Reliability Assessments of Automotive-Grade Tantalum Capacitors for Space Applications

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Outline

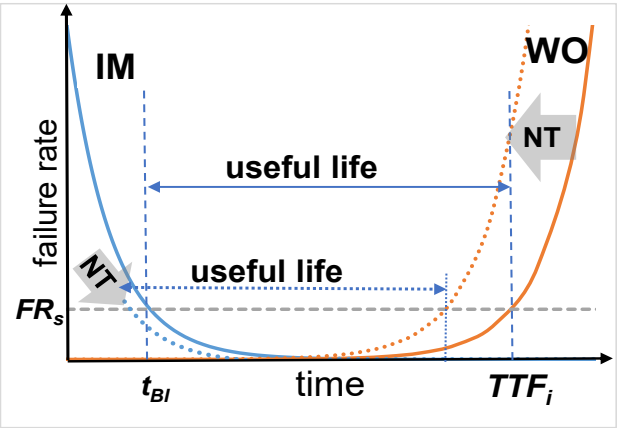
Components qualified to AEC-QXXX requirements are prime candidates for replacement of military parts in space electronics

- ❑ Reliability characteristics and acceleration factors
- ❑ Used part types and HALT conditions
- ❑ Results for MnO2 capacitors and efficiency of Burn-In
- ❑ Results for polymer tantalum capacitors
- ❑ Effect of vacuum on PTCs
- ❑ Effect of HALT on breakdown voltages
- ❑ ACC characteristics
- ❑ Conclusion

✓ *This work demonstrates assessments of AF, FR and UL based on HALT.*

Reliability Characteristics

- Reliability is typically characterized by a single parameter, FR, that supposed to be below FR_s.
- It is generally assumed that IM is reduced to the acceptable level by BI, and UL >> mission time.
- FR can be calculated using different methods, e.g.
  - Reliability handbooks: MIL-HDBK-217, 217Plus™, ANSI/VITA 51.1, Telcordia SR-332, GJB/z 299 (China).
  - Field returns (auto industry).
  - Life testing (MIL specifications).
  - Weibull Grading Test (MIL-PRF-55365).
  - HALT (MIL-PRF-32700).



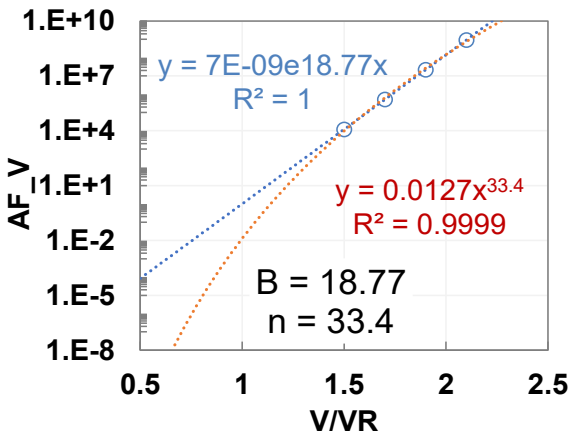
Advances in processes and materials reduced defects and IM failures. However, smaller sizes and higher performance increase risks of WO.

- AEC-Q200 capacitors do not require formal FR assessments. However, calculations show that at $N = 3\times77$, $n = 0$, $t = 1000$ -> FR ≈1E-5 1/hr at 85C.
- FR requirements based on project levels: *≤1E-7 1/hr for L1/2, ≤1E-6 1/hr for L3.*

✓ Reliability characterization by FR is a useful simplification
✓ Characterization by FR only neglects the possibility of WO during mission
✓ AEC-Q200 capacitors need assessments of FR and UL for long space missions

Acceleration Factors

- Two major stress factors for capacitors: voltage ($u=V/VR$) and temperature.
- Most reliability tests are carried out at accelerated conditions, and FR is as accurate as AF.
- Predictions for use conditions also depend on acceleration factors.
- AF_V can be calculated using a power, $\boldsymbol{AF_V = u^n}$, or exponential model $\boldsymbol{AF_V = exp[B \times (u-1)]}$
- Calculations of AF are based on WO failures during HALT and their application for random failures needs explanations.



