Qualification of Bonding Process of Temperature Sensors to Extreme Temperature Deep Space Missions*

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Key words: Extreme temperatures, bonding process qualification, PRT reliability, Bonding materials, staking, PRT failures, installation failures, etc.

Abstract:

A process has been explored based on the state-of-the-art technology to bond the platinum resistance thermometer (PRT) on to potential aerospace material such as a flat aluminum surface and a flexible copper tube to simulate coaxial cable for the flight applications. Primarily, PRTs were inserted into a metal plated copper braid to avoid stresses on the sensor while attaching the sensor with braid to the base material for long duration deep space missions. Appropriate pretreatment has been implemented in this study to enhance the adhesion of the PRTs to the base material. NuSil product has been chosen in this research to attach PRT to the base materials. The resistance (~1.1 kΩ) of PRTs has been electrically monitored continuously during the qualification thermal cycling testing from -150°C to +120°C and -100°C to -35°C. The test hardware has been thermal cycled three times the mission life per JPL design principles for JUNO project. No PRT failures were observed during and after the PRT thermal cycling qualification test for extreme temperature environments. However, there were some failures associated with staking of the PRT pig tails as a result of thermal cycling qualification test.

Introduction

The launch of the JUNO mission in August 2011 begins a five-year journey back to Jupiter, to investigate remaining unanswered questions beneath the surface of the mysterious gas giant. 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. [1]

Some of the critical instrument hardware will experience very extreme temperatures and we addressed some of the reliability issues of PRT bonding to the potential aerospace materials.

PRTs will be used to obtain the temperature telemetry of the hardware during the life of the mission. Therefore, the reliability of PRTs and their bonding to the base materials is of significant value to the intended applications.

Microwave Radiometer (MWR)/NASA instrument which is part of JUNO project requires the PRTs to be qualified from -150^{o}C to +120^{o}C. Therefore, we have developed a process to attach the PRTs to the flat and flex tube materials to qualify for JUNO project over this temperature range.

Requirements:

The bonding of PRTs to the base material should survive 7 thermal cycles from -150^{o}C to +120 ^{o}C and 11 cycles from -100^{o}C to -35^{o}C for one mission life. Per JPL design principles, these test articles should survive 3 times the expected mission life. Therefore, the test hardware should survive 21 thermal cycles (-150^{o}C to 120^{o}C) and 33 cycles (-100^{o}C to -35^{o}C) without any failures. Finally, implement the qualified processes to attach the type X PRTs for MWR instrument of JUNO Project.

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 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.).

Qualification of PRTs for Mars Exploration Rover (MER) project: We had qualified type X PRTs for MER project under various temperature environments (-110^{o}C to +110^{o}C and -105^{o}C to +40^{o}C) that are required for the project. The requirement for MER project was 270 thermal cycles or sols for a given hardware and the corresponding temperature ΔT.

Figure 1 shows the optical photographs of the PRTs (type X), which were bonded to the base material with two epoxy types for thermal cycling (-110^{o}C to +110^{o}C) testing to assess for PRT reliability and their bonding reliability for certain hardware on MER rover (Spirit and Opportunity). The results were negative and not encouraging. There were hard failures of PRT whether it was hot or cold during thermal cycling. All the PRTs have hard failures or open-circuit as shown in figure 2 after 22 thermal cycles whether they are attached with adhesive #1 or adhesive #2.

The qualification temperature range for certain PRTs on the rover was -105^{o}C to +40^{o}C. Only one PRT (type X) was chosen in this study due to unavailability of the test articles. Figure 3 shows the optical photograph of the PRT bonded with reduced bond line thickness and width due to the failures observed in figure 1 where excess of bonding material might have caused the stress over the sensor. The aluminum block was pretreated with primer appropriately prior to bonding. The adhesive bond line width was equal to approximately 10 mil. But, substantially lower bond line width of adhesive #2 was used. PRT (5000 Ohms, 4 leaded) has failed after 81 thermal cycles -105^{o}C to +40^{o}C. It was also a hard failure or an open circuit and was completely open whether it was hot or cold temperature during thermal cycling. The hard failure had occurred for the first time during the cold dwell period. 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 MER mission life cycle (90 sols or thermal cycles). Our objective was to have the PRT life three times the MER mission life of 270 (=90*3) sols/thermal cycles. Therefore, we have chosen other material to bond PRTs to meet MER requirement since we observed the failures.

