Reliability Assessments of Automotive-Grade Tantalum Capacitors for Space Applications

Alexander Teverovsky, Jay Brusse

Columbus Technologies & Services, Inc.
NASA/GSFC, code 526, Greenbelt, MD 20771
alexander.a.teverovsky@nasa.gov, jay.a.brusse@nasa.gov

ABSTRACT

Automotive-grade electronic components are increasingly attractive for space applications due to their lower cost and higher availability compared to military-grade alternatives. While the quality of these mass-produced components is maintained through tight manufacturing controls and Automotive Electronics Council qualification (AEC-Q) testing, some space applications demand long-term mission reliability and useful-life assessments not covered by AEC-Q specifications.

This study evaluates the reliability characteristics of various 10 V tantalum capacitors, manufactured to AEC-Q200 standards by four vendors. The evaluation compared four types of MnO_2 tantalum capacitors (MTCs) and seven types of conductive polymer tantalum capacitors (PTCs). Reliability was characterized by highly accelerated life testing (HALT) at 85°C across multiple stress voltages, allowing for the assessment of voltage acceleration factors and the prediction of time-to-failure (TTF) distributions under operating conditions. To determine the effect of a space environment, HALT for PTCs was conducted in both ambient air and a 1 µTorr vacuum. Leakage currents were continuously monitored throughout testing, and breakdown voltages were measured both before and after HALT.

Preliminary results indicate no significant difference in the reliability of PTCs between dry terrestrial and vacuum applications. HALT revealed that while a substantial proportion of MTCs suffered from infant mortality, wear-out (WO) mechanisms were the prevailing cause of failure for PTCs. However, the time to the inception of WO failures that represents useful life of the parts varied substantially among different part types. Overall, PTCs demonstrated higher reliability than MTCs. Finally, the applicability of the Time-Dependent Dielectric Breakdown (TDDB) model was successfully demonstrated by extrapolating characteristic TTF values to breakdown conditions.

INTRODUCTION

Traditionally, the failure rate (FR) of tantalum capacitors used in high-reliability applications is assessed at stress voltages exceeding their voltage ratings (V_R) and extrapolated to rated conditions using acceleration factors. For space projects, the FR at rated conditions (T-level parts per MIL-PRF-55365 and MIL-PRF-32700) should be below 0.01%/1000 hours, though some projects may relax these requirements by up to a factor of ten. In contrast, the FR for commercial parts is typically assessed at 1%/1000 hours.

Assuming a constant FR (representing the "useful life" or random failure period), the FR can be calculated based on the results of accelerated testing: number of failures (n) occurring during time t when testing N samples at stress voltage and temperature V_s, T_s:

$$FR = \frac{\chi^2(\alpha, 2n+2)}{2} \times \frac{1}{AF(V_s, T_s)} \times \frac{1}{N \times t}, \quad (1)$$

where χ^2 is the chi-square function, α is the confidence level, n is the number of failures occurring during time t, N is the number of samples at stress voltage (V_s)and temperature (T_s), $AF(V_s, T_s)$ is the acceleration factor that is dependent on test voltage and temperature.

Experimental FR assessments for tantalum capacitors are typically conducted at 85 °C. For manganese dioxide tantalum capacitors (MTCs), stress voltages can exceed V_R by up to 1.52 times per MIL-PRF-55365. For polymer tantalum capacitors (PTCs), stress voltages can reach up to 2 times V_R per MIL-PRF-32700. The voltage acceleration factor, AF_V, is presented as an exponential function in MIL-PRF-55365 for MTCs:

$$AF_V = exp[B \times (u-1)], \quad (2a)$$

and as a power law in MIL-PRF-32700 for PTCs:

$$AF_V = u^n, \quad (2b)$$

where u is the normalized stress voltage, $u = V_s/V_R$; B and n are voltage acceleration constants.

At typical stress voltages, both equations describe the experimental data with sufficient accuracy. However, the exponential model provides a more conservative prediction of reliability at the operating conditions compared to the power model [1]. Because the power function (Eq. 2b) yields much more optimistic reliability characteristics, the exponential function (Eq. 2a) is preferred for analyzing high-reliability systems.

The assumption of constant FR is a useful simplification when the level of FR is below the requirement. In reality, FR changes over the lifecycle of the capacitors, forming a "bathtub" curve: it decreases initially during the infant mortality (IM) phase and increases at the end of life during the wear-out (WO) phase.

MTCs typically fail during the IM period. Per MIL-PRF-55365, their FR is calculated using Weibull Grading Testing (WGT), which assumes the voltage acceleration constant is uniform across all capacitor types, specifically B = 18.77. However, calculations based on accelerated testing of MTCs reported in the literature [2-4] reveal a wide range of B values, varying from 6.5 to over 20. J. Paulsen [4] demonstrated that acceleration factors can differ significantly from batch to batch, even among similar capacitor types, meaning that using a fixed B value can introduce substantial errors. Additional error sources associated with the WGT method are analyzed in [5].

The rate of degradation of leakage currents in tantalum capacitors can be also described by Eq.(2a) [6]. Analysis shows that B values calculated from the rate of current degradation vary within a similar range, $6 < B < 21$. Temperature acceleration for leakage current degradation and MTC failures is typically described using Arrhenius equation and is characterized by activation energy, E_a, that might change for MTCs also in a wide range, from 0.6 eV to 2.1 eV.

For PTCs, the probability of IM failures is not large enough for using WGT. Instead, AF_V is determined by analyzing the distributions of time-to-failure (TTF) during wear-out in highly accelerated life testing (HALT). Under MIL-PRF-32700, the voltage acceleration constant n is calculated using Eq.(2b) and the ratio of median TTFs at different stress voltages. It is assumed that capacitors made from the same tantalum powder type and using the same conductive polymer polymerization process have identical values of n.

Voltage acceleration constants for PTCs reported in literature also vary substantially. According to E. Reed, et al. [7], the constant n for low voltage capacitors rated to 6.3 V ranges from 10 to 19 (corresponding to $7 < B < 14$), with E_a decreasing from 1.75 eV at V_R to 1.1 eV at $u = 1.8$. Later studies [8] on higher voltage ratings, from 25 V to 50 V, found n values from 18 to 24 (corresponding to $13 < B < 18$) and E_a decreasing from 1.37 eV at $u = 1.8$ to 0.87 eV at $u = 2.1$. Testing of 220 µF, 25 V PTCs at 105 °C with stress voltages from 1.2 to 1.32 reported in [9] resulted in $B = 10$. For T598 automotive series PTCs, KEMET suggested $n = 16$ (corresponds to $B \sim 14$) and $E_a = 1.4$ eV [10]. An analysis of voltage derating based on PTC acceleration factors [11] showed that 15 µF 35 V capacitors can be characterized by $n = 8.2$ ($B \sim 9$), whereas similar capacitors manufactured using KEMET F-Tech/SBDS technology showed $n = 32.5$ (B exceeding 20). The latter allows for a much steeper reduction in the failure rate with voltage derating.

HALT on various lots of four types of Vishay PTCs rated to voltages from 16 V to 35 V [1] at 85 °C and 105 °C with stress voltages from 1.6 to 2.4 times the rated voltage showed that lot-to-lot variations of the voltage acceleration constants were below 16 %. Different part types in this study demonstrated similar constants of $B = 10.9 \pm 0.8$ ($n = 21 \pm 1.2$).

Automotive-grade capacitors manufactured to the AEC-Q200 standard do not require formal FR assessments. To qualify for the automotive industry, capacitors must pass tests such as High Temperature Exposure (storage for 1000 hours at T_{max}); Temperature Cycling (1000 cycles between -55 °C and 125 °C), Humidity Bias (1000 hours at V_R, 85 °C, 85% RH), and Operating Life (1000 hours at 2/3 V_R and T_{max}). Unlike military specifications where failure criteria are standardized and codified, AEC-Q200 parametric failure criteria are specified by individual manufacturers and can vary substantially.

All test conditions described in AEC-Q200, except for Operating Life, for tantalum capacitors are more severe compared to military specifications. Per AEC-Q200 specification, conditions for life testing are the same for MTCs and PTCs. However, for military capacitors these conditions differ depending on the cathode materials.

Reliability assessment under MIL-PRF-32700 requires testing at least 100 PTC samples for a minimum of 100 hours at manufacturer-selected accelerated conditions to demonstrate an acceptable FR. A maximum of one failure is permitted

(100/1). Additionally, parts must pass a 2000-hour life test at 85 °C and minimum V_R for qualification (45/1), and each lot undergoes a 1000-hour test under the same conditions as a part of Group B testing (24/0).

In contrast, AEC-Q200 Operating Life testing requires three lots of 77 samples each, with zero failures allowed. Although no formal reliability estimations are required, applying Eq.(1) for $N = 231$, $n = 0$, and $t = 1000$ hour yields FR ≈ 1%/1000hr at 90% confidence level. This value is typical for commercial products and is about two orders of magnitude greater than the one acceptable for T-level (space) components. Space mission capacitors often operate continuously without interruption, whereas cars may operate for an average of one hour a day. Under automotive conditions, 1000 hours of testing may equate to 2.74 years of operation. Factoring in voltage and temperature derating, the actual equivalent use life can exceed 15 years.