Both functions describe HALT results accurately

- Literature data on AF:
  - Ta MnO2: $0.15 < E_a < 2.1$ eV, $10 < B < 21$ ($B = 18.77$ per M55365)
  - Ta polymer: $0.9 < E_a < 1.75$, $7 < B < 18$ (determined by testing per M32700)

- ✓ Power AF_V model is much more optimistic than the exponential model.
- ✓ The uncertainty in AF might be significant.

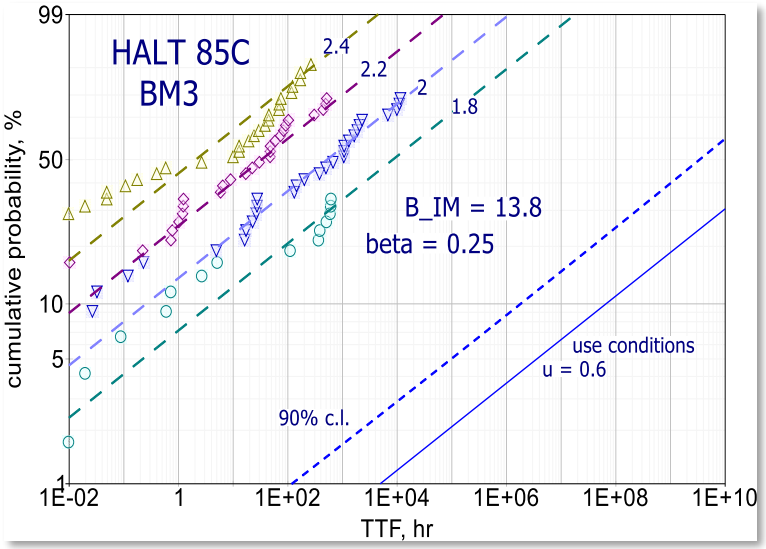
Part Types and HALT Conditions

Code	C, µF	DF, %	ESR, mΩ	DCL, µA	T_{max}, C
AP1-220	220	6	25	220	125
AP1-100	100	6	25	100	125
AP2-470	470	10	15	470	125
AM1-220	220	8	100	22	125
BP1-100	100	10	40	100	125
BM3-100	100	8	100	10	125
BM4-220	220	8	500	22	150
CP1-220	220	10	25	220	125
CP8-220	220	10	40	220	125
CM5-220	220	8	100	22	125
DP1-220	220	10	25	220	105

First letter → Mfr.; Second → 'M' for MnO_2 and 'P' for polymer; Digit → part series

- ✓ All parts were rated to 10V and had footprint size 7343.
- ✓ 4 types of MnO2 and 7 types (14 lots) of polymer caps from 4 Mfrs.
- ✓ Monitored HALT conditions: 85C, from u_{test} =1.8 to 2.6, u_{test} = V_{test}/VR.
- ✓ Failures determined by blown 62 mA/7ohm fuses.
- ✓ Analysis of TTF distributions using Log-Linear Weibull model with $AF_V = exp[B \times (u - 1)]$.

HALT Results for MnO2 Capacitors



Assessments of the Efficiency of BI

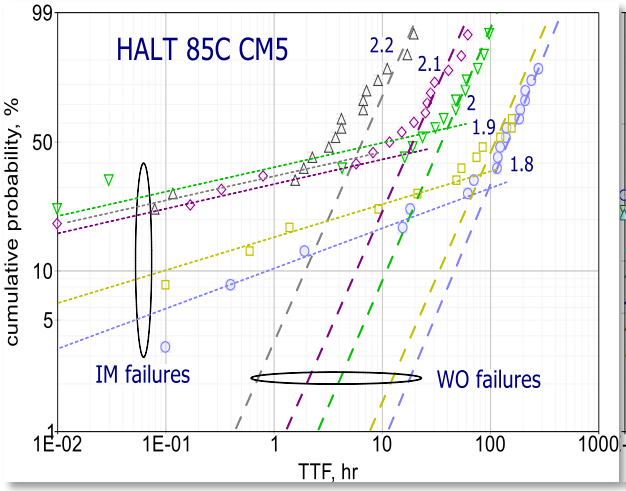
	BI Failures, %		P(u=0.6, 10y), %	P(u=0.6,10y) |BI_1.3, %	P(u=0.6,10y) |BI_1.5, %
	13V	15V			
BM3	3.3 (5.6)	6.4 (9.7)	2 (5)	0.11 (0.23)	0.014 (0.035)
BM4	1.2 (3.9)	5.6 (11.9)	0.16 (1.9)	5.7E-3 (0.06)	8E-4 (9E-3)

