NASA Electronic Parts and Packaging (NEPP) Program

# Useful Life of Tantalum Capacitors


**Alexander Teverovsky**

Jacobs Engineering, Inc.

Work performed for EEE Parts, Photonics and Assembly Branch,

NASA GSFC, Code 562

Alexander.A.Teverovsky@nasa.gov

# Abstract

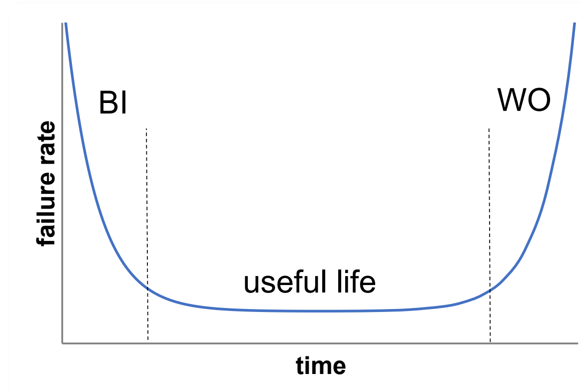
Currently, the major reliability characteristic of tantalum capacitors is the failure rate, which is a constant used to characterize random failures of electronic components. However, contemporary MnO2 and polymer tantalum capacitors have both infant mortality (IM) and wear-out (WO) failures. This requires assessments of the useful life of the parts that is limited by the time of inception of WO failures that can be determined using an adequate reliability model and results of highly accelerated life testing (HALT). In this presentation, a modified time dependent dielectric breakdown (TDDB) model is used to describe both IM and WO failures during HALT. Specifics of physical processes resulting in degradation and failures in polymer and MnO2 tantalum capacitors are discussed, and the increase of IM failures with the level of stress is explained. The model justifies exponential dependence of the acceleration factors on voltage and predicts higher values of the voltage acceleration constant for IM compared to WO failures.

# List of Acronyms

| | | | |
|---|---|---|---|
| AF | acceleration factor | PS | power supply |
| BI | burn in | ReRAM | resistive random-access memory |
| CPTC | chip polymer tantalum capacitor | Ta | Tantalum |
| FR | failure rate | TDDB | time dependent dielectric breakdown |
| HALT | highly accelerated life testing | TTF | time to failure |
| IM | infant mortality | SS | sample size |
| MIL-spec | military specification | WGT | Weibull grading test |
| PDA | percent defective allowable | WO | wear-out |

# Outline

Classic reliability bathtub curve

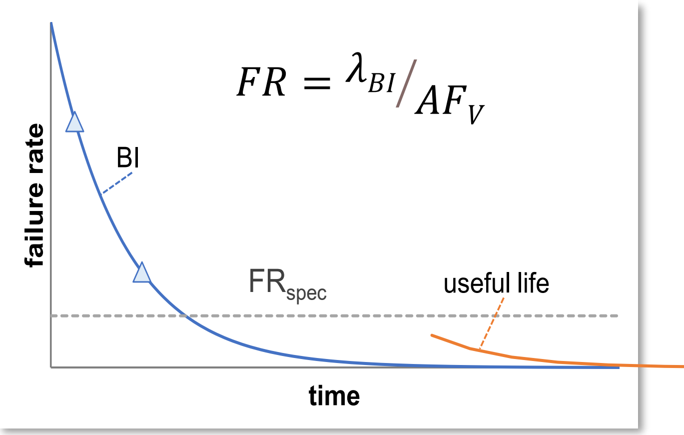



- Why are there no WO failures in MIL-spec Ta capacitors, but they exist in polymer capacitors?
- What are life test failures and is there a life after death?
- How does one assess useful life based on HALT?
- Can we eliminate IM failures and how does one select BI conditions?
- Conclusion

