Voltage Acceleration Factors for Infant Mortality Failures and Derating of Solid Tantalum Capacitors

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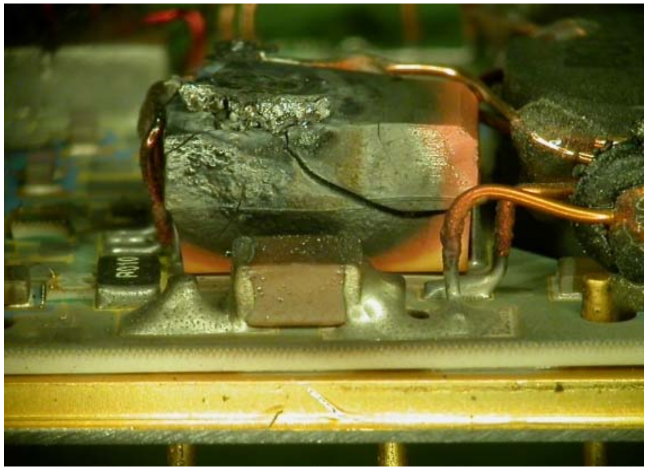
Acronym Table

FR	failure rate
HALT	highly accelerated life testing
IM	infant mortality
LSST	life step stress testing
OEM	original equipment manufacturer
RT	room temperature
TCM	thermo-chemical model
TDDB	time dependent dielectric breakdown
TTF	time-to-failure
WGT	Weibull grading test

Outline

- Failures of tantalum capacitors as time dependent dielectric breakdown (TDDB).
- Justification for Weibull Grading Test (WGT).
- Errors associated with WGT.
- Results of highly accelerated life testing (HALT).
- Results of life step stress testing (LSST).
- Voltage acceleration factors.
- Voltage derating as a means to increase reliability of tantalum capacitors.
- Conclusions.



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Life Test Failures as TDDB

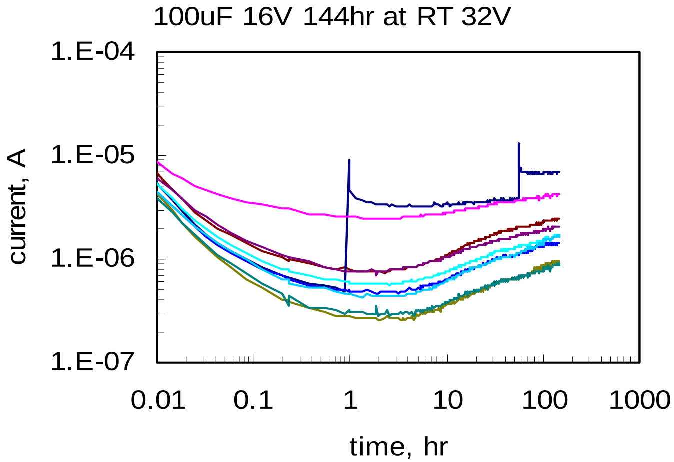
- Thermo-chemical model (TCM) of TDDB: $TTF = t_o \times \exp\left(-\gamma E + \frac{\Delta H}{kT}\right)$

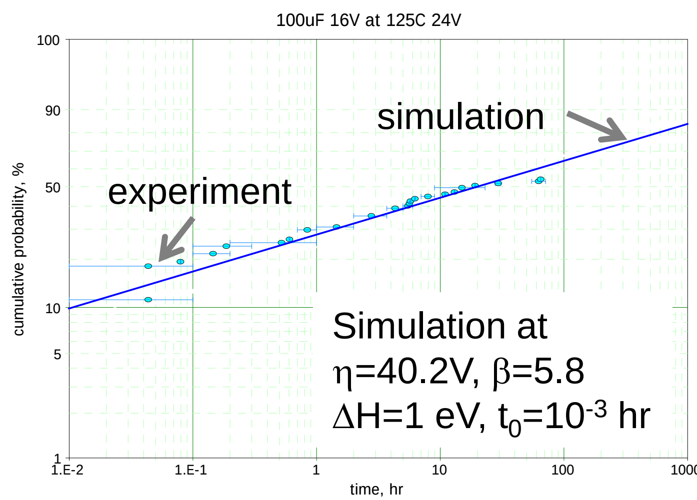
  ΔH -energy for ions displacement, γ - field acceleration parameter, t_o - time constant.

