Weibull Grading and Surge Current Testing for Tantalum Capacitors

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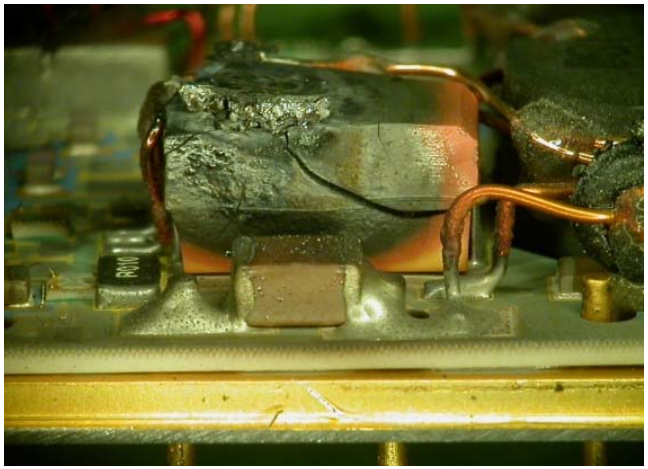
Outline

- Scintillation breakdown and self-healing in tantalum capacitors
- Failures as Time Dependent Dielectric Breakdown (TDDB)
- Weibull Grading Test (WGT)
- Surge Current Test (SCT).



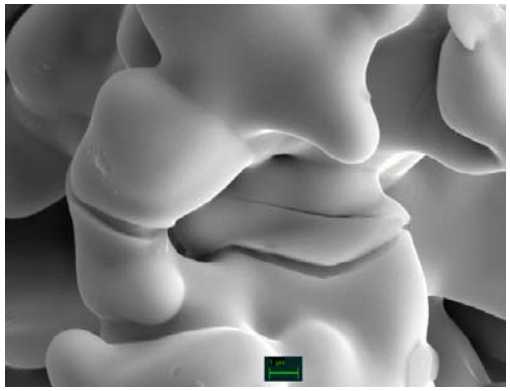
- Failures in Ta capacitors occur typically either under steady-state operating conditions, or at the first power turn-on.
- To reduce the probability of the first type of failures, capacitors are screened/qualified by WGT.
- SCT is used to mitigate the risk of the second type of failures.

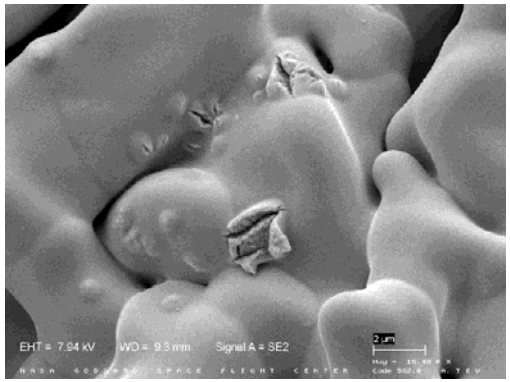
➢ What are these tests, how effective they are, and what can be done to improve the efficiency?

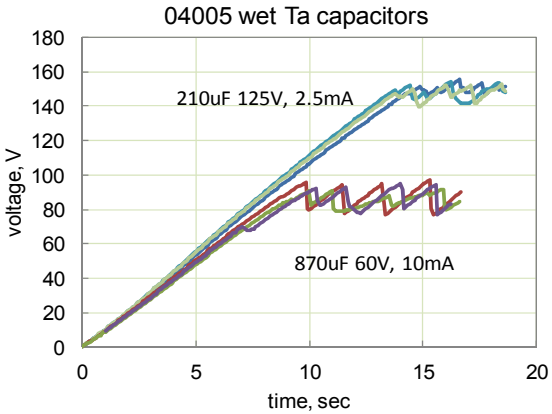
Scintillation Breakdown and Self-Healing (SH) in Tantalum Capacitors

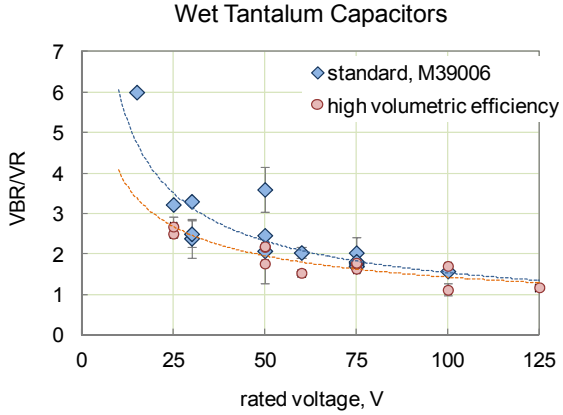
Self-Healing in Wet Ta Capacitors

- Scintillations are local momentary breakdowns terminated by self-healing.
- SH occurs almost instantaneously and is due to additional electrochemical oxidations of Ta in the electrolyte (sulfuric acid).

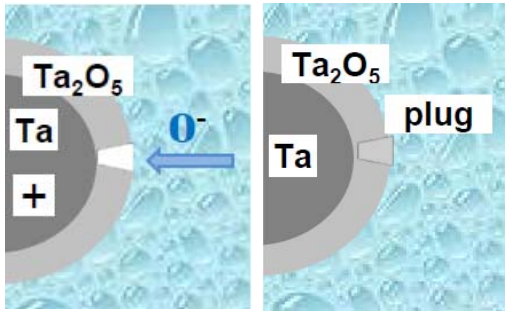








- ✓ Breakdown margin reduces substantially with rated voltage, VR.
- ✓ SH is important to assure reliability of the parts, but it is not a panacea because of the pressure build-up due to H_2 generation.