5400 Ohm PRT was attached to calibration target of 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 (-105^{o}C to +40^{o}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 qualification test based on the analysis of the raw test data. However, the result was PRT has debonded from the aluminum block substrate after 270 thermal cycles. It must have lost its adhesion during 270 thermal cycle test. [2 and 3] (Figure 5) The PRT was lifted intentionally to show in the picture that the PRT lost its adhesion to the RTV. We had used this configuration for our applications since PRTs did not fail but lost its adhesion and they were held close to the surface with Silverized Kapton tape. However, we have tried to improve the process for JUNO project since the temperature requirements are harsher than MER project.

PRT Bonding Process for JUNO project: Qualification process for the type X PRT is needed for JUNO project for extreme temperature environment since we had experienced failures during MER project as discussed in the above sections. Figure 6 shows the optical photographs of the PRTs (type X), which will be used for JUNO project. Reliability of the PRT sensors and their bonding processes is a key element to understand/assess the health of the hardware during all stages of the project. The temperature range is substantially wider than over MER project requirement. The failures of PRTs may be due to the bonding processes to the base materials. Therefore, the PRT was sleeved with metal plated copper braid and bonded the braided PRT to the base material to reduce the direct stress on the PRT. Besides, there are no other commercial PRTs that can meet the temperature range requirements of this project. Due to change in the manufacturing process Type Y PRTs (700 Series Platinum RTDs, -70^{o}C to +500^{o}C) will no longer go to these extreme cold temperatures that are required for JUNO project. Our requirement is to use the PRTs to -150^{o}C to +120^{o}C with a mission assurance margin of +20^{o}C and -15^{o}C where the sensor is still in manufacturer specification. Therefore, we still have to develop a bonding process for type X PRTs to base materials. [4] Figure 4 shows the optical photograph of the 700 series resistance temperature detector (RTD) miniature temperature sensor.

Based on the existing published reliability data to the best of the author's knowledge there is no published systematic experimental data available to assess the reliability of bonding process in extremely low and hot temperatures such as -150^{o}C to +120^{o}C. Therefore, this paper describes the reliability results of the bonding processes in this extreme temperature range. The standard electronic packages are not generally built for low temperature applications down to -150^{o}C, they are built for military specification and others to survive in a temperature range of -55^{o}C to +125^{o}C for a certain duration. Therefore, the qualification of the PRTs with metal plated copper braid shield and their bonding process has been reported in this paper.

Experimental Details [5]:

Al-1145/graphite composite (planar substrate) and copper tube have been used in this study to assess the reliability of PRT bonding materials. Flexible copper tube has been chosen to simulate the coaxial cable to attach PRTs. The substrate materials were cleaned with organic solvents for any oils and also contaminants using standard cleaning processes. They were gently abraded with Scotch-brite. The substrate materials were cleaned with organic solvents for any oils and also contaminants using standard cleaning processes. Initially shielded (metal plated copper braid) PRT (type X) test articles were fabricated. Cleaned the surface of the shields with organic solvents and air-dried the shielded PRTs after wiping at room temperatures. Pretreated the base antenna material (Al 1145/Graphite composite) and shielded PRTs using suitable approach. NuSil Primer was used to provide treatment to the base material and also braid material to enhance the bonding of shielded PRT to the base material. Primer was applied in a thin uniform coat on the surface of the base material and also on the shield. Typical drying time was for a few hours at room temperature. NuSil silicone (adhesive#3) has been used to attach the shielded PRT to the base material. This is a two-part flowable red RTV silicone - 100:0.5 mix ratio (base: curing agent). They were thoroughly mixed 0.5% by weight of catalyst to base. The mixed sample was left for at least a few hours after mixing two parts of base and curing agent. PRTs were attached to the base materials such as Al-1145 and copper tube. These test articles were cured at room temperature and humidity (30 – 70%) for seven days. The resistance of the PRTs was continuously monitored during the thermal cycling to identify any failures during and thermal cycling. Inspected the test articles prior to and at various intermediate steps of thermal cycling and also at the end of the thermal cycling test. Figure 7 show the optical photographs of the test articles that were prepared using the steps described above.

Temperature profile:

Figure 8a shows the thermal cycling temperature profile employed in this experimental study to perform the thermal cycling of the bonded platinum temperature thermometers test articles. The lowest temperature was -150^{o}C and highest temperature used was +120^{o}C. Figure 8b shows the thermal cycling temperature profile employed in this experimental study to perform the cycling of the bonded platinum temperature thermometers test boards. The lowest temperature was -100^{o}C and high temperature used was -35^{o}C. Two temperature profiles were used since the project requires two phases of the mission.