- Time-to-failure, TTF, can be calculated based on distribution of breakdown voltages, V_{BR}:

$$V_{BR} = \eta_{BR} \times \left[-\ln(1-p)\right]^{1/\beta}$$

$$TTF = t_o \times \exp\left(\frac{\Delta H}{kT}\right) \times \exp\left(-\frac{\Delta H}{kT} \times \frac{V}{V_{BR}}\right) = t_o \times \exp\left[\frac{\Delta H}{kT} \times \left(1 - \frac{V}{V_{BR}}\right)\right]$$





- ✓ Scintillations during life testing should be considered as failures.
- ✓ Life test results can be simulated using the TDDB model, but parameters should be adjusted.

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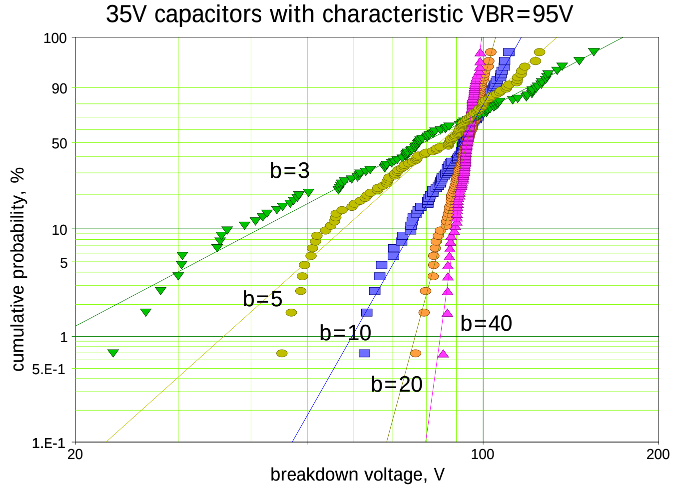
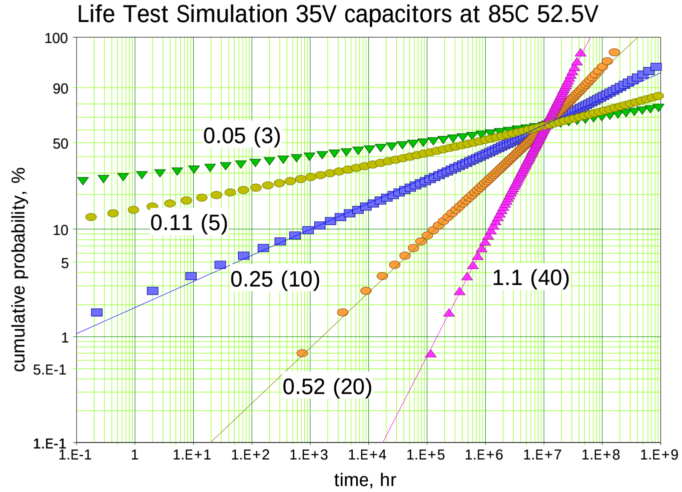
Modeling of Infant Mortality Failures

- Experimental distributions of TTF for chip Ta capacitors in most cases can be described as 2-parameter Weibull function with $\beta < 1$
- Majority of test failures can be considered infant mortality (IM) failures.

Monte-Carlo simulation of VBR distributions at different β



Times to failure calculated based on TDDB model



- ✓ At the range of β_{BR} that is typically observed for tantalum capacitors (5 to 20), simulations show that all failures, up to the end of life, are defect related IM failures ($\beta_{life\ test}$ <1).
- ✓ High quality lots with tight V_{BR} distributions (β_{BR} ~40) fail due to wear-out.