# MIL-grade Ta Capacitors

- Ideal BI conditions: monitor FR in the process and stop when the required level, $FR_{spec}$, is reached
- WGT for MIL Ta capacitors:
  85C, ~40hr, 300pcs $1.2 \le u_{BI}$ = V/VR ≤ 1.52
- WGT allows for FR assessment at 85 ºC and $u$ = 1 is based on $AF_V$: $AF_V = exp[B_{WGT} \times (uBI - 1)]$, $B_{WGT} = 18.77$

Weibull Grading Test

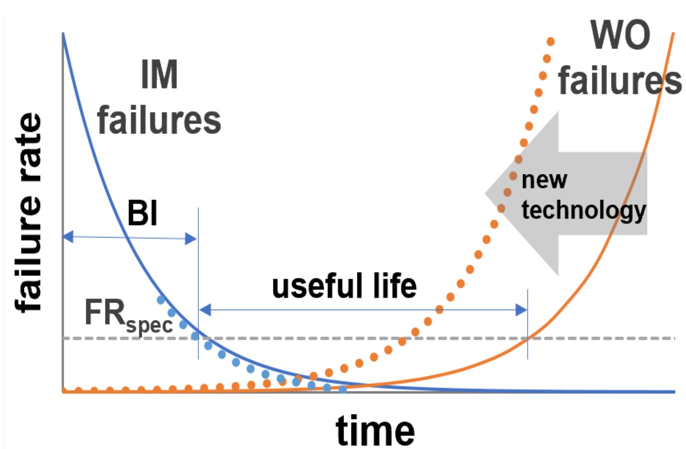



- ✓ WO degradation without WO failures → unlimited useful life?
- ✓ WGT is applicable when majority of failures are due to IM
  - The smaller the proportion of IM failures, the larger SS and $u_{BI}$ needed
  - PDA requirements cannot be determined
- ✓ Historically, most failures were due to defects, so there were not enough samples during life testing to reach the WO region

# New Technology Ta Capacitors

- ❑ Polymer technology creates a lesser stress to the Ta2O5 dielectric → the parts have lower risk of IM and can live to WO failures
- ❑ High quality MnO2 capacitors also have WO failures

*A general trend for advanced technology components*

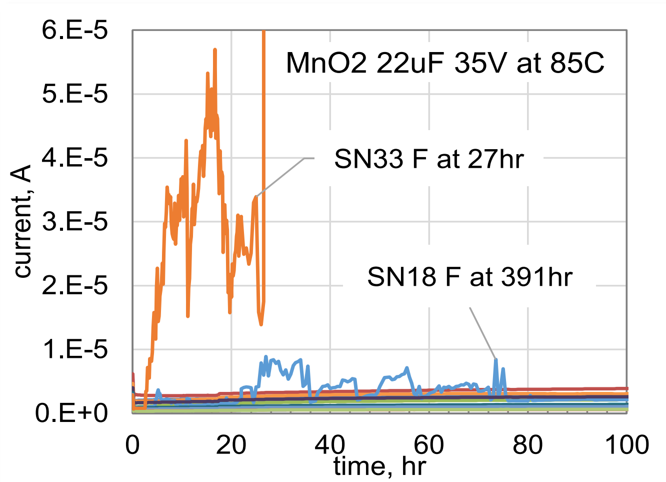


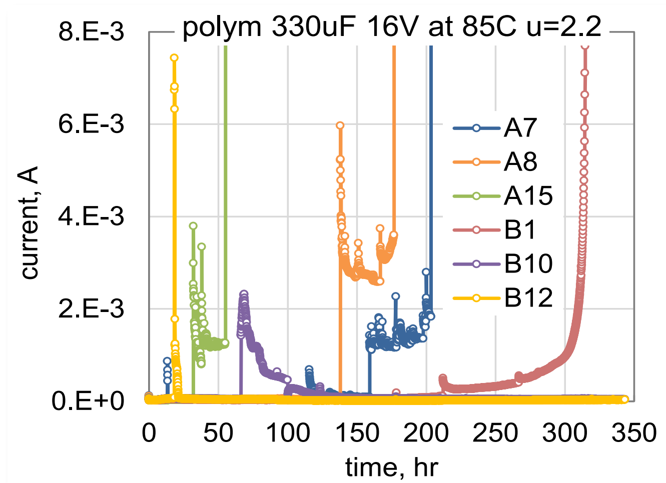

- ✓ Contemporary advanced capacitors have WO failures, so there is a need to assess useful life at application conditions
- ✓ This can be done using HALT and developing adequate reliability models