Results and discussion:

The PRT resistance was continuously monitored during the thermal cycling test using suitable data acquisition set-up. (Figures 9 and 10) We used the PRTs of 1.1 kΩ Ohms in this study. Figure 7 shows optical photograph of the PRTs mounted on the base materials placed in the atmospheric thermal chamber. Figure 9 shows the temperature scan from -150^{o}C to +120^{o} C for 21 thermal cycles. The resistance of PRT data was shown in figure 9 that varies from ~400 Ohms to ~1430 ohms as a function temperature and it has been recorded as a function of temperature from -150^{o}C to +120^{o}C. The resistance of the PRT was unchanged even after 21 thermal cycles at a given temperature. The resistance of PRT data was shown in figure 10 that varies from ~600 Ohms to ~850 ohms as a function temperature and it has been recorded as a function of temperature from -100^{o}C to -35^{o}C. (Figure 10) The resistance of the PRT was unchanged even after 33 thermal cycles at a given temperature. All the PRTs have survived 3 times the expected mission life for JUNO project. No adhesion problems were observed in the PRT sensor area or under the shielded PRT. [6]

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 X) and bonding processes identified in these tests can survive the environmental conditions expected on JUNO with margins meeting JPL design principles. [7, 9, and 10] Staking adhesion failure (two out of eight locations) was observed as shown in Figure 11. A shielded PRT was mounted on the copper tube (figure 7) using the process described in this paper and assessed its reliability as a function of mission requirements. The test articles have successfully survived the project PQV requirements. This process has been adapted since they have survived 3 times mission life in preparing the PRTs with a shield to mount on the MWR/JUNO flight hardware. Staking materials has been replaced with NuSil's adhesive to avoid any staking problems during the mission duration.

Conclusions:

During the first qualification effort all the PRTs with excess adhesive had failed after only 22 thermal cycles for MER project. All PRTs bonded with adhesive #2 with no excess adhesive (bond line was more than 10 mil) had also failed within 22 thermal cycles. All PRTs bonded with adhesive #2 with no excess adhesive (bond line was equal to 10 mil) had also failed only after 81 thermal cycles. A process with RTV silicone 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. However, the PRT may have debonded from the aluminum block substrate during the duration of the thermal cycling test.

A new process has been developed and implemented in bonding the sleeved PRT to the base material. These PRTs were continuously electrically monitored during 21 thermal cycles from -150^{o}C to +120^{o}C and also -100^{o}C to -35^{o}C. [6] No failures were observed after 21 and 33 thermal cycles, respectively. This process is safe enough to implement in JUNO project since they have survived for 3 times the expected mission life. However, staking was debonded in this study performed for JUNO project. Staking material has been replaced with NuSil's product in its application. The NuSil product has the lowest glass transition temperature T_g that is about -115^{o}C per manufacturer specifications. [5] Young's modulus will significantly change as the temperature goes below its glass transition temperature. The bonding material has survived 3 times the mission life in this study. PRTs bonded to the copper tube also have survived three times the mission life without any failures.

Acknowledgements:

The research work described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA. I would like to thank Elizabeth Romo, Maher Natour, etc., for their discussions during the mission assurance effort of PRT work for MWR/JUNO project. Thanks are due to Mike Blakely and Steve F. Franklin for their review and suggestions. We want to particularly thank Jerry Gutierrez for his support in fabricating the PRT test coupons. We also want to thank Linh H. Phan for her support in shielding the PRTs for this study. MWR/JUNO project is highly appreciated for encouraging me to work with Instrument Systems Implementation & Concepts and Thermal and Cryogenics Engineering to address the research, development and their qualification.

