PLATINUM SENSORS EMBEDDED IN ESCC-4006/014 MODIFIED CONSTRUCTION:

A TURBULENT TALE ABOUT THE COEXISTENCE OF DISSIMILAR MATERIALS

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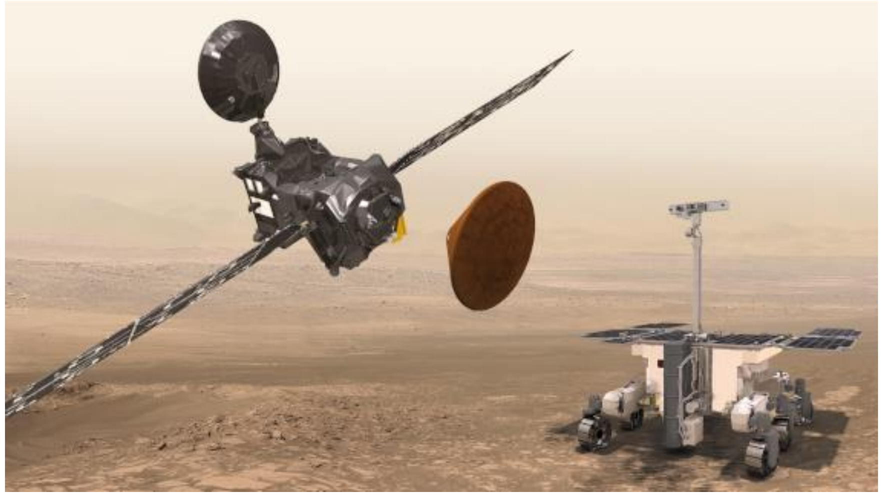
HERITAGE OF USAGE AND QUALITY

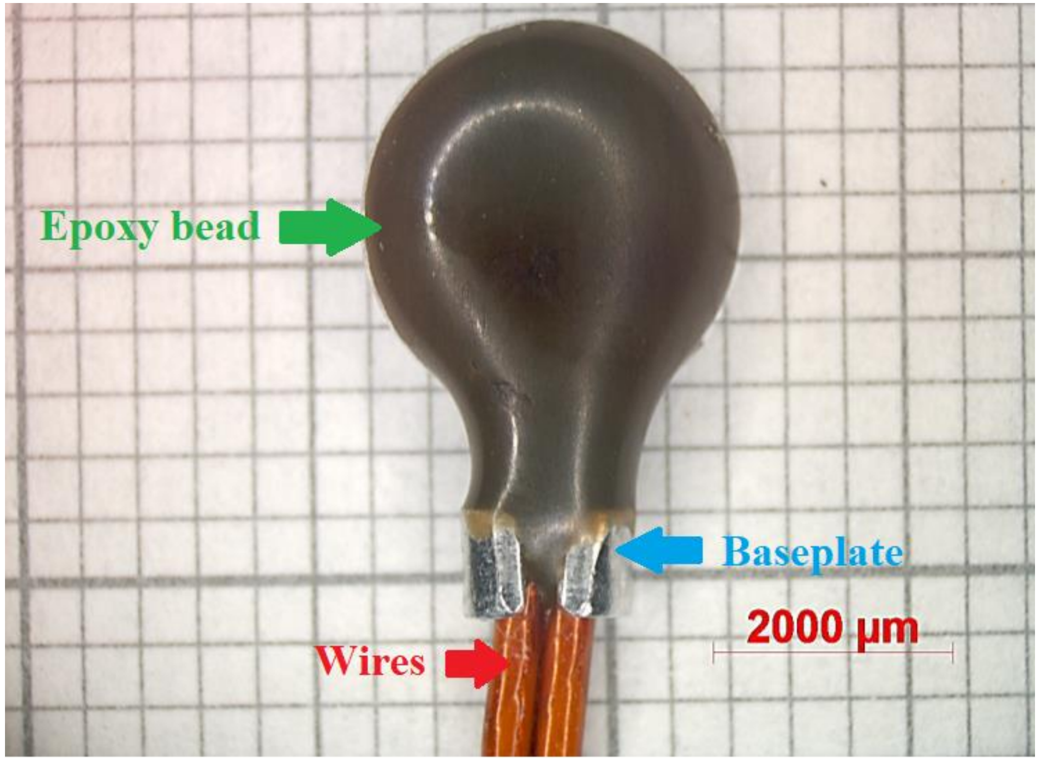


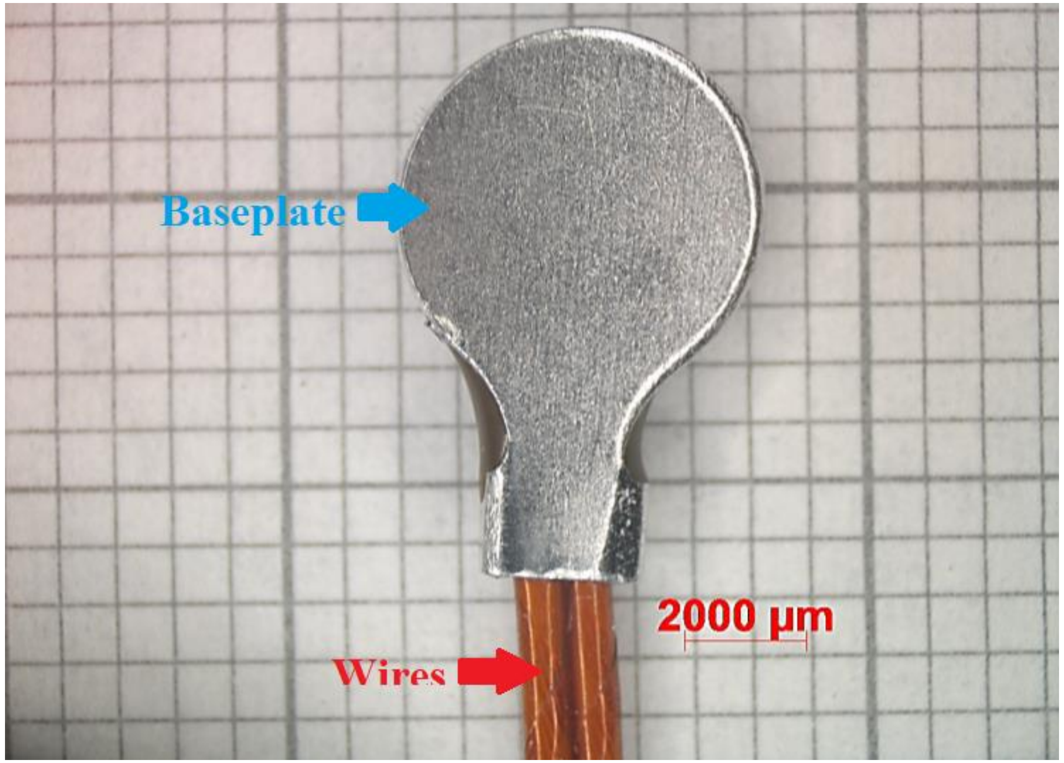


- Platinum RTD. 1000Ω at 0°C particular electrical type used.
- Operating temperature range [-60, 125]°C, storage temperature range [-125, 160]°C.
- Suitability for space applications proven through a production control (F2), screening (F3) and qualification campaign (F4) in accordance with ESCC-4006, slightly tailored to take into account the concrete construction and electrical characteristics of the new sensor and the wider temperature range.

