Evaluation of Commercial-Grade Tantalum Capacitors for Space Applications

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Lya Fontaine, PHD[1], Laurent Guillot [2], Guilhem Vidal [2],
Rodolphe Sellier [2], Frédéric Tilhac [2], Xavier Wiedemann [2]

[1]CNES
18, Avenue Edouard Belin,
31401 TOULOUSE Cedex 9, FRANCE
Email: lya.fontaine@cnes.fr

[2] ALTER TECHNOLOGY FRANCE
Parc Technologique du Canal
2 rue des satellites
31520 RAMONVILLE SAINT AGNE (FRANCE)
Email: L.Guillot@altertechnology.fr
G.Vidal@altertechnology.fr
R.Sellier@altertechnology.fr
F.Tilhac@altertechnology.fr
X.Wiedemann@altertechnology.fr

INTRODUCTION

The ever-increasing demand for commercial-off-the-shelf (COTS) components in the space sector is driven by the need to shorten development cycles, reduce material costs and benefit from the rapid innovation cycles that are typical of the commercial electronics market. Solid tantalum capacitors are especially attractive for spacecraft electronics because they combine a very high volumetric capacitance, low equivalent-series resistance (ESR) and a capacitance that remains stable over a wide temperature range, features that translate directly into weight and volume savings for power-conversion and filtering functions. However, the heritage of these commercial-grade parts in the harsh space environment is limited, and the long-term reliability of tantalum devices under the combined thermal, mechanical and electrical stresses of a mission remain uncertain.

In this study, fifteen commercial-grade tantalum capacitor references were selected from three manufacturers (KEMET, Kyocera AVX and Vishay). The parts span five capacitance values (1 µF, 4.7 µF, 10 µF, 47 µF and 100 µF), nominal voltages from 20 V to 50 V and a 10 % tolerance, and all were obtained from authorised distributors to guarantee lot consistency. Each lot was subjected to a comprehensive evaluation flow that follows the ECSS-Q-ST-60-13 and ESCC 3012 standards including construction analysis, electrical characterization, screening (surge current testing and burn-in) and endurance testing.
Failure analysis was then performed on ten units that exhibited the most severe anomalies during screening or life testing (lock-in thermography, cross-sectioning, internal optical inspection and scanning-electron-microscopy) to determine the root causes of the observed failures.

PART SELECTION

The study targets fifteen commercial tantalum capacitor part numbers, selecting five references from each of the selected manufacturers: KEMET, KYOCERA AVX and VISHAY, and covering values of 1 µF, 4,7 µF, 10 µF, 47 µF and 100 µF, all with a 10 % tolerance and rated voltages between 20 V and 50 V.
All devices are sourced from authorized distributors to ensure the availability and minimize lead-times.

Lot	Capacitance (µF)	Voltage (V)	Package	Manufacturer	Part reference
1	1	50	C	KEMET	T491C105K050AT
2	1	50	C	Kyocera AVX	TAJC105K050RNJ
3	1	50	C	Vishay	293D105X9050C2TE3
4	4,7	50	D	KEMET	T491D475K050AT
5	4,7	50	D	Kyocera AVX	TAJD475K050RNJ
6	4,7	50	D	Vishay	293D475X9050D2TE3
7	10	50	D	KEMET	T491D106K050AT
8	10	50	D	Kyocera AVX	TAJD106K050RNJ
9	10	50	D	Vishay	293D106X9050D2TE3
10	47	35	X	KEMET	T495X476K035ATE300
11	47	35	E	Kyocera AVX	TPSE476K035R0200
12	47	20	E	Vishay	593D476X9020E2TE3
13	100	20	X	KEMET	T491X107K020AT
14	100	20	D	Kyocera AVX	TAJD107K020RNJ
15	100	20	E	Vishay	593D107X9020E2TE3

Table 1. Part selection

TEST SEQUENCE

The test methodology was designed to evaluate the 15 selected tantalum capacitor references by applying the procedures defined in ECSS-Q-ST-60-13 [1] and ESCC 3012, including construction analysis, electrical-temperature characterisation, burn-in and endurance life testing.

- Construction analysis:

For each selected lot, five parts were inspected in accordance with the requirements of ESCC 21001 and EIA 469, using the following steps:

- External visual inspection (appearance and configuration of terminations, case condition).
- X-ray inspection (tantalum pellet, solder joints, terminations).
- Internal visual inspection:
  • Identification of the constituent materials to confirm that the parts conform to their specified characteristics (tantalum pellet and terminations)
  • Measurement of critical dimensions that affect both the component itself and its suitability for placement on a printed-circuit board (length of termination return traces, position of the return relative to the pellet, thickness and uniformity of the termination layers, etc.)

- Electrical characterisation:

For each lot, ten parts were characterised as follows:

- Electrical measurements (capacitance C, leakage current IL, dissipation factor DF, and equivalent series resistance ESR) at +25 °C
- Temperature-dependence of capacitance measured at –55 °C, +25 °C and +125°C
- Measurements of IL, DF and ESR at +125°C

➢ Screening tests:

100 parts were subjected to the following sequence:

- Electrical measurements (C, IL, DF, ESR) at +25 °C.
- Surge-current test at +25 °C.
- A second set of electrical measurements (C, IL, DF, ESR) at +25 °C.
- Burn-in for 168 h at the maximum operating temperature TC (± 3 °C) under the DC rated voltage (UR).
- Post-burn-in electrical measurements (C, IL, DF, ESR) at +25 °C.

➢ Endurance testing:

A 2000 h (± 48 h) life test was performed at 85 °C (± 3 °C) under the DC rated voltage (Ur) on 24 parts per lot.
A 2000 h (± 48 h) life test was performed at +125°C (± 3 °C) under the DC category voltage (Uc) on 16 parts per lot.
Electrical measurements (C, IL, DF, ESR) at +25 °C were performed after the endurance runs.

➢ Failure analysis:

Ten parts selected after the previous testing were subjected to a detailed failure-analysis campaign.

The following schematic (Fig. 1) summarises the sequence of tests that were performed on each reference.

