



NASA Electronic Parts and Packaging (NEPP) Program

Advanced Wet Tantalum Capacitors: Design, Specifications and Performance

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Work performed for the Parts, Packaging, and Assembly
Technologies Office,
NASA GSFC, Code 562

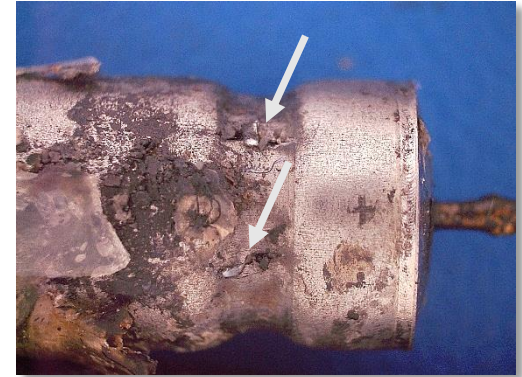
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List of Acronyms

| | | | |
|-----|-------------------------------|-----|--------------------------|
| AC | alternative current | LF | low frequency |
| CCS | constant current stress | LT | low temperature |
| CM | current multiplier | NS | not specified |
| DC | direct current | PO | purchase order |
| DCL | direct current leakage | QA | quality assurance |
| DF | dissipation factor | RB | reverse bias |
| DLA | Defense Logistics Agency | RT | room temperature |
| DPA | destructive physical analysis | RVT | random vibration testing |
| DWG | drawing | TS | thermal shock |
| ESR | equivalent series resistance | VBR | breakdown voltage |
| HF | high frequency | VF | voltage formation |
| HT | high temperature | VR | rated voltage |
| HTS | high temperature storage | WTC | wet tantalum capacitors |
| | | XRF | X-Ray Fluorescence |

Outline

- ❑ Introduction. Specific features of WTC.
- ❑ Design and DPA.
- ❑ Parameters, their measurements and specifics.
- ❑ Factors affecting leakage currents.
- ❑ Hermeticity.
- ❑ Gas generation and internal pressure.
- ❑ Effect of reverse bias.
- ❑ Ripple currents.
- ❑ Random vibration testing.
- ❑ Recommendations.



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Introduction: Problems with new WTC




- ❑ Currently, WTC per MIL-PRF-39006 are among the most reliable components, but they had a rich history of problems.
- ❑ The need for higher capacitance in a smaller volume resulted in development of new technology WTC.
- ❑ Difference between advanced WTC and MIL capacitors.
 - Higher leakage currents increase the risk of excessive internal pressure.
 - High sensitivity to reverse bias;
 - Higher ripple currents require a closer look on self-heating and overheating in vacuum, derating (?);
 - Sensitivity to random vibration;

✓ A common misconception is that new WTC are almost the same as MIL-PRF-39006, but with better characteristics.

DLA L&M Drawings

- Most new WTCs have DLA drawings based on commercial specifications.
- The number of drawings is increasing, and currently exceeds 15.

Example of Vishay DLA Drawings

| DSCC DWG | Features | Case | C | VR |
|--|---|---|--------------------------------|------------------|
| #06013 (CLR79), #06014 (CLR81), #06015 (CLR90), #06016 (CLR91), 2012 | Space level screened, MIL approved; established reliability; tin/lead terminations; “R” or 0.001 %/1000 failure rate; “H” or high shock and vibration rate. |  | 1.7 μ F to 2200 μ F | 6 V to 125 V |
| #93026 (ST), 1993 | Super extended capacitance range; hi-rel screened; Tin/lead terminations. |  | 10 μ F to 1800 μ F | 25V to 125V |
| #10004 (STE, HC2, T18), 2015 | SuperTan® Extended Capacitors, Wet Tantalum Capacitors with Hermetic Seal | | 22 μ F to 10 mF | 10 V to 125 V |
| #13017 (T16), 2013 | Extended Capacitance, Tantalum Case with Glass-to-Tantalum Hermetic Seal, for -55 °C to +125 °C operation. | | 10 μ F to 1.8 mF | 25 V to 125 V |
| #15005 (T18), 2014 | Ultra-High Capacitance, Improved reverse voltage and vibration capability, DLA Approved. |  | 470 μ F to 1 mF | 25 V to 100 V |
| #10011 (HE3), 2012 | Wet Tantalum Capacitors Tantalum-Case with Glass-to-Tantalum Hermetic Seal, for -55 °C to +125 °C operation. | | 1.1 mF to 72 mF | 25 V to 125 V |

M39006 and DLA Drawing Requirements

| Part Type | Rev. Bias | HF vib | Random vib | Mechanical shock | Thermal shock cycles | Life test |
|--------------------|-----------|--------------------------------|--------------------------|---------------------------|---|---|
| M39006 | 3V | cond. D (20g) or cond H* (80g) | cond. II-K* (53.79 grms) | cond. I (100g), D* (500g) | 30 or 300* | 10khr at VR, 85C or 2khr at 125C, 2/3VR |
| #93026, 1993 | <0.05C | cond. D (20g) | NS | cond. I (100g) | 30 | 10khr at VR, 85C or 2khr at 125C, 2/3VR |
| CLR93, 2012 | <0.05C | cond. D (20g) | NS | cond. I (100g) | 300 (Δ DCL increased from 125% to 200%) | 10khr at VR, 85C or 2khr at 125C, 2/3VR |
| #13017 (T16), 2013 | 1.5V | cond. E (50g) | cond. II-G (27.78 grms) | cond. I (100g) | 300 | 2khr at VR, 85C or 1khr at 125C, 2/3VR |
| #15005 (T18), 2014 | 1.5V | cond. E (50g) | cond. II-G (27.78 grms) | cond. I (100g) | 300 | 2khr at VR, 85C or 1khr at 125C, 2/3VR |

*CLR93, CLR79, CLR81, CLR90, and CLR91 only (?)

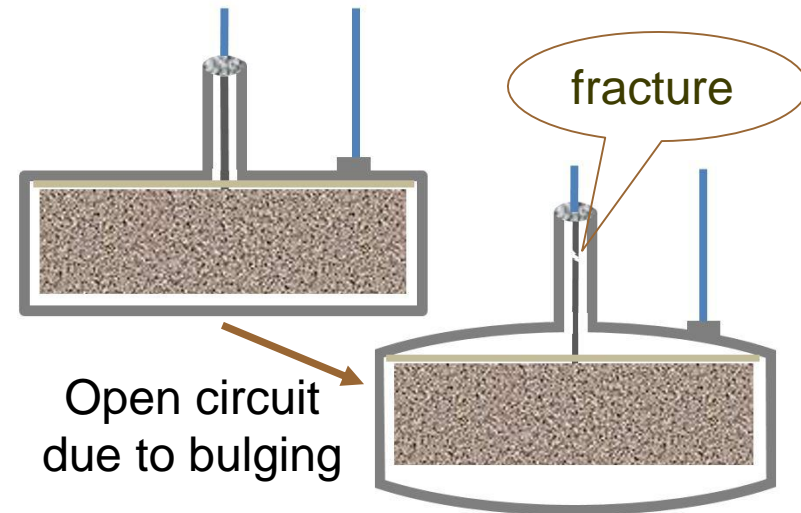
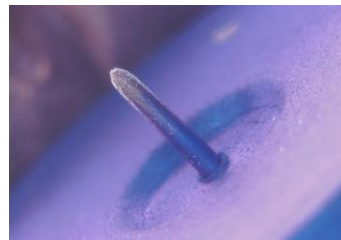
- ✓ Parts that cannot pass RVT cannot be used for space projects.
- ✓ Contrary to M39006 statement, CLR93 caps are similar to #93026.
- ✓ Due to insufficient reliability data, the specified performance of DLA DWG capacitors should be verified for each lot.

Introduction: Failure Modes

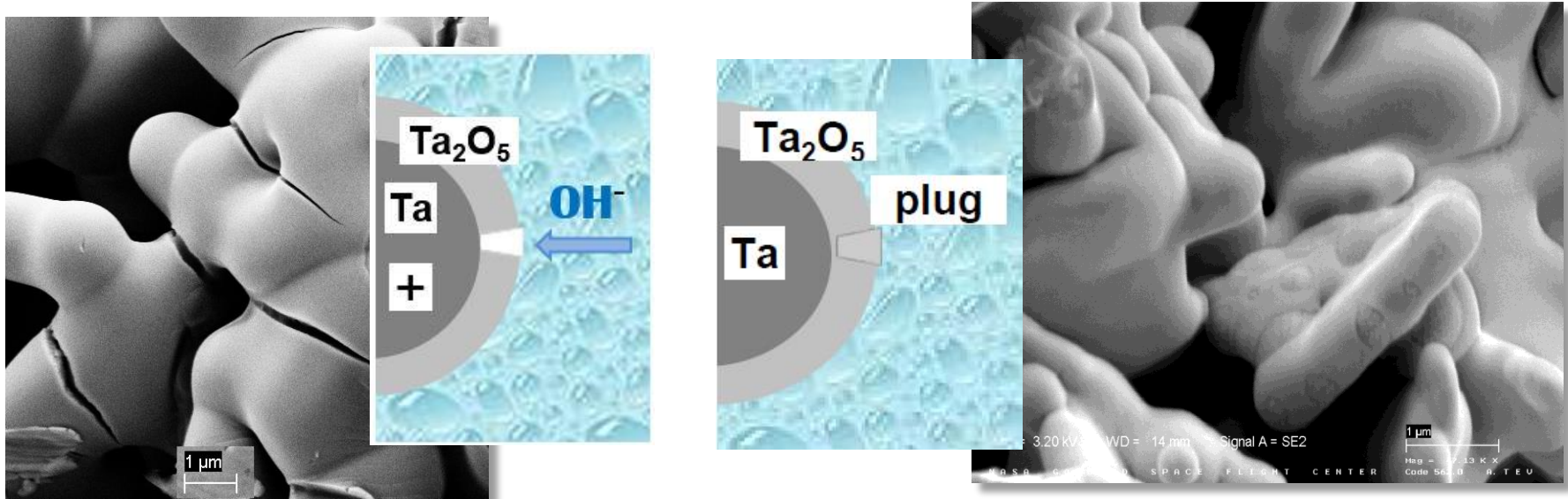
- ❑ Parametric failures (typically during qualification testing).
 - Temperature dependence of capacitance.
 - Degradation of leakage currents during life testing.
 - Degradation of leakage current during TS testing.
- ❑ Unstable leakage currents.
- ❑ Catastrophic failures (can happen during box-level testing or during the mission).
 - Open circuit caused by bulging that results either in fractured anode riser wire or case rupture and leak of electrolyte.