RESISTANCE TEMPERATURE DETECTORS UNDER STUDY

EXTERNAL CONSTRUCTION CHARACTERISTICS

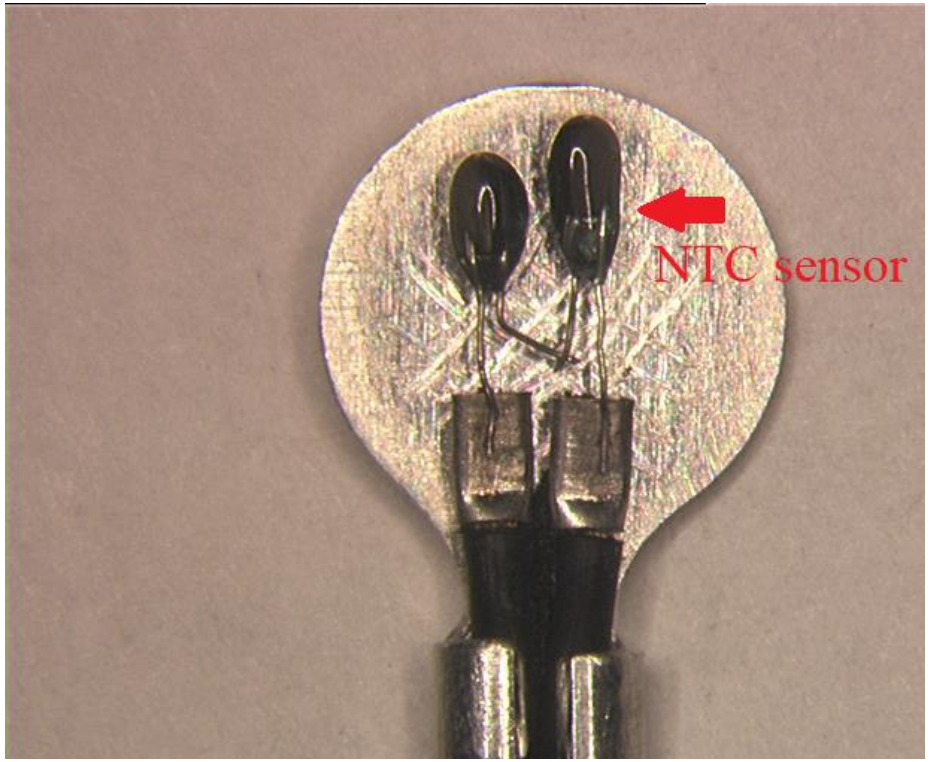




- Construction based on ESCC-4006/014 ESCC QPL NTC sensors manufactured by TE Connectivity.
- Same aluminium first series for the mounting interface. ESCC-3901/019 ESCC QPL wires, longer than the qualified versions.
- Epoxy bead changed from Stycast 2850FT to EC-2216 B/A Gray to extend the storage temperature range to lower temperatures.

RESISTANCE TEMPERATURE DETECTORS UNDER STUDY

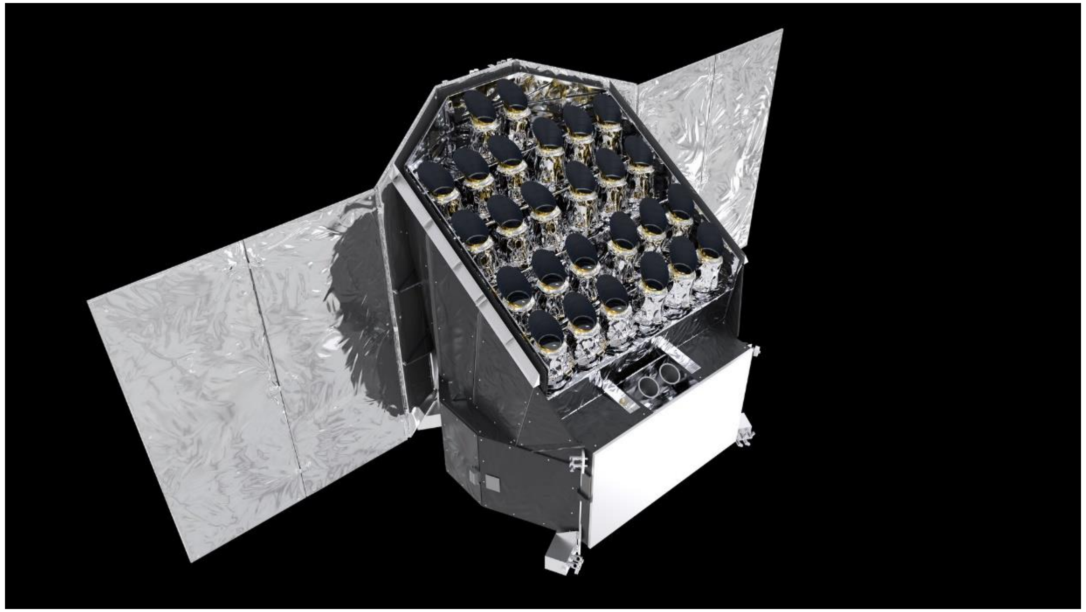
INTERNAL CONSTRUCTION CHARACTERISTICS

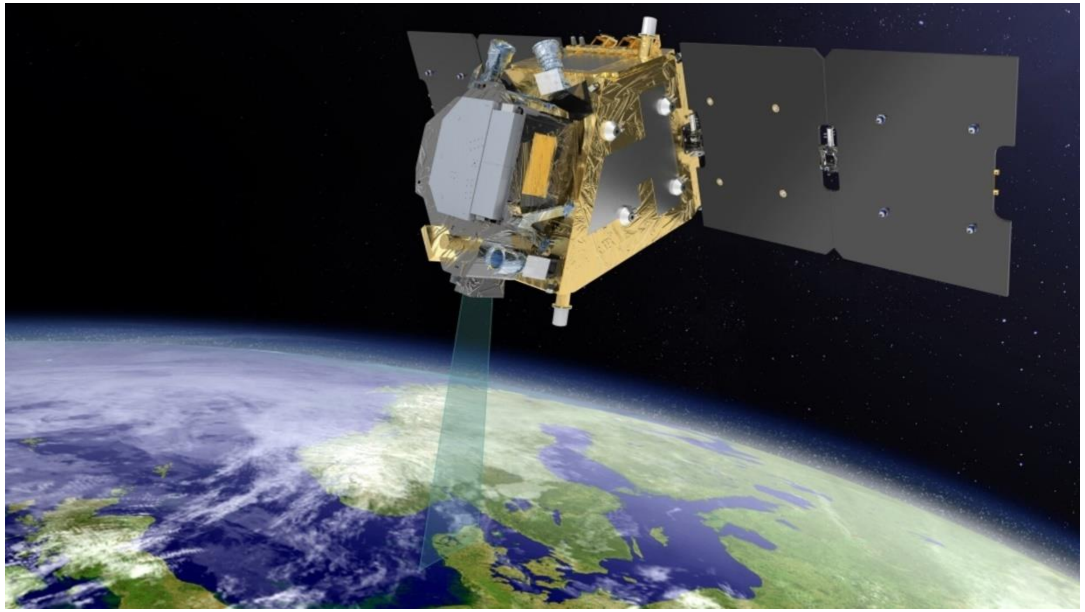


- Same fixation means of the wires to the plate. Same wires‘ jacket stripping process. Same ferrules crimped around the wires‘ core with the same method.
- Substituted the temperature sensing element, from NTC semiconductor metallic oxides to a platinum thin film resistor temperature sensor. The new platinum temperature sensor is manufactured by IST AG, ESCC QPL manufacturer, based on the same design of ESCC-4006/015 sensors, with a slightly smaller substrate size. Accuracy, class B (IEC-60751) and temperature range [-200 600]°C