# Failure as a Powerful Scintillation

- Scintillation is a breakdown terminated by self-healing
- Breakdown occurs within ~0.1 msec for $MnO_2$ and ~1 msec for polymer capacitors

*Examples of scintillation events during life testing*



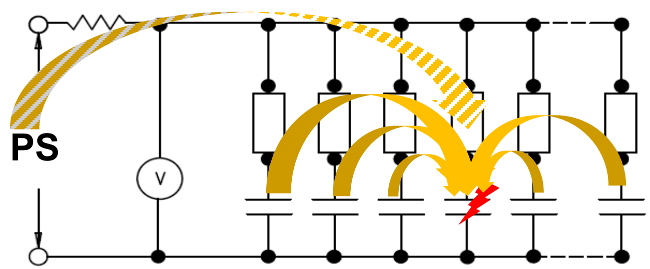

- ✓ Scintillations might not be detected during testing if currents are not continuously monitored
- ✓ After scintillations, the parts might remain operational

# Failures During BI or Life Test

- Per MIL-specs, failures are determined by blown 1 A fuses (a few seconds at 1A or msec at 20A).
- Typically, transient time of a PS is dozens of msec, so only permanent shorts can cause a fuse to blow by currents from the PS

*BI or life test set-up*

*PS suppose to supply ≥ 1 A when a capacitor is shorted*




- ✓ Adjacent capacitors can deliver energy fast and blow a fuse in the case of scintillation breakdown
- ✓ Failure/self-healing conditions during operation and life test might be different
- ✓ Life test conditions are more stressful than during operation of a single part

# Typical HALT Results

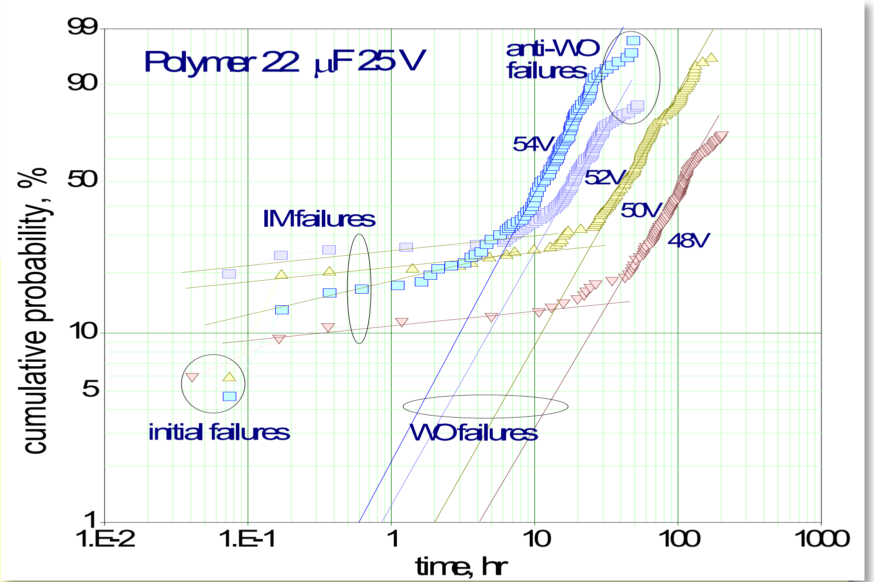
- The shape factor in Weibull distribution of TTF determines the type of failures

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

$\beta$ < 1 => IM failures
$\beta$ = 1 => random failures
$\beta$ > 1 => wear-out failures