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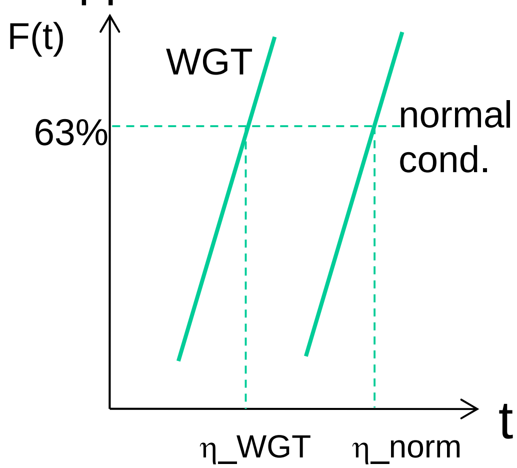
Weibull Grading Test

- To reduce the probability of failures under steady-state operating conditions, all hi-rel capacitors are screened by WGT.
- WGT is a combination of burn-in (screening to remove IM failures) and reliability qualification (testing to assess the failure rate, FR).
- If $\beta < 1$ and failures are monitored during the testing, then the test can be stopped when the necessary FR is achieved.



$$F(t) = 1 - \exp\left[-\left(\frac{t}{\eta}\right)^{\beta}\right] \qquad \lambda(t) = \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1}$$

$$\beta_{norm} = \beta_{WGT} \qquad \eta_{norm} = AF \times \eta_{WGT}$$

$$\lambda_{WGT}(t_{WGT}) = AF \times \lambda_{norm}(AF \times t_{WGT})$$

Original notion [Didinger'64]: "*to pay for only as much grading as needed, without the risk of getting too little or overpaying for too much reliability*".

- ✓ The notion that reliability cannot be screened out, but should be built-in by design and technology is related to random and wear-out failures.
- ✓ If all failures are due to IM, then any lot can be screened out to as high FR level as necessary.

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WGT Conditions

- WGT conditions per MIL-PRF-55365:
  - o 85 ºC for 40 hr and voltages from 1.1VR to 1.53VR.
  - o Failure is defined as a blown 1A or 2A fuse.
  - o Failures calculated at 2 hr and 40 hr of testing.
  - o FR is calculated using an empirical equation obtained ~ 40 years ego:

$$AF = 7.03412025 \times 10^{-9} \times \exp\left(18.77249321 \frac{V}{V_R}\right)$$

- Considering that at V = VR AF= 1: $AF = \exp(B \times u)$ $u = \frac{V}{VR} - 1$

  <u>*B* is the voltage acceleration constant</u> (*B = 18.77249321 ?*)

- Life test at 85 ºC can confirm λ ~1%/1000hrs which is more than 100 times greater than is required for T-grade capacitors.

MIL-PRF-55355 requires 2000 hrs testing of 102(1) parts at V = VR and 85 ºC or 24(0) at V = 2/3VR and 125 ºC.

$$\lambda = \frac{\chi^2(\alpha, 2n+2)}{2} \times \frac{1}{AF} \times \frac{10^5}{N \times t}$$

- ✓ Existing life test conditions are not sufficient to assure the required reliability level, so FR is determined by WGT.
- ✓ Long-term reliability is determined by a 40-hr accelerated test!

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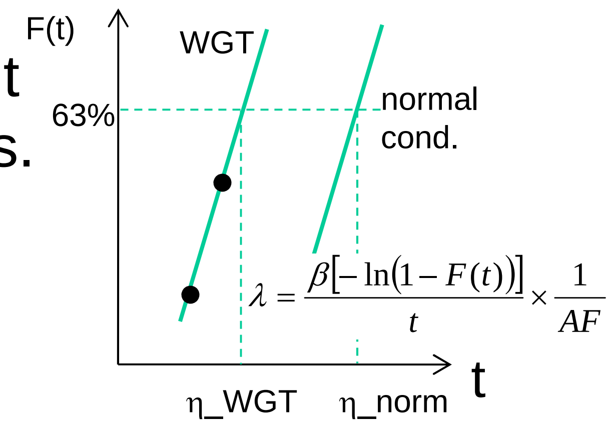
WGT Problems



- Two groups of problems for FR assessment using WGT: test conditions and calculations.
- Problems with test conditions:
  - Verification of contacts in fixtures.
  - Only 300 samples are used for calculations.
  - Test results with different fuses might be different.
  - Short current spikes below ~10A (scintillations) will remain unnoticed.
  - Only two points to draw the F(t) line and calculate β and η.
- Problems with calculations:

$$FR = \lambda_{norm}(VR, AF \times t_{WGT}) = \frac{\lambda_{WGT}(V_{WGT}, t_{WGT})}{AF}$$

  - Early failures (before 15 min) are neglected.
  - Calculations do not account for the uncertainty in time-to-failures.
  - Only two points are used for calculations.
  - If no failures observed, wear-out degradation (e.g. due to field-induced crystallization or V_o^{++} migration) can be missed.