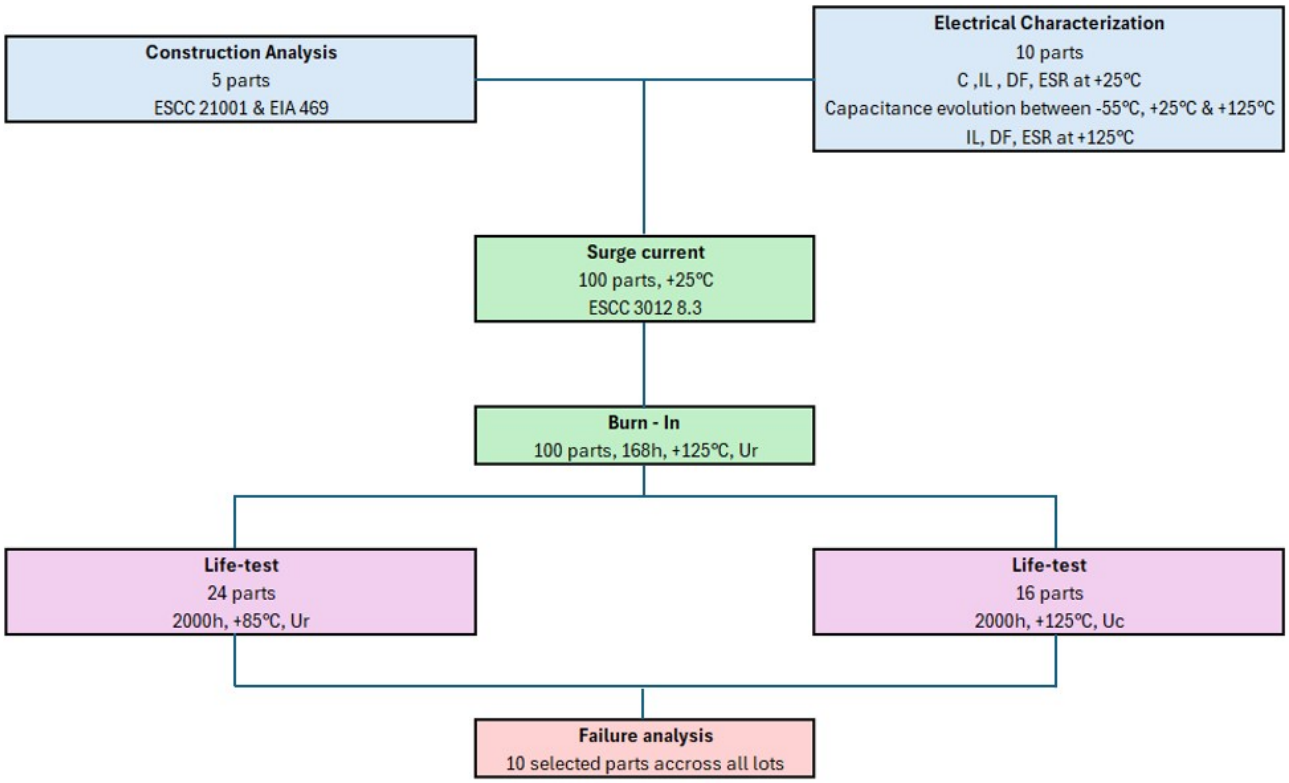


Fig. 1. Test sequence

TEST RESULTS

Phase 1 - Construction analysis and electrical characterization

Construction analysis was performed on five representative parts in accordance with the ESCC 21001 and EIA 469 specifications. Each part underwent an external visual inspection of the case and termination geometry, a general X-ray examination of the tantalum pellet, solder joints and terminations, and an internal visual inspection.
The internal inspection identified the constituent materials (pellet and terminations) to confirm compliance with the specified characteristics, measured critical dimensions that affect both the component itself and its PCB footprint (termination length, positioning relative to the pellet, thickness uniformity), and noted any other relevant observations such as structural defects or foreign objects.

Neither design nor process problem nor anomaly has been noticed, except on one lot 10 (Kemet, 47µF, 35V) part: delamination has been evidenced at plastic package/tantalum wire interface (see Fig 2.).

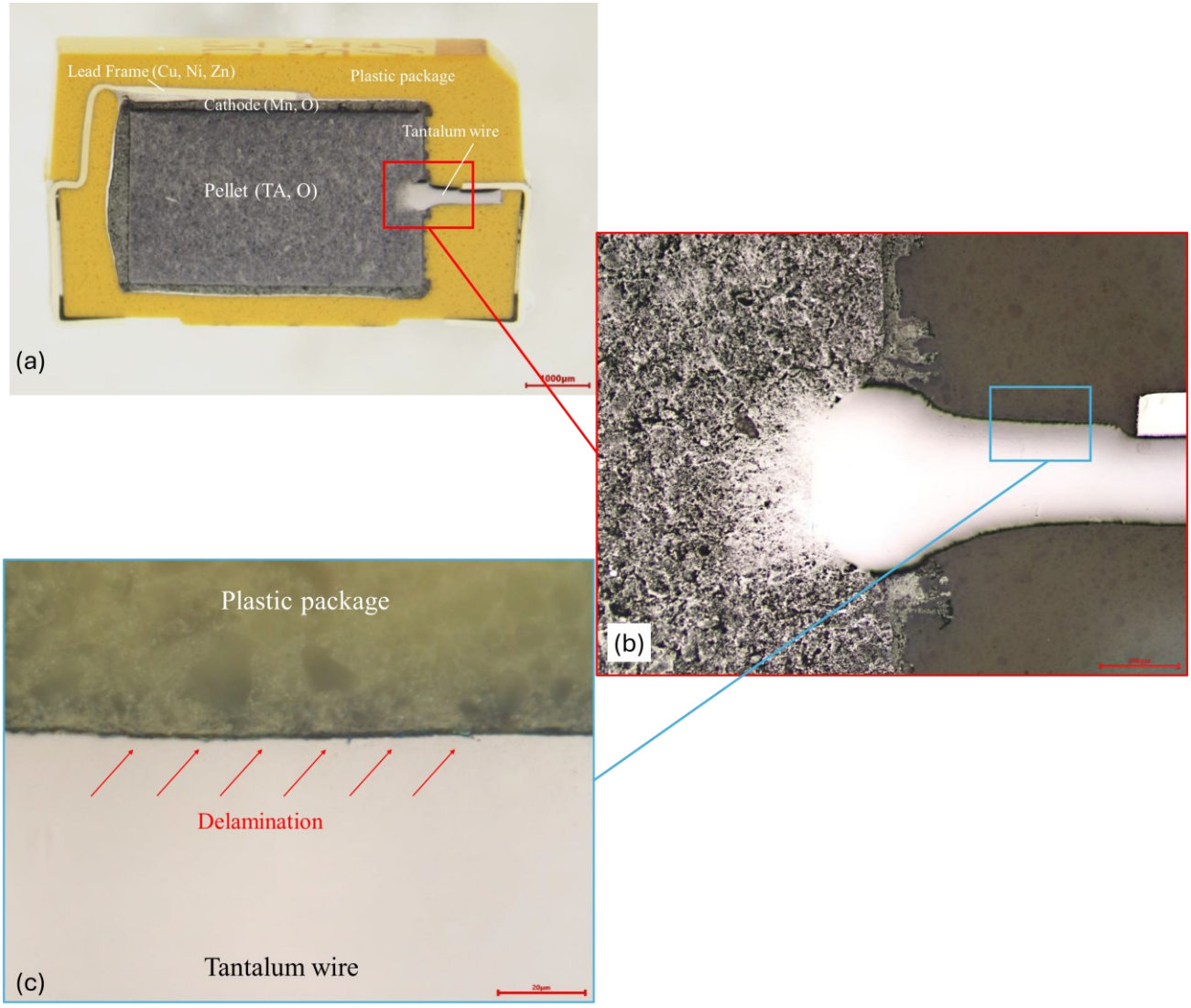


Fig 1. (a) Optical inspection of the capacitor after cross-sectioning (b) Zoomed view on the tantalum wire (c) Zoomed view on the delamination observed between the tantalum wire and plastic package

This kind of non-conformance can lead to “popcorn” effect during reflow assembly process [2]. MSL precautions should be employed to avoid such defects.

The electrical characterization was conducted on ten pieces from each lot. At ambient temperature (+25 °C) the capacitance (C), leakage current (IL), dissipation factor (DF) and equivalent series resistance (ESR) were recorded for all ten units. In addition, the temperature dependence of the capacitance was evaluated between –55 °C, +25 °C and the maximum rated temperature (TC) on five devices The IL, DF and ESR values were then measured at TC on the same subset.
No anomalies were observed for any of the lots, and no values fell outside the announced specifications.

