5.2. Automotive Polymer Tantalum Capacitors with Capabilities Beyond AEC-Q200

Guidelines for Usage in the LEO Satellite Industry

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Abstract

From ground stations to satellite payloads, every segment of the Low Earth Orbit (LEO) satellite industry seeks reliable component technologies combined with mature manufacturing processes and controlled costs. These satellite constellations will expand with thousands of new and enhanced small satellites to deliver next-generation global broadband coverage, offering improved data transfer, and faster, more reliable satellite communication services.

These applications have challenged the capacitor industry during the last few years. New materials and manufacturing processes have enabled polymer tantalum capacitors to fulfill capabilities beyond AEC-Q200 stress test requirements demonstrating higher performance levels during screening and LAT testing protocols. On this presentation we focus on guidelines for usage on the LEO satellite industry.

Market and Applications Considerations

Demand is increasing for cost competitive, high-speed broadband with improved data transmission capabilities, digitalization to sectors like retail, banking, and energy, as well as governmental needs on developed and developing nations. Also, individual consumers in 'rural' area show interest in low-cost broadband services. This growing market demand stimulates investments in Low Earth Orbit (LEO) satellite constellations. The global small satellite market is projected to reach $11.2B by 2029, growing at CAGR of 16.6% from 2024 to 2029[1]

Size and weight are two key factors while designing small satellites. These requirements lead the designer to high volumetric efficient capacitors, such as tantalum polymer surface mount devices. Since the extreme usage application conditions in space require highly reliable bulk capacitance, tantalum polymer capacitors are increasingly considered due to performance benefits: (a) lower equivalent series resistance with improved power delivery and reduced heat generation; (b) small size and weight; (c) self-healing capability under low energy transients and (d) enhanced frequency response than old legacy tantalum MnO_2 technology.

The tantalum polymer SMD capacitors are excellent solutions for power management conversion, from POLs to DC/DC conversion, Figure 1.

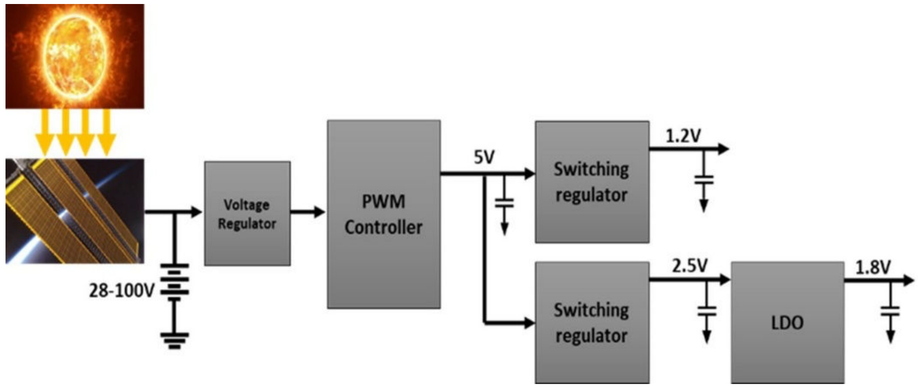


Figure1. Schematic Example: Space POL with typical application use of tantalum polymer SMD capacitors

Tantalum polymer capacitor series T540/T541 High Reliability Polymers Series (DLA 04051/04052)[2] has been adopted successfully during the last decade. KEMET released last March 2024 the first QPL Tantalum Polymer MIL-PRF-32700, T581 Series[3].

Are Automotive Polymer Tantalum Capacitors an Option?

Space qualified components must comply with space agencies or industrial standards, such as ESA ESCC-Q-ST-70-12 and NASA GSFC Guidelines. We can summarize the **KEY RELIABILITY** concern topics and guidelines:

- **A – Screening and Qualification Tests**
- **B – Radiation Sensitivity**
- **C – Outgassing**
- **D – Best Practices – Derating**

These four blocks are covered in the following sections.

Several studies and papers were issued assessing COTS or Automotive-grade components in space. An extensive investigation followed with an update of ESCC-Q-ST-60-13C was issued last May 2022. This standard defines the requirements for selection, control, procurement, and usage of EEE for space projects. It establishes 3 classes of components, which level a trade-off between assurance and risk, Table 1.

Class of Component	Class 1	Class 2	Class 3
Assurance Level	+++	++	+
Risk Level	+	++	+++
Cost Level	**$$$**	**$$**	**$**

Table 1. ESCC-Q-ST-60-13C – Assurance / Risk and Costs

The requirements for evaluation, screening and lot acceptance test are summarized on the Figure 2.

