Evaluation of Automotive Grade Ceramic Capacitors for Space Applications

6th Space Passive Component Days (SPCD), International Symposium

13-16 October 2026
ESA/ESTEC, Noordwijk, The Netherlands

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INTRODUCTION

The increasing demand for commercial off-the-shelf (COTS) components in the space industry is driven by the need for enhanced performance, reduced lead times, and cost savings. However, the use of automotive-grade components, such as ceramic capacitors, introduces risks due to limited experience with their behaviour in space environments. This study aims to evaluate the reliability and performance of type II multilayer ceramic capacitors qualified under the AEC-Q-200 standard for automotive applications.

Multilayer ceramic capacitors (MLCCs) are essential components in electronics systems, accounting for roughly 30% of the parts in a typical hybrid circuit module such as a DC-DC converter.
Their small size, wide range capacitance, temperature stability, and low ESR make them versatile and dependable, providing regulation, filtering, decoupling, and energy-storage functions that are critical for safe and efficient operation of critical aerospace systems.

AEC-Q200 is a reliability test standard for passive components intended for automotive applications. It provides a solid baseline for ensuring the robustness of selected capacitors. While these tests demonstrate that the parts can survive the thermal and mechanical stresses typical of automotive environments, they do not fully address the harsher conditions encountered in space, such as prolonged high temperature exposure, extreme thermal cycling etc.

The ECSS-Q-ST-60-13 standard [1], which governs the space product assurance for EEE parts, extends this automotive baseline. For components qualified under AEC-Q-200 grade 0/1 to be considered class 1, complete evaluation (including construction analysis, temperature characterization and 2000h life test at maximum rated temperature) on a sample of parts and 100% screening (including 96h burn-in at maximum rated temperature) are necessary.

However, these additional tests increase the price and lead times of these components significantly and are sometimes excessive. The automotive baseline might satisfy the reliability needs of low-risk subsystems, provided that the parts are carefully selected.

25 references of automotive-grade ceramic capacitors were evaluated for potential space applications. The evaluation included construction analysis, electrical characterization, burn-in tests under various conditions (12V/µm for components with a nominal voltage ≤ 25V, 2Un for all lots), and endurance tests at +125°C for 2000 hours under different voltage conditions (2Un for all lots, 12V for 16V components, and 15V for 25V components). The study also involved failure analysis to identify potential failure modes and mechanisms.

Key observations include non-conformities in electrical characteristics, failures during burn-in and endurance tests, and insights into the suitability of these components for space applications. The results will help establish guidelines for the selection and use of COTS capacitors in space missions, balancing performance, cost, and risk.

PART SELECTION

The part selection strategy focused on 25 AEC-Q-200 MLCC part numbers with capacitances/voltages values commonly encountered in space projects and produced by different manufacturers, allowing direct performance and reliability comparisons. Finally, all components are stocked by major distributors and can be sourced in large quantities, which minimizes lead-time and cost, preserving the COTS advantage.

Table 1. Part selection

Lot	Capacitance (F)	Voltage (V)	Size (EIA)	Manufacturer	Part reference
1	100 n	16	0402	KEMET	C0402C104K4RACAUTO
2	100 n	16	0402	TDK	CGA2B1X7R1C104K050
3	100 n	16	0402	Taiyo Yuden	EMK105B7104KVHF
4	100 n	16	0402	Murata	GCM155R71C104KA55
5	220 n	25	0603	KEMET	C0603X224K3RACAUTO
6	220 n	25	0603	Murata	GCM188R71E224KA55D
7	220 n	25	0603	TDK	CGA3E1X7R1E224K080AC
8	220 n	25	0603	Taiyo Yuden	TMK107B7224KAHT
9	1 µ	25	0603	Murata	GCM188R71E105KA64D
10	1 µ	25	0603	TDK	CGA3E1X7R1E105K080AC
11	1 µ	25	0603	Taiyo Yuden	TMJ107CB7105KAHR
12	10 µ	16	1206	Taiyo Yuden	EMK316AB7106KLHT
13	10 µ	16	1206	TDK	CGA5L1X7R1C106K160AC
14	10 µ	16	1206	Murata	GCM31CR71C106KA64L
15	4,7 µ	50	1210	Kyocera AVX	12105C475K4Z2A
16	4,7 µ	50	1210	Murata	GCM32ER71H475KA55L
17	4,7 µ	50	1210	KEMET	C1210C475K5RACAUTO
18	4,7 µ	50	1210	TDK	CGA6P3X7R1H475M250AB
19	2,2 µ	100	1210	TDK	CGA6N3X7R2A225K230AB
20	2,2µ	100	1210	KEMET	C1210X225K1RACAUTO
21	2,2 µ	100	1210	Taiyo Yuden	HMK325B7225KMHT
22	2,2 µ	100	1210	Kyocera AVX	12101C225K4Z2A
23	22 µ	16	1210	TDK	CGA6P1X7R1C226M
24	22 µ	16	1210	Taiyo Yuden	EMK325B7226KMHT
25	22 µ	16	1210	Murata	GCM32ER71C226KE19L

TEST SEQUENCE

The test methodology was designed to evaluate the 25 selected MLCC type-2 parts by applying the procedures defined in ECSS-Q-ST-60-13, including construction analysis, electrical-temperature characterisation, burn-in and endurance life testing.
The following schematic (Fig. 1) summarises the sequence of tests that were performed on each reference.