Phase 2 - Screening

The second phase, screening, was carried out on a statistical sample of one hundred components per lot. Each part first underwent a full set of electrical measurements at ambient +25 °C, followed by a surge-current test conducted at the same temperature. After the surge test the same electrical parameters were re-measured at +25 °C, then the devices were subjected to a 168-hour burn-in held at the component's maximum operating temperature (TC ± 3 °C) while being biased at the DC rated voltage (Ur). A final round of C, IL, DF and ESR measurements at +25 °C verified that the components retained their specifications after the thermal stress.
Table 2 presents the results obtained after testing.

Lot	Capacitance (µF)	Voltage (V)	Package	Manufacturer	Part reference	Surge test	Burn in
1	1	50	C	KEMET	T491C105K050AT	1 reject (catastrophic)	
2	1	50	C	Kyocera AVX	TAJC105K050RNJ		
3	1	50	C	Vishay	293D105X9050C2TE3		
4	4,7	50	D	KEMET	T491D475K050AT		1 reject (DCL OOS)
5	4,7	50	D	Kyocera AVX	TAJD475K050RNJ		
6	4,7	50	D	Vishay	293D475X9050D2TE3		1 reject (ESR OOS)
7	10	50	D	KEMET	T491D106K050AT		5 rejects (DCL OOS)
8	10	50	D	Kyocera AVX	TAJD106K050RNJ		
9	10	50	D	Vishay	293D106X9050D2TE3		
10	47	35	X	KEMET	T495X476K035ATE300		
11	47	35	E	Kyocera AVX	TPSE476K035R0200		2 rejects (C OOS) ; 1 reject (DF OOS)
12	47	20	E	Vishay	593D476X9020E2TE3		
13	100	20	X	KEMET	T491X107K020AT	1 reject (catastrophic)	
14	100	20	D	Kyocera AVX	TAJD107K020RNJ		
15	100	20	E	Vishay	593D107X9020E2TE3		

Table 2. Screening results after surge test and burn-in

The screening campaign revealed a limited but significant number of rejected parts across the fifteen lots.
Lot 11 (47 µF, 35 V, Kyocera AVX) exhibited electrical drift: two parts failed the capacitance specification ("C OOS"), and an additional part was out-of-spec for the dissipation factor ("DF OOS").
The screening revealed a series of leakage-current increases ("DCL OOS") in two other lots:

- lot 4 (4,7 µF, 50 V, KEMET): DCL (direct current leakage) of 1 part was measured at $132E^{-6}$ A when the specification limit is $2,4E^{-6}$ A.
- five parts in lot 7 (10 µF, 50 V, KEMET): DCL were measured at $7,4E^{-6}$ A, $5,8E^{-6}$ A, $5,9E^{-6}$ A, $6,1E^{-6}$ A and $8,4E^{-6}$ A, slightly above the specification limit.

Finally, catastrophic failures were detected in three separate lots: a short-circuit was found in lot 1 (1 µF, 50 V, KEMET) after the surge test, one part in lot 6 (4.7 µF, 50 V, Vishay) exhibited an ESR value at 143 MΩ after burn-in, and a part in lot 13 completely burned (100 µF, 20 V, KEMET), also after surge testing.
These defects are especially problematic for space hardware. A drift in capacitance or dissipation factor can alter the frequency response of power-conversion and filtering networks, jeopardizing the proper operation of critical subsystems

[3]. Elevated leakage currents increase power dissipation, can raise local temperatures and may even damage downstream circuitry by injecting unwanted currents.

The screening required at 100 % coverage by ECSS-Q-ST-60-13 when performed, can eliminate these high-risk parts before they are integrated into flight hardware. However, if a program elects to forgo this exhaustive screening, it must recognize that infant-mortality defects can still emerge during operation. To mitigate that risk, the procurement strategy should rely on components that have already been subjected to stringent evaluation so that their performance limits are well documented. By combining careful part selection with extra quality controls, the overall risk can be kept within acceptable bounds even when a 100 % screening campaign is not applied.

Phase 3 - Life testing

The life-test phase follows the ESCC 3012 specification for qualifying solid-tantalum capacitors, which aligns with IEC 60384-1 clause 8.5. Each lot is divided between two temperature groups and subjected to a 2000h endurance test. For the first group, composed of 24 parts for each lot, the components are operated at their rated temperature (Tr = 85°C ± 3 °C) under the DC rated voltage (Ur). The second group, composed of 16 parts of each lot, is run at the upper category temperature (Tc = +125 °C, ± 3 °C) while being biased at the DC category voltage (Uc = 0.66 × Ur).
Table 3. summarizes the results obtained for both tests.

						Life-test	
Lot	**Capacitance (µF)**	**Voltage (V)**	**Package**	**Manufacturer**	**Part reference**	**2000h 85°C Ur**	**2000h / 125°C Uc**
1	1	50	C	KEMET	T491C105K050AT		
2	1	50	C	Kyocera AVX	TAJC105K050RNJ		
3	1	50	C	Vishay	293D105X9050C2TE3		
4	4,7	50	D	KEMET	T491D475K050AT	1 reject (DCL OOS)*	
5	4,7	50	D	Kyocera AVX	TAJD475K050RNJ		
6	4,7	50	D	Vishay	293D475X9050D2TE3		
7	10	50	D	KEMET	T491D106K050AT		1 reject (C OOS)
8	10	50	D	Kyocera AVX	TAJD106K050RNJ		
9	10	50	D	Vishay	293D106X9050D2TE3		
10	47	35	X	KEMET	T495X476K035ATE300		
11	47	35	E	Kyocera AVX	TPSE476K035R0200	1 reject (C OOS) + 1 reject (DF OOS)	1 reject (C OOS)*
12	47	20	E	Vishay	593D476X9020E2TE3		
13	100	20	X	KEMET	T491X107K020AT		
14	100	20	D	Kyocera AVX	TAJD107K020RNJ		
15	100	20	E	Vishay	593D107X9020E2TE3		

* These parts were alreday OOS after screening

Table 3. Life test results

The endurance campaign confirmed the overall robustness of most lots but highlighted a few anomalies:

- In lot 4 (4,7 µF, 50 V, KEMET) the leakage current of one part, which was already elevated after the 168-hour burn-in (132 µA), increased further to 166,8 µA during the 85 °C, Ur life test, indicating a progressive degradation.
- Lot 7 (10 µF, 50 V, KEMET) exhibited a single part whose capacitance value was out of the specified limit, suggesting a minor manufacturing tolerance issue.
- Lot 11 (47 µF, 35 V, Kyocera AVX) showed the most pronounced anomalies. At 85 °C under Ur, one unit failed the capacitance specification (measured 41,6 µF instead of the nominal 47 µF) and another exceeded the dissipation-factor limit dramatically (36 % versus the maximum 6 %). At the 125 °C, Uc condition, one part that already displayed a sub-specification capacitance after the burn-in (41,9 µF) was also measured out-of-specification, but the value did not further deteriorate during the life test, confirming that the drift occurred early in the thermal exposure.

While the overall population seems reliable, the life-testing uncovered instances of leakage-current growth, capacitance drift and excessive dissipation-factor that could compromise voltage regulation, increase power loss and affect the robustness of space-flight electronics.

Phase 4 - Failure analysis

The failure analysis phase follows a structured flow that begins with a comprehensive external examination of each selected component (visual inspection, X-ray radiography, electrical measurements and lock-in thermography) and then proceeds to more invasive techniques on the specimens that exhibited the most severe anomalies during screening and life testing: cross-sectioning, internal visual inspection and scanning-electron-microscope (SEM) analysis.