Historically, most tantalum capacitor failures stemmed from dielectric defects, and the risk of IM failures was effectively mitigated by burn-in (BI) during screening. The probability of WO failures limiting the useful life was considered negligible. Today, advanced manufacturing processes and materials have drastically reduced defects and IM failures [12]. However, the push for smaller sizes, higher capacitances, and higher operating voltages makes WO degradation an increasingly prevalent failure mechanism in modern capacitors, necessitating useful life assessments.

Vacuum environments are often considered benign for most electronic components, especially since moisture is a known hazard for chip tantalum capacitors. However, the absence of moisture in conductive polymers can degrade PTC characteristics, leading to anomalous charging currents (ACC) [13]. While ACC assessments in a vacuum will be reported in a separate paper, this study compares the results of reliability testing in vacuum and air using four types of polymer tantalum capacitors.

As automotive-grade capacitors are increasingly utilized in space systems, it is essential to assess their reliability and the risks of WO failures during long-term missions. In this study, the voltage acceleration constants and useful life of various AEC-Q200 MTCs and PTCs were evaluated using HALT. Leakage currents were continuously monitored throughout testing, and breakdown voltages were measured before and after HALT to better elucidate failure mechanisms.

TECHNIQUE

Automotive grade ten-volt tantalum capacitors selected for this study had the same footprint 7343. All parts were qualified to AEC-Q200 standards. Table 1 below shows characteristics of the parts from four manufacturers. In the capacitor code, the first letter designates the manufacturer, the second letter indicates the cathode type ('M' for MnO_2 and 'P' for polymer), and the subsequent digit corresponds to the part number. The number following the dash represents the capacitance value in µF.

Table 1. Characteristics of capacitors

Code	C, µF	DF, %	ESR, mΩ	DCL, µA	T_{max}, C	Rated Voltage, V	Caze Size, metric	Cathode Type
AP1-220	220	6	25	220	125	10	7343	Polymer
AP1-100	100	6	25	100	125	10	7343	Polymer
AP2-470	470	10	15	470	125	10	7343	Polymer
AM1-220	220	8	100	22	125	10	7343	MnO2
BP1-100	100	10	40	100	125	10	7343	Polymer
BM3-100	100	8	100	10	125	10	7343	MnO2
BM4-220	220	8	500	22	150	10	7343	MnO2
CP1-220	220	10	25	220	125	10	7343	Polymer
CP8-220	220	10	40	220	125	10	7343	Polymer
CM5-220	220	8	100	22	125	10	7343	MnO2
DP1-220	220	10	25	220	105	10	7343	Polymer

HALT was conducted at 85 °C with the voltage stress level ($u = V_S/V_R$) ranging from 1.8 to 2.4. From 20 to 40 units of capacitors reflow soldered onto a test printed wiring board (PWB) were used for each stress level. Breakdown voltages (V_{BR}) were measured at room conditions using Constant Current Stress (CCS) testing [14]. During HALT, currents were monitored by measuring the voltage across 62 mA fast-acting fuses connected in series with each capacitor, utilizing a PC-based setup equipped with a scanner. The fuses featured a 7-ohm resistance, enabling recording of leakage currents

as low as 0.01 mA. Time-to-failure (TTF) was recorded when a fuse opened, which produced a sharp voltage increase across the fuse. Additional experiments demonstrated that the 62 mA fuses open after several seconds at a 100 mA current. At higher currents, the time to blow decreases proportionally to $\sim I^{-2}$.

Analyzing the TTF distributions in Weibull coordinates provides a straightforward method for discriminating between IM and WO failures. TTF distributions with a slope of $\beta < 1$ correspond to the IM region, whereas distributions with $\beta > 1$ indicate the WO region. The experimental TTF data were fitted to a Log-Linear Weibull (LL-Weibull) model using ReliaSoft ALTA software with the voltage acceleration presented as function of the stress voltage per Eq.(2a). This model facilitated the assessment of acceleration factors and the useful life of the capacitors. It also allows evaluations of the efficiency of burn-in (BI) conditions and predictions of reliability under rated ($u = 1$) and application conditions.

RESULTS OF HALT

MnO_2 Tantalum Capacitors

HALT for MTCs was carried out at different voltage stress levels starting $u = 1.8$. Unlike PTCs, failures in MTCs resulted in burning and charring of capacitors even at relatively low stress voltages.

TTF distributions for capacitors manufactured by three vendors are shown in Weibull coordinates in Fig. 1 to 3. The markers in all charts correspond to experimental data, and the lines to results of approximations for IM or WO types of failures. For all failures shown in charts (a) these approximations were made using engineering judgment. After separation of IM and WO failures, LL-Weibull modeling was utilized. This allowed predictions of TTF distributions at the assumed use conditions, $u = 0.6$ and 85 °C (solid blue lines), and assessments of the confidence levels. The dashed lines on the charts below correspond to the 90% confidence levels.

Bimodal TTF distributions for AM1 and CM5 capacitors suggest the presence of both IM and WO failures, whereas all BM3 and BM4 capacitors failed solely due to infant mortality. The proportion of IM failures, which can be determined at the intersection point of the IM and WO lines, increases with the level of voltage stress and reaches ~50% for high stress levels for AM1 and CM5 capacitors. Due to a relatively small number of failures and the spread of the data, the accuracy of the voltage acceleration constants for IM failures in these groups is low. In most cases, the accuracy of WO modeling is acceptable; however, a larger sample size is required to reduce uncertainty in IM modeling.

Infant mortality failures in MTCs cannot be described using a single acceleration factor, as is done in MIL-PRF-55365 ($B = 18.77$). According to our results, the value of B_IM can vary from 11.9 to 25. Assuming a constant value can result in substantial (orders of magnitude) errors in FR.

The presence of WO failures in contemporary MTCs requires assessments of the useful life of the parts. Additionally, aggressive burn-in conditions might reduce UL, and this possibility can be evaluated by modeling TTF distributions and calculating the conditional probability of failure for parts after burn-in. For example, BI for 40 hours at 85 °C and $u = 1.3$ for AM1 capacitors would lead to 0.45% of IM failures. Based on WO modeling, the reliable life (99% reliability) at $u = 1.3$ and 85 °C is 2100 hours. This means that 40-hour BI would reduce the useful life by only 1.9%. Considering that the useful life at the use conditions is ~ 46 years, a 1.9% reduction is acceptable.

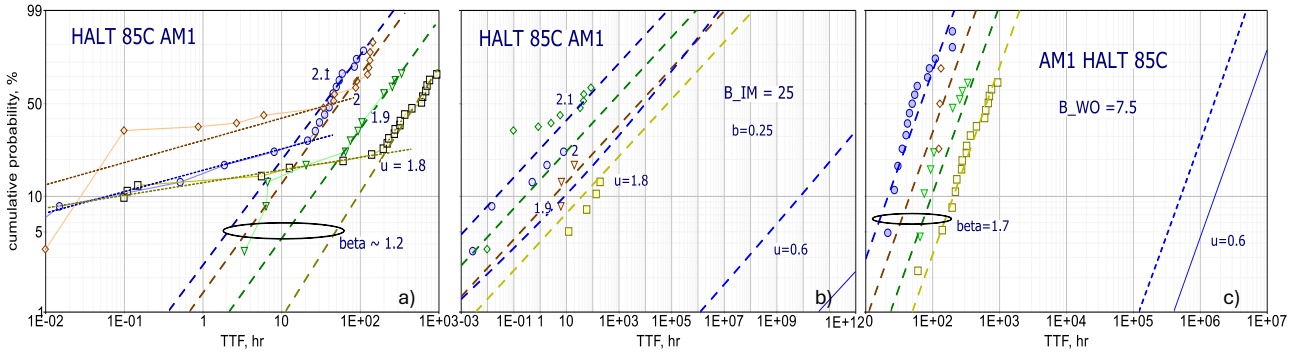


Fig. 1. TTF distributions for AM1 capacitors showing all test results (a) and LL-Weibull modeling of IM (b) and WO (c) failures.

In contrast to AM1 that had a significant proportion of WO failures, all BM3 and BM4 capacitors failed as infant mortalities. Predictions for the use conditions yield a relatively large proportion of failures over 10 years of operation (2%

to 5% at 90% confidence level), suggesting a need for burn-in. Analysis of the efficiency of different BI conditions is discussed in the section below.

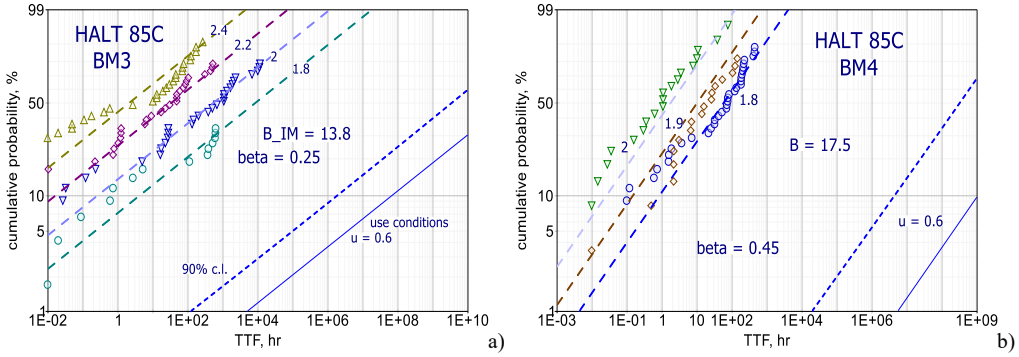


Fig.2. Distributions of TTF for BM3 and BM4 capacitors using all data (a), data for infant mortality (b).