Solid electrolyte tantalum capacitors chips									
Automotive grade	Class 1	Class 2	Class 3	Category	Test type	Sample size	Test Procedure	Specific Test condition	Note
AEC-Q grd 0/1	X	X	X	Evaluation	Construction Analysis	5	ESCC21001		
AEC-Q grd 0/1	X			Evaluation	Life Test 2000h	60	ESCC 3012 chart IV endurance subgroup	36 parts, 85°C @Ur, 2000h 24 parts, 125°C @Uc , 2000h	Note (a)
AEC-Q grd 0/1	x	X	X	Screening	Surge current	100%	Surge current test	MIL-PRF-55365 cond. B or ESCC 3012 ie 9.3.1 + 9.20	
AEC-Q grd 0/1	X			Screening	Complete screening	100%	ESCC 3012 chart III		Note (b)
AEC-Q grd 0/1	X	X	X	LAT	DPA	3	ESCC21001		Note (e)
AEC-Q grd 0/1	X	X		LAT	Life Test 1000h	16	ESCC 3012 chart V - Endurance subgroup	16 parts, 85°C @Ur, 1000h	Note (c)

Figure 2. ESCC-Q-ST-60-13C. Table 8-2 Procurement test table for solid electrolyte tantalum capacitors – Automotive Grade Products

Automotive Polymer Tantalum Capacitors – Capabilities Beyond AEC-Q200

A. Screening and Qualification Tests

In November 2024, T59x Automotive Grade Series celebrated 10 years on the market[4]. The design and manufacturing capability of automotive-grade qualified product combined with the maximum operational temperature up to 150ºC required research and development activities and usage of new material processes[5, 6].

The automotive portfolio includes an extended range of case sizes, from EIA3216-12 to EIA7343-43, maximum rated capacitance up to 680 µF, max rated voltage up to 75V and ESR lower as 6 mΩ. The operational temperature range is available from -55ºC up to 150ºC. The continuous adoption growth has been powered by autonomous driving and ADAS.

To expand the adoption on avionics and defense and provide evidence of capabilities beyond AEC-Q200 for small LEO satellites, the tantalum polymer automotive-grade offers now up-screened options with Sn-Pb termination (5% Pb). The Sn-Pb termination is the primary option in space applications to mitigate tin whiskers per JESD-201. Part Number is shown on Figure 3.

Up-Screen with H Termination and Surge Option

T	598	D	107	M	010	A	H	E	040	
Capacitor Class	Series	Case Size	Capacitance Code (pF)	Capacitance Tolerance	Rated Voltage (VDC)	Failure Rate/ Design	Termination Finish	Surge	ESR	Packaging (C-Spec)
T = Tantalum	598 = AEC-Q200 qualified (125°C)	B D V X	First two digits represent significant figures. Third digit specifies number of zeros.	M = ±20%	2R5 = 2.5 004 = 4 006 = 6.3 010 = 10 016 = 16 025 = 25 035 = 35 050 = 50	A = N/A	H = Standard solder coated (SnPb 5% Pb minimum)	E = None S = 10 cycles 25°C W=10 cycles -55 and +85°C	Maximum ESR in mΩ, 040 = 40 mΩ	Blank = 7" Reel 7280 = 13" Reel

Figure 3. T598 Up-screen – Part Number Explanation

During the manufacturing process all capacitors are subjected to the 100% standard surge testing at room temperature with 4-cycles charge/discharge at rated voltage.

With the up-screened option, the capacitors are tested 100% to MIL-PRF-55365 or MIL-PRF-32700 condition:

- S – Extended to 10 cycles, room temperature, rated voltage.
- W- Extended to 10 cycles, at -55ºC and at 85ºC, rated voltage (MIL-PRF-55365 condition B).

T59x products are qualified to the AEC-Q200 testing protocol. Due to the presence of lead, the H termination is not RoHS-compliant. Our manufacturing plants are TS16949 certified, and the capacitors are subject to PPAP/PSW and change control. The automotive designs are conservative and support the new market requirements of continuous operation up to 15 years.

Figure 4 outlines the evaluation and screening that was performed on the capacitors, and detailed performance results are shown in the following sections.