MISSIONS AFFECTED BY THE FAILURE QUALITY

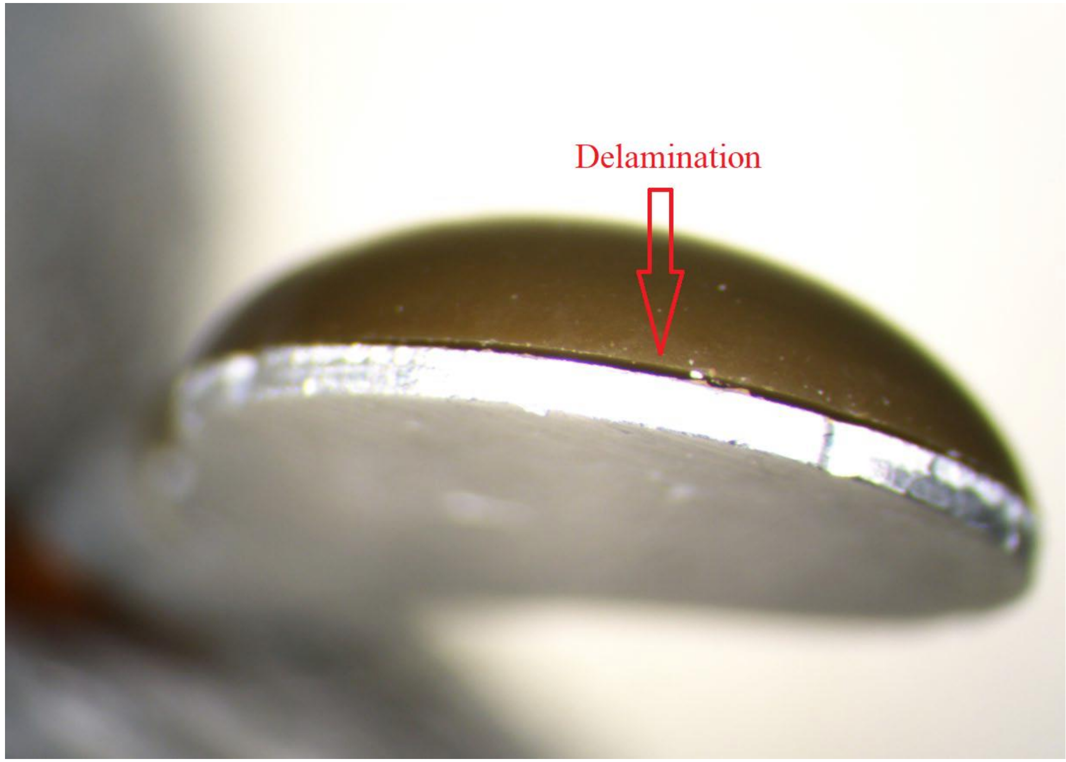
SPCD
SPACE PASSIVE COMPONENT DAYS

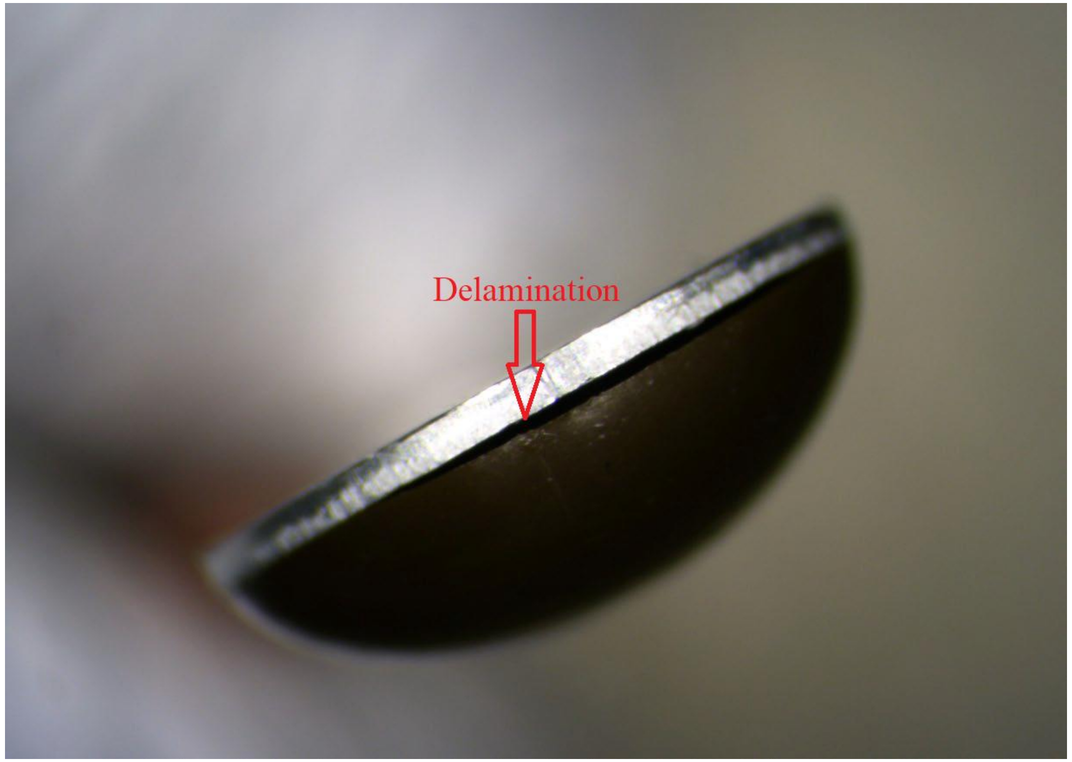




- Platinum RTD. 1000Ω at 0°C particular electrical type used.
- Operating temperature range [-60, 125]°C, storage temperature range [-125, 125]°C.
- Suitability for space applications proven through a production control (F2), screening (F3) and qualification campaign (F4) in accordance with ESCC-4006 and ESCC-4006/014 main provisions, slightly tailored to take into account the concrete electrical characteristics of the new sensor and the wider temperature range.
- Additional (T,R) data acquisition for the FLEX sensors to improve their accuracy through dedicated calibration.