Similar to AM1, approximately half of CM5 capacitors failed HALT due to WO degradation. Modeling of IM failures show that 5.6% (14.8 years at c.l.=90%) would fail during BI at u = 1.3. The conditional probability of IM failures during 10-year operations at 85 °C and u = 0.6 after BI would be 0.79%. Modeling of WO failures shows that the useful life at u = 1.3 is 1960 hours, meaning BI would consume about 2% of the part's life. At operating conditions, the useful life remaining after BI would be 30.8 years (11.2 years at c.l.=90%), which might be not acceptable for some space projects.

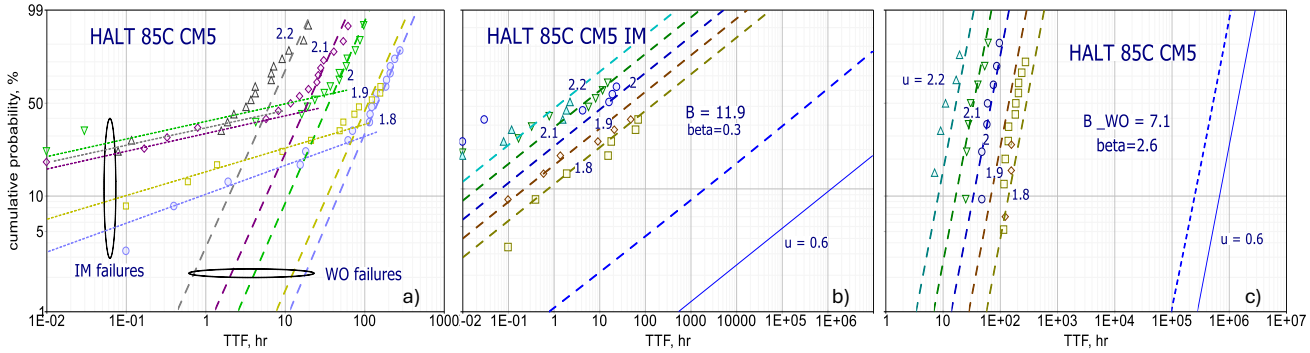


Fig.3. TTF distributions for CM5 capacitors using all data (a), data for infant mortality (b) and wear-out (c) failures.

One of the methods to estimate the voltage acceleration constant is by plotting variations of the characteristic TTF_c values (TTF at 63% failure probability) against the stress level. These variations are shown in Fig. 4. The chart also includes results of breakdown voltage measurements that correspond to a few seconds of high voltage exposure. The data can be approximated with straight lines corresponding to exponential dependance $TTF_c \sim exp(-Bu)$, thus supporting the TDDB model. However, the values of B calculated from the slope of these lines differ from the results of the LL-Weibull modeling by an average of 33%. This deviation might be related to errors in assessments of TTF_c and breakdown voltages, as well as variations of V_{BR} in the process of HALT. Ultimately, LL-Weibull modeling that utilizes all experimental data provides a more accurate assessment of the acceleration factors.

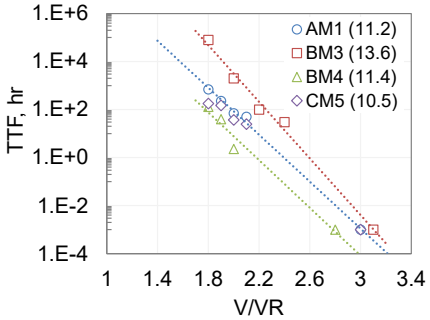


Fig.4. Variations of the characteristic TTF values with the stress voltage during HALT. V_{BR} data correspond to ~1 sec of the TTF. The calculated slopes of the approximating lines (constant B) are shown in the legend.

Assessments of Burn-In Conditions for MTCs

Modeling of IM failures for BM3 and BM4 capacitors (see Fig. 2) allows for predictions of TTF distributions at 85 °C under any voltage stress conditions, as well as assessments of BI effectiveness in improving part reliability. The results of these predictions are shown in Table 2. Assuming that BI is carried out for 40 hours at 85 °C and stress voltages up to u_s = 1.52, as suggested in MIL-PRF-55365, reliability characteristics were calculated for two conditions: u_s = 1.3 and 1.5.

The proportions of failures during BI at a voltage stress of u_s = 1.3 for BM3 and BM4 capacitors was 3.3% and 1.2%, respectively, and increased to 6.4% and 5.6% at u_s = 1.5. Failure rates at rated conditions calculated after BI at u_s = 1.3 were 0.33 %/1000hr and 0.07 %/1000hr for BM3 and BM4 capacitors, respectively. These values exceed the requirement for T-level capacitors (0.01 %/1000hr). Increasing the stress voltage to 1.5 would reduce FR to 0.04 %/1000hr and 0.01 %/1000hr, which is still not sufficient for BM3 capacitors. However, the FR requirements in MIL-PRF-55365 were established using a larger voltage acceleration constant, B = 18.77. Using this value of B would increase acceleration factor and reduce FR by a factor of 12.

The probability of failure during 10 years of operation at 85 °C and u = 0.6 without BI would be 2% for BM3 and 0.16% for BM4 capacitors. Consequently, BM3 capacitors without burn-in may present a high risk of failures during long-term missions. The efficiency of BI can be estimated as a conditional probability of failure at operating conditions over 10 years for parts that passed BI, P(u = 0.6, 10y)|BI. For BM3 capacitors, screening at u_s =1.3 would reduce the probability of failure to 0.11% and to nearly an order of magnitude less after BI at u_s = 1.5. The probability of failure for BM4 capacitors would be negligibly small (below 0.001%) even after BI at u_s =1.3.

Table 2. Reliability prediction for IM failures

Characteristic	BM3	BM4
B_IM	13.8	17.5
slope (β)	0.25	0.45
P(BI_1.3), %	3.3 (5.6)	1.2 (3.9)
P(BI_1.5), %	6.4 (9.7)	5.6 (11.9)
FR at u=1 after BI_1.3, %/1000hr	0.33 (0.56)	0.07 (0.23)
FR at u=1 after BI_1.5, %/1000hr	0.04 (0.06)	0.01 (0.02)
P(u=0.6,10y), %	2 (5)	0.16 (1.9)
P(u=0.6,10y)|BI_1.3, %	0.11 (0.23)	0.0057 (0.064)
P(u=0.6,10y)|BI_1.5, %	0.014 (0.035)	0.0008 (0.009)

Note: Data in parentheses correspond to the values calculated at a confidence level of 90%.

Polymer Tantalum Capacitors

PTCs from Manufacturer A exhibited either zero or fewer than 5% IM failures depending on HALT stress voltage. For this reason, only wear-out (WO) failures and the results of LL-Weibull modeling are presented in Fig. 5. Voltage acceleration constants, B_WO, varied within a relatively narrow range across different part types (from 6.3 to 7.8), and the useful life at operating conditions exceeded 11 years.

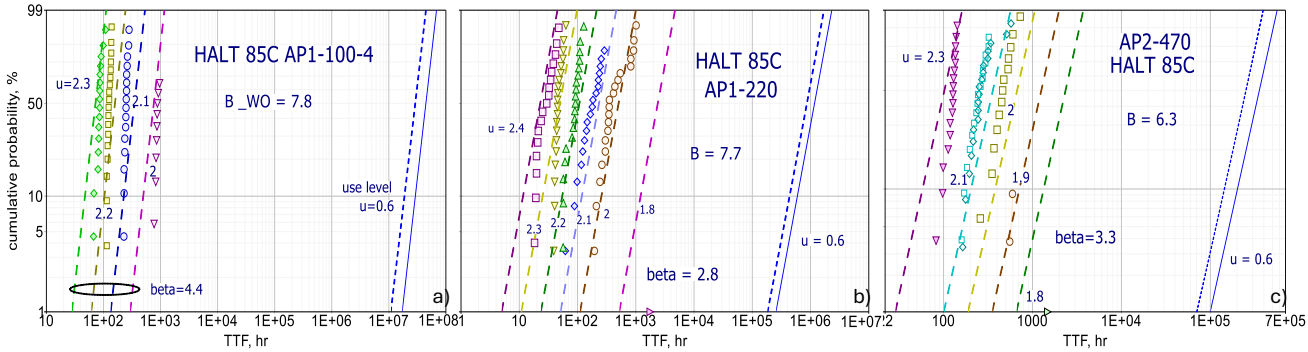


Fig. 5. Variations of TTF distributions during HALT at different stress levels for AP1-100 (a), AP1-220 (b), and AP2-470 (c) capacitors.

No failures were observed during testing of 40 PTC samples from manufacturer B for 3500 hours at u = 1.8. However, increasing stress voltage resulted in a rapid rise of IM failures from 2% at u = 2 and to 50% at u = 2.7. To reduce IM failures, a burn-in for 40 hours at 85 °C and u = 1.3 can be used causing up to 0.27% failures at c.l.=90%. The useful life calculated based on WO failure model at this voltage would be ~ 56 years, so the life consumption during BI would be negligible.