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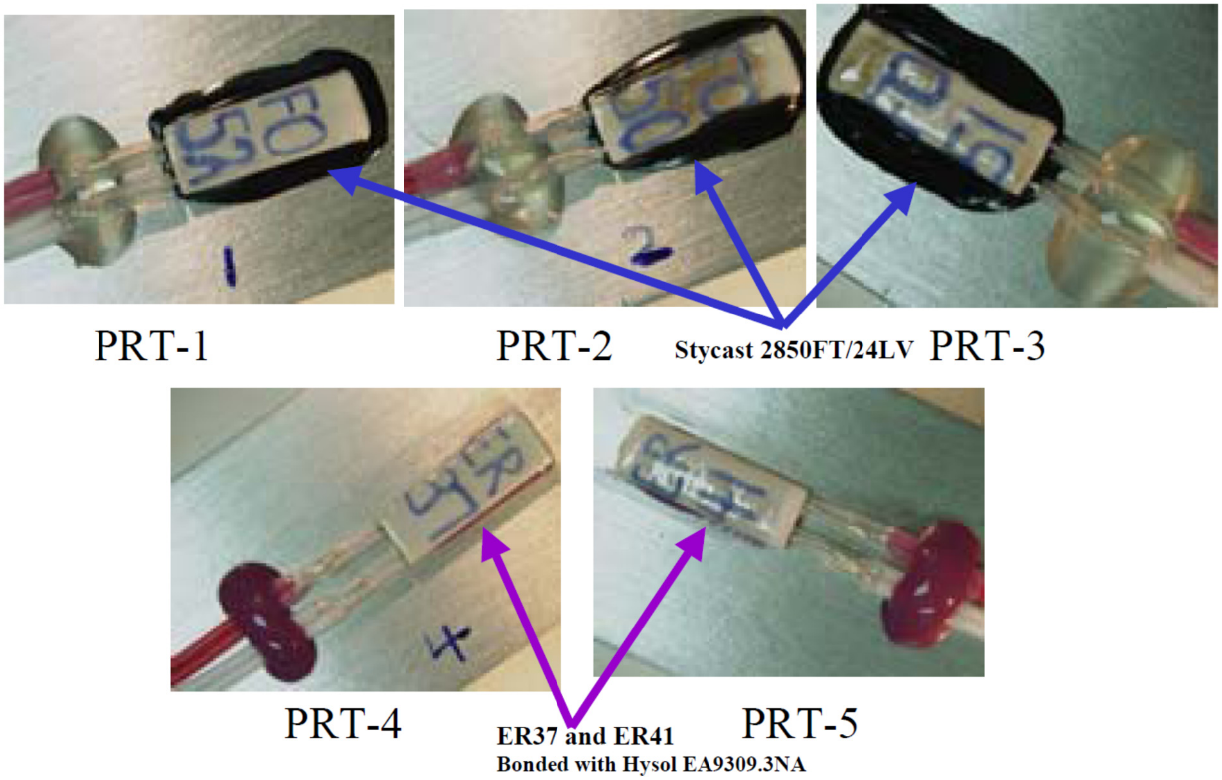
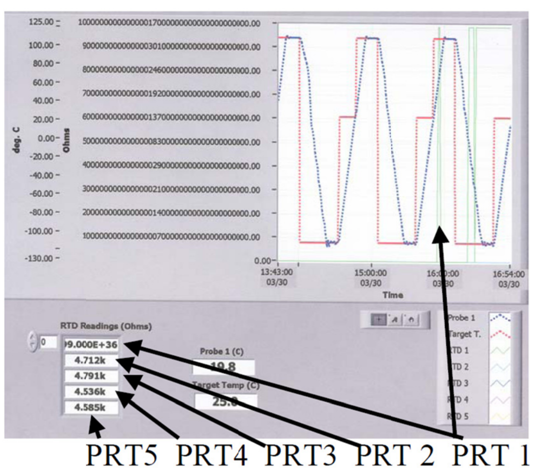


Figure 1: Optical photographs of the PRTs prior to planetary protection bake and PQV thermal cycling.



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

After planetary protection

PRT1 failed as per data
(Please see arrow) after two cycles

PRT2-5 functional (please see arrows)
even after 3 cycles

Figure 2: Resistance of PRTs vs. the temperature.