✓ The most significant errors in FR, up to 3 orders of magnitude, are due to incorrect voltage acceleration factors.

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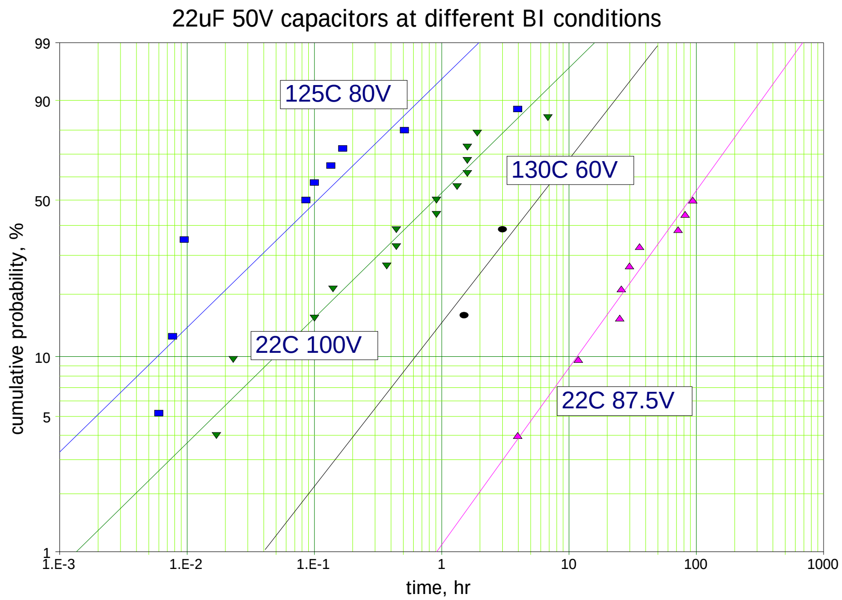
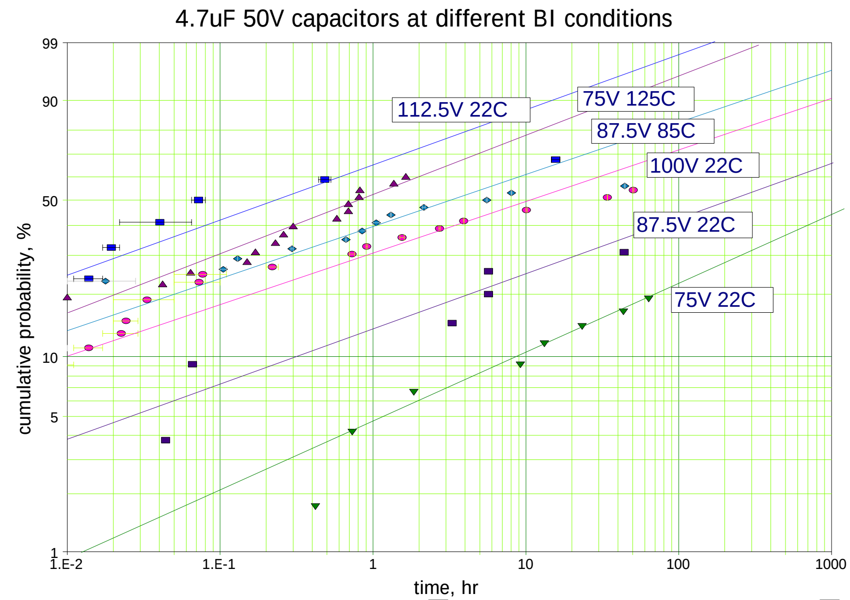
HALT at Different Test Conditions

- HALT for tantalum capacitors is limited compared to ceramic capacitors by low breakdown voltages (typically from 2.5VR to 3.5VR).