Electrolyte leak due to case rupture resulting in open circuit



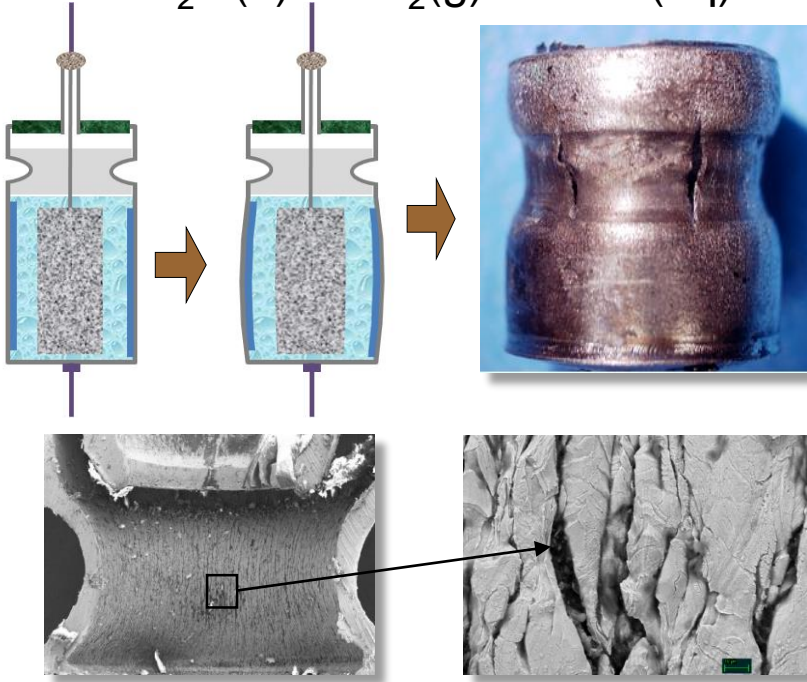
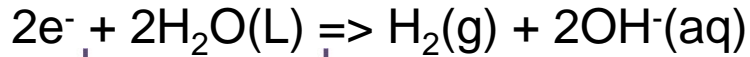
Introduction: Self-Healing in WTC



- ✓ The capability of self-healing plays an important role in assuring reliability, but should not be abused.
- ✓ If Ta₂O₅ is damaged, anodic oxidation continues resulting in oxide growth thus effectively eliminating the defect.
- ✓ However, (i) the quality of oxide is not the same as for normal oxidation, and (ii) self-healing goes along with gas generation.

Introduction: why DCL is Critical?

H₂ generation at cathode:



$$n = \frac{I \times t}{z \times F} \quad P = n \times \frac{RT}{V}$$

For a capacitor with volume ~1 cc, leakage current ~1 μ A can result in ~40 atm after 10 years.

- ❑ What pressure cases can sustain?
- ❑ What are real leakage currents?
- ❑ What requirements we should have to mitigate the risk of case rupture and explosion?

- ✓ The significance of DCL. Electrolysis → gas generation → increasing pressure and H₂ embrittlement → risks of failures.
- ✓ Over crimping and hydrogen embrittlement can reduce the strength of the case substantially.

Screening and Qualification of WTCs

□ Screening (M39006):

- Voltage conditioning (48 hr, 85 °C, VR through 1.1k). Visual examination.
- Seal leak (gross).
- AC (C at 120Hz, DF at 120Hz or 1 kHz), and DC (DCL) measurements at RT (IR and DWV are not related to Ta2O5 dielectric).
- Stability at LT and HT (13 samples only as gr.B insp., some DWGs do not require this test).

□ Qualification:

- Reverse bias (different from M39006);
- Random vibration test (different from M39006);
- Ripple current life test (specifics for vacuum?);
- Thermal shock (might be less than M39006);
- Voltage surge (1000c at 85 °C, 1.15VR, 30sec pol and 390sec depol through 1kOhm);
- Mechanical shock;
- HF vibration;
- DC life test;
- Moisture.



- ✓ Screening does not guarantee reliable operation and is not sufficient for space applications.
- ✓ Qualification testing is not required by DLA DWGs, but can be requested in PO.

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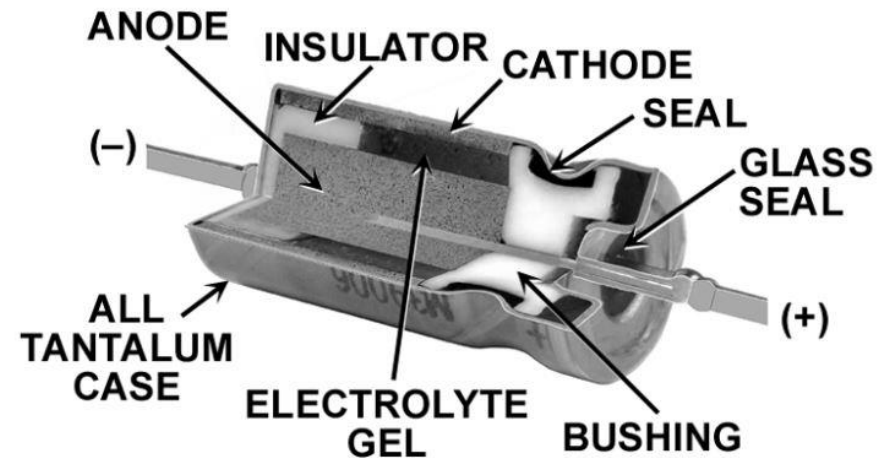
Design

❑ Common features in all WTC:

- Hermetically sealed Ta case;
- Cathode coatings or plates;
- Electrolyte;
- Anode slug.

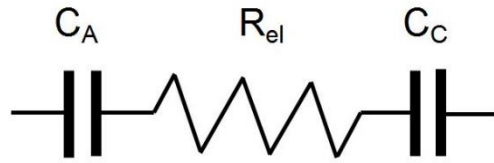
❑ Specific features:

- Different cathode materials;
- Different additions to electrolyte;
- Presence of separators or wrapping cloth;
- Case: cylinder style (dual seal) and button style (single seal).



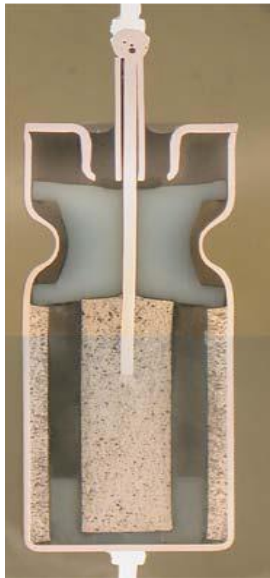
✓ Assembly (fixing the anode slug) is an art of compromise: insufficient pressure might cause failures during vibration, while too much pressure might damage the dielectric or reduce the strength of the case.

Cylinder-Style Design

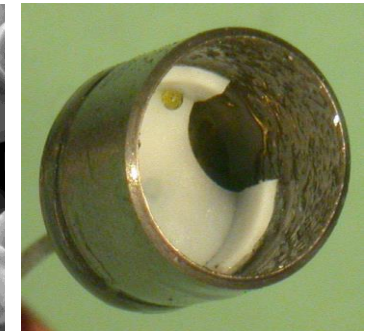
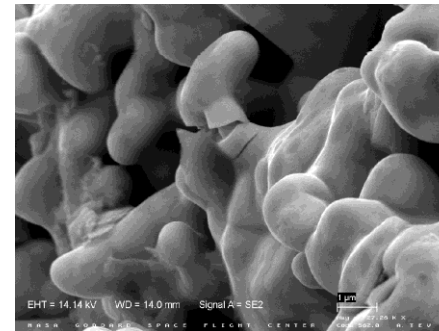


- ❑ M39006: Ta/Ta₂O₅ sleeve as a cathode.
- ❑ To reduce the thickness of cathode layers and increase C_C , new materials are used:

- AVX: NbO-based.
- Vishay: Pd-based/Ta₂O₅.
- Evans: RuO₂-based.
- ❑ Higher CV powder.
- ❑ Lower VF.

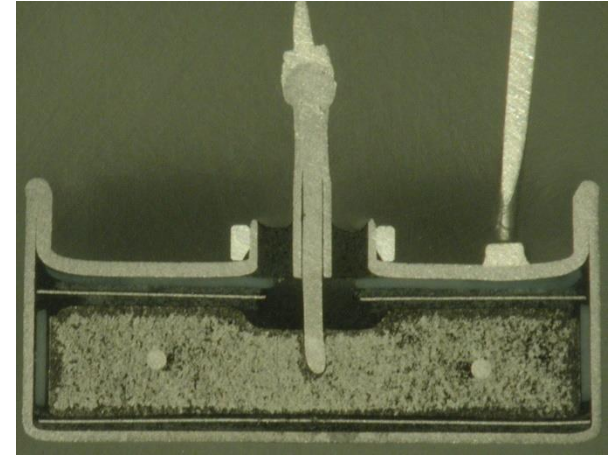
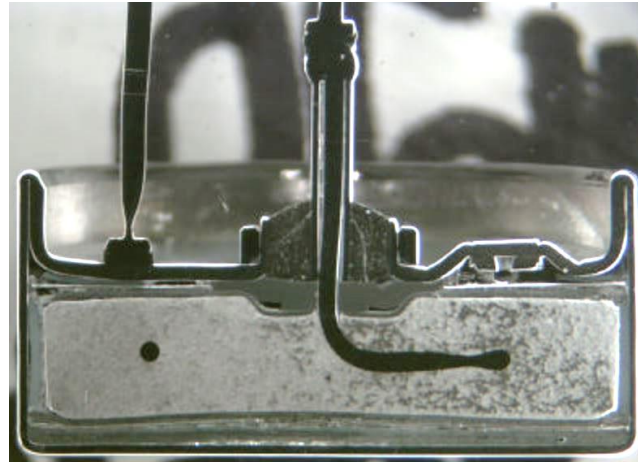


M39006



New technology capacitors

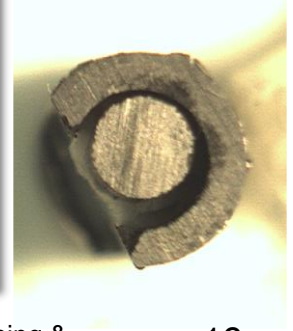
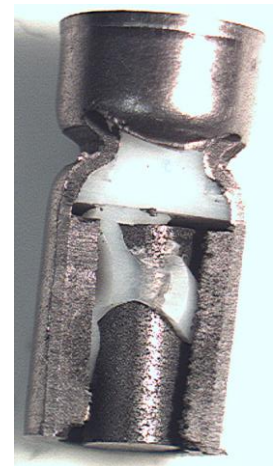
Button-Style Design



- ✓ Cathodes are made of thin Ta disks with special coatings to increase C_C .
- ✓ The disks have tugs welded to cases.
- ✓ An “internal seal” introduced to prevent electrolyte from the tube: a rubber washer compressed between the slug and the case.
- ✓ How effective is this sealing?

