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Qualification Testing of Engineering Camera and Platinum Resistance Thermometer (PRT) Sensors for MSL Project Under Extreme Temperatures to Assess Reliability and to Enhance Mission Assurance

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Abstract—**Package qualification and verification (PQV) of advanced electronic packaging and interconnect technologies and various other types of qualification hardware for the Mars Exploration Rover/Mars Science Laboratory flight projects has been performed to enhance the mission assurance. The qualification of hardware (engineering camera and platinum resistance thermometer, PRT) under extreme cold temperatures has been performed with reference to various project requirements. The flight-like packages, sensors, and subassemblies have been selected for the study to survive three times (3×) 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 has been performed by subjecting above flight-like qual hardware to the environmental temperature extremes and assessing any structural failures or degradation in electrical performance due to either overstress or thermal cycle fatigue. Experiments of flight-like hardware qualification tests are described in this paper.**

Keywords—**Engineering camera, platinum resistance thermometer (PRT), hardware qualification, extreme temperatures, package qualification, package reliability, thermal cycling, leadless chip carrier (LCC)**

Introduction

JPL/NASA is developing a 2009 Mars mission 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. The Mars Science Laboratory (MSL) will be launched in October 2009, arriving at Mars in the summer of 2010. The mobile laboratory will be about twice as long (about 2.8 m or 9 ft) and four times as heavy as JPL/NASA's twin Mars Exploration Rovers (Spirit and Opportunity), which were launched in 2003. 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 life span on Mars' surface of a full Mars year (687 Earth days) or more. This makes the reliability of the hardware very interesting and significantly challenging.

The engineering cameras were designed and developed in parallel with the Pancam [1] and Microscopic Imager [2] 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 [3]. As Maki et al. [3] reports, the MER (Mars Exploration Rover) engineering cameras did, as part of the surface navigation process, contribute 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 [3]. 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.

Objectives of the MSL Project [4]

The science goal of the mission is to assess whether the landing area ever had or still has environmental conditions favorable to microbial life. The investigations to support that assessment include:

- Detecting and identifying any organic carbon compounds.
- Making an inventory of the key building blocks of life.
- Identifying features that may represent effects of biological processes.
- Examining rocks and soils at and near the surface to interpret the processes that formed and modified them.
- Assessing how Mars' atmosphere has changed over billions of years.
- Determining current distribution and cycles of water and carbon dioxide, whether frozen, liquid, or gaseous.

Science Summary of the MSL Project [4]

The Mars Science Laboratory is being designed to assess whether Mars ever had an environment capable of supporting microbial life. Determining past habitability of Mars gives

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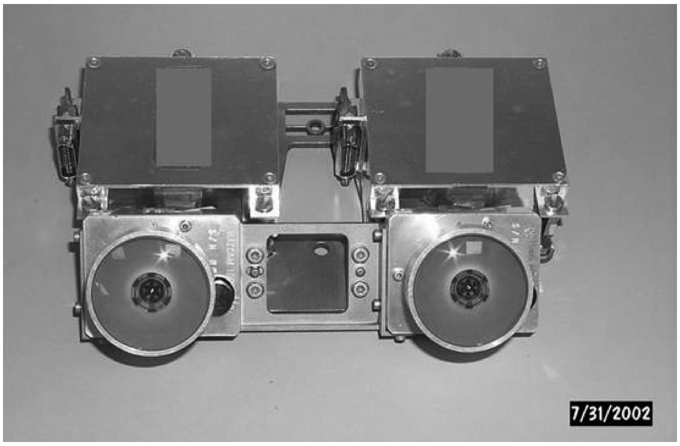


Fig. 1. Optical photograph of the engineering camera that was used in MER project.

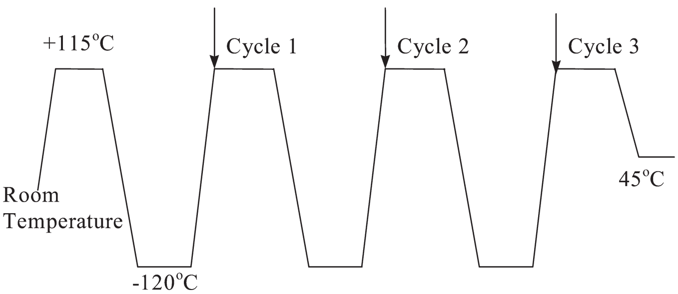


Fig. 2. Temperature profile used for MER mission to qualify the packages.

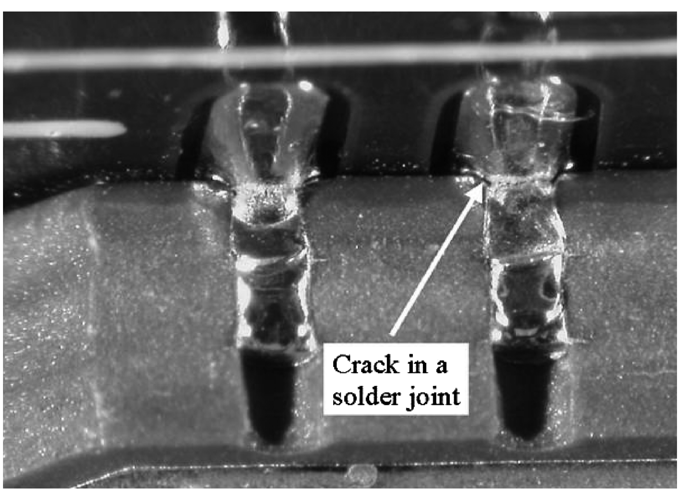


Fig. 3. Optical photograph of a cracked interconnect in a package assembly after 50 cycles with a ΔT of 235°C (–120°C to 115°C) for the MER mission.

