Reliability Assessments for AEC-Q200 Tantalum Capacitors

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Abstract

This presentation is based on two capacitor tasks for 2025:

- Evaluation of Thin Dielectric Metallized Polymer Film Capacitors
- Evaluation of Automotive Grade Tantalum Capacitors for Space Applications

Different approaches for reliability assessments of capacitors are discussed, and preliminary evaluation results of automotive grade polymer and MnO_2 tantalum capacitors using highly accelerated life testing (HALT) are reported.

List of Acronyms

ACC	anomalous charging current	**MTC**	MnO2 tantalum capacitor
BI	burn in	**PoF**	physics of failure
CL	confidence level	**PTC**	polymer tantalum capacitor
CD	cumulative damage	**RH**	relative humidity
DCL	DC leakage	**TDDB**	time dependent dielectric breakdown
ESR	equivalent series resistance	**TTF**	time to failure
FR	failure rate	**UL**	useful life
HALT	highly accelerated life testing	**VBR**	voltage breakdown
IM	infant mortality	**VR**	voltage rating
IL	Initial level	**WGT**	Weibull grading test
MIL	Military	**WO**	wear-out

Tasks 2025

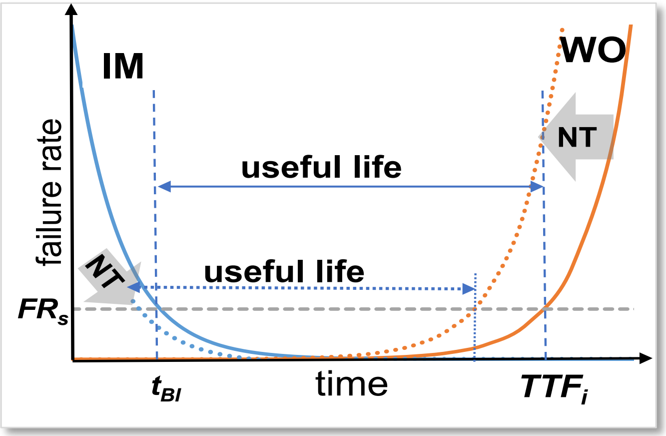
- Thin Dielectric Metallized Polymer Film Capacitors (750uF 60V and 5uF 1kV)
  - Effect of environments
  - Reliability acceleration factors

- Automotive Grade Tantalum Capacitors
  - Effect of environments on characteristics (including DCL, VBR, and ACC)
  - Reliability evaluation of AEC-Q200 tantalum capacitors using HALT

Outline

- Methods of reliability assessment
  - Life test
  - Weibull Grading Test
  - Field returns
  - HALT
- Used part types and HALT conditions
- Preliminary HALT results
- Effect of vacuum
- Conclusion

Methods of Reliability Assessment



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

- ✓ Reliability characterization by FR is a useful simplification.
- ✓ MIL specs give FR assessments at rated conditions, whereas field return at derated conditions.
- ✓ Characterization by FR only neglects the possibility of WO during mission.

Reliability Assessments

- What are failures (catastrophic/parametric/scintillations) per MIL and AEC-Q200 specs?
  AEC: manufacturer's criteria (DCL after life testing from1.25X to 10X IL; ESR from 1 to 3X IL)
- Field returns, SAE-J3083 (March 2017)
  Automotive standards allow for using statistics based on field returns as an alternative to the handbook-based reliability prediction

$$FR_{fr} = {}^{1}/_{MTBF} = \frac{n}{\sum_1^N T_i} \qquad FR_{fr} \sim \frac{n(?)}{N(?)t(?)}$$

Typical FR requirements:
≤ 1E-7 1/hr for L1/2,
≤1E-6 1/hr for L3.

- Life testing

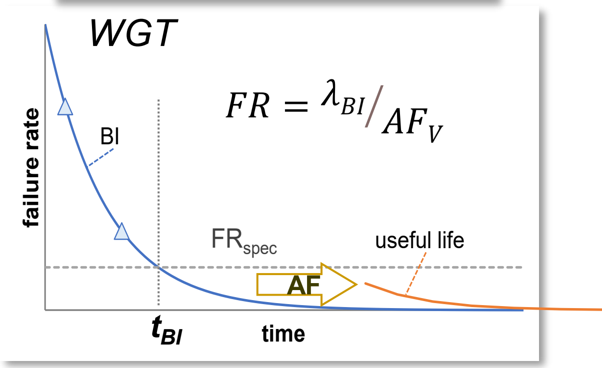
$$FR_{LT} = \frac{\chi^2(\alpha, 2n+2)}{2} \times \frac{1}{AF} \times \frac{1}{N \times t}$$

α - confidence level,
n - number of failures

AEC-Q200: N=3×77, n=0, t=1000 -> FR ≈1E-5 1/hr at 85C.
(231/0 -> max. percent defective: 1% at 90% confidence)

- Weibull Grading Test, WGT (β <1, t = ?);

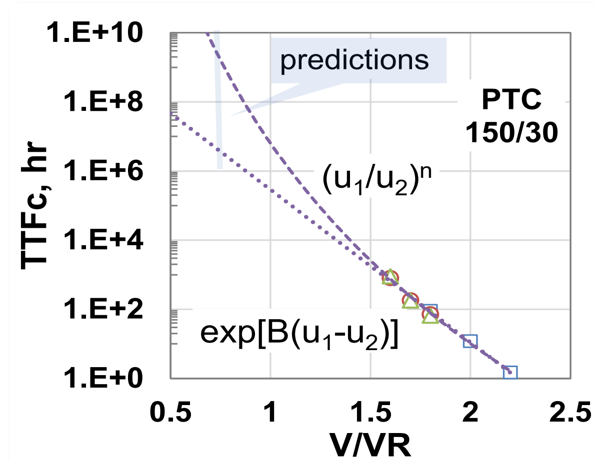
$$FR_{WGT} = \frac{\beta}{\eta} \times \left(\frac{t}{\eta}\right)^{\beta - 1}$$



- ✓ Each method has benefits (mostly drawbacks) and give different FR.
- ✓ Field returns can potentially provide the most accurate FR assessments for specific application conditions (1000hr testing ~ 2.7y application in cars).
- ✓ Life test and WGT require AF.