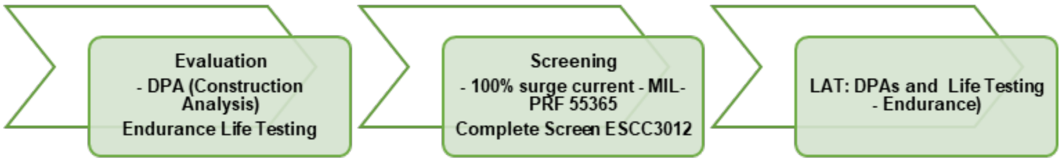


Figure 4. Flow of requirements for T59x Automotive Grade capacitors: Evaluation → Screening and Lot Acceptance Testing (LAT)

Evaluation Phase

Construction Analysis – DPA

Construction Analysis Report includes the Destructive Physical Analysis (DPA) results of 10 solid tantalum capacitors from the T598 Automotive Grade.

DPA is a systematic, logical, detailed examination of parts during various stages of physical disassembly, conducted on a sample of completed parts from a given lot, wherein parts are examined for a wide variety of design, workmanship, and processing problems that may not show up during normal screening tests.

DPA was performed in accordance with MIL-PRF-55365 and MIL-STD-1580.

External Visual examination is performed on the parts per the applicable base specification requirements. Parts are examined at 30X to 100X magnification for the following:

a. Marking and configuration compliance must be met. See Figure 5.
b. The body encapsulate shall be free of cracks, holes and voids that expose internal elements or chip-outs that reduce the case wall thickness by 50% for molded case styles
c. The terminations shall be coated with the specific coating material (gold plate or solder). Minor areas of exposed base metal are acceptable provided they do not collectively exceed 5% of the surface area termination.
d. Surface checking (fracturing of plating layers) of the external terminations in sharp bend areas is acceptable at the exit point where the leads exit the molding material. There shall be no evidence of exposed base metal on any plated surface within the cracked area.

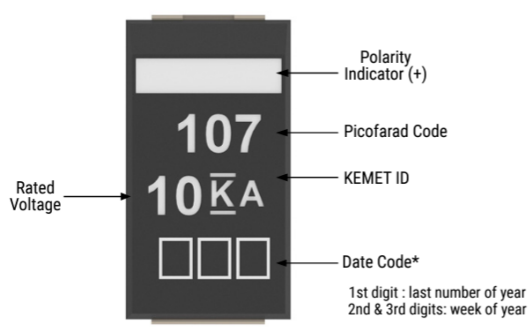


Figure 5: Typical Capacitor Marking

For the **Internal Visual** Examination all parts are potted in epoxy and sectioned axially in a plane along the end caps to the desired midpoint to expose the anode riser weld and slug attachment interfaces. Parts are examined using 30X minimum magnification for the following:

a. For molded styles, evidence of silver going beyond 50% of the distance between the shoulder of the anode and the base of the riser wire is not acceptable. Isolated silver particles not in contact with the riser wire are allowed.
b. For epoxy molded devices, there shall be a silver epoxy attachment joining the cathode terminal to the silver coated terminal slug. There shall be a minimum of 25 percent (end of anode slug only).
c. For all styles, significant silver epoxy segregation or separation/cracking of the silver particles away from the cathode end cap/end clip terminal attach interface with the silver coated tantalum slug shall be unacceptable. There should be no delamination or cracking greater than 25% of the length of the tantalum anode interfacial layers (polymer/carbon/silver). A delamination shall be categorized separately from longitudinal voids.
d. For all styles, no gap in body coating material shall exist that expose the silver epoxy coated tantalum slug.
e. For epoxy molded cased devices, there shall be evidence of a smooth and continuous metallurgical bond/weld between the anode riser and the external anode lead for no less than 25 percent of the available overlap.
f. For epoxy molded cased devices, the riser wire-to-external lead weld shall not create a misalignment greater than 15 degrees between riser and lead. Additionally, this weld shall exhibit molding compound between the end of the riser wire and the outer package edge.
g. There shall be no cracks on the molded case of all molded capacitors that expose any surface of the capacitor element.
See Figure 6.

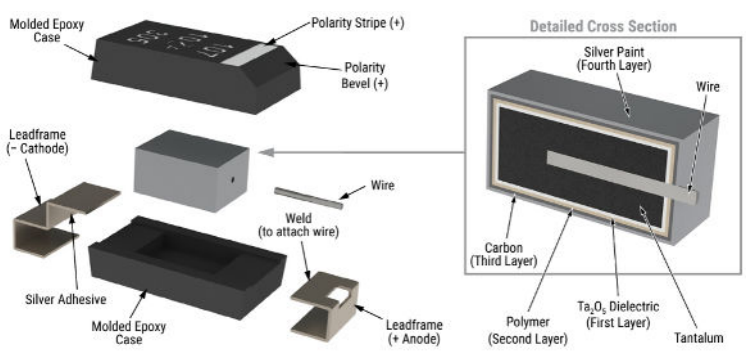


Figure 6: Typical T598 Construction

Part #	Part Type	Batch/Lot Number	Markings
Large Case Size 7343-43	T598X477M006ATE025	2431S70SX	Capacitance Code: 477 Voltage: 6.3 V Print Week Code: 431
Small Case Size 3528-20	T598B107M2R5ATE055	243S720F	Capacitance Code: 107 Voltage: 2.5 V Print Week Code: 430

DPA Results - T598X477M006ATE025 External and Internal Visual Examination

The marking and configuration of the parts was examined and found to be acceptable. The laser marking on the parts indicates the polarity, capacitance, voltage, print week code and the KEMET logo. See Figure 7.

