Jet Propulsion Laboratory
California Institute of Technology

Package Qualification and Verification (PQV) Challenges of Avionics Hardware to Enhance the Safety and Mission Assurance of JPL/NASA Projects

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- Thanks are due to Component Engineering and Assurance Office, Office of Safety and Mission Success, JPL-NASA, Caltech for their encouragement to support this meeting.

JPL Design Principles (DP)

***Ref.*: JPL Rules! DocID 43913, Rev. 6**

- **4.12.2 Electronic Packaging (Avionics)**

  - **4.12.2.1 Qualification of electronic packaging designs -** Electronic hardware shall be capable of surviving **three times the planned mission expected number of thermal cycles, each over the allowable flight temperature (AFT) extremes,** plus an estimate of the thermal cycles expected in the planned ground operations. In the absence of a specific mission thermal cycling profile, electronic hardware shall be capable of surviving 10,000 cycles, each of a 15 degrees C delta-T (ΔT) excursion.

Challenges in Thermal Cycling Environment

- Mars 2020 Rover will be experiencing severe thermal environments than typical spacecraft on other missions.
- Mars Helicopter Concept
- MSL Curiosity Rover have been experiencing severe thermal environments.
- MER Rovers (Spirit and Opportunity) have been experiencing severe thermal environments than typical spacecraft on other missions
- Phoenix lander had experienced severe thermal environments.
- InSight lander will experience severe thermal environments.
- Planned Europa Orbiter and Europa Lander Concept
- MRO/Mars Odyssey orbiters have been experiencing different or benign thermal environments.

Do you need a PQV Program?

- JPL and NASA qualification of packaging methods and processes may not be adequate for Mars 2020, InSight, MSL, MER, and Europa Projects.
- Therefore, Mars 2020 and other projects need a PQV program to review and test hardware to ensure it does not suffer from thermal cycle induced electronics packaging related failures.

Purpose

"Assess and mitigate the risk associated with the avionics and other hardware to enhance the probability of sustaining the hardware functionality for long life"

"The purpose of **Packaging Qualification and Verification (PQV)** implementation in a project is to provide guidance to the designers to significantly reduce the likelihood of packaging related thermal cycle induced failures occurring during the mission duration".

Avionics-Packaging Related Issues and Challenges

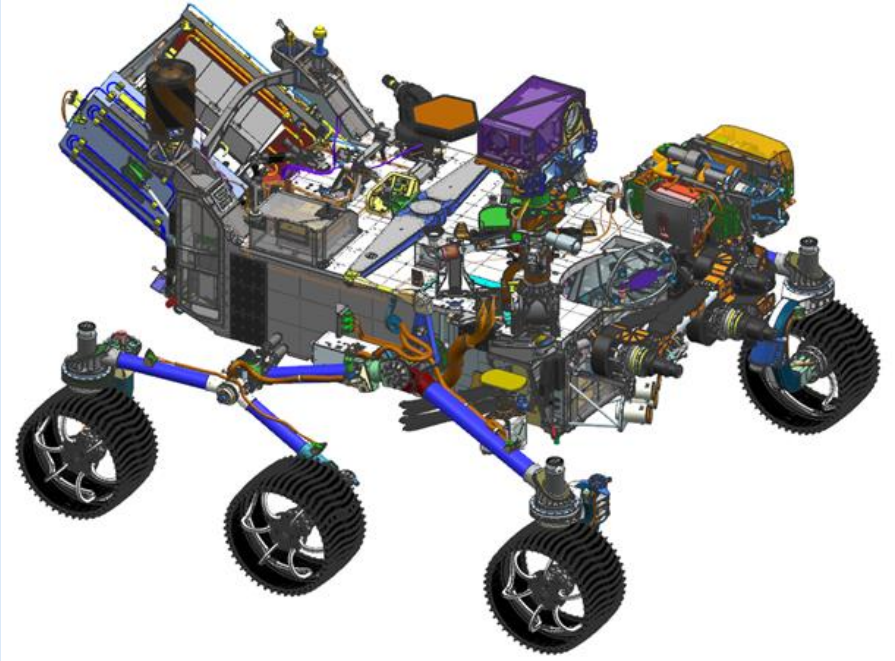
- Advanced Electronics Packaging Technologies such as CCGA
- Interconnects (Surface Mount Technology packages)
- Solder Joints
- Adhesives, Encapsulates, Bonding materials, staking materials, etc.
- Bonded Joints, Welding, etc.
- Laminated Materials
- Vias
- Wire bonds and Windings
- Materials and Processes used in Electronic Packaging
- COTS with or without heritage or space use history
- New Technologies
- Advanced Unqualified Technologies

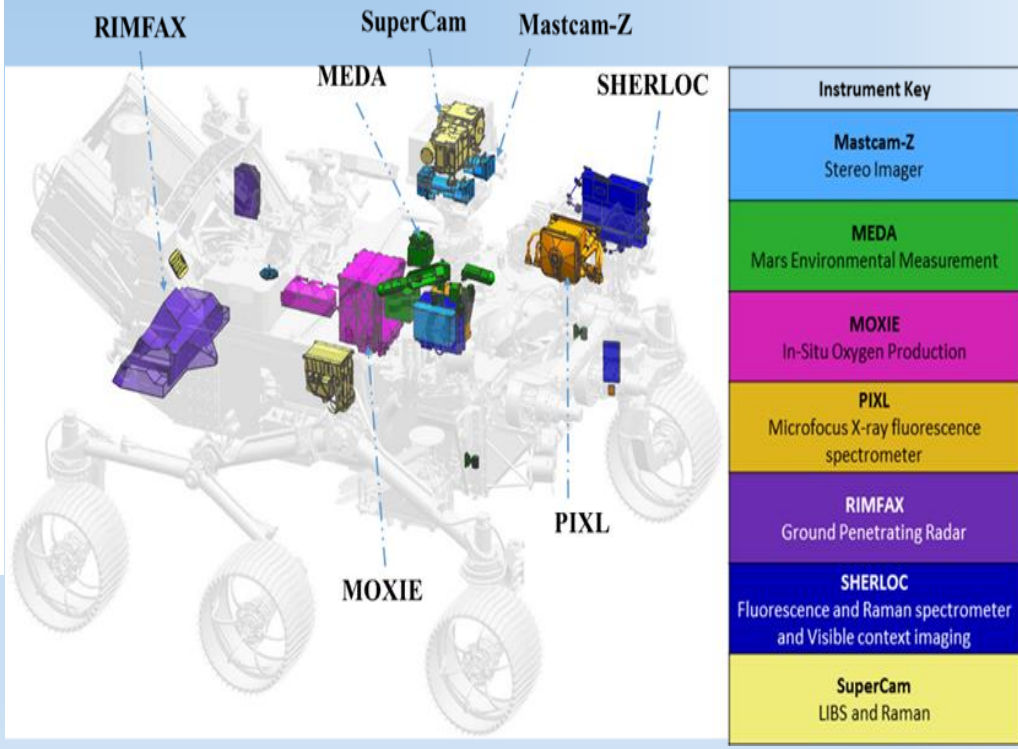
Example: Requirements

- **PQV requirement for thermally controlled hardware**
  - -40°C to +50°C for 3015 (=1005*3)
    - ΔT=90°C for 3015 cycles which is way beyond 200 NASA cycles. PQV Required.
    - 3015 thermal cycles (3X Mars 2020 lives) with ΔT≤ 40°C is equal to 200 NASA cycles. **Therefore, no need to do PQV in rover chassis.** But review of the hardware assembly/subassembly designs is required.
- **<u>However, there are several exceptions such as unqualified, new materials and processes etc., need to be tested for 3x life!!!</u>** **<u>Ex.: CCGA 1752, Virtex-5</u>**
- **PQV first requirement for thermally uncontrolled hardware defined**
  - -105°C to +40°C for summer cycles of 1505
  - -130°C to +15°C for winter cycles of 1505
- **PQV revised requirement for thermally uncontrolled hardware defined**
  - -105°C to +40°C for summer cycles of 2115
  - -130°C to +15°C for winter cycles of 900
- **PQV requirement for CCGA (Virtex-5), DDR2 Memory and other packages have been defined**

Mars Rover Family: Pathfinder, Spirit/Opportunity, Curiosity, & Mars 2020 Rover Project Duration

Mars 2020 Rover and Payload Instruments: Thermally Uncontrolled and Controlled Hardware in Harsh and Benign Thermal Environments



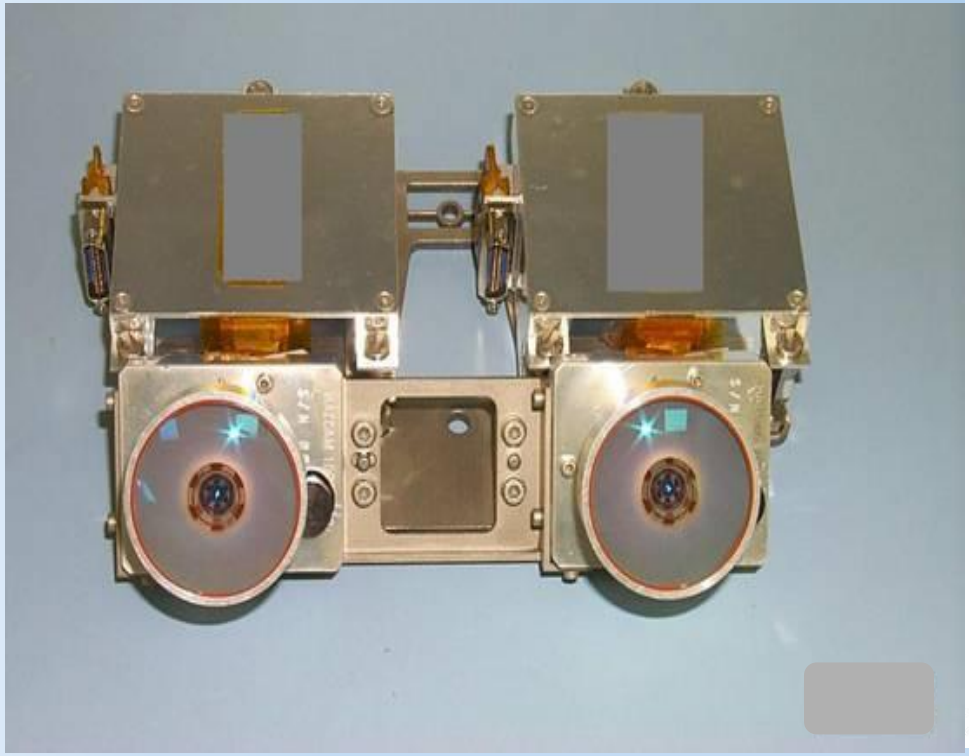


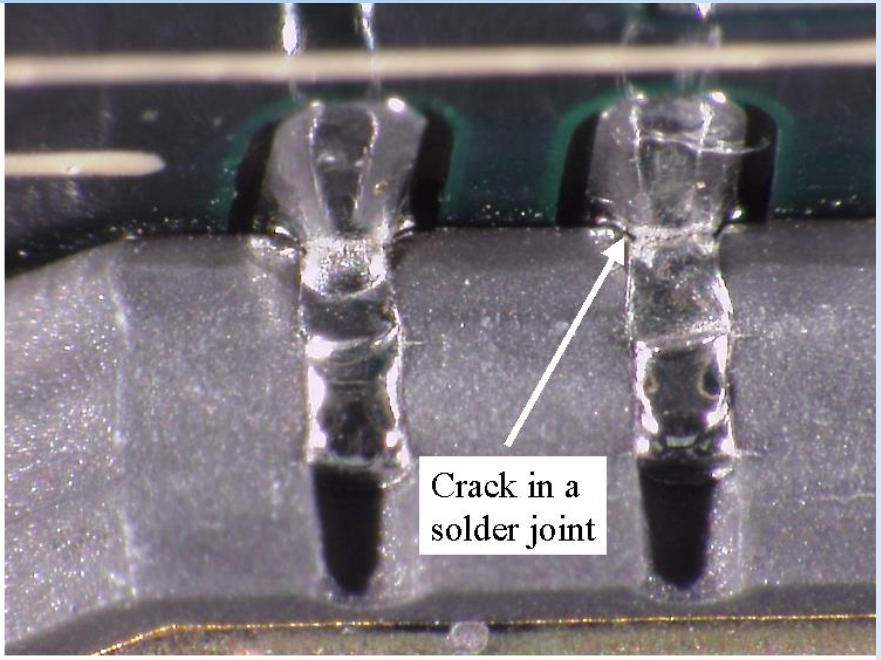
Thermally Uncontrolled Hardware in Harsh Thermal Environments

Hardware Life Cycled to Extreme Temperature Environments

- Camera assembly for guidance and navigation applications
- Ceramic Column Grid Array (CCGA)/FPGA in Avionics
- Flip-chip advanced packaging technology in Avionics
- Motors/encoders in mechanisms
- Force sensor gauges for Robotic Arm /Sample Acquisition/mechanisms
- Tin-whiskers in Telecom Electronics
- Flex print cables in harness/mechanisms
- Platinum temperature thermometer (PRT): Temp sensors in thermal hardware to monitor the health

Engineering Camera used for MER & MSL projects





Optical photograph of a cracked interconnect in LCC 20 assembly after 50 thermal cycles (-120°C to 115°C)

Ref.: Bell, J. F., III, et al., Mars Exploration Rover Athena Panoramic Camera (Pancam) investigation, J. Geophys. Res., 108(E12), 8063, doi:10.1029/2003JE002070, 2003.

Ref.: Rajeshuni Ramesham, Justin N. Maki, and Gordon C. Cucullu, Journal of Microelectronics and Electronics Packaging (JMEP), Vol. 6, No. 2, Quarter 2, 2007, pp: 125-134.