FAILURES FOUNDS DURING THE QUALITY ASSURANCE ACTIVITIES FOR FLEX AND PLATO



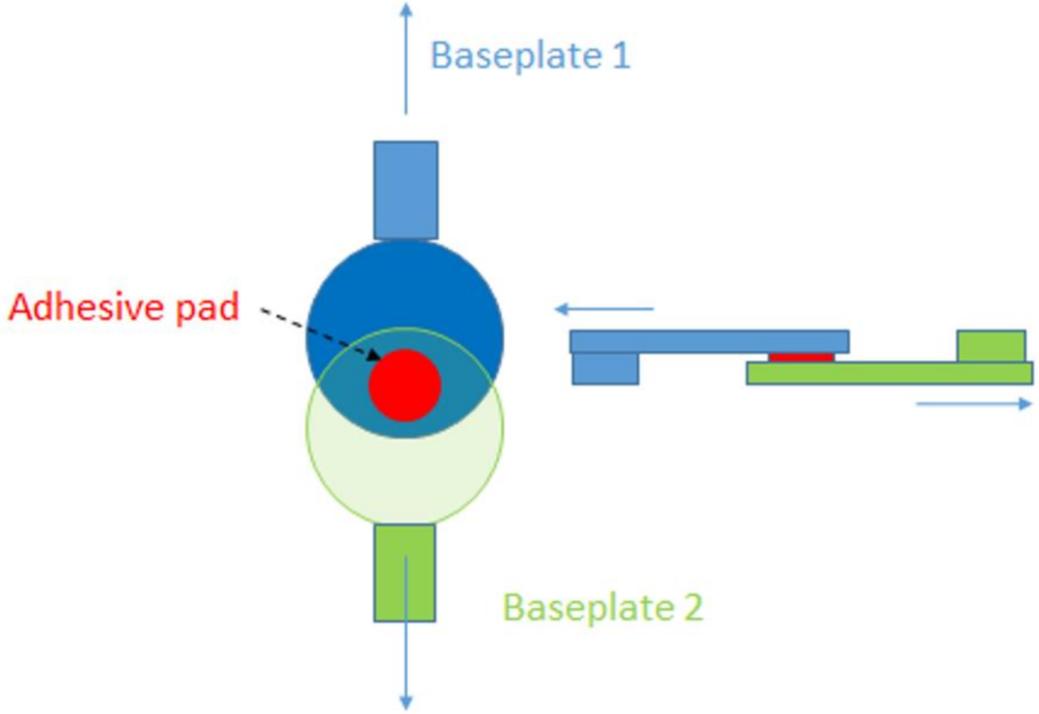


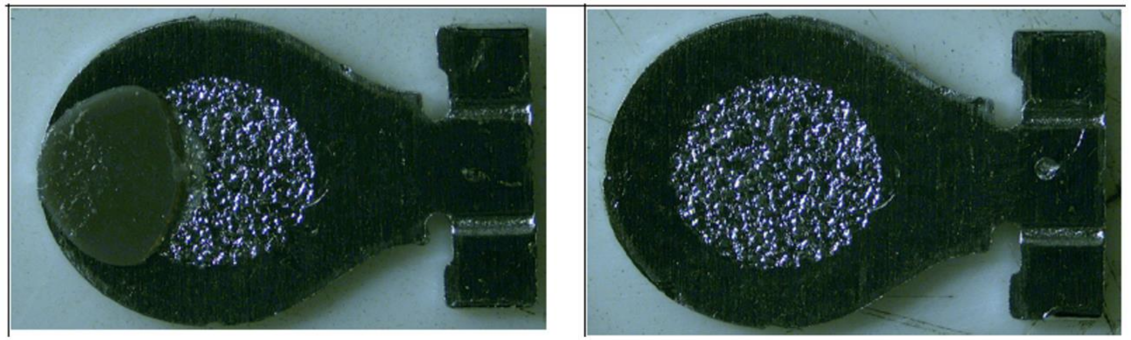
- No failures on sensors after the finishing of the production control (F2) and screening (F3) flows.
- During the qualification flow (F4), 2/12 sensors showed delaminations after the “thermal shock” test. The rest of qualification tests were successful. Zero power resistance at 0°C was nominal.
- Amongst the subset of sensors subjected to additional (T,R) measurements, for calibration purposes, 7/23 showed delaminations.

FAILURE MECHANISM

- The failures occurred in successfully screened parts, after being additionally thermo-mechanically stressed.
  - The qualification sensors were subjected to temperature fluctuations during the additional “thermal shock (air)” to the one conduced during the production control (F2), though this latter one had the double the cycles and enlarged temperature range [-65→-125, 125]°C.
  - The sensors for the calibration were subjected to additional temperature fluctuations to collect (T,R) data in the temperature range [-50, -10]°C.
- The failures localized in the interface between dissimilar materials (aluminium alloy baseplate and EC-2216 B/A epoxy), triggered by temperature changes, suggest that the CTE mismatching amongst those materials, which induces in their interface shear mechanical stresses, can be the physical mechanism that provoked the delaminations, either by its intensity or induced mechanical fatigue, when the adhesion strength is not sufficiently tight and robust.
- But:
  - Same construction was successfully tested in slightly worst-case conditions in the heritage programs.
  - The TDS of the epoxy indicates that the adhesion strength expected (ASTM D1002) should be within [18, 22]MPa, in a temperature range [-253, 24]°C. This property makes this adhesive a frequent choice in the space industry for bonding materials subjected to very low application temperatures.
- **Then, why did we find this issue?... Likely, something was “weakening” the adhesion strength… But, what?**

ADDITIONAL INVESTIGATIONS 1/3
ROUGH ESTIMATION OF THE ADHESION STRENGTH

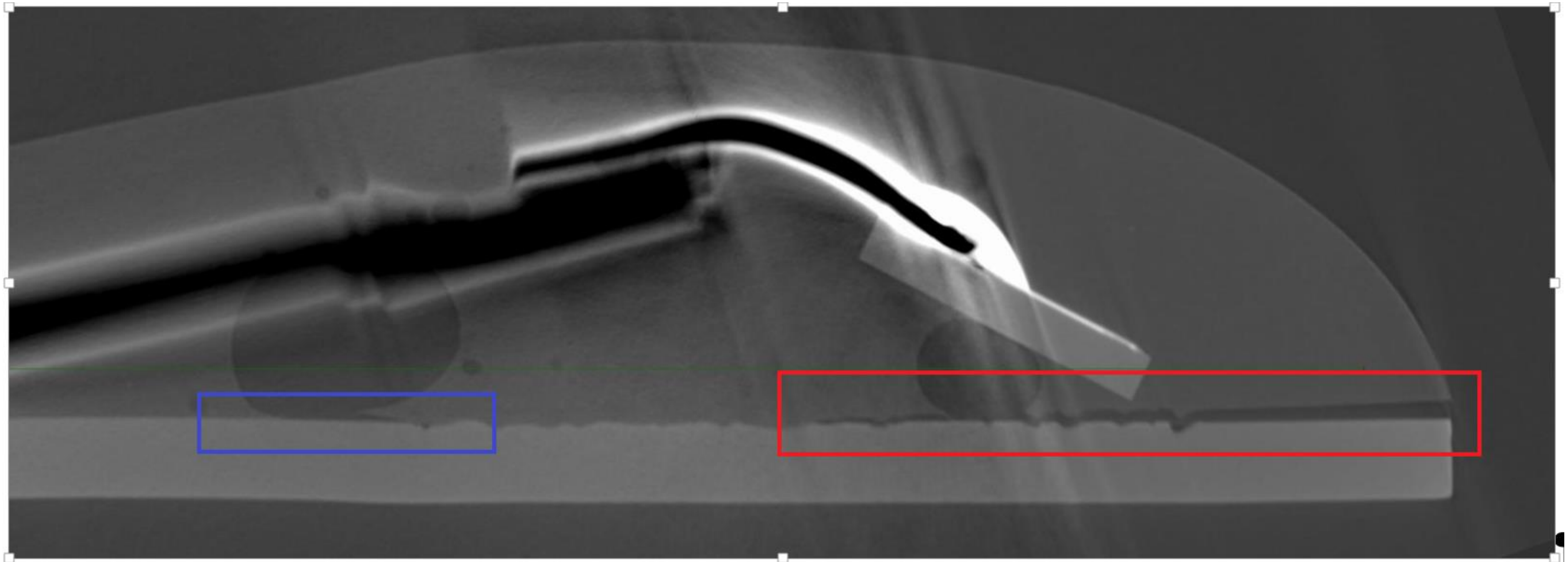




Cleaning Method Baseplate	Shear stress to failure	
	Average (MPa)	Standard Deviation (MPa)
None	6,05	0,65
Acetone (1-2 minutes, 25°C, no US energy)	7,52	1,1

