
<td>400</td>
</tr>
<tr>
<td>145</td>
<td>235</td>
<td>65 (estimated)</td>
<td>170 (MSL Test)</td>
</tr>
<tr>
<td>145</td>
<td>205</td>
<td>85 estimated</td>
<td>170 MSL Test</td>
</tr>
</tbody>
</table>

Table 1: Package Qualification and Verification LCC package Test results of MER and MSL camera.
Figure 9: Optical photographs of the PRTs prior to planetary protection bake and PQV thermal cycling.

Figure 10: Resistance of PRTs vs. the temperature.

PRT1-5: ~5000 ohms
PRT value at 110°C: ~7000 Ohms
PRT value at -110°C: ~2800 Ohms

After planetary protection
PRT1 failed as per data overload data (Please see arrow) after two cycles
PRT2-5 functional (please see arrows) even after 3 cycles
<table>
<thead>
<tr>
<th>Planetary protection bake out cycles</th>
<th>PRT1 or Coupon#1 or FO52</th>
<th>PRT2 or Coupon#2 or FO50</th>
<th>PRT3 or Coupon#3 or FO61</th>
<th>PRT4 or Coupon#4 or ER37</th>
<th>PRT5 or Coupon#5 or ER41</th>
</tr>
</thead>
<tbody>
<tr>
<td>Requirement: 3 thermal cycles</td>
<td>Open after 2nd cycle</td>
<td>Survived 3 cycles</td>
<td>Survived 3 cycles</td>
<td>Survived 3 cycles</td>
<td>Survived 3 cycles</td>
</tr>
<tr>
<td>PQV Test Requirement: 300 thermal cycles</td>
<td>Cycle 1</td>
<td>Open whether hot or cold temperatures</td>
<td>close</td>
<td>close</td>
<td>close</td>
</tr>
<tr>
<td></td>
<td>7 cycles</td>
<td>Close</td>
<td>Close</td>
<td>First open Open at cold Close at hot</td>
<td>Close</td>
</tr>
<tr>
<td></td>
<td>15 cycles</td>
<td>open</td>
<td>First open Open at cold Close at hot</td>
<td>Close</td>
<td>Completely open whether hot or cold during 15th cycle</td>
</tr>
<tr>
<td></td>
<td>21 cycles</td>
<td>open</td>
<td>Open</td>
<td>First open Open at cold Close at hot</td>
<td>Open</td>
</tr>
<tr>
<td></td>
<td>22 cycles</td>
<td>Open</td>
<td>Open</td>
<td>Open</td>
<td>Open</td>
</tr>
</tbody>
</table>

Table 2: Summary of PRT bonded with adhesive 1 and adhesive 2

![Adhesive 2]

Figure 11: PRT failed after 81 cycles of -120°C to 40°C
While lifting this flap of tape with a knife edge, the PRT debonded from surface. Very little force was used to move tape flap.

Figure 12: Optical photograph of the test article after cutting the Silverized Kapton tape. 5000 Ohms PRT attached with RTV 566 (4 lead)

Figure 13: An optical image of the PRTs used in MSL engineering camera
Figure 14: Showing the signs of PRT (Type X) failure at 585\textsuperscript{th} thermal cycle and continued until 609\textsuperscript{th} thermal cycle.

Figure 15: Optical photographs of the temperature sensor/PRTs (Type Y) to be used for MSL project.
**Figure 16a:** Loss of adhesion of staking materials as a function of thermal cycling.

16b. Loss of adhesion of staking at H3 after 21 cycles -150°C to 120°C
Figure 17: Optical photographs of the assembled advanced flip-chip interconnect test boards of FB250 and FB500.