Acceleration Factors

- Two major stress factors for capacitors: voltage (*u=V/VR*) and temperature
- VR is a technical characteristic that is critically important for reliability
- Most reliability tests are carried out at accelerated conditions, and FR is as accurate as AF
- Predictions for use (derated) conditions also depend on AF
- *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 HALT and justified using PoF approach that describes WO degradation processes

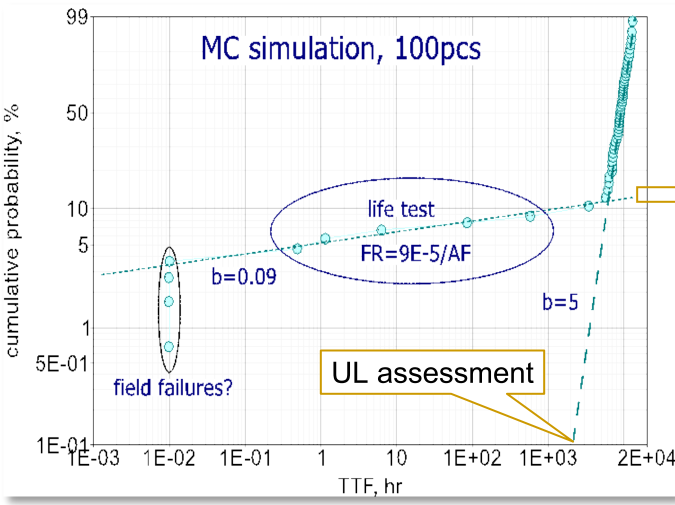


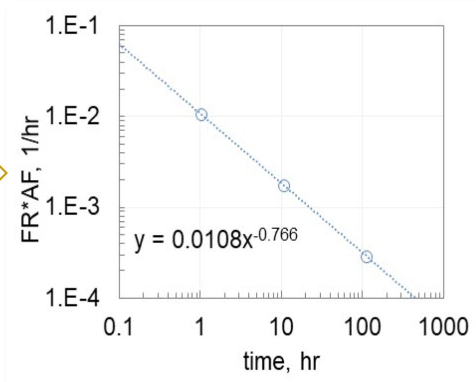
- Can the same AF be used for IM, “random”, and WO failures?
- Literature data on AF:
  - Ta MnO2: 0.15 < E_a < 2.1 eV, 10 < B < 20 (*B* = 18.77 per M55365)
  - Ta polymer: 0.7 < E_a < 1.75, 5 < *B* < 13 (AFs are determined experimentally per M32700)

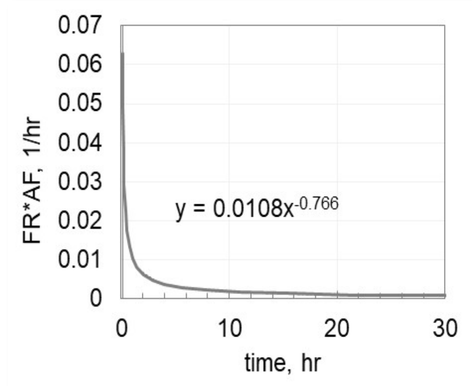
✓ Both presentations for AF$_V$ describe HALT results accurately.
✓ Power AF$_V$ model is much more optimistic than the exponential model.
✓ Based on TDDB model: *AF$_T$ = f(V) and AF$_V$ = f(T) and AF$_V$ ~ exp(Bu).*

Reliability Assessments Using HALT

FR assessment using Life Test and WGT

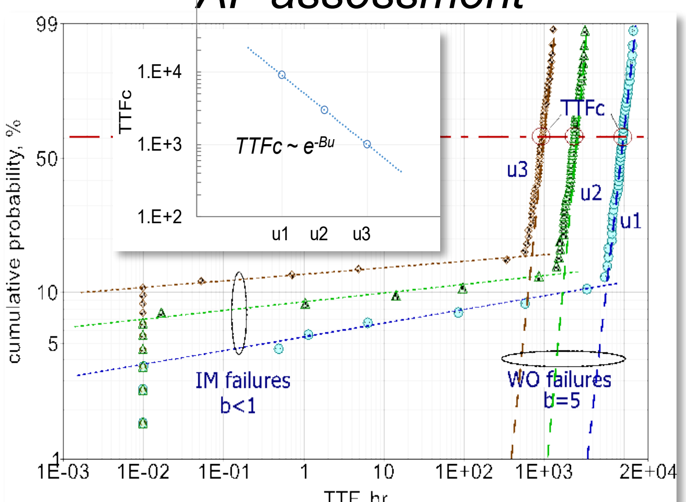






$$UL = TTF_i = TTF_c(VR,TR) \times AF_V \times AF_T \times [-\ln(1-P)]^{1/\beta}$$

