Robust Platinum Resistor Thermometer (PRT) Sensors and Reliable Bonding for Space Missions

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Platinum resistance thermometers (PRTs) provide accurate temperature measurements over a wide temperature range and are used extensively on space missions due to their simplicity and linearity. A standard on spacecraft, PRTs are used to provide precision temperature control and vehicle health assessment. This paper reviews the extensive reliability testing of platinum resistor thermometer sensors (PRTs) and bonding methods used on the Mars Science Laboratory (MSL) mission and for the upcoming Soil Moisture Active Passive (SMAP) mission. During the Mars Exploration Rover (MER) mission, several key, JPL-packaged PRTs failed on those rovers prior to and within 1-Sol of landing due to thermally induced stresses. Similar failures can be traced back to other JPL missions dating back thirty years. As a result, MSL sought out a PRT more forgiving to the packaging configurations used at JPL, and extensively tested the Honeywell HRTS-5760-B-U-0-12 sensor to successfully demonstrate suitable robustness to thermal cycling. Specifically, this PRT was cycled 2,000 times, simulating three Martian winters and summers. The PRTs were bonded to six substrate materials (Aluminum 7050, treated Magnesium AZ231-B, Stainless Steel 304, Albemet, Titanium 6AL4V, and G-10), using four different aerospace adhesives—two epoxies and two silicones—that conformed to MSL's low out-gassing requirements. An additional epoxy was tested in a shorter environmental cycling test, when the need for a different temperature range adhesive was necessary for mobility and actuator hardware late in the fabrication process. All of this testing, along with electrostatic discharge (ESD) and destructive part analyses, demonstrate that this PRT is highly robust, and not subject to the failure of PRTs on previous missions. While there were two PRTs that failed during fabrication, to date there have been no in-flight PRT failures on MSL, including those on the Curiosity rover. Since MSL, the sensor has gone through a change in construction such that the manufacturer significantly restricts the minimum temperature. However, significant subsequent testing was performed with this new version of the part to show that it indeed is still robust to at least Mars minimum temperatures of -135ºC. The additional completed testing will be described. This work has resulted in a successful sensor
package qualification and a reliable bonding method suitable for use over large temperature extremes.

Nomenclature

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>DPA</td>
<td>Destructive Part Analysis</td>
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<tr>
<td>DUT</td>
<td>Device Under Test</td>
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<td>FFX</td>
<td>Fein Focus X-ray</td>
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<tr>
<td>$GN_2$</td>
<td>Gaseous Nitrogen</td>
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<tr>
<td>HRTS-5760-B-U-0-12</td>
<td>Honeywell, 1000-Ω PRT</td>
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<tr>
<td>JPL</td>
<td>Jet Propulsion Laboratory</td>
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<td>$LN_2$</td>
<td>Liquid Nitrogen</td>
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<td>MER</td>
<td>Mars Exploration Rover mission (Spirit and Opportunity)</td>
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<tr>
<td>MRO</td>
<td>Mars Reconnaissance Orbiter</td>
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<td>MSL</td>
<td>Mars Science Laboratory, Curiosity</td>
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<td>PRT</td>
<td>Platinum Resistor Thermometer</td>
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<td>PQV</td>
<td>Packaging Qualification and Verification Testing</td>
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<tr>
<td>SMAP</td>
<td>Soil Moisture Active Passive mission</td>
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<tr>
<td>Sol</td>
<td>1-Martian solar day</td>
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I. Introduction

On January 25, 2004, the second of the two wildly successful Mars Exploration Rovers, Opportunity, landed on Mars at Meridiani Planum. However, within 6 sols a combined total of 6 of the platinum resistance thermometers (PRTs) failed. Another PRT failed prior to completion of the primary mission, and to date, 16 PRTs have failed, though the latter failures have occurred well beyond the 90-sol primary mission. These included all four (two per rover) MER PRTs on the Mini-TES external calibration targets. Additional Mars Exploration Rover (MER) testing showed that this PRT when bonded directly to an Aluminum block with Stycast 2850/24LV or Hysol 9309.3NA was experiencing hard failure (open circuit) within 22 thermal cycles between -110ºC to +110ºC. Those PRT failures prompted JPL thermal engineers to look for and qualify another platinum resistance thermometer (PRT) sensor. Additional failures of these same PRTs have occurred on Grail and recently on the Mars Reconnaissance Orbiter (MRO) solar arrays reinforce the need for a PRT that can withstand the temperature extremes of these missions.