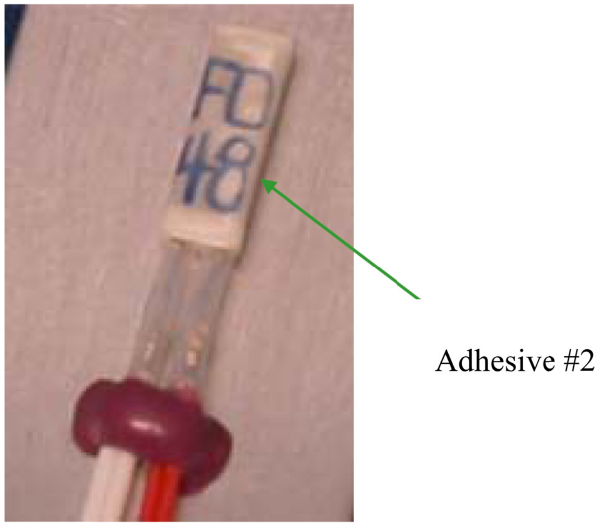


Figure 3: PRT failed after 81 cycles of -120°C to +40°C

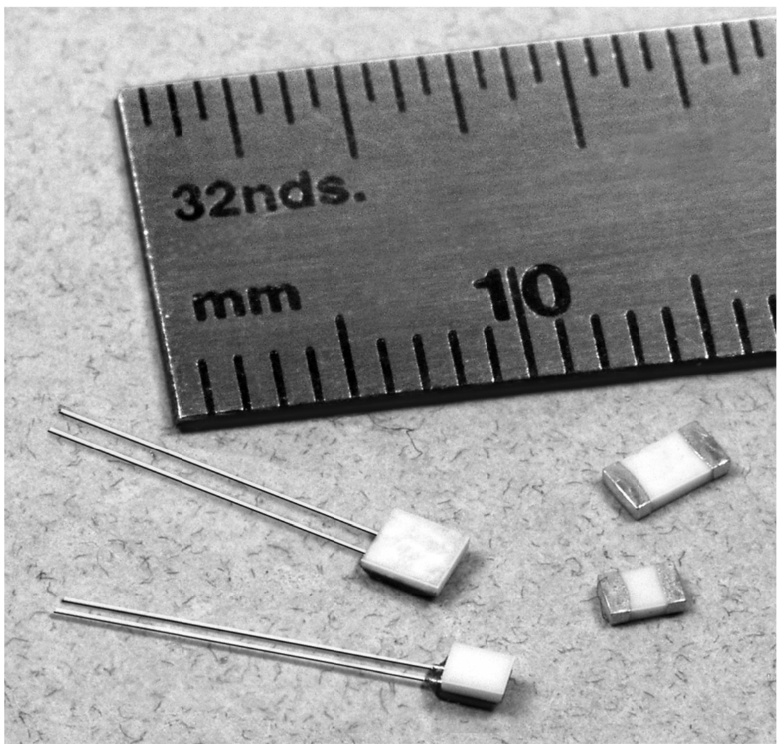


Figure 4: Resistance Temperature Detector, 700 series [2]

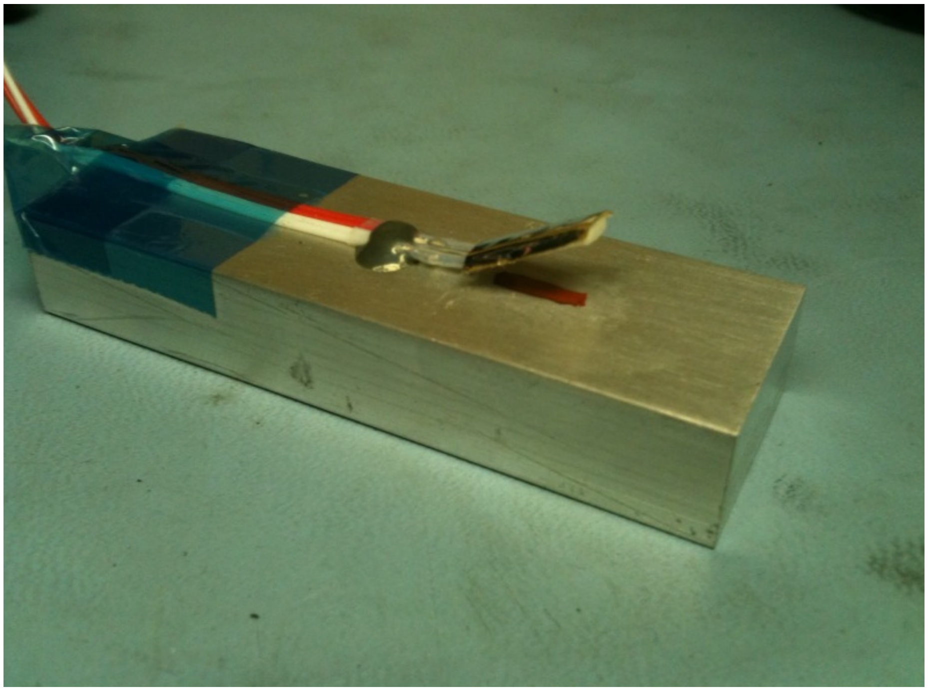


Figure 5: Optical photograph of the PRT after 270 thermal cycles.
PRT was lifted to show that there is no adhesion of PRT to the base material.