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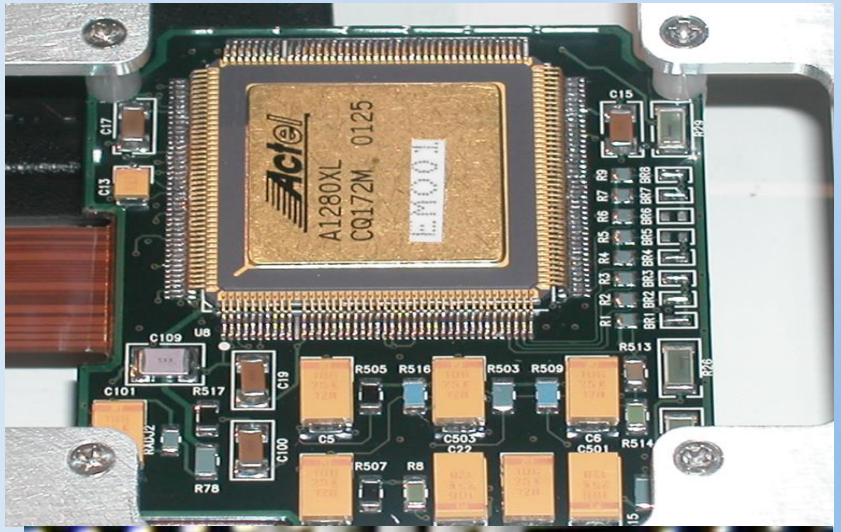
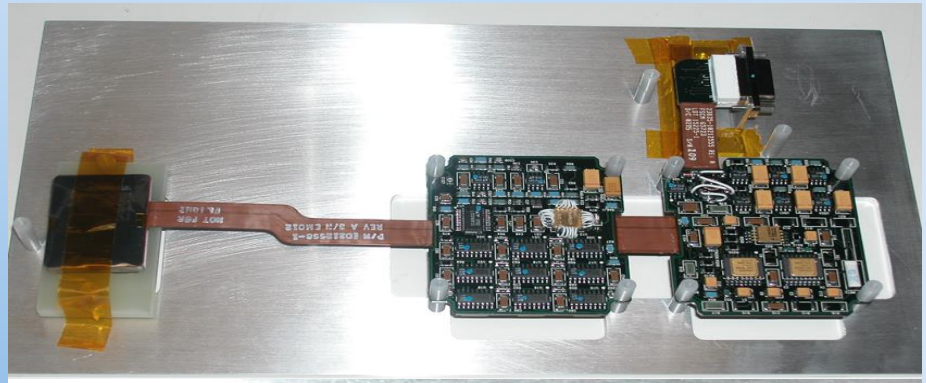
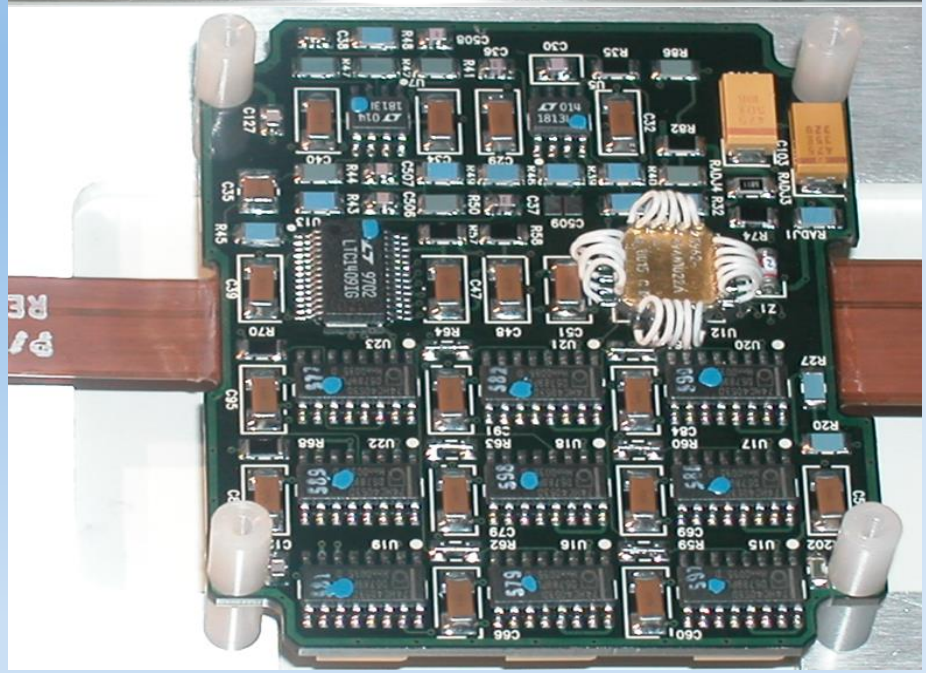
Camera Electronics Assembly for MER (-120°C to +85°C)





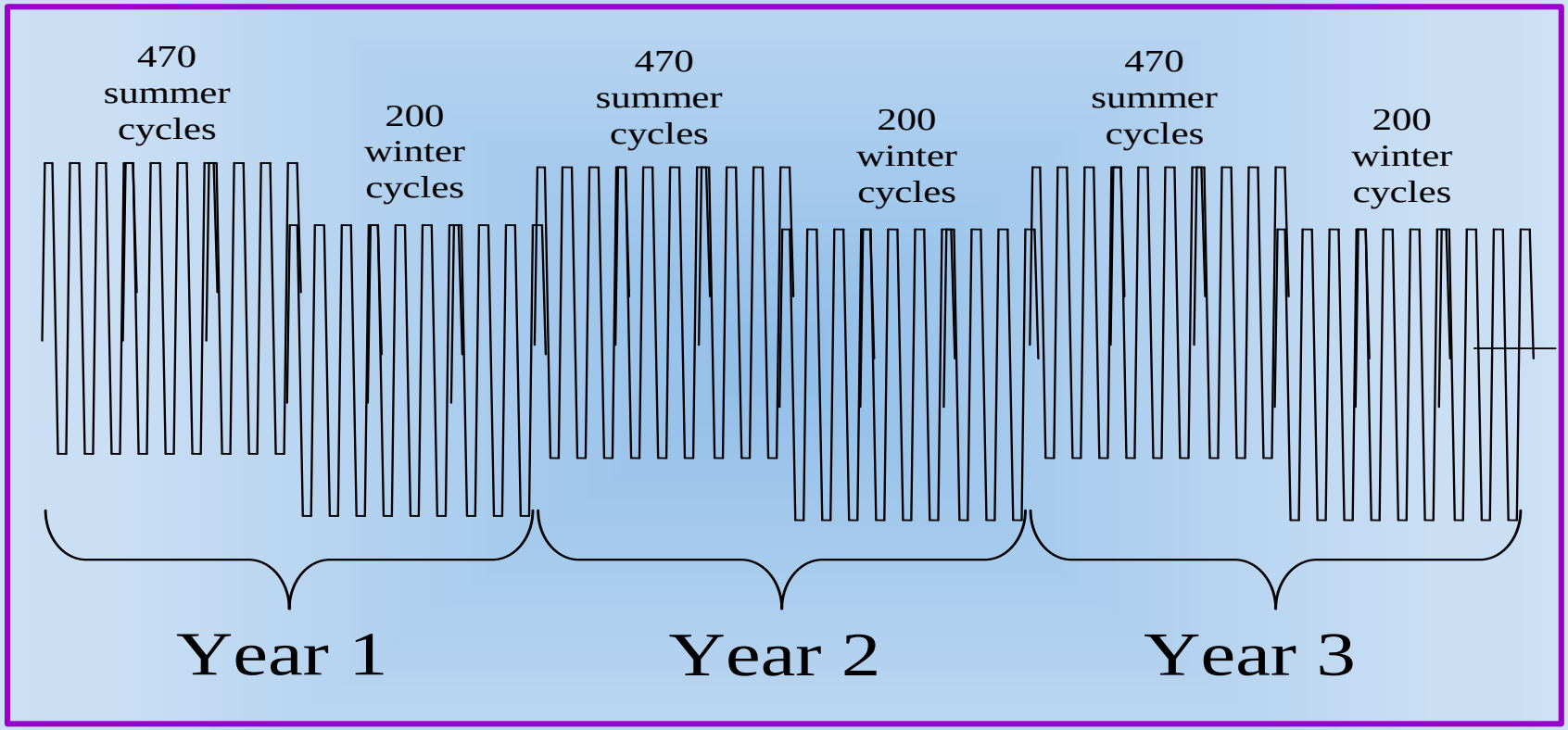


Ref.: Rajeshuni Ramesham, Justin N. Maki, and Gordon C. Cucullu, Journal of Microelectronics and Electronics Packaging (JMEP), Vol. 6, No. 2, Quarter 2, 2007, pp: 125-134.

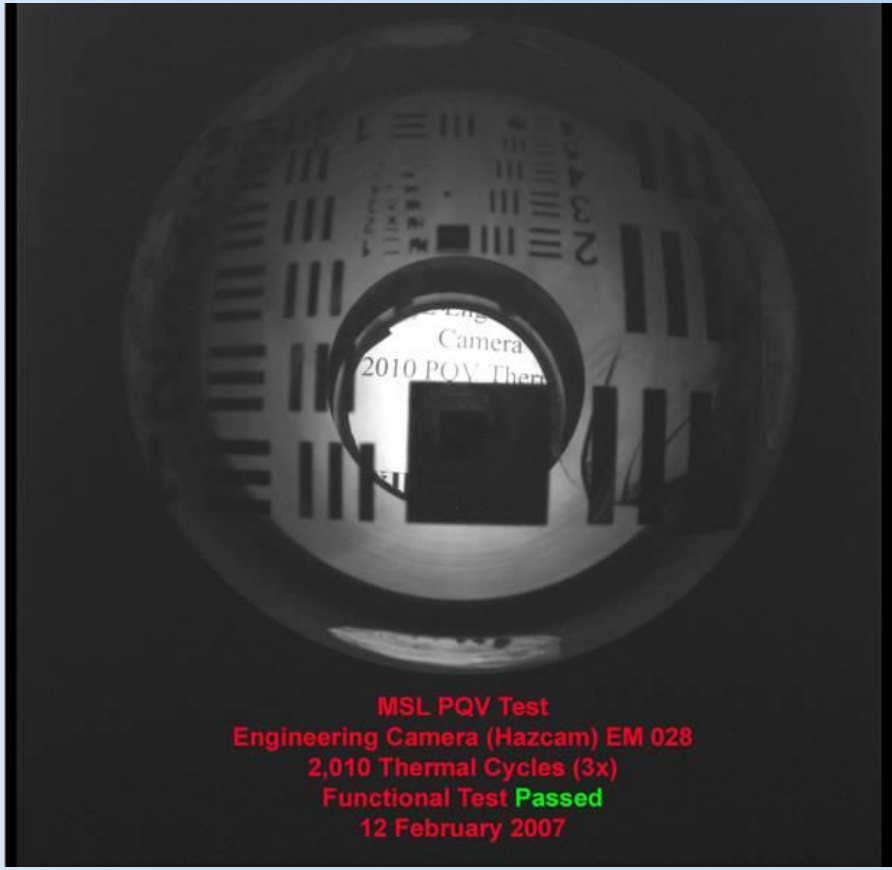
Thermal Cycling

- Thermal cycling is generally represented as **ON-OFF** or **day and night** thermal environment conditions. This warrants the assembly reliability.
- Self-heating due to operation of the associated electronics.

Sequence of thermal testing profile for MSL project

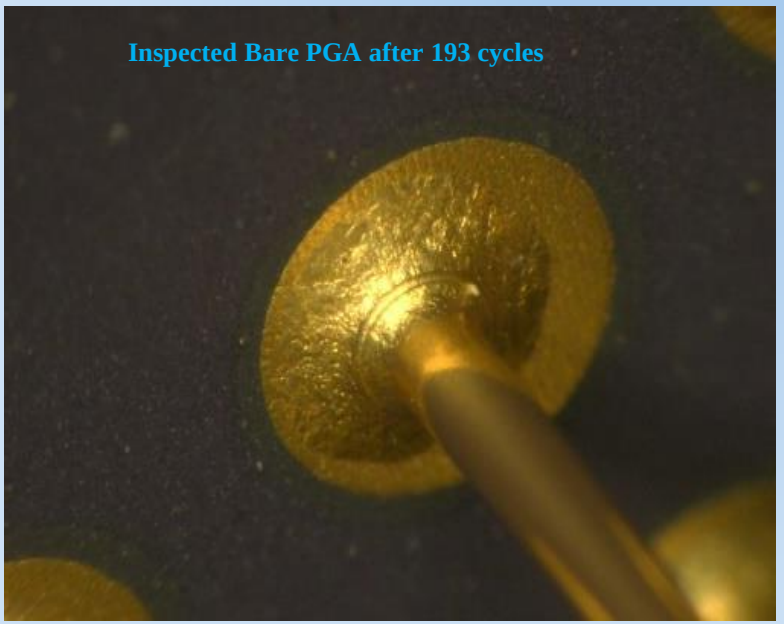


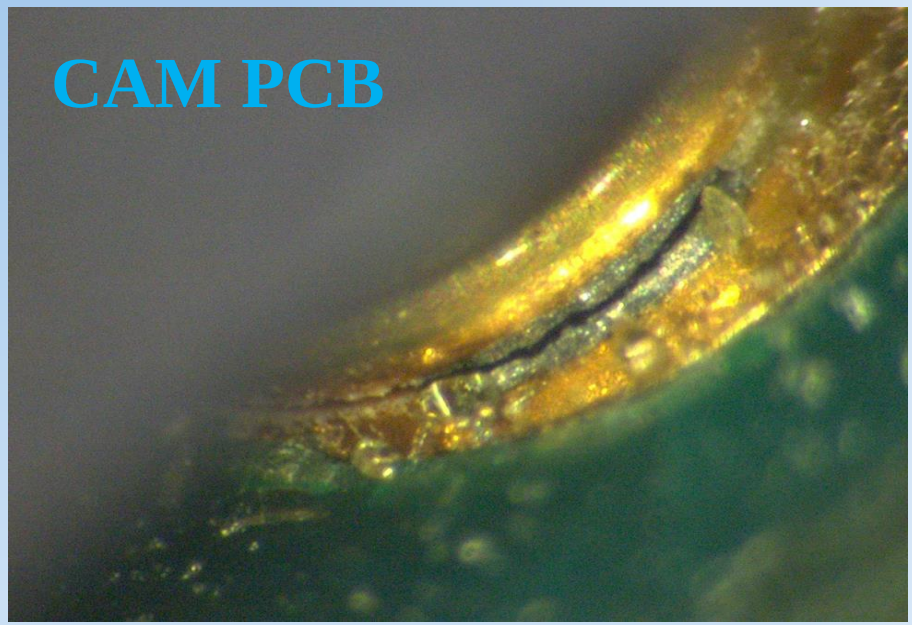
Picture of PQV team taken using the camera after completion of camera PQV test



