Guidelines for Testing of Polymer Tantalum Capacitors

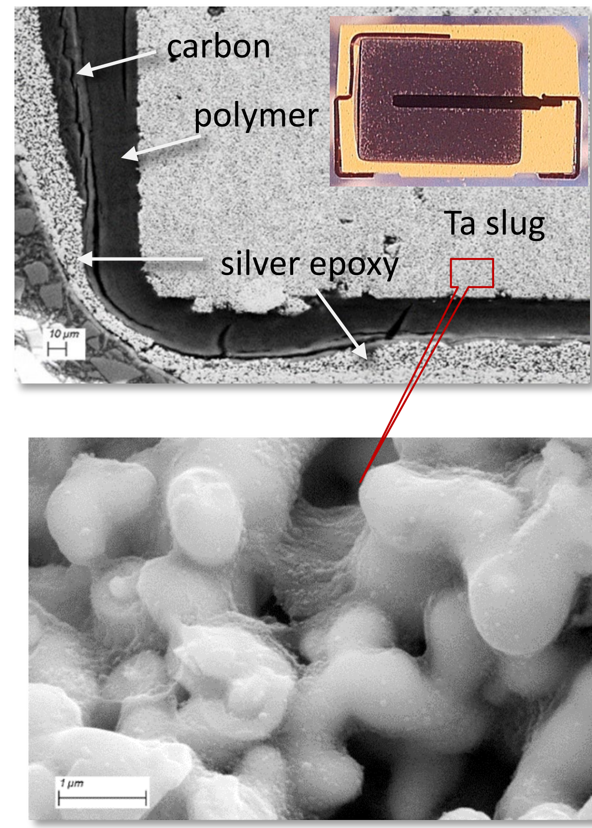
Alexander Teverovsky
Jacobs Engineering, Inc.
Work performed for EEE Parts, Photonics and Assembly Branch, NASA GSFC, Code 562
Alexander.A.Teverovsky@nasa.gov

List of Acronyms

3SCT	Step stress surge current test	**HTS**	High Temperature Storage
AC	Alternative Current	**IM**	Infant mortality
ACC	Anomalous Charging Current	**LAT**	Lot acceptance test
AEC	Aluminum Electrolytic Capacitor	**LT**	Life Test
AF	Acceleration Factor	**MEAL**	Mission, Environment, Applications and Lifetime
AT	Anomalous Transient	**MSL**	Moisture sensitivity level
BI	Burn-in	**MTC**	MnO2 tantalum capacitor
CCC	Constant current charging	**PEM**	Plastic encapsulated microcircuit
CVCM	Collected Volatile Condensable Materials	**PST**	Power surge test
CVR	Constant voltage ramp	**PTC**	Polymer Tantalum Capacitor
DC	Direct Current	**RC**	Room condition
DCL	Direct current leakage	**S&Q**	Screening and Qualification
DF	Dissipation Factor	**SBDS**	Simulated breakdown screening
DLA	Defense Logistics Agency	**SCT**	Surge current test
DWG	Drawing	**TDDB**	Time dependent dielectric breakdown
ESR	Equivalent Series Resistance	**TTF**	Time to failure
FR	Failure rate	**VR**	Voltage rating
HALT	Highly Accelerated Life Testing	**WO**	Wear-out

Outline

- ❑ Benefits of the polymer cathode technology
- ❑ Specifics of PTCs
  - Effect of moisture on AC and DC characteristics
- ❑ Transients in PTCs and ACC
  - Methods for ACC assessment
  - Factors affecting ACC
  - Failures during PST and thermal effect
- ❑ Reliability issues
  - Degradation of AC characteristics during HTS
  - IM and WO failures



Guidelines for PTCs

- Explanations of physical processes in the parts and reasons behand S&Q procedures.
- Recommendations for screening, lot acceptance, and derating procedures.

Guidelines for Screening, Lot Acceptance, and Derating for Polymer Tantalum Capacitors

1. Scope.

These guidelines have been developed for NASA space projects that are planning to use new technology hermetic and chip polymer cathode tantalum capacitors. Polymer Tantalum Capacitors (PTC) selected from MIL-PRF-32700, automotive grade (AEC-Q200) parts, or COTS+ (hi-rel COTS) capacitors should be screened and qualified as suggested in Tables 1-3 and derated per section 9 below. Screening and lot acceptance tests that were carried out for a lot that is intended for flight as a part of the manufacturing process do not need to be repeated.

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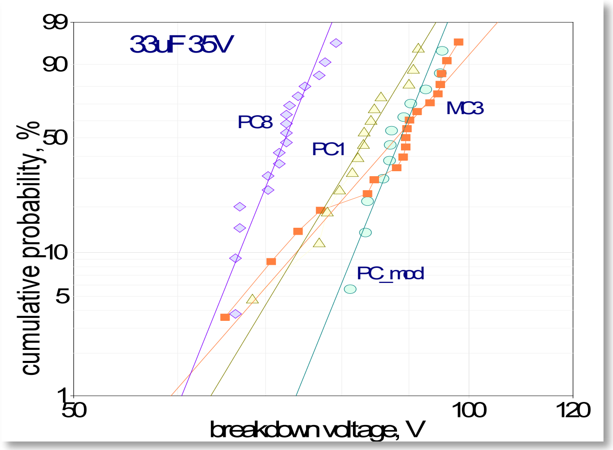
Benefits of the Polymer Technology

- Low ESR (milliohm range).
- A relatively safe failure mode (no ignition).
- High ripple currents and frequency of operation.
- Possibilities of higher operating voltages (up to 125V).
- High radiation tolerance (up to 5 Mrad Si).
- Low infant mortality failure rate due to a less stressful process of the cathode formation (below ~180C for PTCs and up to 350C for pyrolysis of manganese nitrate) that results in a smaller concentration of defects in the dielectric.



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    - Preconditioning
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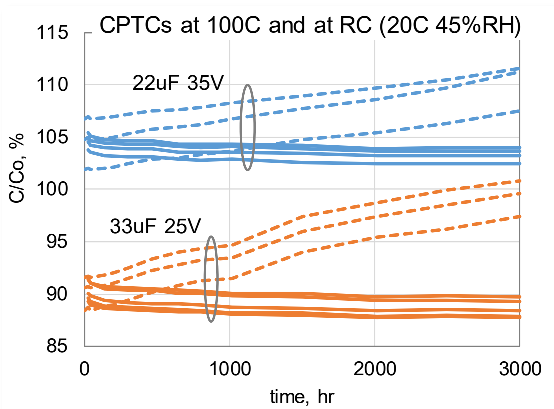
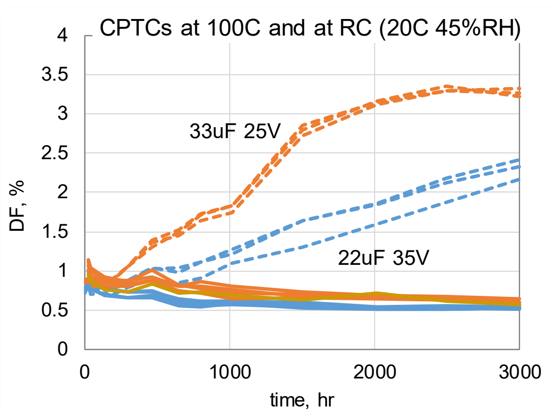
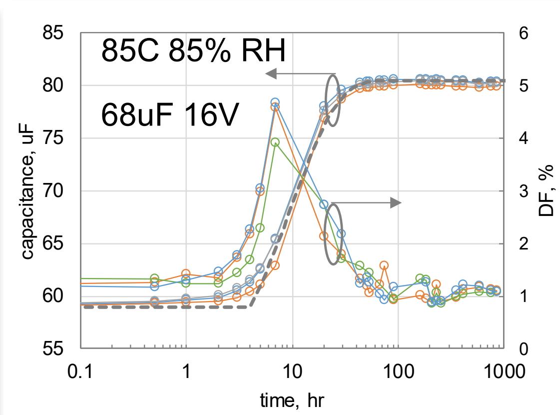
Effect of Moisture on AC Characteristics

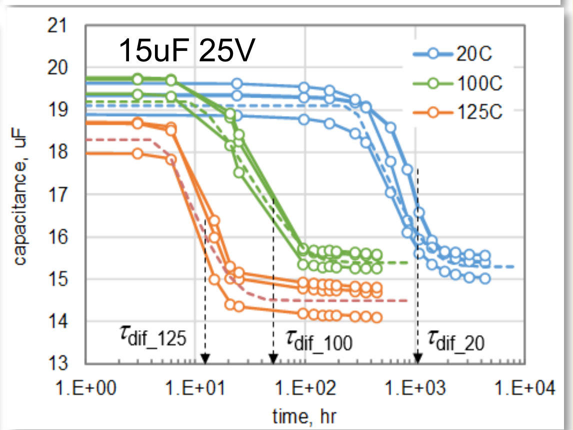
Storage at 100C and at room conditions





Effect of humidity chamber and bake conditions

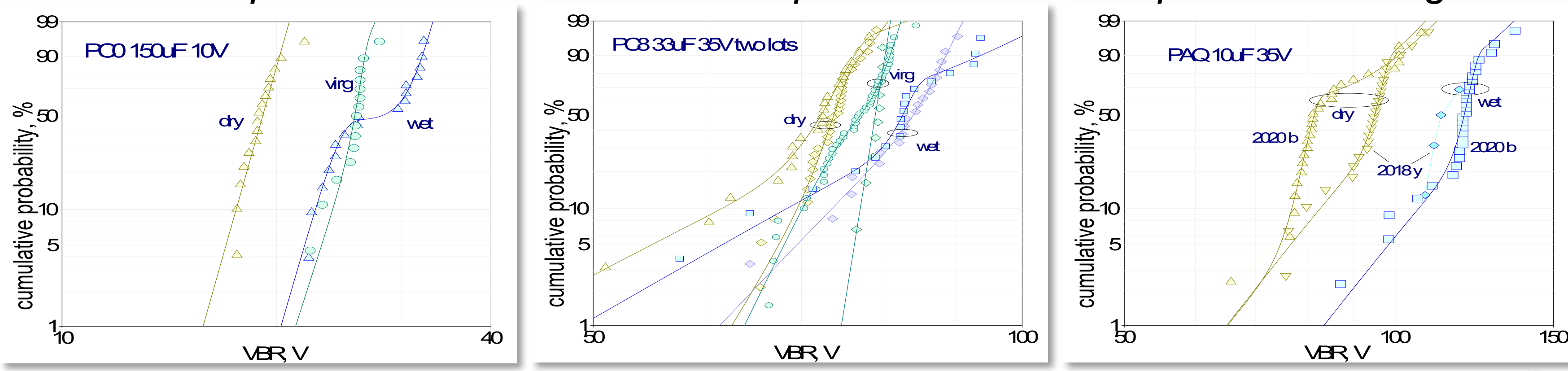




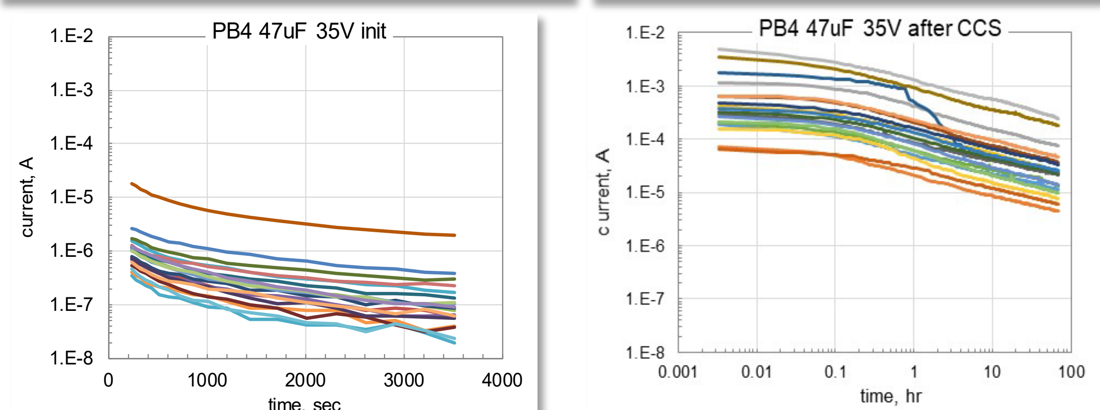
- ✓ Capacitance remains stable in dry conditions but might increase substantially with time at RC.
- ✓ Measurements of AC characteristics require preconditioning (out-of-tolerance failures).
- ✓ Capacitance changes reproducibly with humidity.
- ✓ PTCs can be used as humidity sensors.
- ✓ *C(t)* depends on diffusion characteristics of the case and absorption capability of the slug.