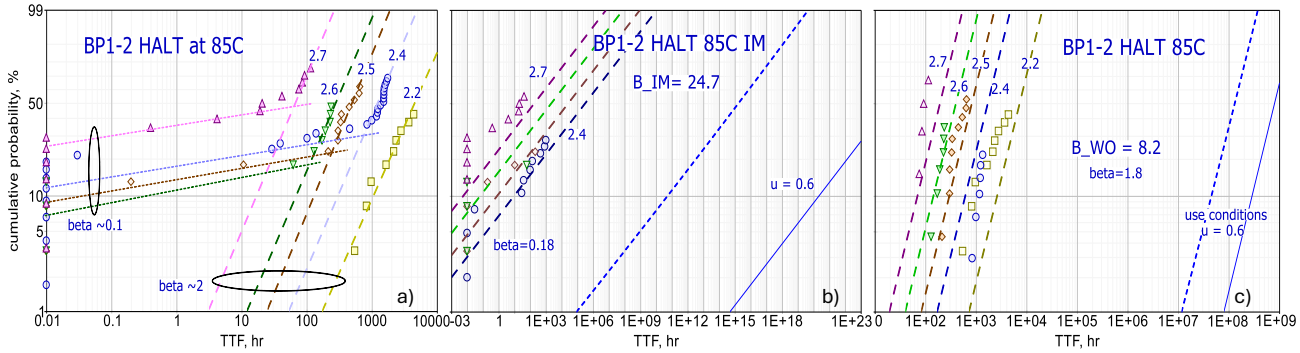


Fig. 6. TTF distributions during HALT for all BP1 failures (a) IM failures (b) and WO failures (c).

A substantial proportion of IM failures was also observed during HALT of PTCs from Manufacturer C (see Figures 7 and 8). For CP8-2 capacitors, this proportion increased with the stress voltage, rising from less than 2% of IM failures at u = 1.8 for 1000 hours to more than 50% at u= 2.3.

To assess the reproducibility of the test results, two groups of CP1 capacitors (one with 40 samples and another with 20 samples) were tested at u = 2.1 using different set-ups (Fig. 7). Results show that TTF distributions for WO failures were practically identical. However, the difference in IM failures was significant, up to ~ 25%. A large proportion of IM failures at high stress voltages happen very rapidly (so-called initial failures), making it impossible to determine the exact time of failure. This complicates modeling of IM failures, results in a wide spread of possible IM acceleration factors and increases uncertainty in reliability forecasting. Improvements in the accuracy of IM modeling can be achieved by increasing sample size during HALT.

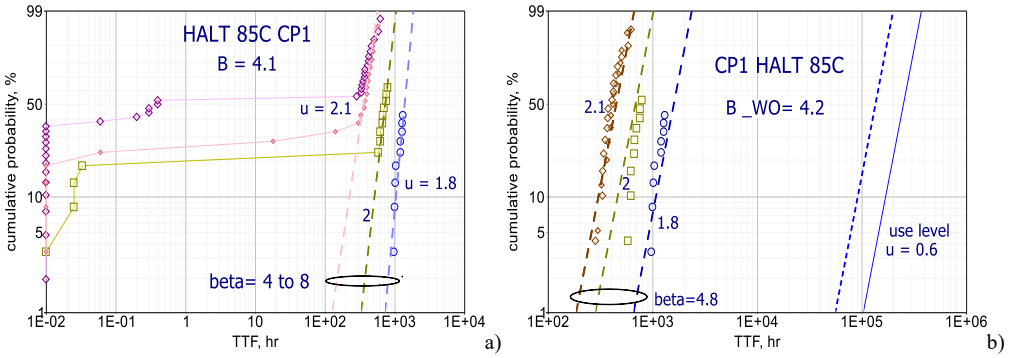


Fig. 7. TTF distributions for all (a) and WO CP1 failures (b). Small and large diamond marks for data at u = 2.1 correspond to two separate groups of capacitors.

Results of HALT for lot 2 of CP8 capacitors (Fig. 8) show that despite a relatively large spread of TTF data in the IM region, LL-Weibull modeling (Figure 8b) indicated a low probability of IM failures over 10 years (8800 hours) at application conditions (0.42% at c.l.= 90%) and negligible risk of WO failures (below 0.1%) for more than 100 years (Fig. 8c).

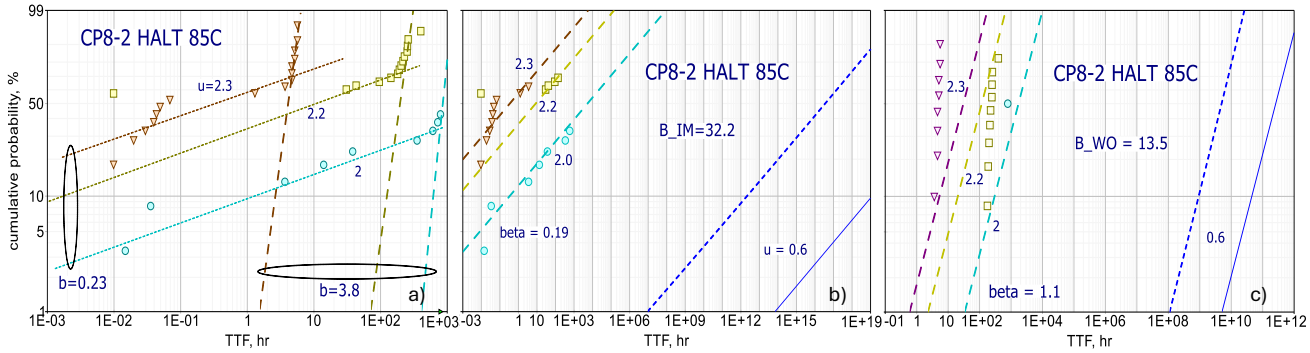


Fig.8. TTF distributions for all failures of CP8-2 capacitors (a) and LL-Weibull modeling of IM (b) and WO (c) failures.

Polymer tantalum capacitors from manufacturer D had a large proportion of IM failures, 54% across all test conditions (see Fig. 9). This value is comparable to capacitors with MnO_2 cathodes, which had an average proportion of IM failures during HALT of 60.2% with a standard deviation of 23%. By comparison, the overall proportion of IM failures for the other PTCs tested was lower, ~ 21%. Despite the large proportion of IM failures for DP1 capacitors, the high value of *B_IM* = 31.9 ensures that the probability of these failures during more than 100 years of operation will remain below 0.1%. Consequently, there is no need for BI for these parts.

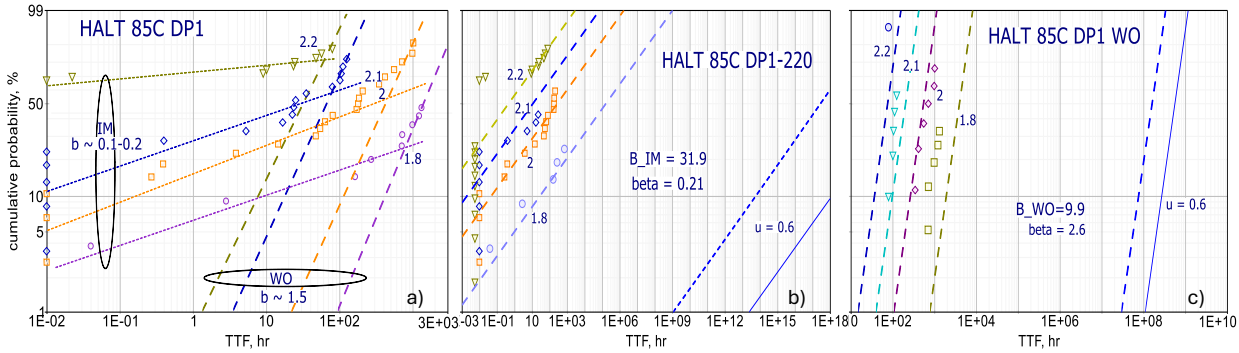


Fig. 9. TTF distributions for DP1 capacitors showing all test results (a) and LL-Weibull modeling of infant mortality (b) and wear-out failures (c).

The characteristic times to failure (TTF_c) determined from the experimental data presented in Fig. 5 through 9 are plotted against stress voltages in Fig. 10. In all cases, results can be reasonably approximated with exponential functions. The *B_WO* values calculated using LL-Weibull modeling agree within 3% accuracy with the data shown in Fig. 10.

Variations of the TTF_c with stress voltage confirm an exponential dependence that is consistent with the TDDB model. Data for all types of capacitors from manufacturer A can be characterized by the same constant $B = 7.07$ (Fig. 10a). This data can also be accurately approximated with the power function, yielding $n = 15.1$. However, extrapolation to the rated voltage using power function would result in TTF and FR values more than 30 times larger than those predicted by the exponential model. Extrapolating further to operating conditions, $u = 0.6$, increases this difference by more than three orders of magnitude (4500 times). For this reason, the exponential function should be used to ensure conservative reliability estimates.

As the two lots of AP1-100 capacitors exhibited similar reliability characteristics, two lots of BP1 capacitors also shared similar traits (Fig. 10b). However, different part types, and even different lots of capacitors from Manufacturer C yielded varying *B_WO* values (Fig. 10c).