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. Four goals of this project are as follows.

1) Determine whether life ever arose on Mars.
2) Characterize the climate of Mars.
3) Characterize the geology of Mars.
4) Prepare for human exploration.

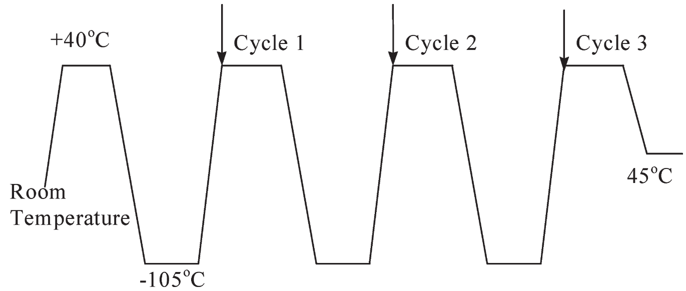


Fig. 4. Temperature profile corresponding to the summer season for the MSL mission.

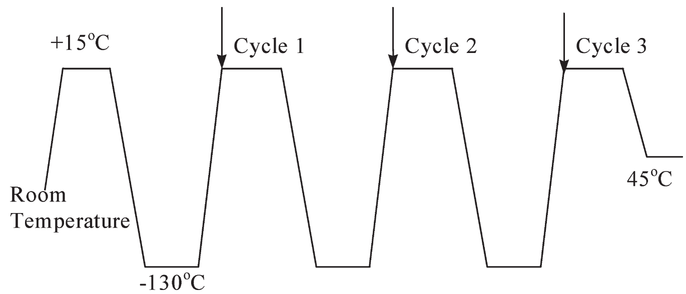


Fig. 5. Temperature profile corresponding to the winter season for the MSL mission.

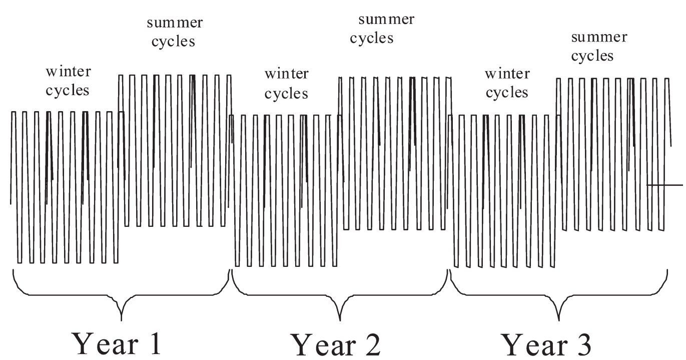


Fig. 6. Sequence of thermal testing profile for the MSL mission.

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, vias, etc.) occurring in flight hardware of JPL/NASA projects. Interconnects that serve as both the electrical and mechanical interconnects are known 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 a combination of these. Successful implementation

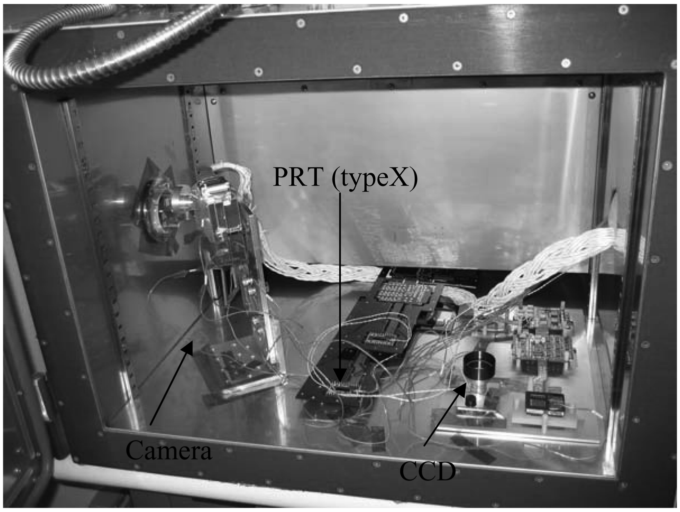


Fig. 7. Photograph of the MSL engineering camera in the side thermal chamber, electronics board, PRTs, CCDS, and so on.

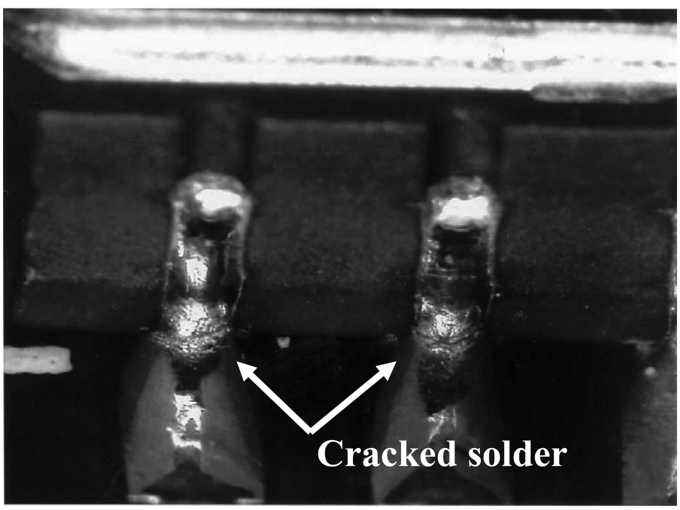


Fig. 8. Photograph of a cracked interconnect in a leadless package of camera assembly after 170 cycles with a ΔT of 145°C (–105°C to 40°C) for the MSL mission.

of the PQV plan/program is necessary to ensure 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 show the package qualification and verification test data associated with engineering/navigational/hazardous camera and platinum resistance thermometers for the MSL project and compare these with the MER data. The Mars exploration rover mission was only a 90 sol (Mars solar

Fig. 9. Images of the test object after complete PQV test.