Engineering Camera

- Several Mega Pixel Camera
- Camera Designs
- Eyes of the Rover

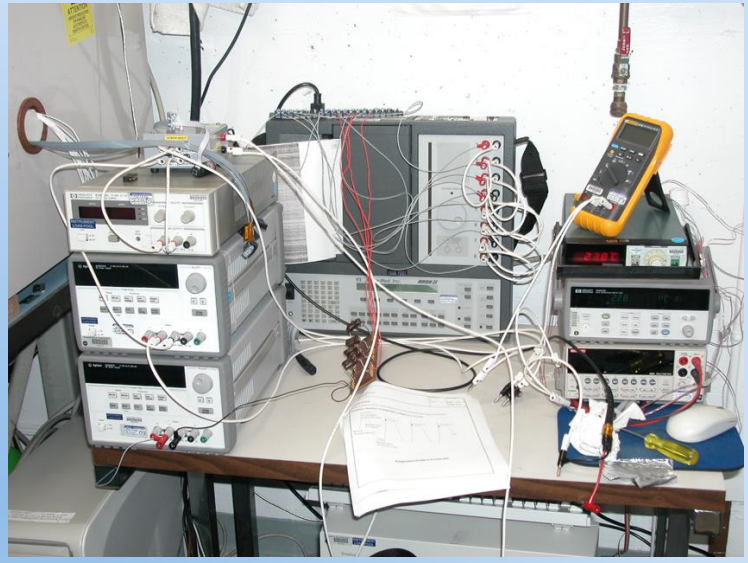




Solder joint fatigue issue

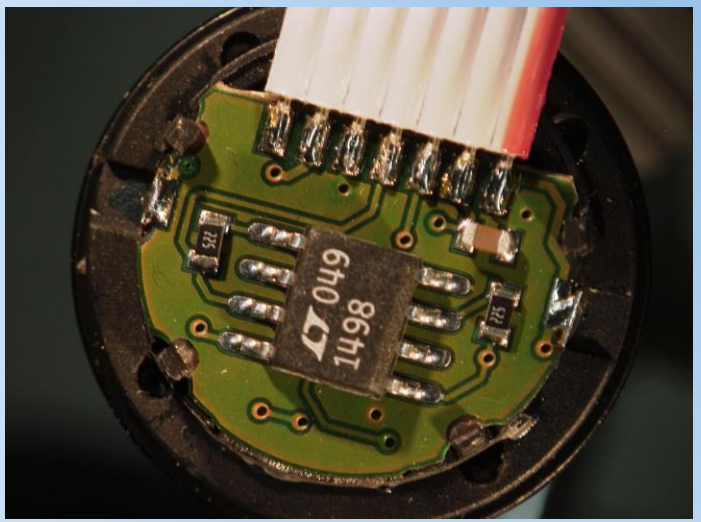
Ram

MAXON Motors/Encoders for Mechanisms

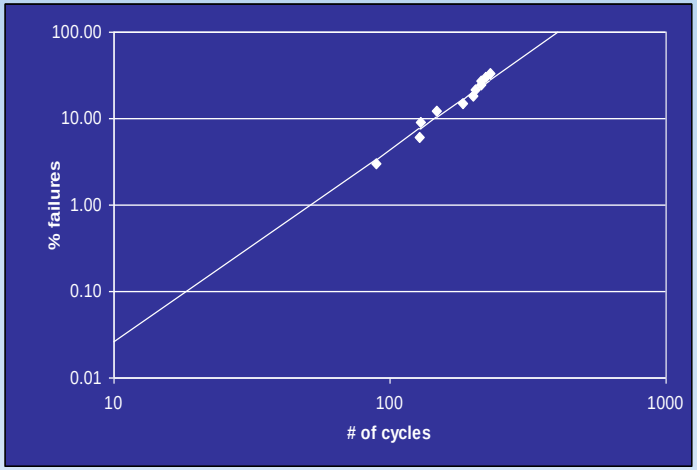


Ref.: Rajeshuni Ramesham, 40th International Conference on Environmental Systems AIAA 2010-6312.

Encoder, x-ray image of solder joint, failure vs. thermal cycles



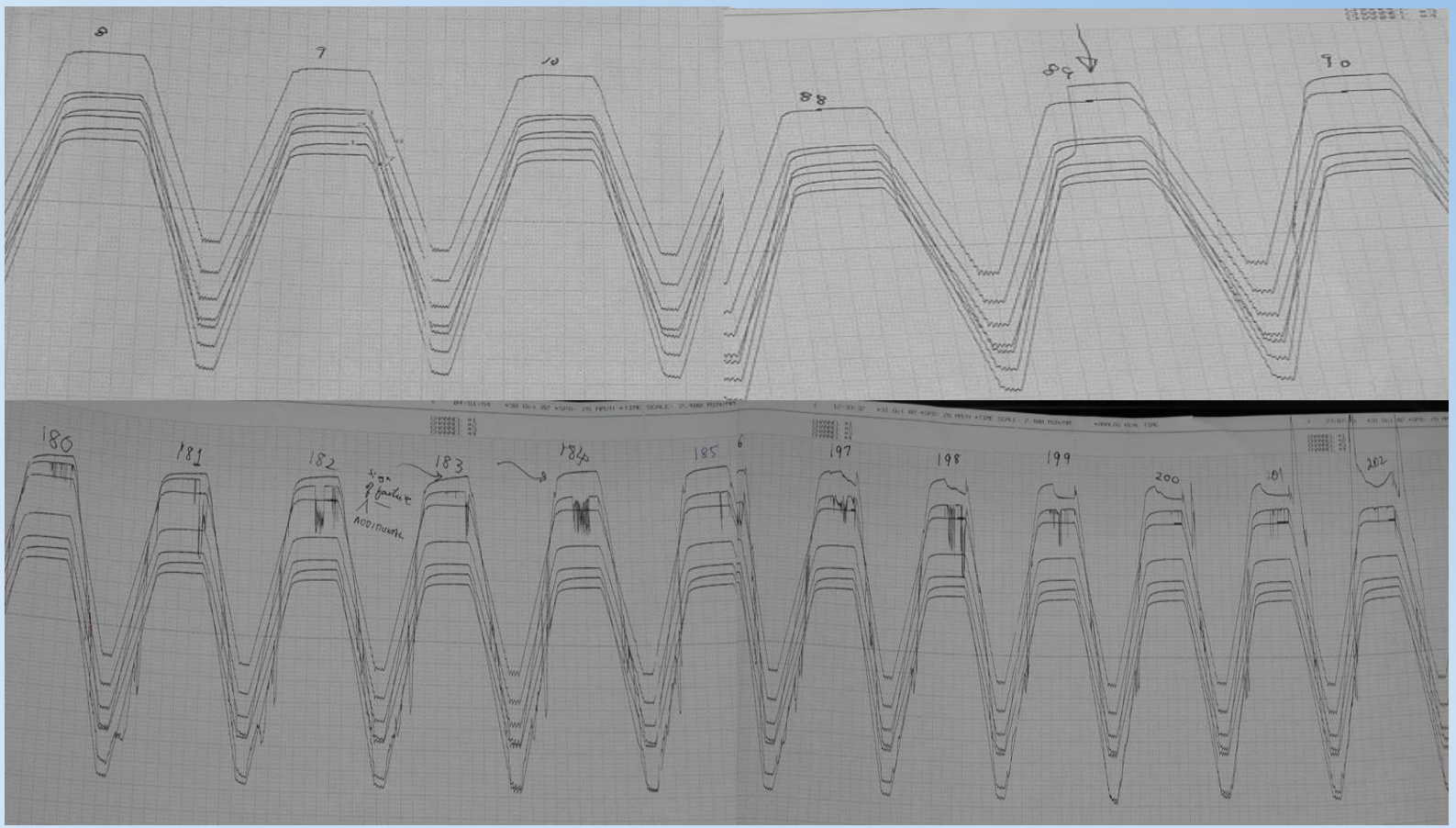
X-ray imaging of solder joints in MAXON Motor#004



Ref.: Rajeshuni Ramesham, 40th International Conference on Environmental Systems AIAA 2010-6312.

PQV of RE 25#041, sign of failure, first and second enhancement of anomalies

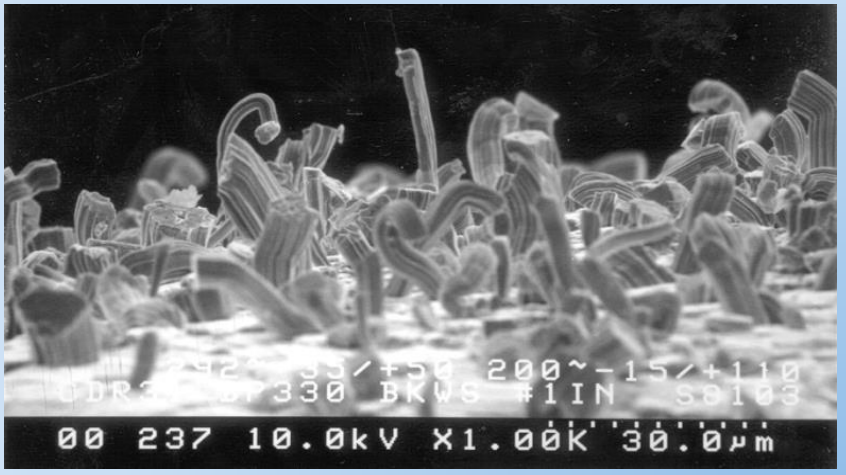
Winding Resistance, Ohms

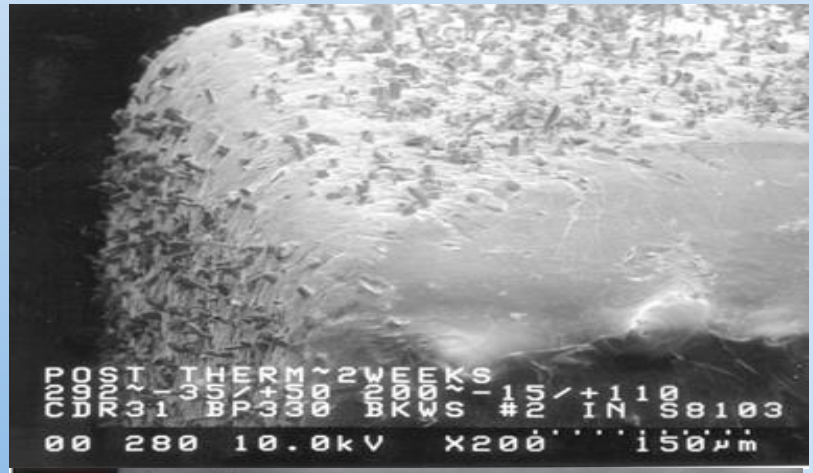


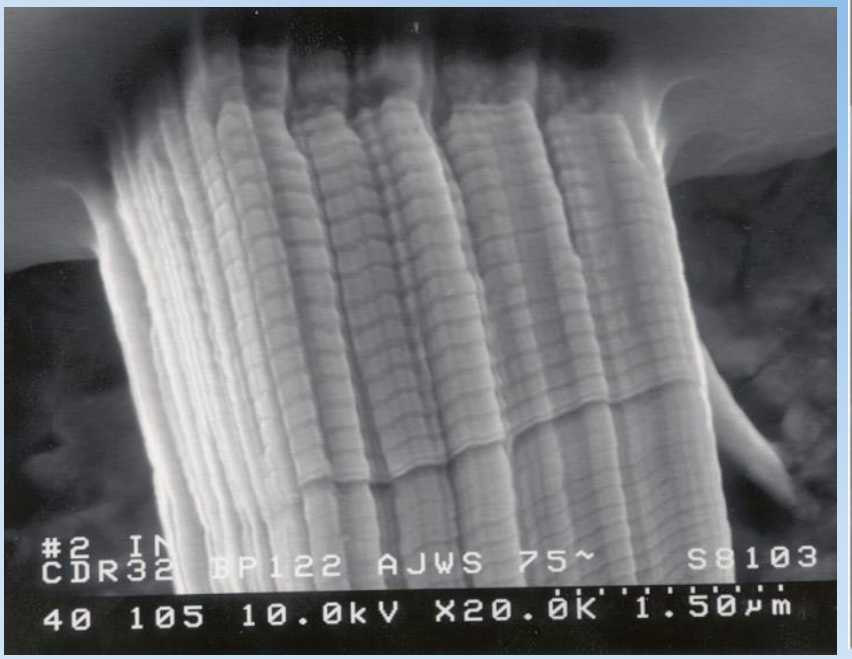
Number of Thermal Cycles or Time

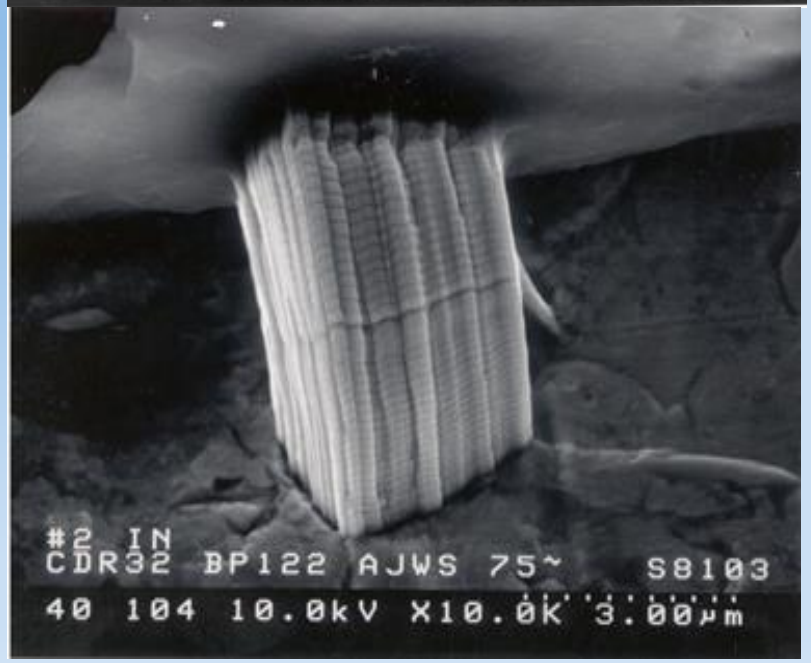
Ref.: Rajeshuni Ramesham, 40th International Conference on Environmental Systems AIAA 2010-6312.