Figure 7: Print Face Front Side of Parts

The body of the parts was examined for defects. Termination was examined for coating coverage. The surface was examined for exposed base metal. All external visuals were found to be acceptable. See Figures 8 through 10.

Figure 8: Glue Pad Side (Back View)

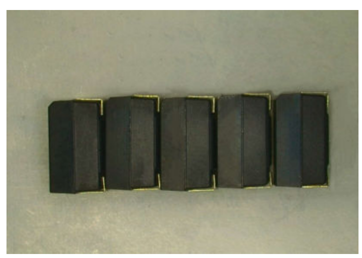


Figure 9: Right Side of Print

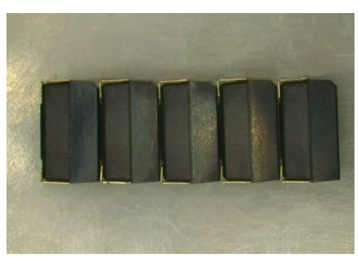


Figure 10: Left Side of Print

Parts were cross sectioned and examined at 18X and 30X. See Figures 11-16.

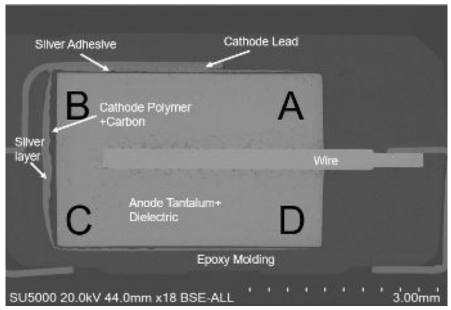


Figure 11: SEM Cross Section 18X

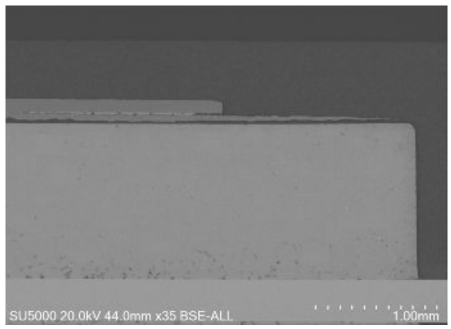


Figure 12: SEM Cross Section 35X (Section A from Figure 11)

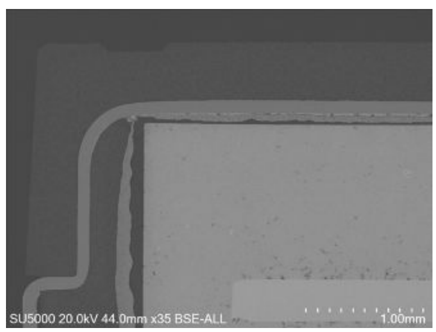


Figure 13: SEM Cross Section 35X (Section B from Figure 11)

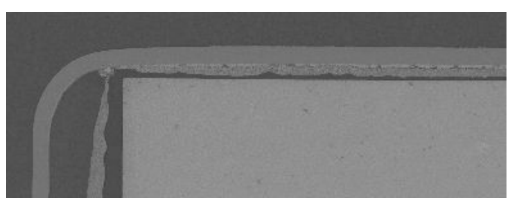


Figure 14: Close up of SEM Cross Section 35X from Figure 11 Detailing Connection and Layers

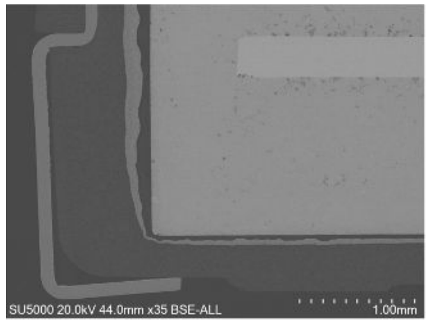


Figure 15: SEM Cross Section 35X (Section C from Figure 11)

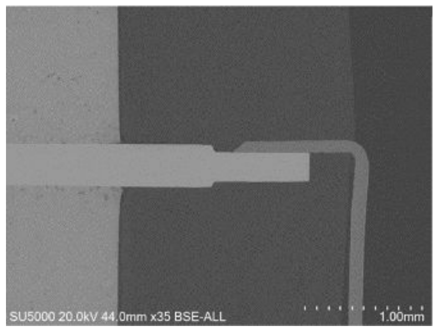


Figure 16: SEM Cross Section 35X (Section D from Figure 11)

Internal visual examination was acceptable per the specifications.