Fig. 10. Picture taken using the PQV tested camera after completing the package qualification and verification test.

day) mission whereas the MSL is a 670 sol mission. The package requirements for the hardware are to survive 270 sols for the MER and 2010 sols for the MSL mission. The standard electronic packages are not generally built for low temperature applications down to –130°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 [e.g., resistors, capacitors, leadless chip carrier (LCC) packages, etc.] is

Table I
Package Qualification and Verification Test Results of MER and MSL Camera

MSL PQV Range	MER ΔT	Tested for MER No. of Cycles	MSL Equivalent Cycles Estimated
145	235	50 (SMT)	131
145	205	121 (L-shaped)	241
145	205	200 (Looped haywire)	400
145	235	65 (estimated)	170 (MSL test)
145	205	85 (estimated)	170 (MSL test)

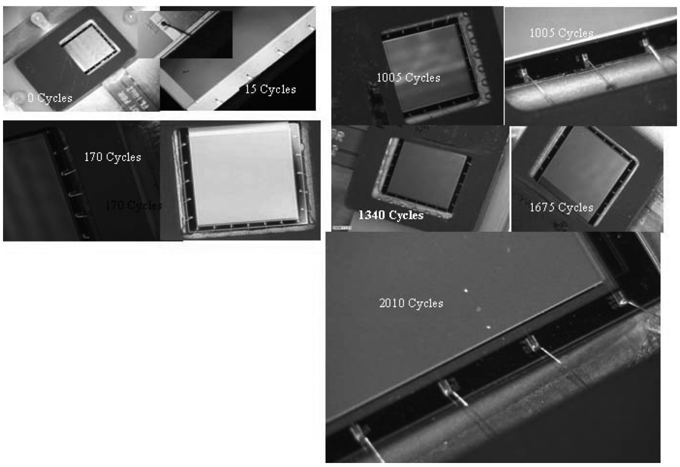


Fig. 11. Photographs of the wire bonds in the CCD as a function of various thermal cycling stages.

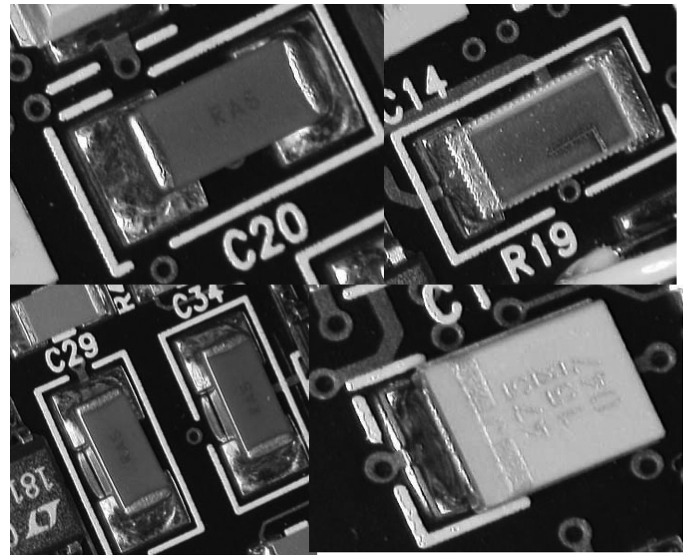


Fig. 12. Photographs of the capacitor and resistance solder joints prior to thermal cycling.

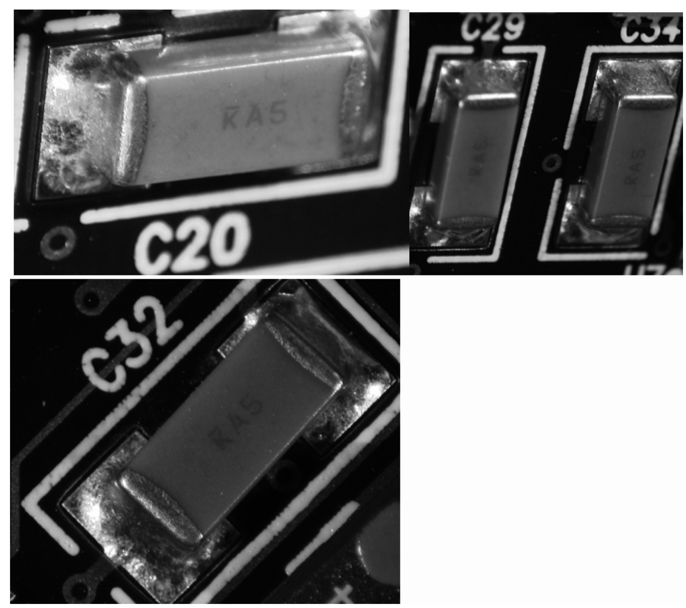


Fig. 13. Photographs of the capacitor solder joints after just 15 thermal cycles.

attempted for low temperature applications to understand the survivability of the hardware and eventually to understand the reliability and enhance the mission assurance.