Effect of Moisture on Breakdown Voltages

Examples of VBR distributions for parts with different preconditioning



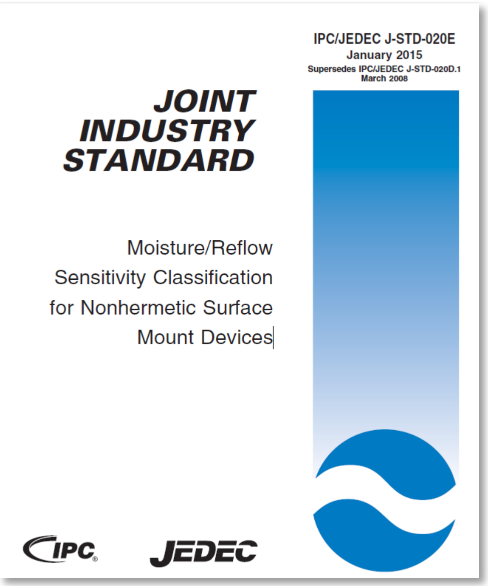
Initial and post breakdown testing leakage currents



- ✓ The presence of moisture increases breakdown voltages in PTCs.
- ✓ The effect is due to anomalous transients and solid-state anodic oxidation.
- ✓ Leakage currents are decreasing with time after scintillation breakdown.

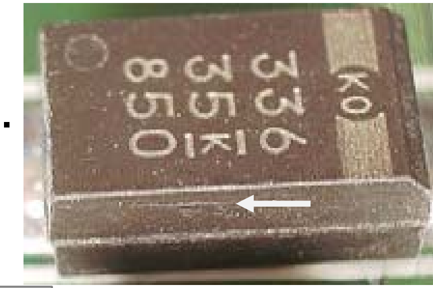
Moisture Sensitivity Level

- MSL is related to the effect of soldering only and does not indicate reliability of parts in humid environments.
- Pop-corning might happen in all plastic encapsulated components.
- MSL ratings are based on J-STD-020 classification.
- The standard specifies preconditioning for different MSL and reflow temperature profiles to verify compliance.
  - T_{max} = 235C for Sn/Pb and T_{max} = 260C for Pb-free processes
- Post-reflow tests and failure criteria are described for PEMs (including CSAM).
- Sample size, test types, and failure criteria to assure reliability of devices should be defined for each type of components.

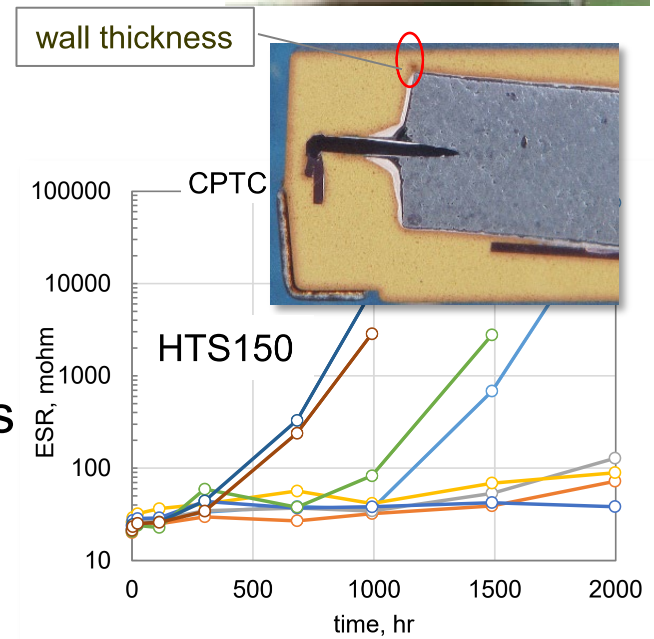


- ✓ Testing to characterize MSL using J-STD-020 for PTCs should include surge current and power surge tests.
- ✓ Reliability tests should be carried out using components soldered onto PWBs per MSL.

Effect of Soldering



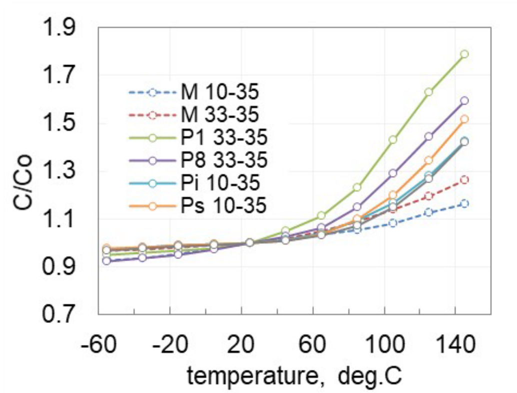
- PTCs absorb ~2x the amount of moisture in MTCs.
  - Most of the moisture is in pores of the slugs.
  - Soldering reduces amount of moisture by 50% to 90%.
- Popcorning in Ta caps can result in:
  - mechanical damage (cracking) of the case;
  - lead-frame/molding compound delamination;
  - fracture in the slug that damages Ta2O5 layer.
- Cracking in cases rises the rate of ESR degradation by facilitating access of air to the polymer cathode.
- Drying of PTCs during soldering increases ACC and can result in the first power-on catastrophic failures.
- The probability of post-soldering failures depends on preconditioning and is lot-related.

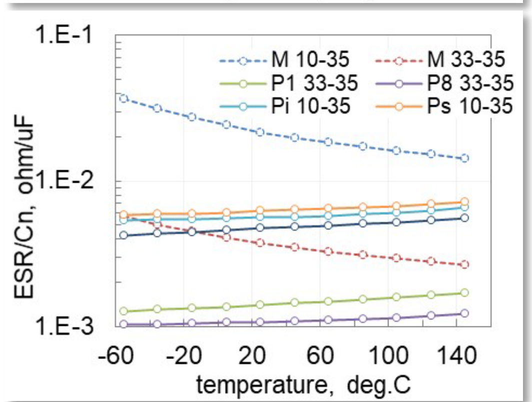


✓ All PTCs should be considered as parts with MSL ≥ 3. If necessary, loose parts should be baked at 125°C for 16 to 24 hours and parts in reels at 55 °C (dry chamber) for one week.

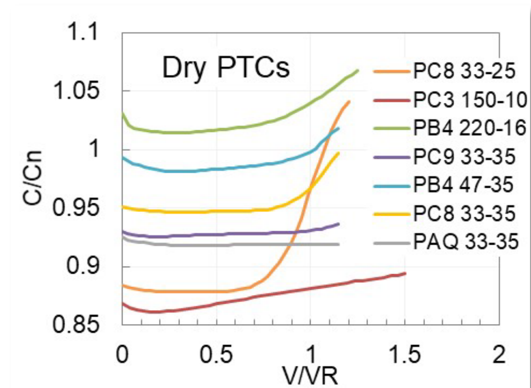
AC Characteristics

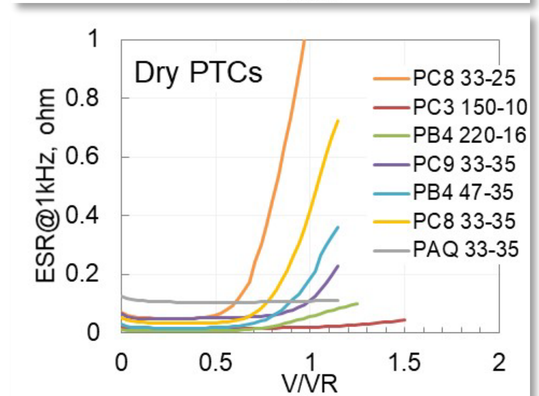
Effect of temperature





Effect of DC voltage

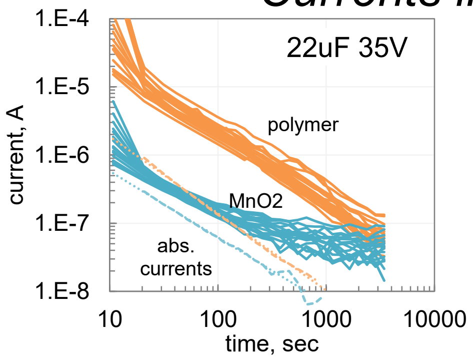


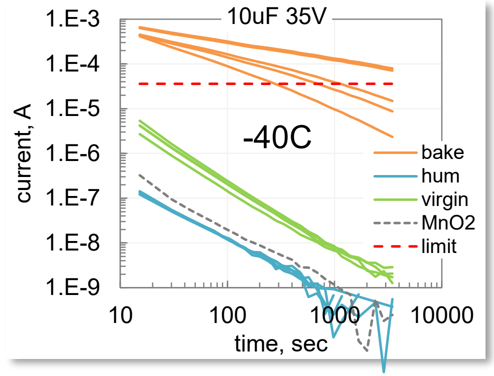


- ✓ Temperature has a stronger effect on AC characteristics of PTCs compared to MnO_2 capacitors.
- ✓ Low frequency AC characteristics are changing with voltage and time under bias (a manifestation of anomalous transients).

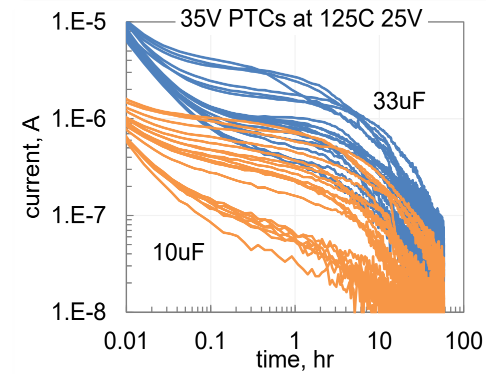
Leakage Currents

Currents in MnO2 and PTCs

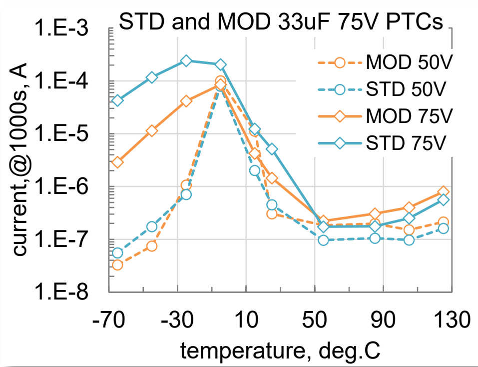


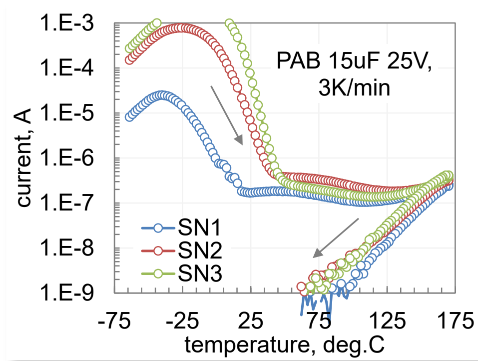


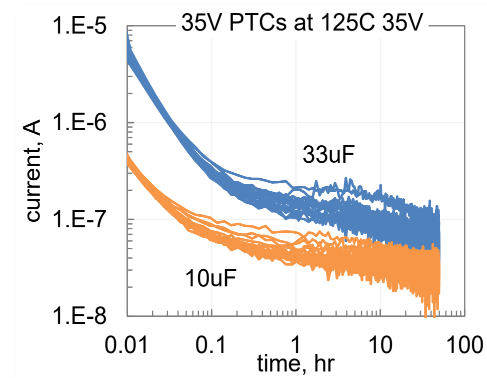
Long-term variations



Effect of temperature







- ✓ High DCL for PTCs (0.1CV vs. 0.01CV) is mostly due to anomalous transients. Operational currents are much lower.
- ✓ Anomalous transients might last for hours, depend on moisture content, previous stresses, and might increase at low temperatures.