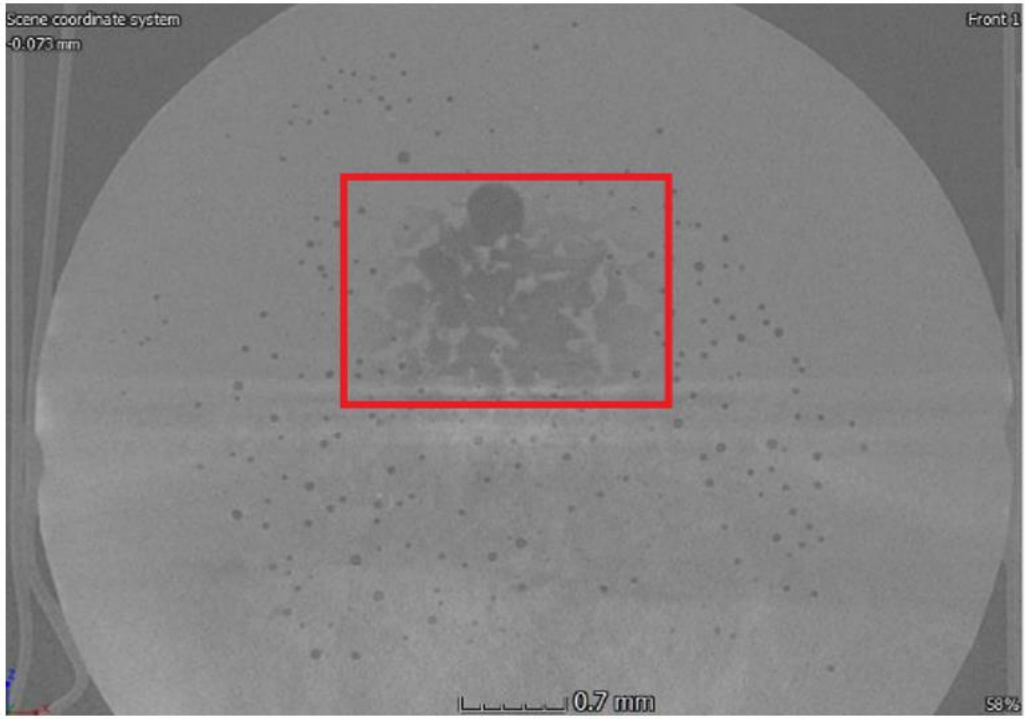
- The estimated adhesion strengths was 1/3 of the expected one. This confirms that the adhesion strength is far from the optimal values expected for the adhesive EC-2216 B/A.
- In all cases, failure mechanism was of adhesive type (no epoxy residues on one surface after detachment). This indicates that the adhesion strength is weaker than the internal cohesive strength of the epoxy and bonded surfaces.

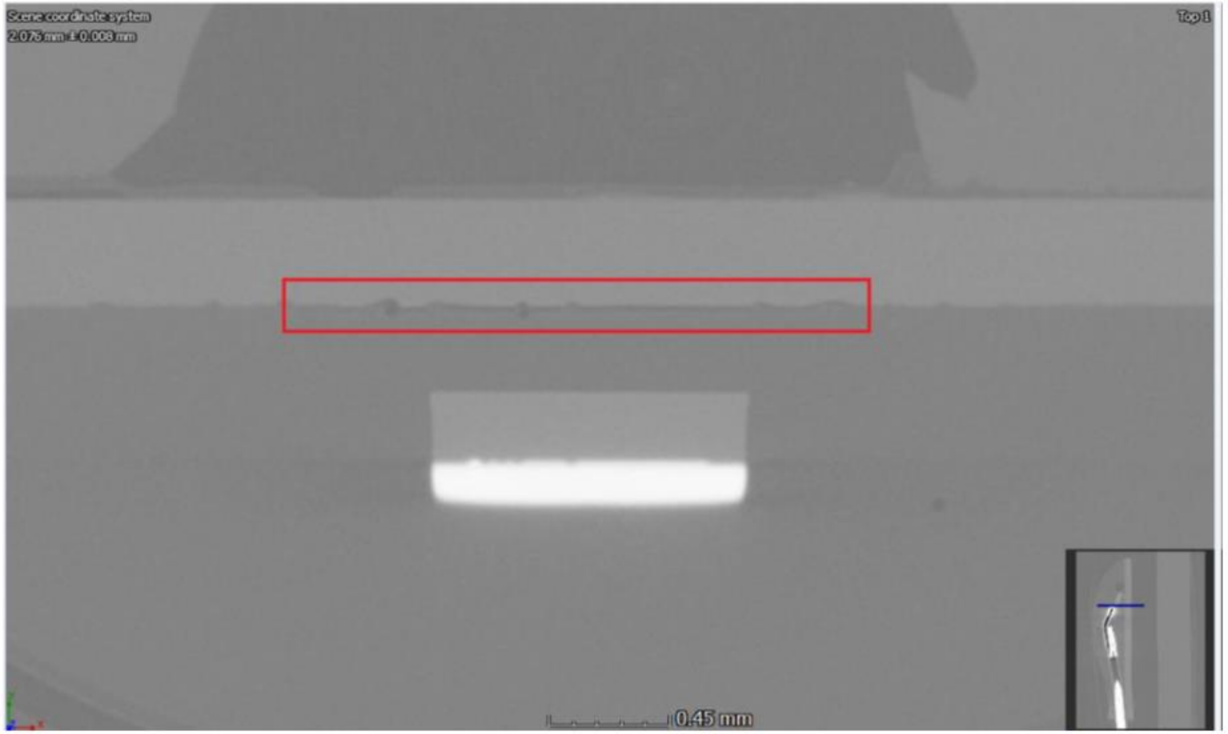
ADDITIONAL INVESTIGATIONS 2/3
CT-SCANS ON FAILED SENSORS



- Red-framed, it can be seen a cut of the area affected by the external delamination. It propagates till an area with non-desirable features: thinner epoxy and a bubble, both reduced the local adhesion strength.
- Blue-framed, it can be seen an internal delamination propagating from a bubble in contact with the baseplate.

ADDITIONAL INVESTIGATIONS 2/3
CT-SCANS ON "GOOD" SENSORS





- Sensors not affected by external delaminations, presented internal delaminations and a swarm of bubbles associated with the central area of the baseplates, made rougher by punching to increase the contact area. These features degrade the effective adhesion strength.