A. Failure Modes

There have been two typical failure modes when certain B.F. Goodrich PRTs are combined with the packaging configurations used at JPL. One was that the ceramic housing would crack, breaking the embedded platinum wire, when surface mounted to a substrate using an adhesive (i.e., the PRT is bonded directly to the substrate surface). The mismatch between the sensor’s coefficient of thermal expansion and that of the substrate and/or adhesive (when going beyond its glass transition temperature) results in such a crack when exposed to the temperature ranges of the aforementioned JPL missions. Consistent with this mode was the fact that larger PRT sizes such as those used on the MER Mini-TES calibration target (5000 ohm sensor with an increased ceramic case size to accommodate the extra platinum wire) were more susceptible to thermally induced strain, extreme care is necessary in handling these PRTs, as the wire is subject to break in tension.

B. Honeywell HRTS-5760-B-U-0-12 PRT

Extensive testing of the Honeywell PRT demonstrates that it can be surface mounted per JPL packaging methods and perform reliably over a wide temperature range. In addition to MSL, the PRT has subsequently been used by Aquarius and SMAP, and is planned for use on the Mars Insight and the 2020

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9 Source JPL ISA #82946, 79691, 81299, 83152, and 83193.
projects.

Honeywell changed their fabrication process for this part between the MSL and Aquarius implementation and the start of the SMAP project, although they retained the same part number. The minimum temperature was advertised as much higher, -70°C, than the previous minimum temperature of -200°C. SMAP performed a DPA and additional thermal tests to demonstrate reliable operation down to -135°C—the same minimum temperatures used for MSL. Honeywell’s advertised maximum temperature is +260°C (unchanged).

This paper documents the PRT tests used to demonstrate the robustness of the Honeywell Platinum Resistor Thermometers (PRTs) used to qualify the PRT for MSL and SMAP. First, the construction of the HRPTS-5760-B-U-0-12 part is described. Second, the packaging methods and thermal tests performed on the sensor are described. Finally, the electrostatic discharge tests that further demonstrate the sensors robustness are described.

II. The Honeywell PRT Construction

The footprint of the Honeywell HRPTS-5760-B-U-0-12, 1000 Ω PRT is 4.8-mm x 9.0-mm and is 3-mm thick. The device is 1.5 grams and is delivered with 304-mm long, 26-gage wire leads. The platinum chip and ceramic die are contained within a white ceramic tub filled with a black epoxy. Nominal specifications are 1000 Ω 0.00375± 0.000029 Ω/°C at 0°C. Temperature range is -200°C to +260°C. Nominal operating current is 2 mA maximum for a self-heating error of 1°C.

JPL performed a Fein Focus x-ray imaging (see Fig. 1A), destructive part analysis and de-processing of the Honeywell PRT (see Fig. 1B). The Honeywell PRT consists of an etched platinum foil, laser-trimmed platinum chip mounted with a small amount adhesive to a ceramic die. Ribbon leads are welded to either side of the chip and are twisted and redirected 180° to provide strain relief. The ribbon wire is then soldered to a 7-stranded, silver-coated copper wire with Teflon insulation. The die is glued inside of a ceramic housing (like a ‘cup’ or ‘tub’) containing the tips of the lead wires and the ribbon wires. The ceramic housing ‘tub’ is then filled with an epoxy.

The use of a laser etched platinum chip opposed to a single strand wire improves the PRT’s ability to withstand thermal expansion cycles. The ribbon wires prevent handling or thermal expansion strain from affecting the chip and are built in strain relief from the seven-stranded wire.