Stability at Low and High T per M32700 and M55365

	Step 1, +25C		Step 2, -55C		Step 4, +85C		Step 5, +125C		Step 6, +25C	
	polym	MnO2	polym	MnO2	polym	MnO2	polym	MnO2	polym	MnO2
DCL	IL	IL	**NR (?)**	**NR**	**10xIL?**	IL	**10xIL?**	IL	IL	IL
C**	IL	IL	+_10%	+_10%	+30% -10%	+_10%	+40% -10%	+_15%	+-10%.	+-5%.
DF	IL	IL	IL	IL	1.2XIL	IL	1.5XIL	IL	IL	IL
ESR	IL	IL	1.2xIL	NR(?)	1.2xIL	NR(?)	1.5xIL	NR(?)	IL	IL

**IL – initial limit*
***AEC-Q200 parts have 20% at 85C and 30% at 125C*

- ✓ Limits for capacitance are tighter for automotive PTCs.
- ✓ Per M32700, temperature variations are specified only DCL and DF.
- ✓ Preconditioning (30 min at 125C) is not sufficient for PTCs, 16-24 hr bake at 125C is necessary.
- ✓ There is a need for DCL requirements for PTCs at low temperatures.
- ✓ Margins for DF are too generous.

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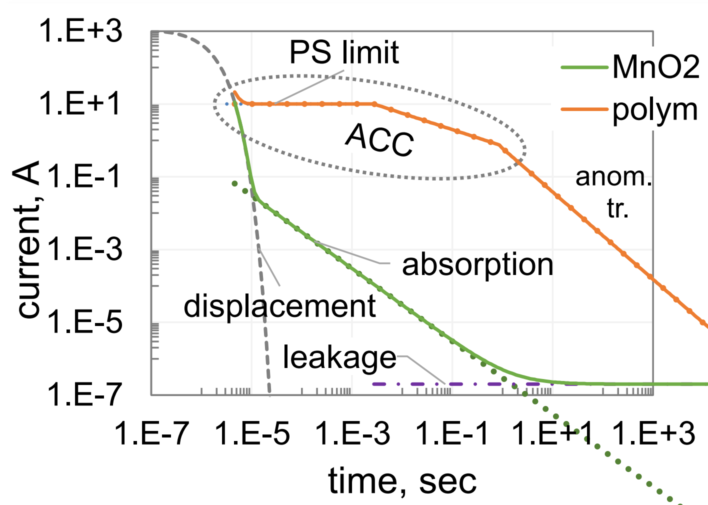
What are Anomalous Transients and ACC?



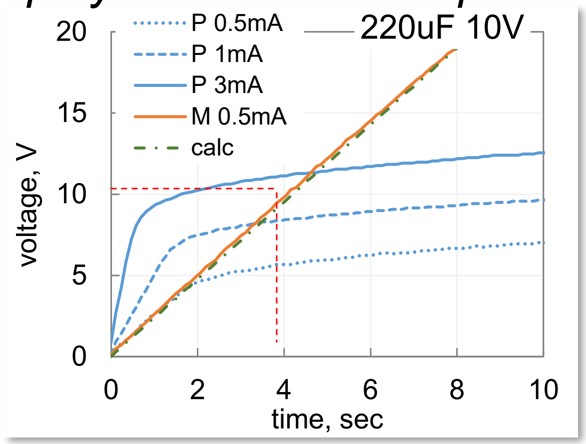
- Normal transients that are due to displacement and absorption currents are reversible, increase linearly with voltage, and have a poor temperature dependence.
- AT can be revealed in dry discharged PTCs and affect most characteristics of the parts.
- AT are likely due to the Schottky emission at the conductive polymer/T2O5 interface. Rising of the barrier was explained by orientation of polymer dipoles or by electron trapping processes.

- ✓ ACC is a manifestation of AT that can be defined as currents exceeding 0.01 A for more than 1 msec.
- ✓ AT can cause parametric failures of the parts, but ACC might result in catastrophic failures.
- ✓ Currently, there is no standard metric for ACC.

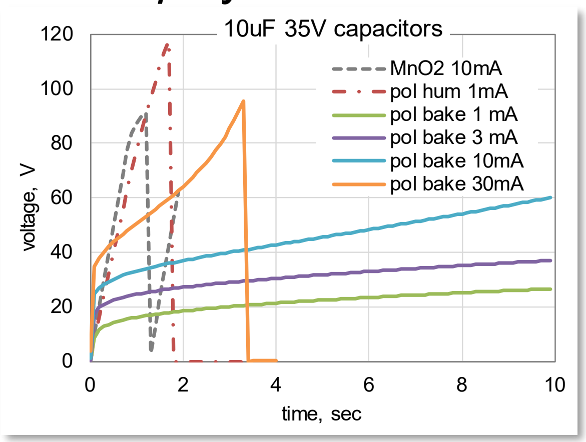
ACC Assessment: Constant Current Charging

❑ Monitoring voltage while charging a PTC at a constant current

V-t curves during CCC testing of MnO2 and polymer tantalum capacitors



V-t curves during CCS breakdown testing of MnO2 and polymer tantalum capacitors



❑ Charge time for an ideal capacitor $t_i = C\times VR/I_{ch}$

❑ Charge time for a capacitor with leakage $t_{ch} = C\times VR/(I_{ch}\text{-}I_{leak})$

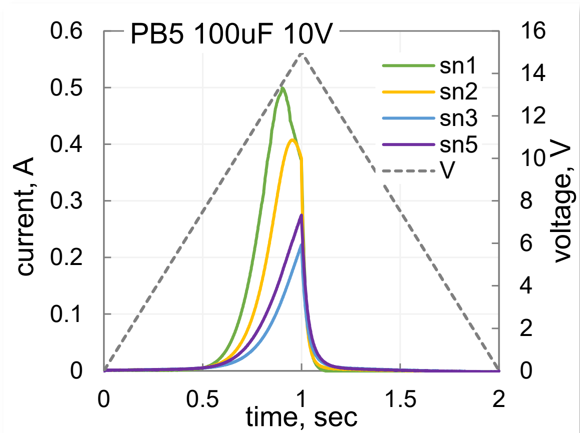
❑ The ratio of experimental charging time, t_{exp}, and t_i can characterize ACC.

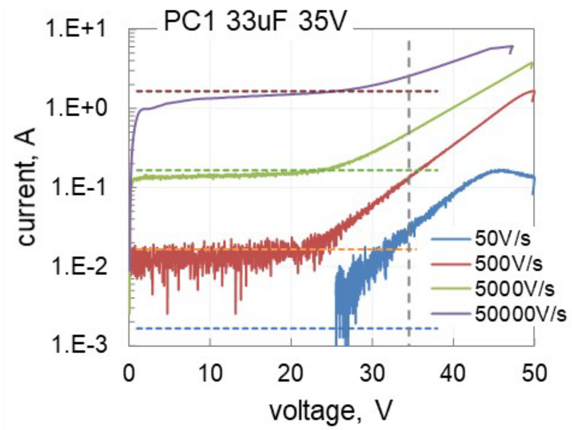
✓ In some cases, t_{ch} are too long for a practical use of CCC method.

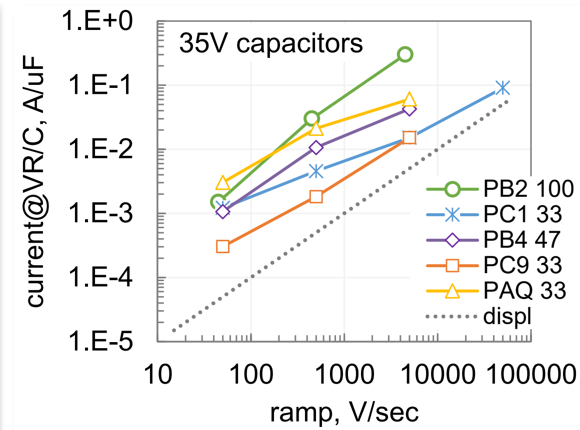
✓ Selection of optimal charging conditions might be a challenge.

✓ SBDS implementation might be difficult due to ACC.

ACC Assessment: Constant Voltage Ramp







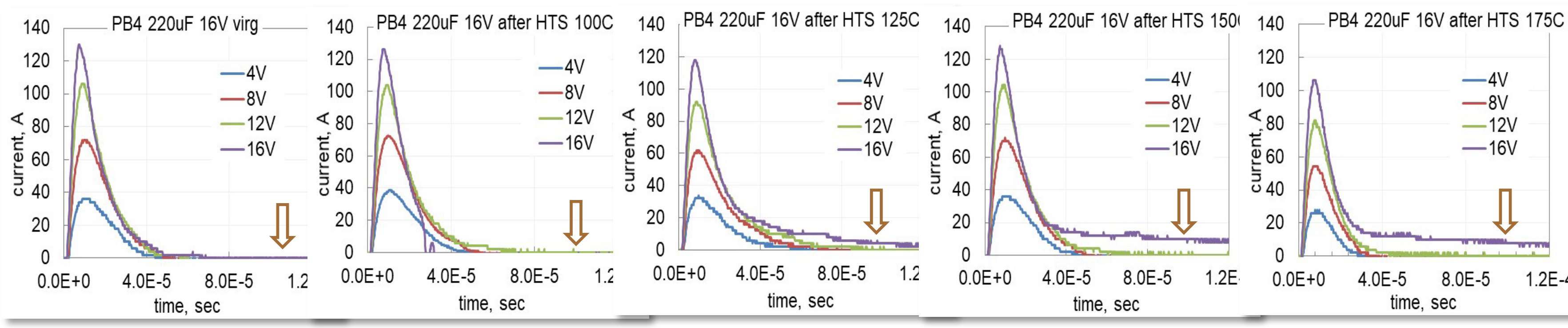
- ❑ CVR: increasing voltage at a constant rate and monitoring currents.
- ❑ CVR does not result in catastrophic failures.
- ❑ ACC can be characterized by the ratio $I_{ACC}(V)$ to $I_{displ} = C\times dV/dt$.
- ❑ Threshold voltage(?) – depends on the ramp rate.

- ✓ During CVR, currents can reach max at V < V_{max}.
- ✓ The ratio $I_{ACC}(VR)/I_{displ}$ changes with the rate.
- ✓ Different part types have max $I_{ACC}(V)/I_{displ}$ at different ramp rates.

ACC during Surge Current Testing

- The purpose of SCT is to assure that the parts will not fail during power-on cycles.

3SCT after different high-temperature storage conditions



M32700 SCT Failure criteria:
"A failure is specified as any capacitor that draws 1 A after the appropriate charge time"

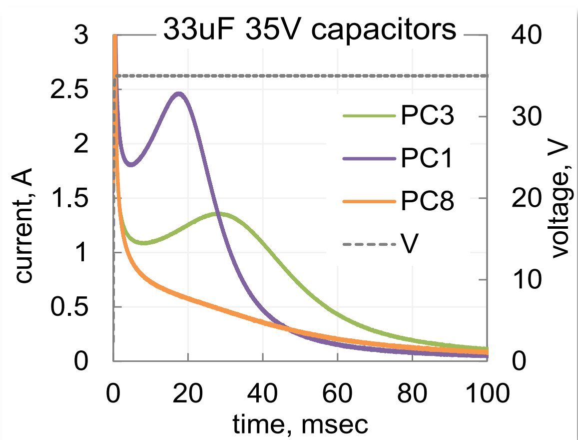
Maximum Charge time (ms)	Capacitance value (µF)
10	<47
25	$\geq$ 47 and <100
100	$\geq$ 100

- ✓ Anomalous transients might affect currents during SCT after ~1 msec.
- ✓ M32700 requirements reflect likely the presence of ACC, but they are not adequate for ACC assessments.

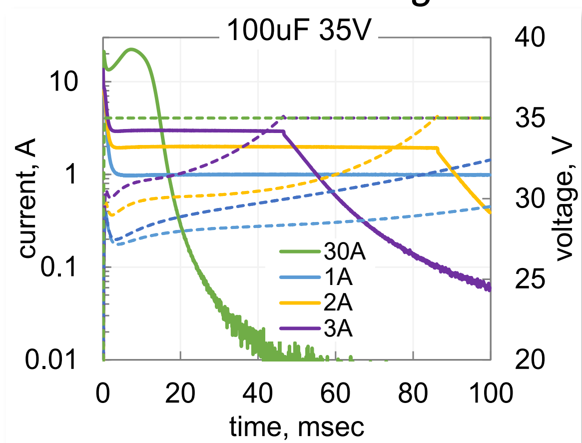
ACC Assessment: Power Surge Test

- Rated voltage is applied by a power supply capable of stabilizing voltage within 1 msec while the current and voltage are recorded with time. PST cycle: 200 msec ON, 200 msec OFF.
- Contrary to SCT, that stresses parts for less than ~1 msec, the level of power dissipation is high during the whole period of the PST.