- SN 1 (Lot 1, 1 µF, 50 V, KEMET): failed the surge-test

External visual inspection and X-ray imaging revealed no anomaly, but lock-in thermography highlighted a hot-spot, shown in Fig 2.

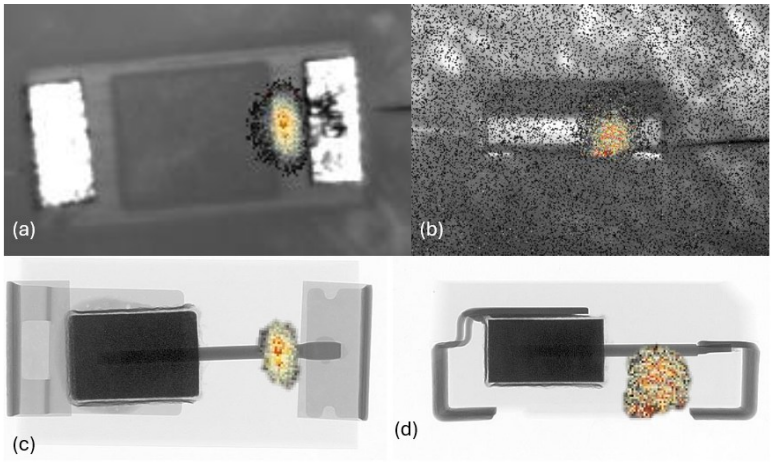


Fig 2. Lock-in thermography (a) Bottom view (b) side view (c) bottom view, superimposed with X-Ray imaging (d) side view, superimposed with X-Ray imaging

These images allowed localization of the defect, and a cross section on this plane was performed (see Fig 3.).

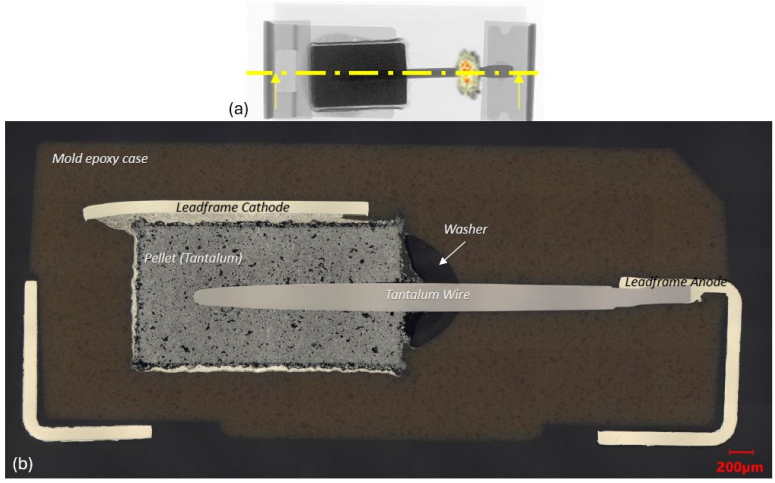


Fig 3. (a) Cross-section plane (b) general view of the capacitor after cross-section

Internal visual inspections (optical and SEM) revealed a small delamination at mold compound/Tantalum Wire interface (Fig 4. (b) & (c)), a delamination at mold compound/washer interface (Fig 4. (d) & (e)), and a crack at Tantalum pellet/Tantalum wire interface (Fig 4. (f)).

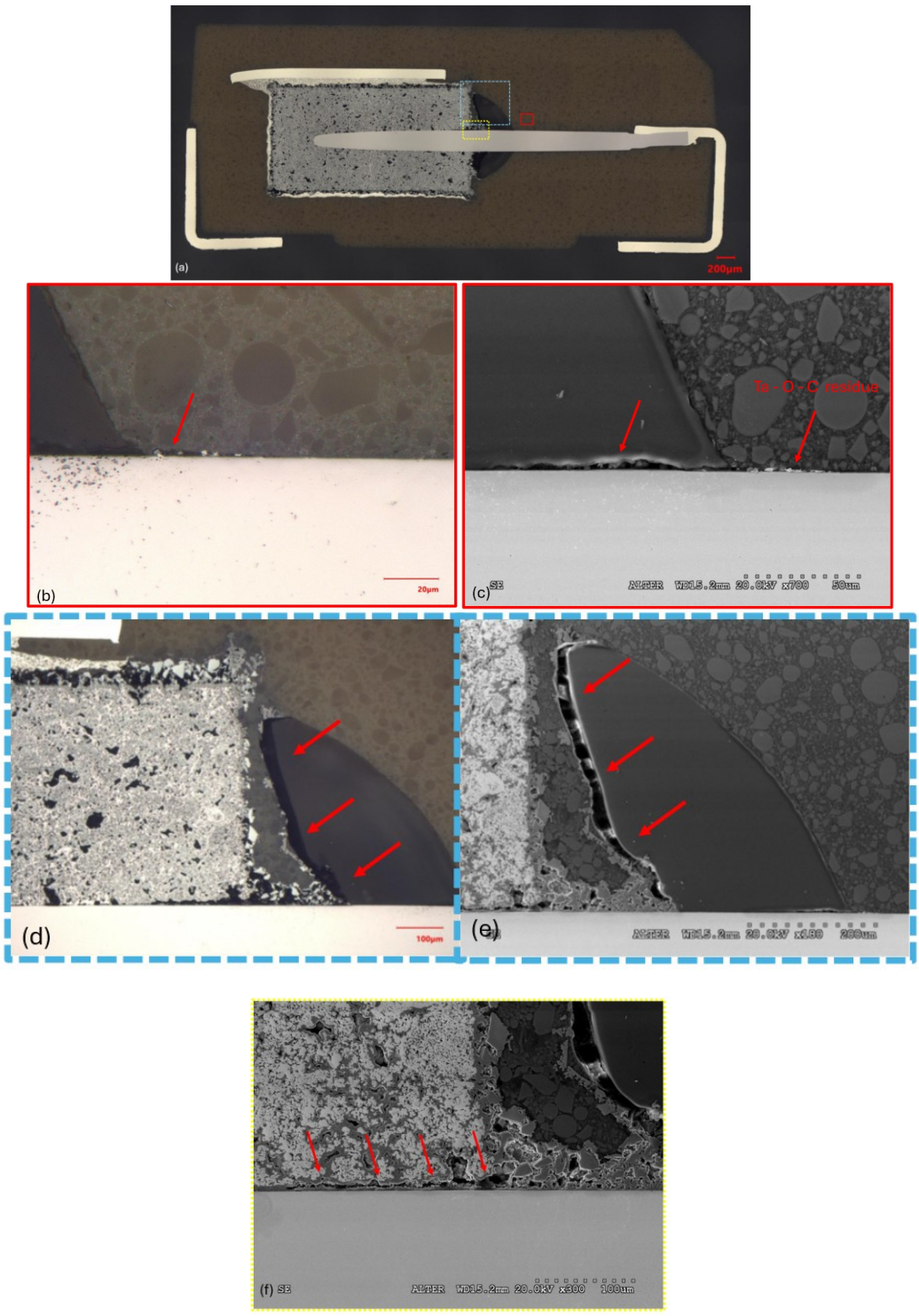


Fig 4. (a) General view showing the zoomed areas
(b) optical & SEM (c) views: delamination at mold compound/Tantalum Wire interface
(d) optical & SEM (e) views: delamination at mold compound/washer interface
(f) SEM view of a crack at washer/Tantalum wire interface

During SEM inspections, Tantalum residue was also observed along the wire in the mold compound. This could explain the hotspot located on the wire with thermal analysis: current propagation through the matter along the wire linked the cathode and anode potentials and broke the insulated resistor.