Results of HALT for 22 µF, 50 V and 4.7 µF, 50 V capacitors at different voltages and temperatures





Model prediction for characteristic life: $\eta = \eta_o \times \exp\left[\frac{\Delta H}{kT} \times \left(1 - \frac{V}{nV_R}\right)\right]$

Statistical Analysis Using ALTA-PRO

The characteristic life can be presented as a general log-linear relationship: $\eta = \exp(\alpha_0 + \alpha_1 X_1 + \alpha_2 X_2)$

Based on TDDB model, the following conversion was used:

$$\alpha_0 = \ln(\eta_0) \qquad \alpha_1 = \frac{\Delta H}{k} \qquad X_1 = \frac{1}{T} \qquad \alpha_2 = -\frac{\Delta H}{k \times n \times V_R} \qquad X_2 = \frac{V}{T}$$

Example of HALT results for three part types.

PART	Failures	Suspended	β	α_0	α_1	α_2	t_0, hr	ΔH, eV	n	B_85
4.7uF 50V	90	117	0.24	-15.06	12761.6	-68.61	2.9E-07	1.1	3.7	9.6
22uF 50V	40	41	0.40	-28.13	21026.1	-124.49	6.1E-13	1.8	3.4	17.4
22uF 63V	59	43	0.24	-28.45	25072.2	-145.03	4.4E-13	2.1	3.5	20.6

- ✓ Results for 7 different part types showed that the acceleration constant *B* varies from 10 to 20.

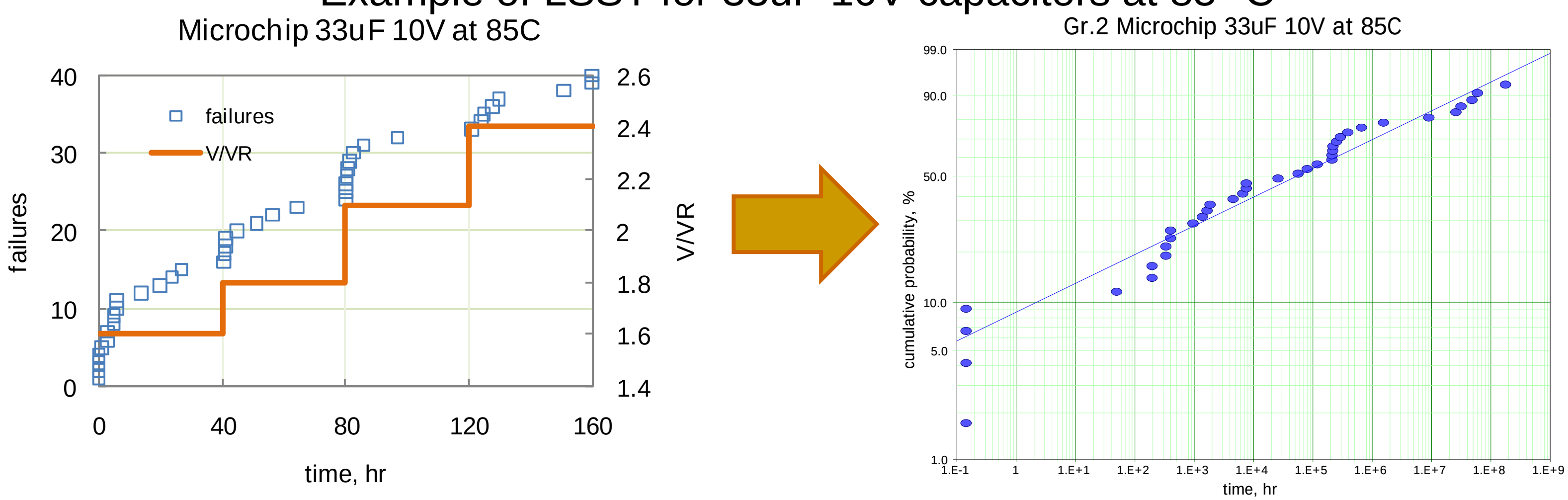
Life Step Stress Testing (LSST)

- LSST is a fast method to assess AF.
- Weibull-exponential cumulative damage model was used.
- Step duration 20 to 40 hrs.
- Testing at 22 ºC, 85 ºC, and 125 ºC allows for estimation of the voltage acceleration constant (*B*) and effective activation energy (E_a).