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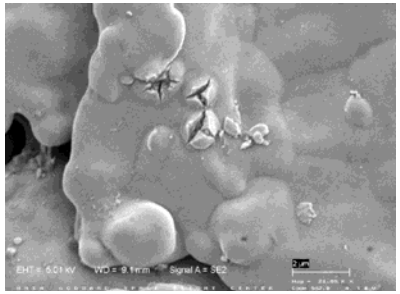
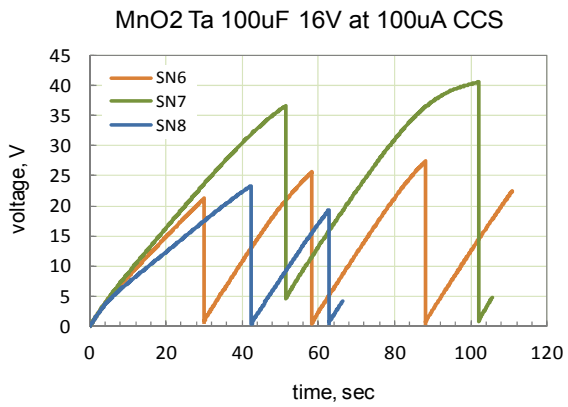
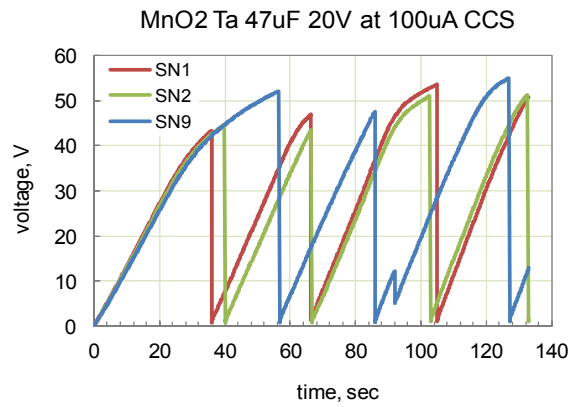
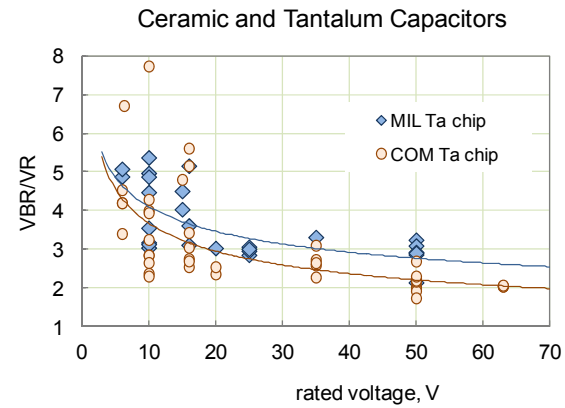
Self-Healing in MnO_2 Ta Capacitors

- SH is due to local overheating of MnO_2 and its transformation to a high-resistive Mn_2O_3, thus isolating the defective area of Ta_2O_5.
- Tantalum can oxidize by oxygen released from MnO_2.









- ✓ Although the breakdown margin decreases with VR, it remains above ~2.
- ✓ Scintillations were damaging in ~30% cases.
- ✓ The larger the nominal capacitance and the lower the equivalent series resistance, ESR, the greater the probability of damage.
- ✓ SH is a benefit of MnO_2 parts, but scintillations should be considered as failures during screening and qualification.

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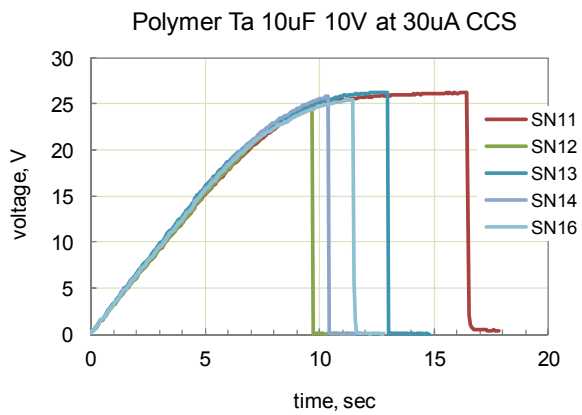
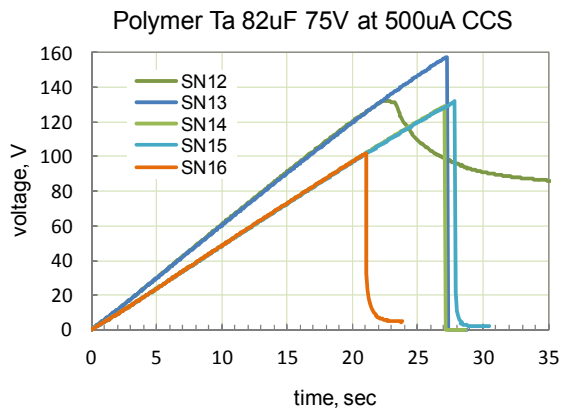
Self-Healing in Polymer Ta Capacitors?

- Contrary to MnO_2 capacitors, where ignition is possible due to the exothermic reaction of oxygen that is emitted by MnO_2 with Ta, polymer capacitors do not ignite.
- For this reason, manufacturers "suggest" derating to 0.8VR compared to 0.5VR that is "recommended" for MnO_2 capacitors.





- ✓ Preliminary results show that all polymer capacitors failed in a short circuit mode – no self-healing.
- ✓ There are other concerns that need to be addressed before using polymer capacitors in high-rel applications (e.g. effect of humidity).

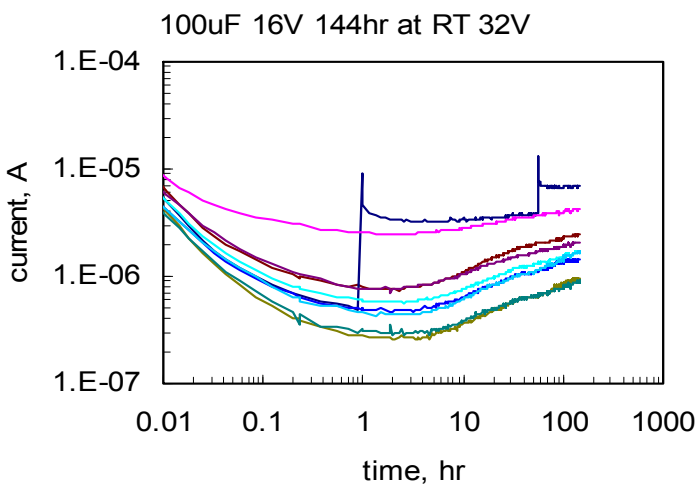
Life Test Failures as TDDB

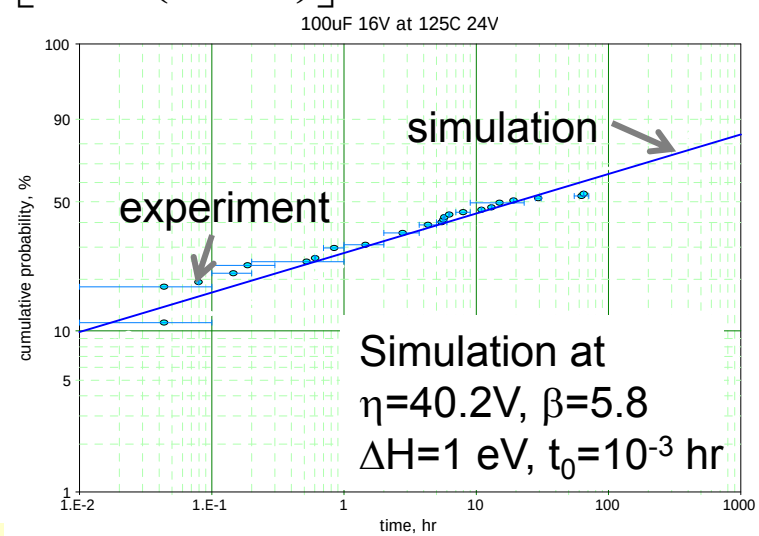
- Thermochemical model (TCM) of TDDB: $TF = t_o \times \exp\left(-\gamma E + \frac{\Delta H}{kT}\right)$