- SN 30 (Lot 4, 4.7 µF, 50 V, KEMET): rejected after burn-in test (DCL OOS)

External visual inspection and X-ray imaging revealed no anomaly. Lock-in thermography highlighted a hot-spot, shown in Fig 5., but not accurate enough to allow precise localization of the defect.

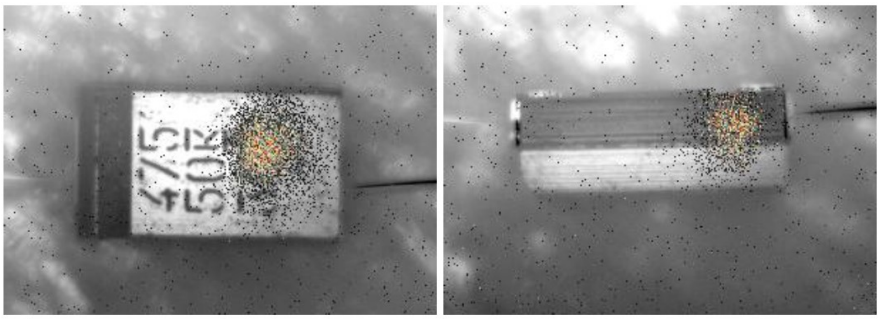


Fig 5. Top and side lock-in thermography images of SN30

- SN 15 (Lot 6, 4.7 µF, 50 V, Vishay): rejected after the burn-in test

External visual inspection and X-ray imaging revealed no anomaly. Lock-in thermography highlighted a hot-spot, shown in Fig 6.

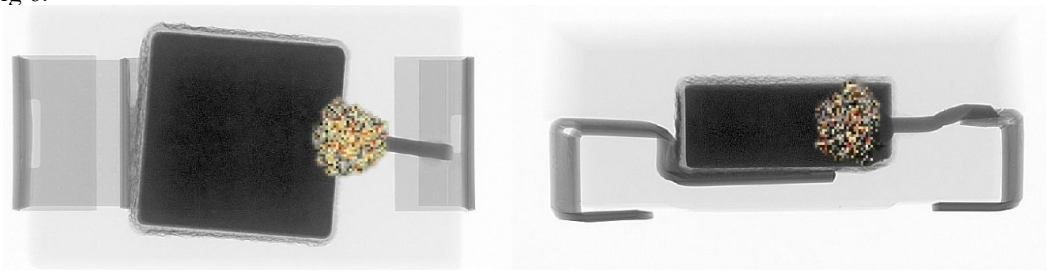


Fig 6. Lock-in thermography and X-Ray imaging superposition (top and side views)

A cross section on this plane was performed (see Fig 7.).

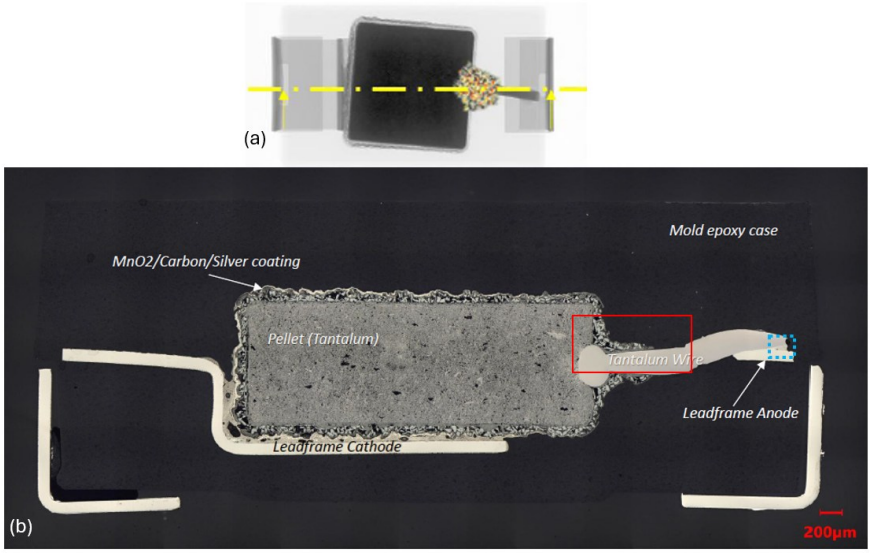


Fig 7. (a) Cross-section plane (b) general view of the capacitor after cross-section

Internal visual inspections (optical and SEM) revealed a crack along the Tantalum wire through mold compound and MnO_2/Carbon/Silver coating (see Fig. 8) and some cracks between the Tantalum wire and the leadframe anode (see Fig. 8).

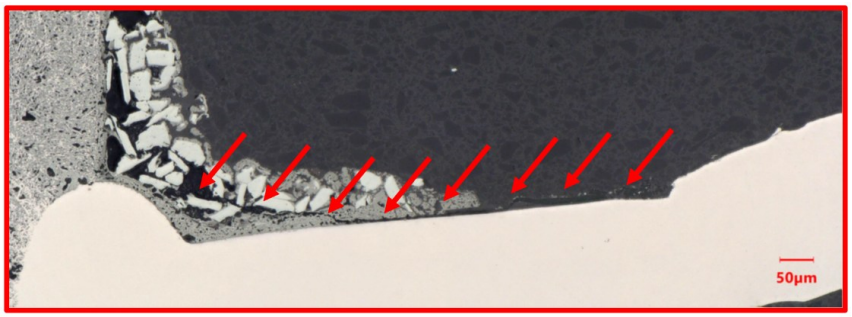


Fig 8. Optical inspection revealing a crack along the Tantalum wire

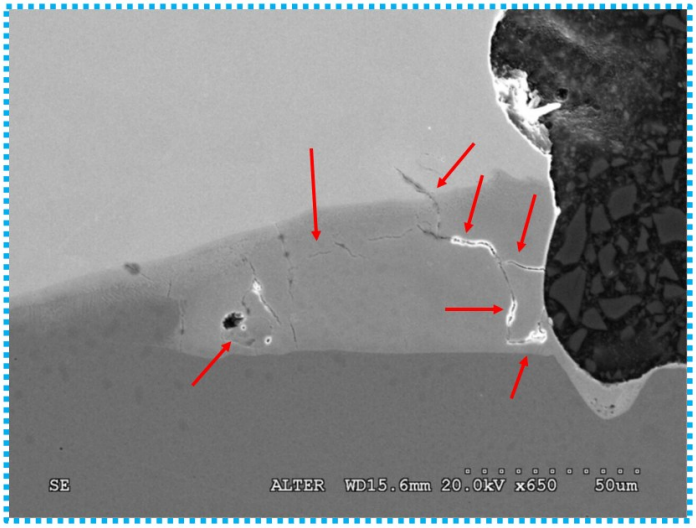


Fig 9. SEM inspection revealing cracks between the Tantalum wire and the leadframe anode

There is migration of MnO_2 around the wire connection in the Pellet matter creating a conductive path.

- SN 57 (Lot 7, 10 µF, 50 V, KEMET) – rejected both in screening and later in the life test (DCL OOS)

External visual inspection and X-ray imaging revealed no anomaly. Lock-in thermography highlighted a hot-spot, shown in Fig 10., but not accurate enough to allow precise localization of the defect.