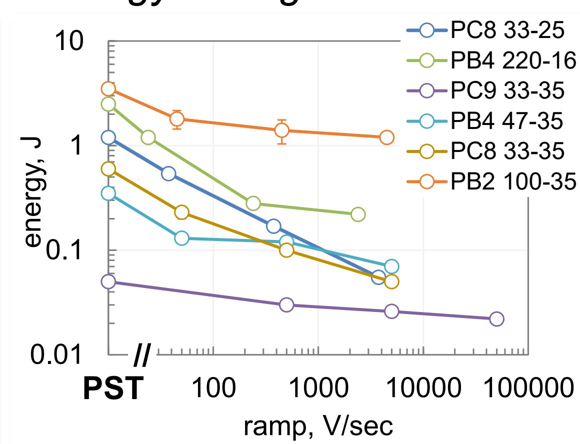
PST for 3 types of capacitors



PST at different limiting currents



Energy during PST and CVR



- ✓ Current relaxation might take more than 100 msec and be not monotonic.
- ✓ PST results in a higher energy dissipation compared to CVR test.

ACC Metrics

- ACC can be characterized by:
  (i) current after 10 msec, I_{10},
  (ii) transfer charge (Q_t), or
  (iii) dissipated energy (U_d).

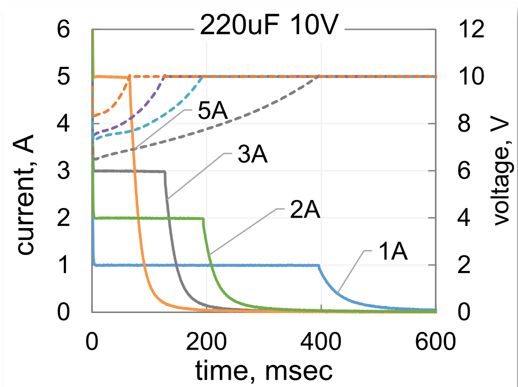
$$Q_t = \Sigma(I_i \times \Delta t)$$

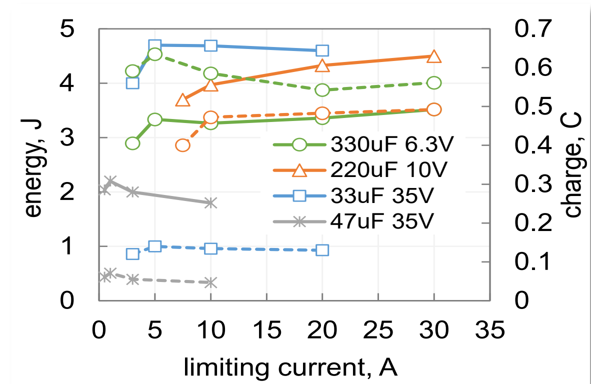
$$U_d = \Sigma(I_i \times V_i \times \Delta t)$$

$$U_d \approx Q_t \times V R$$

- Q_t and U_d are calculated by digital integration till *I(t)* = 10 mA.

PST at different limiting currents





- ✓ Q_t and U_d do not depend on the shape of current relaxation.
- ✓ Measurements of I_{10} is simple and is useful for parts with smooth relaxation when currents are not limited by PS.
- ✓ The level of ACC can be characterized as high at $I_{10} \geq 1$ A or $U_d \geq$ 1 J, low at $I_{10} < 0.1$ A or $U_d < 0.1$ J, and as medium in other cases.

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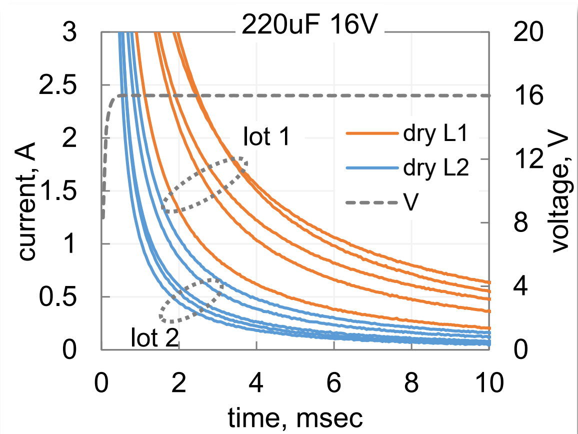
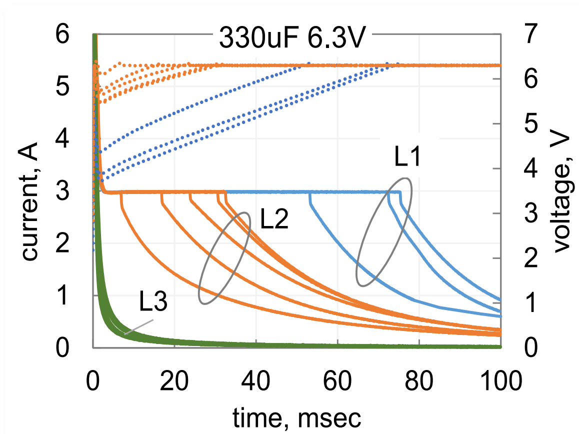
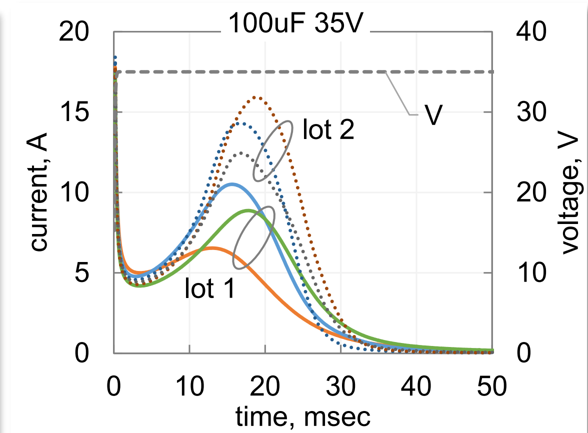
Reproducibility of PST Results

Lot-to-lot and sample-to-sample variations

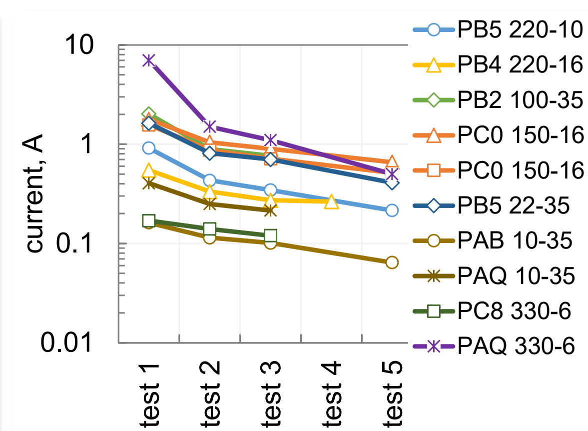






- ✓ Different lots might have substantially different level of ACC.
- ✓ For the same lot, sample-to-sample variations of I_{10} are ~20% and ~10% for U_d.
- ✓ Repeat measurements reduce ACC currents substantially, up to 5 times.

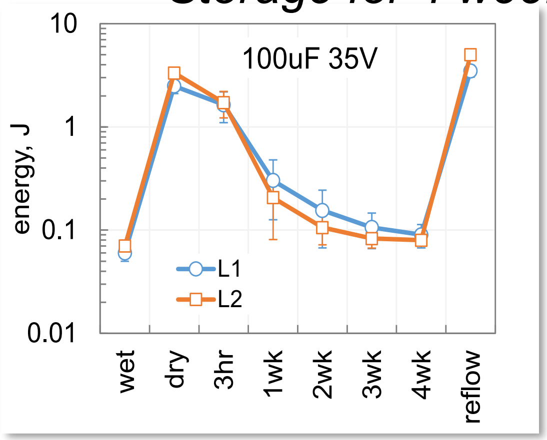
Repeat testing

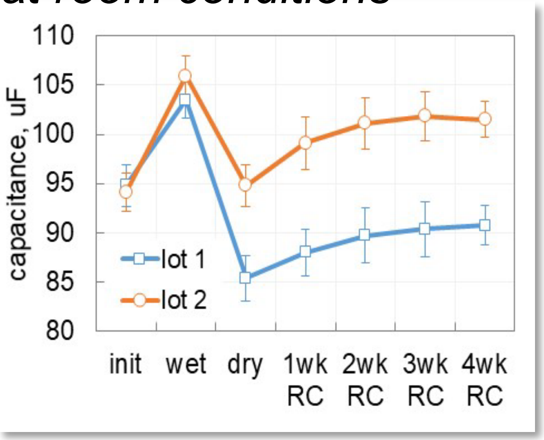


Effect of Preconditioning

- Wet capacitors: storage at 85 °C and 85% RH for one week.
- Dry capacitors: baking for 16 to 24 hours at 125 °C.
- Capacitors were tested with time of storage at room environments (20 °C and 40% RH) for four weeks.

Storage for 4 weeks at room conditions





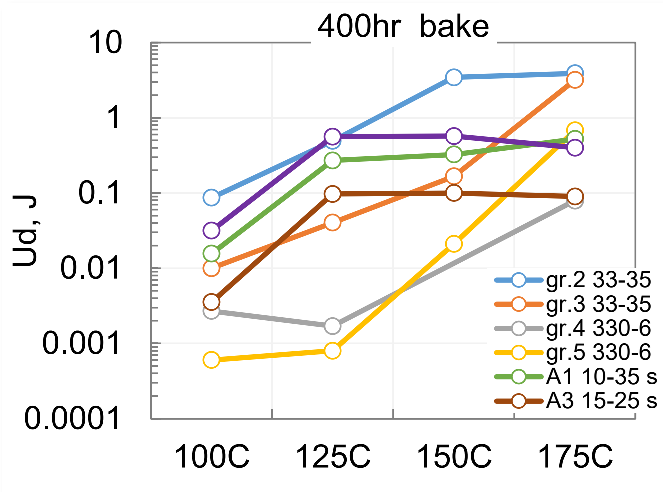
Capacitors as moisture sensors:

$$\Delta m = 100\frac{C - C_{dry}}{C_{wet} - C_{dry}}, \%$$

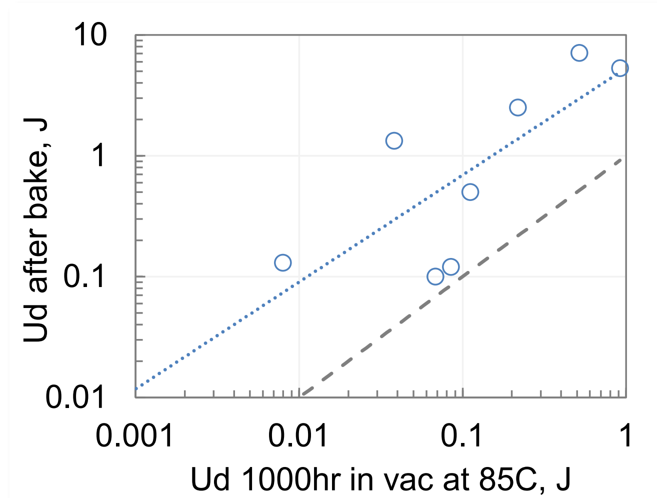
- ✓ ACC is negligible for wet parts (<0.1J), but for dry parts U_d might exceed 1J.
- ✓ Even a relatively small amount of moisture can change ACC significantly and reduce it to the level of wet capacitors.

Effect of Preconditioning, Cont'd

Different types of capacitors were baked for 400hr at T from 100C to 175C to assess the effect of bake temperature on the level of ACC.