A soldered connection on a printed circuit board is not well suited to withstand 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 an 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/Navigational/Hazardous Camera

A. MER Hardware

The MER camera was qualified for only 200 thermal cycles (–120°C to 115°C; ΔT = 235°C) to satisfy the 3× mission life per the JPL design principle. A similar camera with the same design should be qualified for 2010 thermal cycles (ΔT = 145°C) for the MSL project to satisfy the JPL design principles. This test is a time-consuming process and involves challenging qualification processes. Qualification of such hardware will enhance mission assurance significantly since we understand the survivability and reliability of the hardware with reference to the project requirements. The MER engineering camera (Fig. 1) was qualified using the thermal profile shown Fig. 2 for 200 thermal cycles. Fig. 3 shows the failure of a standard leadless chip carrier (LCC) package after a test of only 50 thermal cycles. This package did not meet the requirements of the MER project. The improvements for the LCC design were made and the improved LCC package design was

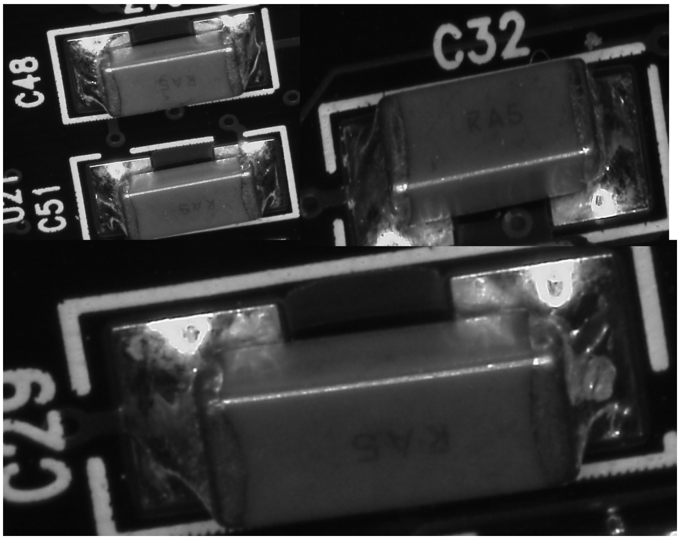


Fig. 14. Photographs of the capacitor solder joints taken after 170 thermal cycles.

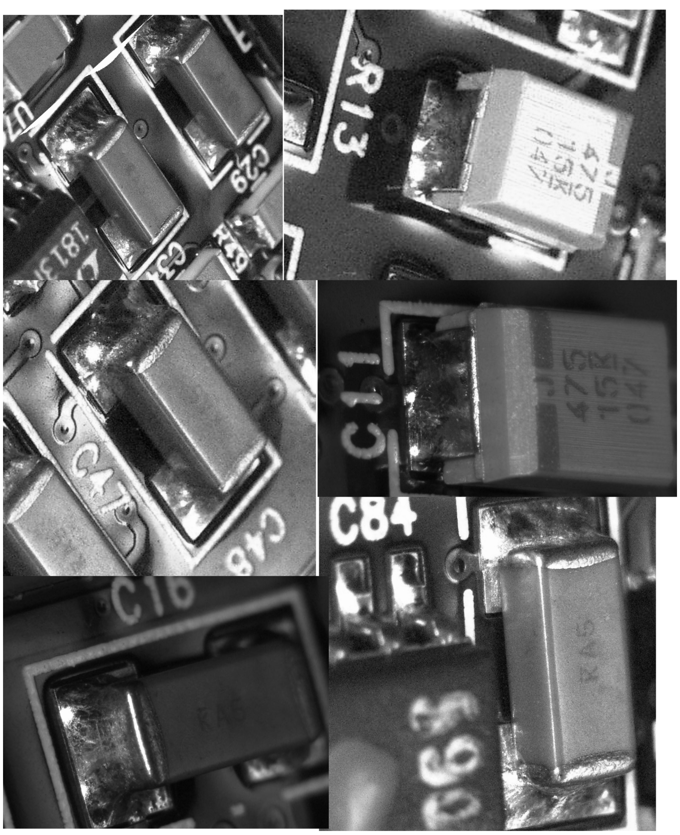
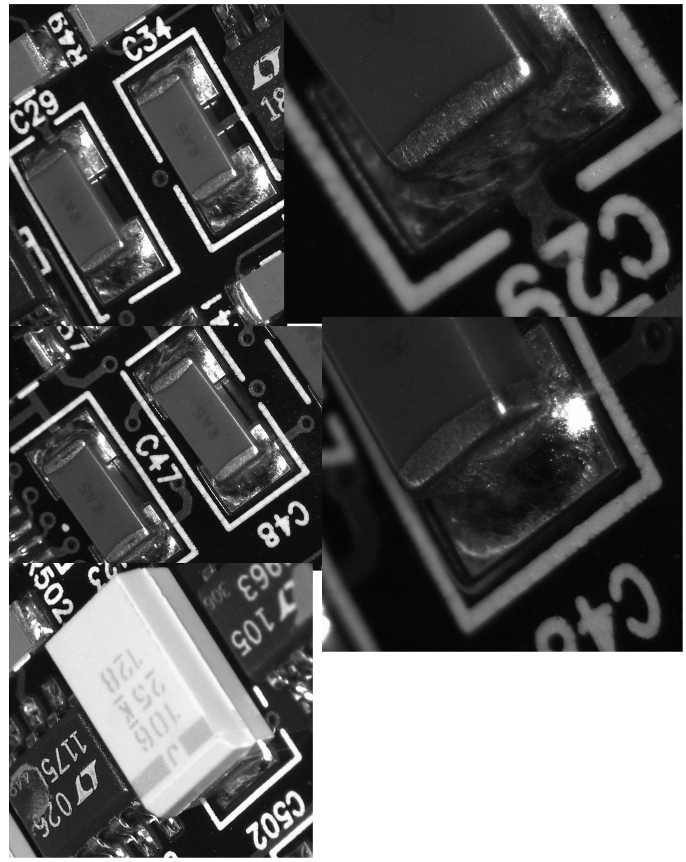
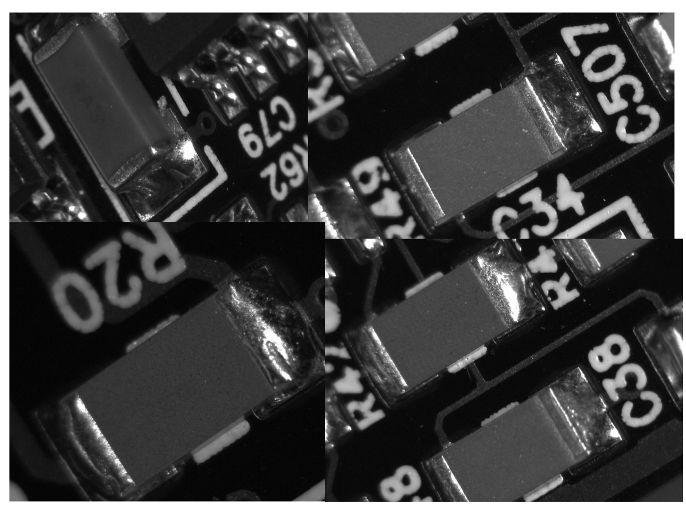