III. Testing

Over the past seven years, JPL has gained considerable experience with the Honeywell HRPTS-5760-B-U-0-12 PRT both in testing and flight. There are two categories of tests that JPL has performed. The first set of tests is demonstration and the second set tests is related to flight qualification.

Additionally, JPL now has flight experience with the Mars Science Lander and Aquarius missions (see below).

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11 Images courtesy of the JPL Failure Analysis Laboratory.
A. Demonstration Testing

JPL has performed three sets of thermal cycling on the Honeywell PRTs: (1) Extreme Temperature Shock Tests, (2) MSL Packaging Qualification and Verification (PQV) Testing, and (3) SMAP thermal cycle tests. Additionally, (4) an electro-static discharge test was performed to further demonstrate the durability of the PRT to handling. These tests are described in detail below.

There are two categories of thermal shock tests described below. Device-only tests and bonded tests that test both the device and the attachment process.

1. Extreme thermal shock test (device only test)

The first testing performed on the Honeywell PRTs was a quick and dirty test to determine the possible robustness of the device. PRTs were dunked in LN₂ (-195°C), allowed to reach equilibrium, then pulled out put in front of a heat gun set to +125°C. Though little knowledge would have been gained had the PRT had failed, passing would lend confidence to its durability from a small number of extreme cycles. Tests were performed this test two times on two different groups of PRTs.

The first test was performed prior to the much longer MSL PQV testing (see next section). One PRT was dunked 15 times into LN2 and then placed in front of a heat gun. There was no noticeable change in the PRTs function. There was no external evidence of stress, and Fein Focus X-ray images of the PRT did before and after did not reveal any changes.

The second test was performed for SMAP when it was learned that Honeywell had made a change to the part. The Honeywell specification sheet listed the minimum PRT temperature as -70 °C, instead of -200°C. The second test was performed on two units from different date lots. Each PRT was exposed to 10 cycles between LN2 (-195°C) and a calibrated heat gun set at +125°C, a 320°C temperature difference. Each PRT was alternatively dunked completely into an LN2 bath and left there until the resistance stabilized, then immediately placed 1-cm from a calibrated heat gun nozzle until the resistance measurement stabilized, and then immediately dunked again. Again the PRTs were allowed to reach equilibrium, and the resistance at that temperature was recorded. No notable change in resistance was noted and there appeared to be no visual change in the PRTs.13

Again, the point of these harsh tests was qualitative in nature. Since the extreme thermal shock does not represent a physical case to which flight PRTs would ever be exposed, a failure would not rule out the use of these PRTs. However, passing these extreme tests suggests the parts were rugged, and in the case of the second test, possibly more rugged than the vendor’s data sheet suggested.

2. MSL PQV Testing, Long Duration (device and attachment test)

The MSL PQV testing qualified both the temperature sensor device and the mounting process since MSL was the first JPL project to use the HRTS-5760-B-U-0-12 PRTs.

The MSL Curiosity rover must survive a minimum of one Martian year on Mars. So the MSL project required a PQV test (Packaging Qualification & Verification) consisting of 2010 thermal cycles over a ΔT of 145°C simulating three Martian years, from -130°C to +15°C (winter, 3 x 200 cycles) and -105°C to +40°C (summer, 3 x 470 cycles). In addition there was a qualification cycle of 0°C to +70°C and a cycle of 0°C to +125°C to simulate temperature

13 Email from author to SMAP project manager, October 10, 2012.
cycles seen during MSL hardware mechanical integration.\textsuperscript{14} The dwell time for all cycles (min/max) was 15-

minutes.

MSL had six different substrate materials that required surface mounted PRTs. The PRTs were therefore bonded onto six representative coupons. The six substrates were: aluminum 7050, treated Magnesium AZ231-B, Stainless Steel 304, Albemet, Titanium 6AL4V, and G-10. An additional aluminum coupon was added. This coupon was the sloppy installation, and was used to see if there were any sensitivity to deviations to the process we developed. PRTs were installed in two, off-procedure methods: with the sensor’s black epoxy surface side down and with PRTs completely covered in the JPL mounting epoxy.