DPA Results - T598B107M2R5ATE055 External and Internal Visual Examination

The marking and configuration of the parts was examined and found to be acceptable. The laser marking on the parts indicates the polarity, capacitance, voltage, print week code and the KEMET logo. See Figure 17.

Figure 17: Print Face Front Side

The body of the parts was examined for defects. Termination was examined for coating coverage. The surface was examined for exposed base metal. All external visuals were found to be acceptable. See Figures 18 through 20.

Figure 18: Glue Pad Side (Back Side)

Figure 19: Right Side of Print

Figure 20: Left Side of Print

Parts were cross sectioned and examined at 30X and 80X. See Figures 21-25.

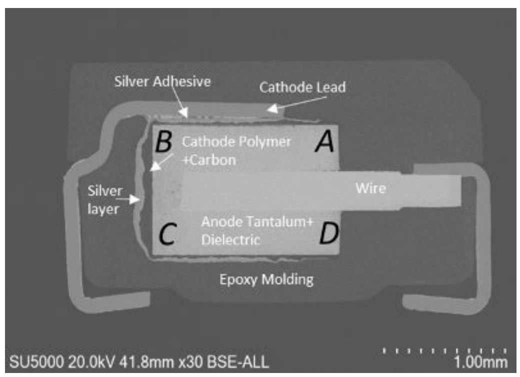


Figure 21: SEM Cross Section 30X

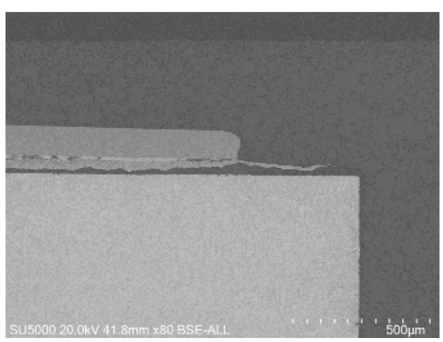


Figure 22: SEM Cross Section 80X (Section A from Figure 21)

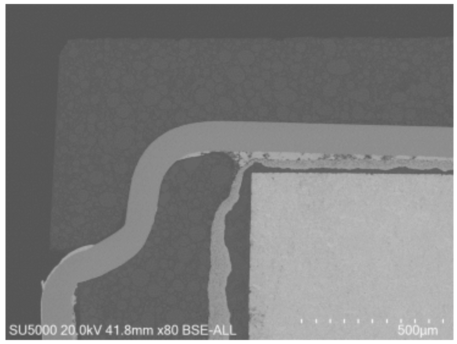


Figure 23: SEM Cross Section 80X (Section B from Figure 21)

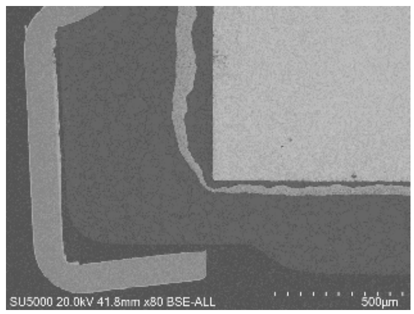


Figure 24: SEM Cross Section 80X (Section C from Figure 21)