Fig. 15. Photographs of the capacitor solder joints and resistor solder joints taken after 1005 thermal cycles.

retested to qualify for the MER mission for 200 thermal cycles. The Mars rovers are still functional even after more than 1727 sols (Spirit) and 1706 sols (Opportunity) since we have improved the package designs to enhance mission assurance by qualifying the technologies for extreme low/hot temperatures [5, 6].



(a)

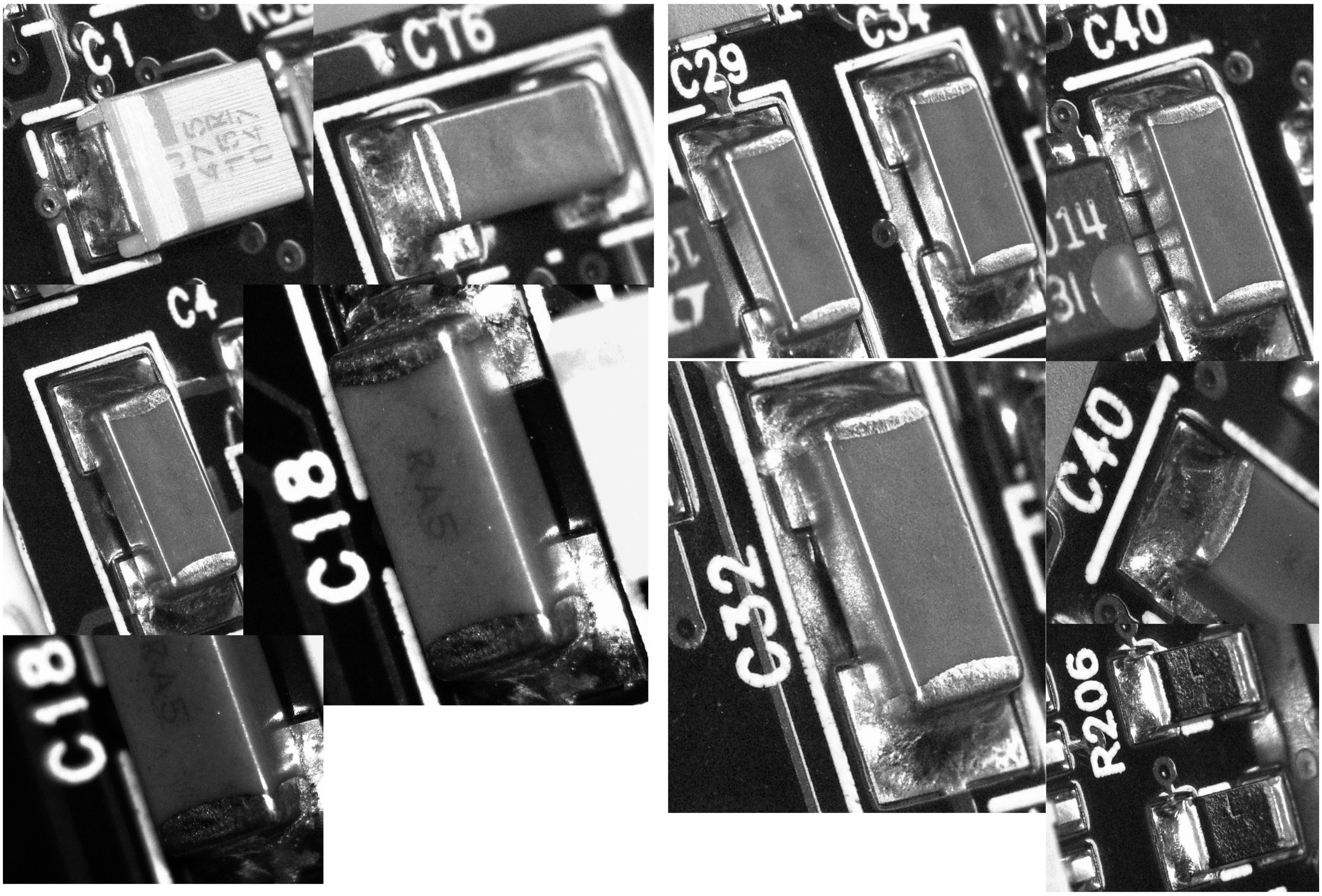


(b)

Fig. 16. Photographs of the capacitor solder joints and resistor solder joints taken after 1340 thermal cycles.