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

- Time-to-failure, TTF, can be calculated based on distribution of VBR:

$$TTF = t_o \times \exp\left(\frac{\Delta H}{kT}\right) \times \exp\left(-\frac{\Delta H}{kT} \times \frac{V}{V_{BR}}\right) = t_o \times \exp\left[\frac{\Delta H}{kT} \times \left(1 - \frac{V}{V_{BR}}\right)\right] \qquad V_{BR} = \eta \times \left[-\ln(1-p)\right]^{1/\beta}$$





- ✓ 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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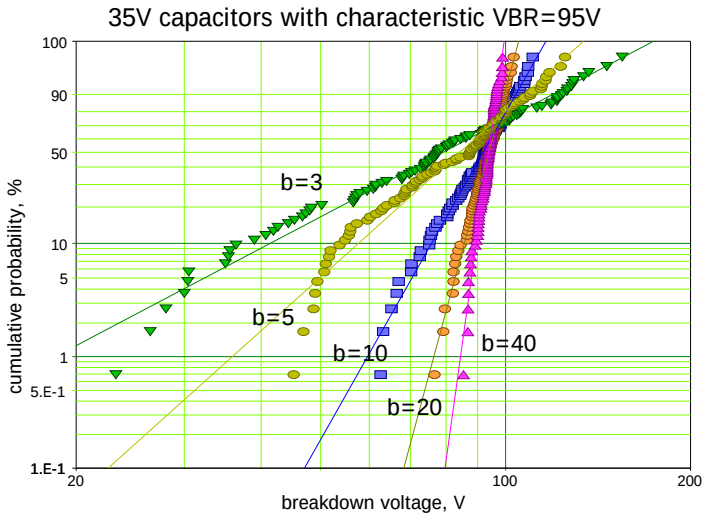
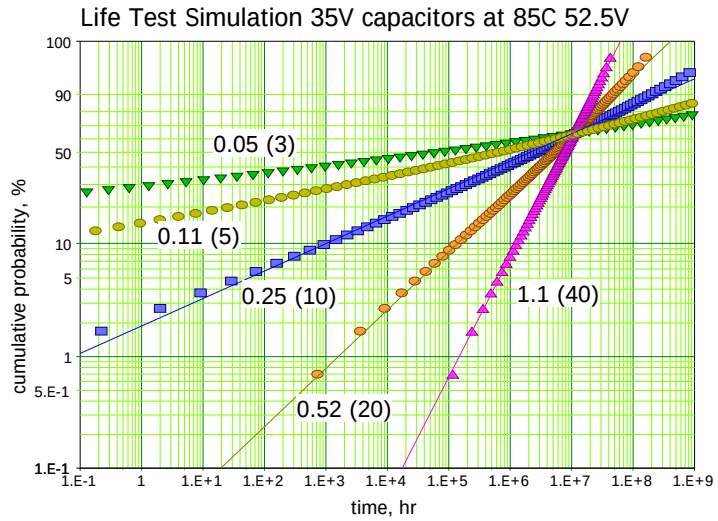
Infant Mortality Failures

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

Monte-Carlo simulation of VBR distributions at different β



Times to failure calculated based on TDDB model

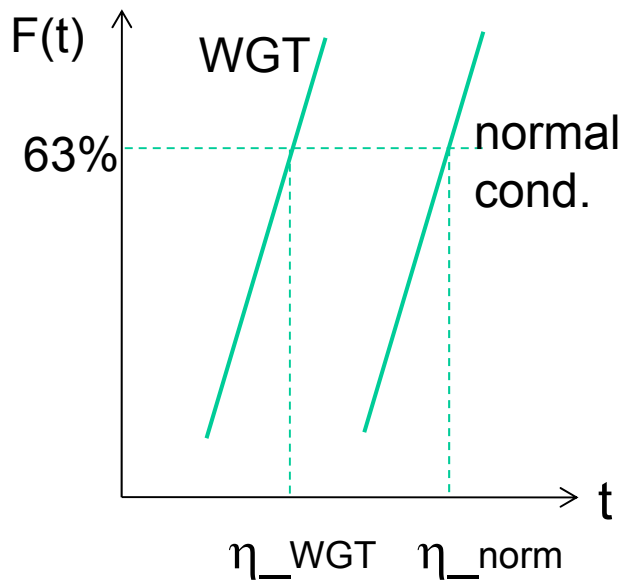


✓ At the level of β_{VBR} that is typically observed for tantalum capacitors (5 to 20), simulations show that all failures, up to the end of life, are defect related IM failures.

Weibull Grading Test

Weibull Grading Test

- WGT is a combination of two tests: burn-in (screening to remove IM failures) and reliability qualification (to assess the failure rate, FR).
- If $\beta < 1$ and λ can be monitored during testing, then the test can be stopped when the necessary λ 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*".

✓ If all failures are due to IM, then any lot can be screened out to as high FR level as necessary.

WGT Condition

- WGT condition per MIL-PRF-55365:
  - At 85 °C for 40 hr and voltage from 1.1VR to 1.53VR.
  - A failure is defined as a blown 1A or 2A fuse.
  - Failures calculated at 2 hr and 40hr of testing.
  - FR is calculated using an empirical equation obtained ~ 40 years ego:

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

- Considering that at V = VR accelerating factor AF, is equal to 1:

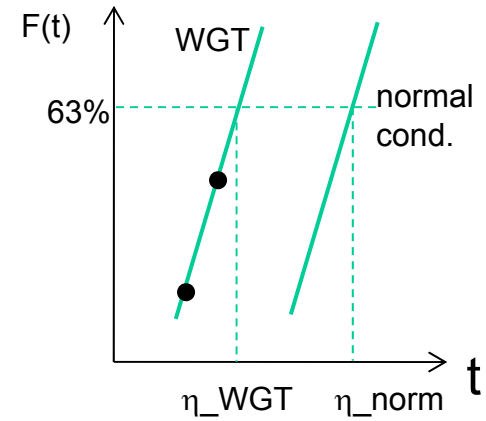
$$AF = \exp(B \times u) \qquad u = \frac{V}{VR} - 1$$

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

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

✓ Long-term reliability is determined by a 40-hr accelerated testing!