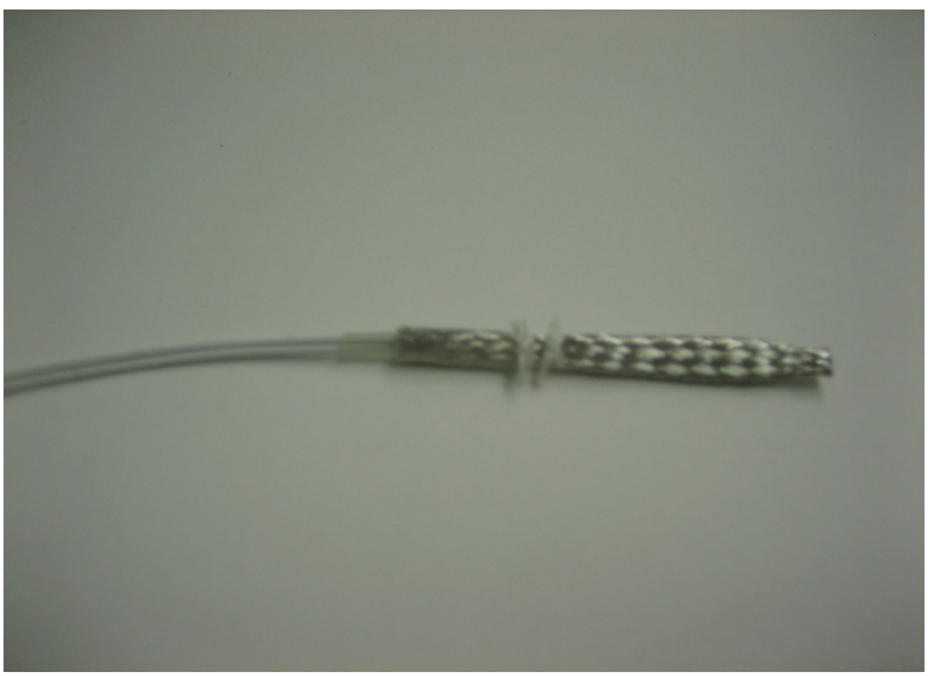


Figure 6: Optical photograph of the shielded type X PRT

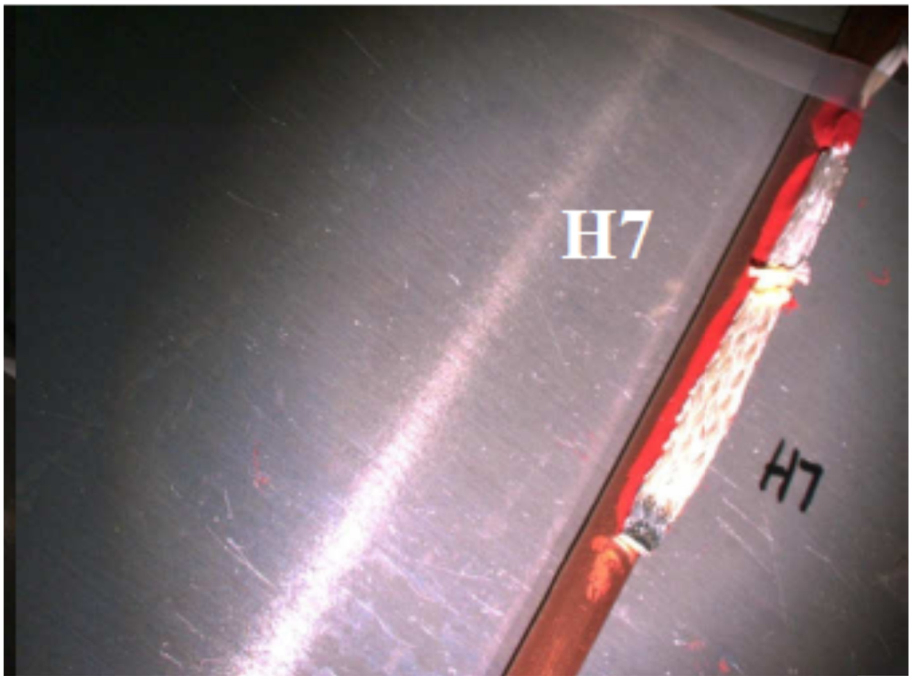


Figure 7: Optical photographs of the PRTs bonded to Copper tube and the planar Al-1145 substrate materials

(a)

(b)

Figure 8: (a and b): Extreme Temperature Thermal Cycling Profiles used in this study