- Interception between IM and WO failure lines gives proportion of IM failures

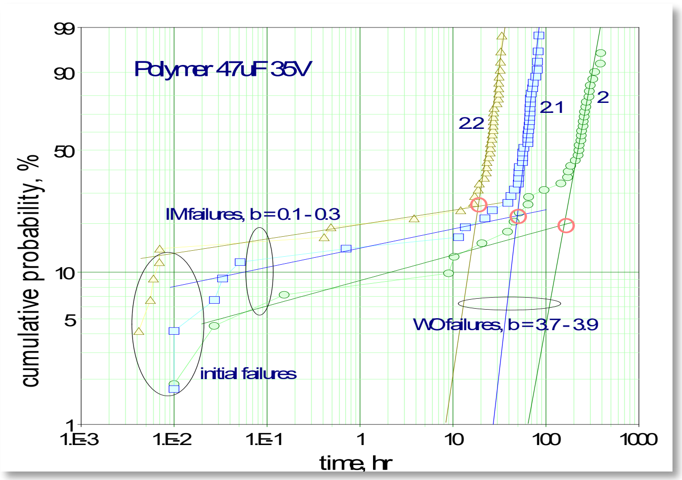
*TTF distributions during HALT*

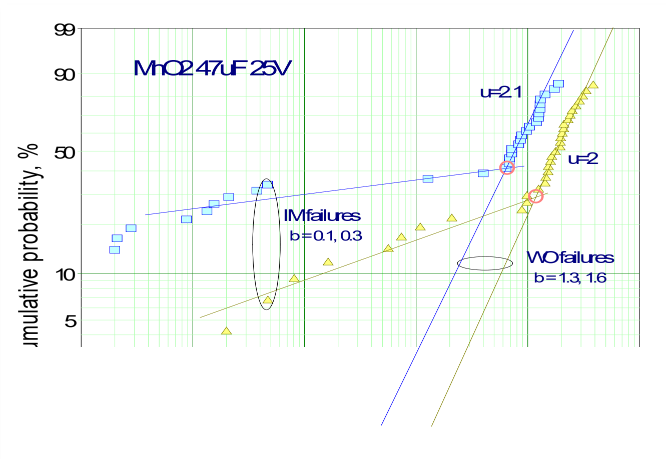



- ✓ Anti-WO failures might be due to less stressful scintillation events when a small number of samples left at the end of HALT
- ✓ Another reason is solid-state oxidation during HALT that increases breakdown voltages with time of testing