WGT Problems

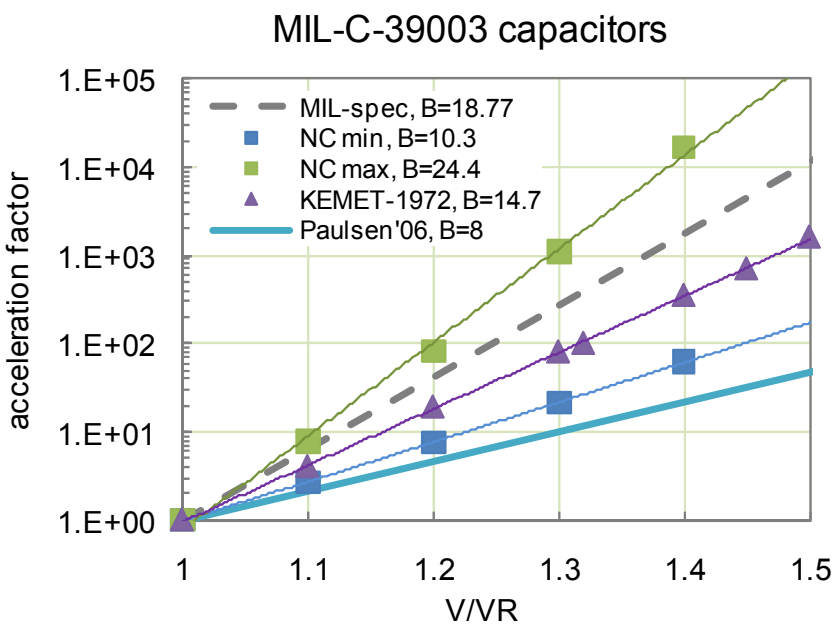


- Two groups of problems for FR assessment using WGT: testing and calculations.
- Problems with test conditions:
  - Verification of contacts in fixtures.
  - Only 300 samples are used for calculations.
  - Test results with different fuses might be different.
  - Short current spikes below ~10A (scintillations) will remain unnoticed.
  - Only two points to draw the F(t) line and calculate β and η.
- Problems with calculations:
  - Early failures (before 15 min) are neglected.
  - Calculations do not account for the uncertainty in times to failure.
  - Due to insufficient sample size, small changes in the number of failures might result in significant variations of FR.
  - 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, up to 3 orders of magnitude, are due to incorrect voltage acceleration factors.

Historical Data on Voltage Acceleration Factor (AF)

- Experimental data from Navy Crane report, 1982, for various hermetic solid tantalum capacitors and data reported by KEMET in 1972 and 2006



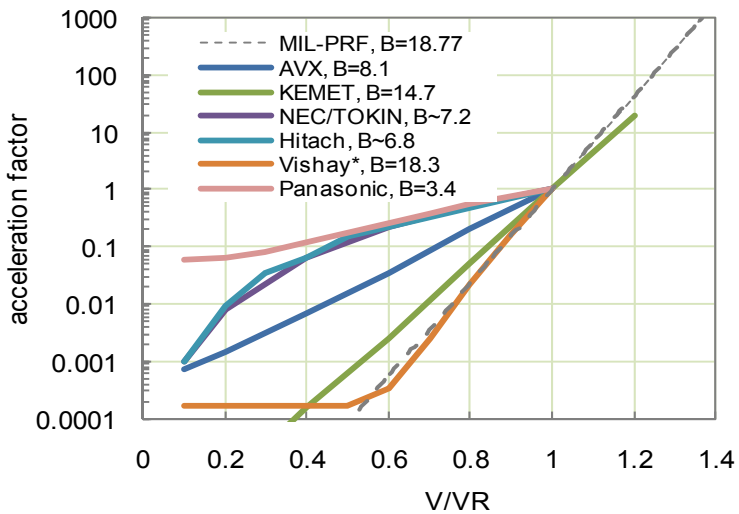
The data confirm an increase of AF errors with V and wide range of variations of B, from 8 to 24.4.

Note: Paulsen's data for chip capacitors were recalculated from power [$AF=(V/VR)^n$] to exponential [$AF=\exp(Bu)$] dependence on voltage.

✓ The range of B is close to predictions of the TDDB model.

Manufacturers' Reliability AF

AF calculated at 85 °C using vendors' and MIL-spec data



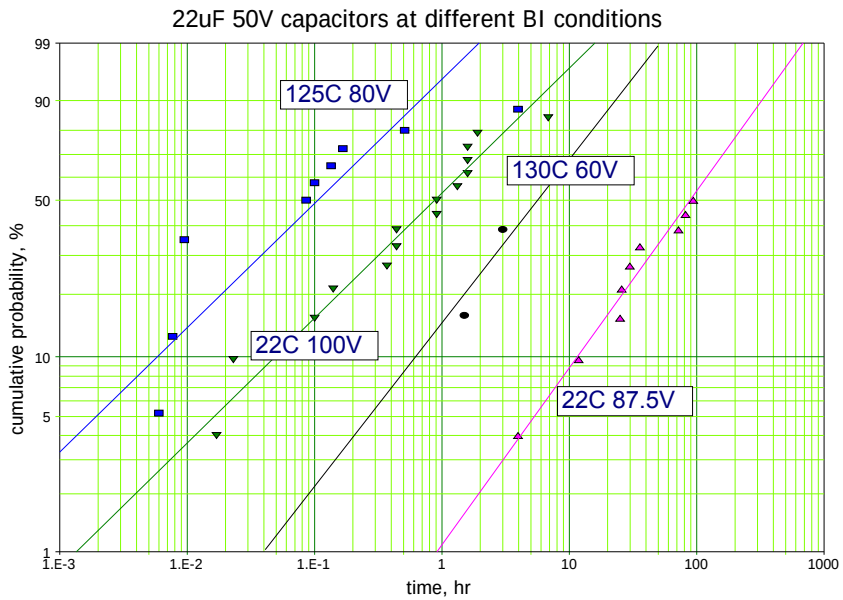
Activation energy, E_a, calculated based on vendors' and MIL-spec data

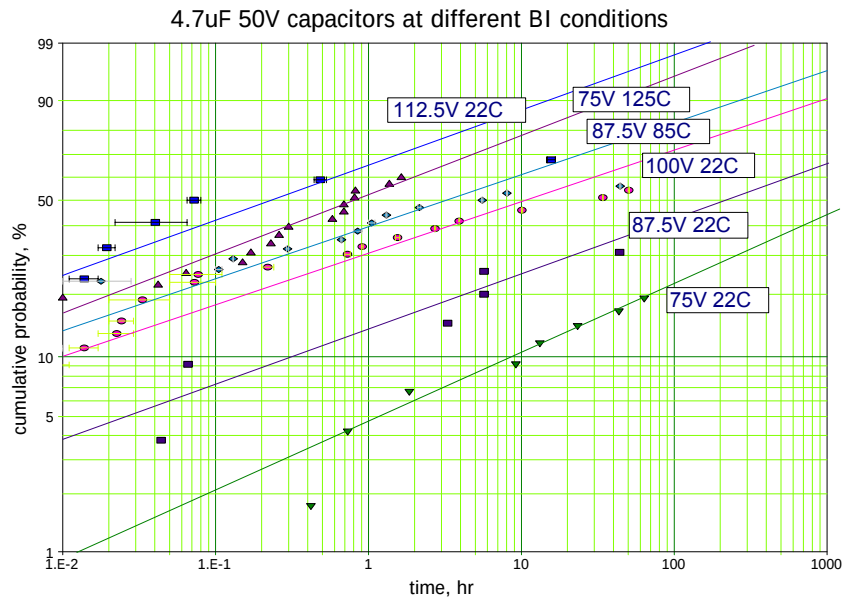
Manufacturer	Ea, eV
AVX	0.63
KEMET	1.17
MIL-PRF-55365	2.1
HITACHI	0.62
NEC/TOKIN	0.66
Vishay*/MIL-HDBK-217F	0.15
Panasonic	0.16

- ✓ Manufacturers' data on voltage and temperature acceleration factors vary substantially.
- ✓ Inconsistency in the data require more analysis.