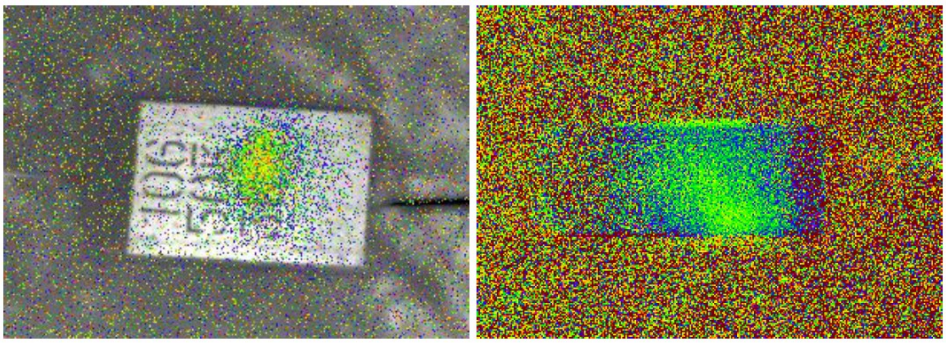


Fig 10. Top and side Lock-in thermography images

- SN 31 (Lot 7, 10 µF, 50 V, KEMET) – rejected during screening (DCL OOS)

External visual inspection and X-ray imaging revealed no anomaly. Lock-in thermography highlighted a hot-spot (see Fig 11.).

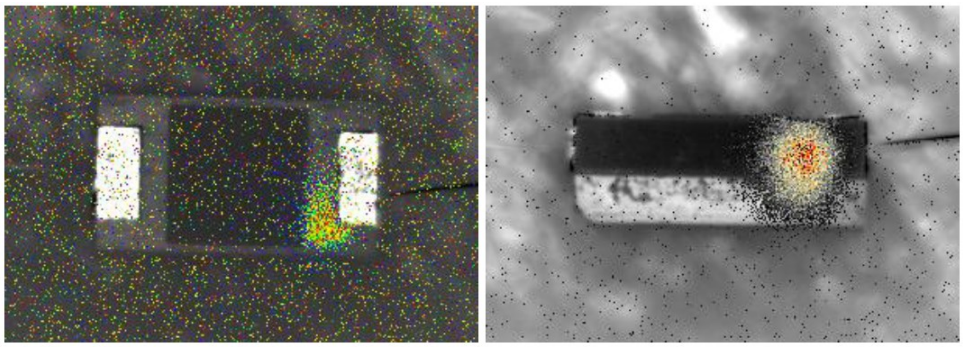


Fig 11. Bottom and side Lock-in thermography images

- SN 81 (Lot 11, 47 µF, 35 V, Kyocera AVX) – exceeded the dissipation-factor limit in screening

External visual inspection and X-ray imaging revealed no anomaly. Lock-in thermography highlighted a hot-spot (see Fig 12.).

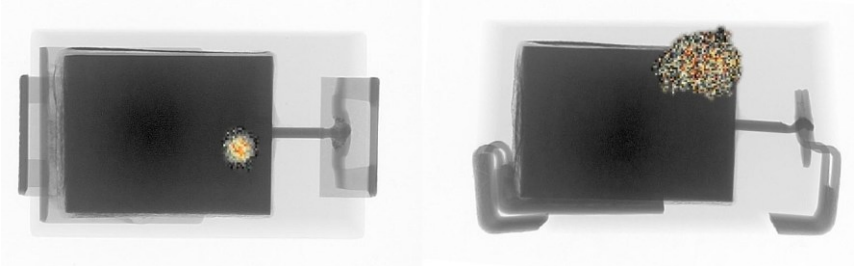


Fig 12. Lock-in thermography and X-Ray imaging superposition (top and side views)

A cross section on this plane was performed (see Fig 13.).

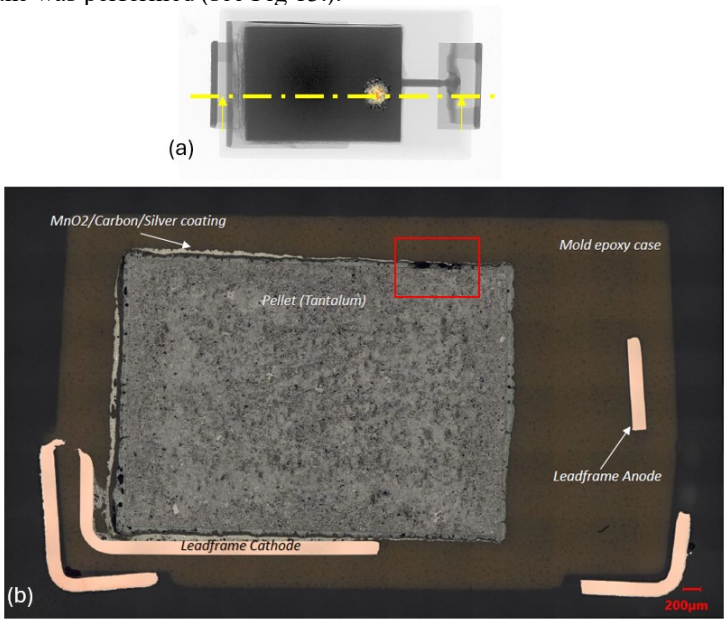


Fig 13. (a) Cross-section plane (b) general view of the capacitor after cross-section

Internal visual inspections (optical and SEM) revealed a burnt area at the LIT hotspot location (see Fig 14.), on the top right side of the Pellet matter: silver coating in contact with the Tantalum. This contact locally intensifies the electric field, creating a hot spot that can either cause the insulated resistor to fail outright or trigger a self-healing response. In this particular sample, the current was too high for the self-healing mechanism to succeed.

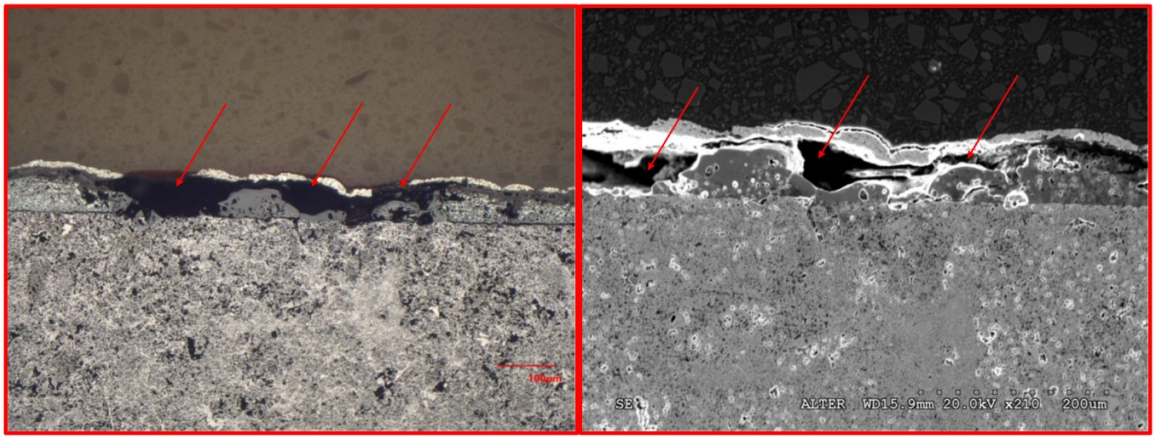


Fig 14. Optical and SEM view of the burnt area

- SN 43 (Lot 11, 47 µF, 35 V, Kyocera AVX): rejected during the life test

External visual inspection and X-ray imaging revealed no anomaly. Lock-in thermography highlighted a hot-spot (see Fig 15.).