$$\eta = \exp\left(\alpha_0 + \alpha_1 \times \frac{V}{V_R}\right)$$

$$AF_V = \frac{\eta(V)}{\eta(V_R)} = \exp\left[\alpha_1 \times \left(\frac{V}{V_R} - 1\right)\right] = \exp(B \times u)$$

Example of LSST for 33uF 10V capacitors at 85 ºC



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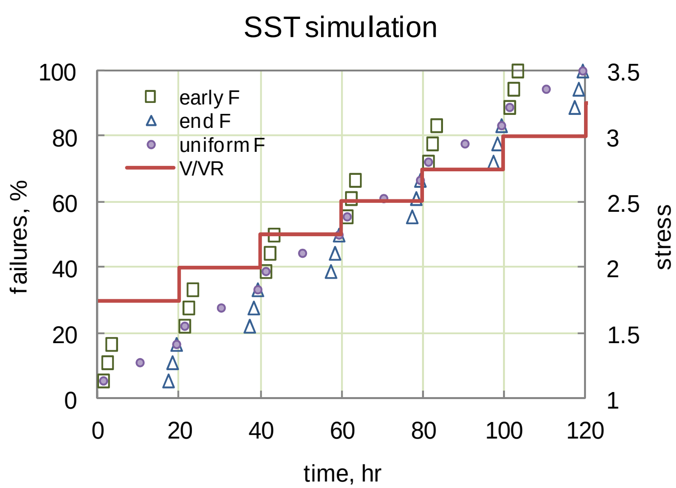
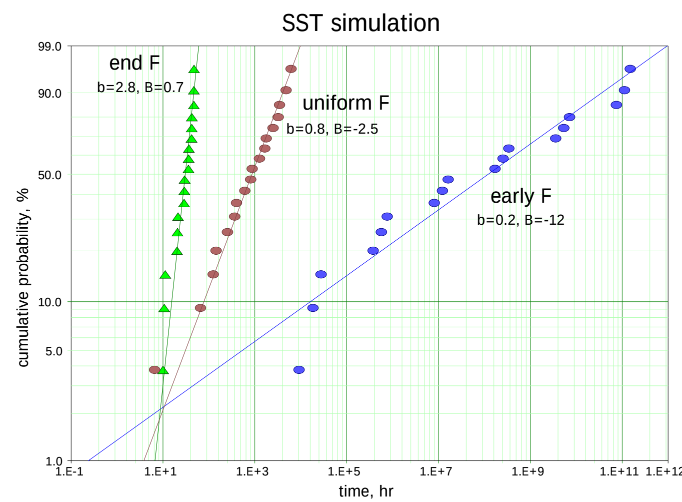
Specifics of LSST

- The model parameters, α_1, α_2, and β were computed using ALTA-PRO utilizing a maximum likelihood estimation (MLE) method.
- LSST simulation: *V/VR* varied from 1.75 to 3 at 6 20-hour steps.
  Three test results with 18 samples each were generated: 1 - early failures (three failures at each step after 1, 2, and 3 hr); 2 - failures occurred at the end of steps (after 17, 18, and 19 hrs); 3 - failures were distributed evenly through the steps (after 1 hr, 10 hr, and 19 hr).
- Results: $2\times10^3 < \eta < 2\times10^{10}$ hr, $0.2 < \beta < 2.8$, $0.7 < B < 12$.