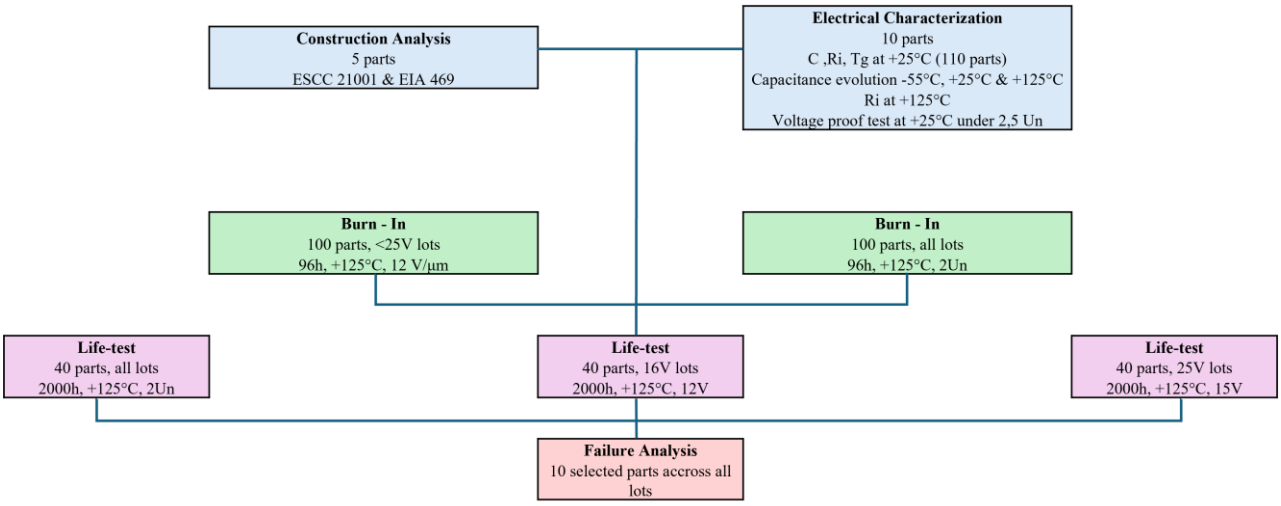


Fig. 1. Test sequence

A burn-in performed at 2Un (twice the rated voltage) might not address the specific issues that have been observed on thin-dielectric, low-voltage ceramic capacitors [2]. These parts could require harsher stress conditions than the conventional 2Un test. This is true for both space-qualified devices that use precious-metal electrodes (PME), for which were defined burn-in procedures that guarantee a minimum voltage gradient, and for the far more common base-metal-electrode (BME) technologies used in automotive applications.

In addition, several studies on BME ceramics [2][3] have reported reliability losses when the parts operate around 15 V, a problem linked to incomplete re-oxidation of the ceramic during manufacturing. This defect may not be revealed by the standard endurance test at 2Un required by ECSS-Q-ST-60-13, yet it can be harmful for applications at 15 V and potentially even at 12 V.

TEST RESULTS

Phase 1 - Construction analysis and electrical characterization

The screening of the MLCCs (construction analysis followed by initial electrical characterization) revealed a range of recurring defects across the different values, sizes and manufacturers. While most components passed the basic visual and electrical checks, several systematic non-conformities were identified:

- Barrier-layer anomalies were the most frequent finding (observed on parts from all manufacturers), see Fig 2.

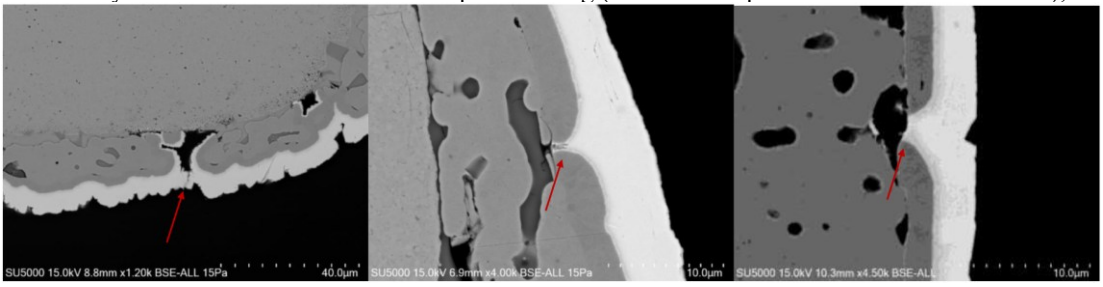


Fig 2. Examples of barrier layer discontinuities observed

- Porosities and voids in the ceramic were detected on a lot 8 part and two lot 13 parts, as shown on Fig 3.

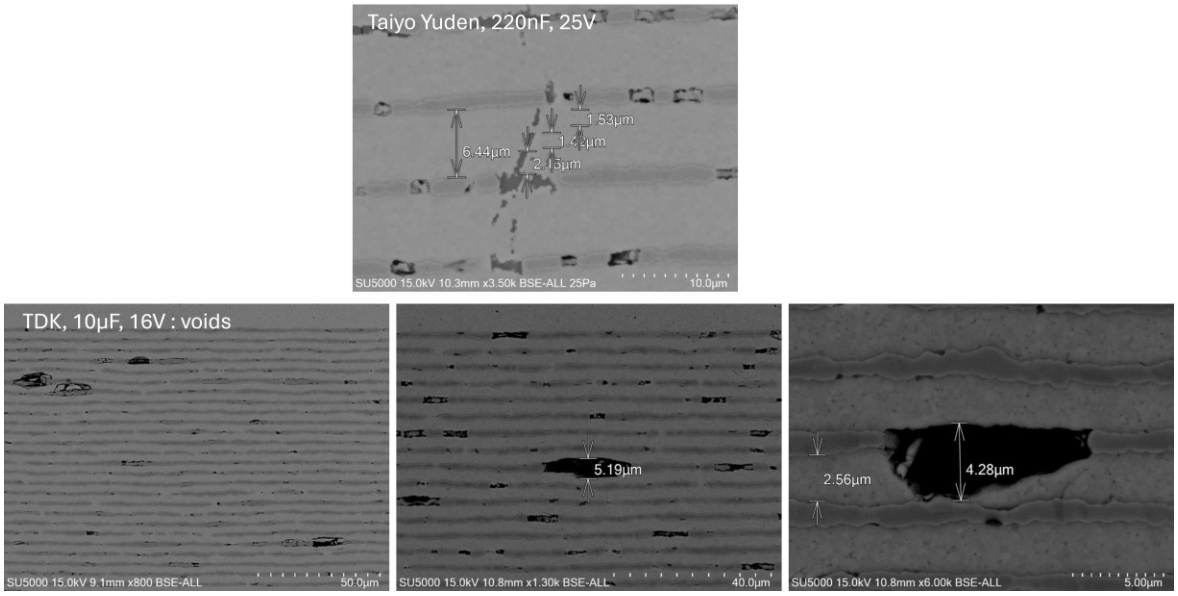


Fig 3. Examples of voids observed

- Delamination appeared on three Taiyo Yuden 100 V devices (lot 21, see Fig 4.).