Tin whiskers in Telecom Avionics Hardware



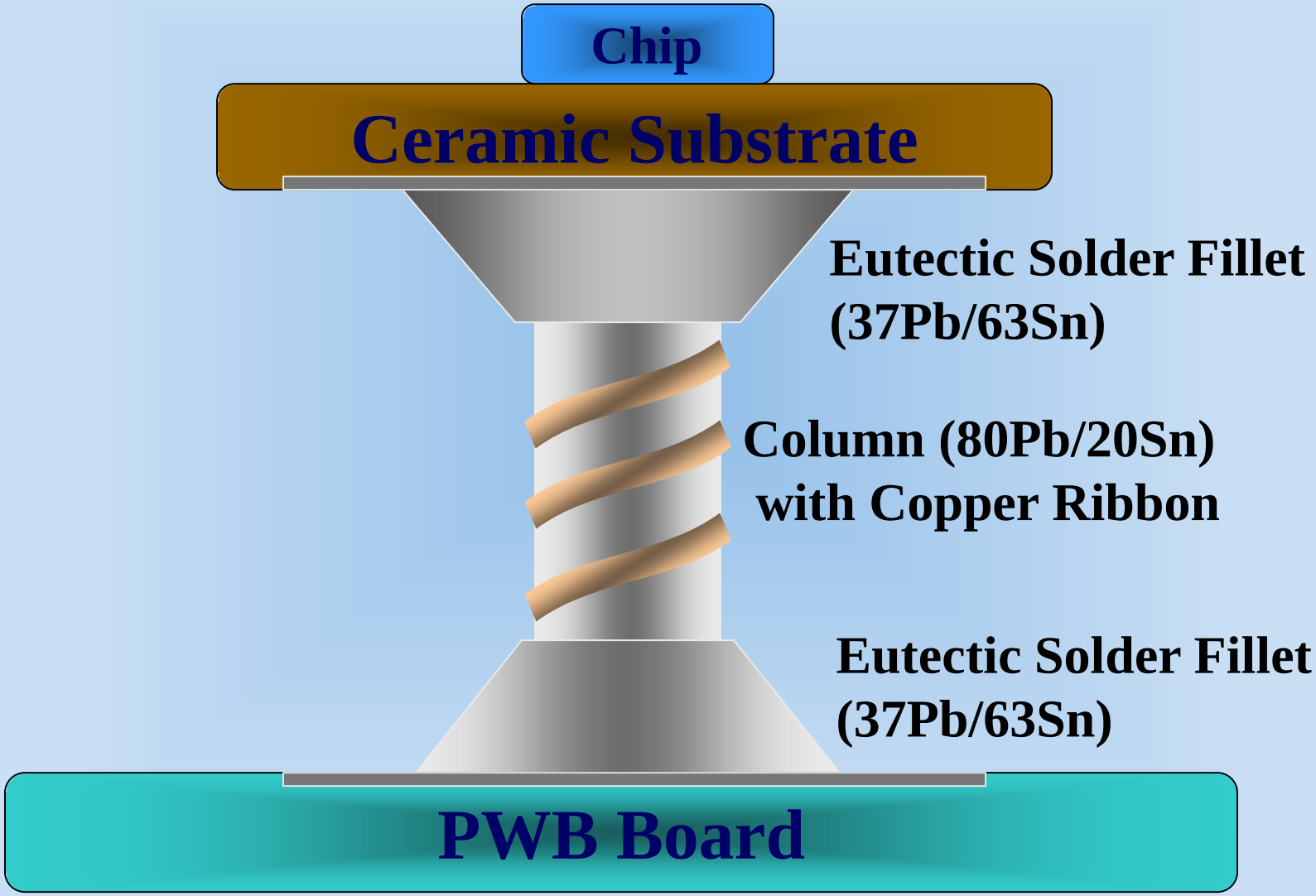






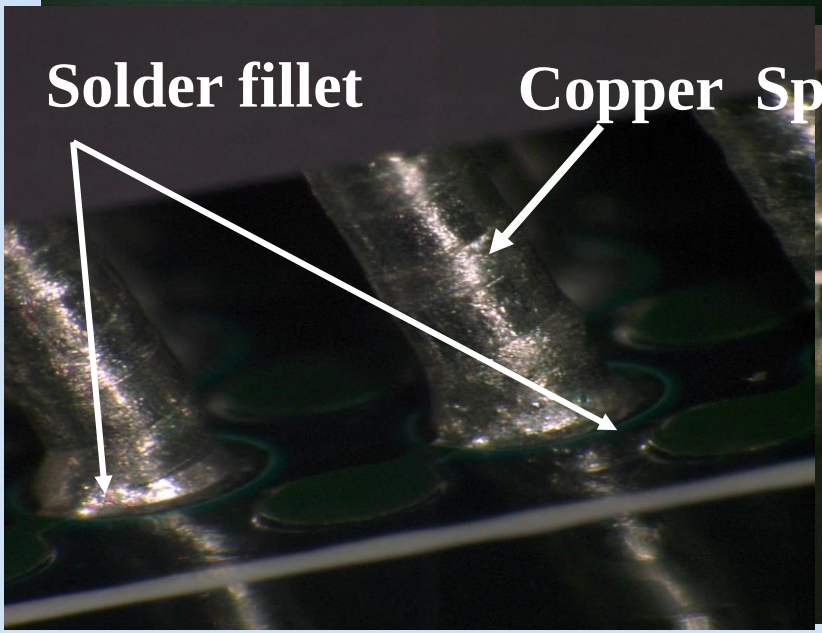
Ref.: Rajeshuni Ramesham, 40th International Conference on Environmental Systems AIAA 2010-6312.

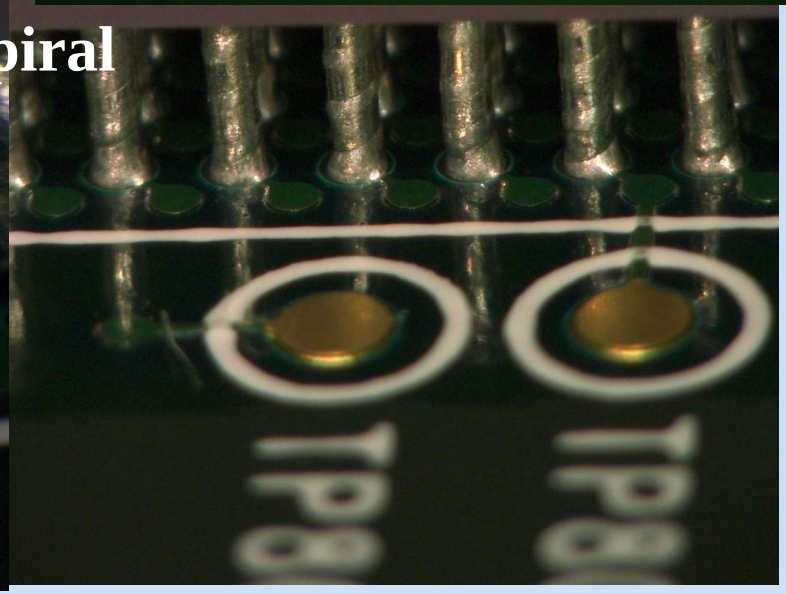
Avionics CCGA Schematic



CCGA Package

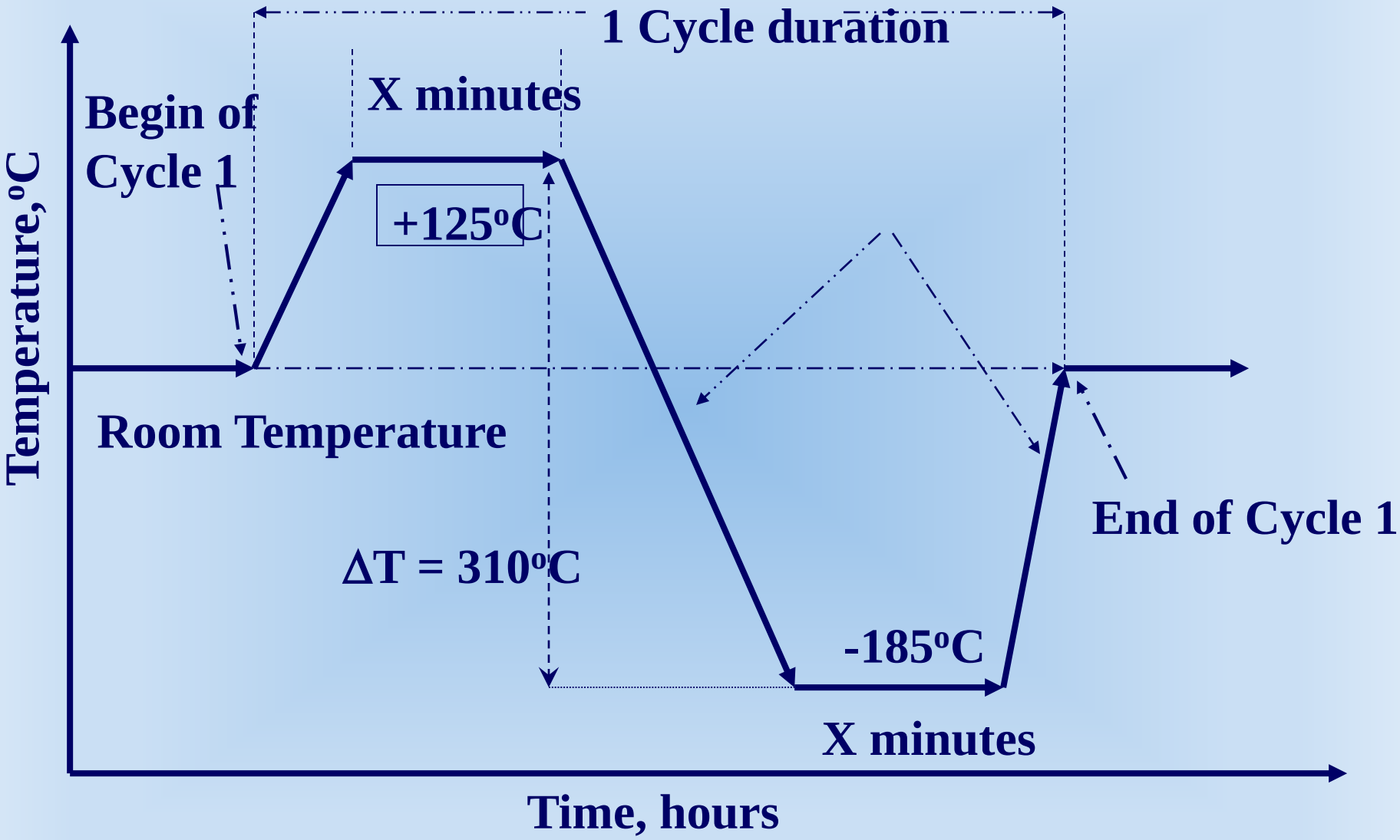
- Pad pitch: 1.27 mm (~51 mil)
- Diameter of the column: ~22 mil
- Solder fillet material: Pb37/Sn63
  - Melting point: ~183°C
- Column material: 80%Pb and 20%Sn
  - Melting point: ~280°C
- Copper spiral around column to enhance the integrity of column during reflow of solder

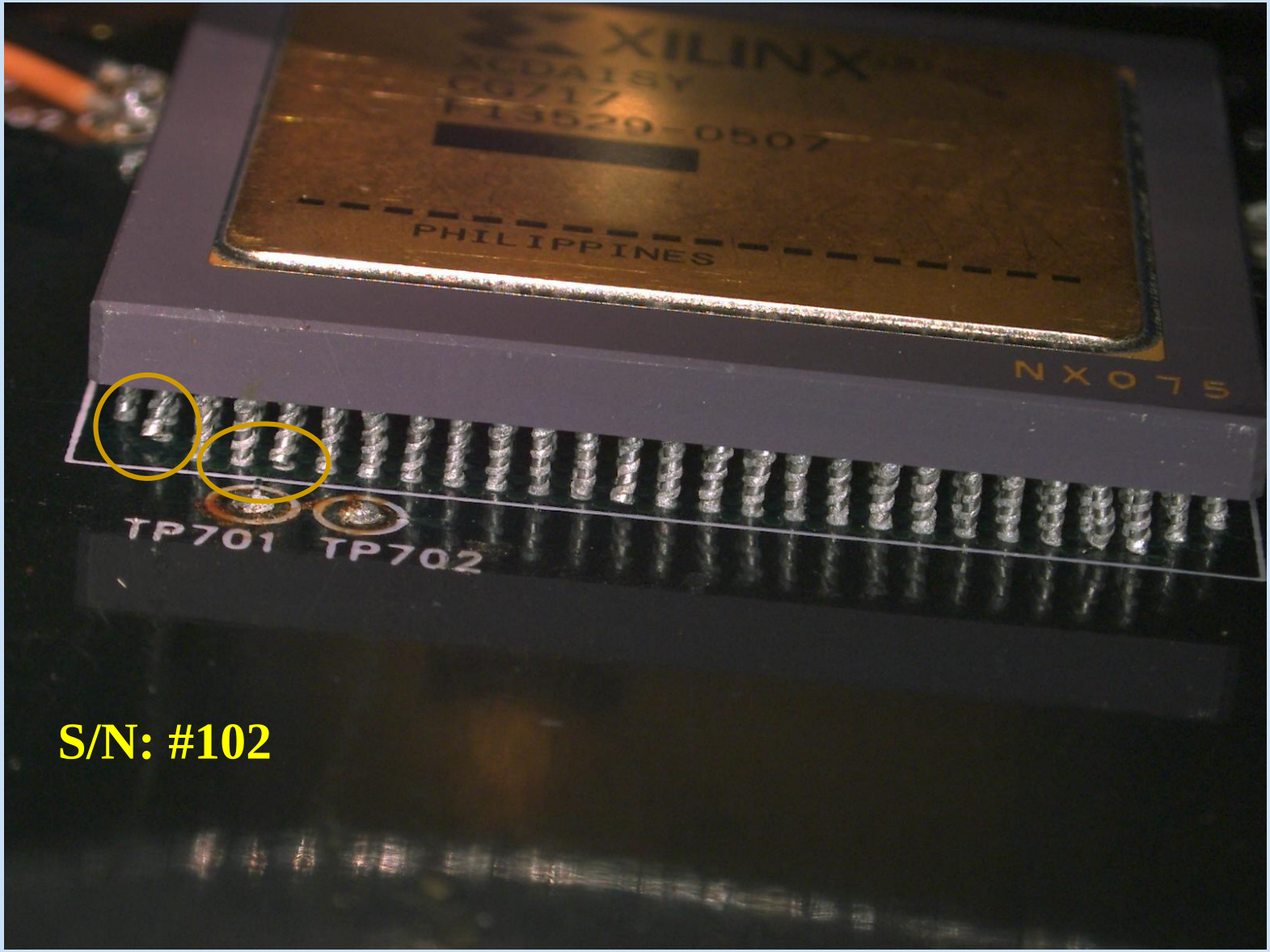




Ref.: Rajeshuni Ramesham, Journal of Microelectronics and Electronics Packaging, 2009, 7, pp: 1-9

Extreme Temperature Thermal Cycling Profile



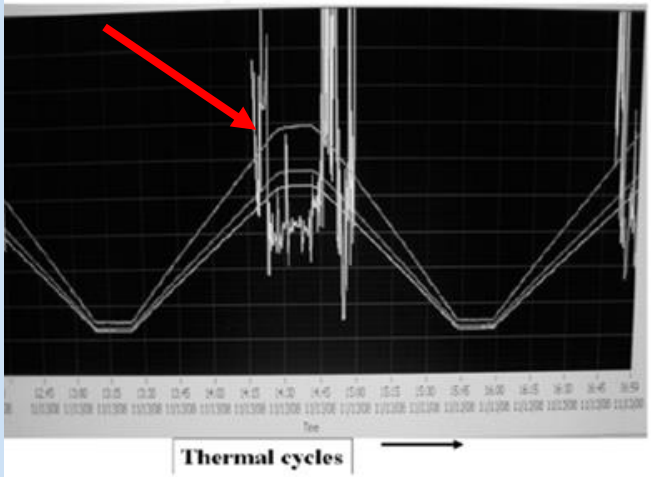


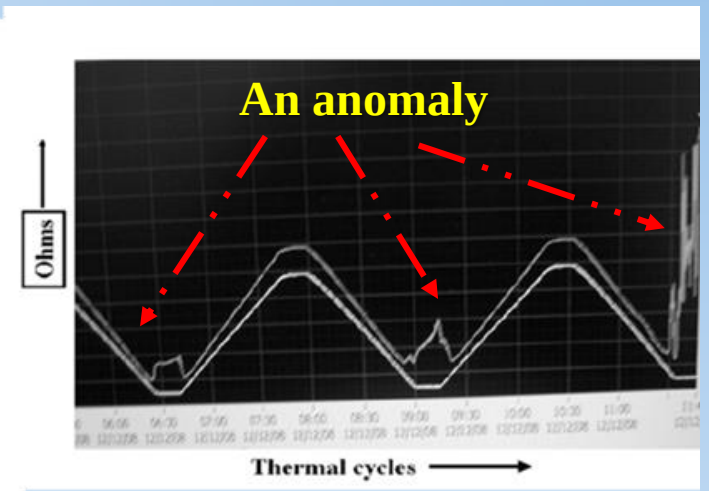
Ref.: Rajeshuni Ramesham, Journal of Microelectronics and Electronics Packaging, 2010, 7, pp: 1-9

