NASA Electronic Parts and Packaging (NEPP) Program

Parametric Failures in COTS Capacitors

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List of Acronyms

AF	acceleration factor	MLCCs	multilayer ceramic capacitors
BME	base metal electrode	NT	new technology
COTS	commercial off the shelf	PME	precious metal electrode
DCL	direct current leakage	PTC	polymer tantalum capacitors
ESR	equivalent series resistance	S&Q	screening and qualification
HALT	highly accelerated life testing	TTF	Time to failure
HTS	high temperature storage	WTC	wet tantalum capacitors

Outline

- General comments on insertion of COTS in hi-rel systems.
- Rating-related failures.
- Degradation-related failures.
  - Catastrophic and parametric failures in tantalum capacitors and multilayer ceramic capacitors (MLCCs).
  - ESR in polymer tantalum capacitors.
  - Degradation of leakage currents in tantalum capacitors.
- Conclusion.

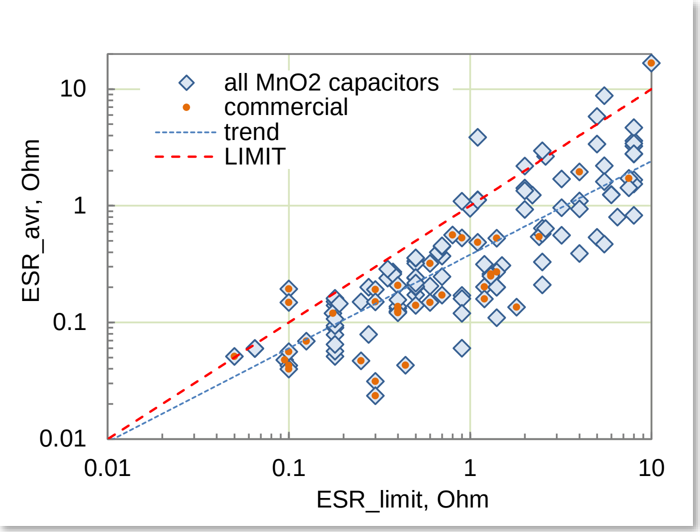
Two Approaches for COTS Insertion

1. Reliability of COTS is inferior to MIL parts, and to qualify for space one need to run extensive testing per the existing requirements.
   - The major concern is cost and time rather than technical issues.
2. COTS are NT devices and need analysis of new degradation processes and failure mechanisms.
   - Existing procedures for S&Q have to be evaluated and adjusted.
   - New mechanisms might require new testing techniques.
     - HTS does not affect MnO2 caps, but causes degradation of PTC.
     - Cracks in packages affect degradation of ESR in PTCs, but can be considered mostly as cosmetic defects for MnO2 caps.
     - Weibull grading testing works with MnO2 caps, but does not with PTC.

✓ "COTS as NT" approach requires understanding of new degradation mechanisms, specific reliability issues, and development of adequate S&Q procedures.
✓ The consistency of COTS quality still remains a problem.