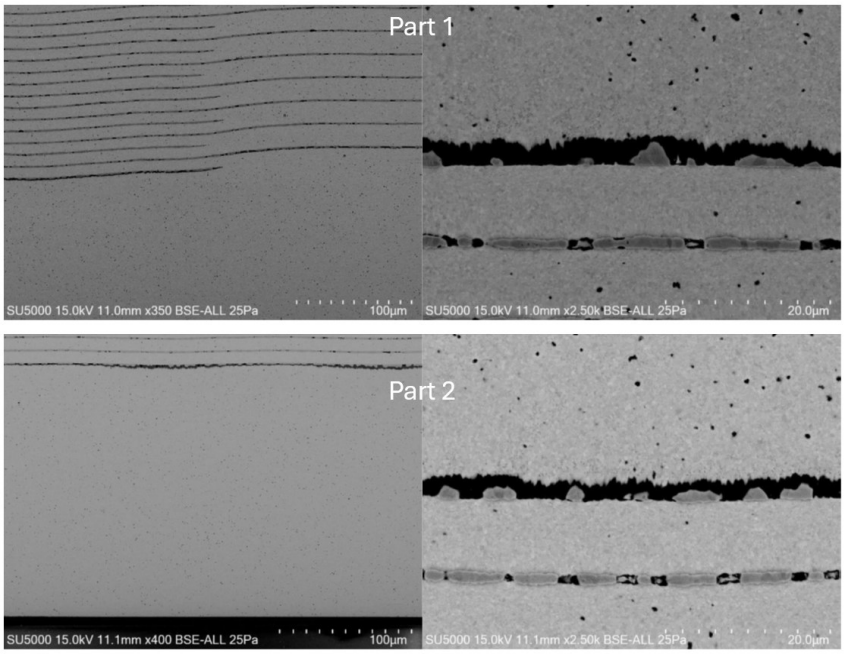


Fig 4. Exemples of delamination observed across the full electrode

- Several parts exhibited capacitance values at the lower limit of specification or outright out-of-spec (OOS):
  - 3% of tested parts of lot 11 (Taiyo Yuden, 1µF, 25V) show capacitance values under 0,8µF at +25°C, exceeding the 10% tolerance specified in the product datasheet
  - 100% of tested parts of lot 12 (Taiyo Yuden, 10µF, 25V) show capacitance values under 8,5µF at +25°C, exceeding the 10% tolerance specified in the product datasheet
  - 29% of tested parts of lot 13 (TDK, 10µF, 16V) show capacitance values under 8,9µF at +25°C, exceeding the 10% tolerance specified in the product datasheet

Phase 2 - Screening

To assess whether a 100 % burn-in screening is worthwhile for automotive-grade MLCCs, every part went through 96-hour, +125 °C burn-in. Two stress regimes were used:

- Standard 2 × U_n bias for all lots
- High-field 12 V / µm stress, applied only to the lots with a nominal voltage below 25 V (the thin-dielectric, low-voltage devices that are most vulnerable to field-induced degradation).

Table 2 presents the results obtained after testing. Many parts presented out-of-spec capacitance values ("C OOS"), often accompanied by excessive leakage ("IR OOS") or dissipation-factor readings ("DF OOS") and, in a few cases, catastrophic failures during the burn-in.
The data show that the vast majority of references experienced a high percentage of capacitance drift when exposed to the 2Un bias, and the additional 12 V / µm high-field stress performed on the Un<25 V components further uncovered defects that remained hidden under the conventional test.

Lot	Manufacturer	Part reference	C value	Voltage (V)	Initial	2 × U_n burn-in	12 V / µm burn-in
1	KEMET	C0402C104K4RACAUTO	100 nF	16		4% IR OOS + 1 catastrophic failure	78% C OOS + 8% IR OOS + 5% C & IR OOS
2	TDK	CGA2B1X7R1C104K050	100 nF	16			
3	Taiyo Yuden	EMK105B7104KVHF	100 nF	16		98% C OOS	98% C OOS
4	Murata	GCM155R71C104KA55	100 nF	16		60% C OOS + 1% DF OOS	
5	KEMET	C0603X224K3RACAUTO	220 nF	25		45% C OOS	98% C OOS
6	Murata	GCM188R71E224KA55D	220 nF	25		64% C OOS	11% C OOS
7	TDK	CGA3E1X7R1E224K080AC	220 nF	25			
8	Taiyo Yuden	TMK107B7224KAHT	220 nF	25		1% C OOS	
9	Murata	GCM188R71E105KA64D	1 µF	25	Lower limit C	64% C OOS + 9% DF OOS	100% DF OOS
10	TDK	CGA3E1X7R1E105K080AC	1 µF	25		6% C OOS	4% C OOS
11	Taiyo Yuden	TMJ107CB7105KAHR	1 µF	25	3% C OOS	42% C OOS	69% C OOS
12	Taiyo Yuden	EMK316AB7106KLHT	10 µF	16	100% C OOS	100% C OOS	100% C OOS
13	TDK	CGA5L1X7R1C106K160AC	10 µF	16	29% C OOS	100% C OOS	78% C OOS
14	Murata	GCM31CR71C106KA64L	10 µF	16	Lower limit C	100% C OOS	100% C OOS
15	Kyocera AVX	12105C475K4Z2A	4.7 µF	50		100% C OOS	
16	Murata	GCM32ER71H475KA55L	4.7 µF	50		97% C OOS	
17	KEMET	C1210C475K5RACAUTO	4.7 µF	50	Lower limit C	97% C OOS	
18	TDK	CGA6P3X7R1H475M250AB	4.7 µF	50			
19	TDK	CGA6N3X7R2A225K230AB	2.2 µF	100		1 catastrophic failure	
20	KEMET	C1210X225K1RACAUTO	2.2 µF	100		100% C OOS	
21	Taiyo Yuden	HMK325B7225KMHT	2.2 µF	100		49% C OOS	
22	Kyocera AVX	12101C225K4Z2A	2.2 µF	100		100% C OOS	
23	TDK	CGA6P1X7R1C226M	22 µF	16			
24	Taiyo Yuden	EMK325B7226KMHT	22 µF	16		97% C OOS	100% C OOS
25	Murata	GCM32ER71C226KE19L	22 µF	16		26% C OOS + 1 catastrophic failure	99% C OOS