AF assessment



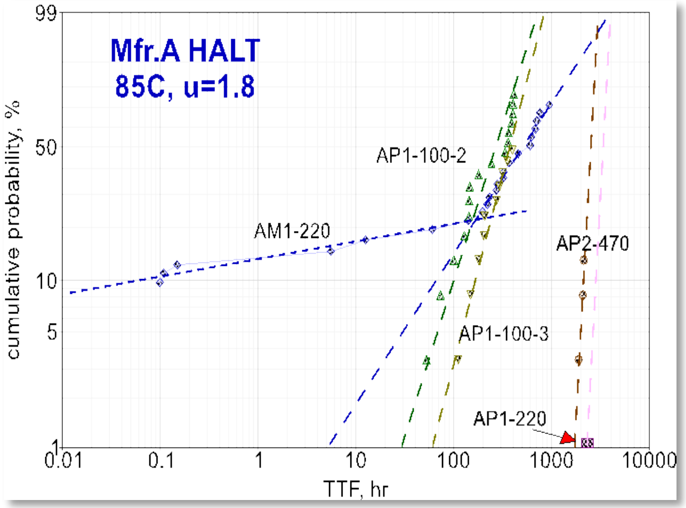
- ✓ TTF distributions in Weibull coordinates allow for simple discrimination of IM and WO failures.
- ✓ HALT allows for assessments of AF for WO failures that might have physical interpretation.
- ✓ Assessments of AF for IM failures are less accurate and require more samples.
- ✓ TTF predictions for operating conditions allow for UL calculations.

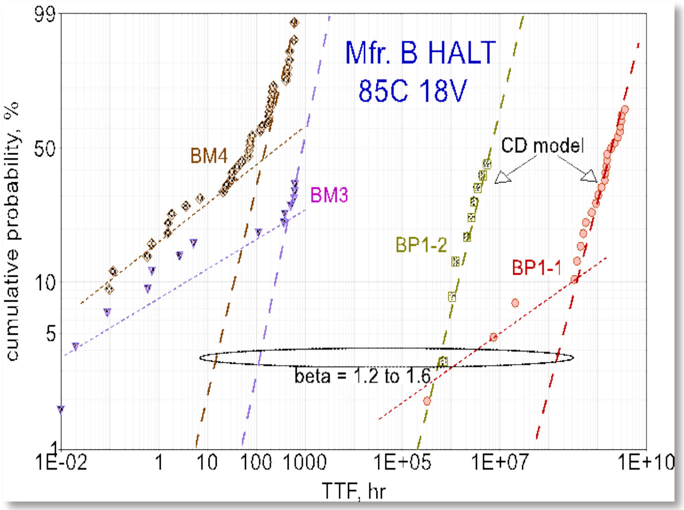
Part Types and HALT Conditions

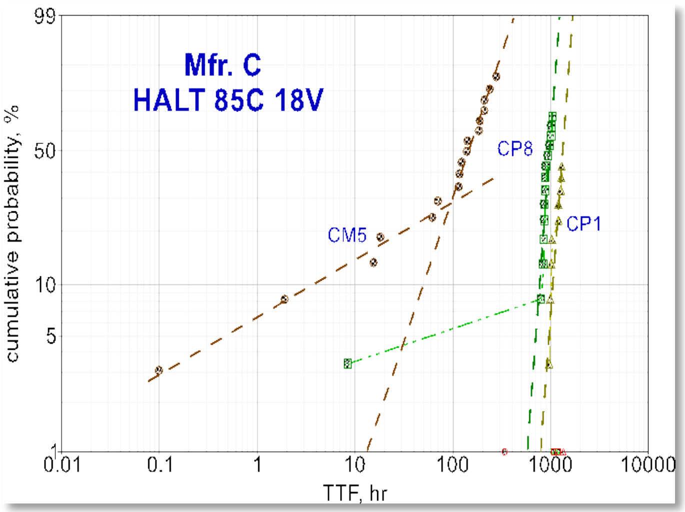
Group	C, uF	DF, %	ESR, mohm	DCL, uA	T_{max}, C	Notes	LDC	Prod.
AP1-220	220	6	25	220	125	Czech Rep.	2244	
AP1-100-1	100	6	25	100	125	Czech Rep.	2410	
AP1-100-2	100	6	25	100	125	Czech Rep.	2426	
AP1-100-3	100	6	25	100	125	Czech Rep.	2424	
AP1-100-4	100	6	45	100	125	Czech Rep.	2235	
AP2-470	470	10	15	470	125	Czech Rep.		
AM1-220	220	8	100	22	125	Czech Rep.	2329	
BP1-100-1	100	10	40	100	125	Japan	2311	2023
BP1-100-2	100	10	40	100	125	Japan	2302	2023
BP2-220	220	10	40	220	125	USA	2404	2022
BM3-100	100	8	100	10	125	China	2422	2013
BM4-220	220	8	500	22	150	USA	2348	
CP1-220	220	10	25	220	125		2419	2015
CP8-220-1	220	10	40	220	125	China	2335	2015
CP8-220-2	220	10	40	220	125	China	2452	2015
CM5-220	220	8	100	22	125		2237	
DP1-220	220	10	25	220	105		2201	
DP2-150	150	10	25	150	125	Japan	2210	

- ✓ All parts were rated to 10V and had footprint size 7343.
- ✓ 4 types of MnO2 and 8 types (14 lots) of polymer caps from 4 Mfrs.
- ✓ Monitored HALT conditions: 85C, 18V to 26V, 62mA fuses (0.1A/1sec).