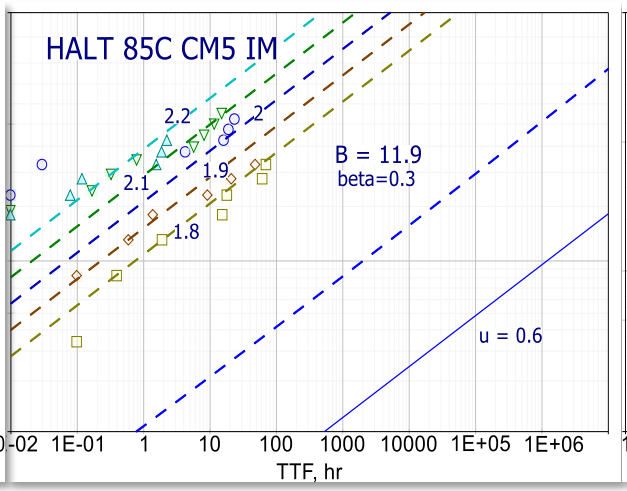
Data in brackets => 90% confidence level

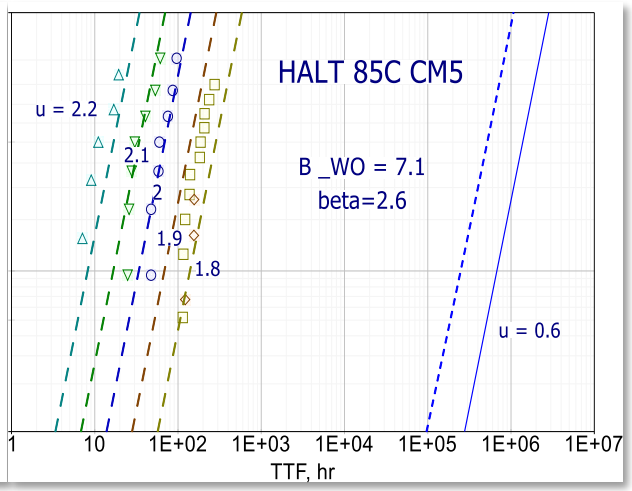
- ✓ All failures in BM3 and BM4 parts were due to IM and had B_IM = 13.8 and 17.5, respectively.
- ✓ The probability of failure for a 10-year operation at 85 °C and u = 0.6, P(u=0.6, 10y), without BI would be 2% for BM3 and 0.16% for BM4 capacitors, thus suggesting a need for burn-in.
- ✓ Simulations assuming 40 hours BI at 85C and u_{BI} = 1.3 reduced P(u=0.6, 10y) to 0.11% for BM3 and to 5.7E-3% for BM4.
- ✓ Increasing u_{BI} to 1.5 will reduce P(u=0.6, 10y) almost tenfold.

Analysis of IM and WO Failures

- ~50% of CM5 capacitors failed HALT due to WO processes.
- By dividing parts into two subgroups, IM and WO failures can be analyzed separately.