DPA per MIL-STD-1580

- ❑ External visual: glass seal, weld.
 - ❑ Hermeticity.
 - ❑ Internal examinations:
 - Absence of electrolyte, or insufficient level of liquid. (?)
 - Scratches or cracks that are not oxidized. (?)
 - Secondary color or spot graying ...cause for rejection.(?)
 - Any other defect that may reduce part reliability. (?)
 - Foreign material in electrolyte. (?)
 - Improper seating (fit) of the Teflon, rubber. (!)
- ✓ The existing DPA requirements are ambiguous, XRF and X-ray are not required.
 - ✓ For new technology WTC, DPA can be limited to external examinations, XRF, and radiography.
 - ✓ Construction analysis might be useful.



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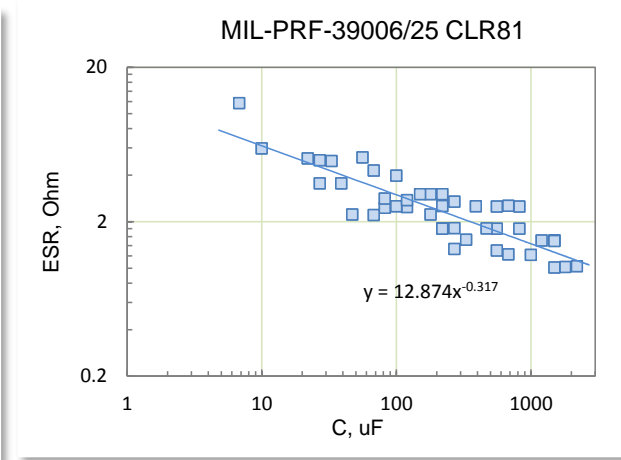
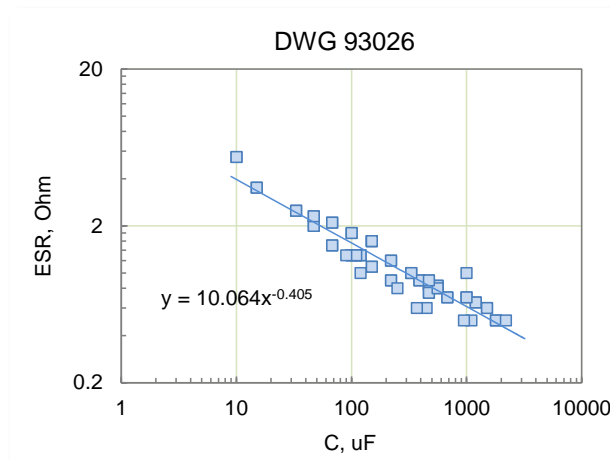
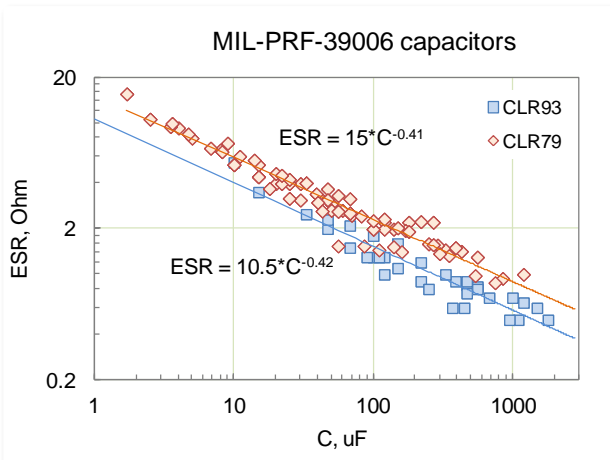
Characteristics of WTC

| Characteristic | Comments |
|------------------------|--|
| C, DF, ESR | C at 120 Hz, DF or ESR at 120 Hz or 1 kHz. Effect of f , T , V ? |
| Rated voltage | How much margin compared to VBR we have and how to set derating? |
| DCL | Specified at VR at $T \leq 85 \text{ }^\circ\text{C}$ and $2/3\text{VR}$ at $T = 125 \text{ }^\circ\text{C}$. How determined, and what is the significance? Effect of t , T , V ? |
| Hermeticity | $10^{-8} \text{ atm_cm}^3/\text{s}$ He per qual tests. Screening: only gross leak testing. Is it sufficient to avoid drying of electrolyte? |
| Ripple current | Ripple life test: 40 kHz, $2/3\text{VR}$, still air, $T_{\text{amb}} = 85 \text{ }^\circ\text{C}$. How I_{rm} is determined? What if application f is different? Derating? Operation in vacuum? |
| Operating Temp. | $-55 \text{ }^\circ\text{C}$ to $+125 \text{ }^\circ\text{C}$ ($2/3\text{VR}$). Problems with stability at LT and HT? |
| Storage Temp. | Typically for button style: $-62 \text{ }^\circ\text{C}$ to $125/130 \text{ }^\circ\text{C}$. T_{min} is verified by LT test (72 hrs at $-62 \text{ }^\circ\text{C}$). What verifies T_{max} ? The specific and significance of T_{max} ? |

Specified Values of C, DF, and ESR

- ❑ Some data sheets specify DF, others ESR.
- ❑ Test frequencies are different (120Hz, #93026 and 1kHz #04005).
- ❑ Both parameters determine active portion of the impedance.

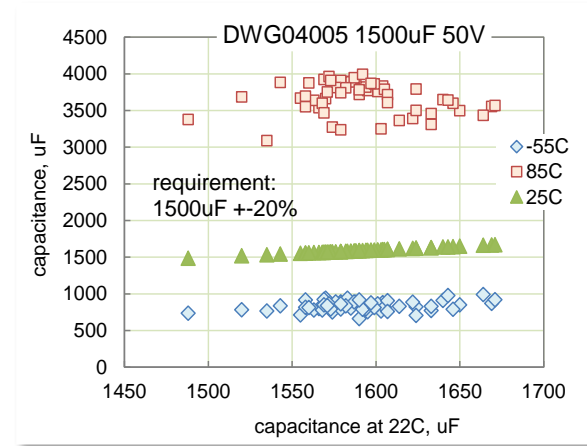
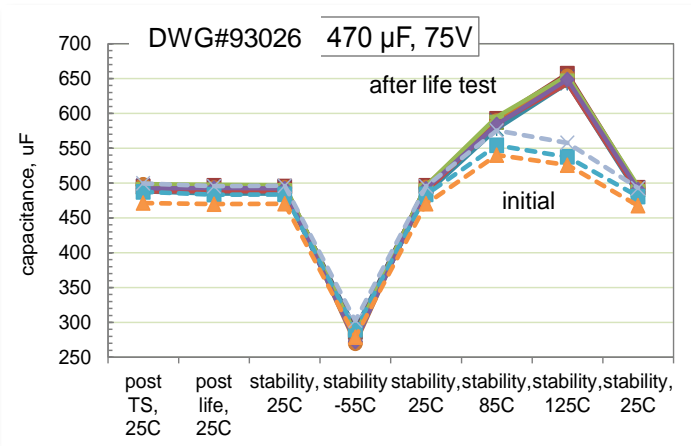
$$ESR = \frac{DF}{2\pi fC}$$



- ✓ ESR is closely correlated with capacitance: $ESR \sim C^{-n}$, $n \sim 0.41$.
- ✓ Specified ESR values are not related to power dissipation caused by ripple currents due to frequency dependence.

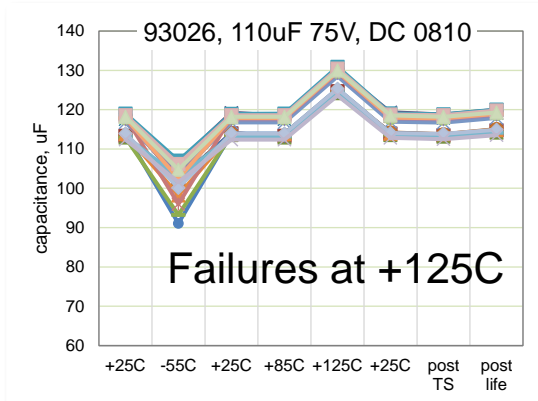
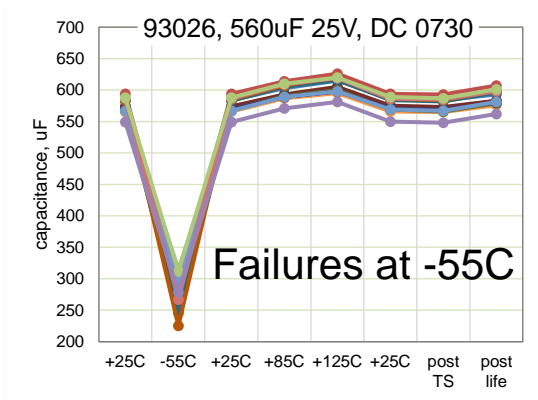
Stability of C and ESR at Low and High Temperatures

- ❑ Measurements are sequentially at +25C, -55C, +25C, +85C, +125C, +25C.
- ❑ C/ESR/DF and DCL should stay within the specified tolerances.
- ❑ Only 13 samples from each lot are tested even for M39006.



- ✓ A lot failed stability test after life testing, but passed for virgin parts.
- ✓ There is no requirements for stability for DWG#04005, which is a drawback in QA system.
- ✓ “Stability” is not specified for #0400X parts; substantial variations are possible.