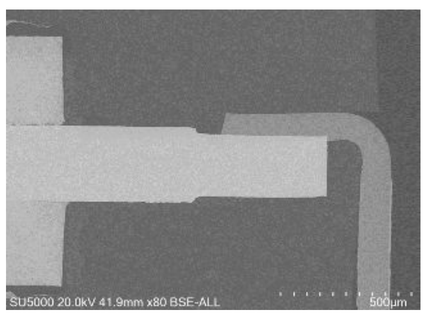


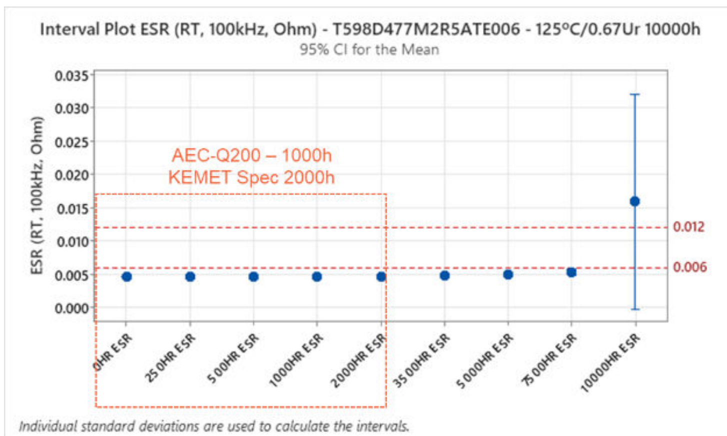
Figure 25: SEM Cross Section 80X (Section D from Figure 21)

External and internal visual examination was performed on 10 parts of solid tantalum surface mount capacitors from the T598 Series. Externally, all parts met the general requirements. Internal construction was verified as acceptable per requirements.

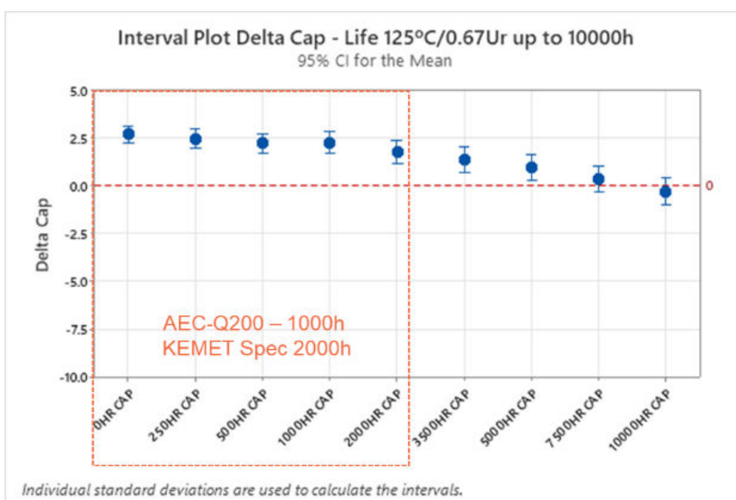
Endurance Life Testing – Extended capability

One of the most important benefits of tantalum polymer capacitors in comparison of the 'old legacy' MnO_2 counter electrode is the significant reduction of the ESR (Equivalent Series Resistance). This reduction improved the efficiency of the capacitors for filtering in power lines and decreases self-heating resulting in lower operating temperatures and probability of failures(7). Extensive characterization investigations during last decade reveal one of major limitation of tantalum polymer capacitors compared with MnO_2 is the limited long-term stability. Significant enhancements have been introduced to optimize package integrity and new materials(8)

Examples of endurance life results with extended capabilities are presented for the single-digit ESR capacitor, 470µF 2.5V with 6 mΩ specifications. The AEC-Q200 specifies a 1000-hour requirement at 125ºC, while the T598 Series KEMET specification meets the testing for 2000 hours. The data demonstrate a high safety margin when the capacitors are tested up to 10,000 hours, Figure 26.



(a) *ESR Aging at 125ºC/0.67Ur up to 10,000 hours*



(b) *Capacitance Loss at 125ºC/0.67Ur up to 10,000 hours*

Figure 26. T598D477M2R5ATE006 Endurance Life results up to 10,000 hours

In addition, leakage current shown robust performance, revealing a stable Ta_2O_5 dielectric up to 10000 hours with the entire population with the initial specification of 117 µA (2.5V, 5min room temperature), Figure 27.