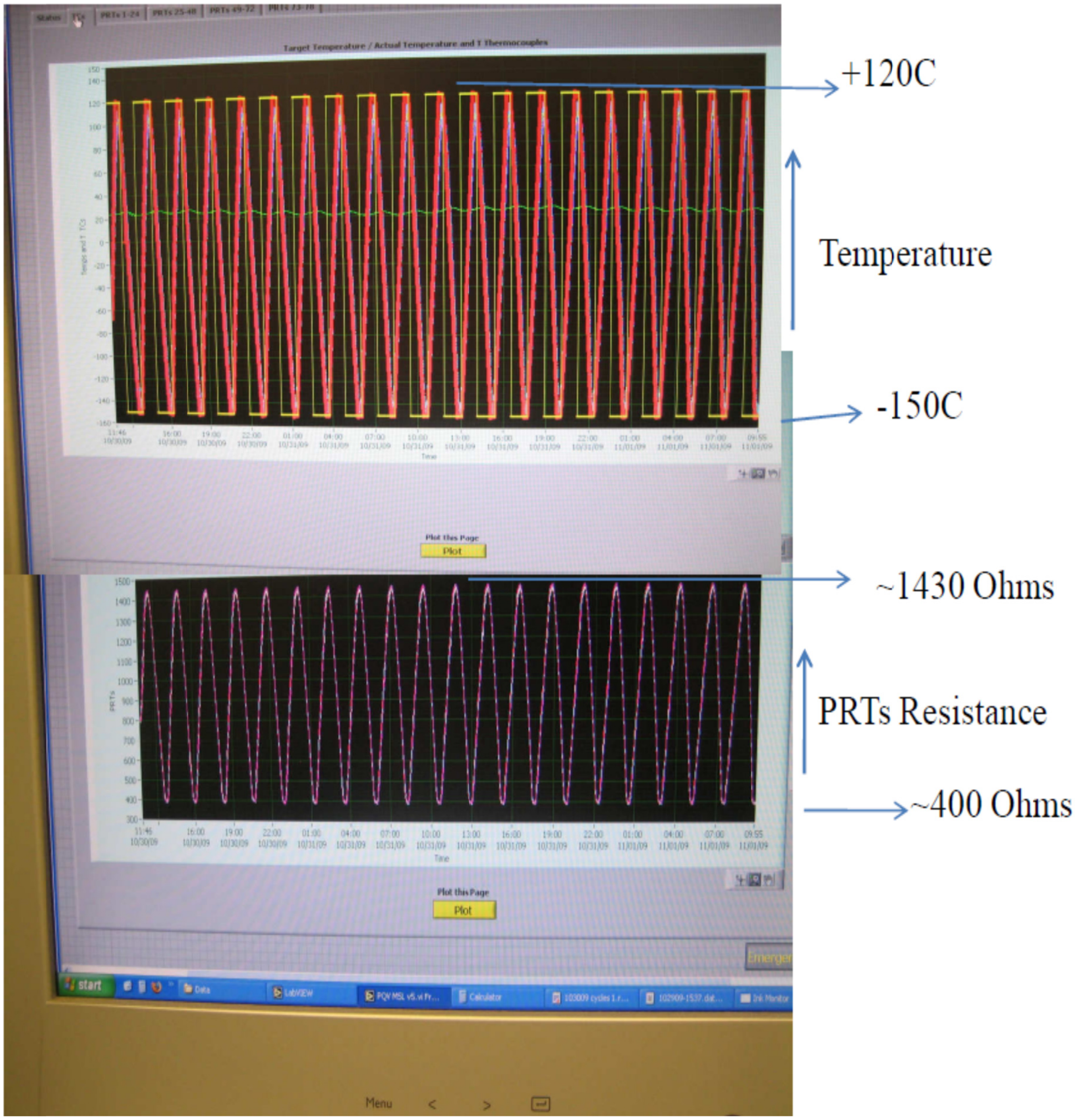


Figure 9: Temperature vs. time (thermal cycling, +120^{o}C to -150^{o}C) and resistance of PRT. Vs. thermal cycling