Table 2. Burn-in test results

Overall, every capacitor that was already out-of-spec in capacitance at the initial inspection continued to drift downward during the accelerated aging. For instance, lot 12 (Taiyo Yuden, 10 µF, 16 V) was 100 % out-of-spec at the start; after the 2Un burn-in its capacitance had dropped by about 12 % on average, and after the 12 V/µm high-field burn-in the drop increased to roughly 14 %.
Importantly, even the parts that passed the initial electrical check showed a measurable reduction in capacitance (typically 3-8 % after the 2Un test and up to 13 % after the high-field test). This progressive loss of capacitance

confirms that components passing the first electrical check can degrade further under prolonged thermal-electric stress, highlighting the necessity of a careful evaluation of the part before its use in applications where it could be detrimental.

Phase 3 - Life testing

After the burn-in campaign, 40 parts of each capacitor lot were subjected to an accelerated life-test at 125°C, for 2000h. Three stress regimes were used:

- Standard 2Un bias for all lots
- 12V for all lots rated at 16V
- 15V for all lots rated at 25V

Table 3 presents the results obtained after testing.

					2 Un life test			12V or 15V life test		
Lot	Manufacturer	Part reference	C value	Voltage (V)	Catastrophic failure during test	Rejected after final measurements	Passed	Catastrophic failure during test	Rejected after final measurements	Passed
1	KEMET	C0402C104K4RACAUTO	100 nF	16	19	19 IR OOS	5%		3 IR OOS + 1C OOS	80%
2	TDK	CGA2B1X7R1C104K050	100 nF	16			100%			100%
3	Taiyo Yuden	EMK105B7104KVHF	100 nF	16		1 IR OOS	98%		31 C OOS	20%
4	Murata	GCM155R71C104KA55	100 nF	16		14 C OOS	65%		14 C OOS	65%
5	KEMET	C0603X224K3RACAUTO	220 nF	25			100%			100%
6	Murata	GCM188R71E224KA55D	220 nF	25		3 C OOS	93%			95%
7	TDK	CGA3E1X7R1E224K080AC	220 nF	25		1 C OOS + 1 DF OOS	95%		2 C OOS	90%
8	Taiyo Yuden	TMK107B7224KAHT	220 nF	25		19 C OOS	53%		33 C OOS	18%
9	Murata	GCM188R71E105KA64D	1 µF	25	1		98%		40 OOS DF	0%
10	TDK	CGA3E1X7R1E105K080AC	1 µF	25	4	20 C OOS	40%		5 C OOS	88%
11	Taiyo Yuden	TMJ107CB7105KAHR	1 µF	25	1	39 C OOS	0%		26 C OOS	35%
12	Taiyo Yuden	EMK316AB7106KLHT	10 µF	16		40 C OOS	0%		40 C OOS	0%
13	TDK	CGA5L1X7R1C106K160AC	10 µF	16		1 C OOS	98%		27 C OOS	33%
14	Murata	GCM31CR71C106KA64L	10 µF	16	1	39	0%		40 C OOS	0%
15	Kyocera AVX	12105C475K4Z2A	4.7 µF	50	3	35 C OOS + 1 C & DF OOS + 1 DF OOS	0%			
16	Murata	GCM32ER71H475KA55L	4.7 µF	50	1	3 IR OOS	90%			
17	KEMET	C1210C475K5RACAUTO	4.7 µF	50		40C OOS	0%			
18	TDK	CGA6P3X7R1H475M250AB	4.7 µF	50			100%			
19	TDK	CGA6N3X7R2A225K230AB	2.2 µF	100	1	22 C OOS	43%			
20	KEMET	C1210X225K1RACAUTO	2.2 µF	100		40 C OOS	0%			
21	Taiyo Yuden	HMK325B7225KMHT	2.2 µF	100		40 C OOS	0%			
22	Kyocera AVX	12101C225K4Z2A	2.2 µF	100		40 C OOS	0%			
23	TDK	CGA6P1X7R1C226M	22 µF	16			100%			100%
24	Taiyo Yuden	EMK325B7226KMHT	22 µF	16			100%		39 C OOS	3%
25	Murata	GCM32ER71C226KE19L	22 µF	16			100%		40 C OOS	0%

Table 3. Life test results

The 2Un life test provides a baseline assessment of each lot's endurance. Across the 25 lots, it reveals a wide spectrum of behavior: many parts merely drift in capacitance or show a modest increase in leakage, while a few experience catastrophic breakdowns that render the capacitor completely unusable. These severe failures are especially problematic because they not only eliminate the component's functionality but can also jeopardize the reliability of the surrounding circuitry.

When the 12 V/15 V condition is imposed, some lots see their pass percentage drop dramatically. For instance, lot 3 (Taiyo Yuden, 100 nF, 16V) falls from 98 % to 20 % pass rate, lot 9 (Murata, 1µF, 25V) falls from 98% to 0%, lot 24 (Taiyo Yuden, 22 µF, 16V) from 100 % to just 3 % and lot 25 (Murata, 22µF, 16V) from 100% to 0%. This decline indicates that this different stress uncovers latent dielectric defects that the 2Un test does not provoke.

Conversely, some lots seem to improve under the 12 V/15 V stress, suggesting that the failures observed in the 2Un test are driven by the higher voltage and could potentially be avoided by applying an appropriate derating margin to the component.

The wide spread in yields, ranging from complete failure in some lots to flawless performance in others, further highlights the need to assess the suitability of a specific capacitor family for the intended voltage, temperature and reliability needs.