HALT at 85C 18V



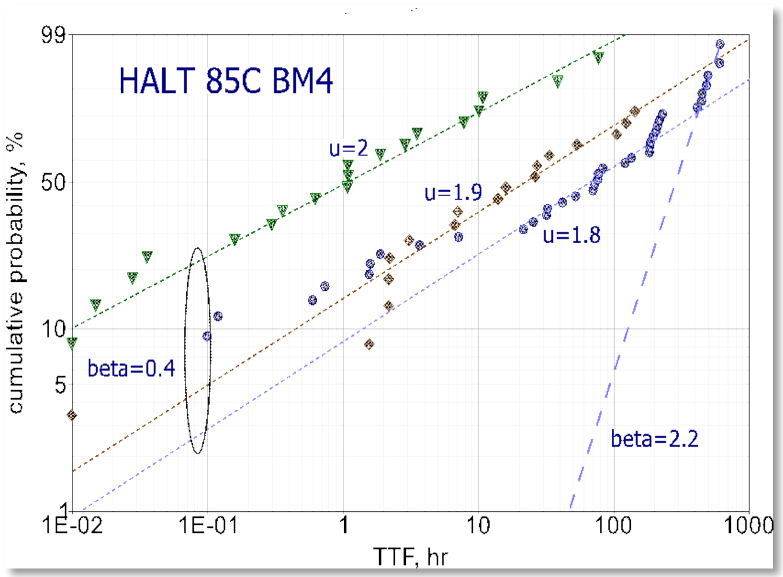


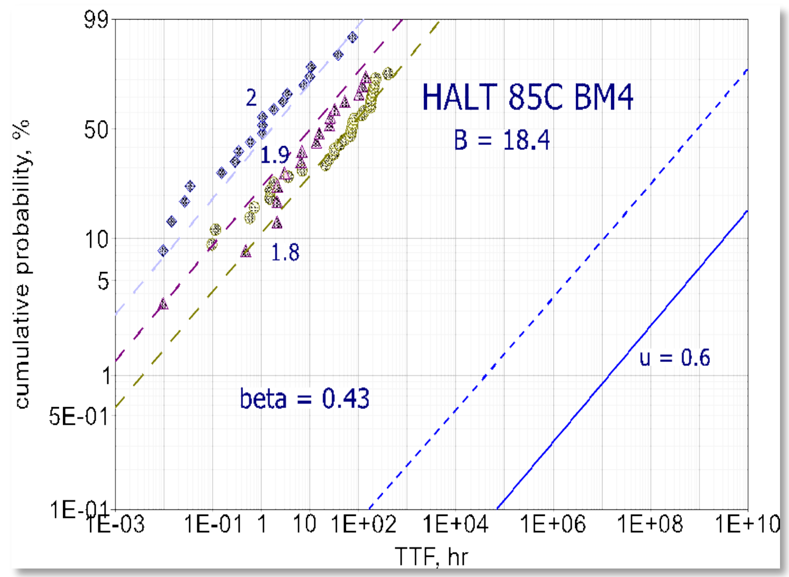


- ✓ Probabilities of failure differ substantially
- ✓ Reliability of PTCs is higher than for MTCs
- ✓ All MTCs had both, IM and WO failures
- ✓ Proportion of IM failures varied from 0 to 60% and is greater for MTCs, whereas majority of PTC failures is due to WO

Reliability Estimations for BM4-220

- Most failures are due to IM
- Log-Linear model predictions at use conditions (85C, *u* = 0.6):
  - Initial FR at 85C and *u* = 1 (1hr) = 8.5E-5 1/hr and 1.7E-6 after 1000hr
  - Probability of failure for 10 years, P(10y) = 1.1E-3 (1.4E-2 at 90% CL)
  - Conditional probability of failure for 10y after 40 hr BI at *u* = 1.3 is below 1E-6