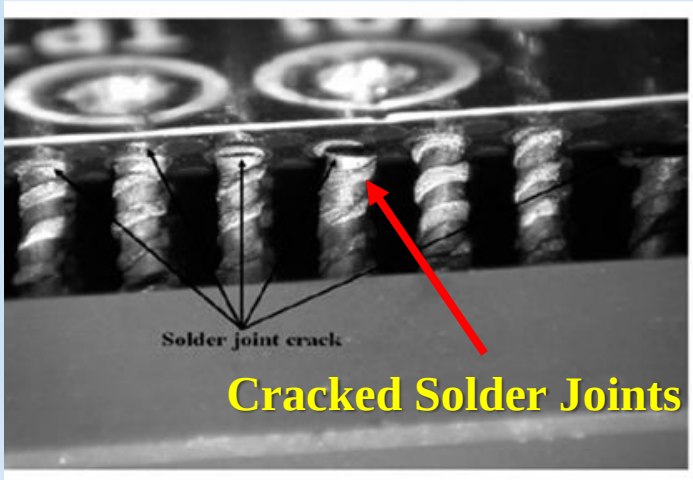
Failed CCGA Package vs. Thermal Cycling

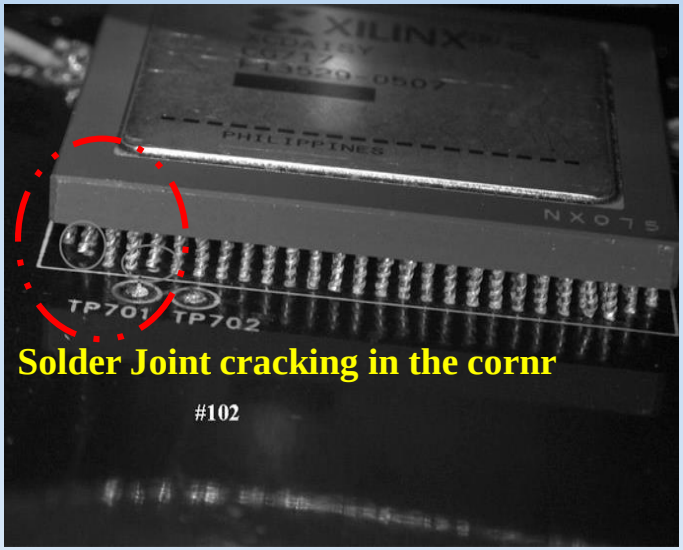
Intermittent Failure

Resistance, Ohms



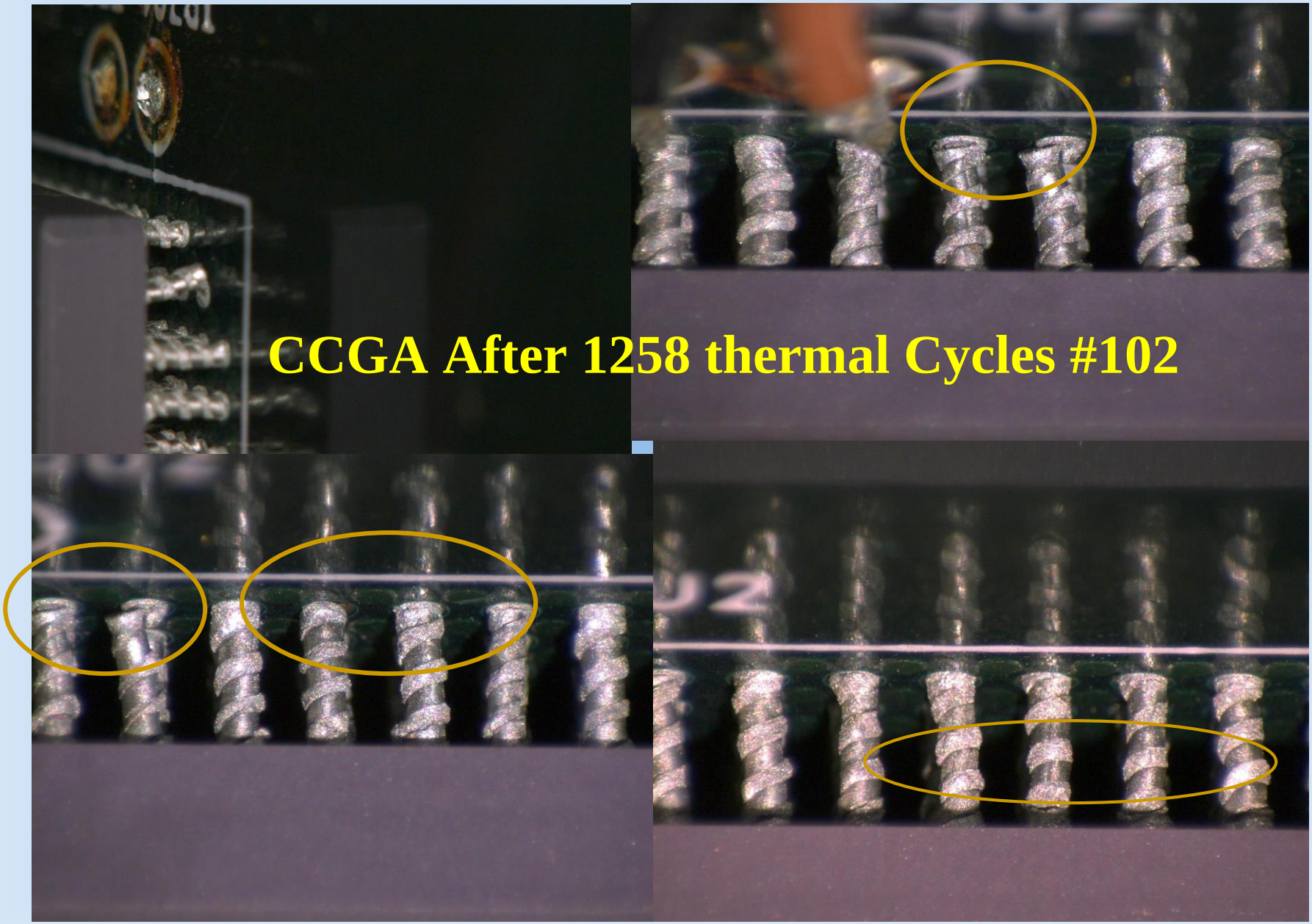




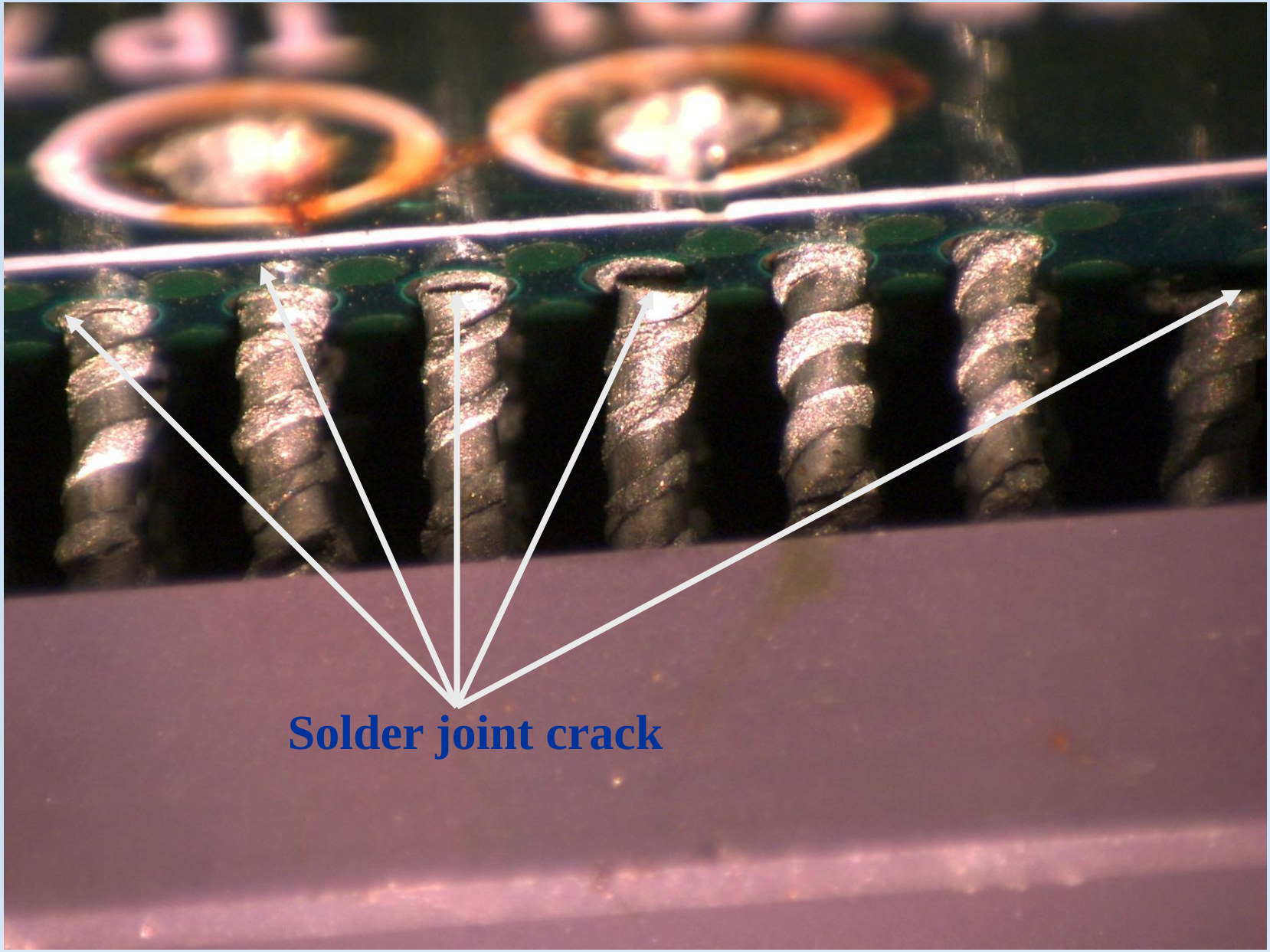


Ref.: Rajeshuni Ramesham, "Reliability of CCGA Interconenct…"J. Microelectronics and Electronics Packaging, Vol 7, No.1, 2010