Phase 4 - Failure analysis

After the life-test several capacitors displaying abnormal electrical behaviors were identified. For the detailed failure analysis, we selected two representative parts: SN13 of lot 14, that showed electrical failure during the 2Un life-test (SN13, lot 14, Murata, 10µF, 16V) and SN81 of lot 1, which insulation resistance dropped drastically after burn-in, and continued to decrease after the 12V life-test (SN81, lot 1, Kemet, 100nF, 16V).

Both capacitors went through external visual inspection (EVI), X-ray radiography, lock-in thermography, cross-sectioning, internal optical inspection, and SEM examination.

- Failure analysis of SN13, lot 14, Murata, 10µF, 16V:

This capacitor presented a short circuit after life testing.
The analysis started with EVI and X-Ray radiography (see Fig.5) but revealed no anomaly.

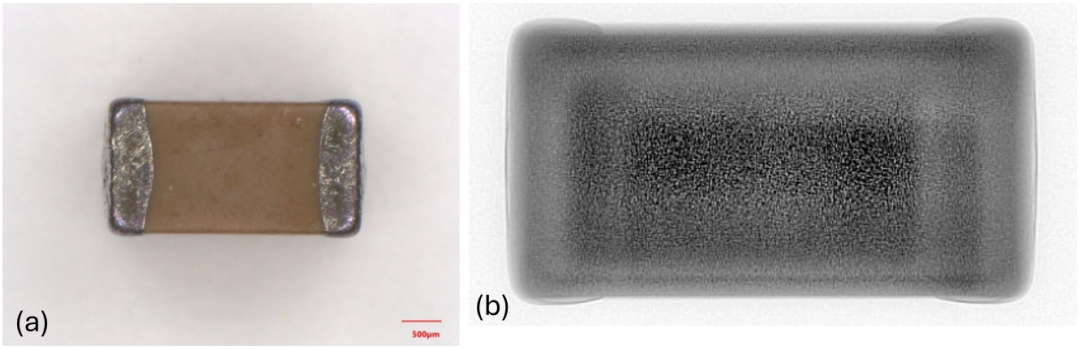


Fig 5. (a) EVI of SN13; (b) X-ray radiography of SN13

Lock-in thermography detected an overheating aera, on the right side of the capacitor (see Fig. 6).

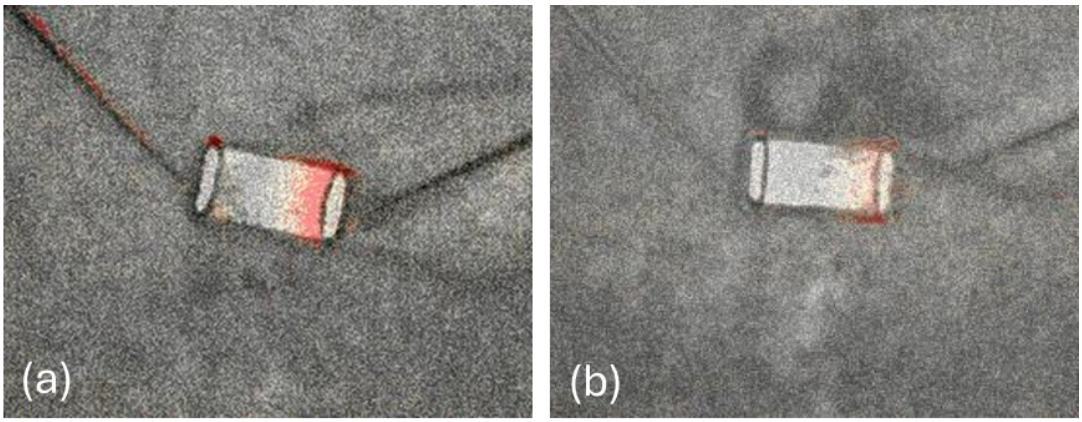


Fig 6. Lock-In thermography (a) Top view; (b) Side view (90°)

The capacitor was then cross-sectioned, first parallel to the conductor layers by mistake, then in the plane indicated on Fig 7. (a). The optical inspections (Fig 7. (b)-(c)) revealed long crack that starts from the right side of the capacitor, coinciding with the Lock-In observations. This crack extends through several layers of the capacitor electrodes.