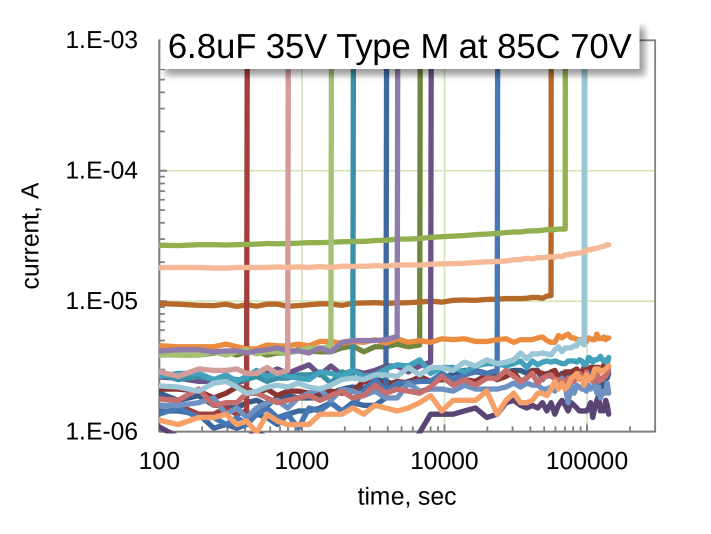
Rating-related Parametric Failures

- Failures during environmental testing might be due to the marketing pressure that forces manufacturers to squeeze performance of COTS components thus leaving insufficient margin between the rated and actual characteristics.
- Examples:
  - Ripple currents.
  - Temperature stability in wets.
  - Leakage currents in wets.
  - ESR in chip tantalum and polymer capacitors.

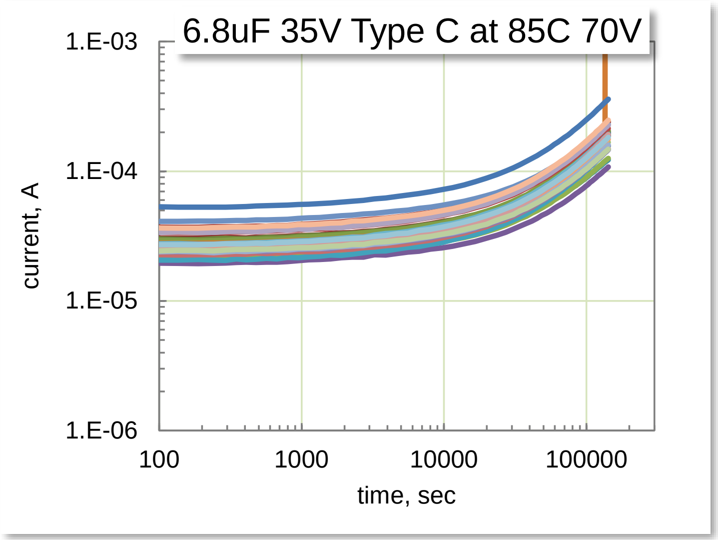


Catastrophic and Parametric Failures in MnO2 Tantalum Capacitors

Variations of leakage currents with time for two lots of 6.8 μF 35 V capacitors from the same Mfr. during 100hr HALT



Type I: A sharp increase of DCL indicating breakdown.

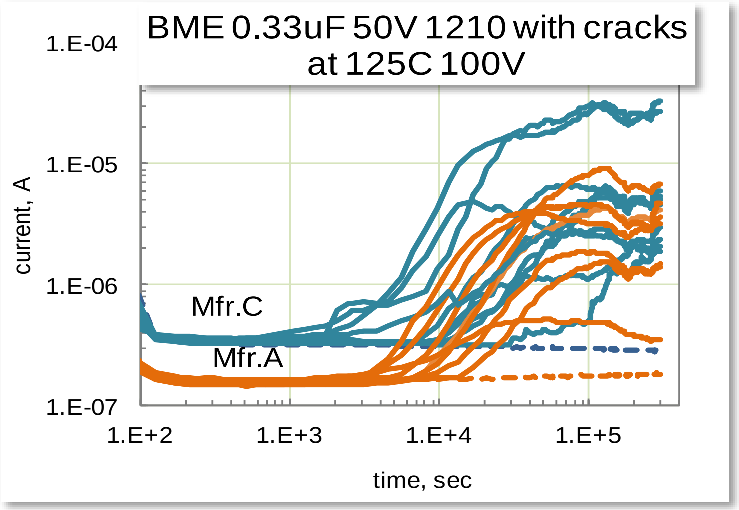


Type II: gradual increase of DCL resulting in parametric failures.