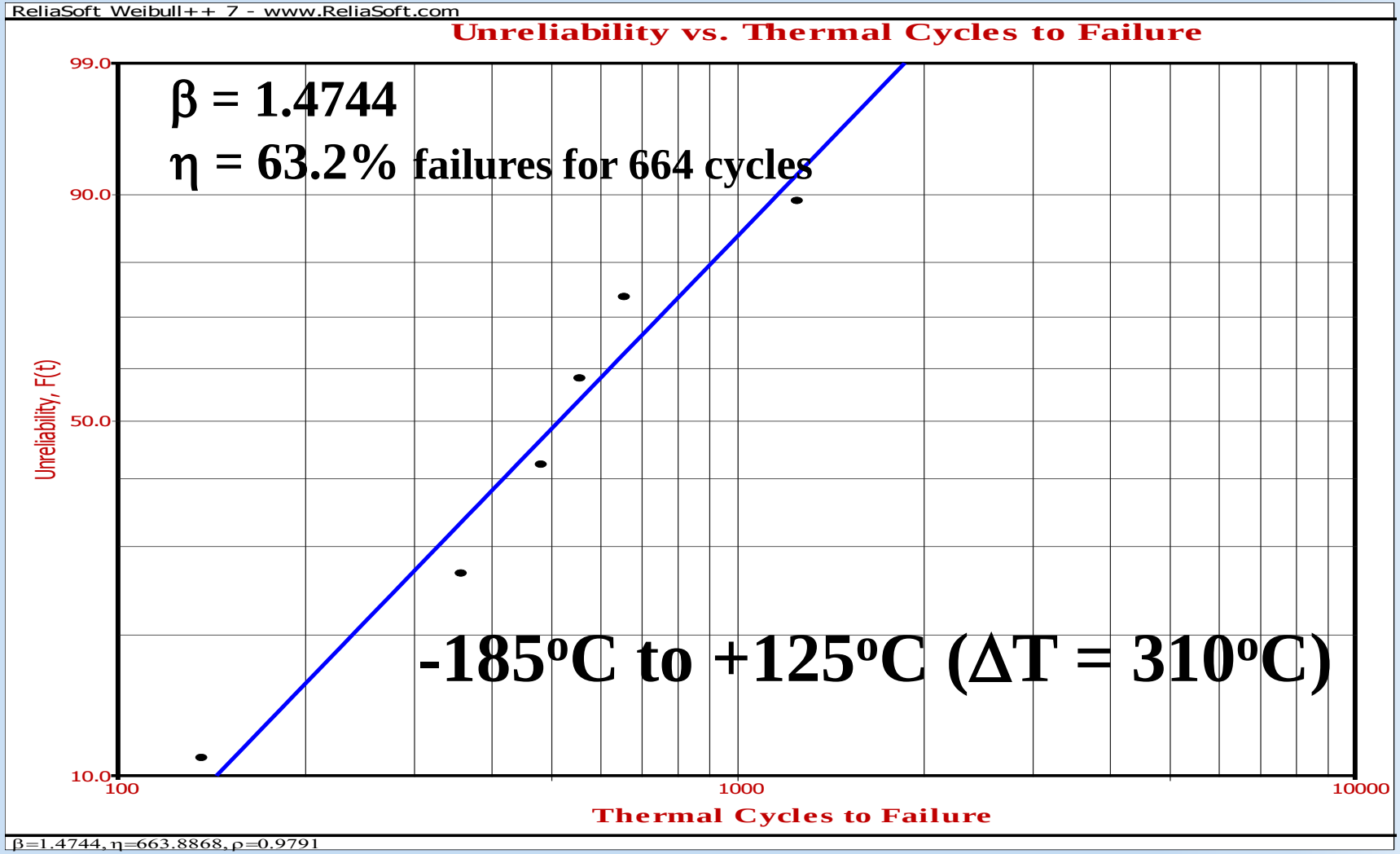
CCGA After 1258 thermal Cycles #102



Inspection of CCGA Columns

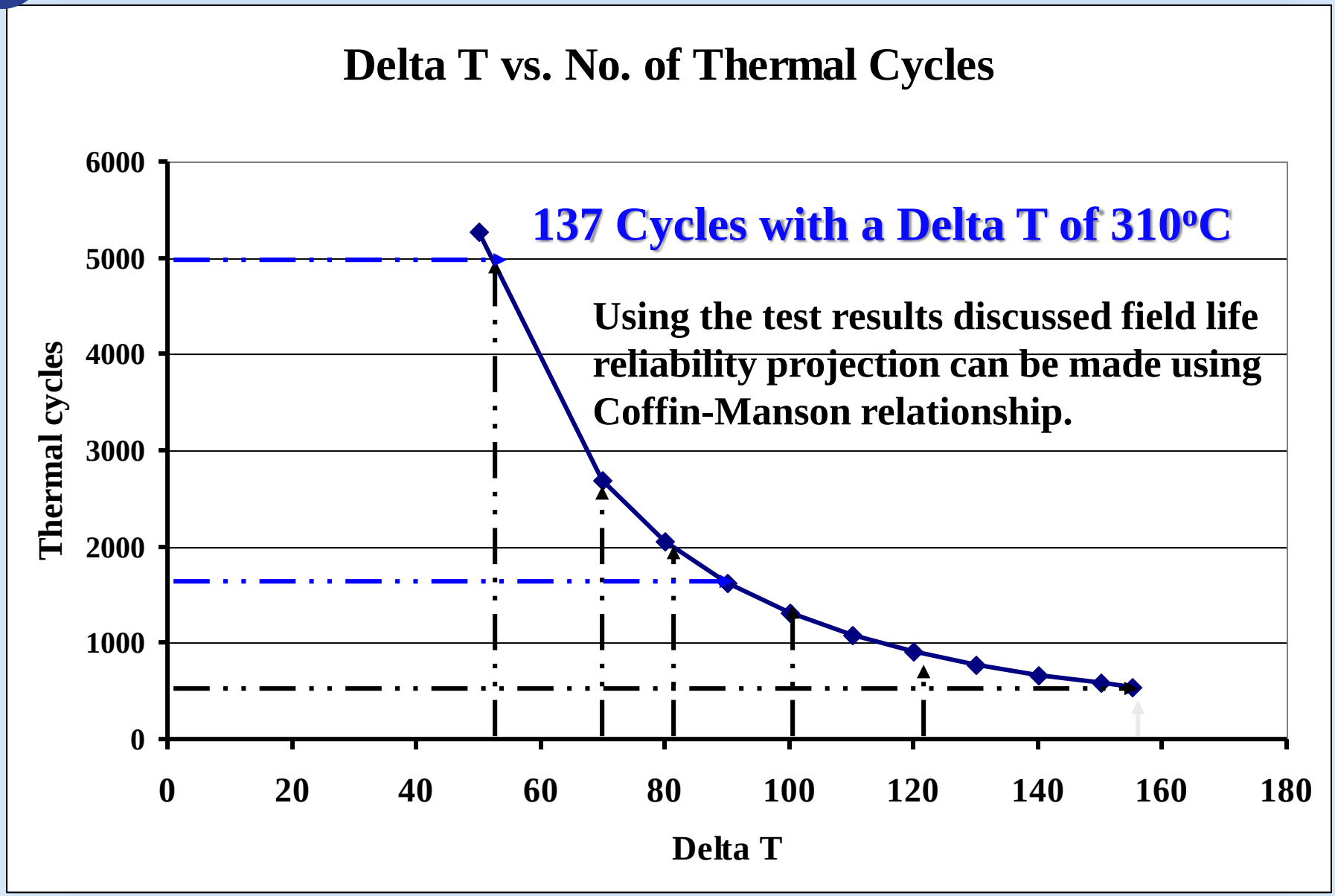


Ultra reliability vs., Thermal Cycles



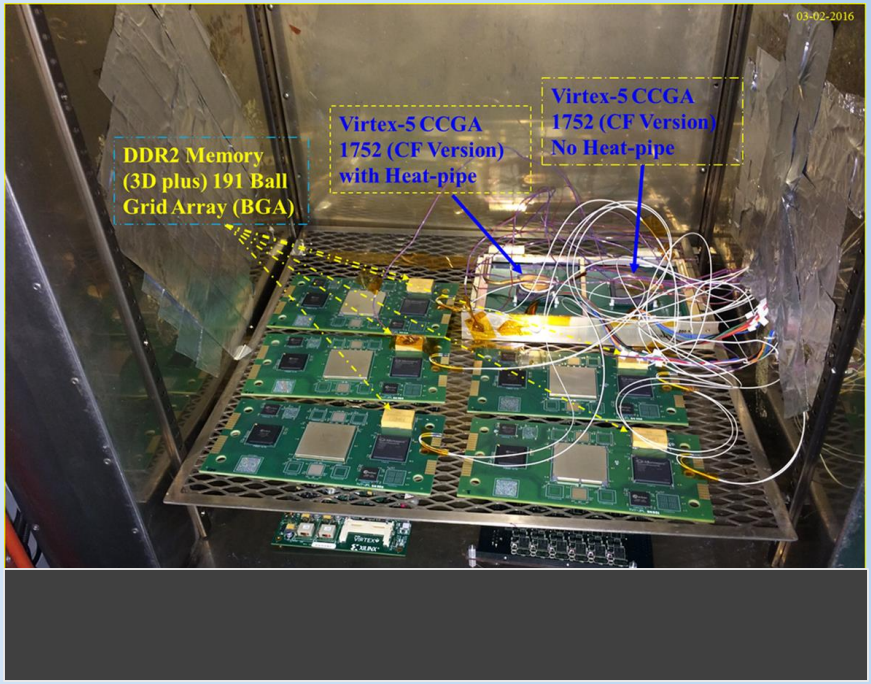
Ref.: Rajeshuni Ramesham, Journal of Microelectronics and Electronics Packaging, 2010, 7, pp: 1-9

Temperature Cycle Life Projections

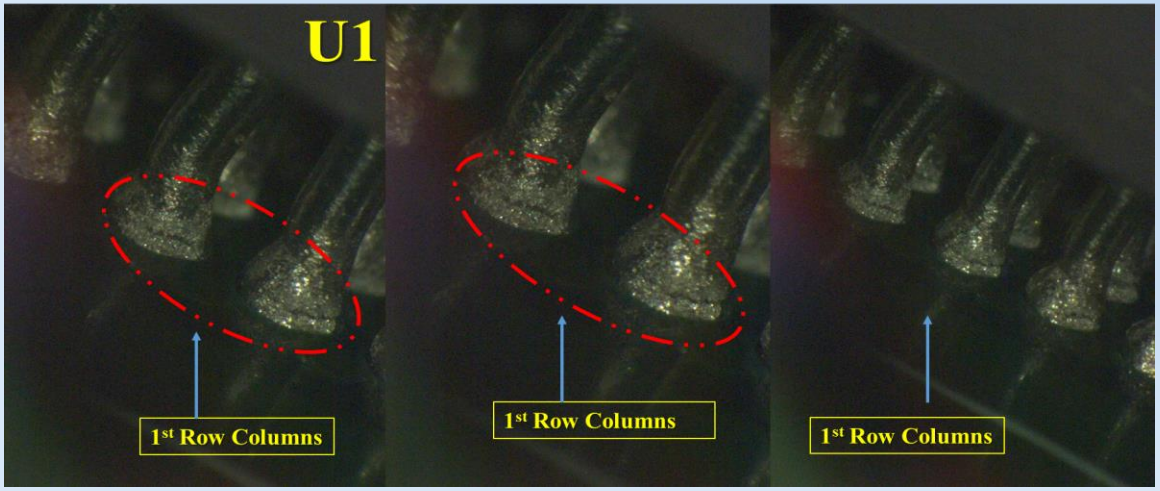


Ram

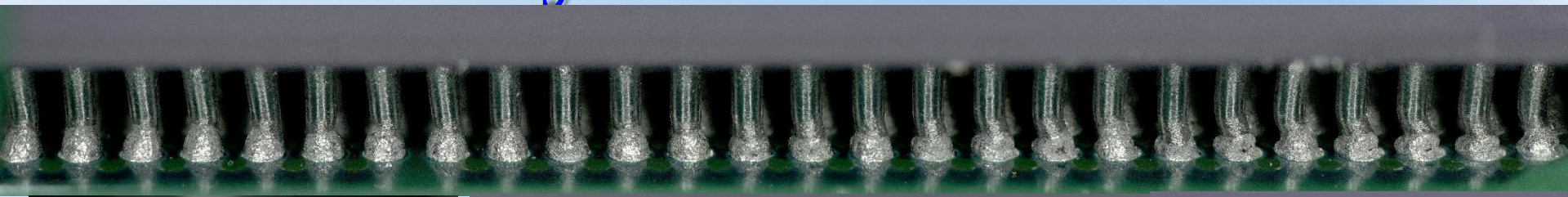
Virtex-5 (CF Version)