ADDITIONAL INVESTIGATIONS 3/3
STATE OF THE BASEPLATES BONDING SURFACE

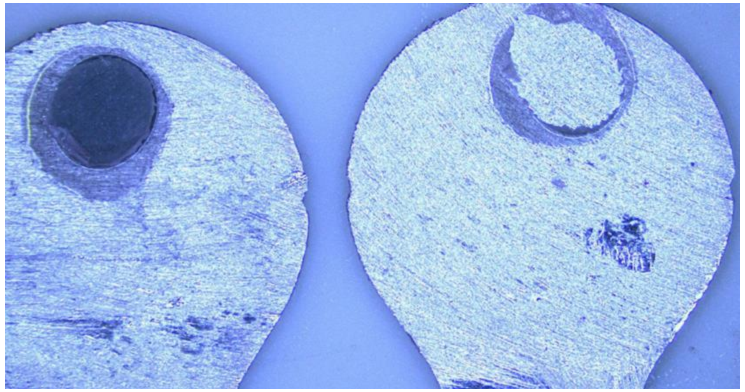
- ATR-FTIR spectroscopy on the baseplates, both as received and as cleaned, shows an absorption peak near 3000cm^{-1}, associated with absorption frequencies of C-H bonds. Hence, organic contamination was present.
- Water droplet test results show contact angles near 90°, with indicated a far from optimal wettability of the bonding surface, hence low surface energy/bonding affinity.

ROOT CAUSE HYPOTHESIS

- As per these results, the likely ultimate root cause of the poor adhesion strength was an insufficient surface preparation of the baseplates before the application of the epoxy. In order to validate this hypothesis, three main changes were proposed for the surface preparation:
  - Improving the cleaning of the bonding surface, using solutions of non-polar solvents (hexane and Isopropyl alcohol), polar solvents (acetone) and proprietary alkaline cleaner Sococlean type, from Socomore. To enhance the cleaning actions, usage of elevated temperature and US (Ultra-Sonic) energy.
  - De-oxidizing the bonding surface, through mechanical abrasion, fine grit abrasives, and chemical etching, using REACH compatible proprietary acidic etchant Socosurf type, from Socomore.
  - Using primer EC-3901 to enhance the adhesion strength and its robustness against the environmental aging.

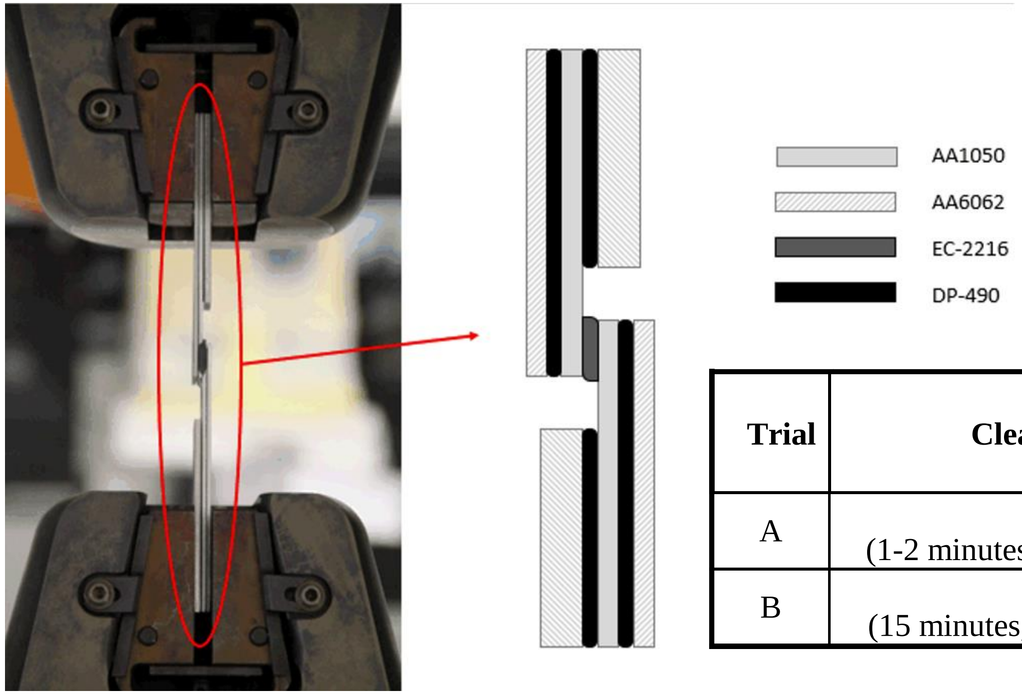
ROOT CAUSE HYPOTHESIS VALIDATION 1/3
ROUGH ESTIMATION OF THE ADHESION STRENGTH

Trial	Cleaning Method	De-Oxidizing Method	Primer EC-3901	Shear stress to failure	
				Average (MPa)	Standard Deviation (MPa)
I	Hexane/Isopropyl alcohol+Acetone (15 minutes, US energy and 40°C for both solutions)	None	No	12,55	1,21
II	Hexane/Isopropyl alcohol+Acetone (15 minutes, US energy and 40°C for both solutions)	None	Yes	13,71	1,82
III	Acetone (15 minutes, US energy and 40°C)	Mechanical grinding	No	11,75	2,47
IV	Acetone (15 minutes, US energy and 40°C)	Mechanical grinding	Yes	14,93	3,17
V	Sococlean (15 minutes, US energy and 40°C)	Socosurf (5 minutes, US energy and 40°C)	No	15,93	1,42
VI	Sococlean (15 minutes, US energy and 40°C)	Socosurf (5 minutes, US energy and 40°C)	Yes	20,29	3,60
VII	Hexane/Isopropyl alcohol+Acetone (15 minutes, US energy and 40°C for both solutions)	Socosurf (5 minutes, US energy and 40°C)	Yes	18,52	3,48



- The estimated adhesion strengths were improved in all the cases. Primer improved consistently the adhesion strength. Best configuration was using Socomore product for the cleaning and etching.
- Failure mechanism was consistently of cohesive type (epoxy residues on one surface after detachment). This indicates that the adhesion strength is stronger than the internal cohesive strength of the epoxy.