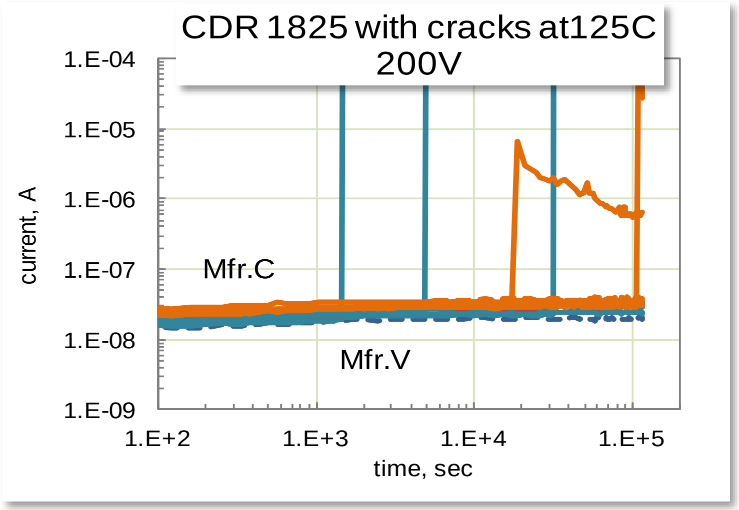
- ✓ Type I (catastrophic failures) is more often observed for MIL and Type II (parametric failures) for commercial capacitors.

Failures in BME and PME Capacitors

0.33μF 50V BME MLCCs with cracks



0.33μF 50V PME MLCCs with cracks



- ✓ Cracking in BMEs does not affect IR measured at 125 °C but facilitates degradation and parametric failures.
- ✓ Degradation in PMEs with cracks results often in instantaneous failures.
- ✓ Contrary to PMEs, degradation in BMEs occurs gradually and energy generated at the defect can be balanced by heat dissipation. “Leaky” BME capacitors often degrade, but do not fail catastrophically, whereas PME capacitors with prevailing avalanche-like breakdown might not degrade, but fail short circuit.