B. MSL Hardware

The camera design that was used for the MER will be used for the MSL project. However, this design needs to be qualified for 2010 thermal cycles with reference to the MSL project requirements and JPL design principles. This hardware does not have a sufficient heritage not to perform the qualification process. Therefore, the qualification must be performed for 2010 thermal



(a) (b)

Fig. 17. Photographs of the capacitor solder joints and resistor solder joints taken after 1675 thermal cycles.

cycles with a desired temperature range based on the landing site on Mars. Figs. 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 [7] and Mars surface atmosphere models by Ashwin Vasavada [8]. Fig. 6 shows the sequence of the seasons that correspond to the PQV testing of camera designs for the MSL project. Fig. 7 shows the optical photograph of the engineering camera, PRTs, and camera electronics boards used to perform the package qualification and verification test. Fig. 8 shows the failure of the same leadless chip carrier package occurred only after 170 MSL thermal summer cycles with a small ΔT. Figs. 9 and 10 are the image of the test object and also the camera PQV team members taken after the completion of the PQV engineering camera test of 2010 extreme temperature thermal cycles. The PQV tested camera is still functional even after the test of 2010 thermal cycles.

It is interesting to note that the same LCC package failed after 50 thermal cycles with a ΔT of 235°C for MER project and the same package failed after 170 cycles with a ΔT of 145°C for the MSL project. These experimental test results and observations corroborate well within the experimental error per reliability of solder joint principles. We have redesigned the package and retested the LCC package for 2010 thermal cycles for the MSL project with complete success. Table I 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 three Martian years on Mars. The camera has been functional even after 2010 thermal cycles as shown in Figs. 9 and 10. This test will particularly enhance the mission assurance and reduce the risk, enhance the confidence about this hardware, and also meet the JPL design principle.

The engineering camera has a charge coupled device that has several wire bonds as shown in Fig. 11. These wire bonds have been tested for 2010 thermal cycles. Fig. 11 show the optical photographs of the wire bonds that have been obtained at various stages of thermal cycling test [0 cycles prior to thermal cycling, 15 cycles, 170 cycles, 1005 cycles, 1340 cycles, 1675 cycles, and 2010 cycles (after the completion of PQV test)]. There were no wire bond failures observed after a test of 2010 thermal cycles. CCD packages were reliable to these temperatures.

The camera electronics were inspected prior to thermal cycling (Fig. 12), and after 15 thermal cycles (Fig. 13), 170 cycles (Fig. 14), 1005 cycles (Fig. 15), 1340 cycles [Fig. 16(a-b)], 1675 cycles [Fig. 17(a-b)], and 2010 cycles [Fig. 18(a-c)]. The