Each coupon used four different adhesives: two epoxies, Hysol 9309.3 and Stycast 2850 24/LV with 3-5 mil glass beads; and two silicones, GE RTV-566 with SS4155 primer and Nusil CV15-2500 with SP 270 primer. The silicones used stainless steel 304-series CRES, 20-mil bond wire to maintain a generous bond line.

With the exception of the Albemet substrate, each coupon employed all four adhesives, with three PRTs installed per adhesive types. The Albemet coupon was smaller and so only 6 PRTs were bonded: two using Nusil CV15-2500, two using RTV-566, one using Hysol 9309.3, and one using Stycast 2850/24 LV. This accounts for 78 PRTs in the test. An additional eleven PRTs were placed in the chamber as part of a device only test. These PRTs were functionally and visually inspected before and after the test. So there were a total of 89 PRTs in this test.

The PRTs were cleaned with Freon prior to bonding and the substrates were cleaned with 200-proof acetone, abraded with Scotchbrite (except the Albemet), and wiped cleaned again using 200-proof ethyl alcohol. Substrate temperatures were monitored using

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure5.png}
\caption{(A) Simulated Martian winter thermal cycles, 600 cycles performed. (B) Simulated Martian summer thermal cycles, 1410 cycles performed.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure7.png}
\caption{PRT PQV Test Results for End of Summer 1 Cycle.}
\end{figure}

Type K thermocouples (TCs) spot-welded to the sides of the substrates. A T/C placed outside the thermal test chamber was also monitored. The temperature indicated by one of these T/Cs on substrate #4 was used as the temperature control point for all substrates. Labview software used a control loop to compare the target temperature to the temperature indicated by the temperature control point T/C and adjust the chamber heaters or chilled gaseous nitrogen (GN₂) as needed to maintain the substrates to the target temperature.¹⁵

The resistance of each of the PRTs was recorded using an Agilent 34970A data acquisition system and controlled by a Labview program for the test. The PRTs were visually inspected using a Keyence VHX-100 digital microscope before and after the test, as well as between ten planned chamber break inspection points.

All 78 PRTs survived the 2010 prescribed cycles. There was no noted deviation in the resistance value from the beginning of the test. There was no visual change in the PRTs or the bonds. The post-test inspections indicated that there were no severe discolorations visible on the PRT packages, the external leads were not frayed or damaged, and no delamination, separations or bubbling between the PRTs and substrates was visible. Bonding of all PRTs to the substrates was checked by manually pulling on each PRT. There was no apparent degradation in bonding of any PRT to any of the substrates. PRT resistance measurements made during a cold dwell on cycle 1 near the beginning of thermal cycle testing were compared to PRT resistances for the final [cycle] indications that the PRT resistances for all PRTs were essentially unchanged after 2,000 thermal cycles.¹⁶ All of the device only tests passed the Fein Focus X-ray inspections. None of the devices showed any change in resistance or visual inspection from inspection points at any of the inspection points nor at the conclusion of the test.¹⁷

The beginning and final resistance readings were recorded and compared, and there was no change in the parts. Ideally, the testing should have included a pre and post calibration (or at least an ice point measurement), but unfortunately these tests were not performed largely due to schedule and the need to get a quick answer as to whether the devices were suitable for flight, so that a qualification and screening program could begin.

3. SMAP Thermal Cycling Test (device only test).

Following the PRT’s success on MSL, the SMAP project decided to primarily use this sensor as well. Unfortunately, it was discovered that Honeywell had made a change to the PRT. This lead to a second extreme test, as mentioned above, additional destructive part analysis, and a second long duration thermal cycling test. This latter test is discussed below. This test was only on the devices, not the bonding process.