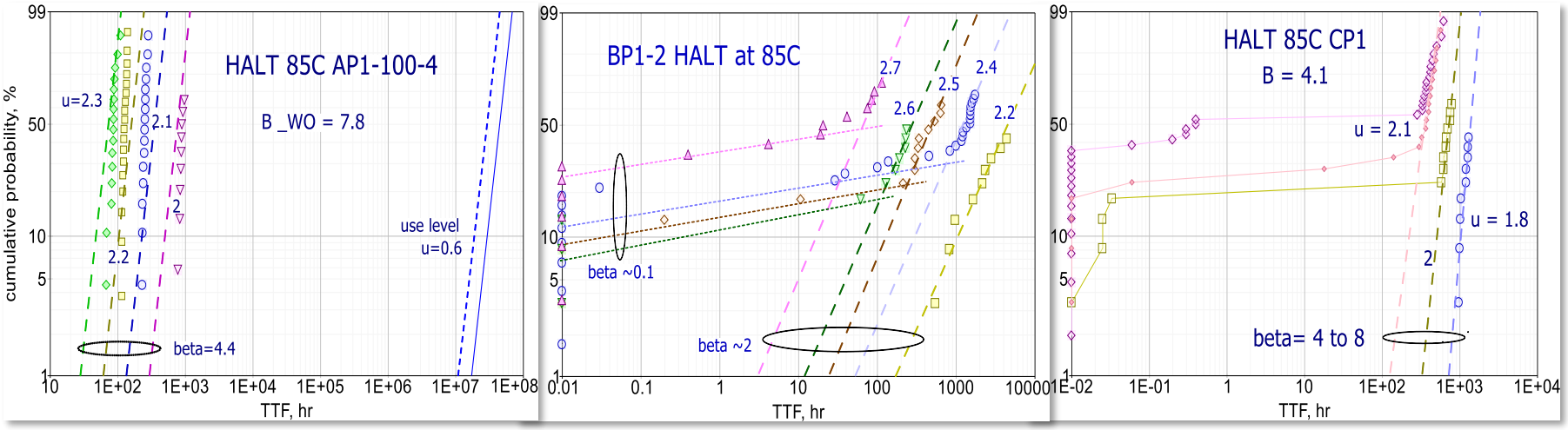






- ✓ For CM5 capacitors, B_IM = 11.9 exceeds B_WO = 7.1, which is consistent with TDDB model.
- ✓ The useful life of the parts at 85C and 60% voltage derating exceeds 20 years.
- ✓ Assessments of AF for IM failures are less accurate than for WO failures and require more samples.

HALT Results for PTCs



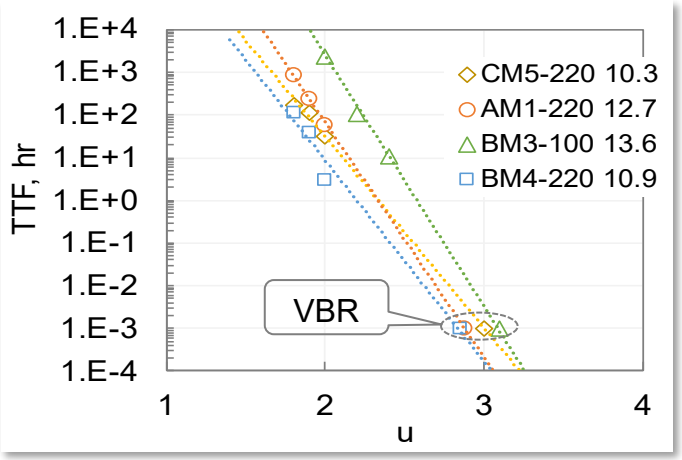
- ✓ PTCs from Mfr. A exhibited fewer than 5% IM failures; other Mfrs. had up to 50% IM failures at high stress voltages.
- ✓ At low stress voltages, the majority of PTC failures is due to WO.
- ✓ Voltage acceleration constant for Mfr.A varies in a narrow range, from 6.3 to 7.8, For two lots of Mfr.B it is slightly higher, 8.2; for Mfr.C it varies in a vide range, from 4.2 to 18.

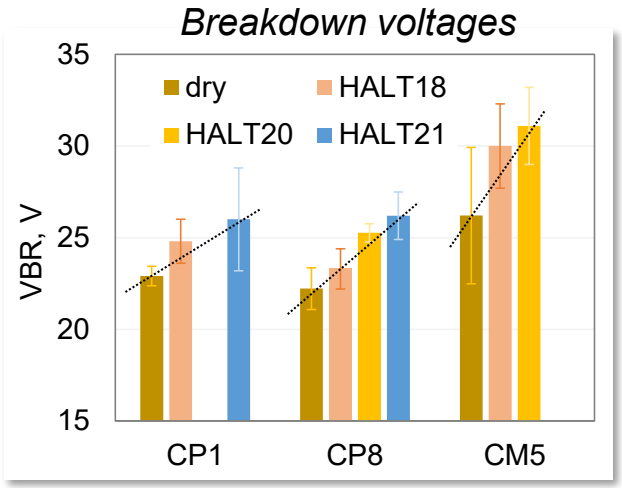
TDDB Model

- Breakdown voltages vary from 2.2 to 3.5VR and sets the limit stress testing.
- A modified thermochemical TDDB model allows for expressing constant B as a function of u_{BR}:

$$B = \frac{\Delta H}{kTu_{BR}}$$

ΔH is energy required for displacement of ions in Ta2O5 dielectric





- ✓ Results for MTCs support TDDB model.
- ✓ Based on TDDB, AF_V for IM should be larger than for WO failures.
- ✓ VBR increases in the presence of moisture and after HALT. Both effects are driven by solid-state anodic oxidation.