Temperature Stability of Capacitance



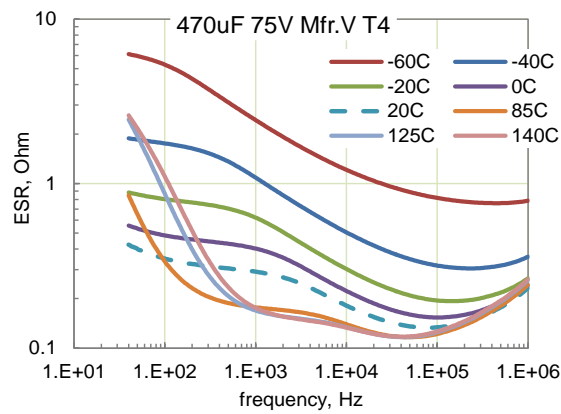
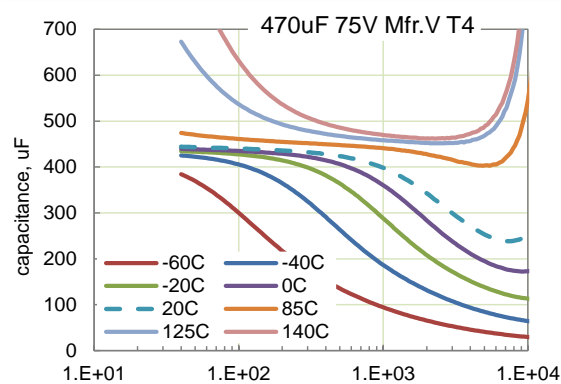
Examples of requirements for δC

| part | -55C | +85C | +125C |
|-----------------|------|------|-------|
| 560uF 25V | -49% | +10% | +15% |
| 560uF 25V CLR91 | -72% | +20% | +25% |
| 110uF 75V | -30% | +6% | +10% |
| 1200uF 25V | -54% | +12% | +18% |

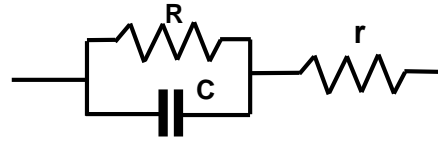
Failures of δC are common and due to (i) substantial $C(T)$ variations that are specific to design, and (ii) non-adequate criteria.

- ✓ More analysis is necessary to understand mechanism.
- ✓ Capacitance variations likely do not indicate reliability risks.
- ✓ Getting used to accepting parametric failures might result in disregarding anomalies that might be significant.

C(f, T) and ESR(f, T)

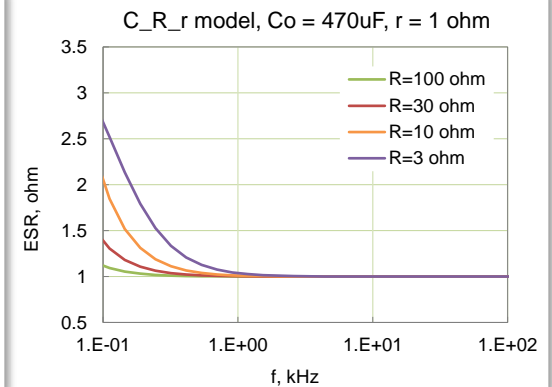
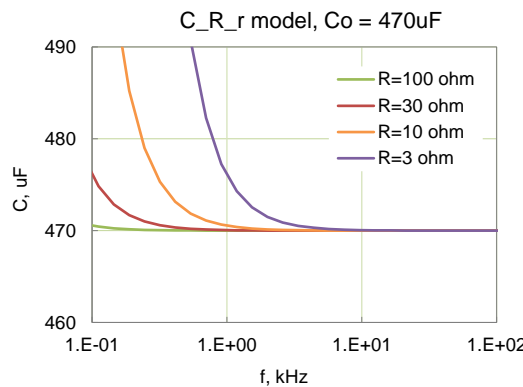


Capacitor with excessive leakage



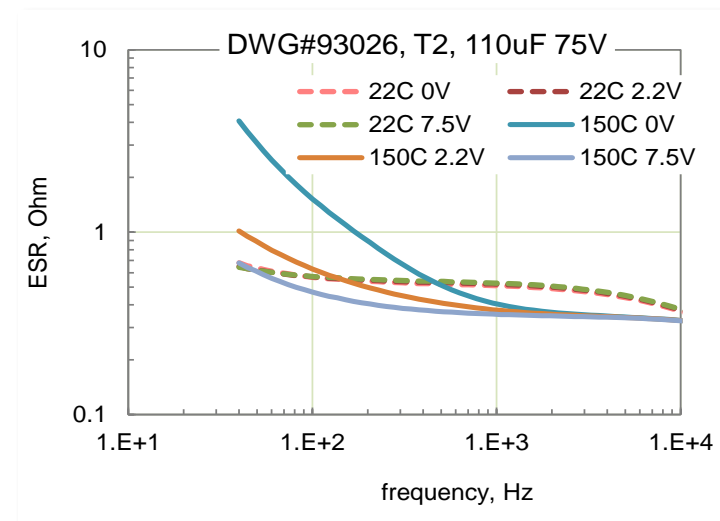
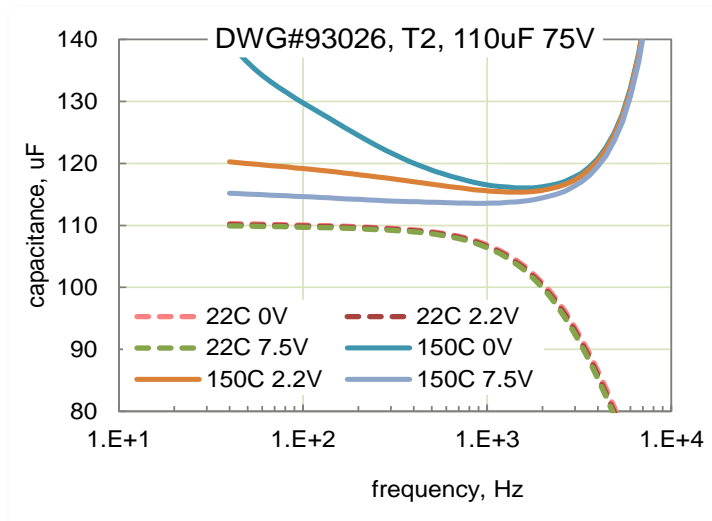
$$C = C_0 \times \left[1 + \frac{1}{(R\omega C_0)^2} \right]$$

$$ESR = r + \frac{R}{1 + (\omega C R)^2}$$



- ✓ Variations of C and ESR are related to temperature dependence of conductivity of electrolyte (roll-off) and increasing ϵ of Ta2O5 with temperature at low frequencies.
- ✓ High C at 125C might be also due to excessive leakage currents.

Effect of DC Bias on AC Characteristics

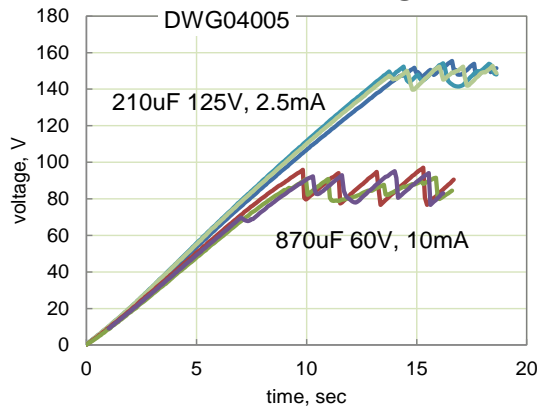


- ✓ At low frequencies and high temperatures DC bias affects C and ESR.
- ✓ Measurements at 120 Hz: $V_{osc}=0.5$ V, $V_{DC} = 2.2$ V or 10%VR (!?).
- ✓ Ambiguous requirements for VDC are not consistent with QA practice.

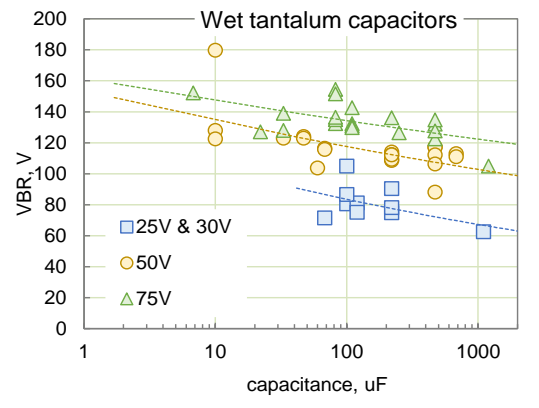
Rated and Breakdown Voltages

VBR is a natural limit for operating (rated) voltages

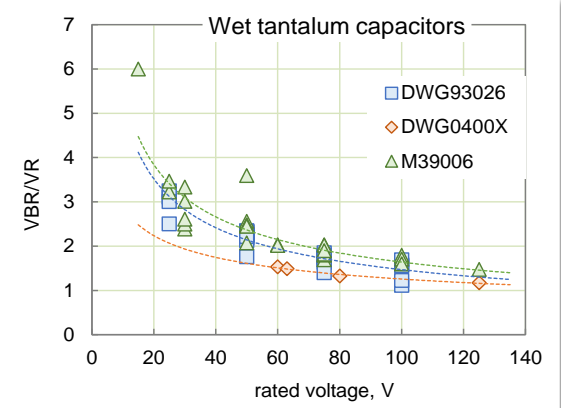
Constant current stress (CCS) testing



Variations of VBR with capacitance



Variations of VBR with rated voltage, $VBR = 21 \times VR^{0.58}$



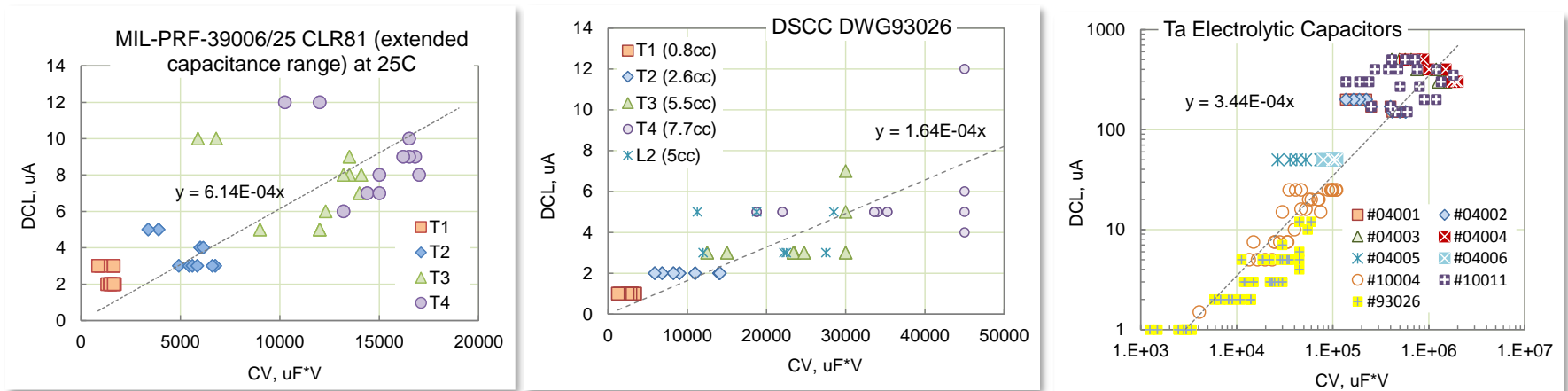
- ✓ Based on voltage drop during CCS, the self-healing capability changes in a row: WTC > MnO₂ > polymer.
- ✓ For a given VR, VBR decreases with C. (i) thinner dielectrics; (ii) greater probability of having a defect for higher ratings.
- ✓ Breakdown margin decreases with VR. This might explain a higher probability of life test failures for HV WTC.
- ✓ Different derating might be used for different rated voltages.