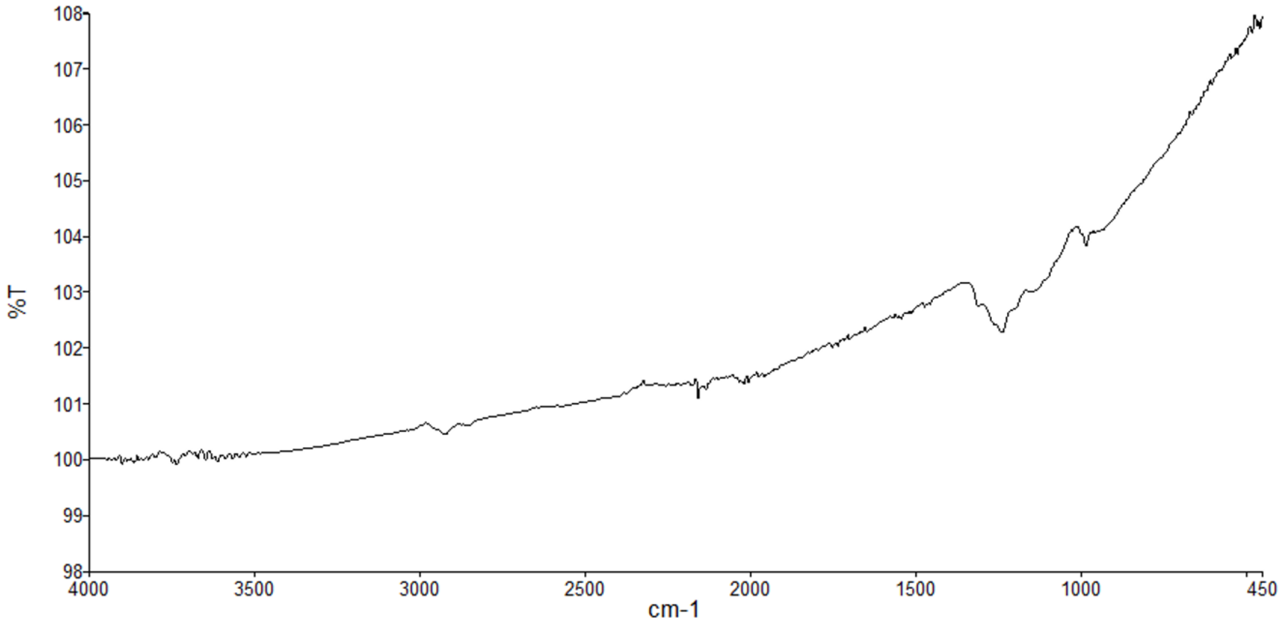
ROOT CAUSE HYPOTHESIS VALIDATION 2/3
ACCURATE ESTIMATION OF THE ADHESION STRENGTH

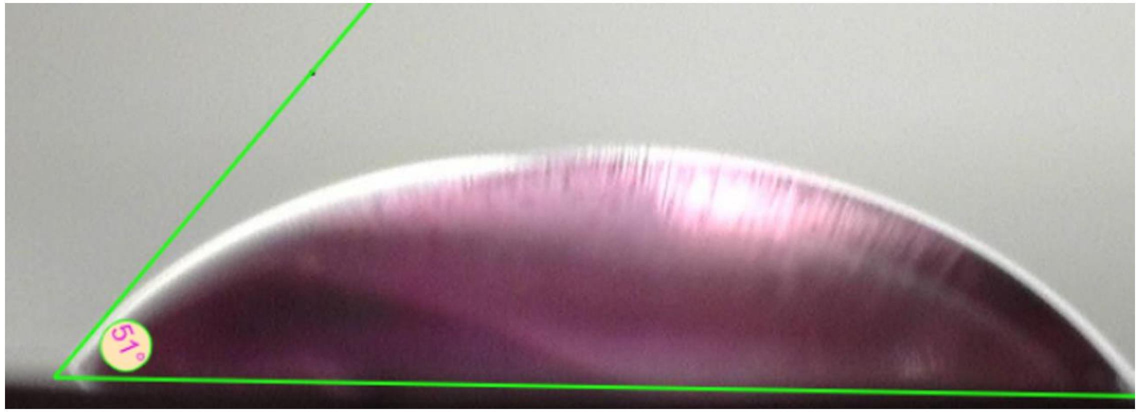


Trial	Cleaning Method	De-Oxidizing Method	Primer EC-3901	Shear stress to failure	
				Average (MPa)	Standard Deviation (MPa)
A	Acetone (1-2 minutes, 25°C, no US energy)	None	No	9,69	0,39
B	Sococlean (15 minutes, US energy and 40°C)	Socosurf (5 minutes, US energy and 40°C)	Yes	18,88	0,57

- The estimated accurate adhesion strengths, as per the test ""Apparent Shear Strength of Single-Lap-Joint Adhesively Bonded Metal Specimens by Tension Loading (Metal-to-Metal)" test, according to ASTM D1002" could reproduce both the poor adhesion strength on a non-optimally prepared aluminium surface and the improvement when it is, close to the values suggested by the manufacturer as feasible.

ROOT CAUSE HYPOTHESIS VALIDATION 3/3
STATE OF THE BASEPLATES BONDING SURFACE





- ATR-FTIR spectroscopy on the baseplates doesn’t show the absorption peak near 3000cm-1: the organic contamination was removed.
- Water droplet test results show contact angles around 50°, with indicated an improved wettability of the bonding surface, hence higher surface energy and better bonding affinity.

ZERO POWER RESISTANCE MEASUREMENT METHODOLOGY
A HIDDEN DESTRUCTIVE STRESS

SPCD
SPACE PASSIVE COMPONENT DAYS

- The delaminations found in 7/23 sensors subjected to additional “zero power resistance” measurements in the temperature range [-50, -10]°C were puzzling, as such measurements should be innocuous for the sensors, but they were not. Why?
- Followed test method ESCC-4006 §8.3.1.1 requires to set a temperature for the sensors “**a controlled uniform medium capable of maintaining an accuracy of ±0,01°C**”. In our case, this medium was a liquid thermal medium, cooled or heated to the desired temperature for the measurement, where the sensors were immersed from ambient temperature.
- This immersion process was essentially a “thermal shock” test, as described in MIL-STD-202, Test Method 107, using liquid baths. This type of “thermal shock” is more severe than the one applied during production control and qualification tests, using gaseous mediums, due to the quicker rate of temperature change. This is a severe stress that can easily explain why it added, on its own, a great deal of thermo-mechanical fatigue to the RTDs during the “zero power resistance” measurements, in the frame of the calibration process, triggering the delaminations, but also during the production control, screening and qualification tests.
- This hypothesis was validated reproducing this process by immersing 12 sensors in a liquid medium at -60°C 40 times, with 4 minutes of immersion time and 4 minutes of waiting time, at ambient temperature, before the new immersion. 4/12 failed showing the same delaminations.

IMPROVEMENTS IN THE PRODUCTION AND TESTING FLOWS
END-OF-LIFE VALIDATION

- The centre rougher area was removed from the baseplates, ,as correlated with internal delaminations and voids.
- Prior to the epoxy application, the baseplates were prepared following the best process based on the Socomore products and the primer. A “water droplet” test was introduced on two samples in order to check the suitable surface energy of the baseplates.
- In the production control (F2) flow, after the “encapsulation” step, it was introduced a new destructive test on 10 samples randomly selected: a “liquid thermal shock” test, alike to the one described, capable of spotting very early weak assembly lots regarding the adhesion between the epoxy beads and the baseplates.
- The procedure to measure the “zero power resistance” was modified to minimize any thermo-mechanical stresses.
- The storage temperature range was narrowed to the worst-case expected in FLEX FLORIS FPS and PLATO Payload FEEs applications: [-95, 125]°C.
- Additional “zero power resistance” measurements, for calibration purposes, if needed, were embedded within the “High and Low Temperatures Electrical Measurements” conducted during the screening (F3) flow, before the final “external visual inspection”.
- Two new flight assembly lots were produced: 97 sensors, subjected to full charts F2+F3+F4; 309 sensors, subjected to full charts F2+F3 and reduced F4, focused in thermally related tests. Successful results. EOL robustness was proven.