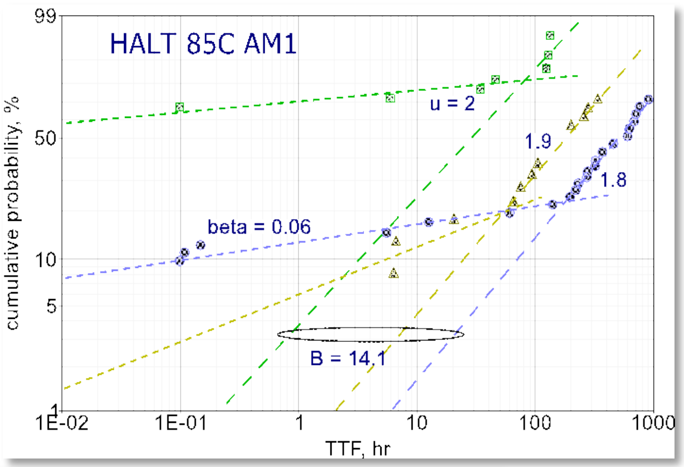


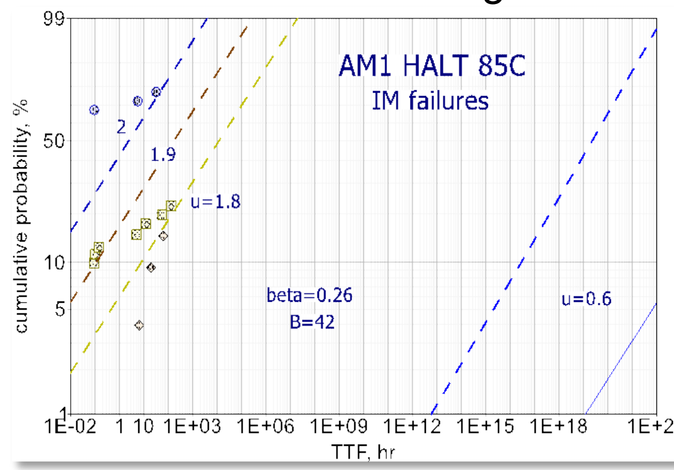


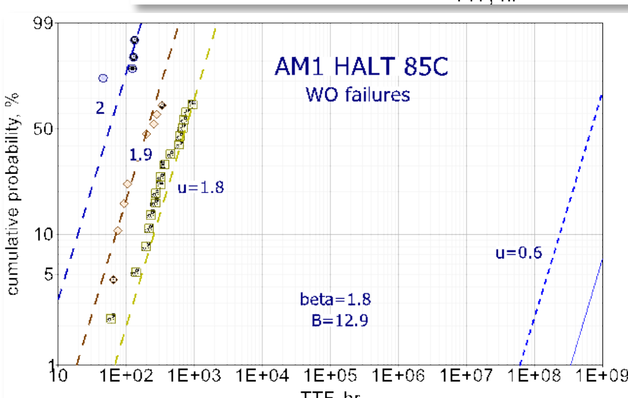
- ✓ Voltage acceleration constant *B* = 18.4 is close to the MIL spec. (18.77).
- ✓ Burn-in would help to reduce the risk of failure substantially.

Reliability Estimations for AM1-220

- AM1-220 capacitors have both, IM and WO failures
- Log-Linear model predictions at use conditions (85C, u = 0.6):
  - The probability of WO failures during 10y, is 4.8E-9 (1.9E-7 at 90% CL)
  - A wide spread of IM data does not allow for accurate modeling.







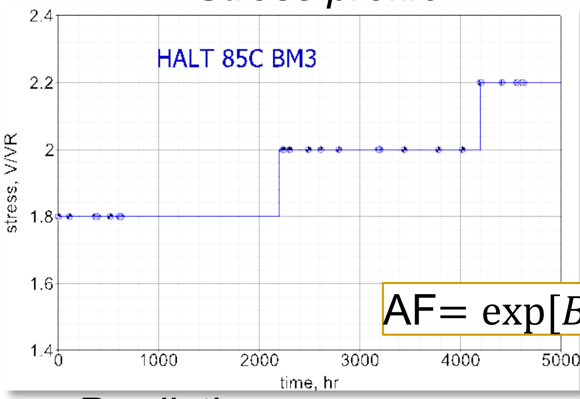
✓ Voltage acceleration constant for WO failures is 12.9, and the probability of WO failures during a 10y mission is negligibly small (1.9E-7).

✓ Due to insufficient data, the voltage acceleration constant is anomalously large and accuracy of predictions for IM failures is low.

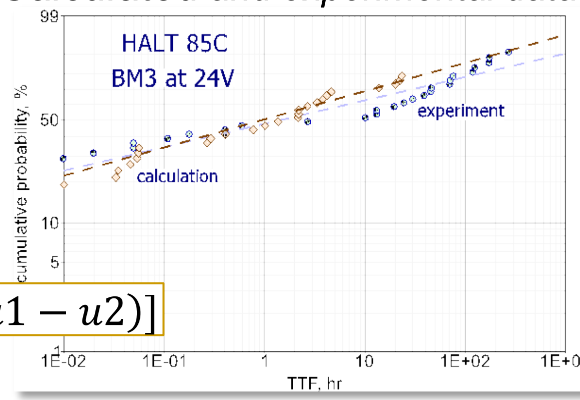
Reliability Estimations for BM3-100

- Problem with selection of HALT conditions: generation of a substantial number of failures within ~1000 hours
- Results of life testing at various stresses can be analyzed using Cumulative Damage model (exponential life-stress relationship)