Figure 18: Flip-chip board with the first failure observed at 322nd thermal cycles -190°C to 85°C.
Figure 19: Tin whiskers grown over pure tin finishes used on ceramic capacitor terminations

Figure 20: (a) motor, (b) encoder, (c) x-image of solder joint, (d) failure vs. thermal cycles
<table>
<thead>
<tr>
<th></th>
<th>Cycles finished</th>
<th>Failure</th>
<th>Failure 1 at</th>
<th>Failure 2 at</th>
<th>Failure 3 at</th>
<th>Failure 4 at</th>
<th>Failure 5 at</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotor</td>
<td>026</td>
<td>240</td>
<td>Yes</td>
<td>214 cycles</td>
<td>214-229 cycles</td>
<td>231 cycles</td>
<td></td>
</tr>
<tr>
<td>Rotor</td>
<td>041</td>
<td>240</td>
<td>Yes</td>
<td>89 cycles</td>
<td>183 cycles</td>
<td>201 cycles</td>
<td></td>
</tr>
<tr>
<td>Rotor</td>
<td>042</td>
<td>240</td>
<td>Yes</td>
<td>128 cycles</td>
<td>129 cycles</td>
<td>133-163 cycles</td>
<td>204 cycles</td>
</tr>
<tr>
<td>Rotor (PQV1 test article)</td>
<td>065</td>
<td>240</td>
<td>Pre-failed (multiple failures)</td>
<td>Too many pre-existing failures; removed from instrumentation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Motor</td>
<td>040</td>
<td>240</td>
<td>Yes</td>
<td>206-229 cycles</td>
<td>Subsequent failures can not be determined</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Motor</td>
<td>051</td>
<td>240</td>
<td>Yes</td>
<td>93-133 cycles</td>
<td>Subsequent failures can not be determined</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Motor (PQV1 test article)</td>
<td>064</td>
<td>240</td>
<td>Pre-failed (multiple failures)</td>
<td>Subsequent failures can not be determined</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3: Summary of the motor PQV test for MER project.

Figure 21: PQV test article RE 25#041, sign of failure, first enhancement of failure, enhancement of failure 2
Figure 22: Bubbling under Kapton thin film heater during protoflight qualification

Figure 23: Optical photograph of the Kapton thin film heater after 270 cycles PQV test.
Figure 24: Resistance of the active element in the sensor vs. thermal cycling

Figure 25: Optical photograph of the sensor after 15 thermal cycles.
Figure 26: Optical photographs of the flex print cables for wiring and harness application.

Figure 27: Digital photographs that were taken after 1058 thermal cycles. Digital photograph of failed solder joint in a CCGA package.
Figure 28: A plot of unreliability vs. thermal cycles to failure data generated using experimental data.

Figure 29. Flexible sensor packages of Army (-55°C to 100°C)
Dr. Rajeshuni Ramesham joined JPL in Nov 1997 and presently is a Principal Member of Engineering Staff. At the Academic level, he has worked as a research faculty in Auburn University, Auburn, Alabama from 1989 - 1997. He was an adjunct professor at Auburn University, Auburn, AL. His present research-work at JPL is focused on extreme temperature electronics and interconnects reliability, the reliability of packaging and interconnects associated with the MEMS/MOEMS for space applications. Ram currently has devoted most of his time towards JPL/NASA Mars Science Laboratory, JUNO, GRAIL, etc., projects. He worked on the application of polycrystalline synthetic diamond for MEMS, electrochemical and corrosion resistant coating applications. Ram is the recipient of several NASA awards for the research work he has performed at JPL. He has also received an outstanding research performance award from the Electrical Engineering Department of Auburn University and a best research paper award published in J. Electrochemical Society from the IEEE Alabama Section; both of which he received in 1990.

Ramesham has published over 130-refereed journal and proceedings articles and has made over 110 national and international conference presentations. He was a Key Note speaker at the IEEE conference held in Las Vegas in May 2000. He is an editor of over 12 conference proceedings. Ram has been awarded three U.S. patents and seven NASA internal disclosures. He has published a chapter in “Fundamentals of Microsystems Packaging” published by McGraw-Hill. Ramesham has been a conference chair, workshop general chair and technical chair for various MEMS, MOEMS, E-Nose, optoelectronics packaging, and low temperature electronics sponsored by various societies. He served as Symposium Chair for MOEMS-MEMS Micro & Nanofabrication Symposium a part of Photonics West. He is presently serving as a Steering Committee Chair for MOEMS/MEMS symposium and also as a conference Chair for Reliability, Packaging, Testing and Characterization of MEMS/MOEMS. He organized thermal testing panel discussions at TFAWS-2008 and ICES-2009 addressing for NASA’s space and other space agencies applications.