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DCL: Existing Requirements

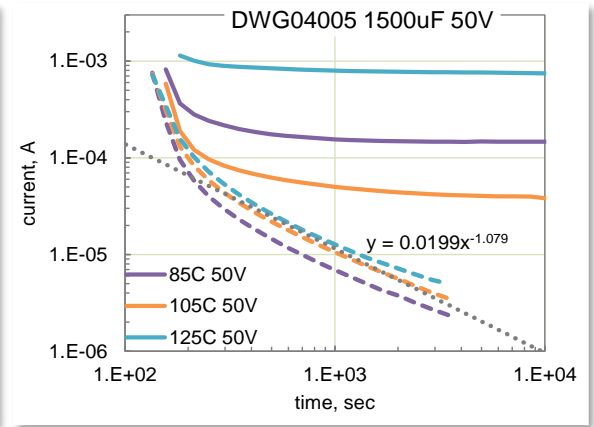
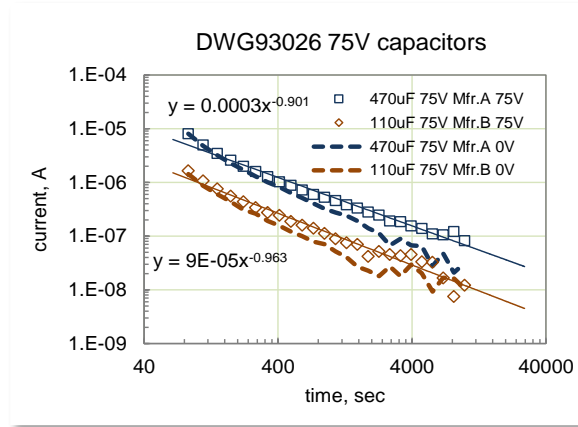
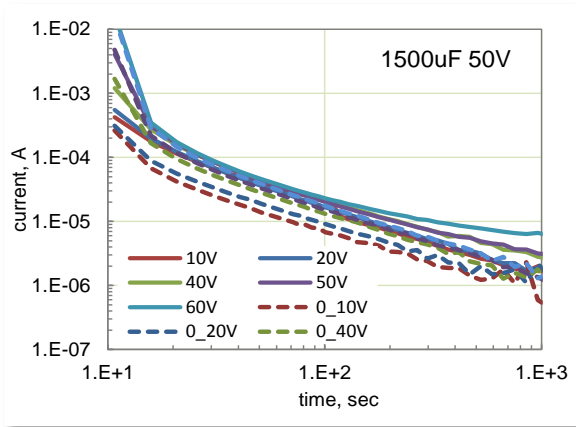
- ❑ $I \sim S/d \times V$, $C \sim S/d \Rightarrow DCL = \alpha \times C \times VR$. ($\alpha = 0.01$ for MnO₂, 0.1 for polymers)
- ❑ Similar relationships are used for aluminum electrolytic capacitors.
- ❑ Significance of DCL: (i) most sensitive to quality of dielectrics, (ii) leakage current determines the rate of gas generation.

Correlation between DCL requirements and CV values



- ✓ There is no standard procedures to set DCL requirements.
- ✓ The spread of the limits for similar CV parts is substantial.
- ✓ A procedure for DCL_{max} should be set and requirements revised.

Absorption and Intrinsic Leakage Currents



✓ Absorption currents:

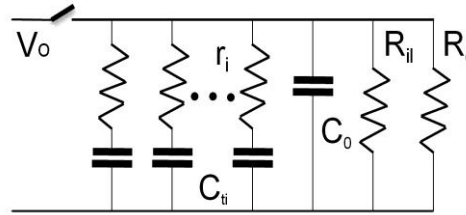
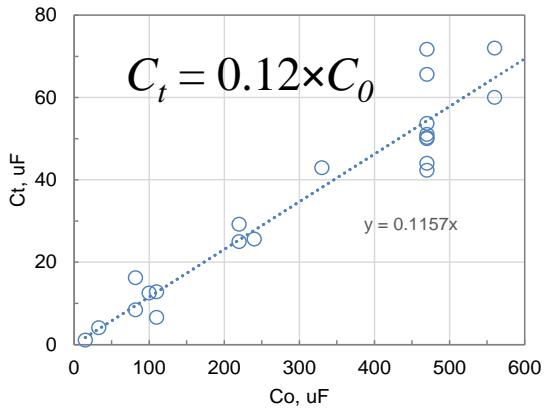
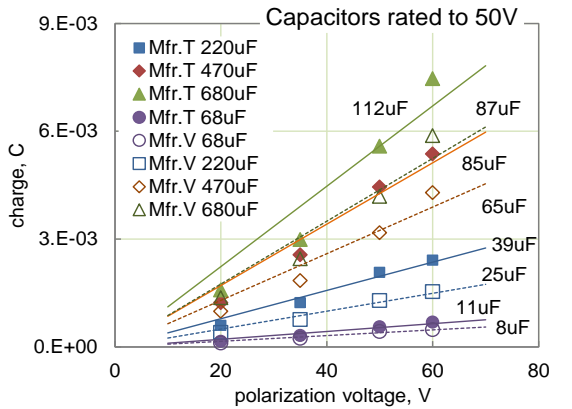
- Decrease with time, $I \sim 1/t$ Curie-von-Schweidler law;
- Preval during first minutes of electrification;
- Increase linearly with voltage and capacitance;
- Have poor temperature dependence.

✓ Intrinsic currents caused by conduction of Ta2O5:

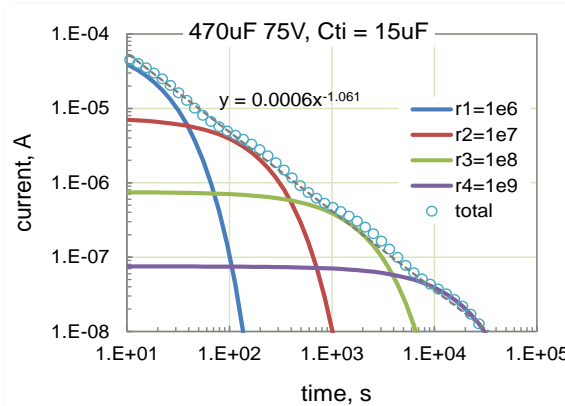
- Typically, are much smaller than absorption currents at RT;
- Increase exponentially with voltage and temperature.

Absorption Capacitance and DCL Model

Absorption capacitance:
 $C_t = Q_t/V$



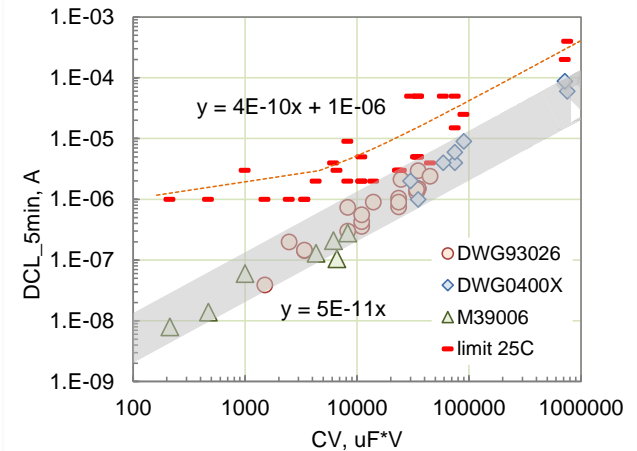
$$I(t) = \frac{V_0}{R_d} + \frac{V_0}{R_{il}} + \sum_i \frac{V_0}{r_i} \exp\left(-t/\tau_i\right)$$



$$DCL \approx \frac{VR}{r_{300}} = \frac{0.25 \times \alpha}{300} \times C_o \times VR$$