Reliability Estimations Based on HALT

- FR was calculated in assumption of random failures based on HALT results at the lowest stress voltage using test duration before inception of WO failures.

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

- The probability of failure for a 10-year mission can be calculated based on FR and AF.

$$P(u=0.6,10y) = 1 - exp(-FR_{0.6} \times 87600),$$
$$FR_{0.6} = FR/AF_{0.6,}\ AF_{0.6} = \exp(B \times 0.4) \qquad 2)$$

- The useful life is calculated based on the characteristic TTF at rated conditions, AF, and the slope of TTF distribution, β.

$$UL = TTFc(V,T) \times AF_V \times \left[-\ln\left(1 - P_{life}\right)\right]^{1/\beta} \qquad 3)$$

P_{life} –acceptable level of failures during the mission that depends on the criticality of applications. In this work, it is set at 1%.

✓ Failure rate calculations using AF_V determined for WO failures gives a conservative estimation of FR.

Reliability Estimations, Cont'd

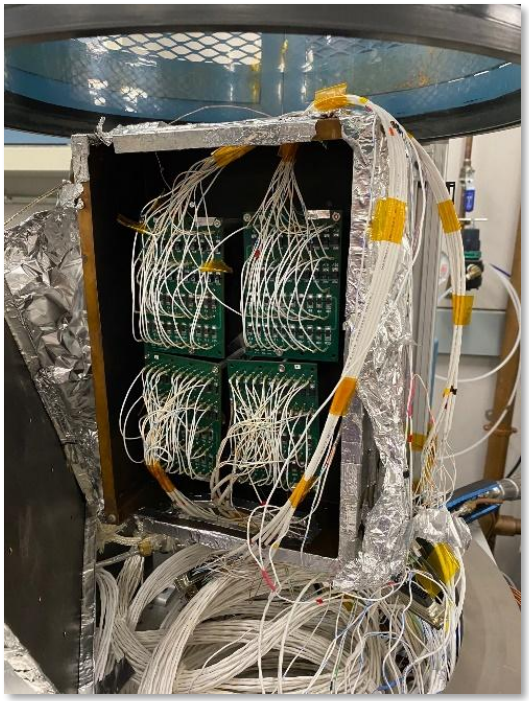
Group	B_IM	B_WO	Data for FR calculation (random)				FR, %/1000hr c.l.= 60%, u = 1 (random)	FR, FIT c.l.=60%, u = 0.6 (random)	P(10y), u = 0.6 (random)	UL, year at P=1%, c.l.=60%, u = 0.6 (LL-Weibull)
			u_s	n	N	t, hr				
AM1	25	7.5	1.8	7	46	200	0.23	113	9.85E-3	36
BM3*	13.8		1.8	14	40	2200	2.8E-4	2.9	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

- ✓ FRs at rated conditions differ substantially, from 5.9E-6 to 1.4 %/1000 hr.
- ✓ UL at operating conditions varies from 10 to more than 1000 years.
- ✓ Overall, FR and UL for PTCs is better than for MTCs.

Effect of Vacuum

- The absence of moisture can degrade characteristics of PTCs leading to anomalous charging currents (ACC).
- The assumption that degradation of PTCs during HALT in air and vacuum are the same might not be true. (At 20C and 40% RH in room, humidity in a temperature chamber is 1.8% at 85C and 0.45% at 125C)
- Four types of PTCs (AP1-100, BP1-100, CP8-220 and DP1-220) were tested in vacuum at 1E-6 torr and 85C at the same stress voltages as in air.