Stress profile

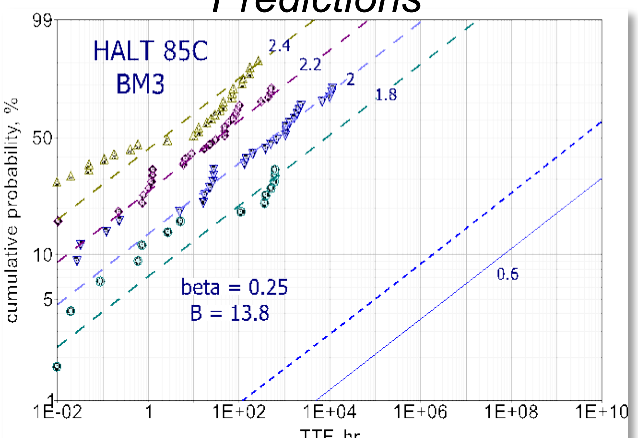


Calculated and experimental data



$$AF = \exp[B \times (u1 - u2)]$$

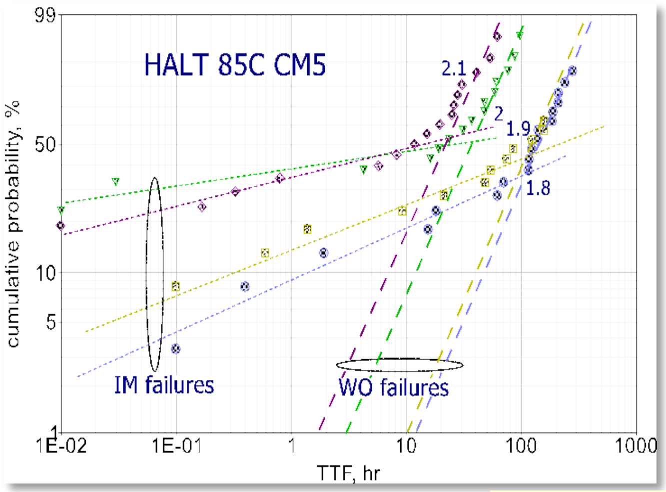
Predictions

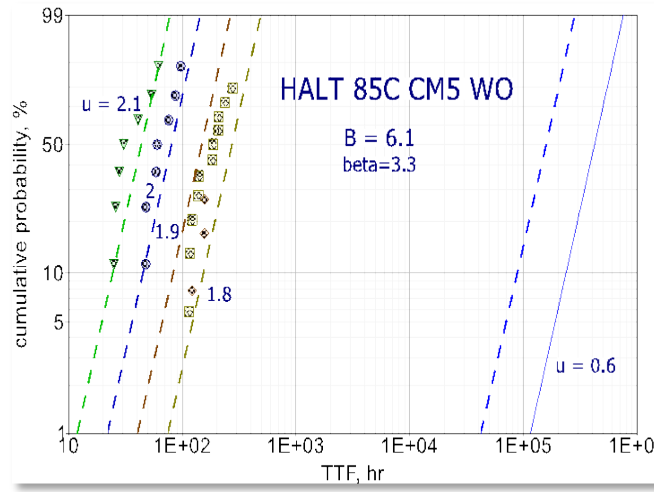


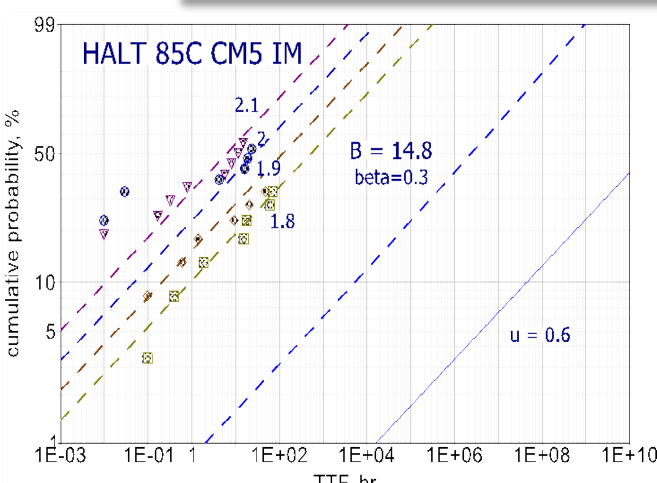
- ✓ All failures can be characterized as IM with B = 13.8.
- ✓ CD model is useful for various stresses.
- ✓ At operating conditions (85C, 6V), P(10y)=2% (5% at 90% CL).
- ✓ Conditional probability of failure during a 10y mission after 40 hr BI at *u* = 1.3 is 4.3E-7.

Reliability Estimations for CM5-220

- Up to 50% of CM5 parts are failing due to IM, and WO failures can be observed within dozens or hundreds of hours







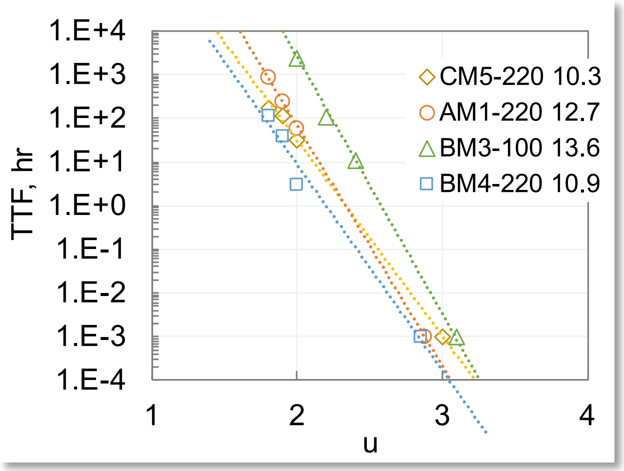
- ✓ Voltage acceleration constant for WO failures is 6.1 and 14.8 for IM failures.
- ✓ Predictions for reliability for a ten-year mission at 85C, *u* = 0.6 using a Log-Linear model:
  - The probability of WO failures is 4.2E-3 (0.11 at 90% CL).
  - The probability of IM failures is 1.7% (21% at 90% CL).