The new Honeywell PRT version had the same packaging, same ribbon wire strain relief, and the same laser trimmed platinum foil chip, but differed in the adhesive used to hold the thin film PRT to a ceramic board embedded within the package. Significantly, the as-advertised minimum temperature had been raised from -200°C to -70°C. Based on our testing and inspection, however, the new version of this PRT appears to be equally robust as the previous design.¹⁸


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SMAP began a device-only test to assure the project that the changes Honeywell made to the PRT had not grossly changed its robustness to thermal cycling. Unlike the MSL test, the SMAP test did not bond the sensors to substrates. Like MSL the units were tested in GN2. The SMAP test used a more extreme temperature cycle, -135ºC to +125ºC, a 260ºC temperature delta. SMAP tested 20 units from three different date codes, along with two HRTS-5760-B-U-1-12 parts as well. The test is on going, and to date the SMAP PRTs have completed 520 cycles, with 15-minute dwell times at minimum and maximum temperatures without any failures.

A DPA analysis was conducted and compared to the de-processing of a PRT of the previous construction, showing no significant changes that would warrant the higher minimum temperature rating of the device.\(^{19}\)

4. MSL Electro-Static Discharge (ESD) Testing

The Honeywell data sheet indicates that the devices are electro-static class-3 (4kV – 15kV) sensitive. NASA & JPL’s ESD manual also calls out thin-film resistors as ESD sensitive. So JPL conducted a test via contract with DPA Components International (DPACI) in Simi Valley to perform two ESD tests: a machine model test (a human body model test was an option if and only if the device under test (DUTs) failed the machine model test) and a repeated exposure (load life) test. The machine model test was defined per MIL-STD-1686C (and subsequent JEDEC and ASTM ESD Shock specification documents), machine model test conditions: M1(0-100 V) to M5(>800 V) to measure five parts as DUTs and five controls (not exposed to the shock, but in the same environment). A similar test range is defined for the human body model per MIL-STD-1686C\(^{20}\). A final test was to shock the parts at maximum voltage five times while measuring R-values. This was repeated for fifty cycles. The devices were immersed in an inert Galden PFPE fluid in a vacuum flask, to minimize the effect of the laboratory ambient temperature variation on the resistance measurements.

The Honeywell HRTS-5760-B-U-0-12 PRT survived both the human body and the machine model ESD tests as well as a 50 shock load life sequence based on the maximum (800 V) Machine Model ESD level. There were no significant changes in the DUTs resistance, measured at 25ºC in an insulating inert fluid bath, for all shock levels (positive and negative) 100 V, 200 V, 400 V, 800 V. There were no significant changes in the device resistance for all five DUTs measured at 25 C in an insulating inert fluid bath, for a shock level 800 V applied a total of fifty times in ten cycles of five positive, five negative shocks.

For the ten devices (five DUTs and five control devices) in the Machine Model test the resistance values before the first shock and the values after the final +/-800 V shock showed an increase in resistance of about 220 milliOhm (see Fig. 7 at right). So we are confident there is no difference due to the shock. The difference is clearly due to the local increase in temperature of the inert fluid bath from the Joule energy of the shock. The Galden fluid temperature rose 0.14ºC during the test.

B. Qualification & Screening Tests

The Honeywell PRT does not come calibrated, screened or qualified from the vendor. As a result, JPL has performed these processes, giving us additional insight into the durability of the PRT. To date JPL has conducted the following qualification and screening programs for this device with zero failures. The screening requirements for each of the programs vary.

MSL qualified one lot, and screened 900 PRTs. For MSL, the screening process required 25 air-to-air thermal shock cycles from -55ºC to +125ºC. The qualification lot was exposed to ten cycles from LN2 (196ºC) to +100ºC.\(^{21}\) Aquarius adopted the MSL screening requirements for their PRTs.