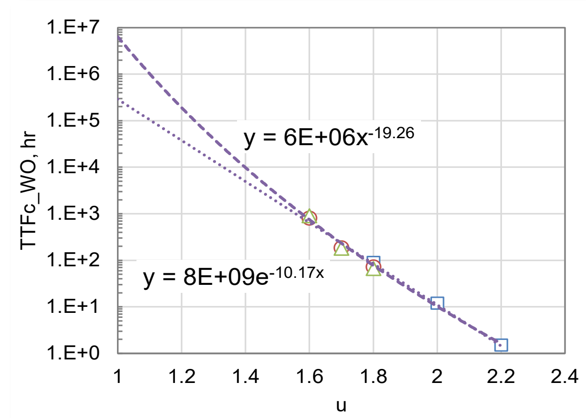
# Modeling of HALT Results

*Weibull distributions of TTF during HALT for polymer and MnO2 capacitors*




*Prediction of TTF$_{c_WO}$ for u = 1*

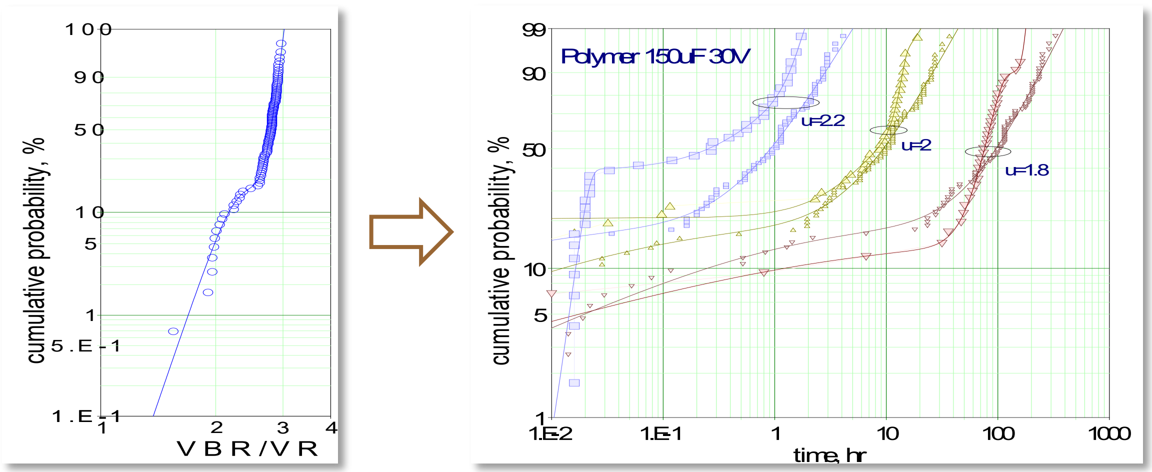



- ✓ Both types of capacitors had bimodal distributions indicating presence of IM and WO failures
- ✓ A power model for CPTCs, $AF_V = u^n$, gives a more optimistic prediction compared to the exponential model, $AF_V = exp(-B(u\ -1))$
- ✓ TDDB model validates exponential dependence $AF_V(u)$

# TDDB Model

- TTF distributions can be calculated based on VBR distributions
- TDDB model: $TTF = t_0 \times exp[B \times (u_{BR} - u)]$ , $B = {\Delta H}/{kTu_{BR}}$

*Experimental and calculated TTF distributions*



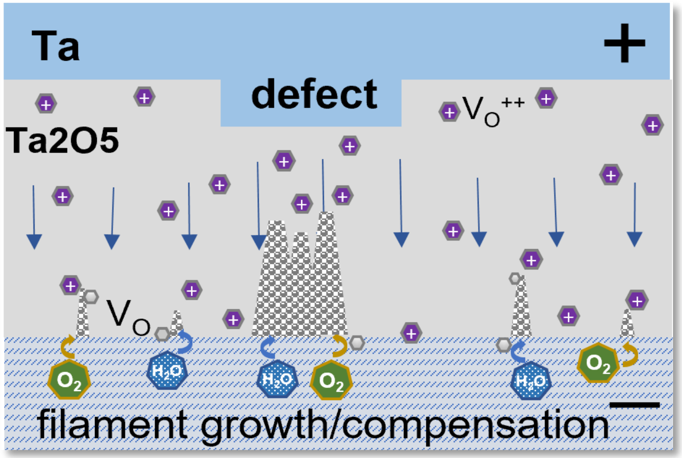

*Proportion of IM failures*

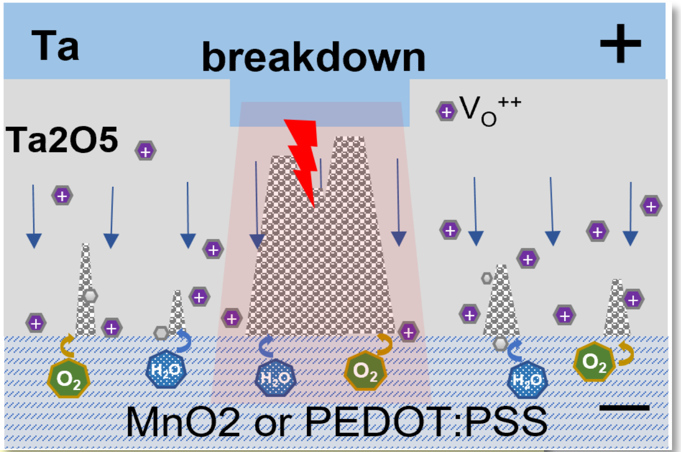
| u | $p_{exper.}$, % | $p_{simul.}$, % |
|---|---|---|
| 1.8 | 14 | 17.5 |
| 2 | 21 | 17.5 |
| 2.2 | 39 | 17.5 |