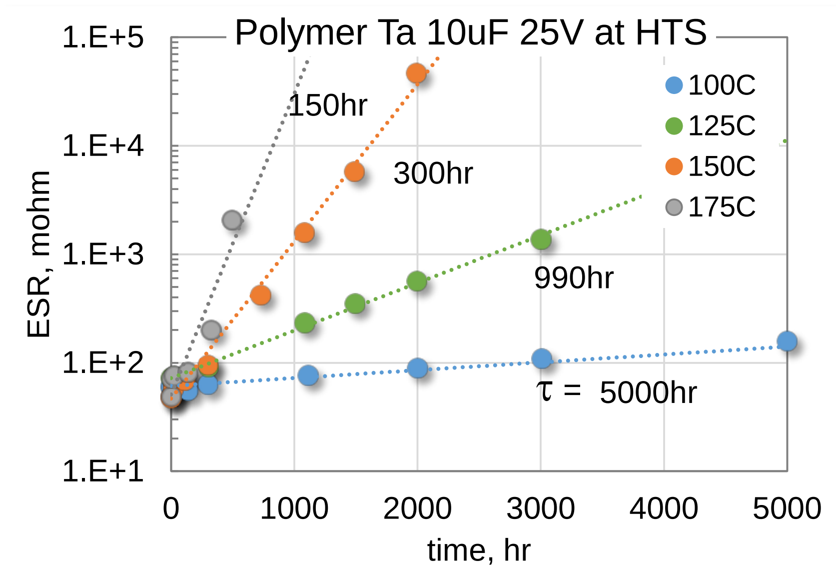
ESR Degradation in Polymer Ta Caps

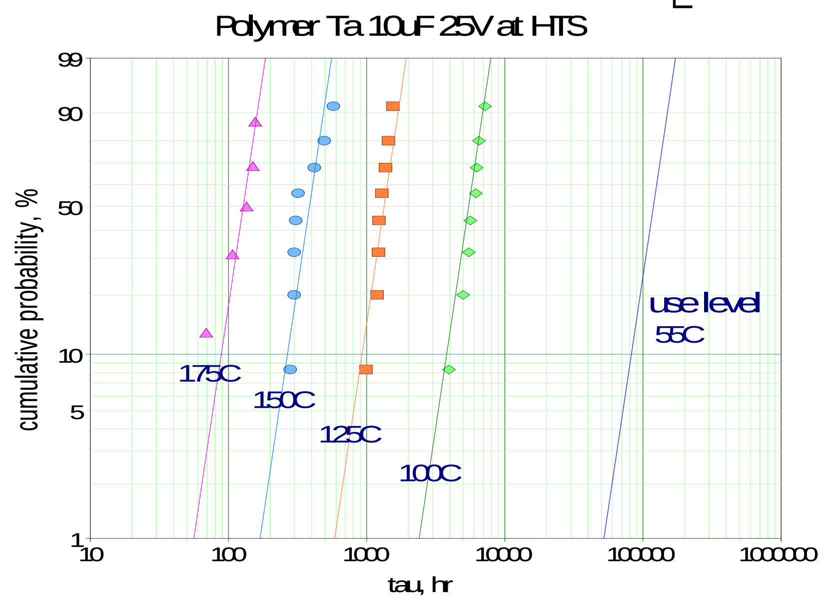
Approximations:

$$ESR = ESR_0 \times \exp\left(t / \tau \right)$$

$$\tau = \tau_0 \times \exp\left(-E_a / kT \right)$$

$$P(\tau) = 1 - \exp\left[-\left(\frac{\tau}{\eta} \right)^{\beta} \right]$$





- ✓ $E_a \approx$ 0.72 eV, which is close to results for 10 V capacitors.
- ✓ Simulations allow for the end-of-life predictions.
- ✓ More complex models might be necessary to accommodate for degradation inception times.

A History Case

❑ Background

- Commercial 6.8 μF 25 V Ta caps that were screened and qualified to MIL-PRF-55365.
- Parts successfully tested in voltage regulator units.
- Operating conditions: 9 V at 45 °C.

❑ Problem

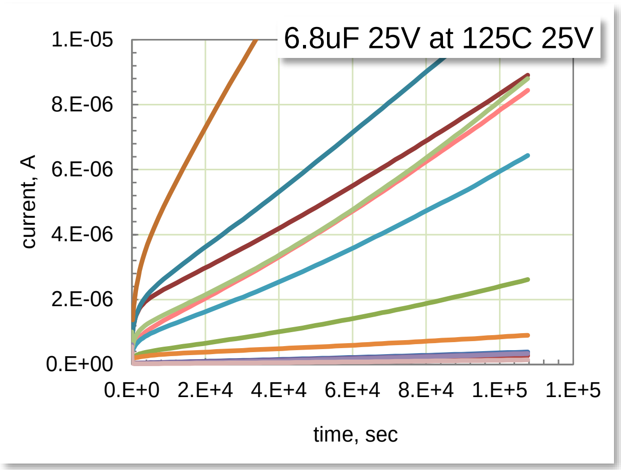
- Per the project request, six capacitors have been subjected to life testing at 125 °C and 16.7 V.
- Two parametric failures were observed.

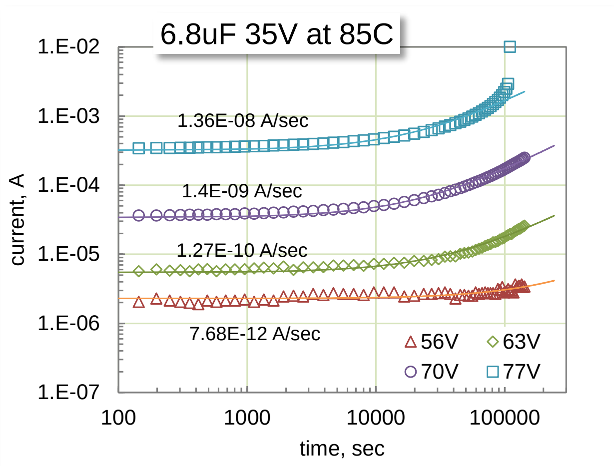
✓ The risk of failure during the mission should be assessed.