At $\alpha = 0.12$, $DCL \approx 10^{-4} C_o \times VR$

Experimental DCL values and specified limits for different lots of WTC



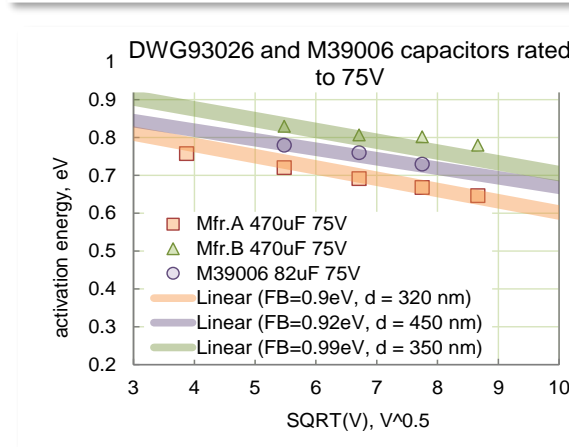
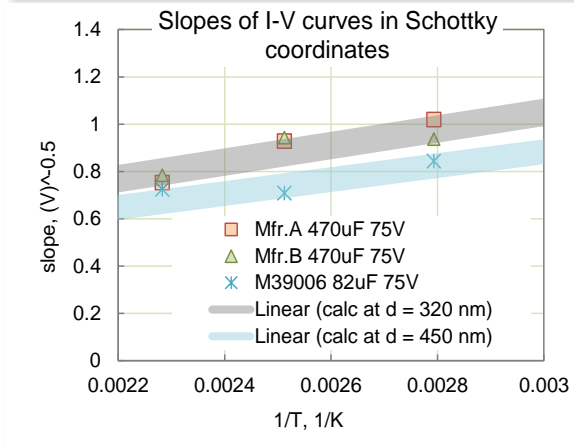
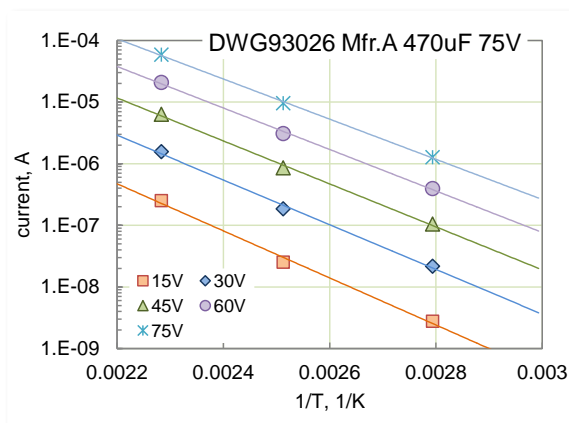
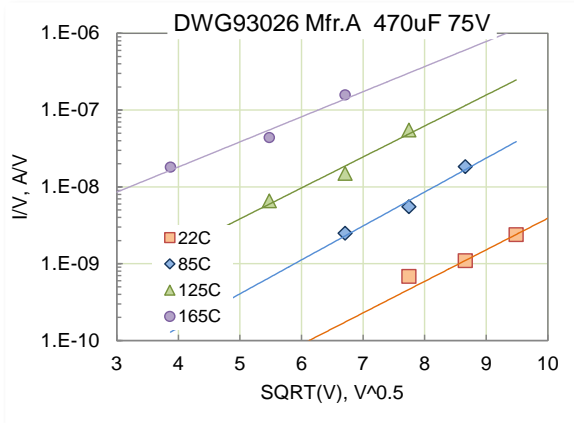
$DCL_{exp} = 5 \times 10^{-5} \times C_o \times VR$,
 which is close to the model

At 5X margin:

$$DCL_{max} = 2.5 \times 10^{-4} \times C_o \times VR$$

✓ Absorption model allows for reasonable assessments of DCL.

Intrinsic Leakage Currents



✓ Intrinsic conduction is limited by the barrier at the Ta₂O₅ - electrolyte interface ($0.9 \text{ eV} < \Phi_B < 1 \text{ eV}$).

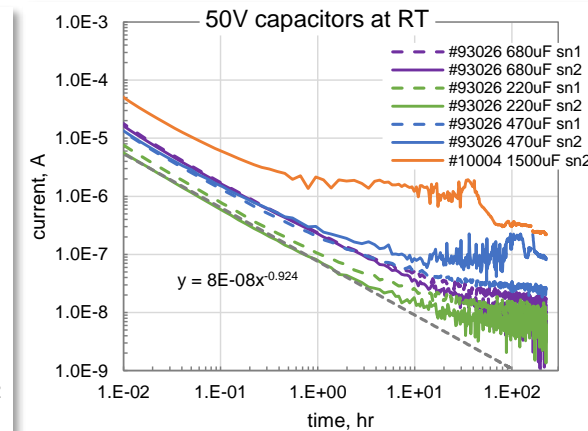
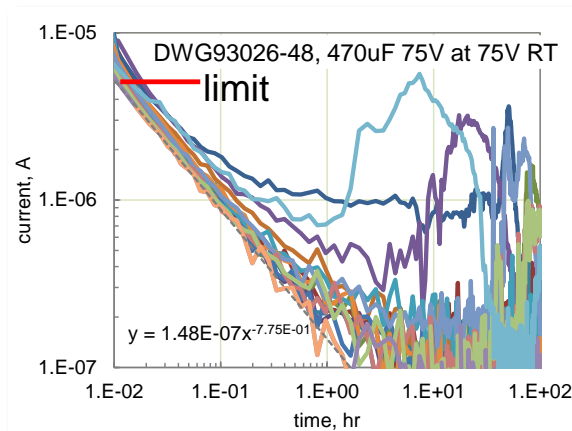
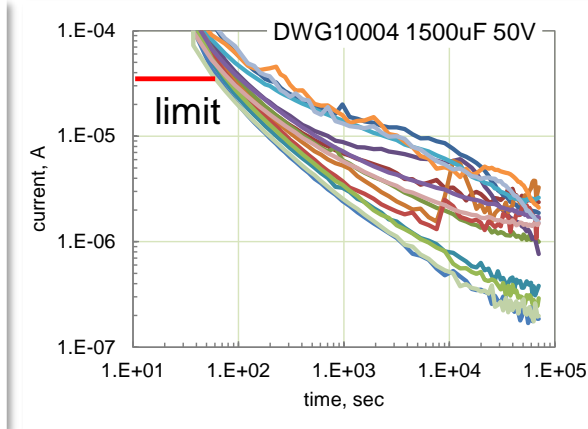
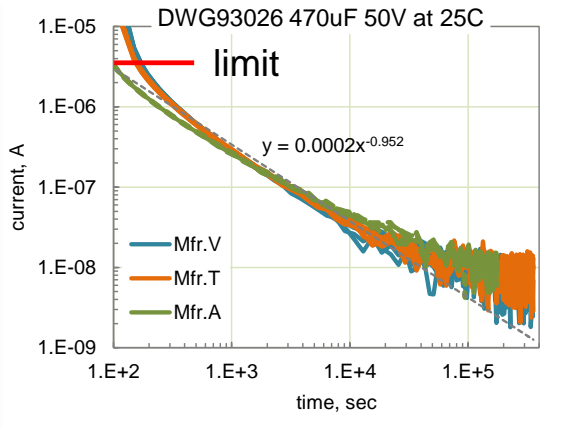
✓ Extrapolations to RT show that intrinsic leakage currents are several orders of magnitude below the specified limits:

DCL_{max} for 470 μF 75 V capacitors is 5 μA; measured value after 5 min is ~1.6 μA, while intrinsic currents are from 6 nA to 20 nA.

Simmons/Schottky model:

$$J_S = AT^{3/2} \mu E \exp\left(-\frac{\Phi_B}{kT}\right) \exp\left(\frac{\beta_s E^{0.5}}{kT}\right)$$

Long-term Variations of Leakage Currents at RT



- ❑ In normal quality parts currents continue decreasing during operation.
- ❑ Some parts might pass DCL screening, but have unstable and wide spread leakage currents.
- ❑ Currently, there is no control over stability of currents.

✓ High quality WTCs should have limited intrinsic currents and their stability should be verified during qualification testing.

Life Testing

❑ M39006:

- gr. B (each lot) – 10/0 pcs for 2 to 10 khr (periodic measurements) at VR, 85 °C. (≤ 1.25 DCL);
- gr. C (periodic, every 6 months) -10/1(?) pcs (representative samples) 2000 hr (periodic measurements) at 2/3VR, 125 °C (≤ 1.25 DCL).

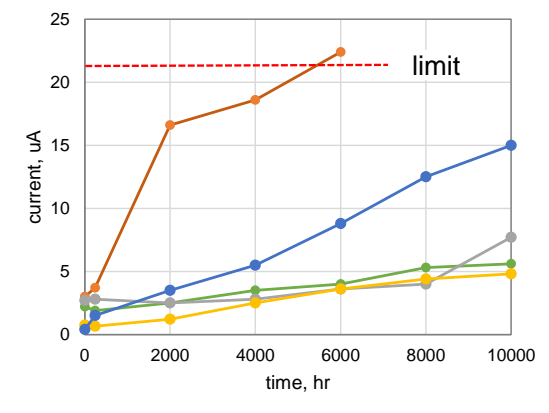
❑ DLA DWGs – testing can be done by PO.

- #93026: capable to withstand 10 kh at VR, 85 °C or 2000 hr at 2/3VR, 125 °C . (≤ 1.25 DCL);
- #13017, #10004 capable: 2,000 hr at VR, 85 °C or 1000 hr at 2/3VR, 125 °C . (≤ 1.25 DCL);
- #10011 – life testing is not mentioned.

❑ Specifics of life testing:

- Carried out at rated conditions, so derating is necessary.
 - Leakage currents often increase with time and might cause parametric failures.
 - Results of testing typically come when parts are installed.
- ✓ If high currents are due to localized damage (e.g. field-induced crystallization), substantial gas generation is possible.
- ✓ If degradation is due to charge instability (migration of V_O^{++}), then voltage drop across electrolyte might be negligible (no gas generation).

Example of life testing at 85C



- ❑ Introduction. Specific features of WTC.
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- ❑ Gas generation and internal pressure.
- ❑ Effect of reverse bias.
- ❑ Ripple currents.
- ❑ Random vibration testing.
- ❑ Recommendations.

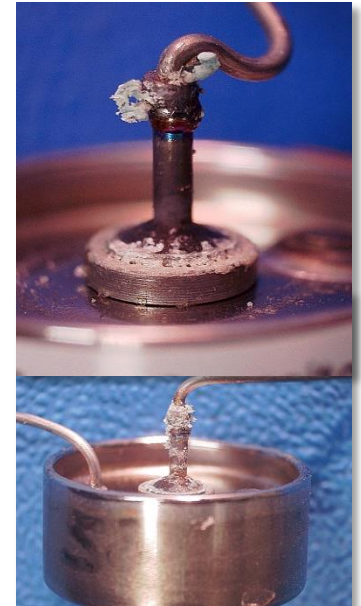
Hermeticity

- ❑ Qualification requirements: 10^{-8} atm_{cm}³/s, He.
- ❑ Screening: only gross leak test is required. (R1 up to $\sim 10^{-5}$ atm_{cc}/s He)

Four lots of DWG93026 110uF 75V T2

DWG #04005

| | DC0849 | DC0850 | DC0947 | DC1006 |
|------|----------|----------|----------|----------|
| SN1 | 6.21E-11 | 5.38E-08 | 3.16E-10 | 7.84E-11 |
| SN2 | 7.40E-11 | 2.04E-08 | 3.11E-10 | 7.01E-11 |
| SN3 | 5.22E-11 | 5.97E-11 | 2.85E-10 | 6.10E-11 |
| SN4 | 6.32E-11 | 8.28E-08 | 2.74E-10 | 4.99E-11 |
| SN5 | 5.12E-11 | 3.69E-08 | 2.41E-10 | 4.86E-11 |
| SN6 | 4.43E-11 | 2.98E-08 | 2.73E-10 | 5.01E-11 |
| SN7 | 2.75E-11 | 5.64E-11 | 2.36E-10 | 4.99E-11 |
| SN8 | 4.34E-11 | 4.84E-08 | 1.96E-10 | 4.90E-11 |
| SN9 | 4.46E-11 | 3.16E-08 | 2.02E-10 | 4.65E-11 |
| SN10 | 4.38E-11 | 2.13E-07 | 2.06E-10 | 4.05E-11 |

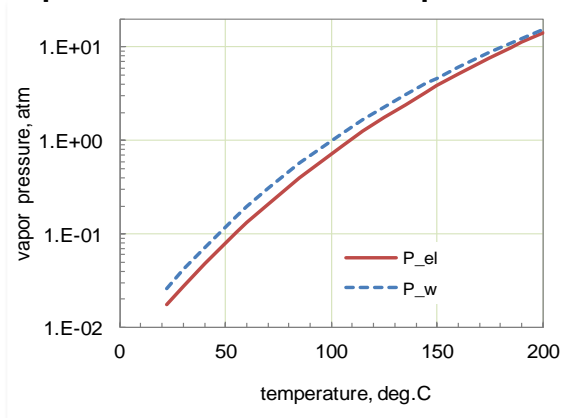


- ✓ Hermeticity failures and electrolyte leaks are sample- and lot-related problems and should be revealed by screening.
- ✓ The capability to sustain high internal pressure should be addressed by HTS testing.