TDDB Model

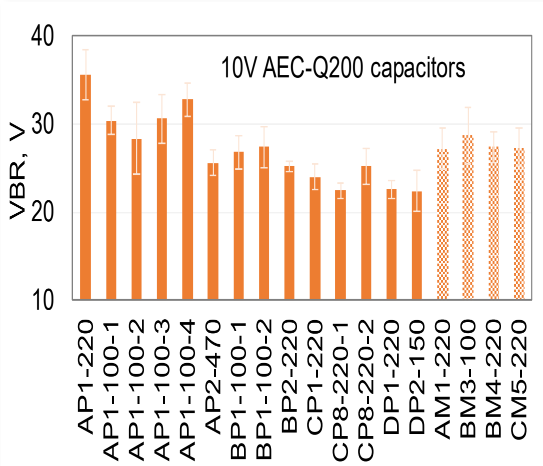
- A modified thermochemical TDDB model allows for expressing constant B as a function of u_{BR}:

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

- Breakdown voltages sets the limits for the stress test voltages



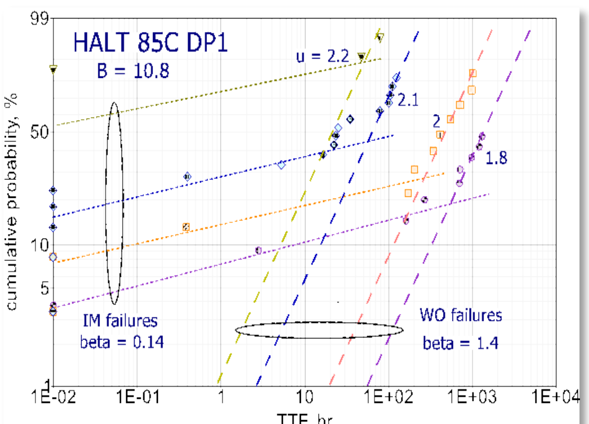
Breakdown voltages

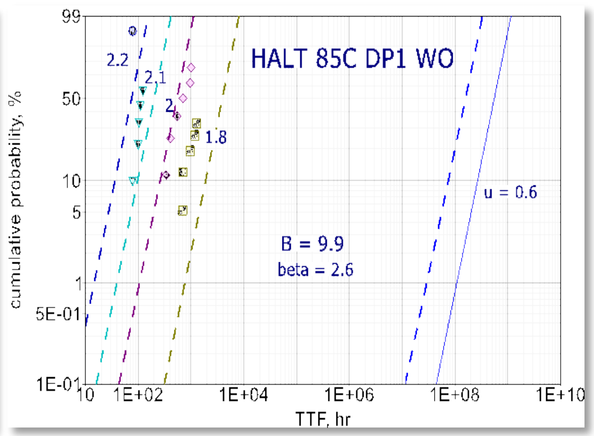


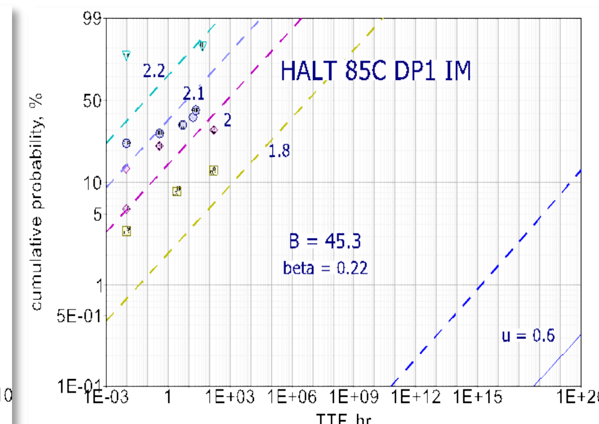
- ✓ Results for MTCs support TDDB model.
- ✓ Based on TDDB, AF_v for IM should be larger than for WO failures.
- ✓ Breakdown voltages in different types of tantalum capacitors rated to the same voltage differ substantially.

Reliability Estimations for DP1-220

- ❑ DP1 PTCs in many aspects (ACC, DCL) behave as a MnO2 parts
- ❑ EDS was not conclusive in detecting MnO2 in the cathode materials
- ❑ A substantial proportion of failures during HALT was due to IM



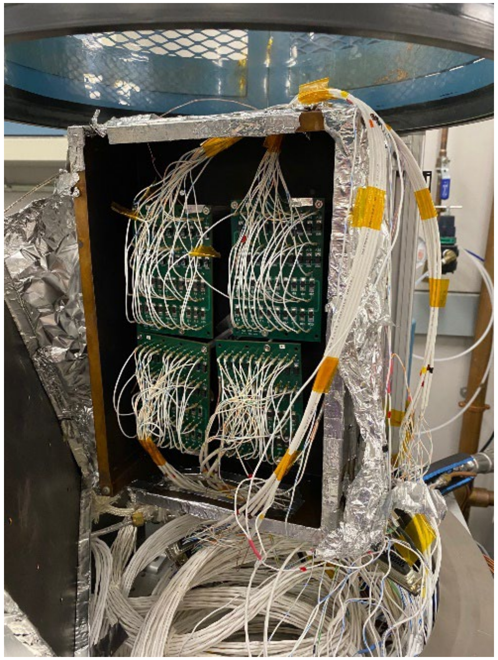




- ✓ Voltage acceleration constant for WO failures is 9.9 but due to a poor approximation of distributions for IM failures using the same β, additional data are required for reliability prediction.
- ✓ The risk of WO failures for a ten year mission at 85C and *u* = 0.6 is negligibly small (1.5E-8).