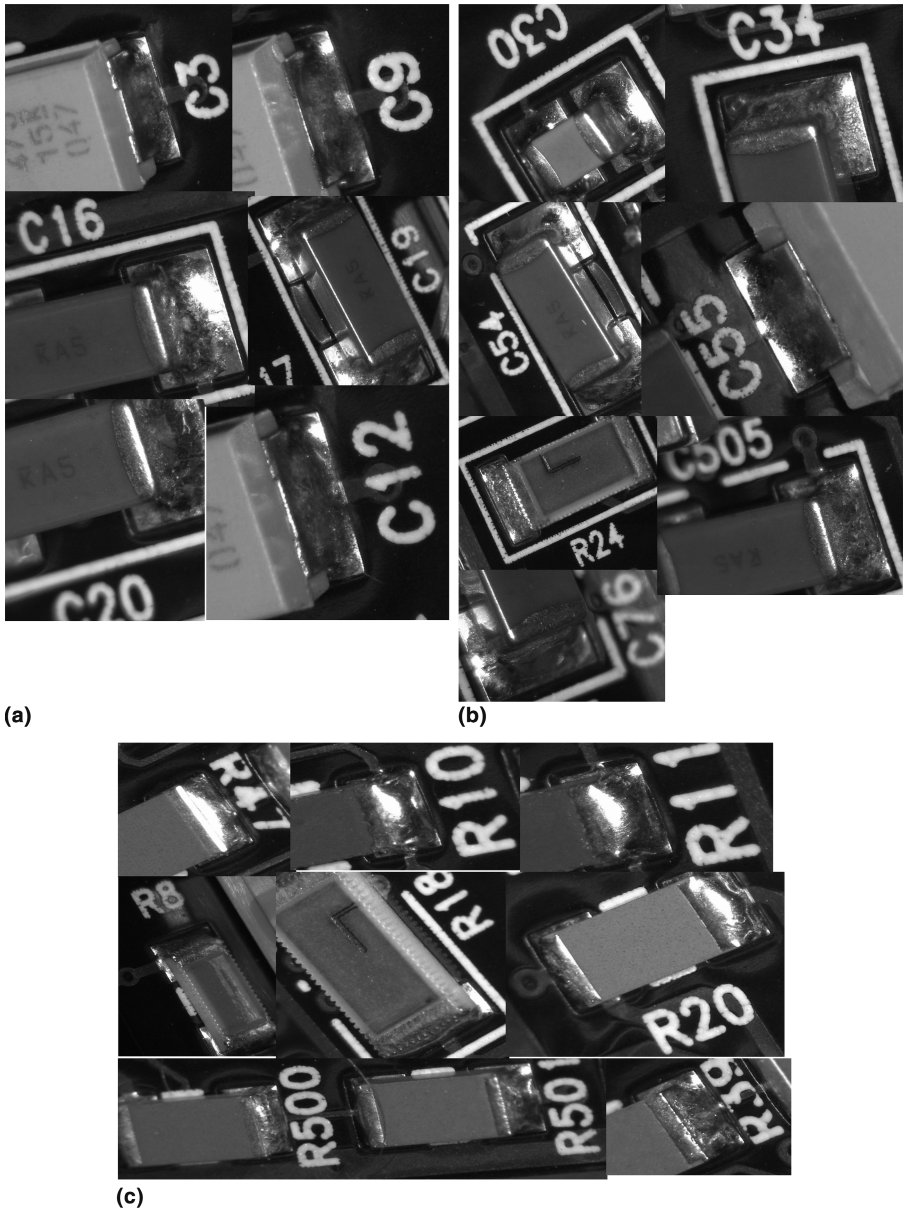


Fig. 18. Photographs of the capacitor solder joints and resistor solder joints taken after 2010 thermal cycles.

components of interest were particularly the resistive, capacitive, and LCC components since they are highly prone to failure due to thermal cycling or thermal fatigue problems. The optical photographs in Figs. 12-18 suggest that the solder joints are reliable except for the LCC package attachment [9-15]. Further tests may be carried out to explore a more deep understanding of the packages and the materials.

C. Platinum Resistance Thermometers (PRT)

Fig. 19 shows photographs of the PRTs (Type Y) that will be used for the MSL project. This is the first time these sensors will be used for Mars related projects. A different type of PRTs (Type X) were employed for the MER project and several reliability issues were experienced even for a short duration mission like the MER. Fig. 20 shows a photograph of the PRTs that were used for MER project and also nondestructive images of the PRT using x-ray imaging. 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 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. Fig. 21 shows the failure of a type X PRT after the 585th thermal cycle. Therefore, the MSL project will be using advanced technology based PRT sensors of type Y. The reliability of the type Y PRT sensors is critical since they allow us to monitor the health of the hardware during the mission life cycle on the Mars surface. Fig. 22 shows the x-ray images of the Type Y PRTs to be used for

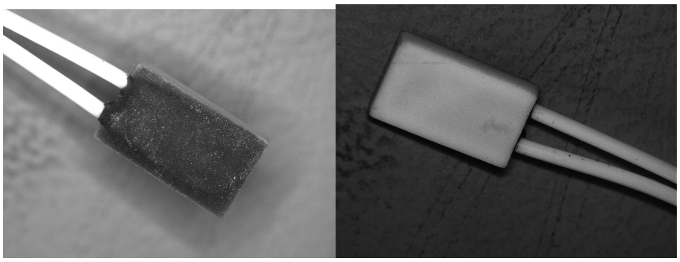


Fig. 19. Photographs of the temperature sensor/PRTs (Type Y) to be used for the MSL project.

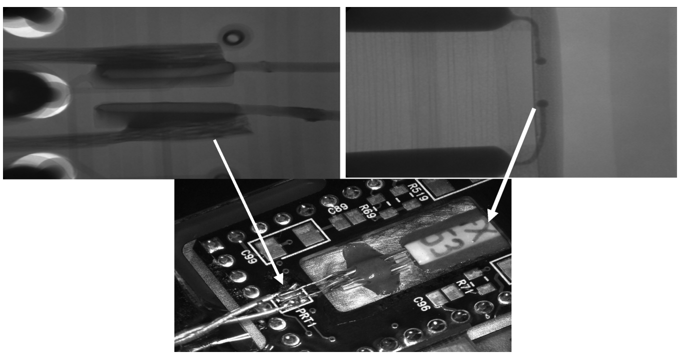


Fig. 20. X-ray images and an optical image of the PRTs that used in MSL engineering camera.

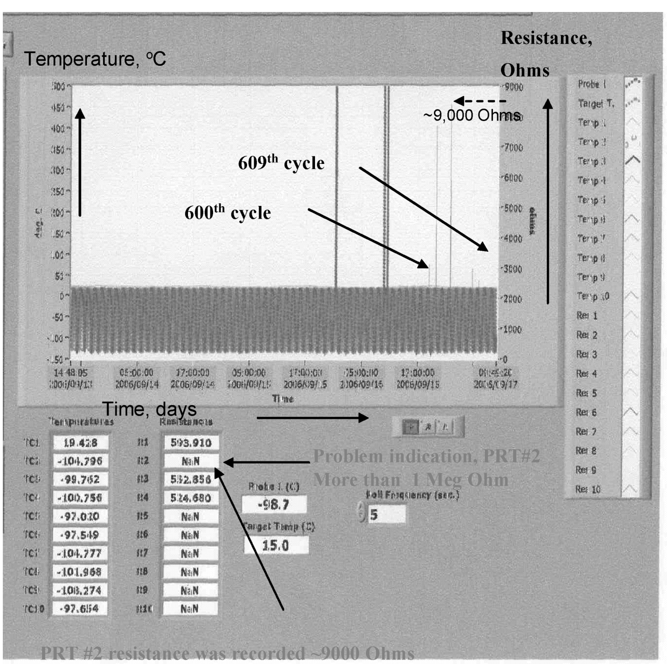


Fig. 21. Showing the signs of PRT (Type X) failure at 585th thermal cycle and continued until 609th thermal cycle.