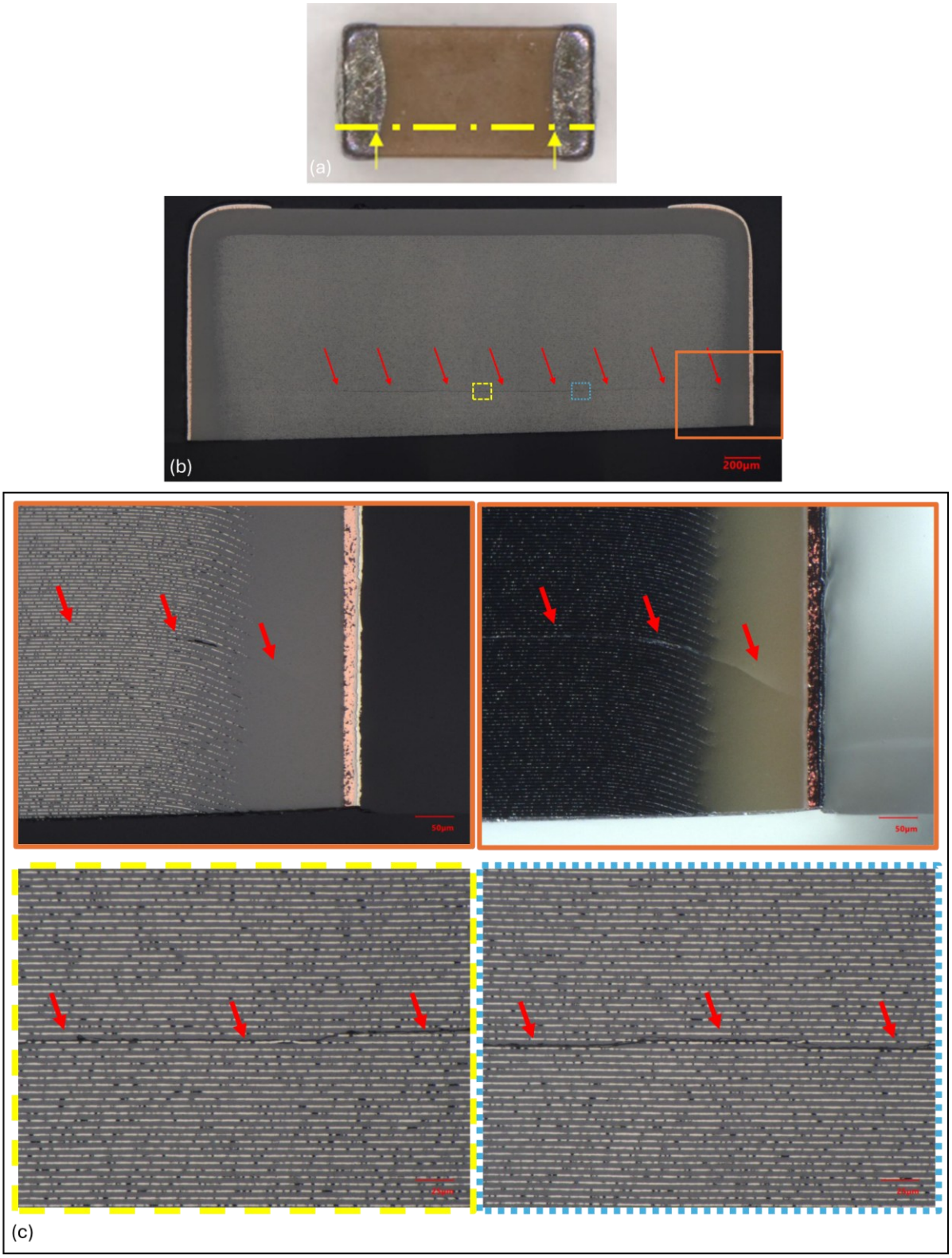


Fig 7. Internal optical inspections after cross-sectioning.
(a) Cross section plane; (b) Global view of the capacitor; (c) Zoomed views

The SEM views of the crack (Fig. 8) confirm the extent of the damage, explaining the loss of functionality observed during the life-test.

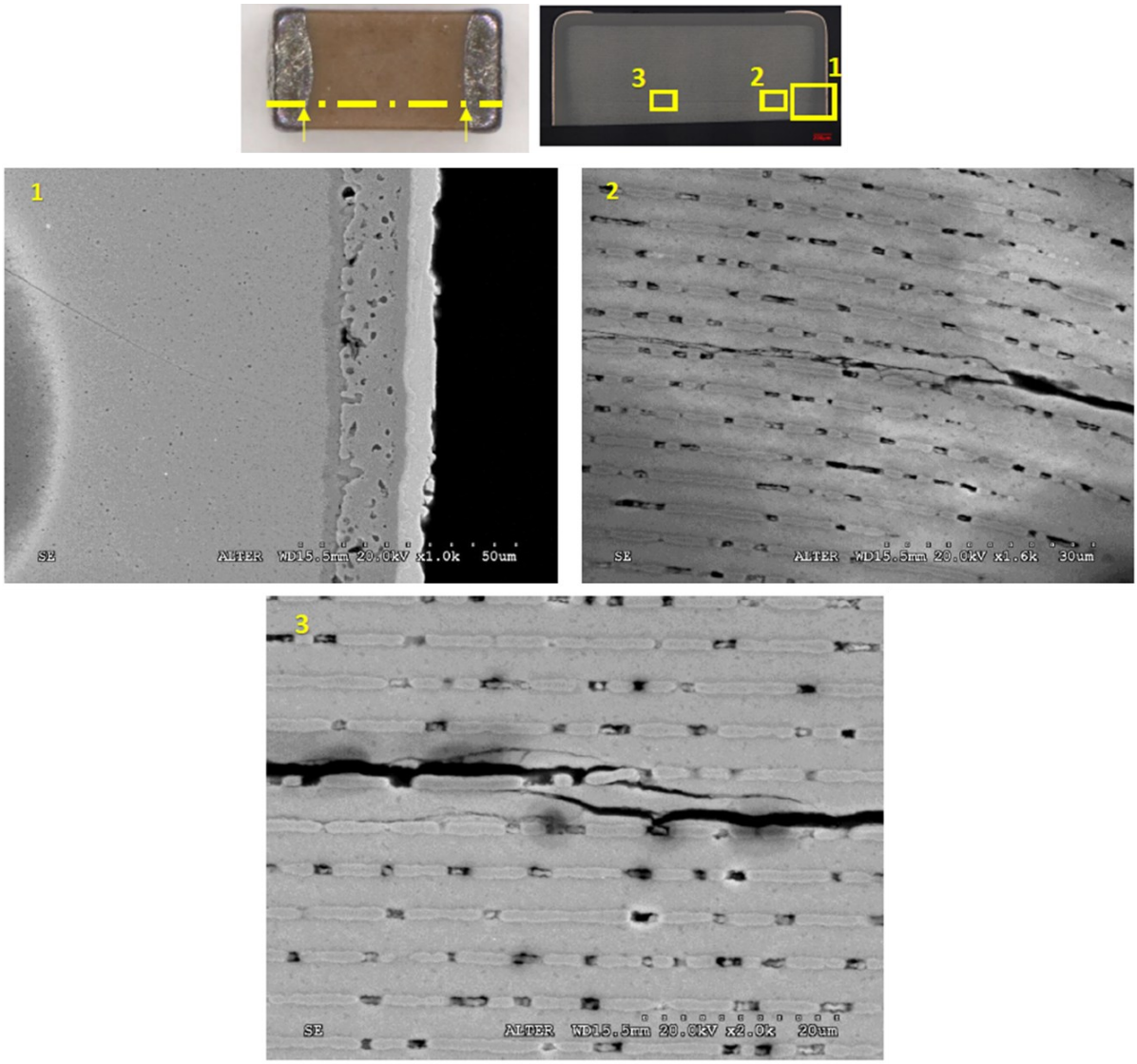


Fig 8. SEM observations

- Failure analysis of SN81, lot 1, Kemet, 100nF, 16V:

This part was chosen because of the high increase in leakage current it demonstrated after burn-in (2Un, 125°C, 96h). Its insulation resistance was measured at 9,28e+09 Ω, well above the minimum of 5,00E+09 Ω specified in the datasheet, and measured at 5,31E+06 Ω after the burn-in, and then again at 1,08E+6 Ω after the life-test at 12V, 2000h, +125°C.