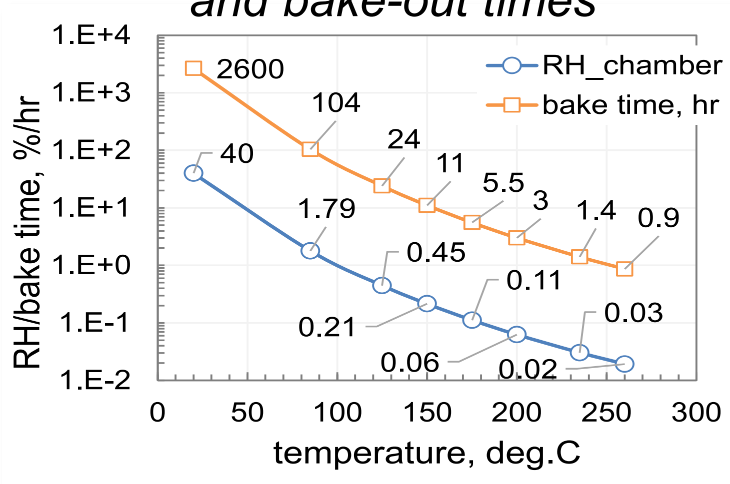
Eight groups of capacitors were tested using PST after 1000hr vacuum storage at 85C and after 24 hr bake at 125C.



- ✓ Increasing bake temperature above 125C might increase the level of ACC.
- ✓ Moisture desorption in vacuum at low temperatures might increase ACC less significantly compared to 125C bake in air.

Effect of Preconditioning, Cont'd

RH in a temperature chamber at room conditions (40% RH, 20C) and bake-out times

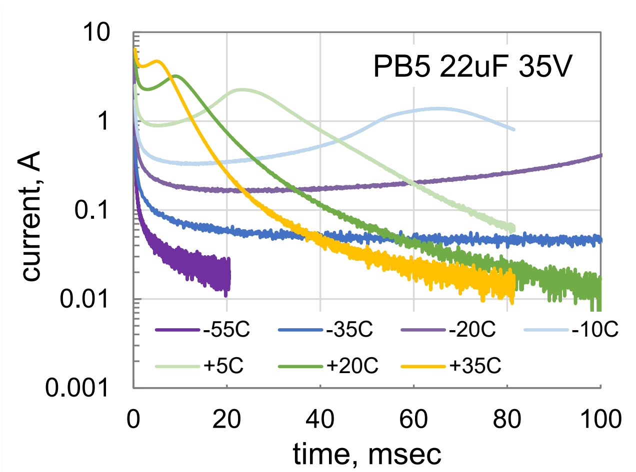


- ACC depends on the moisture content that is a function of bake temperature and time.
- Keeping parts at 85C (or in a dry box with RH~10%) after bake at 125C might decrease ACC due to a higher RH in the camber/box.

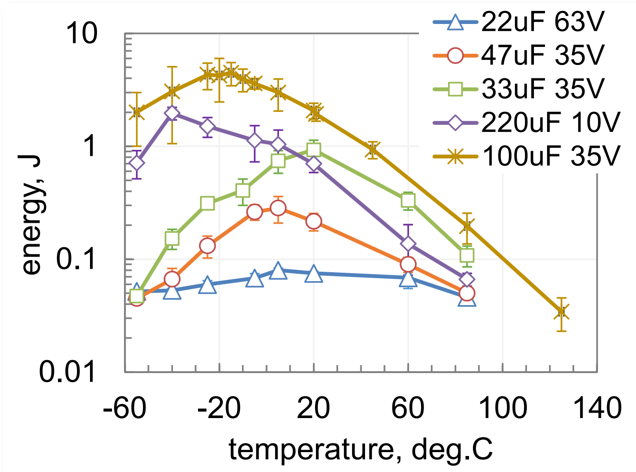
- ✓ The amount of moisture is not the only environmental factor affecting ACC. It depends also on the combination of moisture content and annealing conditions.
- ✓ ACC depends on the structural changes in PEDOT:PSS polymers caused by exposure to high temperatures.
- ✓ These changes depend on the initial moisture content, temperature and duration of annealing.

Effect of Temperature

- Current relaxation might have a hump at times that depend on temperature and might exceed 100 msec.
- No correlation to VR;
- Wide range of U_d levels: 0.08J < U_{d_max} < 6J.
- In most cases, U_d at temperatures above 85 ºC is below 0.1J.



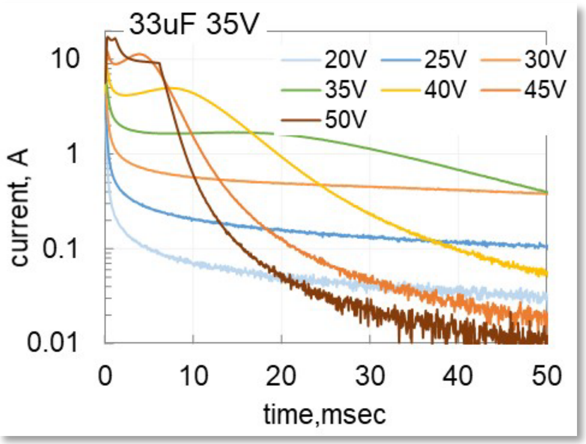
- ✓ $U_d(T)$ has maximum, that depending on the part type varied, between -40 ºC and +20 ºC.
- ✓ ACC will have negligible effect for parts operating at high temperatures.



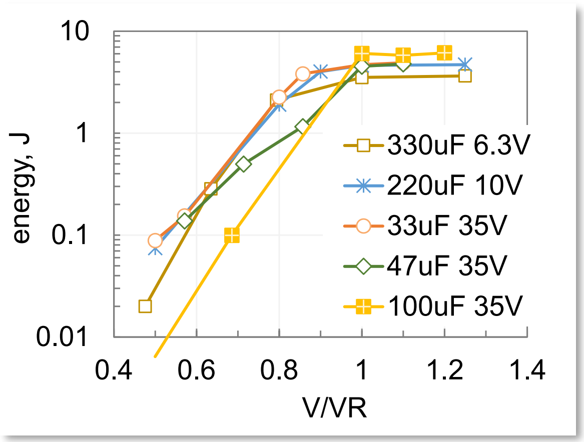
Effect of Voltage

- Decreasing voltages reduce the level of ACC substantially.
  (currents depend exponentially on $V^{0.5}$ indicating Schottky conduction)
- U_d did not change significantly at VR < V < 1.25VR but reduced more than 100X at 0.5VR.

An example of I-t_V curves



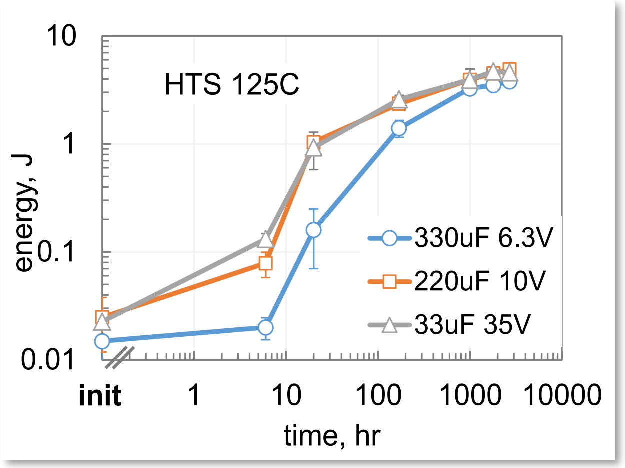
Voltage dependencies of U_d

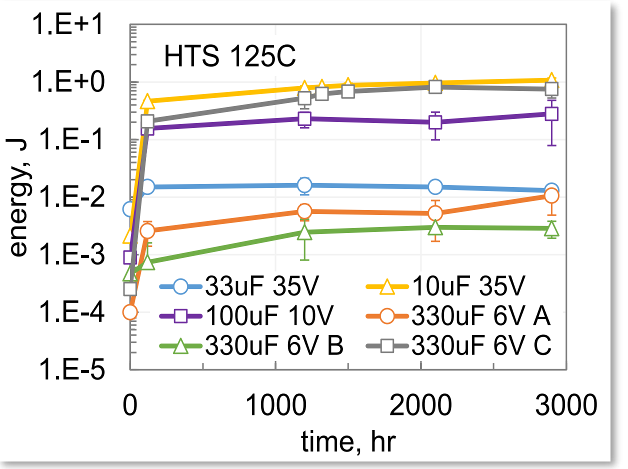


- ✓ In most cases, derating to 0.5VR reduces U_d to below 0.1 J.
- ✓ Voltage derating allows for a substantial reduction of ACC.

Effect of High Temperature Storage

Effect of storage at 125C on results of PST

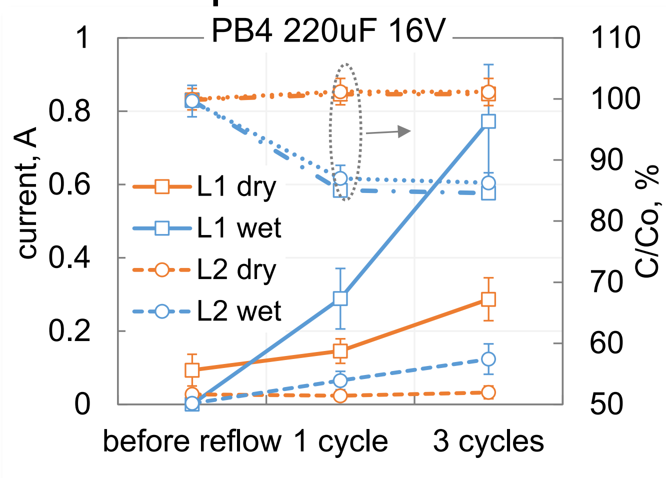


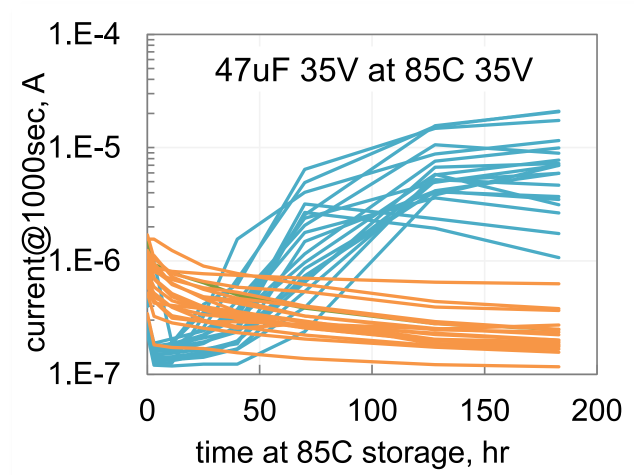


- ✓ The energy might increase up to 1000X during first 100 to 200 hours of HTS125 and remain practically the same for thousands of hours afterwards.
- ✓ The 24-hour bake at 125C that is typically used to dry-out PTCs allows for assessments of ACC but might be not sufficient to reach maximum levels.
- ✓ The parts that have a relatively low level of ACC will not degrade further during long-term aging at high temperatures.

Effect of Moisture and Reflow Soldering

- ❑ Reflow soldering at 235 °C reduces moisture content by 50% to 75%, so increasing of ACC was expected.
- ❑ Based on capacitance measurements, the bake time at 85C is ~ 100hr.



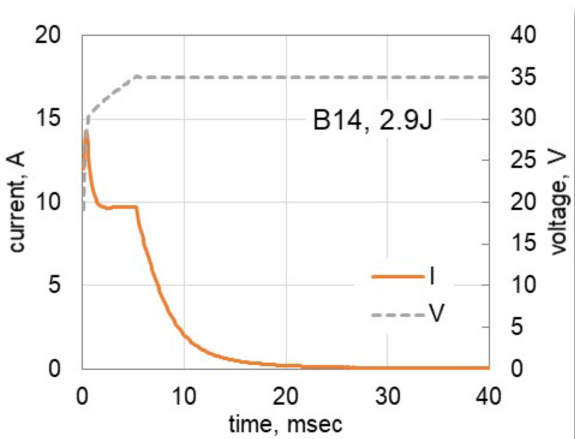


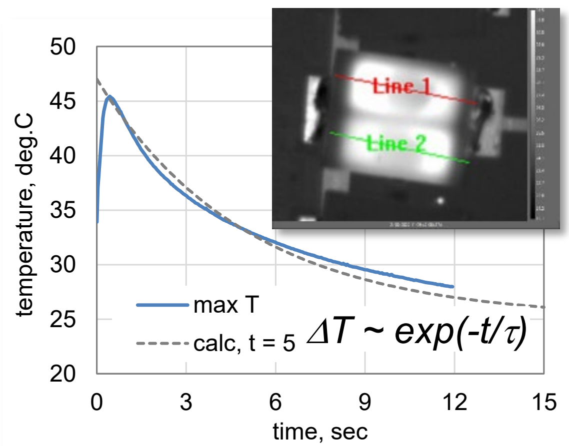
- ✓ Increasing number of reflow cycles increases the level of ACC.
- ✓ ACC increases even for initially dry capacitors.
- ✓ Reflow soldering might increase ACC in initially wet parts to a much greater degree compared to dry parts.
- ✓ Exposure to HT results in structural changes in PEDOT:PSS that depend on the initial moisture content and can cause variations in the traps' density and distributions.