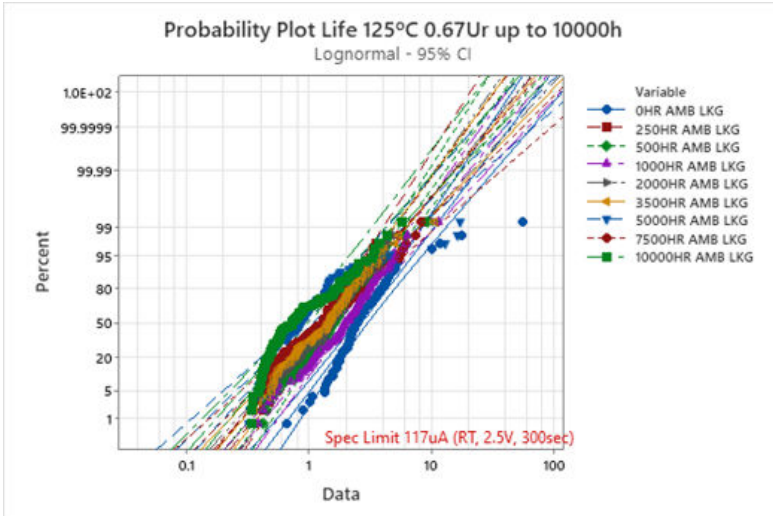
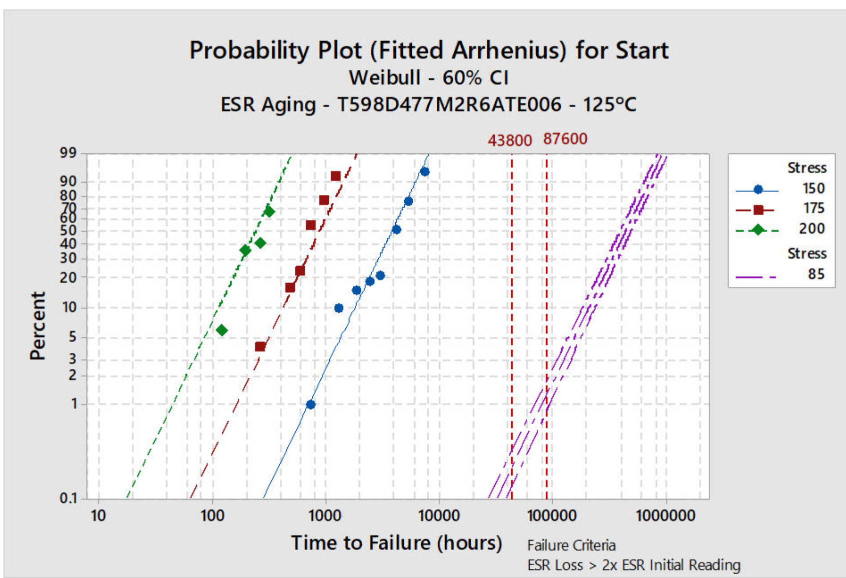
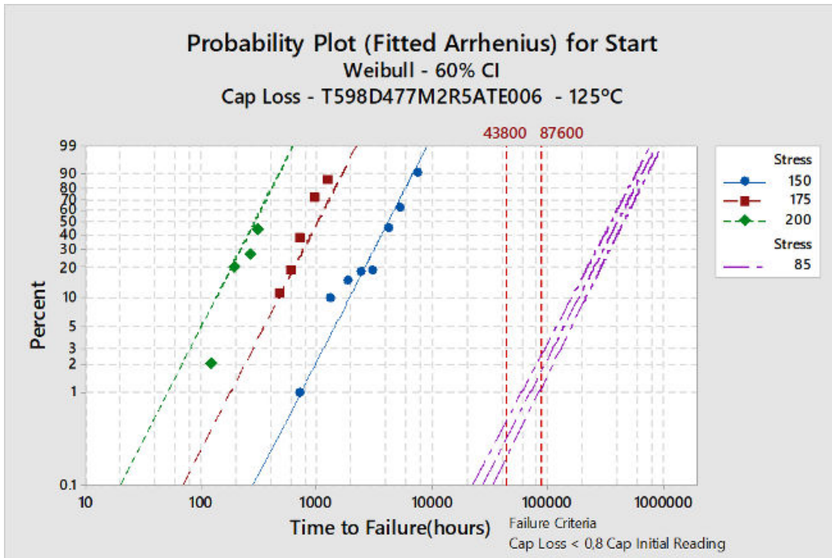


Figure 27. T598D477M2R5ATE006 Endurance Life up to 10,000 hours – DC Leakage Performance

Extensive storage test and ESR Aging / Cap Loss modelling tests based on accelerated storage have been executed. The projections determine these capacitors to be used with success in extended automotive mission profiles. The accelerated storage results are shown in Figure 28.



(a) *ESR Aging – Accelerated Storage Testing – T598D477M2R5ATE006*



(b) *Capacitance Loss – Accelerated Storage Testing – T598D477M2R5ATE006*

Figure 28. T598D477M2R5ATE006 Accelerated Storage Testing – ESR Aging and Cap Loss Modelling

B. Radiation Sensitivity

In comparison with semiconductor devices, old legacy MnO_2-based tantalum capacitors are considered unaffected by radiation. Since the same Ta_2O_5 dielectric are employed in tantalum polymer capacitors, these components were also expected to be unaffected by radiation effects. Extensive evaluation was presented during RADECS 2016 [(9)].