LESSONS LEARNT

SPACE PASSIVE COMPONENT DAYS

- During the failure analysis, a great effort for replicating the failures, empirically identifying the root causes and validating experimentally the modified product was pursued. But it came at a high price: time, many hundreds of hours of integrated work-time and around one year of natural time to resolve the non-conformance. We think that, this price is cheap in the broader view of securing the quality of a component to be used recursively in the future year in multiple applications. This is only possible when there is a open collaboration between manufacturers and users were the expertise is shared both ways. Sometimes, shortcuts only postpone the recurrent appearance of the problem.
- Due to the clear nature of the failure, MMPP engineering support was requested since the beginning and they were the leading voice in the NRBs to propose the methodology to confirm the poor adhesion strength, to identify the deficiencies in the processes of preparation of the baseplates and to point to the right mitigation strategies. A EEE part is in itself a pile-up of raw materials and mechanicals parts put together through many specialized processes, and many of them are common to those applied. We think that a strengthening in the collaboration between the EEE parts and MMPP engineers in the addressing of any quality issue and their contribution to the evaluation of new EEE parts technologies is very much advisable.
- For many of the test methods used during the testing flows, there are required environmental conditions to be met, but not precisely how to reach them, which could be a source of unintended thermal, mechanical, radiation and reliability stresses. To detect these cases, we recommend the users to pursue, and the manufacturers to share, a detailed description on how each method is executed, step-by-step, in order to judge if there is such a potential hidden stress. In some, occasions, these stresses can be useful as where for us to add another layer of quality verification.

ACKNOWLEDGMENTS

12.2 CHART F2 - PRODUCTION CONTROL

COMPONENT LOT MANUFACTURING	
SPECIAL IN-PROCESS CONTROLS	
Para. 5.2.1	Pre-Encapsulation (Internal Visual) Inspection
-	Encapsulation
Para. 5.2.2	Thermal Shock
Para. 5.2.3	Room Temperature Electrical Measurements
Para. 5.2.4	External Visual Inspection
Para. 5.2.5	Dimension Check
Para. 5.2.6	Weight
TO CHART F3 – SCREENING TESTS	

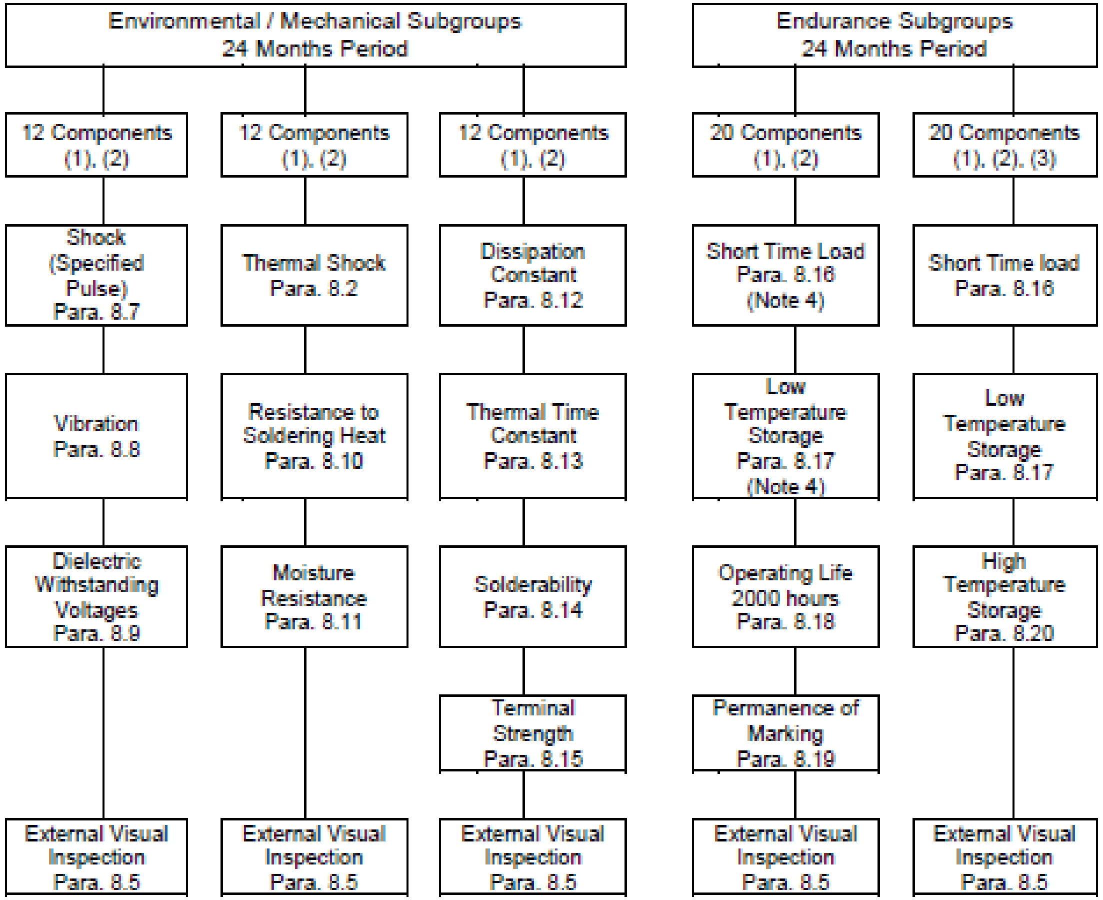
NOTES:
1. Performed on a sample basis.
2. Guaranteed but not tested.

12.3 CHART F3 – SCREENING TESTS

COMPONENTS FROM PRODUCTION CONTROL		
Para. 6.1	Serialisation	
Para. 8.3.2	Parameter Drift Values (Initial Measurements)	(1)
Para. 8.4	Burn-in	
Para. 8.3.2	Parameter Drift Values (Final Measurements)	(1)
Para. 8.3.3	High and Low Temperatures Electrical Measurements	(1)
Para. 8.3.4	Room Temperature Electrical Measurements	(1) (2)
Para. 6.4	Check for Lot Failure	(3)
Para. 8.6	Radiographic Inspection	(4)
Para. 8.5	External Visual Inspection	
TO CHART F4 WHEN APPLICABLE		

NOTES:
1. The lot failure criteria of Para. 6.4 apply to this test.
2. Measurements of Parameter Drift Values need not be repeated in Room Temperature Electrical Measurements.
3. Check for Lot Failure shall take into account all electrical parameter failures that may occur during Screening Tests subsequent to Serialisation.
4. Radiographic Inspection may be performed at any point during Screening Tests after Serialisation.

12.4 CHART F4 – QUALIFICATION, PERIODIC TESTS AND LOT VALIDATION TESTING



NOTES:

1. For distribution within the subgroups see Para. 7.1.2 for qualification and qualification maintenance and Para. 7.4 for Lot Validation Testing.
2. No failures are permitted.
3. This Subgroup of tests shall be performed only if the maximum storage temperature of the components, as specified in Maximum Ratings in the Detail specifications, is higher than the Maximum Operating Temperature, also as specified in Maximum Ratings in the Detail Specification.
4. This test shall be performed only if the Maximum Storage Temperature of the components, as specified in Maximum Ratings in the Detail Specification, is equal to the Maximum Operating Temperature, also as specified in Maximum ratings in the Detail Specification.

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