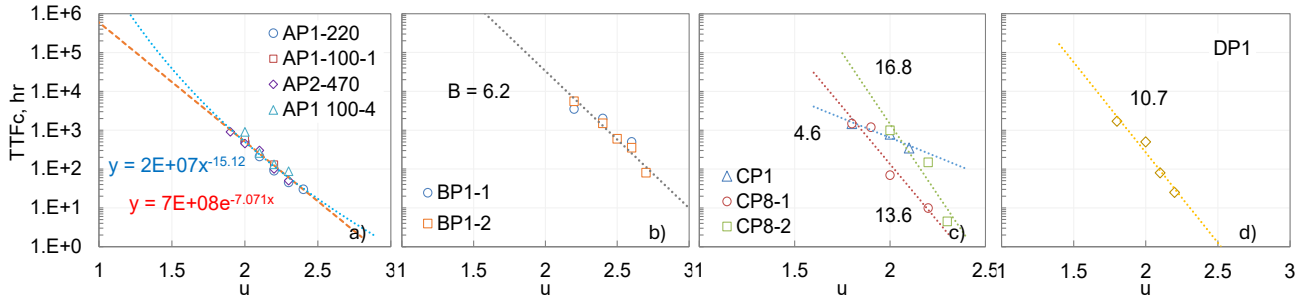


Fig. 10. Variations of the characteristic TTF values (63% failure probability) with the stress level for PTCs manufactured by different vendors (A through D). Numbers correspond to the values of constant B_WO determined by the approximating exponential functions.

Reliability Assessments

Using AEC-Q200 capacitors without additional burn-in assumes that majority of defective parts have been screened out, the parts are ready for use, and that any possible failures can be considered random. Assuming random failures, the characteristics necessary to calculate failure rates at rated (u = 1 and T = 85 °C) and use (u = 0.6 and T = 85 °C) conditions are shown in Table 3. HALT data at the lowest voltage stress levels, u_s, and testing duration, t, that in the presence of WO failures was limited by the time of WO inception, were used for these calculations.

Table 3 presents voltage acceleration constants for IM and WO regions for cases when enough failures were accumulated to get acceptable estimates. As expected from the modified thermochemical model, which treats failures as a time-dependent dielectric breakdown (TDDB) with the constant B that can be expressed as an inverse function of u_{BR} [15]:

$$B = {}^{\Delta H}/_{kTu_{BR}}, \quad (3)$$

where ΔH is the activation energy required for displacement of ions in Ta2O5 dielectric from their normal bonding environment, k is the Boltzmann constant, and T is the absolute temperature. According to Eq.(3), *B_IM* is expected to be greater than *B_WO* because capacitors with defects have lower breakdown voltages. Based on the data presented in Table 3, on average, the ratio *B_IM/B_WO* = 2.7 ± 0.7.

The value of B for random failures cannot be determined experimentally, but it is reasonable to assume that *B_WO* < *B_rand* < *B_IM*. Considering the defect-related origin of IM failures, it is difficult to expect accurate assessments for acceleration factors for the IM range. This is especially true for PTCs that have a much smaller proportion of IM failures compared to capacitors with MnO_2 cathodes. Consequently, the accuracy of B_IM estimations is below that of *B_WO*. For conservative assessments of FR, *B_WO* values will be employed, similar to the method used in MIL-STD-32700.

Assuming random failures, the probability of failure diring a 10-year misson for capacitors operating at 0.6 V_R can be calculated based on FR assessments:

$$P_{0.6}(10y) = 1 - exp(-FR_{0.6} \times 87600), \quad (4)$$

where $FR_{0.6}$ = FR/$AF_{0.6}$, $AF_{0.6}$ = exp(B×0.4), and 87600 is the duration of 10 years in hours.

For capacitors with WO failures, FR does not fully characterize reliability of the parts. A more important characteristic for long-term missions is the useful life that can be determined as the time to the inception of WO failures, or the time when the probability of WO failures reaches a certain level, P_{life}:

$$UL = TTF_C(V,T) \times AF_V \times \left[-\ln(1 - P_{life})\right]^{1/\beta} \quad (5)$$

The value of P_{life} depends on the criticality of applications. In this work, it is set at 1%.

Voltage acceleration constants for different types of capacitors from manufacturer A have similar values, *B_WO* = 7.3 ± 0.7. This may be caused by similar dielectric formation conditions for capacitors rated to the same voltage. However, *B_WO* varied significantly, from 4.2 to 18, for manufacturer C.

The results confirm that FR calculations are primarily determined by the value and accuracy of the acceleration factor. Additionally, different methods of FR calculations can yield substantially different results. For example, the probability of failure during 10 year operations for BM3 and BM4 capacitors based on LL-Weibull modeling were 2% and 0.16%

(Fig.2) whereas P(10y) calculated based on random failures is lower by more than 3 orders of magnitude (Table 3). Consequently, estimates of failure probability may contain significant uncertainties when applied to long-term missions, and similar assessments should be interpreted with caution. The accuracy of reliability predictions can be improved by using larger sample sizes for HALT (60 samples or more) and by verifying reliability through field return data.

Table 3. Reliability characteristics of capacitors at 85 °C

Group	*B_IM*	*B_WO*	*Data for FR calculation (random)*				FR, %/1000hr c.l.= 60%, u = 1 (random)	FR, FIT c.l.=60%, u = 0.6 (random)	P(10y), u = 0.6 (random)	UL, year at P=1%, c.l.=60%, u = 0.6 (LL-Weibull)
			u_s	*n*	*N*	*t*, hr				
AM1	25	7.5	1.8	7	46	200	0.23	113	9.85E-3	36
BM3*	13.8		1.8	14	40	2200	2.8E-4	2.9	2.5E-4	-
BM4*	17.5		1.8	30	40	400	1.7E-4	1.7	1.5E-4	-
CM5	11.9	7.1	1.8	7	20	100	1.4	837	7.1E-2	25.9
AP1-100		7.8	2	6	30	800	0.012	5.5	4.86E-4	1792
AP1-220		7.7	1.8	0	20	1500	6.4E-3	3.0	2.61E-4	593
AP2-470		6.3	1.8	0	20	1500	0.02	15.9	1.39E-3	11
BP1-2	24.7	8.2	2.2	0	20	550	4.4E-4	0.2	1.47E-5	6300
CP1		4.2	1.8	1	20	1000	0.35	655	5.6E-2	10.4
CP8-1		18	1.8	3	39	1000	5.9E-6	4.5E-5	3.92E-9	3.70E+7
CP8-2	32.2	13.5	2	6	20	800	6.2E-5	2.8E-3	2.50E-7	1.10E+4
DP1	31.9	9.9	1.8	4	20	700	0.14	2.6	2.28E-4	2300
Median value:				MTC			0.12	58	0.005	31
				PTC			0.009	2.8	0.0002	2046

*due to the absence of WO failures, reliability characteristics for BM3 and BM4 capacitors were calculated based on *B_IM* values.

Failure rates requirements for T-level tantalum capacitors in MIL-PRF-55365 (for MTCs) and MIL-PRF-32700 (for PTCs) can be used as references for the acceptable failure rate at V_R and 85 °C. Both specifications require that regardless of the cathode type, space level capacitors have a maximal FR_T = 0.01%/1000 hours. According to Table 3, these requirements are satisfied for 2 out of 4 types of MTCs and 4 out of 8 PTCs. However, calculations per MIL-PRF-32700 are based on the power voltage acceleration model that provides orders-of-magnitude larger acceleration factors; therefore, majority of PTCs in Table 3 would be acceptable for space-level systems. Note that a draft of NASA parts selection standard NASA-STD-8739.11 employs a more conservative exponential model. Calculations per MIL-PRF-55365 would also result in lower FR values for MTCs because of using a higher value of *B* (18.77)

FR can be estimated by field returns and typically does not exceed a dozen FITs at the use conditions. Estimations based on HALT in this work show that 8 out of 12 types of capacitors fall within this category. However, FR calculations based on the field returns might be too optimistic due to the possibility that not all failures were considered or reported, whereas estimations based on HALT are more conservative.

Reliability predictions for a ten-year mission at 85 °C and *u* = 0.6 using the random failures approach show that the probability of failures varies from 7.1E-2 for CM5 to below 2.5E-7 for CP8 capacitors. Furthermore, the expected life (time to the inception of WO failures) at 85 °C and *u* = 6varies from 10.4 years for CP1 to more than 10,000 years for CP8 capacitors. Note, that all reliability characteristics will be further improved at operating temperatures lower than 85 °C.

Despite a large spread in the data, overall, PTCs exhibit better reliability characteristics compared to MTCs. The median values for FRs and the probability of failure during a 10-year operation shown in Table 3 are more than 10 times lower for PTCs, and their useful life is correspondingly greater. The useful life for all evaluated capacitor types, as determined by the inception of WO failures, exceeds 10 years. However, for long-term missions only 7 out of 10 types of capacitors can satisfy the more conservative requirements of a useful life exceeding three times the mission duration.

Degradation of Leakage Currents

Examples of leakage current degradation during HALT are shown in Fig. 11 for MTCs, and in Fig. 12 and 13 for PTCs. In all cases, after a certain incubation period, currents begin to increase gradually and eventually rise by orders of magnitude. As the stress voltage increases, the incubation period decreases while the rate of degradation increases. This behavior may be attributed to the redistribution of positively charged oxygen vacancies in the Ta2O5 dielectric and the subsequent modification of the cathode barrier [16].

Failures in some units were caused by scintillation events, whereas in others, they resulted from a gradual degradation of leakage currents that could reach tens of milliamperes. The former type of failure is typical for MTCs and is most likely related to the presence of defects in the dielectric. The latter is typical for PTCs from all manufacturers evaluated, except for Manufacturer D.