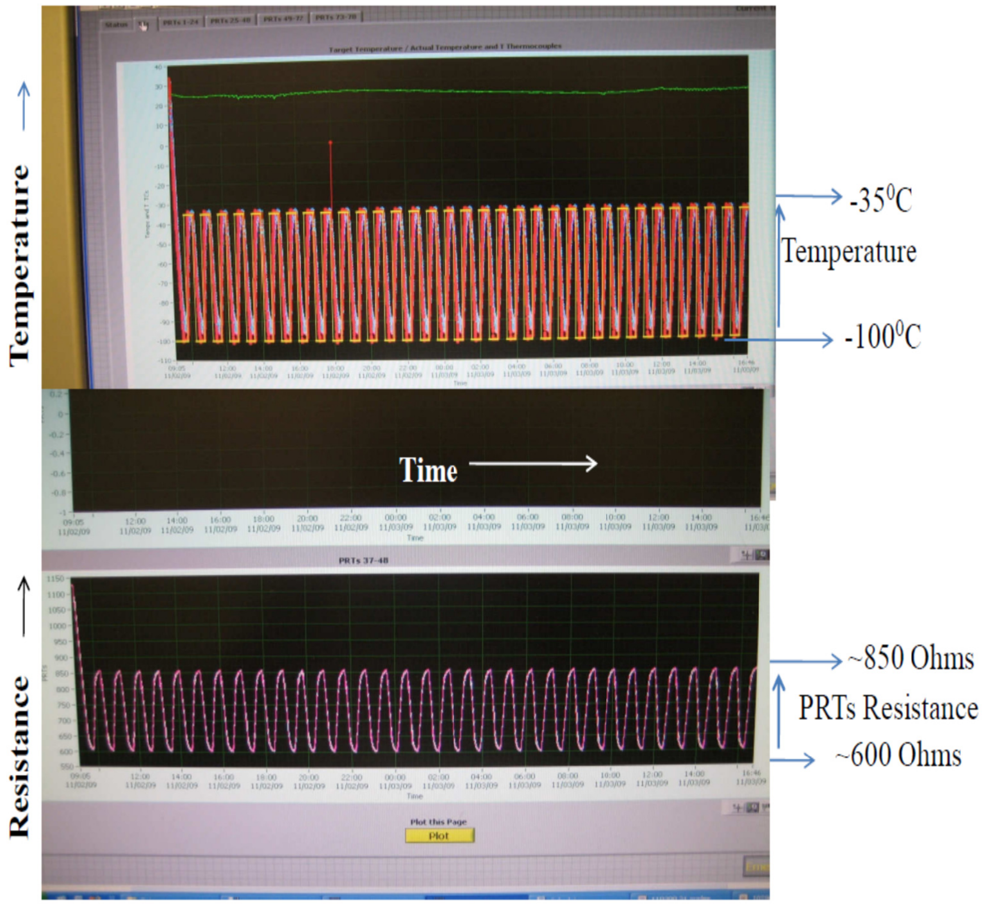


Figure 10: Temperature vs. time (thermal cycling, -100°C to -35°C) and resistance PRT. Vs. thermal cycling

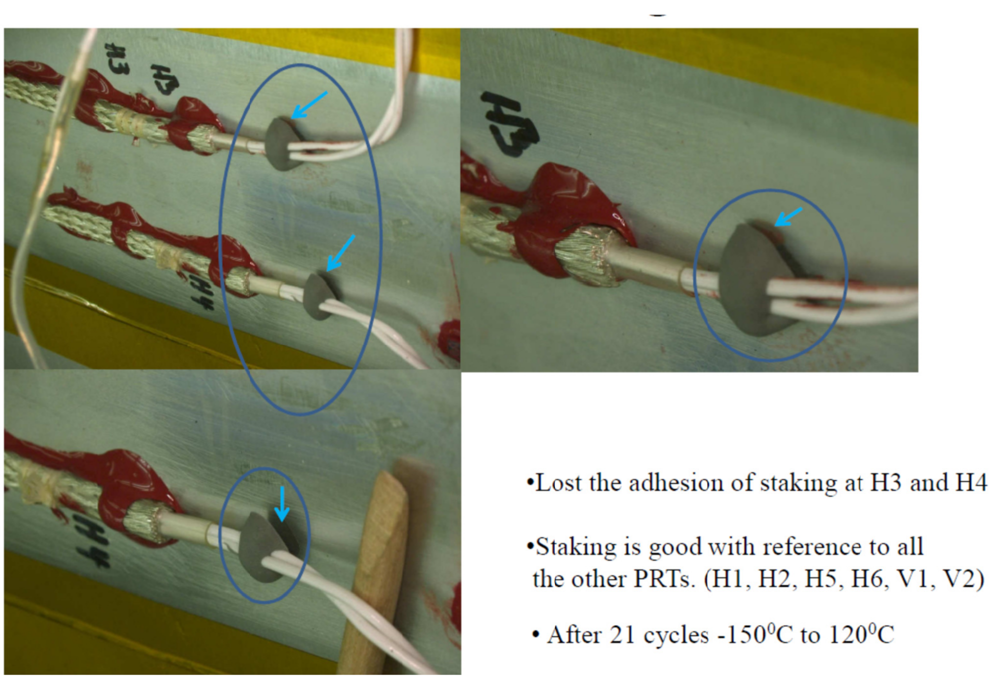


Figure 11: Loss of adhesion (2 out 8 staking points) of staking as a result of thermal cycling