Highly Accelerated Life Testing (HALT) at Different Test Conditions

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

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Statistical Model of Failures

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:

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

PART	F	S	β	α_0	α_1	α_2	t_0, hr	ΔH, eV	n	B_85C
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 part types showed that the acceleration constant B varies from 10 to 20.

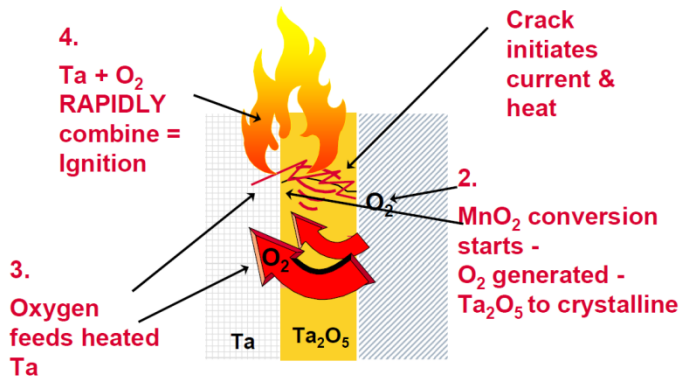
WGT Summary

- Errors in FR calculations related to the testing conditions sum up to an order of magnitude.
- Errors related to incorrect AFs can change FR up to 10^3 times.
- Reliance on MIL-PRF-55365 method for reliability rating might be misleading.
- TDDB model predicts an exponential dependence of AF on voltage with the voltage acceleration constant *B* depending on temperature.
- Temperature dependence of AF can be presented in the Arrhenius-like form with E_a varying with voltage.
- AF can be obtained using HALT and approximation of test results with a general log-linear relationship at two levels of stress factors.

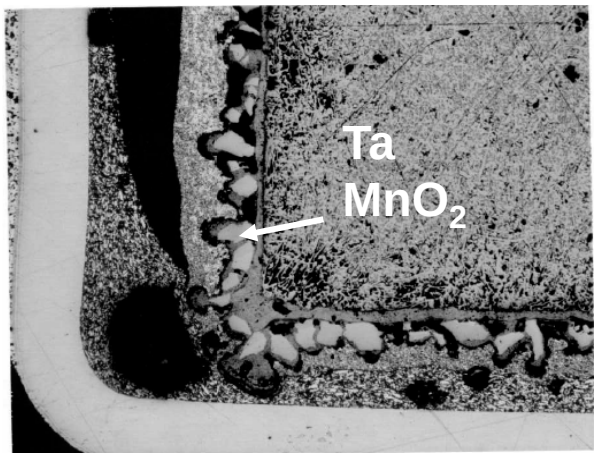
Surge Current Testing

Mechanisms of Surge Current Failures

- Sustained scintillation breakdown.
  If current is not limited, self-healing does not have time to develop.
- Electrical oscillations in circuits with high inductance.
- Local overheating of the cathode.
- Mechanical damage to tantalum pentoxide dielectric caused by the impact of MnO_2 crystals.
- Stress-induced-generation of electron traps caused by electromagnetic forces developed by high currents.



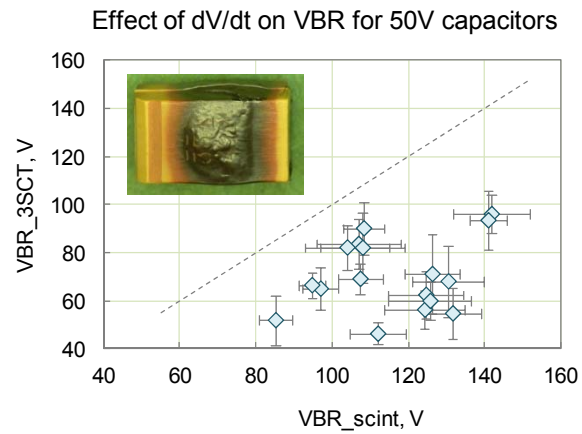
Ignition due to exothermic reaction in tantalum capacitors. Prymak 2006.



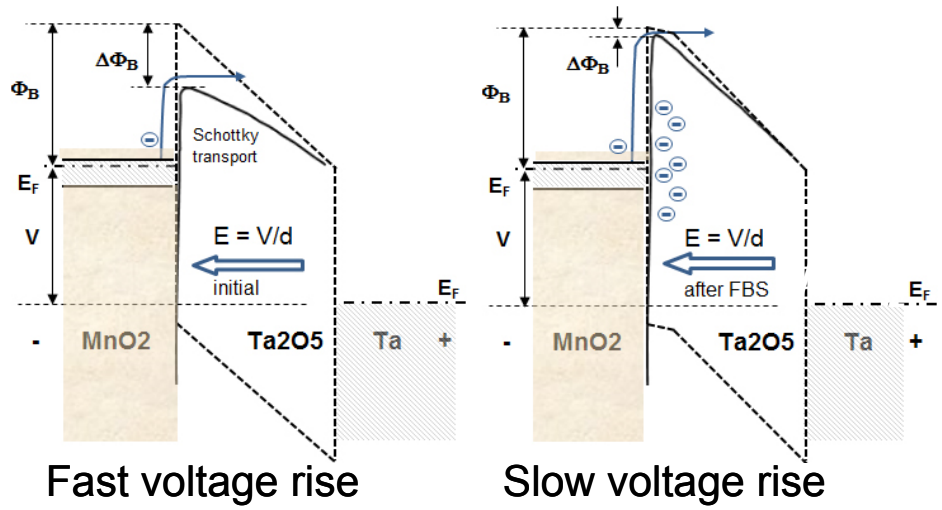
✓ In all models the rate of voltage increase is critical.

Effect of *dV/dt* on Breakdown Voltage

- Scintillation breakdown voltage, VBR_{scint} (*dV/dt* ~ 1 to 5 V/sec) is always greater than the surge current breakdown voltage, VBR_{surge} (*dV/dt* ~ 10^5 to 10^6 V/sec)
- The rate of voltage increase changes charges and electrical field at the interface.



Accumulation of electrons on traps at the MnO_2-Ta_2O_5 interface with time increases the barrier, the level of electron injection, and the probability of avalanching.