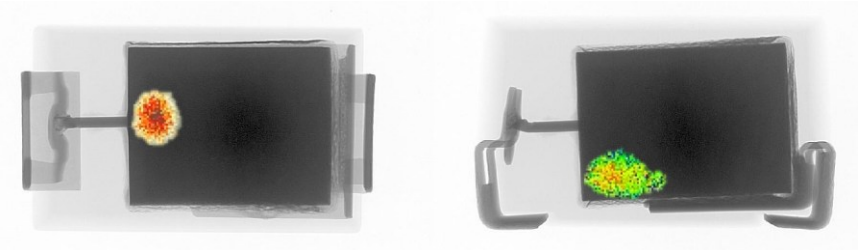
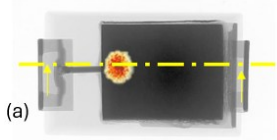


Fig 15. Lock-in thermography and X-Ray imaging superposition (top and side views)

A cross section on this plane was performed (see Fig 16.).



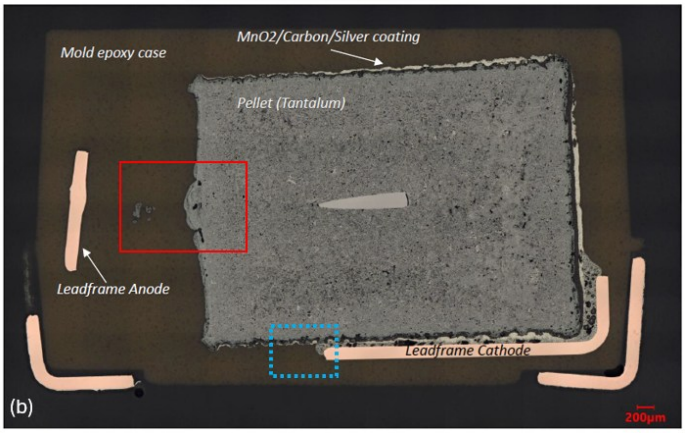


Fig 16. (a) Cross-section plane (b) general view of the capacitor after cross-section

Internal visual inspections (optical and SEM) some deformation at the Tantalum-MnO_2/C/Ag interface (see Fig 17).

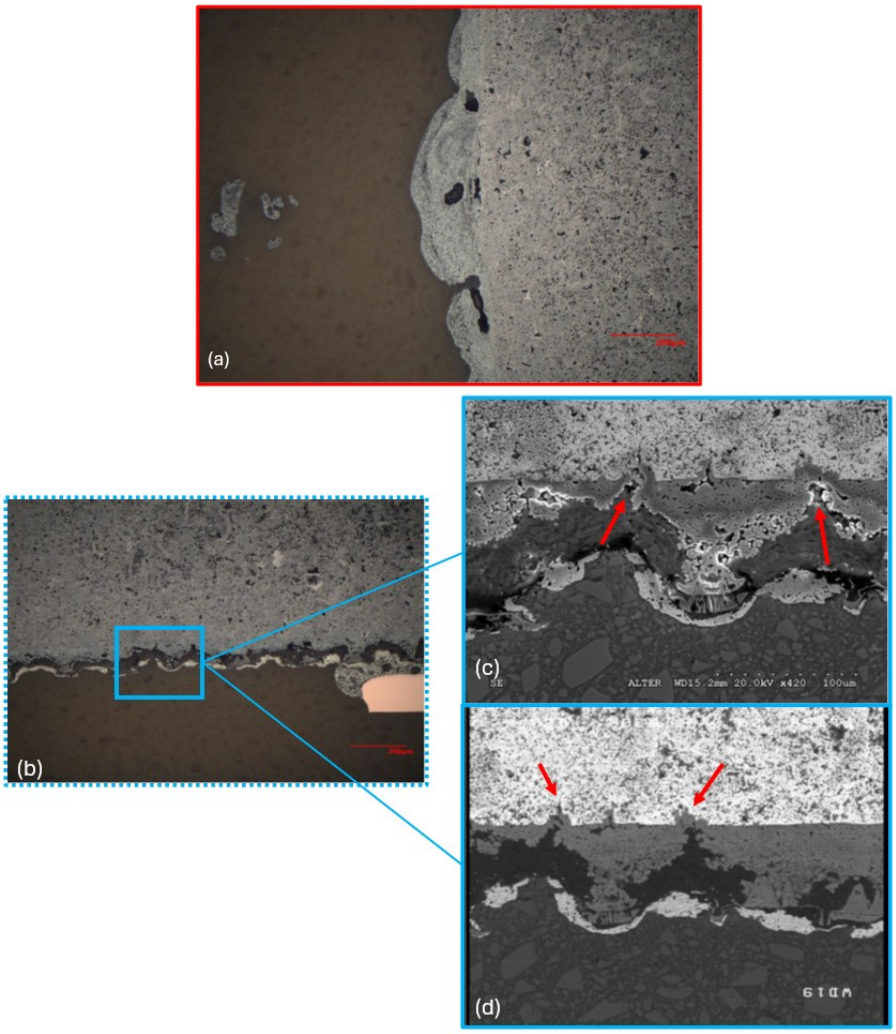


Fig 17. Internal visual inspections (a) & (b) optical views, (c) SEM view revealing broken cathode barrier, (d) same view with Back Scatterd Electrons detector

The non uniformity of the MnO_2 layer was already observed during the construction analysis. It can lead to an increase of the local electric field and generate a local hot spot which breaks the insulation.

- SN 53 (Lot 11, 47 µF, 35 V, Kyocera AVX): rejected during the life test

External visual inspection and X-ray imaging revealed no anomaly. Lock-in thermography highlighted a hot-spot, shown in Fig 18., but not accurate enough to allow precise localization of the defect.

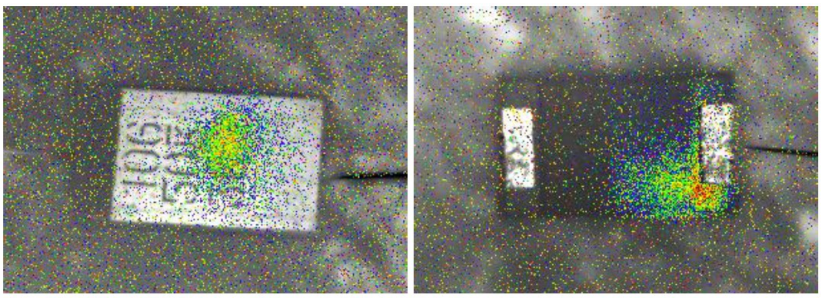


Fig 18. Top and side Lock-in thermography images

- SN 83 (Lot 11, 47 µF, 35 V, Kyocera AVX): rejected both in screening and in the life-test

External visual inspection and X-ray imaging revealed no anomaly. Lock-in thermography highlighted a hot-spot, shown in Fig 19., but not accurate enough to allow precise localization of the defect.