Effect of TTF distributions on the use-level life calculations



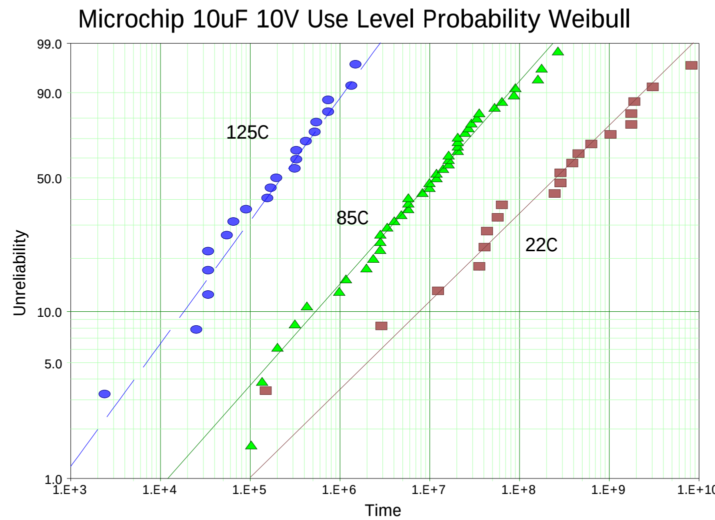


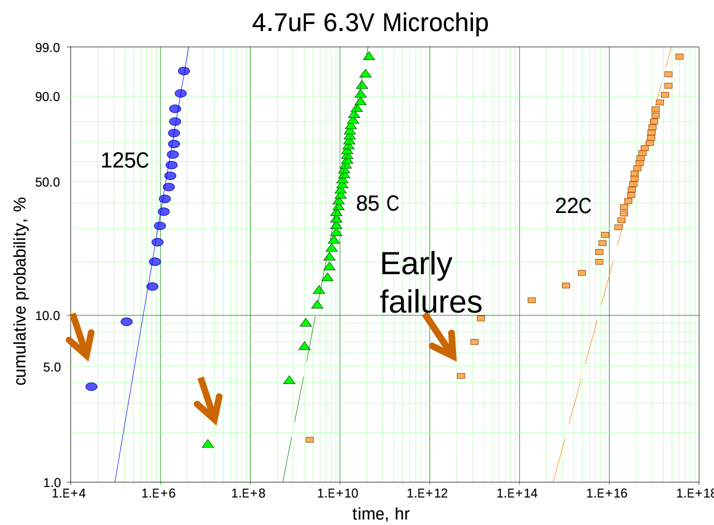
✓ Inaccuracy in TTF might result in substantial errors of reliability estimation.

Life Step Stress Testing Results

- ❑ 5 types of tantalum capacitors have been tested using LSST.
- ❑ One out of 5 groups had $\beta > 1$ indicating wear-out.
- ❑ Inception time was ~100 years at 125 °C and >10^{10} years at RT.
- ❑ This group had high V_{BR} thus indicating high quality dielectric.
- ❑ Early failures were likely due to defects in the oxide.

✓ High quality tantalum capacitors might fail due to wear-out mechanisms at high voltage stress conditions.





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Results of LSST at 85 ^{o}C

- At 85 ^{o}C: 6 < *B* < 18. Some lots deviate substantially from the accepted standard voltage acceleration constant (B_s = 18.77).
- FR calculated at conditions simulating Weibull grading test per MIL-PRF-55365 showed that microchip capacitors can be screened to high FR levels up T-level (0.001%/1000hr).

Part (C, VR)	case	QTY	β	α_0	α_1=-B	η(VR), hr	WGT FR, %.1000hr
33uF, 10V	µR	40	0.19	26.98	-14.12	3.85E+05	1.6E-02
10uF, 10V	µR	43	0.62	35.05	-18.23	2.01E+07	6E-03
47uF, 10V	µT	60	0.34	31.87	-9.92	3.39E+09	4.7E-04
4.7uF, 6.3V	µM	40	1.4	29.40	-6.02	1.43E+10	1.2E-11
4.7uF, 50V	C	40	0.32	29.7	-14.2	1.2E+08	5E-4

✓ Acceleration constants determined by LSST are consistent with HALT results and indicate substantial variations from the standard value.

Voltage Derating

- Derating is a reduction of operating electrical and temperature stresses used by original equipment manufacturers (OEM) to increase reliability of components compared to the rated conditions.
- For capacitors that passed WGT the probability of failure during a mission duration (t_M) can be determined using Weibull functions, F(t):