The analysis also started with EVI and X-Ray radiography (see Fig.9) but again revealed no anomaly.

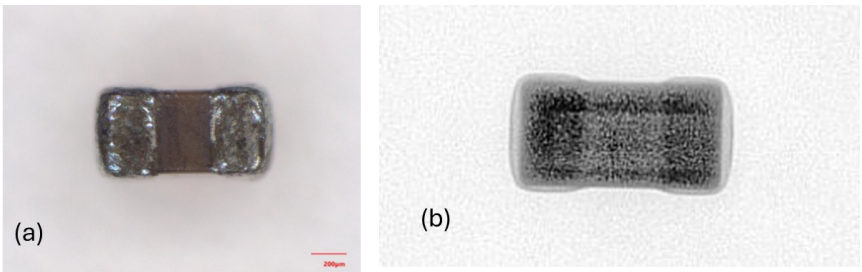


Fig 9. (a) EVI of SN81; (b) X ray radiography of SN81

Lock-in thermography also detected an overheating aera, this time on the left side of the capacitor (see Fig. 10).

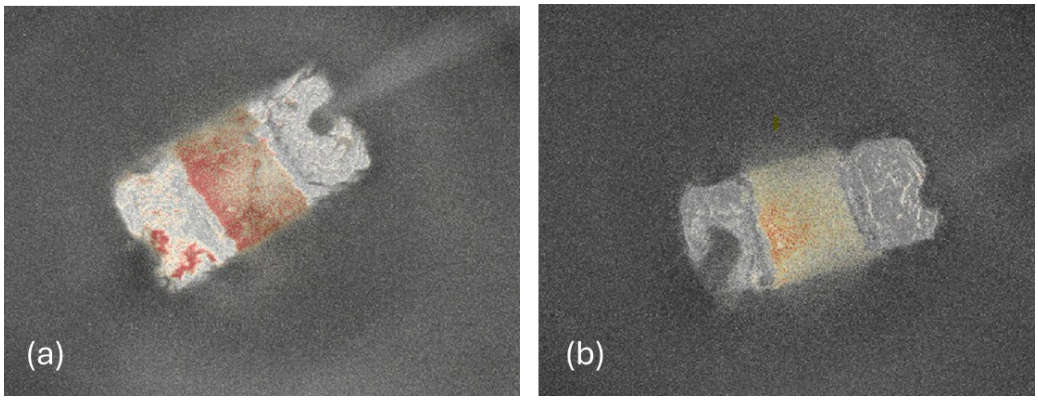
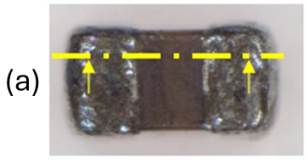


Fig. 10. Lock-In thermography (a) Top view; (b) Side view (90°)

The capacitor was then cross-sectioned, in the plane indicated on Fig 11. (a). The optical inspections (Fig 11. (b)-(c) and Fig. 12) revealed a small crack on the left side of the capacitor. Some small cracks/chip-ins are observed on top and bottom of the capacitor, outside of the electrodes.



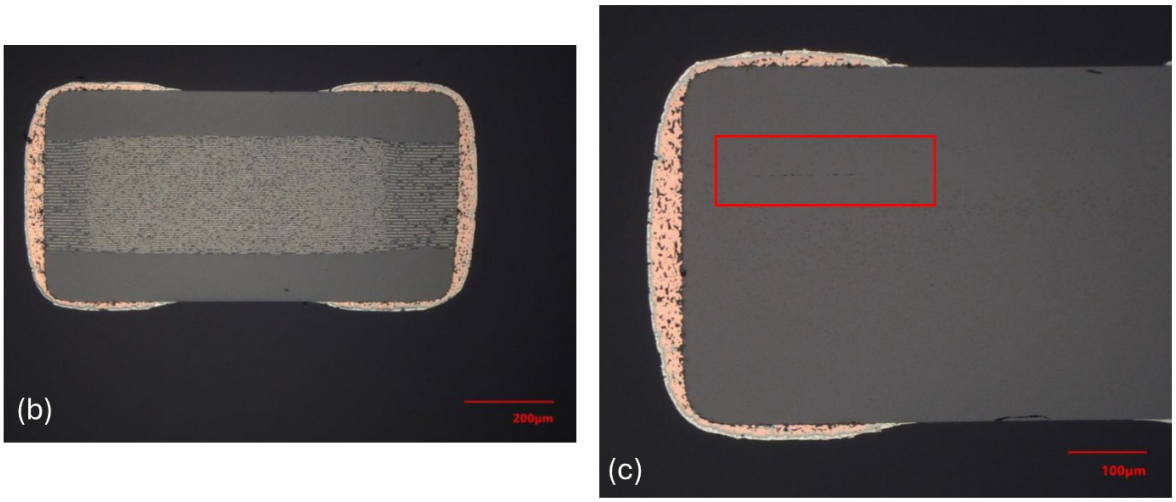


Fig 11. Internal optical inspections after cross-sectioning.
(a) Cross section plane; (b) Global view of the capacitor; (c) Zoomed view