Fast voltage rise Slow voltage rise

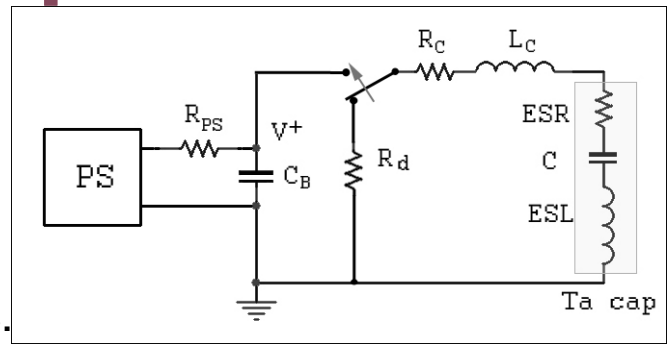
- ✓ The rate of voltage increase is critical for breakdown.
- ✓ A resistor in series with a capacitor reduces *dV/dt* and failures.

Surge Current Derating Requirements

- History of requirements for circuit resistance (R_{ac}):
  - In the 1960s: 3 Ω per each volt of operating voltage.
  - By the 1980s: 1 Ω per each volt.
  - From the 1990s: 0.1 Ω per volt or 1 ohm, whichever is greater.
- Manufacturers consider surge current failures as the major reason for voltage derating.
- Do we need derating of currents in addition to voltage?
- The limit for acceptable surge currents is set by the SCT conditions: <u>the current during applications should not exceed the current during testing</u>: $I_{appl.} < I_{test}$ *"use as tested"*

- ✓ Improvements in reliability and the need to increase the efficiency of power supply systems resulted in reduction of R_{ac}.
- ✓ At what conditions we can allow circuit designs without R_{ac}?
- ✓ Need a closer look at how the I_{test} is specified.

MIL-PRF 55365 SCT Requirements



- SCT per MIL-PRF-55365H:
  - Number of cycles: N_c = 4 surge cycles.
  - Energy storage capacitor: $C_B = 20 \times C_{DUT}$
  - Test voltage: VR
  - Charge time, t_{ch}, and discharge time, t_{disch}, ≥ 1sec.
  - Total DC resistance of the test circuit, R_{tc}, including the wiring, fixturing, and output impedance of the power supply should not exceed 1 Ω.
  - Measurements after SCT: DCL, C, DF (still no requirements for ESR)
  - The minimum surge peak current shall be: $I_{test} \geq VR/(R_{tc} + ESR_{spec})$, R_{tc} = 1 Ω.
  - Failure condition: current = 1A after 1ms for $C \leq$ 330uF; 10ms for $C \leq$ 3.3mF, and 100ms for $C >$ 3.3mF.

- Before 12/1/2012:
  - N_c = 10.
  - $t_{disch} = t_{ch}$ = 4 sec.
  - $R_c \leq$ 1.2 Ohms.
  - $C_B \geq$ 50 mF.
  - No I_{test} requirements.

✓ New specifications recognize the role of *ESR* as a limiting factor for surge currents. However, no specifics for I_{test} verification.

✓ M55365 does not guarantee reliable operation at VR: $V_{test} = V_{C_MAX}$ = 0.95×VR, => the need for voltage derating.

Application vs. Testing Conditions

- Typical application conditions:
  - No limiting resistors, minimal inductance.
  - Minimal contact resistance.
- Resistance of the circuit, R_{ac}, is minimal and the current is limited mostly by ESR.
- Surge Current Test conditions:
  - Unspecified contact resistance of fixtures.
  - Limiting resistor can be up to 1 Ω.
  - Relatively long wires and inductance.
  - No clear requirements for I_{test} verification (when, how?).
- Parts with poor contacts in the fixture can pass the testing.

Example:

- A 15μF 10V CWR06 capacitor with specified ESR=2.5Ω and real ESR = 0.5Ω is used in a 5V line.
- During application the part can experience a spike:

  I_{appl} = 5/0.5 = 10 A.
- During the testing it will be verified to the current:

  $I_{test} \geq VR/(R_{tc} + ESR_{spec})$

  I_{test} =10/(1+2.5) = 2.8 A

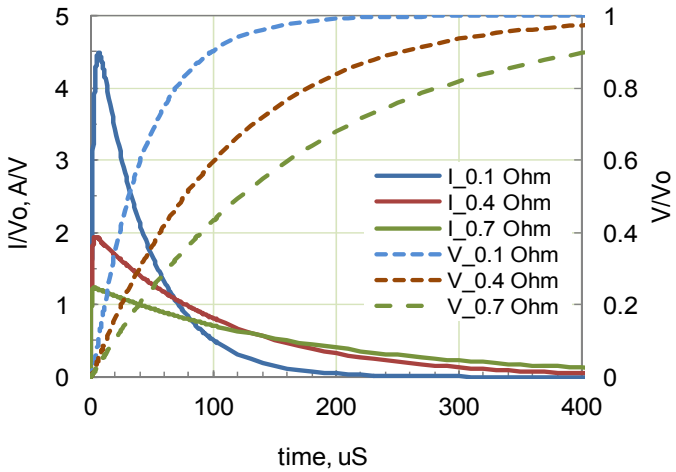
✓Application conditions might be more severe than test conditions.

✓There is a need in tightening test requirements.

Specifics of Surge Current Testing

- Theory and experiments show that the rate of the voltage increase is critical for SCT.
- High current spike is a byproduct of the fast voltage rise, rather than the major cause of failure.
- Even minor variations (~0.1 Ω) of R_c affect results of SCT.
- Measurements of voltage level across the capacitor during testing that are used to assure that the part passed SCT are not informative without indication of timing.

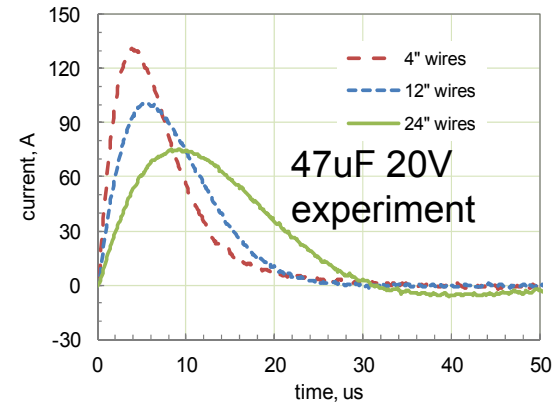
Calculations for 220uF capacitor at L_c= 400 nH, ESR=0.1Ω R_c-var

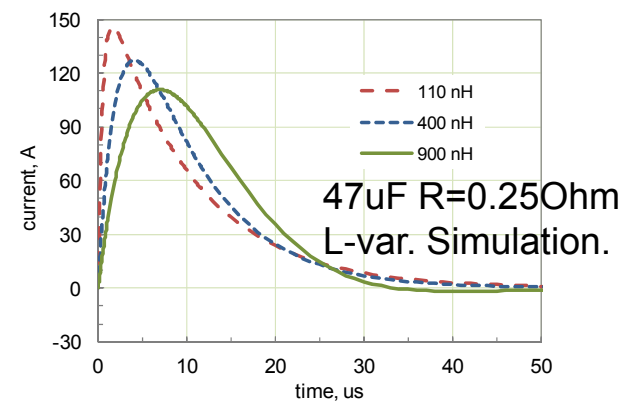


✓The amplitude of the current spike is the most adequate characteristic to verify SCT conditions.