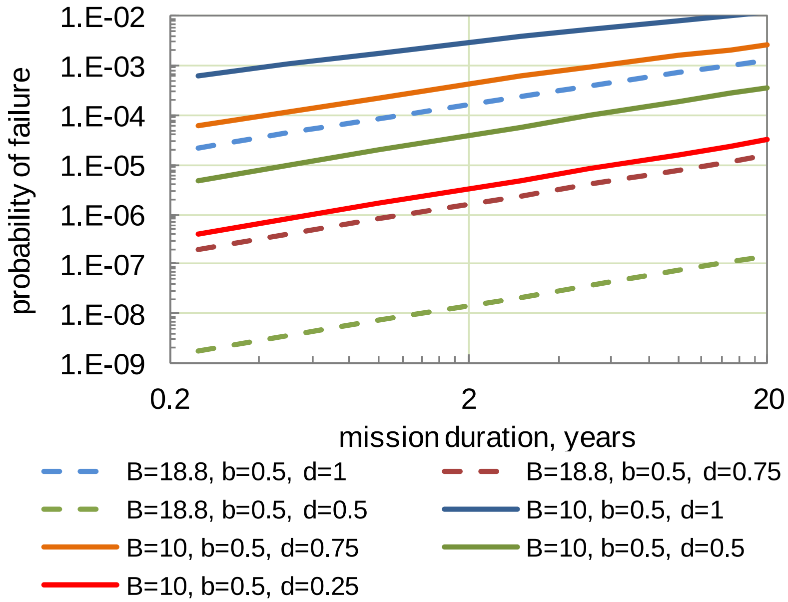
$$P(t_M) = \frac{F(t_M + AF \times t_{WGT}) - F(AF \times t_{WGT})}{1 - F(AF \times t_{WGT})}$$

- Suppose t_M = 10 years and the required reliability is P(10) < 3×10^{-5}. At FR = 0.001%/1000 hr (10^{-8} 1/hr) and V = VR, P(10) is ~ 8.8×10^{-4}, which exceeds the required level.
- At B = 18.772 derating to 0.8VR would reduce P(10) to below 2×10^{-5}, which is in compliance with the requirements.
- If the acceleration constant B is much smaller than it is assumed by MIL-PRF-55365, then a more severe derating is necessary.

Effect of Voltage Derating on the Probability of Mission Failure

$$P(t_M) = \frac{F(t_M + AF \times t_{WGT}) - F(AF \times t_{WGT})}{1 - F(AF \times t_{WGT})} \qquad F(t) = 1 - \exp\left[-\left(\frac{t}{\eta}\right)^{\beta}\right]$$

$$AF = \exp(B \times u) \qquad u = \frac{V}{VR} - 1 \qquad \eta(V) = \left[\frac{\beta \times (t_{WGT} \times AF)^{\beta-1}}{FR(V)}\right]^{1/\beta}$$



- Assuming t_{WGT} = 40 hr and nominal failure rate calculated at B = 18.772 FR = 10^{-8} 1/hr, the characteristic life, $\eta(V)$ was calculated at a given β.
- The probability of failure, $P(t_M)$, during mission time, t_M was calculated at different voltage derating d = V/VR.

Voltage Derating, Cont.'d

- Suppose B = 10, then AF would be ~100 times less than at B=18.77, and the part that have nominal FR =10^{-8} 1/hr would have FR = 10^{-6} 1/hr and P(10) = 8.4%.
- At this conditions voltage derating to 0.5VR would reduce AF to 0.0067, decrease FR to 6.7×10^{-9} 1/hr and P(10) to 5.6×10^{-4}, which is still larger than the required level.
- For such a capacitor derating down to 30%VR is necessary.
- Substantial errors of FR estimations refute the notion of WGT and the benefits of this test for the user.
- Excessive derating requires using capacitors with larger size and weight that makes them more susceptible to assembly failures.

✓ Without the knowledge of acceleration factors OEM cannot make a decision on how significant derating should be.

✓ The uncertainty in AF is compensated by a severe voltage derating.

Conclusion

- IM failures in tantalum capacitors can be simulated using the thermo-chemical model of TDDB and Weibull distributions of breakdown voltages at β_{BR}<40.
- Incorrect AFs used for WGT can change FR up to 10^3 times.
- The values of AF can be obtained using HALT and approximation of the test results with a general log-linear relationship.
- Although step stress testing allows for a fast estimation of AF, errors due to the uncertainty of time-to-failures might be substantial.
- Voltage acceleration constant B for tantalum capacitors varies for different part types in the range from 6 to 20.
- Substantial deviations of B from the “standard” value (B=18.77) requires severe voltage derating.