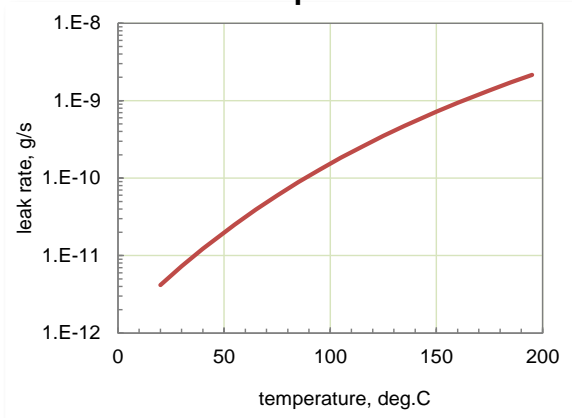
How Much Electrolyte can be Lost?

- The rate of evaporation in g/s was calculated based on R1 atm_cc/s He at different temperatures.

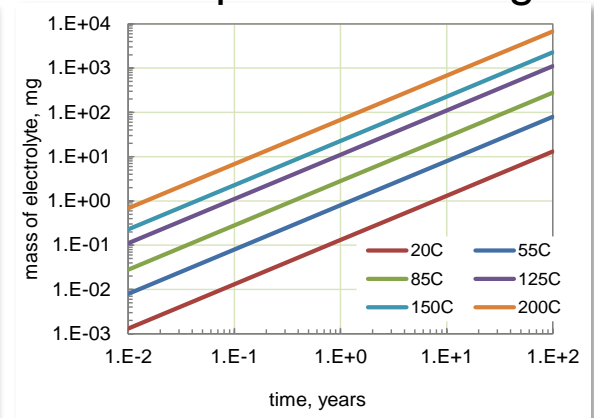
Variations of internal pressure with temperature



Variations of leak rate with temperature



Mass loss of electrolyte with time of operation/storage



- ✓ Internal pressure at 150°C is ~ 5 atm (some WTC can operate at 200°C).
- ✓ At 10⁻⁸ atm_cc/s He the loss is ~1 mg at 22°C and ~30 mg at 85°C in 10 years after sealing, which is negligible for large size WTCs.
- ✓ At 10⁻⁵ atm_cc/s He (gross leak), the risk of evaporation is real, so requirements should be tightened.

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- ❑ Random vibration testing.
- ❑ Recommendations.

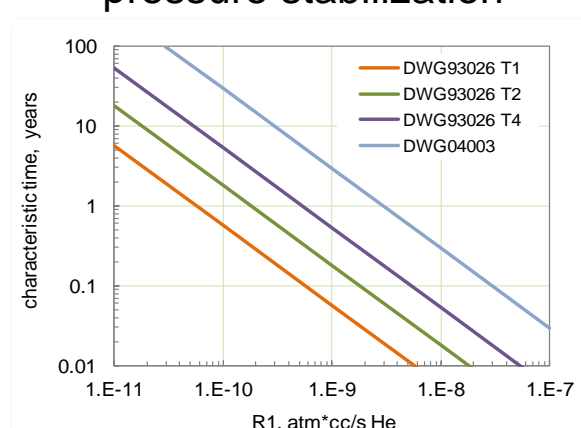
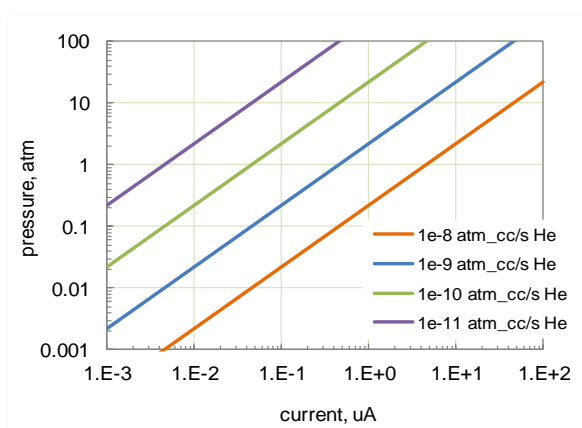
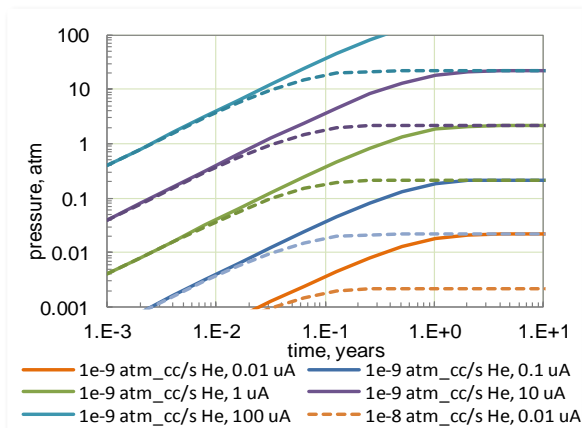
Hermeticity and Internal Gas Pressure

□ Gas generation in the presence of leaks: $\frac{dn}{dt} = \frac{I}{zF} - \frac{n}{\tau}$ $\tau = \frac{P_0 \times V}{L}$

$$P(t) = \frac{P_0 \times RT}{L} \times \frac{I}{zF} \times (1 - e^{-t/\tau})$$

Capacitors with 1 cm³ case at different currents and leak rates

Characteristic times for pressure stabilization



- ✓ The lower the leak rate, the higher pressure can be developed.
- ✓ At R1= 10⁻¹⁰ atm*cc/s He, and current of 1 μA, the pressure during 10 years of operation can exceed 20 atm.
- ✓ In the range 10⁻⁹ to 10⁻¹¹ atm*cc/s He, τ varies from 20 days to half a year for T1 cases to many years for DWG04003 capacitors.

Critical Pressure and Maximum Current

- Cylindrical surface of the case: $\sigma = \frac{P \times R}{h}$ $\Delta R = \frac{\sigma}{E} \times R$
- Clamped membrane: $\sigma = \frac{3}{8} \times (1 + \mu) \times \frac{P \times R^2}{h^2}$ $\varpi_{\max} = \frac{P \times R^4}{64D}$
- Tantalum: $E = 185 \text{ GPa}$, $\mu = 0.34$, the strength is $\sim 280 \text{ MPa}$, but considering embrittlement, for conservative estimations $\sigma_{cr} = 100 \text{ Mpa}$.

$$D = \frac{E \times h^3}{12 \times (1 - \mu^2)}$$
- I_{cr} was calculated based on P_{cr} for a 10 year mission.

| | #93026 T1 | #93026 T2 | #93026 T3 | #93026 T4 | #93026 L2 | #04005 | #04003 |
|----------------------------------|--------------|--------------|--------------|--------------|--------------|---------|---------|
| P_{cr} , atm | 83.3 | 69.4 | 52.1 | 52.1 | 69.4 | 50.8 | 21.2 |
| ΔR_{cr} , mm | 1.3E-03 | 1.9E-03 | 2.6E-03 | 2.6E-03 | 1.9E-03 | 6.1E-03 | 9.7E-03 |
| ω_{m_cr} (bulging), mm | 0.031 | 0.067 | 0.16 | 0.16 | 0.067 | 0.92 | 3.6 |
| I_{cr} 10 years, μA | 2.1 | 5.9 | 9.5 | 13.1 | 9.2 | 5.6 | 29.0 |

✓ Requirements for intrinsic currents should be verified by measurements during voltage conditioning.

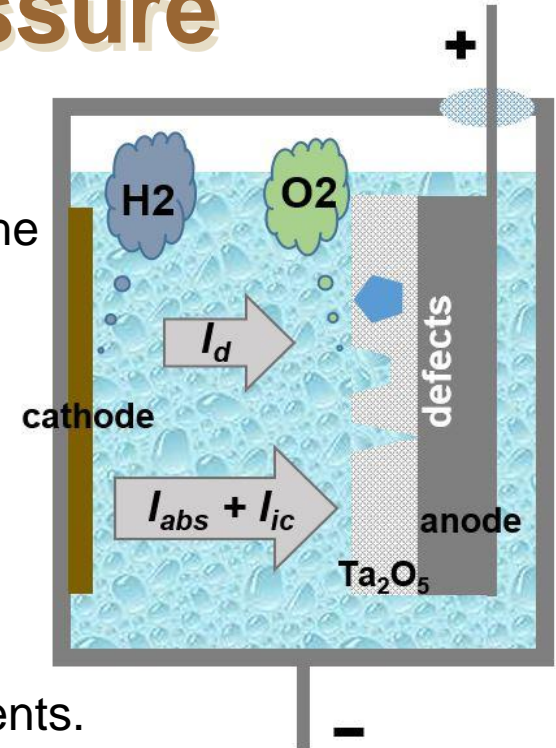
Factors Mitigating and Aggravating Excessive Gas Pressure

❑ Mitigating:

- Hermeticity leak.
- Hydrogen absorption in Ta and penetration through the case reduce the pressure. Generated oxygen (~50% of H₂) remains in the case.
- Non-Faradaic currents.