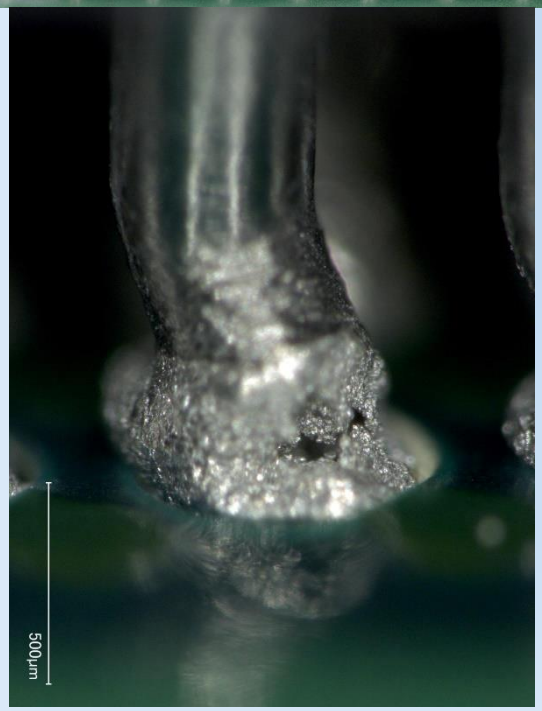


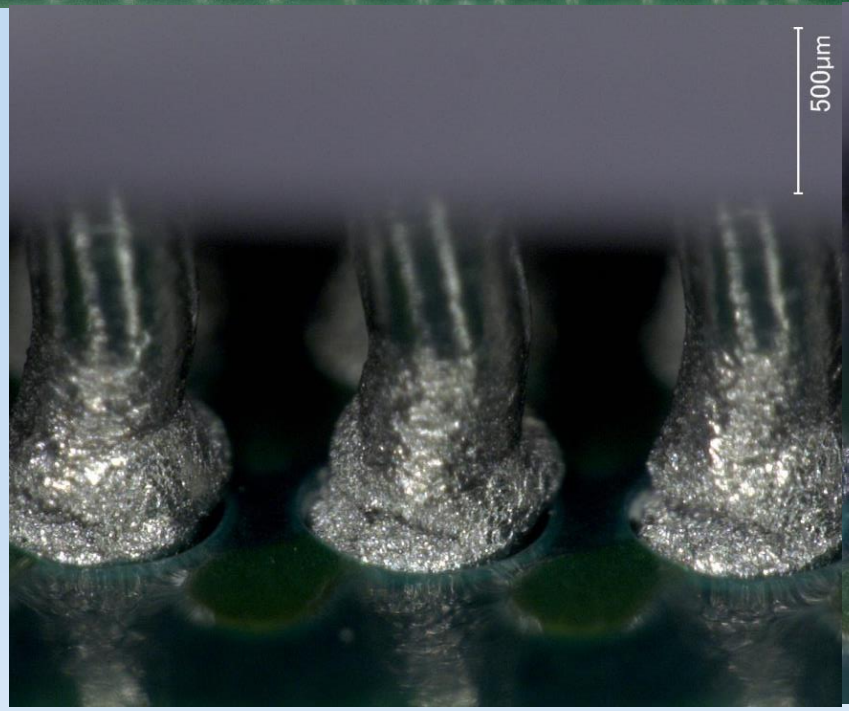
Virtex-5: New Technology

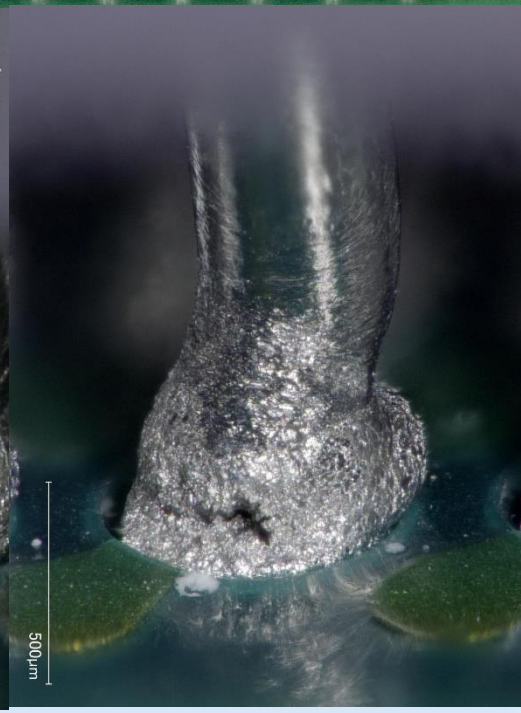


Virtex-5 CCGA Package CF Version 492 Cycles -55°C to +100°C

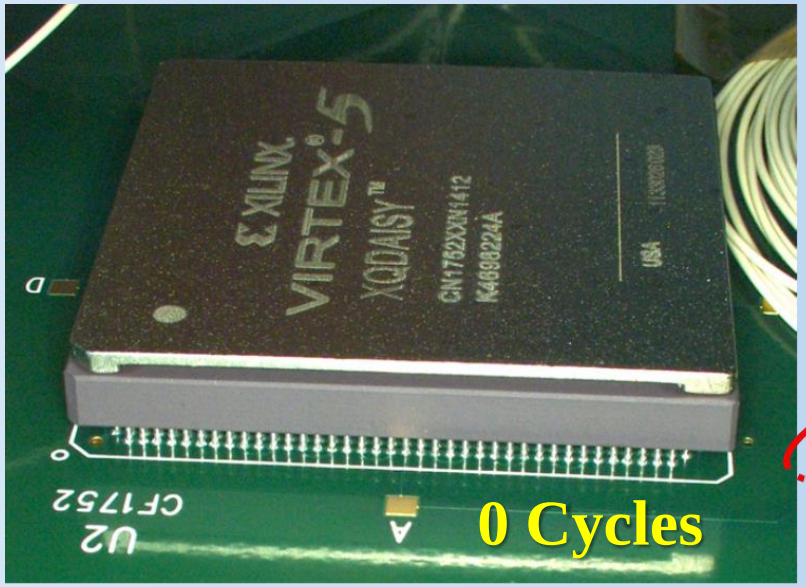


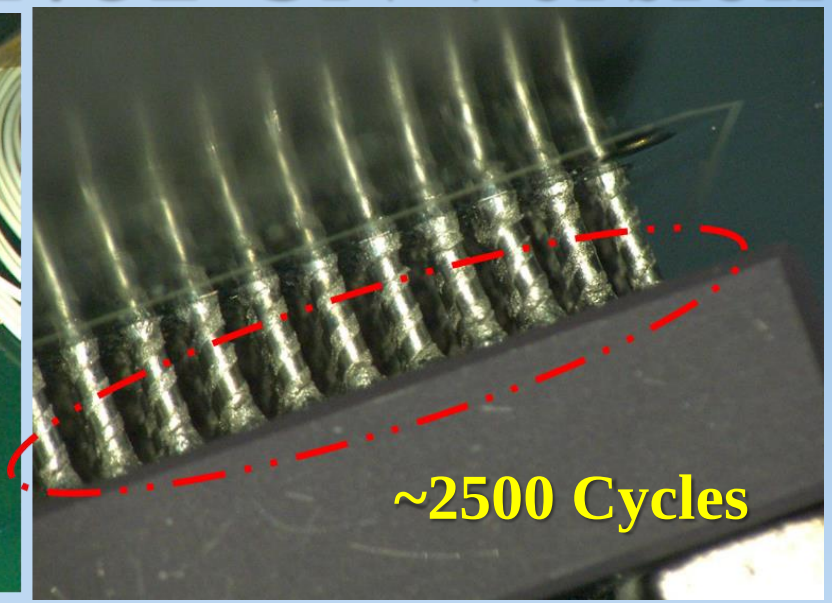


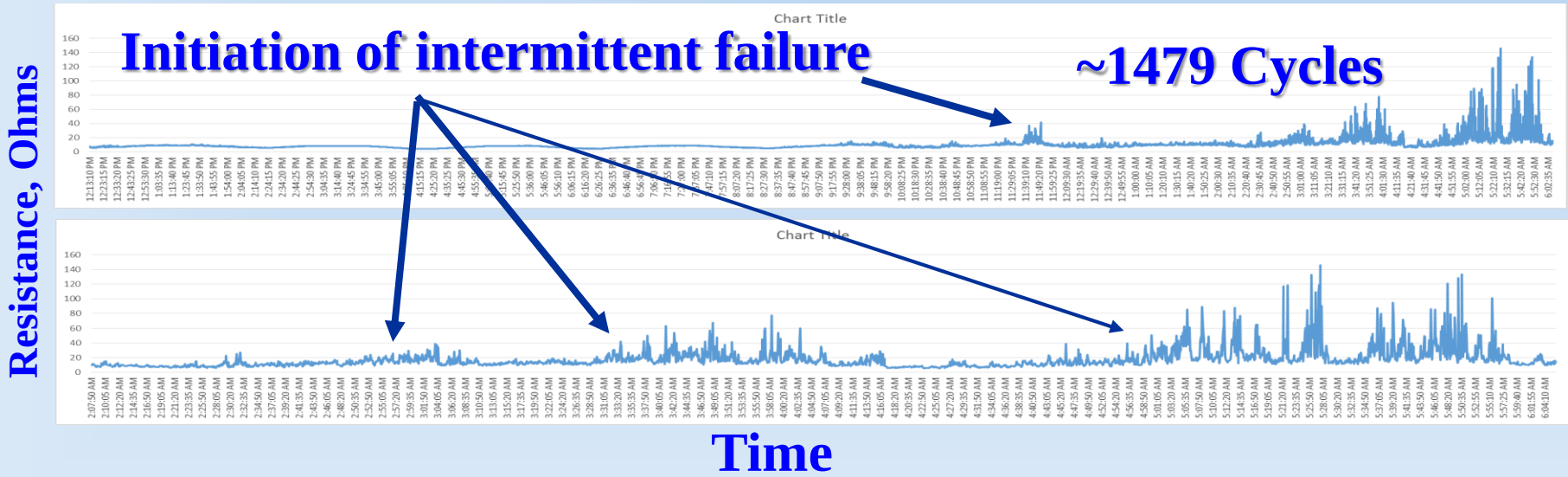




CCGA1752 CN Version

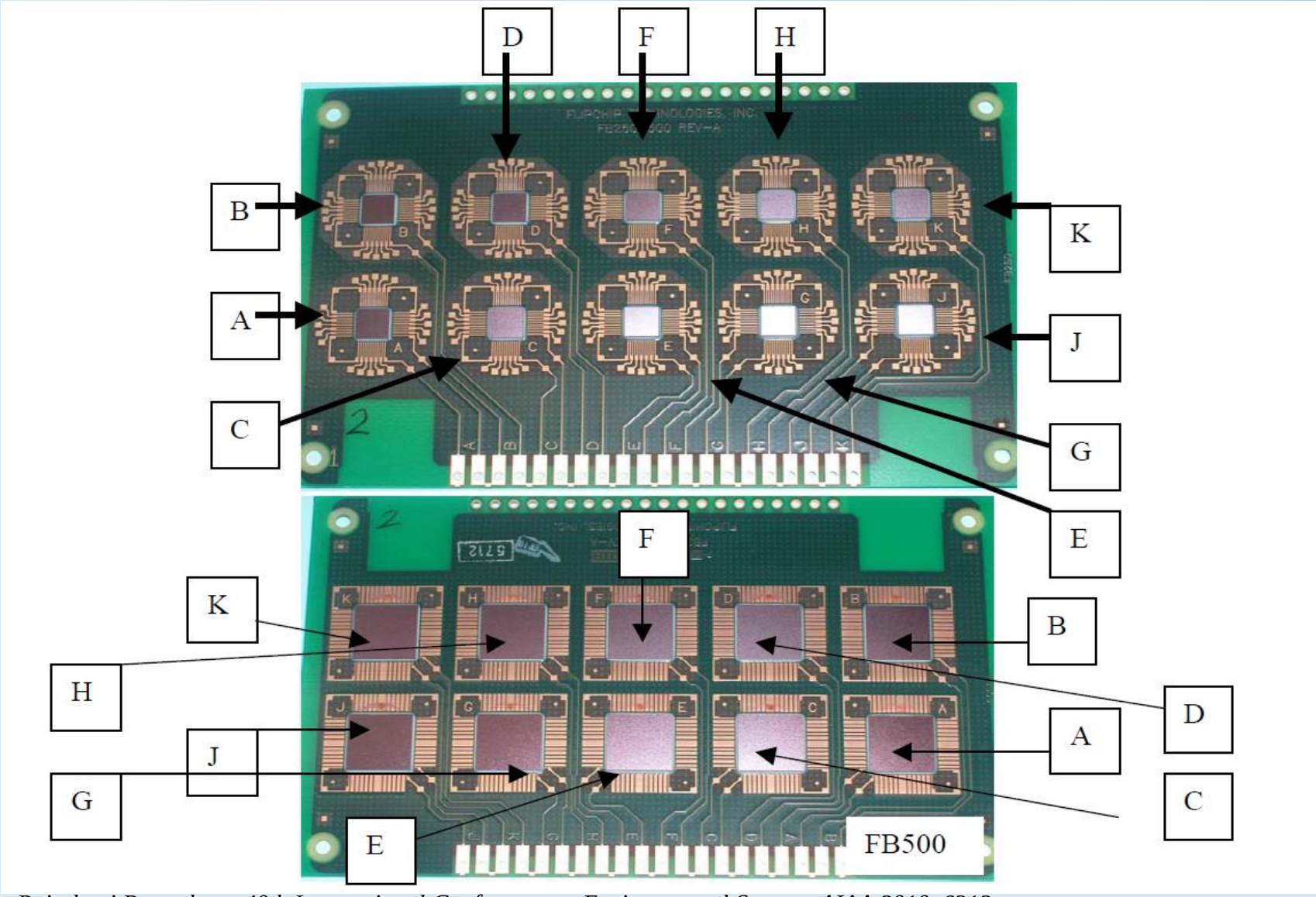






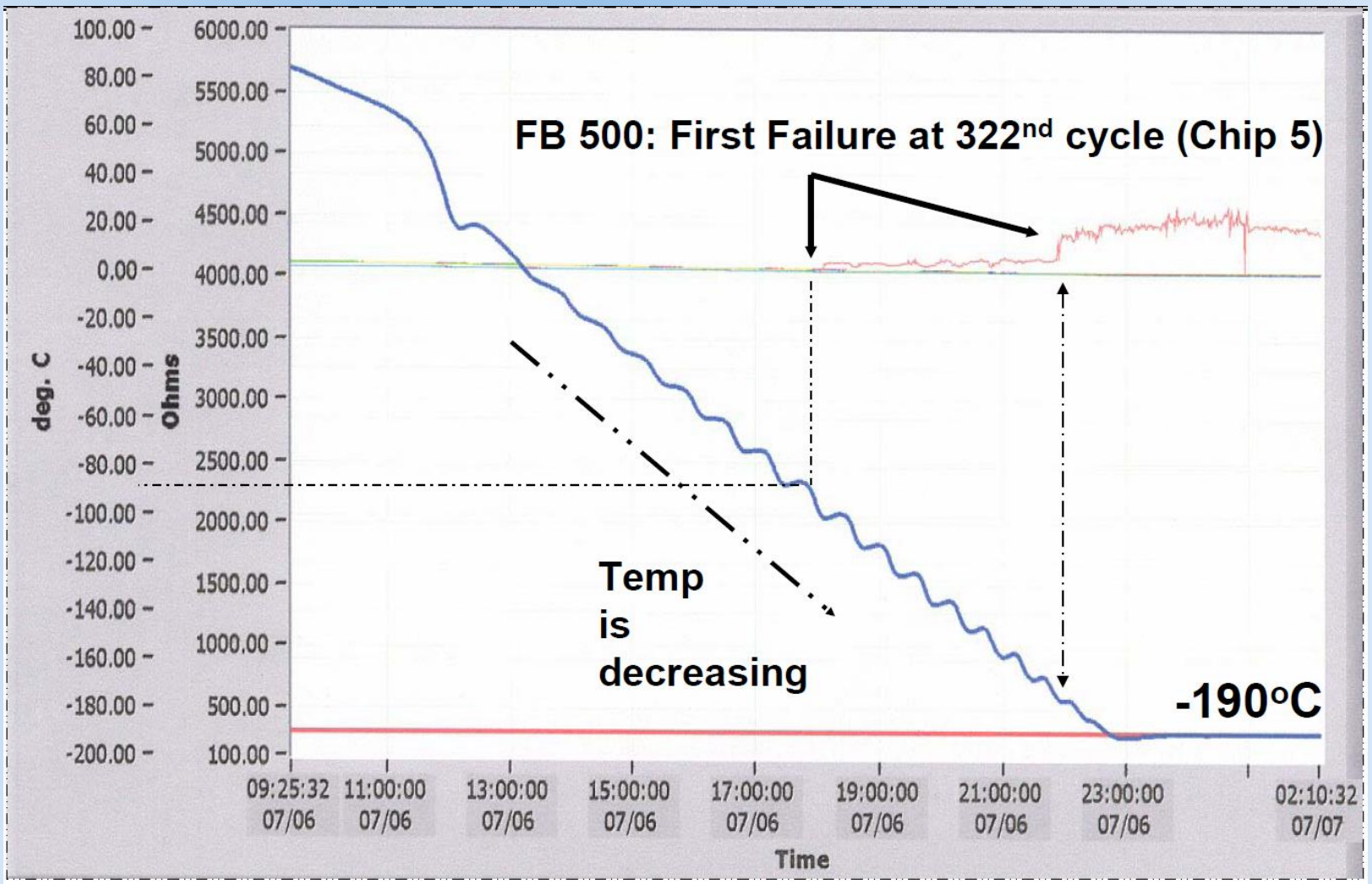
Ref.: Rajeshuni Ramesham, NASA Tech Brief, May 2016, NPO -49917 (Appeared)

Advanced flip-chip interconnect test boards of FB250 and FB500



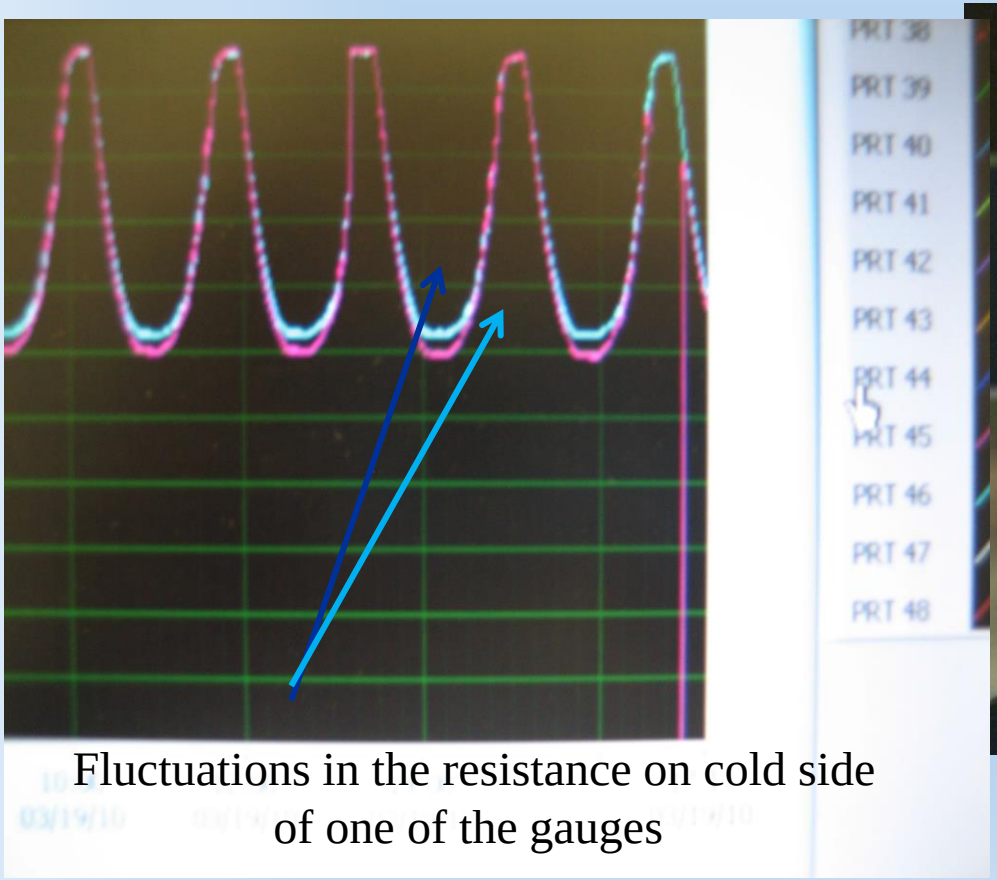
Ref.: Rajeshuni Ramesham, 40th International Conference on Environmental Systems AIAA 2010, 6312.
Ref.: Rajeshuni Ramesham, Journal of Microelectronics and Electronics Packaging, Vol. 4, No. 4, Quarter 4, 2007, page: 155-166

Flip-chip board with the first failure observed at 322nd thermal cycles -190°C to +85°C

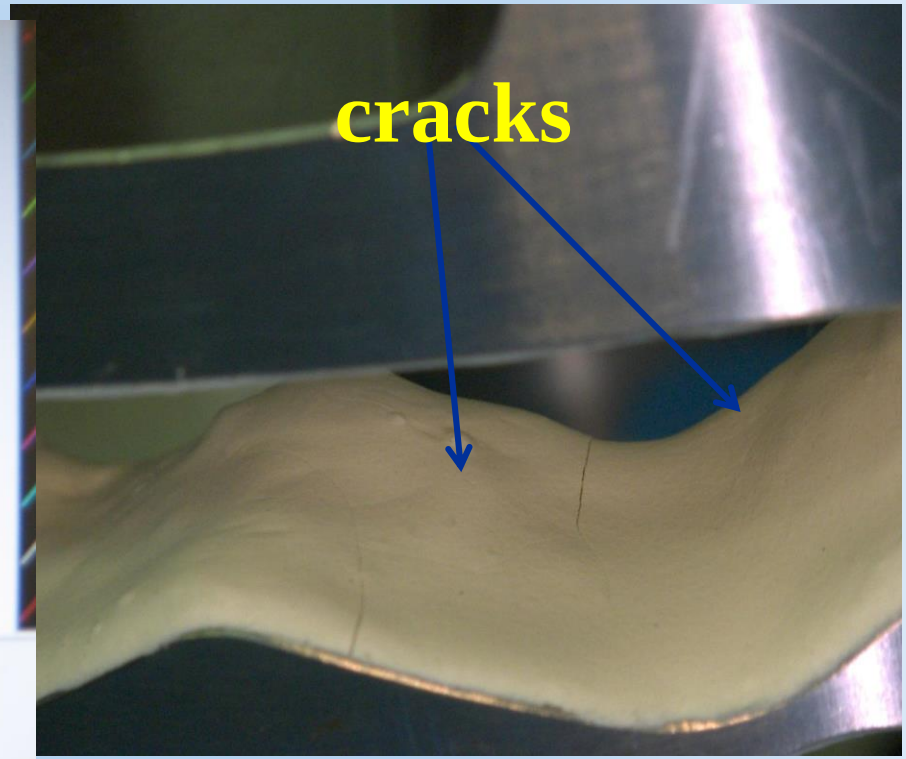


Ref.: Rajeshuni Ramesham, Journal of Microelectronics and Electronics Packaging, Vol. 4, No. 4, Quarter 4, 2007, page: 155-166
Ref.: Rajeshuni Ramesham, 40th International Conference on Environmental Systems AIAA 2010, 6312.