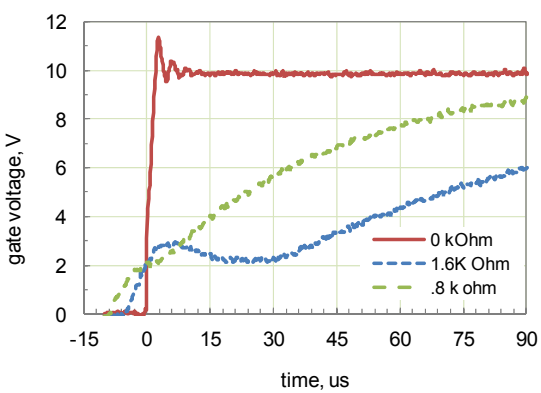
Factors Affecting SCT Results

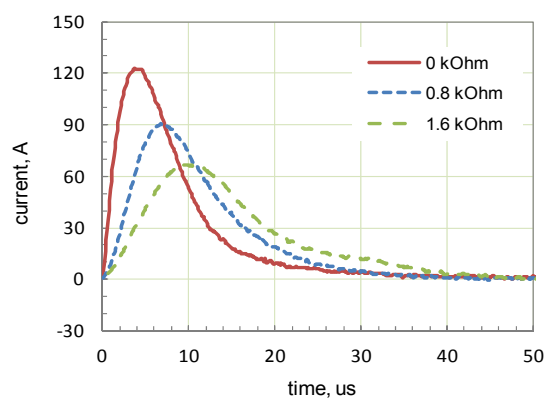
- R_{ac} includes resistance of wires and contacts.
- The length of wires affects inductance.
- Type of switch.
- The rate of voltage increase in case of using field effect transistor (FET)





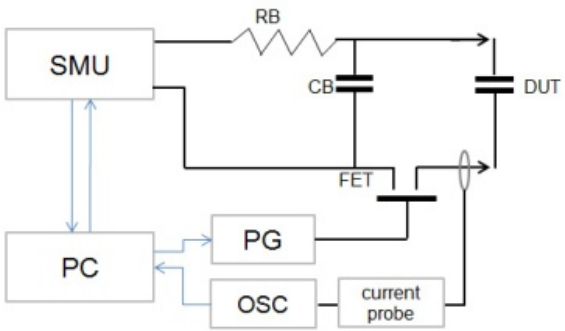
Effect of resistors at FET gate on V_g and I_{sp} for 47uF 20V capacitors

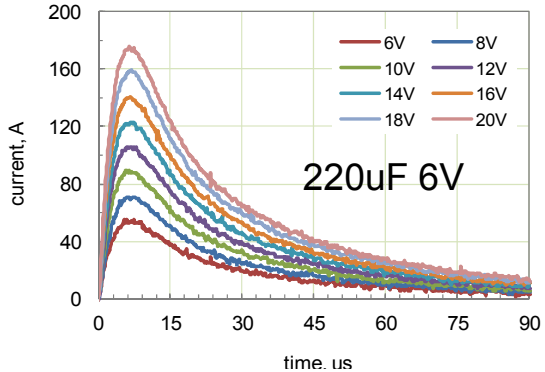


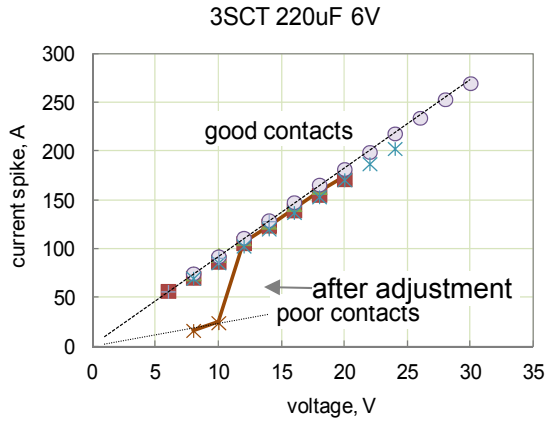


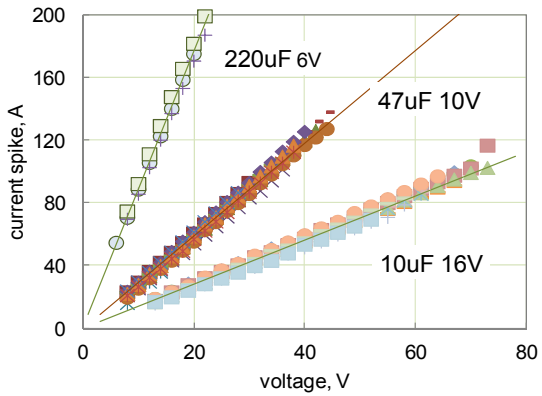
✓ To simulate worst case conditions I_{sp} should be maximized.

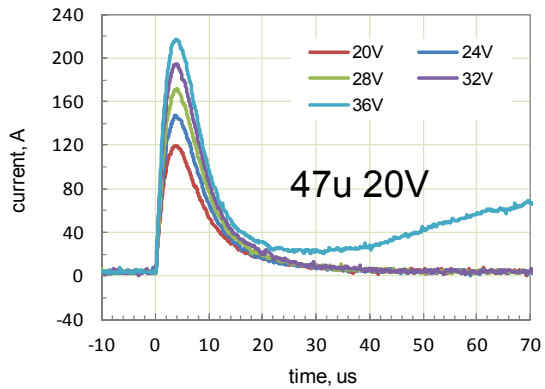
Effective Resistance of the Circuit









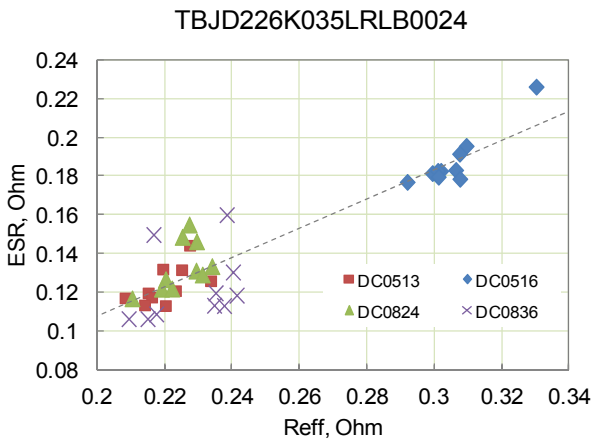


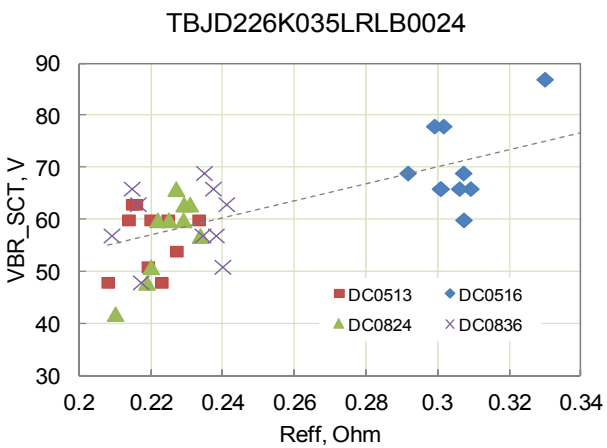
Test anomalies, e.g. poor contacts, can be revealed by $I_{sp}(V)$ curves

- ✓ I_{sp} increases linearly with voltage allowing for calculations of the effective resistance of the circuit, R_{eff},.
- ✓ R_{eff} corresponds to the impedance of the circuit and includes R_{ac}, ESR, resistance of contacts, and circuit inductance, L_c.