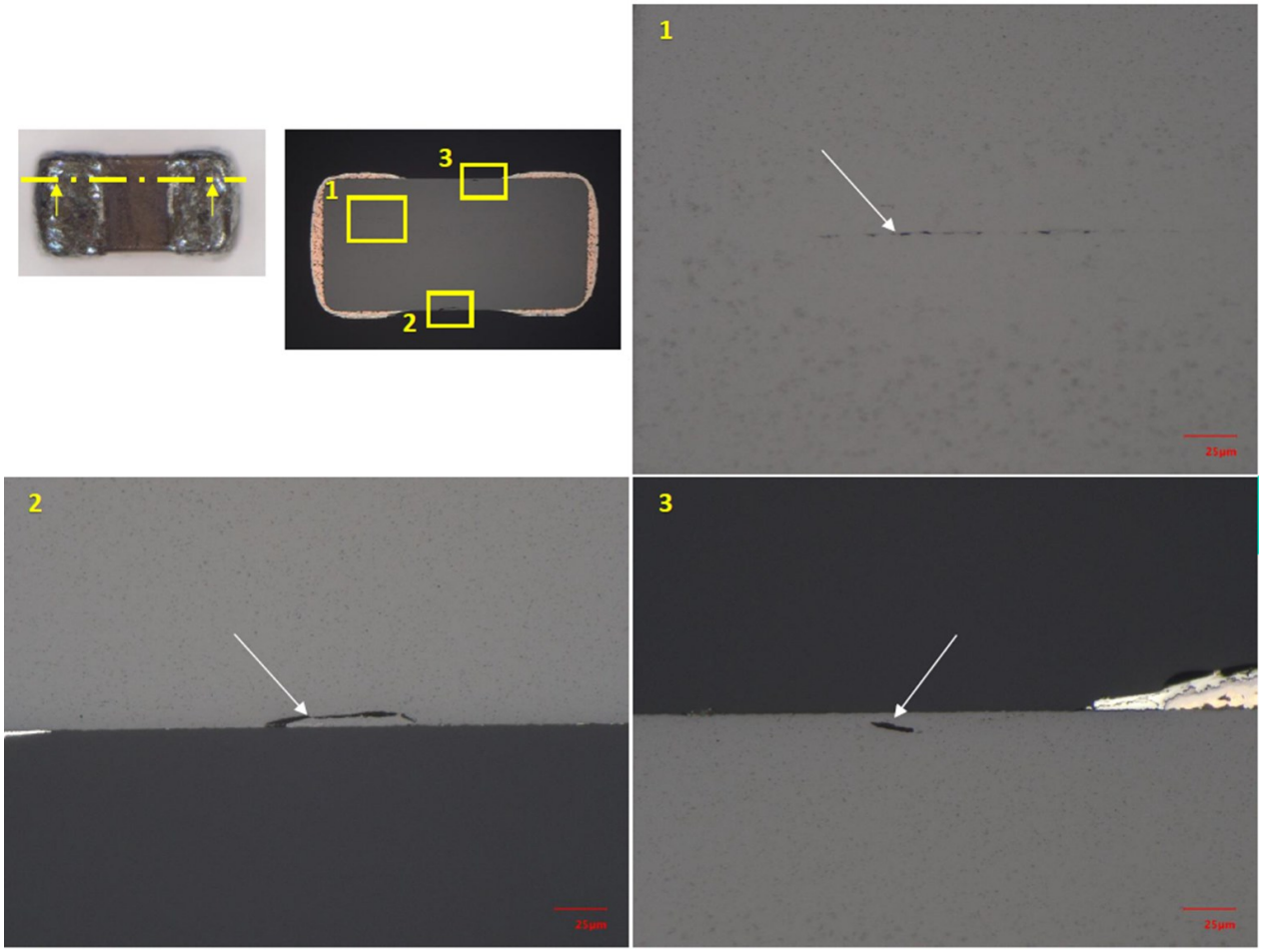


Fig 12. Internal optical inspections after cross-sectioning, zoomed view

This crack does not seem to impact several electrode layers on this cross-section plane. It is although highly suspected that this kind of crack is the cause of the leakage current increase on this capacitor.

CONCLUSION

The increasing reliance on commercial-off-the-shelf (COTS) parts for space hardware has driven interest in leveraging automotive-grade multilayer ceramic capacitors (MLCCs) as low-cost, readily available solutions. This study therefore set out to determine whether MLCCs qualified under the AEC-Q-200 standard can meet the reliability requirements of space missions.
An evaluation program was applied to 25 different MLCC references covering a broad range of capacitances, voltage ratings and manufacturers. The program comprised four successive phases:

Construction analysis and electrical characterization: visual inspection, X-ray, and initial electrical tests revealed recurring defects such as barrier-layer discontinuities, porosities, voids and delamination, as well as a number of parts that were already out-of-specification in capacitance.

Screening (burn-in) tests: all parts underwent a 96-hour, +125 °C burn-in under two stress regimes (standard) 2Un bias and high-field 12 V/µm bias for Un<25V devices). Most of the lots exhibited significant capacitance drift and, in some cases, catastrophic failures. Even parts that passed the initial electrical check lost 3-13 % of their capacitance after the high-field burn-in.

Accelerated life testing: 40 samples per lot were aged for 2000 h at 125 °C under three voltage conditions (2Un for all lots, 12 V for 16 V parts, 15 V for 25 V parts).

The 2Un test showed most components only drifting in capacitance or modestly increasing leakage, but a few suffered catastrophic breakdowns.
Concerning the 12V and 15V test, yields varied widely: some lots maintained > 90 % pass rates, while others dropped to 0 %. This demonstrated that the standard 2Un test does not always expose latent dielectric defects that become fatal under realistic mission voltages.

Failure analysis: detailed inspections of representative failed parts (a Murata 10 µF/16 V capacitor and a KEMET 100 nF/16 V capacitor) identified cracks propagating through electrode layers as the primary failure mechanism responsible for short circuits and increased leakage currents.

The study demonstrates that automotive-grade ceramic capacitors can indeed be used in space missions, but only when their intrinsic limitations are fully understood and matched to the mission's requirements. Nominal specifications alone are insufficient, a comprehensive evaluation flow is required to expose hidden defects that could jeopardize mission-critical performance.
Understanding these limitations (a parts susceptibility to crack under thermal-electric stress, its behavior under long-duration bias for example) allows system designers to make an informed choice and select the appropriate screening level, LAT testing flow and derating to ensure that the components used are fit for the intended operating environment while balancing cost and schedule constraints.

AKNOLEDGMENTS

Thank you to the teams at ELEMCA who procured the parts and performed the construction analysis and initial electrical characterization, and to the teams at ALTER Technology France for their help with the rest of the testing and valuable discussions.

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