According to the test conditions 9 capacitors were irradiated (5 biased and 4 unbiased). The radiation source was the field of a Cobalt 60 gamma, in compliance with ESCC 22900, The maximum test level of 212krad (Si), with intermediate steps; 25krad (Si), 50krad (Si) and 100krad (Si).

After radiation, the capacitors were subject to an extra annealing of 24 hours at room temperature followed by 168 hours at 100ºC. Electrical measurements were performed before, intermediate, at end of the radiation test and after annealing.

Capacitance results are shown on Figure 29. These results confirm the radiation hardness of tantalum polymer capacitors, revealing a stable capacitance during the radiation and extra heating, and thus showing that the Ta_2O_5 dielectric and polymer interface are stable under high radiation levels. All the results are inside the capacitance specification interval 297uF to 363uF (RT, 120Hz).

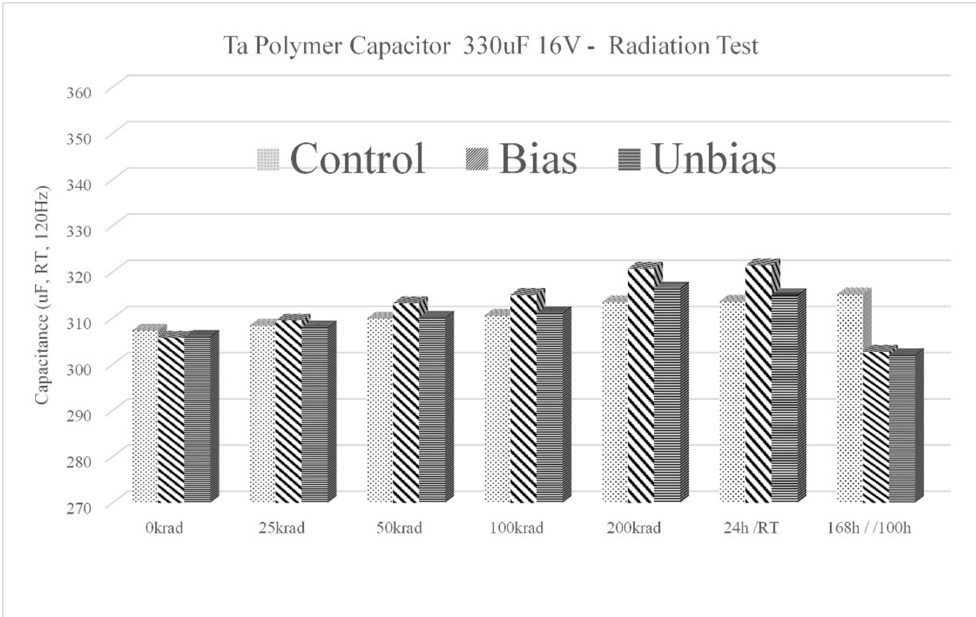


Figure 29. Tantalum Polymer Capacitor – Radiation Test Performance

C. Outgassing

High altitude, low pressure and vacuum operation conditions, such as on space, have no impact on the function of tantalum polymer capacitors.

The ASTM E595 Standard Test Method for Total Mass Loss and Collected Volatile Condensable Materials from outgassing in a vacuum environment is common request for space applications.

T598 Series representative part numbers have been tested: Total Mass Loss (TML), Collected Volatile Condensable Materials (CVCM) and Water Vapor Regain (WVR) with the results shown on Table 2.

PN	Test	Results (%)	Acceptance Criteria (%)
T598 6,3V	TML	0.09	1,00Max
	CVCM	0.08	0.10Max
	WVR	0.00	Information only
T598 35V	TML	0.12	1,00Max
	CVCM	0.08	0.10Max
	WVR	0.04	Information only

Table 2, T598 Series – ASTM E595 Results

D. Best Practices: Derating

Anomalous charging current (ACC) after step voltage application in discharged and dry parts is a peculiar phenomenon in tantalum polymer capacitors. This high transient current was first discovery by Dr. Yuri Freeman *et al*.[10, 11]

ACC is a higher amount of current flowing into a capacitor while charging than would be predicted by the formula I = C*dv/dt. Although ACC does not pose a reliability risk to a capacitor itself, it can pose risk to applications. To minimize this effect when using tantalum polymer capacitors in an extremely dry and cold environmental, such as space vacuum, 50% derating is recommended. This drastically reduce the likelihood of experiencing the ACC phenomenon.

Conclusion

Overall, we show strong performance characteristics of the tantalum polymer automotive grade capacitors. The up-screen surge capability option per MIL-PRF-55365, combine with the Sn-Pb termination (H option), opens new opportunities for the double-digit growth market of small satellites in Low Earth Orbit constellations.

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