The behavior of DP1 capacitors was similar to MTCs in many respects. This similarity was further demonstrated by a low level of anomalous charging current (ACC) and comparable behavior during scintillation breakdowns. Additionally, a substantial proportion of HALT failures for these parts was attributed to infant mortality, which often resulted in short circuits. It is possible that ACC suppression in DP1 capacitors was achieved through treatments with MnO_2 containing materials prior to the application of conductive polymers. However, energy-dispersive X-ray spectroscopy (EDS) analysis of the fractures in these parts was inconclusive regarding the presence of MnO_2 in the cathode composition.

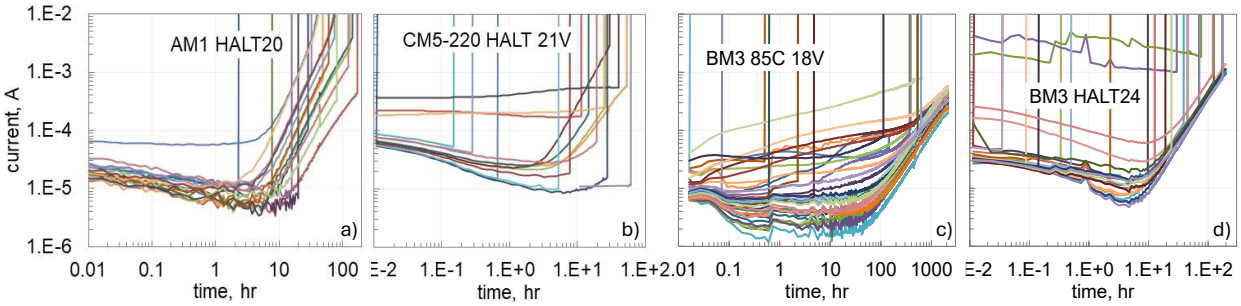


Fig. 11. Leakage currents during HALT at 85 °C and various stress voltages for MTCs. Sharp current increases exceeding 100 mA indicate blown 62 mA fast-acting fuses.

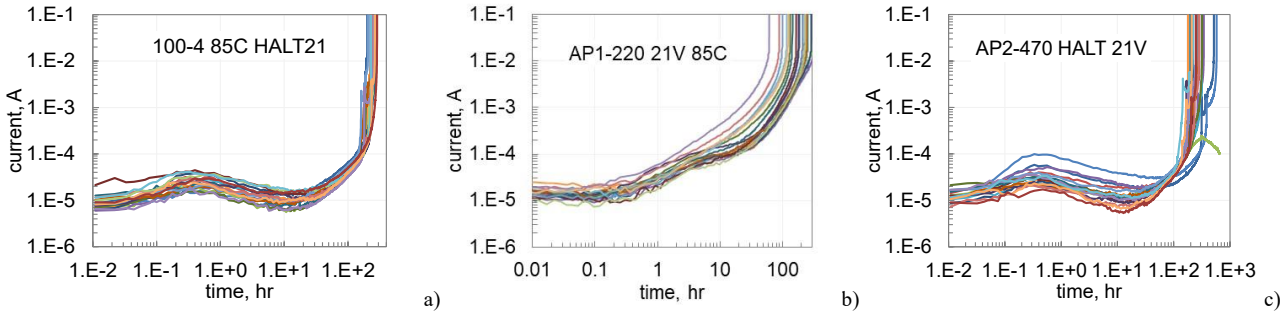


Fig. 12. Degradation of leakage currents during HALT21 for AP1-100-4 (a) and AP2-470 (c) capacitors.

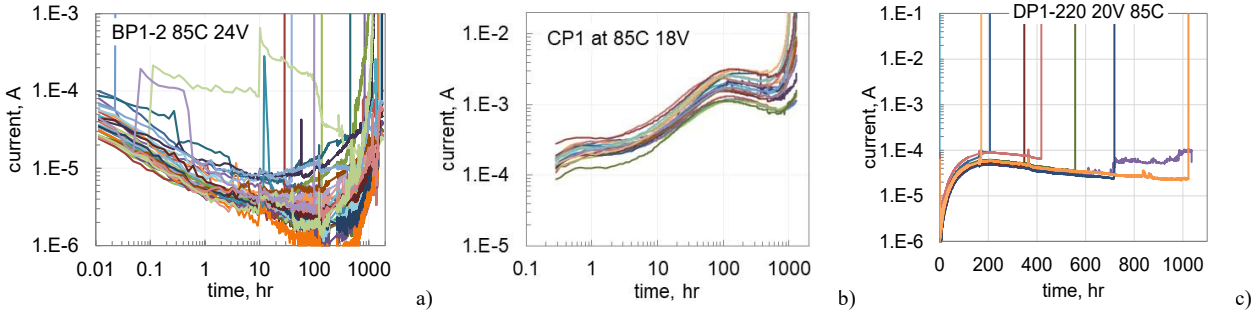


Fig. 13. Variations of leakage currents during HALT24 for BP1-2 (a), HALT18 for CP1 (b) and HALT20 for DP1 (c).

Effect of HALT on Breakdown Voltages

Analysis of scintillation breakdowns indicates that the energy and power of scintillations in PTCs are lower compared to MnO_2 capacitors [14]. This difference explains why MTCs have a higher probability of catastrophic failure, whereas PTCs tend to remain functional despite degraded characteristics (primarily increased leakage current and dissipation factor). Furthermore, MTCs typically exhibit a broader spread in breakdown voltage (V_{BR}) than PTCs. This wider distribution is likely due to an increased concentration of dielectric defects caused by the manganese cathode formation process. This process requires higher temperatures than conductive polymer deposition and generates greater mechanical stress on the dielectric.

Breakdown voltages were measured for all components under dry (after a 100-hour bake at 125 °C) and wet (after one week of storage at 85 °C and 85% RH) conditions. Results, presented in Fig. 14a, demonstrate that V_{BR} varies substantially among different types of tantalum capacitors sharing the same voltage rating. Because of their higher breakdown voltages, AP1 capacitors (averaging 31 V for 100 µF and 220 µF capacitors) exhibit reliability characteristics more than an order of magnitude better than AP2-470 capacitors (averaging V_{BR} at ~26 V).

For PTCs, the presence of moisture increases V_{BR}. On average, breakdown voltages for dry polymer tantalum capacitors (25.8 ±3.8 V) were 16% lower than for wet capacitors (30.7 ±3.6 V). The presence of moisture did not significantly affect MTCs, where V_{BR} only marginally increased from 25.1 ± 1.4 V for dry capacitors to 27.0 ± 3.9 V after humidification. This humidification effect in PTCs is likely caused by solid-state anodic oxidation occurring in defective areas of the oxide under high electric fields in the presence of moisture. Note, that for MTCs, oxygen for this process can be provided by MnO_2 cathode. Because moisture desorbs relatively slowly from chip tantalum capacitors at low temperatures (taking thousands of hours at room temperature) [17], reliability testing conducted in a vacuum may yield different results depending on whether the capacitors undergo initial drying.

Fig. 14b illustrates that V_{BR} tends to increase after HALT, with higher stress voltages leading to greater V_{BR} increases. Figure 14c compares average post-HALT breakdown voltages with the initial V_{BR} for dry capacitors. Overall, HALT increased the breakdown voltages in PTCs by ~14% (from 25.8 ± 3.8 V to 29.4 ± 3.6 V). Similar results were observed for Low Inductance Bulk Capacitor (LIBC) 33uF 35V PTCs where V_{BR} increased by 16% after HALT at 85 °C and u_s = 1.7 [18].

For MTCs, this increase was more pronounced at ~18% (from 25.1 ± 1.4 V to 29.8 ± 1.1 V). An even more significant increase of ~29% was observed in DP1 capacitors (from 22.0 ± 1.8 V to 28.5 ± 2.0 V). This post-HALT V_{BR} enhancement cannot be solely attributed to the elimination (weeding out) of capacitors with lower initial V_{BR} during testing. It is highly likely that solid-state anodic oxidization processes within the dielectric also play a significant role.

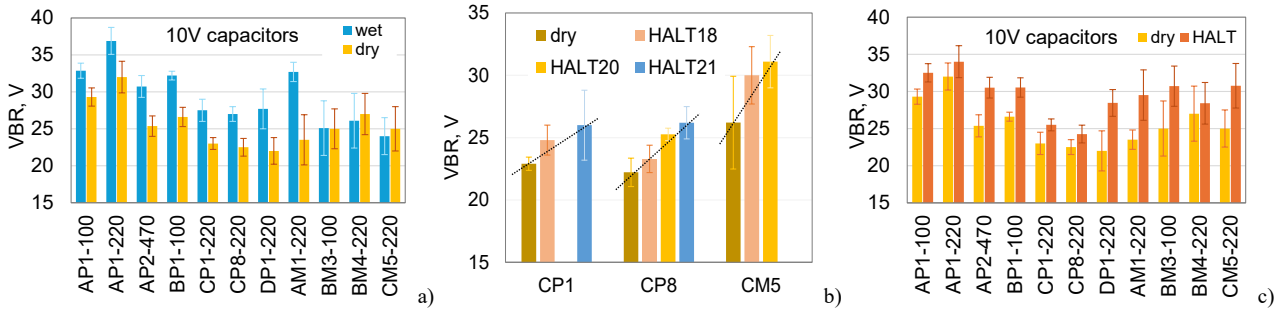


Fig.14. Effect of environments (a) and HALT (c) on breakdown voltages of the parts. Figure (b) illustrates variations in breakdown voltages relative to the level of HALT stress for capacitors from manufacturer C. Error bars correspond to standard deviations.