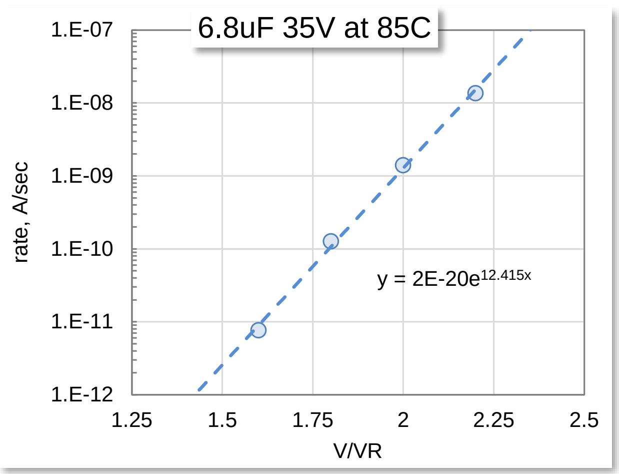
✓ A model for leakage currents degradation should be developed to evaluate the probability of parametric failures.

Degradation of Leakage Currents

Linear approximation of *I-t* characteristics







- ✓ Linear approximation is applicable for initial stages of degradation. Degradation rate $\alpha = f(T, V)$.
- ✓ Degradation rate increases with voltage exponentially, $B \approx 12$.

Technique, Cont'd

Acceleration factors for α

$$AF_V = \exp\left[B \times \left(\frac{V_{test}}{VR} - 1\right)\right]$$

$$AF_T = \exp\left[-\frac{E_a}{k} \times \left(\frac{1}{T_1} - \frac{1}{T_2}\right)\right]$$

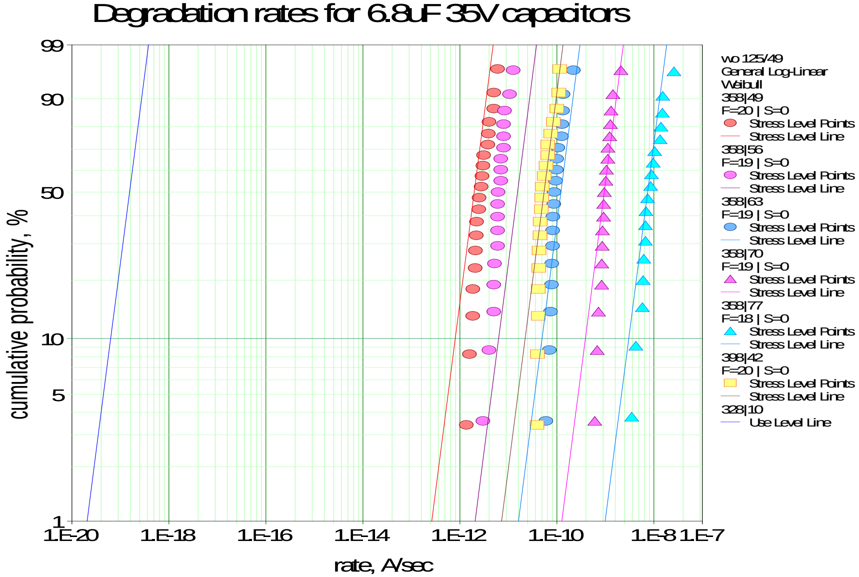
- Capacitors: 6.8 μF 25 V and 6.8 μF 35 V.
- Monitored HALT:
  - o Temperature: 85 ºC to 145 ºC in 20 ºC increments;
  - o Voltage: 15 V to 35 V in 10 V increments;
  - o step duration 30 hr.
- Degradation rate, $\alpha(T, V)$, was calculates for each sample.
- Distributions of α at different T and V were approximated with a general log-linear model:

$$F(\alpha) = 1 - \exp\left[-\left(\frac{\alpha}{\eta}\right)^{\beta}\right] \qquad \eta(T,V) = a_0 \times \exp\left(\frac{a_1}{T}\right) \times \exp\left(a_2 \times V_{test}\right)$$