SMAP has performed qualifications on four date code lots, and has screened approximately 250 PRTs. SMAP has three distinct screening requirements that vary from a minimum of -135ºC to -65ºC and a maximum of +150ºC. Each SMAP part must go through ten cycles per MIL-STD-202, Method 107, with a dwell time of 15 minutes at each extreme depending upon the screening regime proscribed for the subsystem. The maximum temperature delta

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\(^{20}\) According to MIL-STD-1686 Class 3 ESD sensitivity is 4kV to 15.99kV.

for the SMAP screening is 285°C. The thermal shock qualification requirement for SMAP is 25 cycles between -135°C to +150°C per MIL-STD-202, Method 107.  

There have been no failures in qualification or screening from either of these programs. There have been parts “dead on arrival” to JPL. Also JPL quality assurance has rejected parts for visual defects prior to the start of the screening and qualification programs for things such as cracks in the epoxy or ceramic housing, nicks in the leads, protrusions of the die out of the epoxy, or large voids around the wire egress areas.

Other qualification and screening tests include load life, insulation resistance, and resistance to solvents. These are not considered (for this part) to be the most challenging test, and so are not documented in this paper.

Of the approximately 2,250 PRTs JPL has processed, only one PRT has failed—not including handling issues—following screening and qualification. The DPA on this PRT indicates that the platinum foil had been cut during fabrication. During qualification of the hardware upon which it was installed the PRT failed open.

Confidence in the robustness of this PRT is greatly increased by its performance in the demonstration and the qualification and screening tests. Additionally, the PRT is now logging significant flight hours.

C. Flight Heritage

Both MSL and Aquarius have flown the Honeywell PRT, and to date have not logged a failure in flight. In the extreme category, the MSL four flight thermal batteries (as well as the set of test batteries fired on the ground) had temperatures at or in excess of +250°C without failure. The MSL PRTs have survived launch, a 9-month cruise, entry-descent-landing (EDL), and 300-Sols (to date) on the Martian surface without incident, with low temperatures near -90°C.

III. Conclusion

In conclusion, the Honeywell HRTS-5760-B-U-0-12 PRT has been extensively tested, screened and qualified for space flight missions. The PRT is robust to survive in most surface mount conditions, and is durable over extreme thermal shocks form 260 °C (repeated on SMAP 520 times) to 296°C as part of the liquid-to-liquid shock qualification for MSL. Though the vendor lists a minimum temperature of -70°C for the part, the SMAP project has demonstrated a much lower temperature threshold, of at least -135°C, and perhaps to liquid nitrogen temperatures. Further, the PRT has been shown to be immune to ESD concerns though a machine model test and a 50-cycle load life shock test at machine model levels. Of the approximate 2,250 PRTs the authors have handled and examined, only one has failed following screening, prior to flight, due to a problem within the part during fabrication. No parts have failed in screening or qualification of the part, and all of the 350+ PRTs on MSL have performed nominally.

This PRT is a thermally robust device useful for implementation on flight space vehicles.

Acknowledgments

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22 JPL Drawing 10344320-001, -002, & -003 Platinum RTD, Temperature Sensor Source Control Drawing, Revision E, November 2, 2011.

23 Note that there have been handling failures, such as wires breaking due to mishandling during hardware removal and a PRT breaking due to an object being placed on the object. These are not considered here, since the PRT isn’t immune to ‘hammers and pliers.’
Author G. Cucullu would like to thank the following persons who made significant contributions to this effort: Jackie Lyra, JPL MSL Thermal Project Element Manager for her technical and managerial support and guidance for the extensive testing documented herein, as well as the SMAP Thermal Engineering Lead, Nick Emis for his support in the re-demonstration efforts on the SMAP PRT implementation; Eric Sunada and Glenn Tsuyuki were instrumental in their upfront discovery work in selecting the Honeywell PRT and as technical advisors; Charles Garner for putting together the final report on the PRT testing, from which much of the data in the paper is based; Gus Forsberg and Don Lewis for providing technical guidance for adhesive selection and bonding. Parts specialists Doug Sheldon, Cate Harris, and James Skinner for parts analysis, ESD test setup and screening and qualification expertise; and Shane Pootrakul for providing PRT failure data from the MER spacecraft.

References