Effect of Vacuum

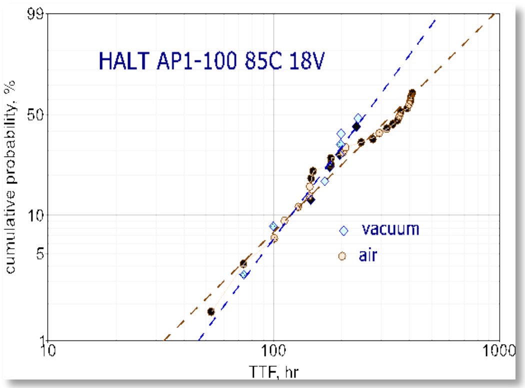
- Anomalous transients in PTCs, specifically ACC, are highly sensitive to the presence of moisture
- The assumption that degradation of PTCs in air and vacuum are the same might not be true
  (At 20C and 40% RH in room, humidity in temperature chamber is 1.8% at 85C and 0.45% at 125C)
- Four part types (AP1-100, BP1-100, CP8-220 and DP1-220) were tested in vacuum (1E-6 torr ,85C) at the same conditions as in air

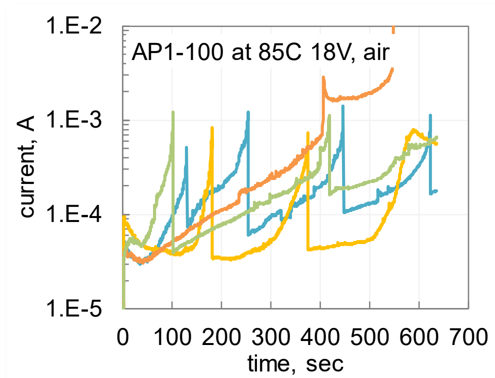


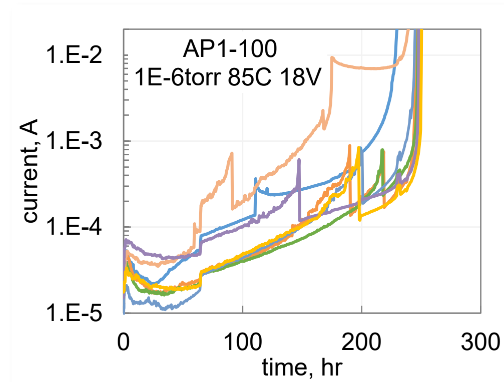
- ✓ Although moisture is considered a hazard for electronic components, some processes in PTCs are activated by the absence of moisture.
- ✓ The purpose of vacuum testing was to verify that reliability testing in vacuum and air give similar results and the worst-case ACC conditions can be simulated by baking in air.

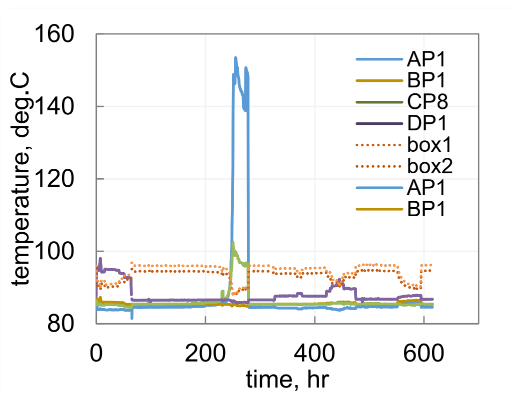
Effect of Vacuum, Cont’d

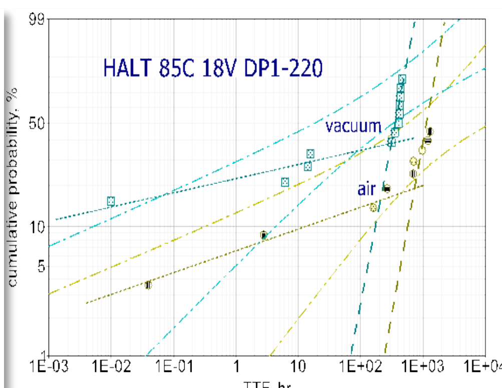
- No failures for 800 hrs, both in air and vacuum, for BP1 and CP8 capacitors
- A similar TTF distributions and behavior of leakage currents for AP1 parts
- Earlier WO failures in vacuum for DP1 capacitors are likely due to problems with temperature stabilization











- ✓Preliminary data indicate that the level of ACC in vacuum can be simulated by air baking.
- ✓No significant difference in TTF distributions in vacuum and air.
- ✓Thermal management affect results of HALT in vacuum.

Conclusions

- HALT allows for estimations of AF and reliability predictions for operating conditions
- Most failures for MTCs are due to IM and for PTCs to WO mechanisms
- Reliability evaluation of PTCs in air are valid for space
- Low FR might not guarantee low risk of failures during long-term missions
- Preliminary results of HALT are summarized below

Part type	B_IM	B_WO	AF_V (1.8 to 1)	Failures, % (18V 85C 1000hr)	FR (u=1, 85C)	P(10y, 90% c.l.) WO	P(10y, 90% c.l.) IM	need for BI
AP2-470	?	5.8	1.0E+02	80	1.11E-06	5.9E-5	?	no?
AM1-220	42?	12.9	3.0E+04	0	3.62E-08	1.9E-07	?	yes?
BM3-100	13.8	NA	6.2E+04	87.5	8.07E-09	NA	0.05	yes
BM4-220	18.4	NA	2.5E+06	35	5E-10	NA	0.014	yes
CP8-220-1	?	13.7	5.8E+04	100	1.44E-08	<1e-5	?	?
CM5-220	14.8	6.1	1.3E+02	55	9.4E-06	0.11	0.21	yes
DP1-220	45.3?	9.9	2.8E+03	90	2.25E-07	1.5E-08	5.3E-5?	?

? = more data needed