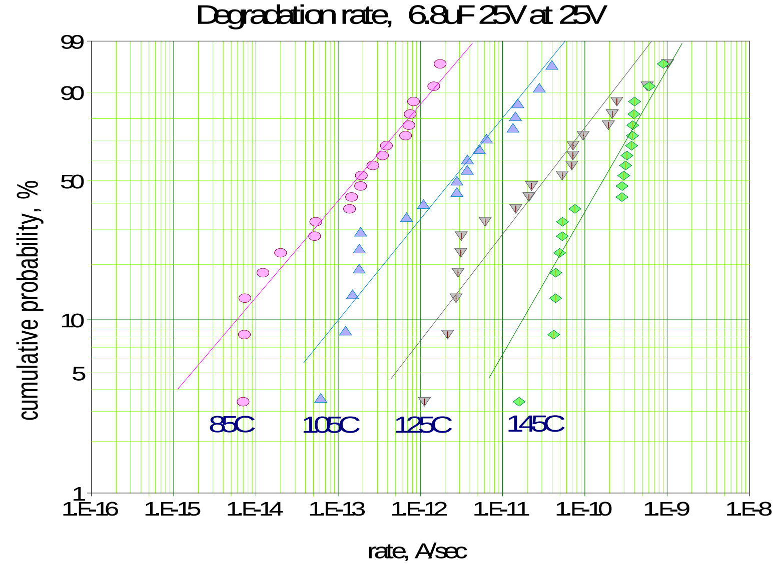
- Acceleration constant B and the activation energy: $B = a_2 \times VR$, $E_a = -a_1/k$.
- Time to failure was calculated as $TTF = \dfrac{I_{crit} - I_0}{\alpha}$

Distributions of Degradation Rates for 35V and 25V Capacitors

35 V capacitors at different temperatures and voltages



25 V capacitors at 25 V and different temperatures



- ✓ Unimodal distributions for 35 V capacitors.
- ✓ Bimodal distributions for 25 V capacitors.
- ✓ Slow- and fast-degrading subgroups in 25 V capacitors have been analyzed separately.

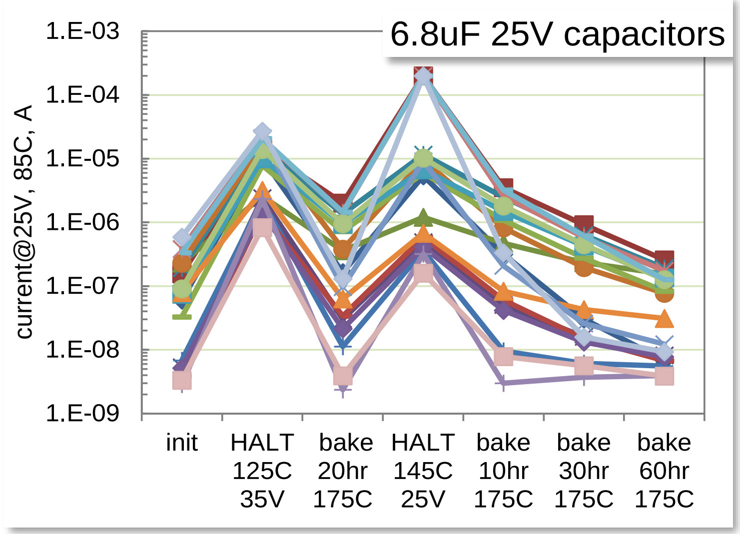
Parameters of the Model and Mechanism

$$AF_V = \exp\left[B \times \left(\frac{V_{test}}{VR} - 1\right)\right]$$

$$AF_T = \exp\left[-\frac{E_a}{k} \times \left(\frac{1}{T_1} - \frac{1}{T_2}\right)\right]$$