Thermal Effect During PST

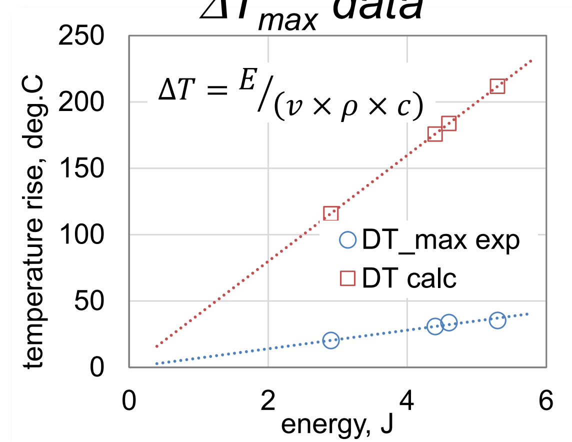
- Temperature of the parts soldered onto PWBs was monitored using an IR camera.
- $\Delta T_{max}(t)$ was approximated with an exponential function at $\tau = R_\theta \times C_\theta$.
- For power pulses <100 msec, the heating is adiabatic, and U_d increases temperature of the slug.
- The actual temperature of the slug, $T_{exp} << T_{act} < T_{calc}$.

An example of PST and temperature relaxation





Calculated and experimental ΔT_{max} data

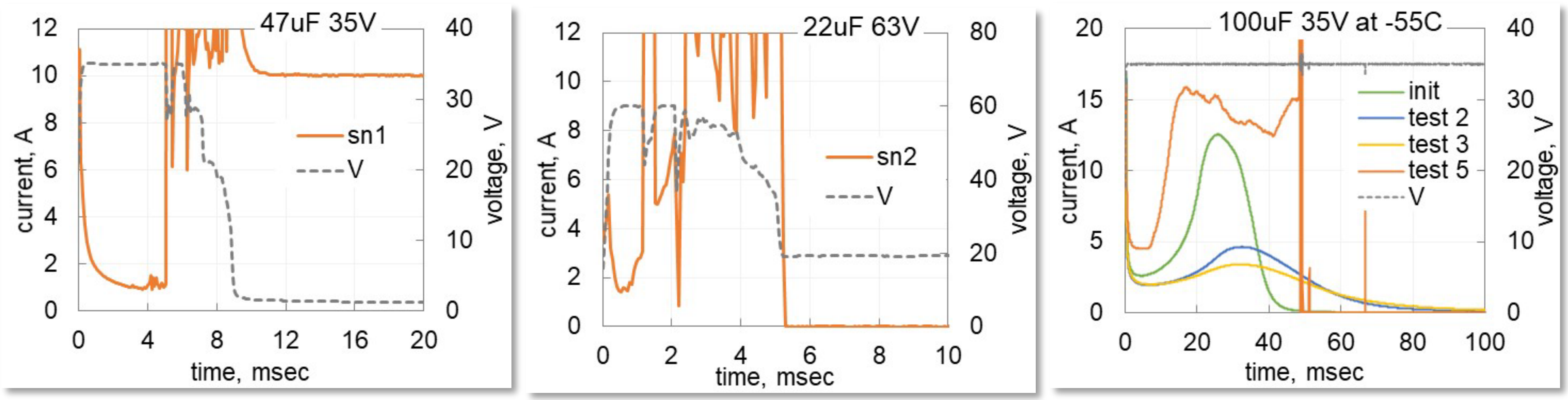


✓ ACC can create substantial thermo-mechanical stresses in the slug resulting in failures.

Failures During PST

- No failures caused by ACC were reported during CVR testing.
- PST results in higher dissipated energy and can cause failures.

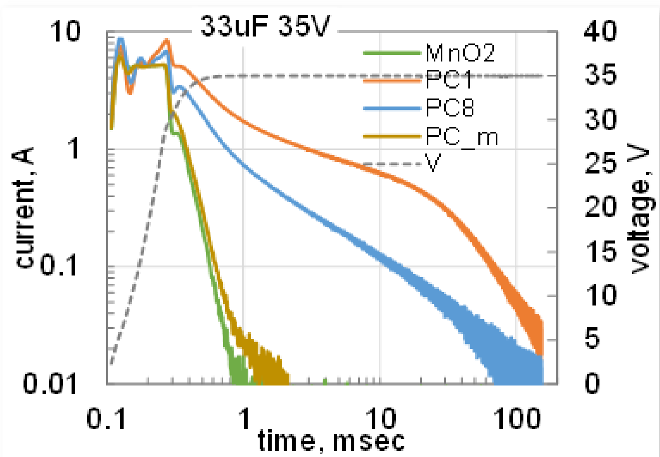
Examples of failure events during PST

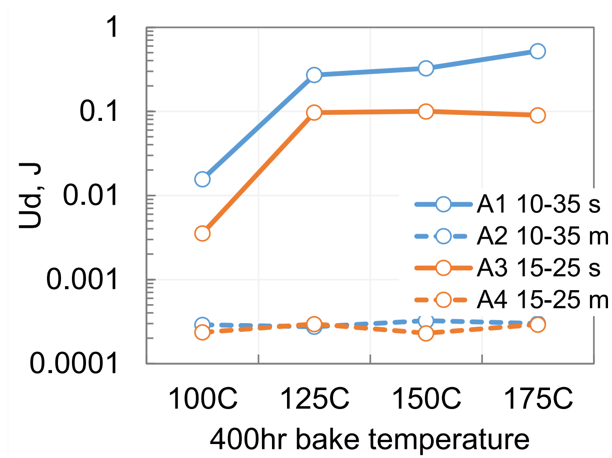


- ✓ The propensity to failure is lot-related and increases after reflow soldering.
- ✓ There is a need to use PST as a screening procedure.

Effect of Polymer/Process Modification

- ❑ Managing ACC issues: screening, assessment during LAT, and derating.
- ❑ Reduction of ACC level during manufacturing: modification of conductive polymers and processes of their application.





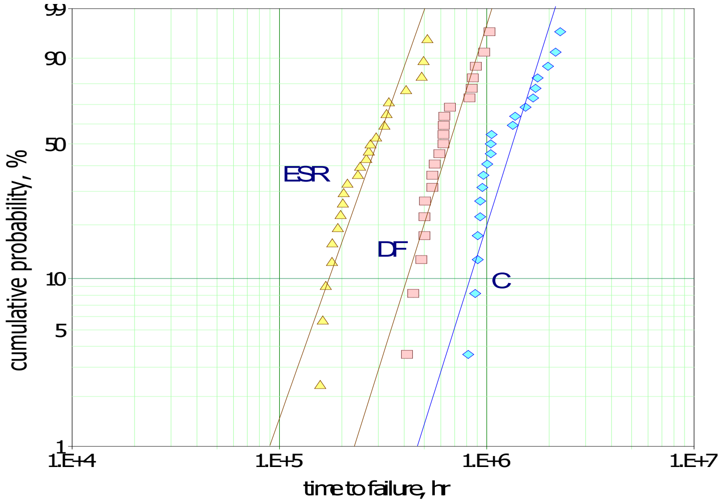
- ✓ Modification can reduce ACC by orders of magnitude and the result might be stable even after long-time baking at high temperatures.
- ✓ This might be not always the case and more testing and control is necessary.

Outline

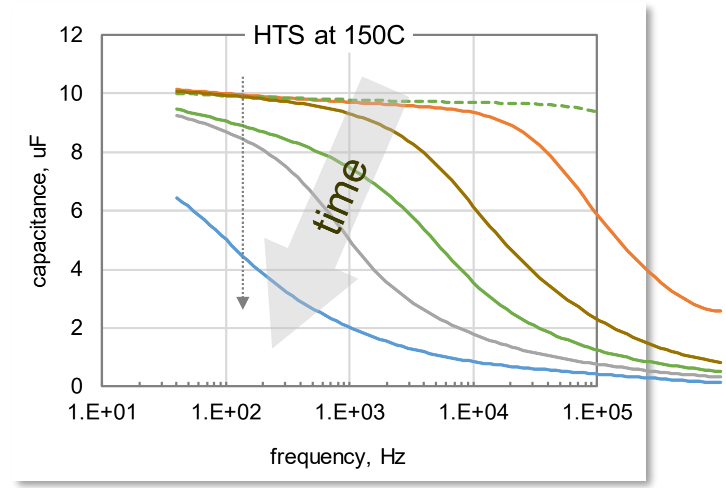
- Benefits of the polymer cathode technology
- Specifics of PTCs
  - Effect of moisture
  - Moisture Sensitivity Level (MSL)
  - AC and DC characteristics
- Transients in PTCs and ACC
  - Methods for ACC assessment
    - Constant current charging (CCC)
    - Constant voltage ramp (CVR) charging
    - Power surge test (PST) and metrics
  - Factors affecting ACC
    - Reproducibility of PST
    - Preconditioning
    - Temperature and Voltage
    - Reflow soldering
    - High temperature storage
  - Failures during PST and thermal effect
- Reliability issues
  - Degradation of AC characteristics during HTS
  - IM and WO failures

Degradation of AC Characteristics

Sensitivity of AC characteristics to ageing



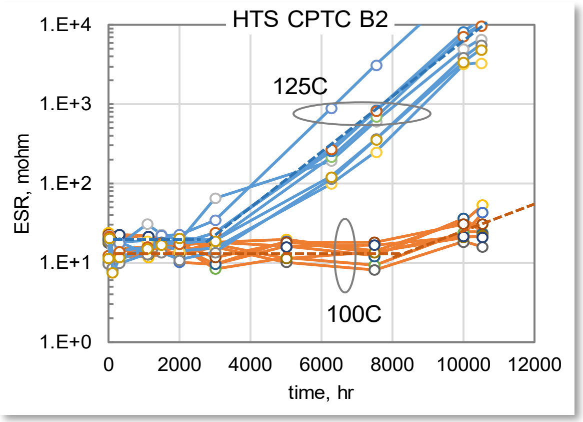
10 μF CPTC during HTS at 150 ºC

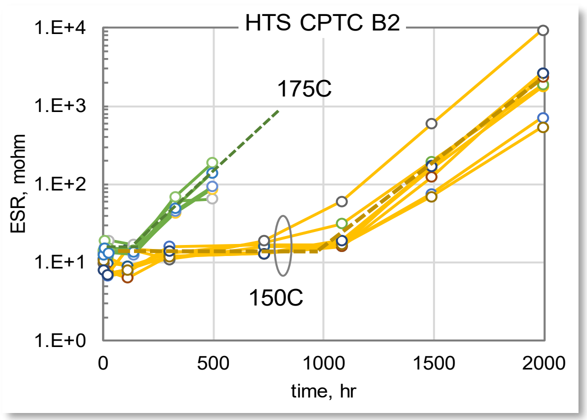


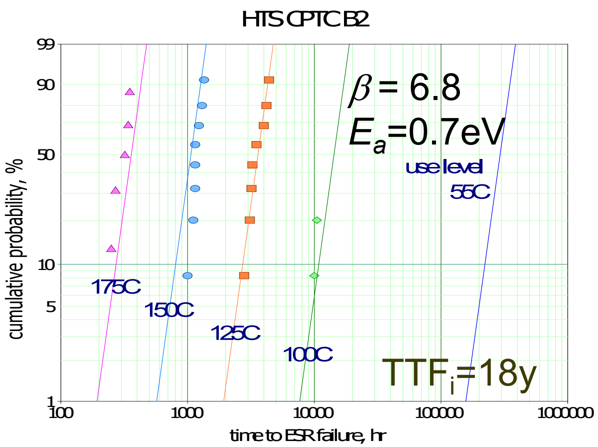
- ✓ On average, the times for capacitance failures (TTF_C) are ~3.5 and for DF failures (TTF_{DF}) ~2 times greater than for ESR (TTF_{ESR}).
- ✓ Degradation of C and DF is due to increasing of ESR.