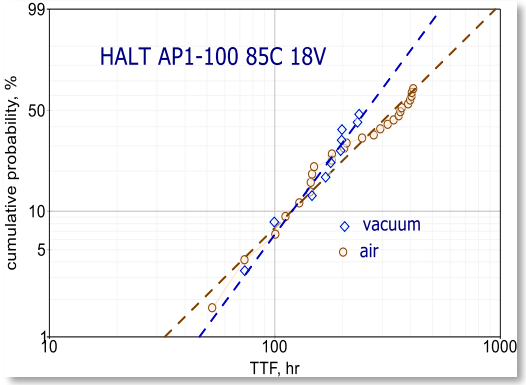
Test boards in a vacuum chamber

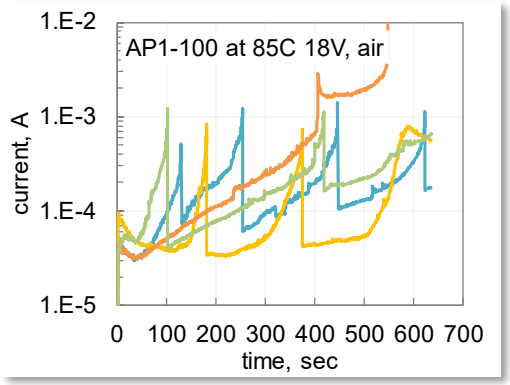


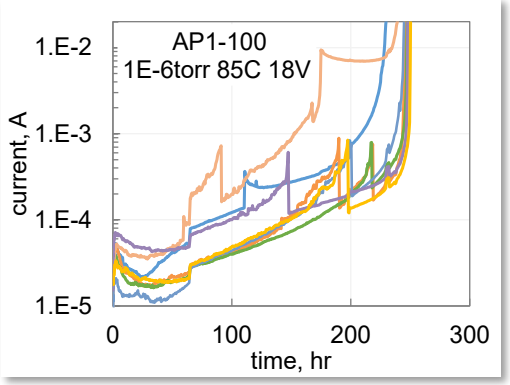
✓ The purpose of vacuum testing was to verify that reliability testing in vacuum and air give similar results and the worst-case ACC conditions can be simulated by baking in air.

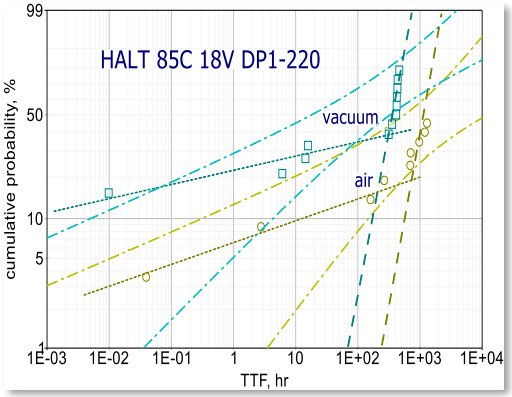
Effect of Vacuum, Cont'd

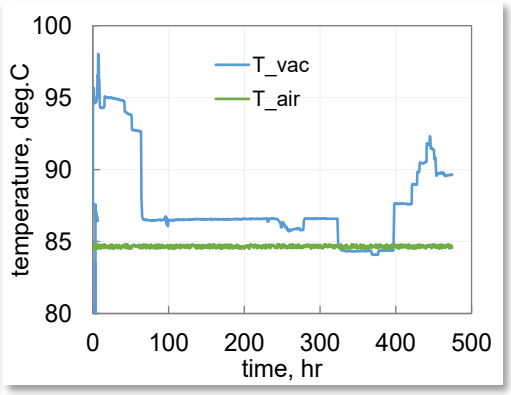
- No failures for 800 hrs, both in air and vacuum, for BP1 and CP8 capacitors.
- A similar TTF distributions and behavior of leakage currents for AP1 parts.
- Earlier WO failures in vacuum for DP1 capacitors are due to problems with temperature stabilization.











- ✓ No significant difference in TTF distributions in vacuum and air.
- ✓ Thermal management affect results of HALT in vacuum.

Conclusions

- Reliability of AEC-Q200 parts might differ substantially.
- Most failures for MTCs were due to IM and to WO processes for PTCs. More than 50% of samples in some MTCs fail HALT due to WO.
- AF_V can be described with an exponential function and explained by TDDB model that provides conservative reliability predictions compared to the power model.
- Low FR for parts with WO failures might not guarantee reliability during the mission. Assessments of useful life provide more adequate reliability predictions.
- PTCs generally exhibit higher reliability than MTCs and have more than 10 times lower probabilities of failures during a 10-year operation.
- LL-Weibull modeling enabled simulations of the burn-in efficiency and assessments of risks of consuming useful life of the parts.
- Preliminary data indicated no significant differences in the behavior of PTCs during HALT in vacuum versus air chambers.