	6.8 µF 25V		6.8 µF 35V
	Low-rate subgroup	High-rate subgroup	All data
B	9.25	5.45	10.3
E_a, eV	1.66	1.42	1.65

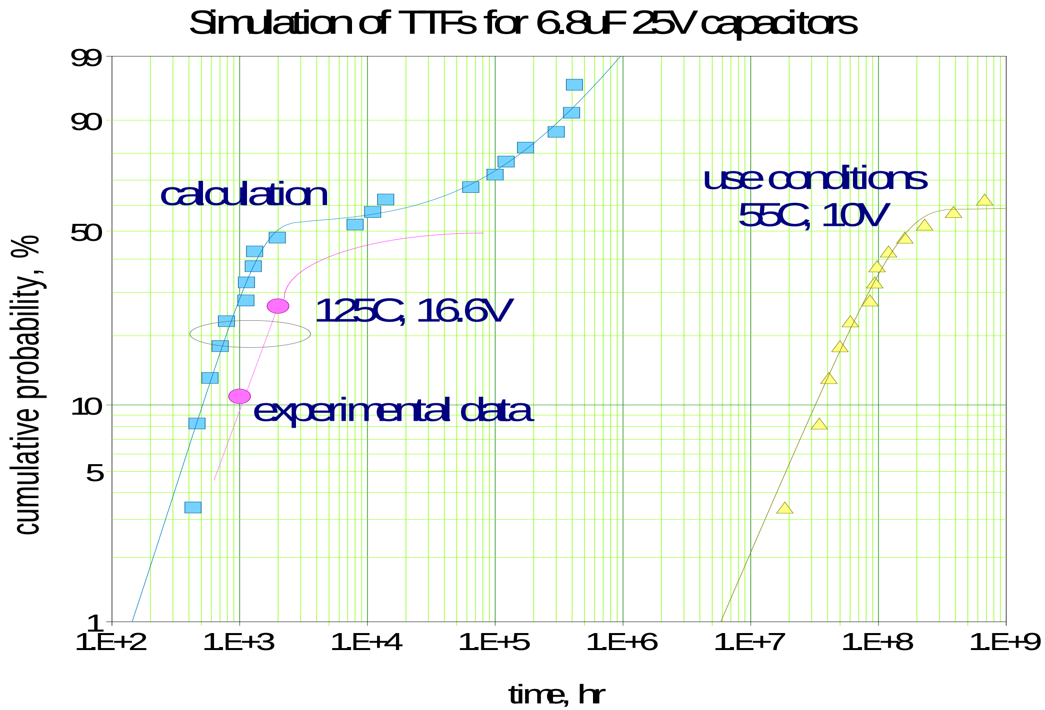
Variations of leakage currents caused by HALT and annealing



- ✓ Similar constants for the slow-degrading subgroup of 25 V and 35 V capacitors, B_{avr} = 9.8 ±0.5 and E_{a_avr} = 1.65 eV.
- ✓ $E_a = E_{migr} + E_{leak}$. At E_{leak} ~ 0.5 eV, E_{migr} ~ 1.1 eV, which is typical for oxygen vacancies (E_a, E_{migr} and E_{leak} are activation energies of the degradation rate, migration of V_o^{++} and of leakage current respectively)
- ✓ DCL degradation is reversible that is in agreement with the model.

Distributions of Times to Failure

Distributions of experimental and calculated times to failure at life test and use conditions



- ✓ Calculated and experimental data are close thus validating the model.
- ✓ Model allows for conservative estimations.
- ✓ The slope of distributions, $\beta \approx 2$, indicates wear-out failures.
- ✓ The probability of failure at use conditions is negligibly small.

Conclusion

- Two reasons for parametric failures in COTS:
  (i) due to insufficient margin in specified parameters and
  (ii) due to degradation processes.
- Degradation is typically caused by wear-out processes and can be modeled relatively easily.
- Determining physical mechanisms of degradation is more challenging, but is important to justify the models.