Specifics of ESR Degradation

HTS of B2 220 µF 10 V capacitors



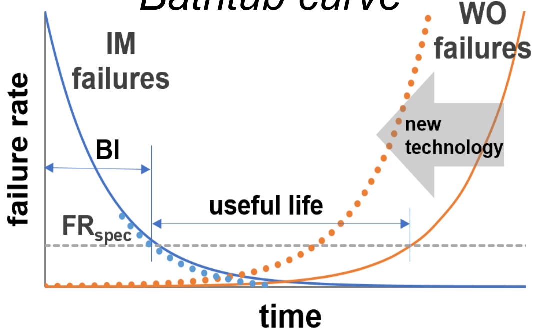




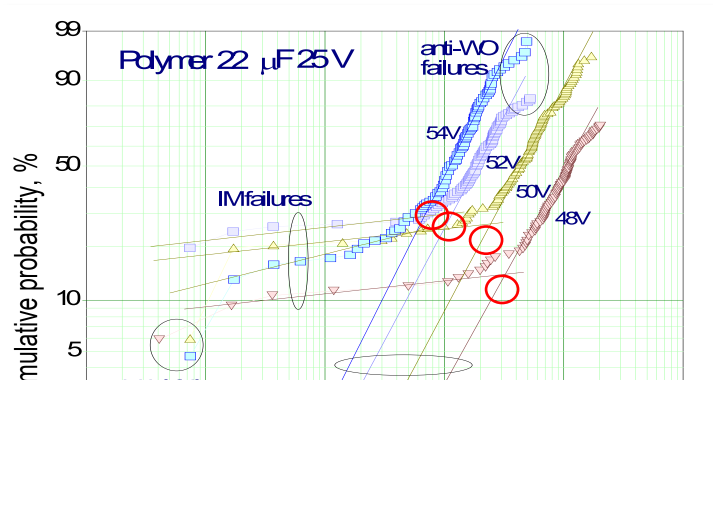
- ✓ Incubation period, t_i, before the inception of ESR growth.
- ✓ After t_i, ESR increases with time exponentially.
- ✓ Degradation of *ESR* is due to thermo-oxidative processes in conductive polymers.
- ✓ Permeability of air depends on packaging quality that affects the rate of ESR degradation and times-to failure.
- ✓ In vacuum E_a increases substantially (likely above 1.5eV).

IM and WO Failures

Bathtub curve



Examples of TTF distributions



- ❑ IM failures are due to defects in the components.
- ❑ WO failures are due to degradation processes in the materials.

The type of failures is determined by the shape factors of Weibull distributions.

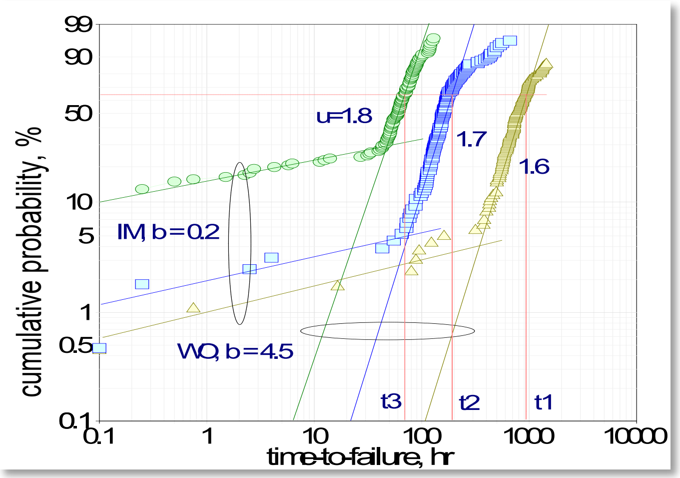
$$\lambda(t) = \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1}$$

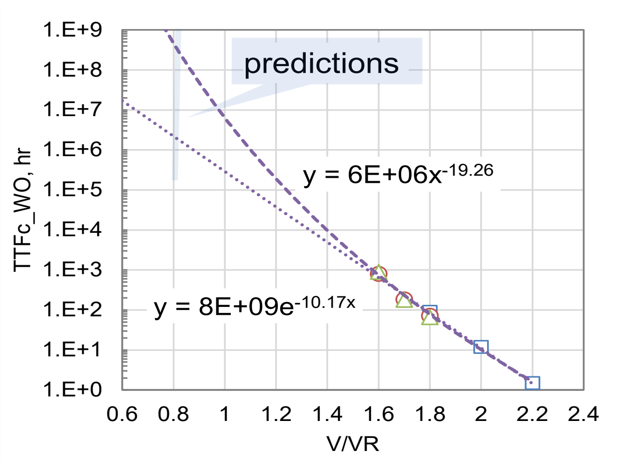
$\beta < 1$ => IM failures
$\beta > 1$ => WO failures

- ✓ TTF distributions indicate the presence of both, IM and WO failures.
- ✓ The proportion of IM failures increases with the level of stress.

Voltage Acceleration Factors

- AF_V can be calculated using a power, $AF_V = u^n$, or exponential, $AF_V = exp[B \times (u-1)]$, model.
- MIL-PRF-32700 suggests a power model for PTCs.
- Results of HALT can be approximated equally well with both models.





- ✓ Anti-WO failures can be explained by increasing breakdown voltages (solid-state oxidation).
- ✓ Power model gives more optimistic predictions for reliability (benefits for manufacturers, misleading for users).
- ✓ Exponential presentation of AF_V is justified by the TDDB model.

Useful Life

- Useful life = time to inception of WO failures: TTF_i at P = 0.1%:

$$TTF_i = TTF_c(uo_p, Top) \times [-\ln(0.999)]^{1/\beta}$$

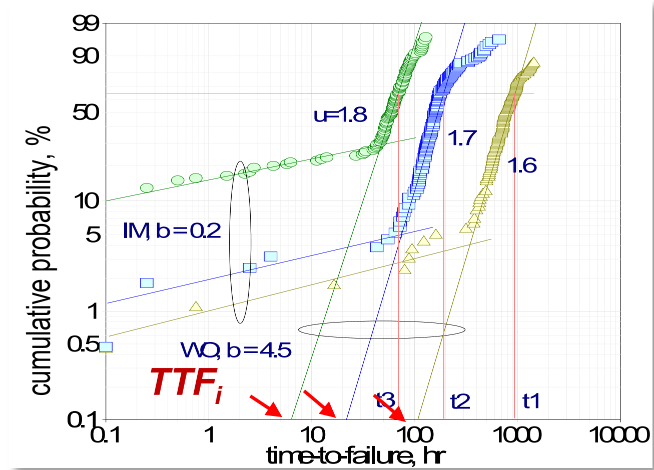
- Characteristic times to WO failures at u = 1 and T = 85C, $TTF_c(85C, VR)$, can be determined by HALT.
- AFs can be determined using a general log-linear Weibull model.
- Characteristic times of WO failures at operating conditions:

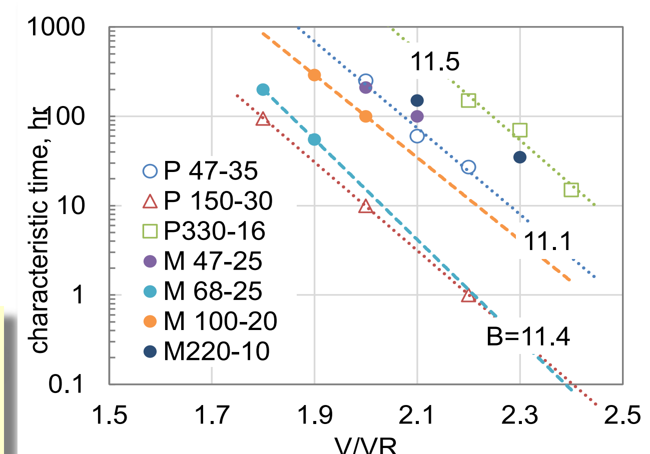
$$TTF_c(To_p, Vop) = TTF_c(85C, VR) \times AF_V \times AF_T$$

✓ The useful life duration should exceed 3 times the mission duration.

✓ B_{WO}= 10.8 ±1.1 for PTC and 9.3 ±2.4 for MnO_2

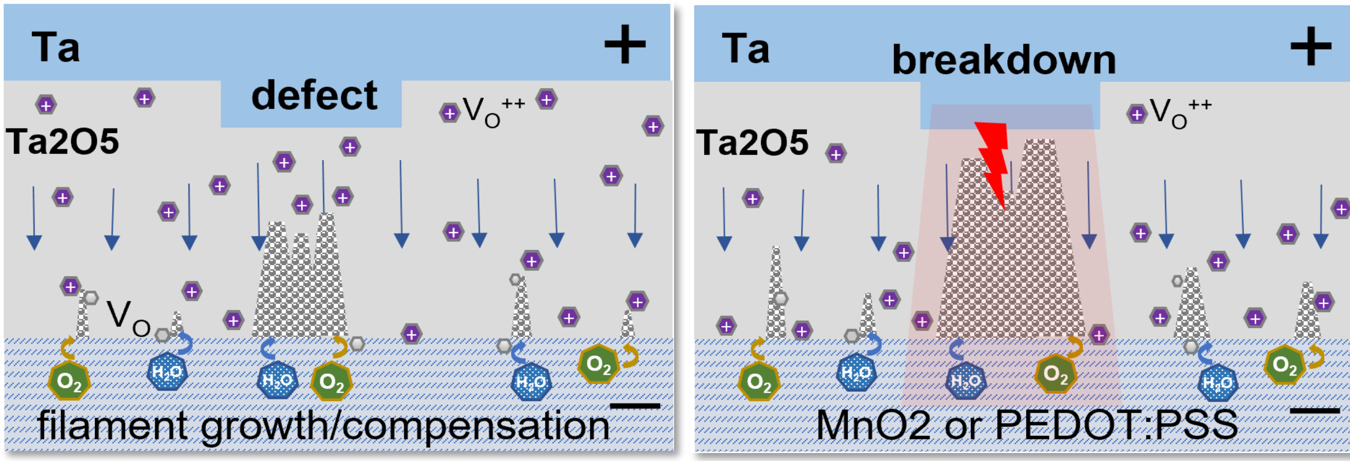
✓ Degradation of current and failures are due to the same mechanisms.





Effect of stress voltage on characteristic times of WO failures

Physical Model of Life Test Failures

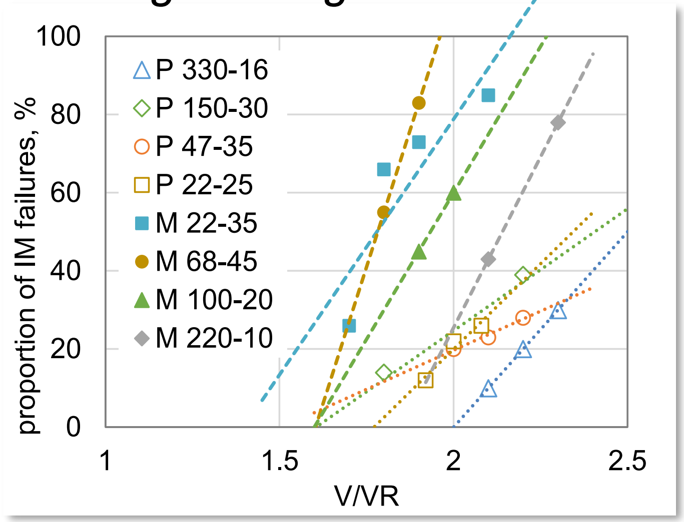


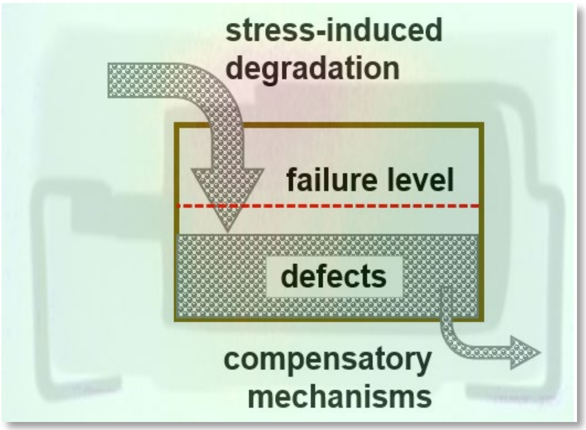
- *Degradation*: migration of V_O^{++} leads to accumulation of positive charges at the cathode/Ta_2O_5 interface and formation of conductive filaments.
- *Compensation*: generation of oxygen-containing species that compensate positive charges and filaments.
- Probability of failure depends on the balance between the rates of degradation and compensation.