Based on the oxidation mechanism, the most substantial increase in V_{BR} should occur after HALT under room conditions for parts that bypass the initial baking phase. Experiments with AM1 capacitors supported this, showing that a one-week test at room conditions and 14 V increased the V_{BR} by 53% (from 23.5 ± 1.3 V for dry capacitors to 36.0 ± 6.0 V post-test). However, a similar group of components subjected to a one-week HALT at 14 V and 105 °C saw only a 25% increase (reaching 29.5 ± 3.0 V).

EFFECT OF VACUUM ON RELIABILITY OF PTCS

Moisture is typically considered a hazard for electronic components; however, certain processes in PTCs associated with ACC phenomena are activated in the absence of moisture [19]. These processes might also affect the reliability of the

components. The purpose of this vacuum testing was to utilize HALT to assess potential reliability differences between operating the parts in a vacuum versus in air.

Leakage currents in AP1-100, BP1, CP8, and DP1 capacitors (20 pcs each), which were reflow soldered onto a test PCB (see Fig.15a), were monitored using 100-ohm current sense resistors. The monitoring occurred during HALT at 18 V in a vacuum (1μ torr at 85 °C). A control group of these parts was tested under identical conditions in air. Prior to vacuum testing, the components were baked at 125 °C in a vacuum of 1μ torr for 24 hours.

The test results for the AP1-100 capacitors (Fig. 15b) showed no significant difference in time-to-failure (TTF) distributions between the vacuum and air environments. The behavior of the leakage currents for these two groups was also similar (Fig. 16). The currents gradually increased over time until a scintillation breakdown occurred, after which the currents dropped and then began to increase again. A significant increase in currents observed in the vacuum after 250 hours was the result of failures on a neighboring test board containing different component types. Because of the challenges associated with thermal management in a vacuum, the excessive heat generated by these neighboring failures increased the temperature of the AP1-100 board, leading to a substantial current increase and subsequent failures (see Fig. 16c).

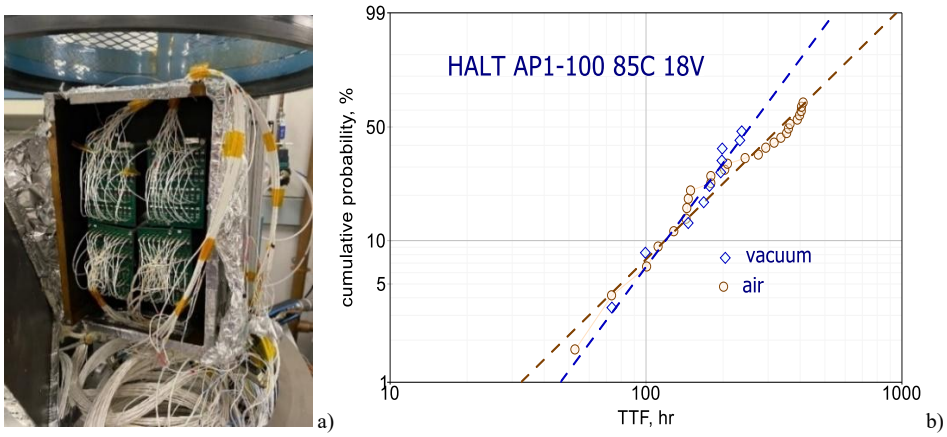


Fig. 15. Vacuum chamber (opened) containing the test boards (a). Note that aluminum foil covers a temperature box with attached heaters and coolers (the lid is removed). Figure (b) displays TTF distributions for AP1-100 capacitors during HALT (18 V at 85 °C) in air and in a vacuum.

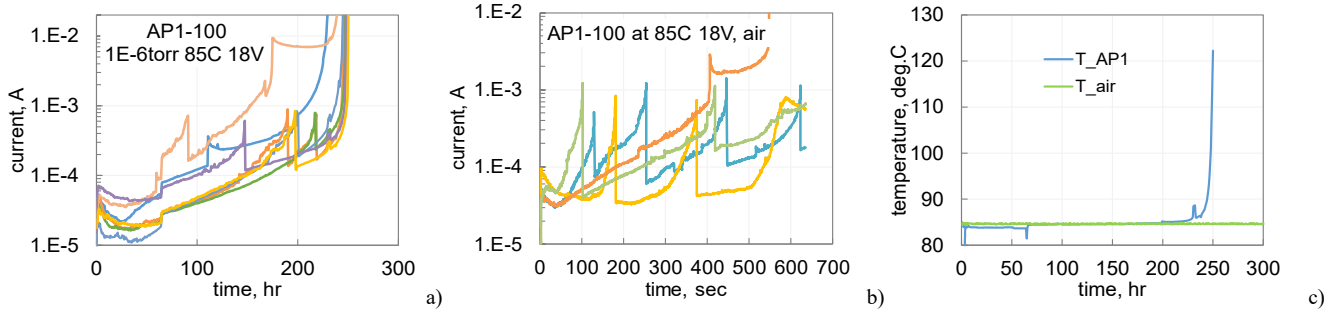


Fig. 16. Variations in leakage currents during testing in a 1μ torr vacuum (a) and in air (b), alongside the temperatures of the test board holding the AP1-100 capacitors (c).

No failures were observed for the BP1 capacitors over 1600 hours of testing in either air or vacuum, nor for the CP8 capacitors over 800 hours (see Fig. 17 and 18). However, leakage currents in some BP1 capacitors degraded more in the vacuum than in air. This discrepancy was likely due to the vacuum chamber operating at temperatures a few degrees Celsius higher than the air chamber (Fig. 17c). Poor temperature stability also explains the differences observed in the current behavior between vacuum and air conditions for the CP8 capacitors (Fig. 18).

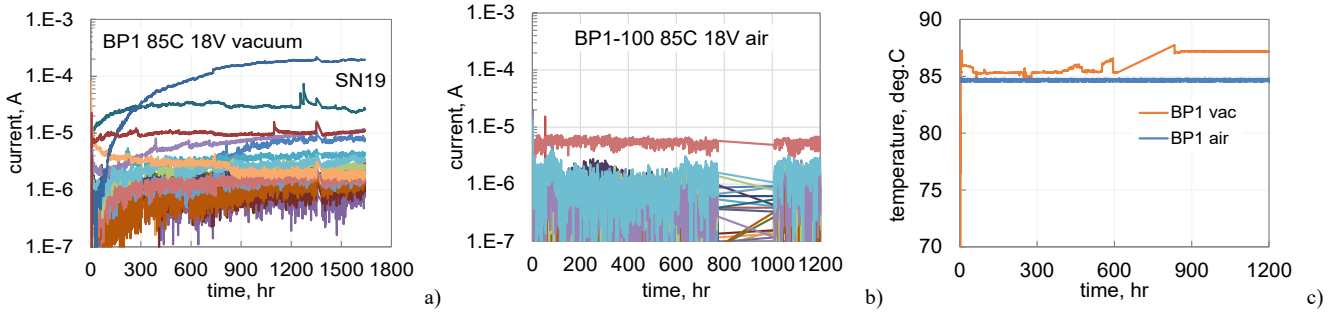


Fig. 17. Variations in currents for BP1 capacitors during HALT at 85 °C in a 1µ torr vacuum (a) and in air (b). Figure (c) illustrates the board temperatures during HALT in the vacuum and air chambers.

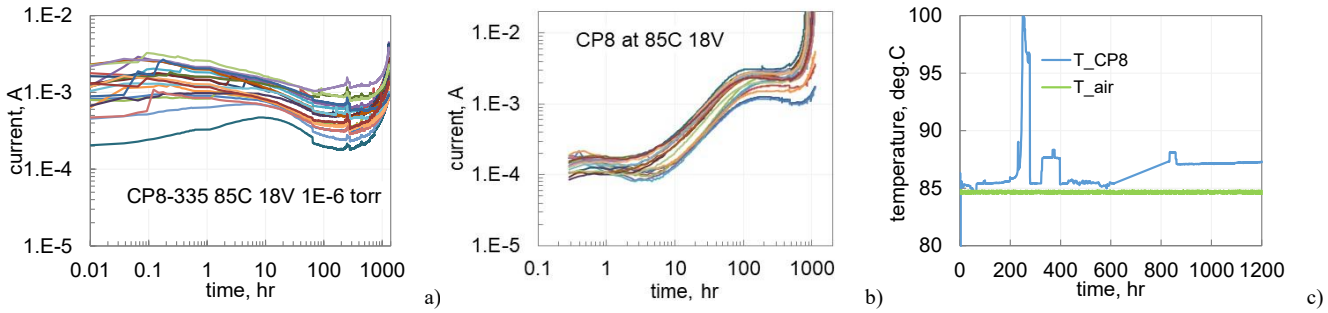


Fig. 18. Variations in currents for CP8 capacitors during HALT at 85 °C in a 1µ torr vacuum (a) and in air (b). Figure (c) illustrates the board temperatures during HALT in the vacuum and air chambers.

The DP1 capacitors exhibited the most significant board temperature instability and the highest proportion of failures (Fig. 19). Although the slopes of the infant mortality (IM) TTF distributions and the inception times for WO failures appear similar between the two environments, a higher temperature during the initial 80 hours of vacuum testing likely explains the approximately 20% higher proportion of IM failures observed in the vacuum (Figure 19a). Similarly, a temperature increase after 400 hours of testing may be responsible for the steeper rise in WO failures compared to the air conditions.