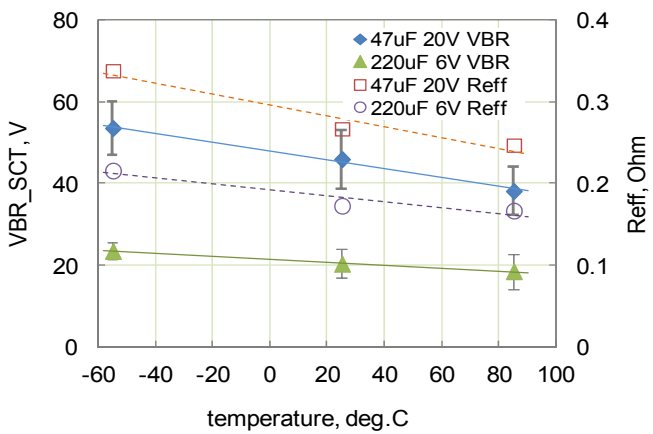
Effect of R_{eff} on Breakdown Voltage

- Different lot date codes of 22 μF 35V capacitors.





- Effect of temperature

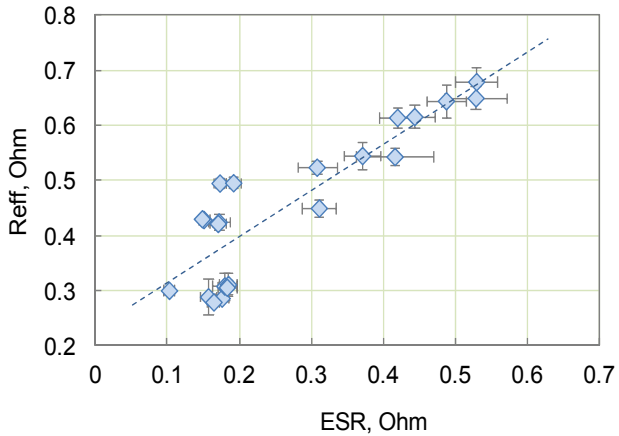


- ✓ Parts with larger *ESR* (R_{eff}) had greater VBR.
- ✓ Temperature decreases ESR resulting in lower VBR.
- ✓ An increase in R_{eff} by ~0.1Ω results in increase of *VBR ~10%.*

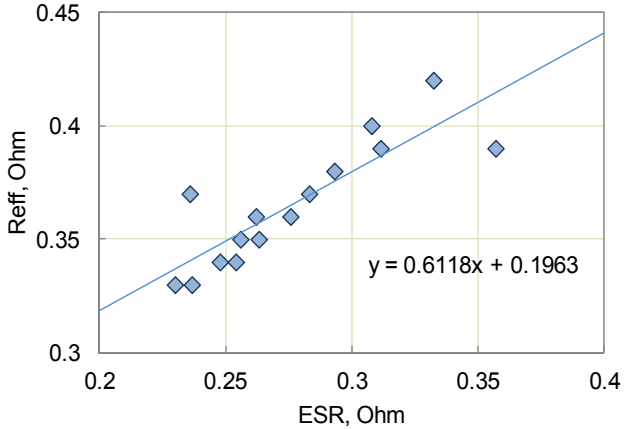
Presented by Alexander Teverovsky at an iNEMI (International Electronics Manufacturing Initiative) WebEx, June 2013 and deliverable to NASA Electronic Parts and Packaging (NEPP) Program to be published on nepp.nasa.gov.

Correlation between ESR and R_{eff}

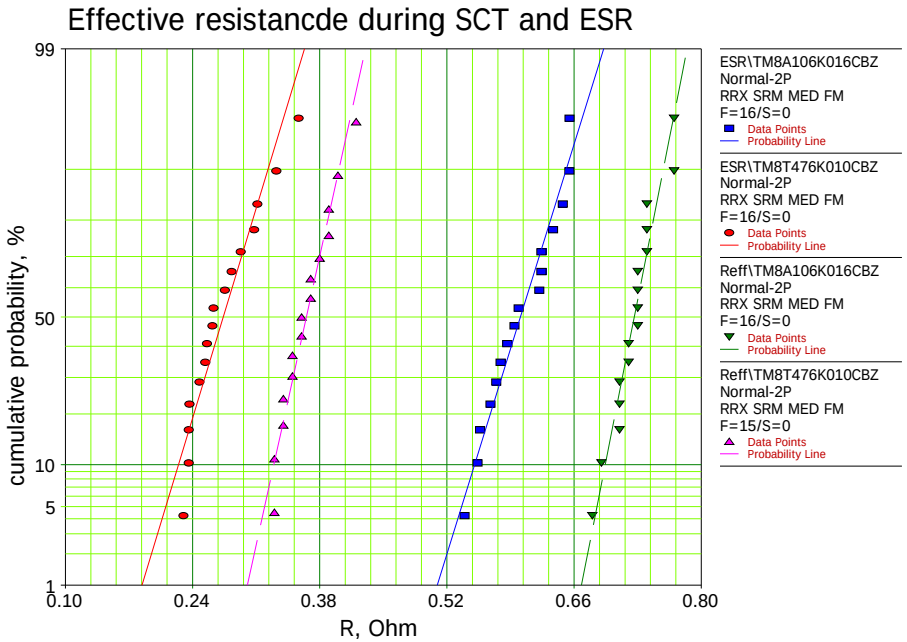
20 lots of HV capacitors



47uF 10V uchips



microchips



- ✓ In an optimized set-up the difference between R_{eff} and ESR is 0.1 - 0.2 Ω.

$$R_{eff} = \frac{VR}{I_{sp}} \approx R_{ac} + ESR$$

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SCT Summary

- Results of SCT depend on the rate of voltage increase.
- To assure proper SCT conditions, current spike amplitudes, I_{sp}, should be measured for each part, and conditions $VR/I_{sp} = R_{eff} < 0.5 + ESR$ should be verified.
- Tantalum capacitors manufactured per M55365 might fail at first power turn-on due to non-adequate SCT conditions.
- Additional testing and analysis (to compare levels of current spikes during testing and application) are necessary to use tantalum capacitors without limiting resistors.