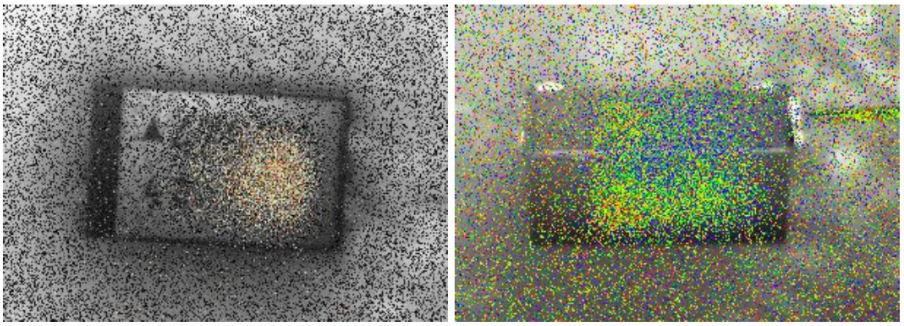


Fig 19. Top and side Lock-in thermography images

- SN 33 (Lot 13, 100 µF, 20 V, KEMET): failed the surge-test

This part showed the most damage: catastrophic failure occurred during the surge testing. Burnt marks can be observed (see Fig 20.) and the cathode leadframe is disconnected, preventing further analysis.

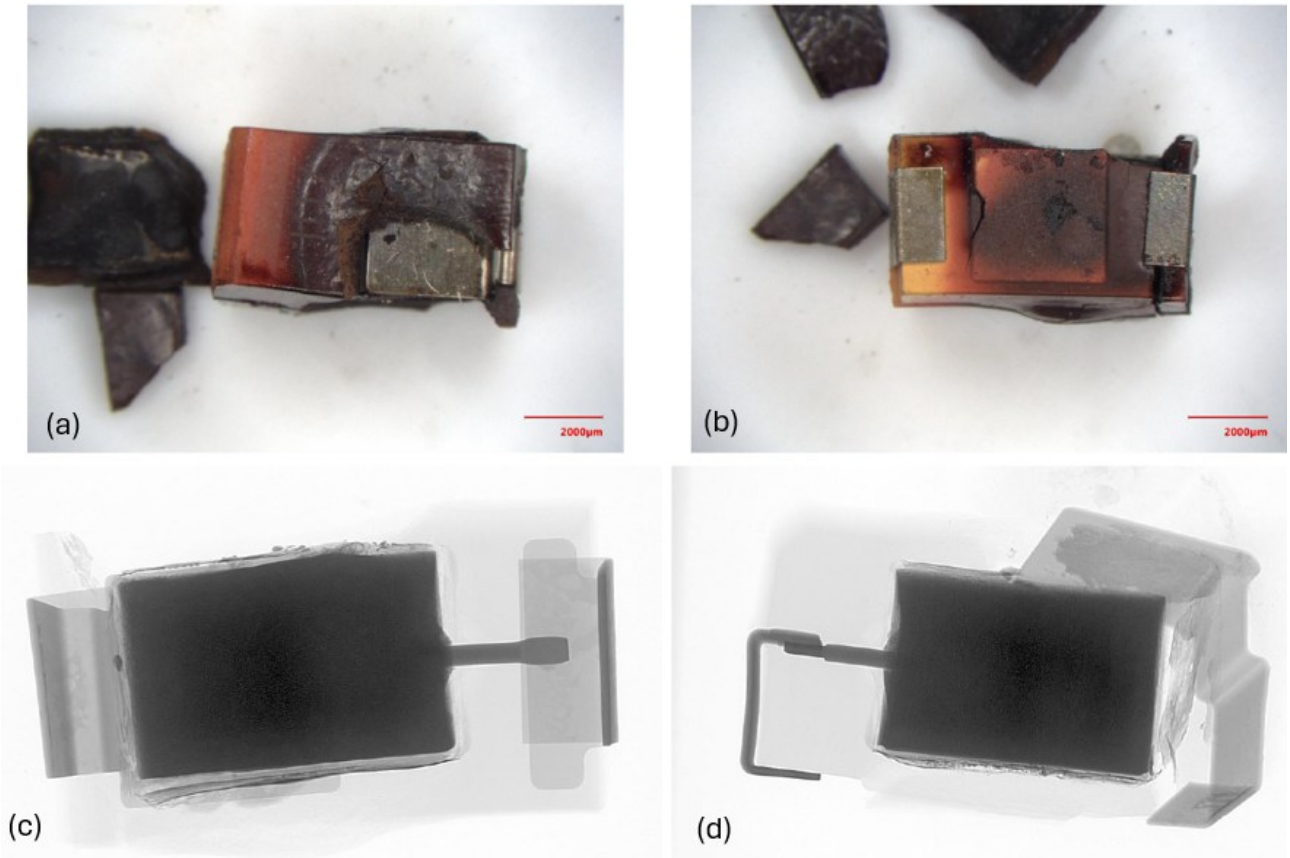


Fig 20. External visual inspection (a) Top view (b) Bottom view)
and X-ray inspection (c) Top view (d) side view
showing the catastrophic damages

CONCLUSION

The evaluation of fifteen commercial-grade tantalum capacitor references demonstrates that the majority of the lots meet the endurance requirements defined by ECSS-Q-ST-60-13, while a limited subset exhibits failure mechanisms that could jeopardize spacecraft performance if they are not addressed.

Construction analysis confirmed that the parts are largely free of gross manufacturing defects. Only two isolated anomalies were identified: a delamination at the plastic-package/tantalum-wire interface in Lot 10 and a non-uniform MnO_2 layer in Lot 11.

Screening uncovered the following critical issues:

- Leakage-current out-of-spec values in Lot 4 (the current increased from 132 µA after burn-in to 166,8 µA during the 85 °C life test) and in Lot 7 (five pieces showed slightly elevated DCL after burn-in).
- A capacitance loss and an excessive dissipation-factor in Lot 11 (capacitance measured at 41.6 µF instead of the nominal 47 µF and DF at 36 % versus the 6 % maximum). These were the only instances of capacitance drift across all lots.
- Short or near-short circuit failures in Lots 1, and 6.
- SN 33 of lot 13 completely burned during surge testing, which could cause catastrophic failures in a satellite.

The 2000h life tests confirmed the overall robustness of most lots but highlighted persistent problem areas. In Lot 4 the leakage current continued to rise after the life test on one part, indicating progressive dielectric degradation. Lot 7 exhibited a single part with a marginally out-of-spec capacitance, a tolerance issue that could affect filter tuning but does not threaten overall functionality. Lot 11 exhibited some anomalies, with one capacitor's capacitance reduced to ~41 µF at 85 °C, another's dissipation factor spiking to 36 % (vs 6 % max), and a third already low at 41,9 µF after burn-in but remaining unchanged after life-test.

Failure-analysis investigations linked electrical anomalies to a physical cause. Lock-in thermography revealed hot-spots that corresponded to delamination, cracks at the tantalum-wire/lead-frame interface, and migration of MnO_2 residues, which created conductive paths and locally enhanced electric fields. In the case of SN 81 (Lot 11) the high field at a delaminated interface resulted in permanent damage.

Taken together, the findings lead to the following practical recommendations for the use of commercial tantalum capacitors in space missions:

- Select parts with proven space-heritage data and maintain strict lot traceability to enable rapid identification of problematic batches.
- Apply the full ECSS-Q-ST-60-13 screening flow (100 % inspection) for critical subsystems; if a reduced screening level is desired, restrict the design to parts that have already passed stringent evaluations.
- Derate the operating voltage and temperature to provide margin against the leakage-current growth and the isolated capacitance drift observed in the most vulnerable lots.

In conclusion, commercial tantalum capacitors can be used for space applications, but only after a thorough evaluation program that identifies and eliminates early-life defects, verifies long-term stability under mission-representative thermal and electrical stress, and documents the underlying failure mechanisms. By knowing the limit of each reference and implementing these recommendations, system designers can reap the performance and cost advantages of COTS tantalum capacitors while keeping the overall mission risk within acceptable limits.

AKNOLEDGMENTS

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