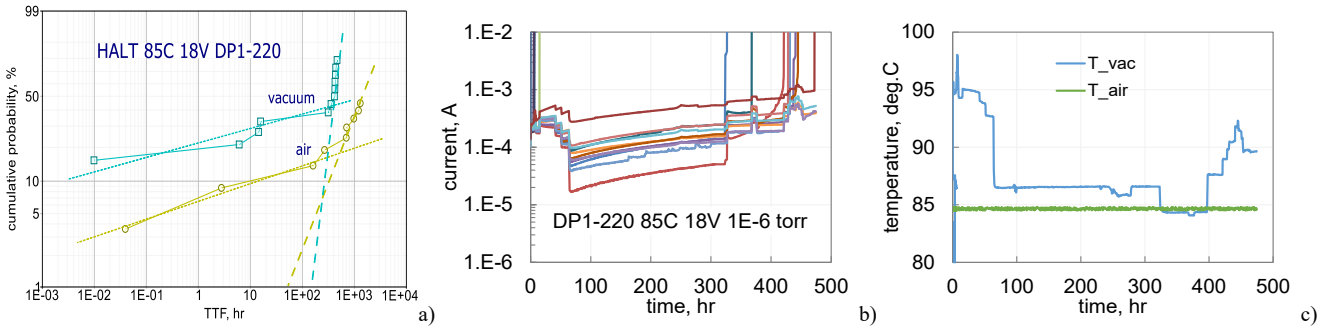


Fig. 19. Comparison of TTF distributions during HALT (18 V) in air and a 1µ torr vacuum (a), and leakage currents during vacuum HALT (b) for DP1 capacitors. Figure (c) shows the variation in test board temperatures during HALT in air and vacuum environments.

Although additional test data comparing vacuum and air environments—along with improved temperature controls—are necessary, these preliminary results indicate that the TTF distributions and leakage current behaviors of PTCs during HALT are similar in both vacuum and air chambers. If these findings are confirmed, reliability data obtained from air testing could be confidently used to predict performance for vacuum operations.

CONCLUSION

The results of HALT conducted at 85 °C on seven types of polymer cathode and four types of manganese cathode tantalum automotive-grade capacitors from four manufacturers can be summarized as follows:

1. **Failure Modes:** Weibull analysis of time-to-failure (TTF) distributions confirms that majority of MTC failures are attributed to infant mortality (IM), whereas wear-out (WO) mechanisms dominate PTC failures. Under accelerated conditions, however, up to 50% of PTC failures can be attributed to defect-related mechanisms. The proportion of IM failures also tends to increase with stress voltage. Also, more than 50% of MTCs in some types of capacitors can fail HALT due to WO.
2. **Voltage Acceleration:** Variations in the characteristic times to failure with stress voltage can be described by an exponential function. This aligns with the Time-Dependent Dielectric Breakdown (TDDB) model and provides conservative reliability estimations for operating conditions compared to the power model. Experimental data showing greater acceleration factors for IM than for WO failures is also consistent with the TDDB model. Voltage acceleration factors are assessed with greater accuracy for WO than for the IM region even at a relatively small sample size (20 to 40 pcs). The accuracy of AF_V assessments for the IM region can be improved by increasing sample size during HALT.
3. **Reliability:** While failure probabilities for similar AEC-Q200 qualified capacitors differ substantially, PTCs generally exhibit higher reliability than MTCs. For the evaluated parts, the median failure rate and the 10-year failure probabilities were more than an order of magnitude lower for PTCs. Despite failures, PTCs might remain functional and often retain acceptable characteristics that continue improving over time under normal operating conditions. Conservative useful life estimations indicate that 7 out of the 10 capacitor types tested can satisfy long-term mission requirements.
4. **Failure Rate**: FR calculations are highly sensitive to both the calculation method and the acceleration factors used. Consequently, FR estimates for long-term missions may carry significant uncertainties and should be interpreted cautiously. Using log-linear (LL) Weibull modeling, rather than calculations based on the assumption of random failures, provides more adequate and conservative reliability predictions.
5. **Modeling and Burn-in:** Approximating the experimental TTF data with a LL-Weibull model enabled the assessment of voltage acceleration factors, reliability predictions for application conditions, and simulations of the burn-in efficiency. Simulations for the IM region indicated that a 40-hour burn-in at 85 °C and u = 1.3 would substantially reduce IM failures for both types of MnO_2 capacitors from Manufacturer B without consuming useful life. Simulations for the WO region allow for assessments of risks of reducing useful life of the parts.
6. **Breakdown Voltage:** Breakdown voltages in PTCs tend to increase in the presence of moisture and following HALT. Both effects are likely driven by solid-state anodic oxidation in the defective areas of the dielectric under high electric fields. The effect of HALT on V_{BR} may explain the cause of anti-WO failures.
7. **Vacuum vs. Air Testing:** Preliminary data indicated no significant differences in the behavior of the four types of PTCs during HALT18 in vacuum versus air chambers. If confirmed, reliability characteristics derived from air testing can be applied to operations in a vacuum, though thermal management will require special attention in vacuum environments.

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REFERENCES

[1] A. Eidelman, S. Zlatopolsky and A. Teverovsky, "Acceleration Factors for Reliability Assessment of Polymer Tantalum Capacitors," in *3rd PCNS Passive Components Networking Symposium*, Milan, Italy, 2021, September 7-10, pp. 119-129.

[2] C. Reynolds, "Reliability management of tantalum capacitors," *AVX Technical information,* 2001 http://www.avx.com/docs/techinfo/rmtant.pdf

[3] E. K. Reed and P. L. Spence, "Long-Term Reliability of Hand-Soldering M55365 Ta Capacitors," JPL, Pasadena CA, NASA WBS: 724297.40.43, 2009, http://nepp.nasa.gov

[4] J. L. Paulsen, "Reliability Characterization of Tantalum Capacitors with MnO_2 Counter-Electrode," in *CARTS Europe: 24th Annual Capacitor and Resistor Technology Symposium*, Bad Homburg, Germany, 2006, 25-28 September 2006.

[5] A. Teverovsky, "Analysis of Weibull Grading Test for Solid Tantalum Capacitors," presented at the CARTS Europe, Munich, Germany, 2010. https://ntrs.nasa.gov/api/citations/20180000031/downloads/20180000031.pdf

[6] A. Teverovsky, "Degradation of leakage currents and reliability prediction for tantalum capacitors," in *2016 Annual Reliability and Maintainability Symposium (RAMS)*, Tucson, AZ, 2016, 25-28 Jan., pp. 1-7.

[7] E. K. Reed, J. N. Kelly and J. L. Paulsen, "Reliability of Low-Voltage Tantalum Polymer Capacitors," in *CARTS USA 2005*, Palm Springs, CA, 2005, March 21-24, 2005, pp. 189-198.

[8] E. Reed and G. Haddox, "Reliability of High-Voltage Tantalum Polymer Capacitors," in *CARTS International*, Jacksonville, FL, 2011, March 28-31, p. 3.3.
[9] P. L. Y. Freeman, I. Luzinovz, "Reliability and Failure Mode in Solid Tantalum Capacitors," *ESC J. Solid State Sci. Technol.,* vol. 10, 2021
[10] C. MotaCaetano, "Polymer Tantalum Capacitors Continue to Toughen Up to Meet Automotive Demands," KEMET Engineering Center, 2019, https://ec.kemet.com/polymer-tantalum-capacitors-continue-to-toughen-up-to-meet-automotive-demands.
[11] P. L. Y. Freeman, "Derating and Technology in Solid Electrolytic and Polymer Tantalum Capacitors," in *the 4th Passive Components Networking Symposium (4th PCNS)*, Sonderberg, Denmarkl, 2023, 11-14 Sept., pp. 123-128.
[12] A. Gaonkar, R. B. Patil, S. Kyeong*, et al.*, "An Assessment of Validity of the Bathtub Model Hazard Rate Trends in Electronics," *IEEE Access,* vol. 9, pp. 10282-10290, 2021
[13] A. Teverovsky, "Anomalous Transients in Chip Polymer Tantalum Capacitors," presented at the ESA 3rd International Symposium - Space Passive Component Days, Noordwijk, The Netherlands, 2018.
[14] A. Teverovsky, "Breakdown and Self-healing in Tantalum Capacitors," *IEEE Transactions on Dielectrics and Electrical Insulation,* vol. 28, pp. 663-671, 2021
[15] A. Teverovsky, "Scintillation Breakdowns and Reliability of Solid Tantalum Capacitors," *IEEE Transactions on device and materials reliability,* vol. 9, pp. 318-324, 2009
[16] A. Teverovsky, "Degradation of leakage currents in solid tantalum capacitors under steady-state bias conditions," in *Electronic Components and Technology Conference (ECTC), 2010 Proceedings 60th*, 2010, 1-4 June 2010, pp. 752-757.
[17] A. Teverovsky, "Effect of Moisture on AC Characteristics of Chip Polymer Tantalum Capacitors," *IEEE Transactions on Components, Packaging and Manufacturing Technology,* vol. 9, pp. 2282-2289, 2019
[18] A. Teverovsky, "Evaluation of Feed-Through Polymer Tantalum Capacitors for Space Applications," NASA STI Program, Greenbelt, MD, NEPP report 2024,
[19] Y. Freeman, G. F. Alapatt, W. R. Harrell*, et al.*, "Anomalous Currents in Low Voltage Polymer Tantalum Capacitors," *Ecs Journal of Solid State Science and Technology,* vol. 2, pp. N197-N204, 2013