Sensor Package Design Assessment



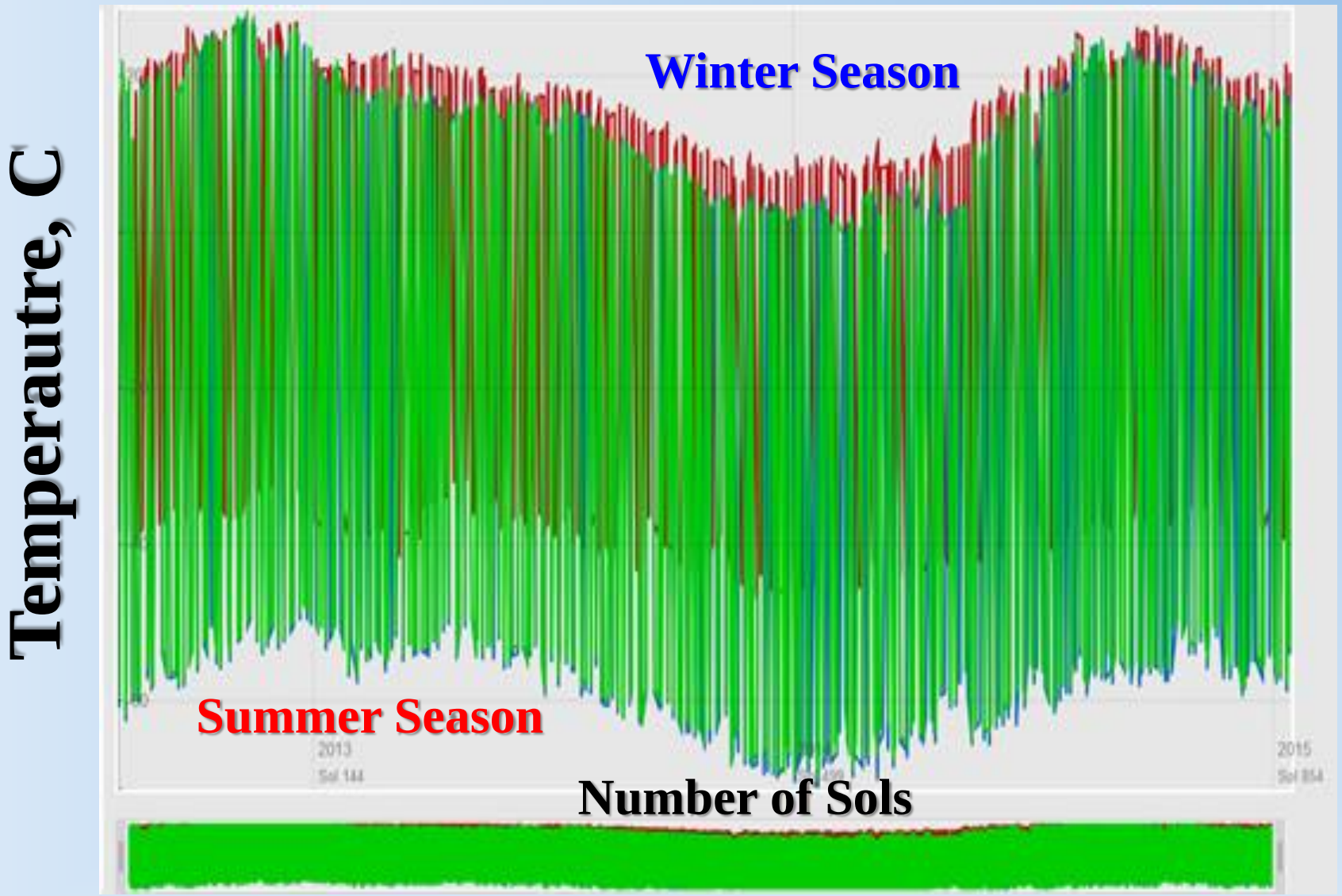
Fluctuations in the resistance on cold side of one of the gauges



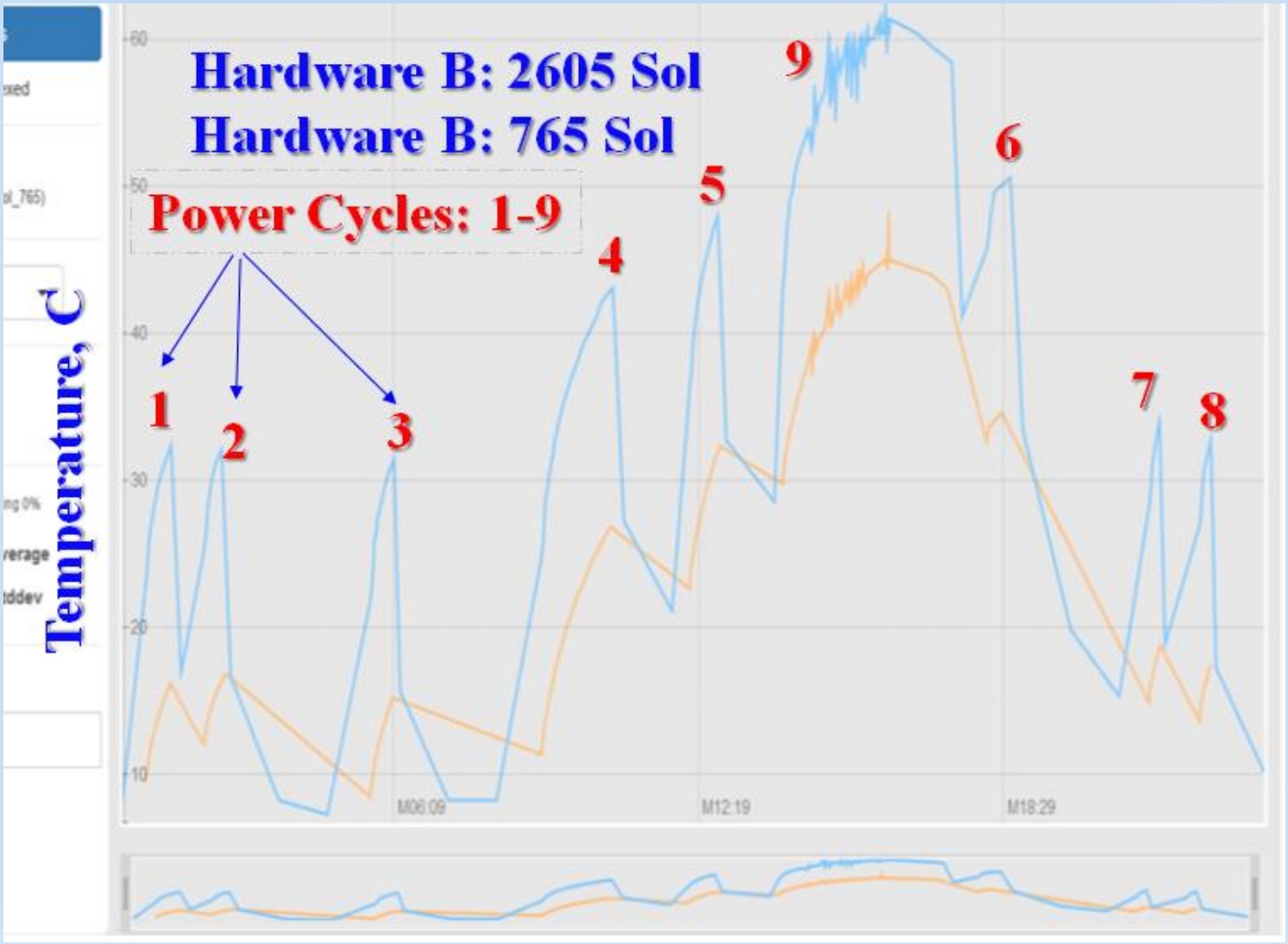
Resistance of the active element in the sensor vs. thermal cycling

Ref.: Rajeshuni Ramesham, 40th International Conference on Environmental Systems AIAA 2010-6312.

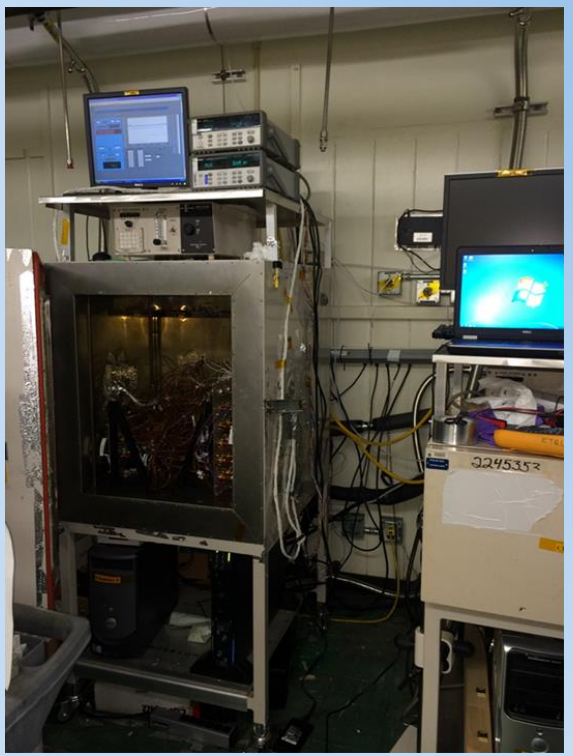
MSL Telemetry

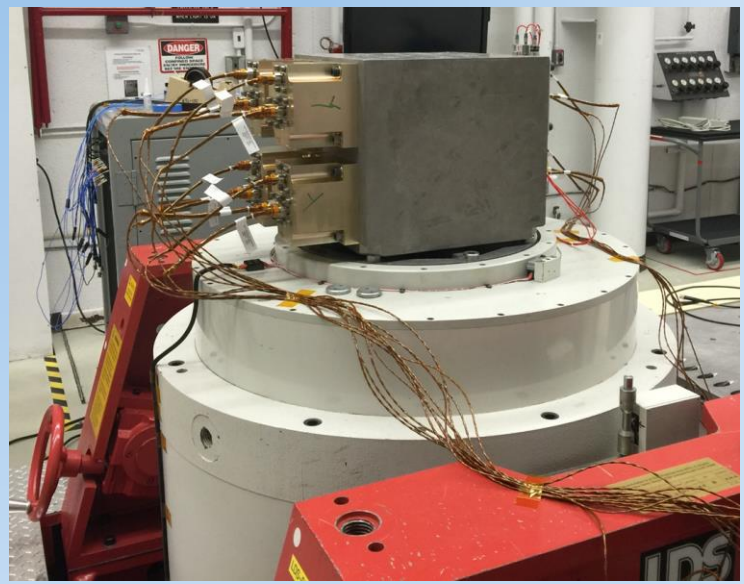


MSL Telemetry: Challenge of Power Cycling



Mighty Mouse Connectors





Anomaly During MSL Assessment
M2020 mission life > MSL mission life
Several mighty mouse designs have been under test
Harness to use electrical communications

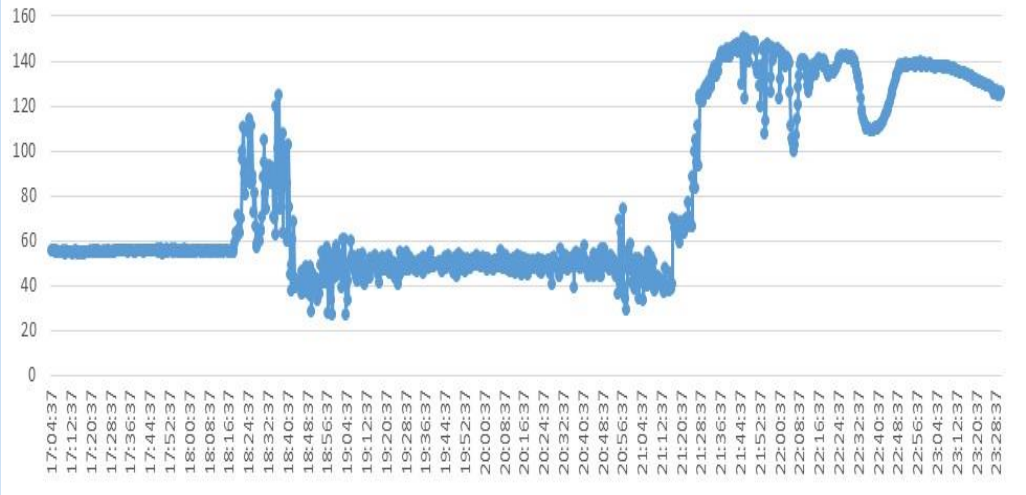
During Protoflight Thermal Testing

Temperature, C

Time

SN 042

Resistance, Ohm



Time

1.Motor S/N 041
2.Motor S/N 042
3.Motor S/N 051

Challenges in Avionics

- Power cycling
- Long duration projects
- Use of advanced new technologies (CCGA, SMT, large packages, LCC, etc.)
- Use of COTS packages and devices
- Extreme environments such as thermal and radiation
- Packaging standards for qualification?
- Can we qualify or life test all the packaging designs to failure?

Summary

- Many challenges and issues were observed during various projects which have been addressed to minimize the risk.
- Several electronics packaging designs (CCGA, Flip Chips, LCC, etc.) were tested with reference to the respective project requirements to mitigate any solder joint issues.
- Experimental long term thermal cycling was performed using the various critical non-deliverable hardware for projects to assess reliability.
- Actuator designs were assessed for various projects and mitigated the risk.
- Assessment of tin whiskers on the reliability of the hardware for long duration missions and mitigated the risk.
- First solder joint failure was observed at 137 thermal cycles for a ΔT of 310°C. Solder joints of corner columns have failed first and dislodged.