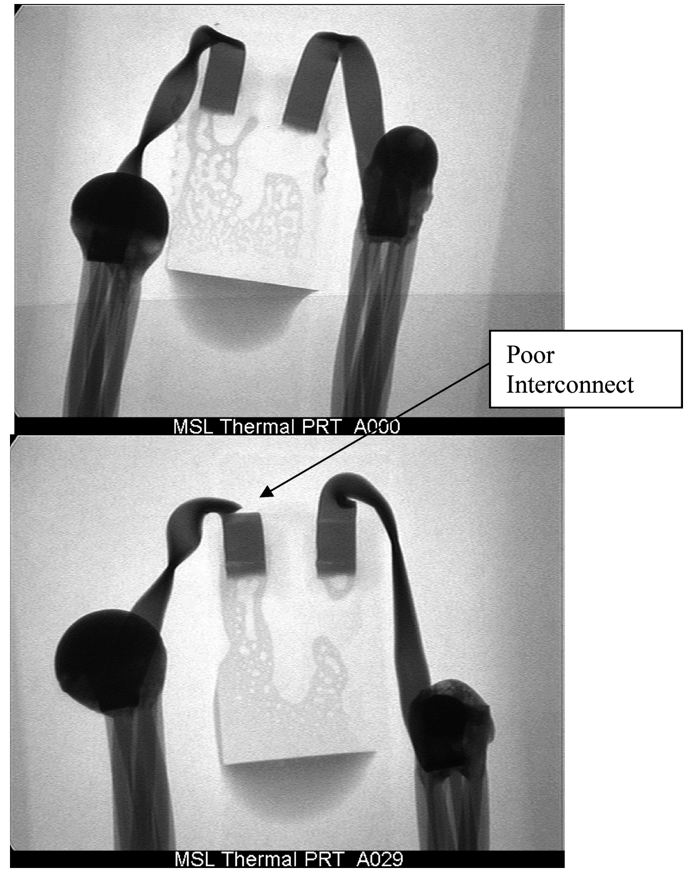


Fig. 22. X-ray images of the Type Y PRT (good and bad quality qualitatively).

Fig. 23. PRTs (Type Y) under the extreme temperature thermal cycling test.

MSL project. Fig. 23 shows the optical photograph of all the PRTs with various substrate materials and attached with various bonding materials. The Type Y PRT has survived 2010 extreme temperature thermal cycles (Figs. 4-6) to meet the requirements of the MSL project requirements. The Type Y PRT attachment was intact even after 2010 thermal cycles. Fig. 24 shows the Type Y PRT attached with a polymeric material that was subjected to various MSL thermal cycles (100 cycles, 470 cycles, 670 cycles, 1140 cycles, 1810 cycles, and 2010 cycles). All the PRTs were intact in bonding to the

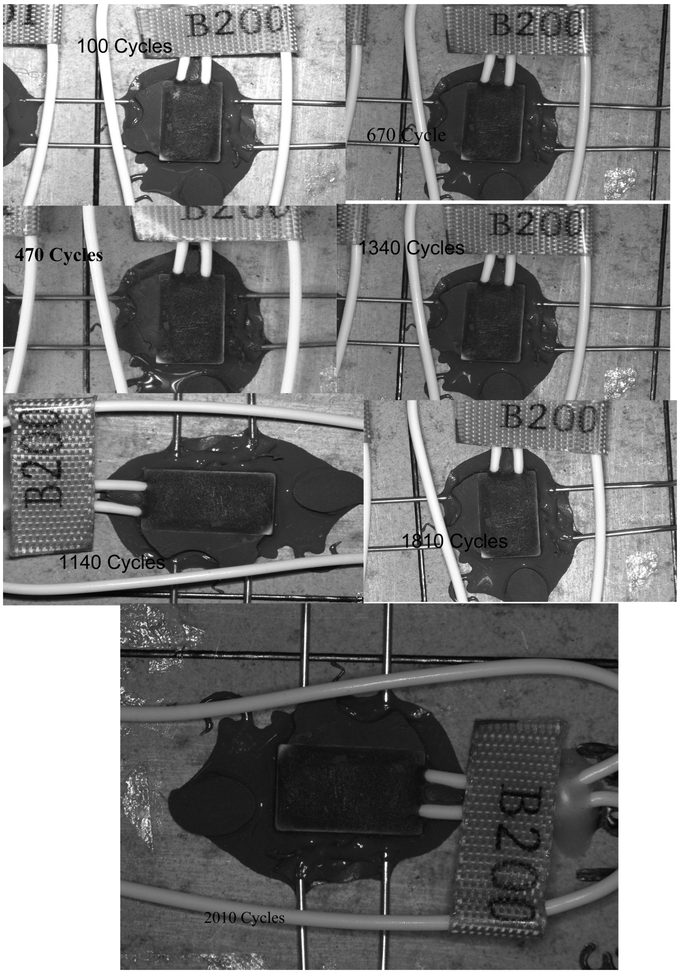


Fig. 24. Photographs of the PRTs that were taken as a function of number of the MSL thermal cycles.

substrate materials even after 2010 thermal cycles. Fig. 25 shows the loss of cable stacking material adhesion to the substrate after 2010 thermal cycles. This will not affect the performance of the PRT.

Seventy-eight Type Y PRTs 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 2 hr, three 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.

Conclusions

Engineering camera packaging designs, CCDs, 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

Fig. 25. Loss of adhesion of stacking materials as a function of thermal cycling.

and package redesigns were then made and tested to enhance the reliability and subsequently mission assurance. A 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 so for long-term missions. Type X PRTs experienced some failures as shown in this paper as a result of extreme temperature thermal cycling.

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