- ✓ Similarity between experimental and calculated TTF distributions validates TDDB model
- ✓ Major discrepancy: the model predicts constant proportion of IM failures, whereas experiments show that it increases with the level of stress

# IM Failures

- ❑ <u>Degradation</u>: Migration of $V_O^{++}$ leads to accumulation of positive charges at the cathode/Ta2O5 interface and formation of conductive filaments (redox-based ReRAM), which intensifies at a defect site
- ❑ <u>Compensation</u>: Generation of oxygen-containing species to compensate for positive charges and conductive filaments




- ✓ Probability of failure depends on the rates of degradation and compensation
- ✓ Slow degradation at low *u* can provide sufficient time for the compensation to prevent breakdown
- ✓ The proportion of IM failures will increase with the stress voltage
- ✓ Some IM failures revealed during HALT might never happen at operating conditions

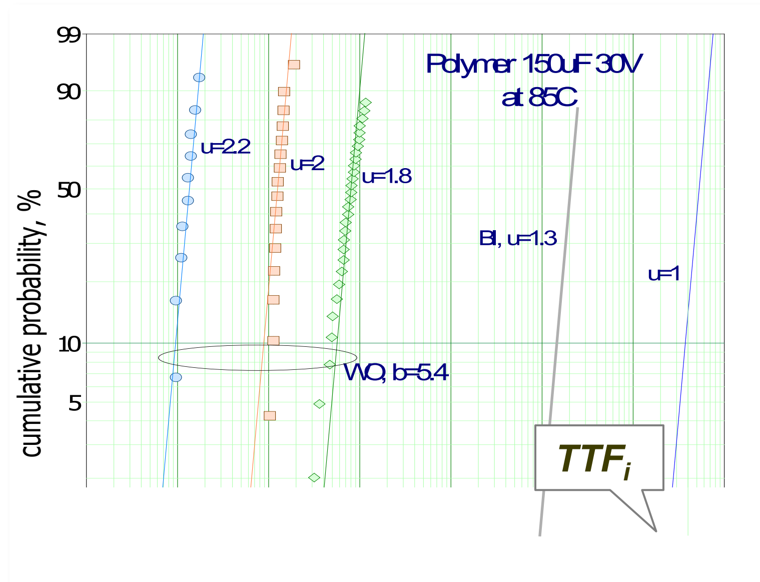
# Useful Life

- Useful life is the time between end of screening (BI) and $TTF_i$

$$TTF_i(u) = TTF_{WO} \times \exp[B(1-u)] \times [-\ln(0.999)]^{1/\beta}$$

- Modeling using a general log-linear Weibull distribution allows for predictions of WO failures at BI and usage conditions
- There might be a temptation to increase $u_{BI}$ to screen out more IM failures, but this might reduce the useful life of the parts

*Distributions of WO failures during HALT allow for assessments of the time to failure inception during the mission and BI conditions*




✓ $TTF_i$ and BI conditions can be determined based on HALT results

# Conclusion

- ✓ Historically, HALT in MnO2 capacitors resulted mostly in IM failures. Contemporary MnO2 and polymer capacitors have both IM and WO failures.
- ✓ Failures are due to powerful scintillation events that can be simulated using a TDDB model
- ✓ Useful life of tantalum capacitors at operating conditions can be estimated based on the exponential model and results of HALT
- ✓ The proportion of IM failures increases with the level of stress; however, increasing stress voltage during BI might be not effective:
    1. Increased risk of damage by undetected scintillations
    2. Reduction of useful life consumed during BI
    3. BI failures might never happen at operating conditions