✓ Slow degradation at low voltages can provide sufficient time for compensation to prevent breakdown → failures during HALT might never happen during operation.

Proportion of IM Failures

Variations of IM failures with stress voltage during HALT at 85C





- ✓ Proportion of IM failures increases with voltage and was larger for MnO_2 capacitors.
- ✓ Although all parts passed BI during screening, the proportion of IM failures during HALT was large and increased with stress voltage.
- ✓ Based on the mechanism of failures, some IM failures revealed during HALT might never happen during operations.
- ✓ There is a risk of overstressing parts during BI.

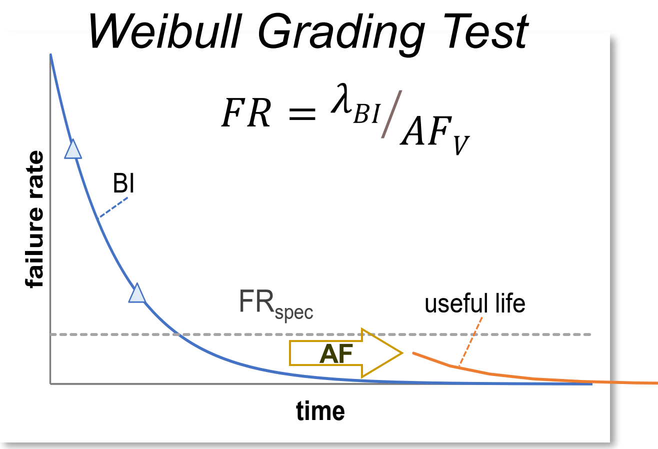
Burn-in for Tantalum Capacitors

- BI supposed to reduce IM failures to the acceptable level
- Per M883 TM1015: at or above maximum rated operating conditions.

Type	Specification	Procedure	t_{BI}, hr	T, C	$V_{BI.}$, V
Wet	MIL-PRF-39006	Voltage Conditioning, R ≤ 1.1 kΩ	48	85	VR
	EEE-INST-002	Voltage Conditioning (Burn-In)	160 - L1 96 - L2 48 - L3	85	VR
MnO2	MIL-PRF-55365	WGT	40	85	(1.1-1.5)VR
	EEE-INST-002 diff. FRL for L1, L2, L3	Voltage Conditioning (Burn-In)	160 - L1 96 - L2 48 - L3	85	VR
	NASA 8739.11	WGT	L1-FRL D; L2/3-FRL C,B	85	(1.1-1.5)VR
Polym.	MIL-PRF-32700	Voltage ageing	40	85	≥ VR
	Guidelines	Monitored BI	40	85	1.3VR

Weibull Grading Test

- WGT is a combination of two tests: burn-in (screening to remove IM failures) and reliability qualification (to assess FR).
- Best BI: monitor FR during testing and stop when the required FR_{sp} is reached.
- Reliability of MnO2 capacitors is determined using an exponential model: $AF_V = exp[B_{WGT} \times (u-1)]$, $u = V_{test}/VR$ (M55365: AF= 7.03412025×1E-9×exp(18.77249321×V/VR), but actually $B_{WGT} = 8$ to 24.
- If all failures are due to IM, then any lot can be screened out to as high FR level as necessary.
- Long-term reliability is determined by a 40-hr accelerated test.

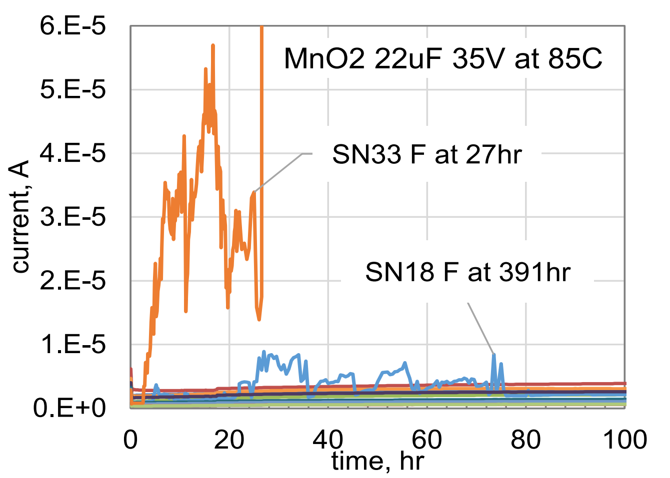


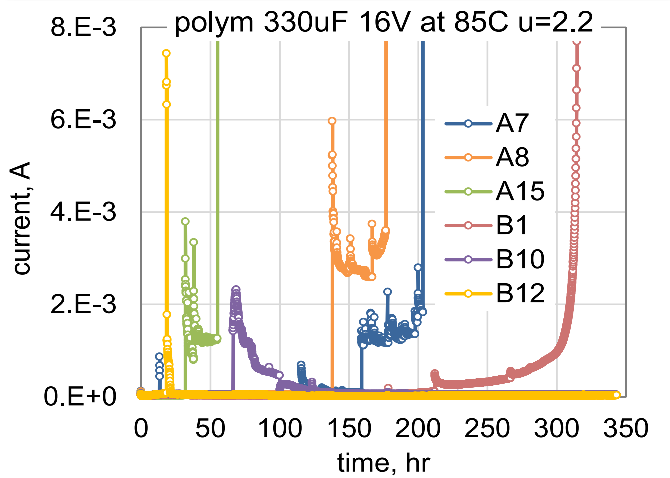
✓ PTCs have a lower risk of IM failures than MnO2 capacitors → not enough failures to calculate FR, + presence of WO failures.

Monitored BI and Life Test

- ❑ 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

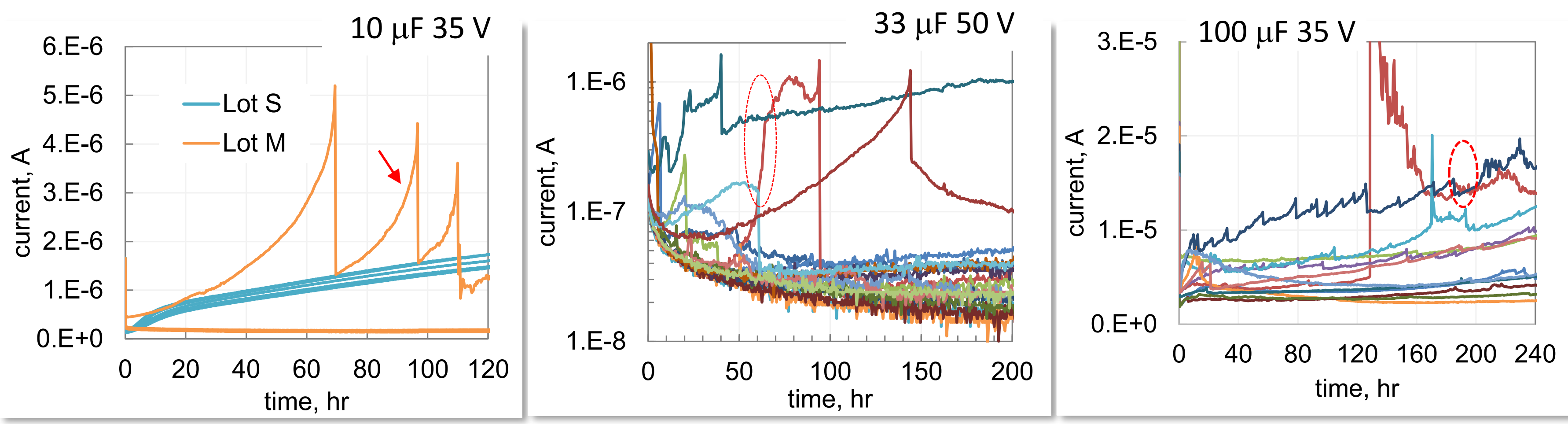




- ✓ Per MIL-specs, failures are determined by blown 1 A fuses (a few seconds at 1A or msec at 20A).
- ✓ Scintillations can not be detected during testing if currents are not continuously monitored.
- ✓ After scintillations, the parts might remain operational.

Monitored BI

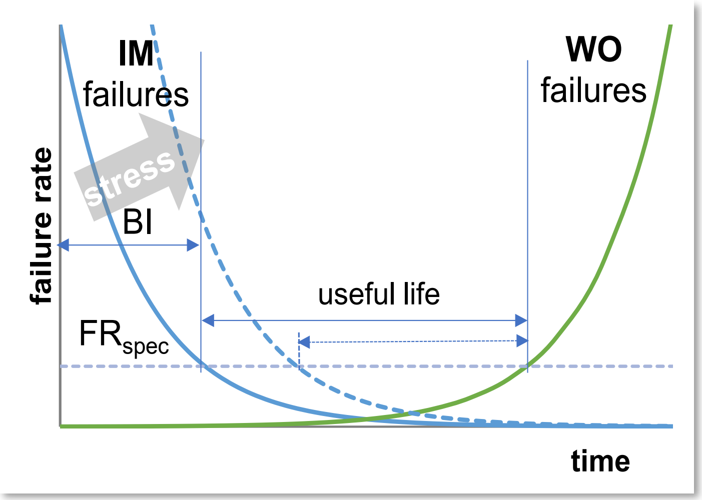
- Spiking in PTCs is typically greater than in MnO2 capacitors likely due to a less efficient self-healing.

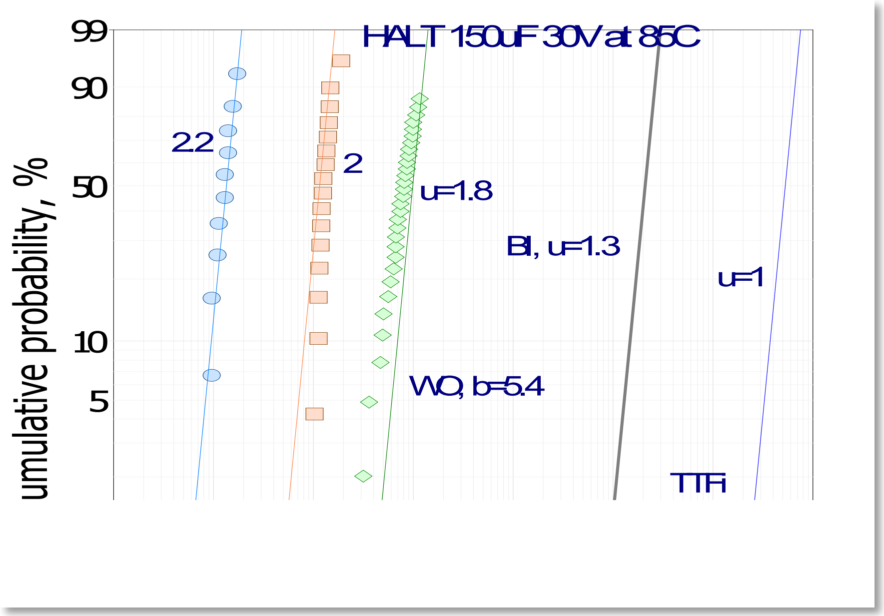


✓ Monitored BI allows for screening-out parts with excessive spiking that have a higher risk of failures.

BI Conditions

- Overstressing of capacitors during BI might reduce useful life of parts.
- Modeling of WO failures in PTCs can be used to validate BI conditions.





✓ No WO failures during BI at u = 1.3 for 40 hours