❑ Aggravating:

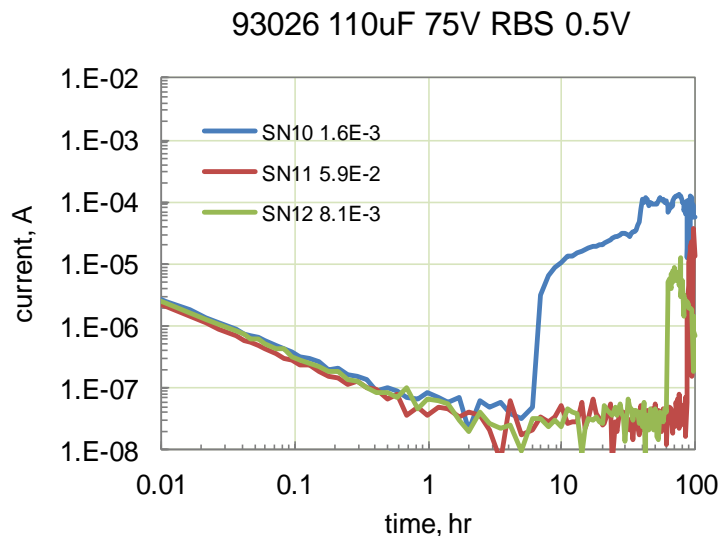
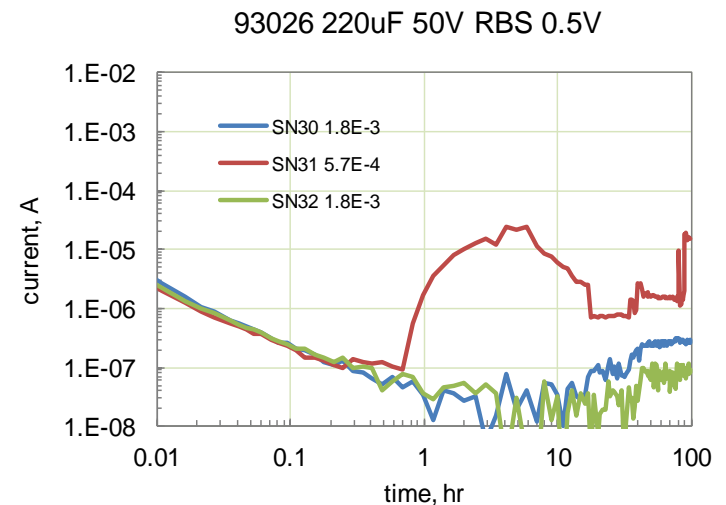
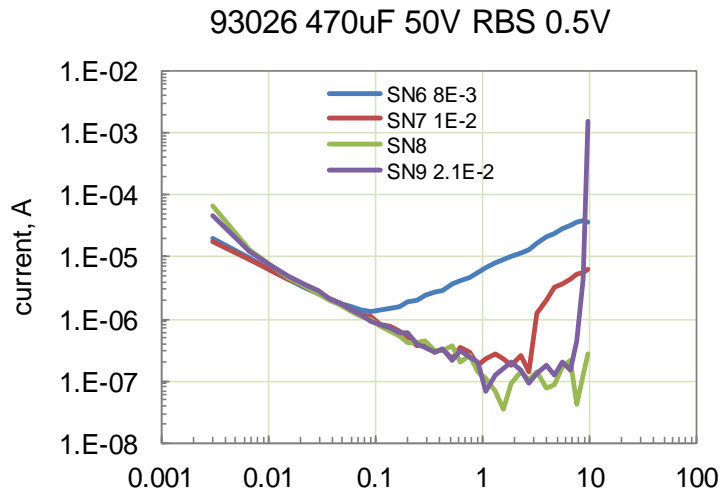
- Presence of defects in oxide.
- Presence of electrolyte at the glass seal.
- Damage to dielectric caused by vibration or TS.
- Increased temperatures due to excessive ripple currents.



- ✓ Overpressure and failures are more likely to be caused by fast gas generation due to overvoltage, RB or damage to the dielectric during RVT.
- ✓ WTCs will operate reliably if proper control over leakage currents is established.

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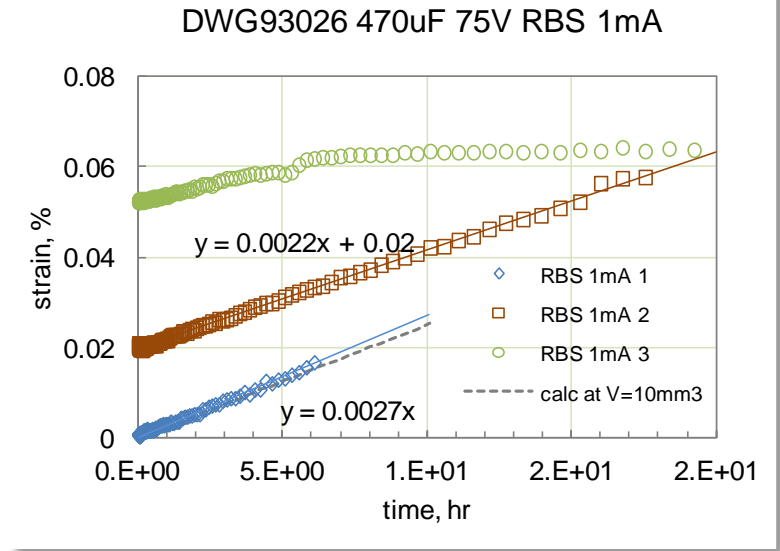
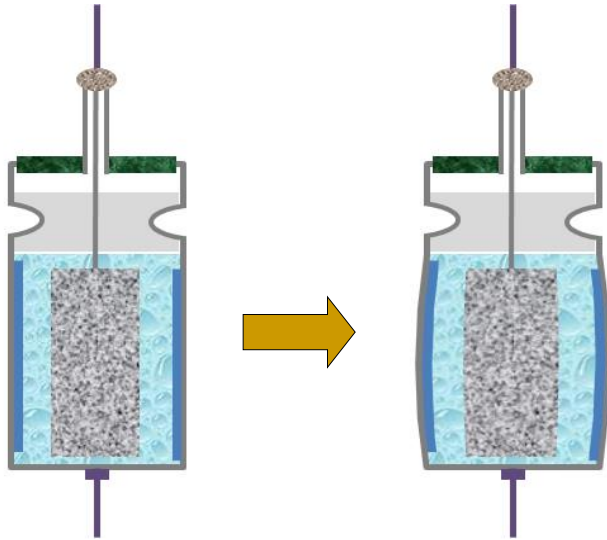
DWG#93026 RB Degradation at 0.5V



- ✓ Degradation might appear after hundreds of hours.
- ✓ In most failure cases the transfer charge is below the specified value of 0.05 C.
- ✓ Time to failure varies from part-to-part substantially.

Bulging under Reverse Bias

- H₂ generation at cathode:
 $2e^- + 2H_2O(L) \Rightarrow H_2(g) + 2OH^-(aq)$
- Temperature and deformation of the case were measured using flexible sensors.



$$n = \frac{I \times t}{z \times F}$$

$$P = n \times \frac{RT}{V}$$

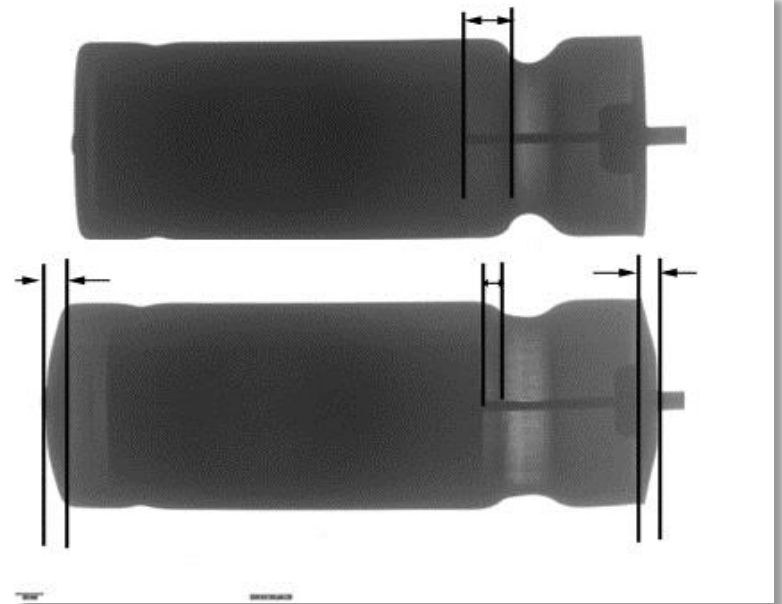
$$\varepsilon = \frac{P \times r}{E \times h}$$

- ✓ Strain increases linearly with time due to the pressure building up.
- ✓ Strain ~0.07% corresponds to pressure of dozens of atmospheres.

Example of RBS Failure



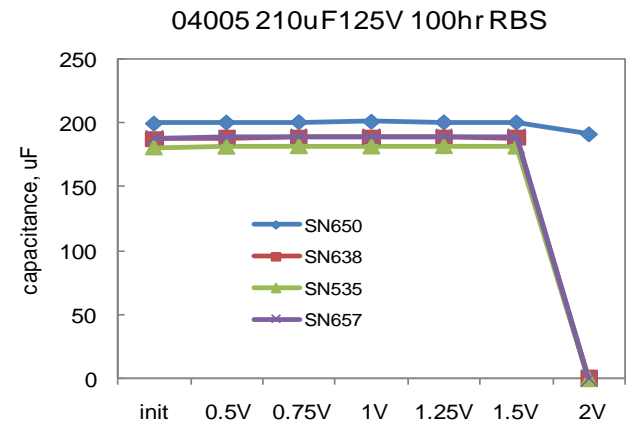
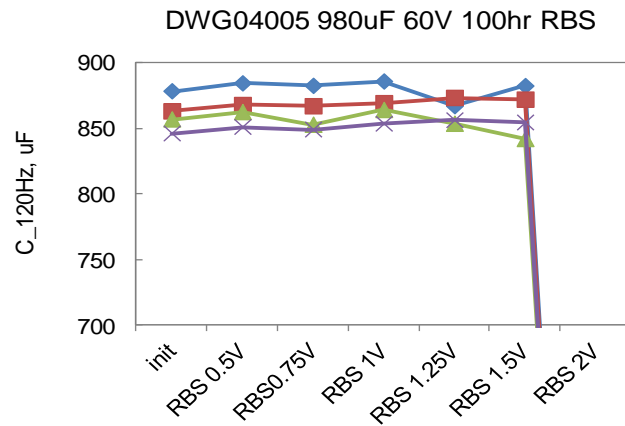
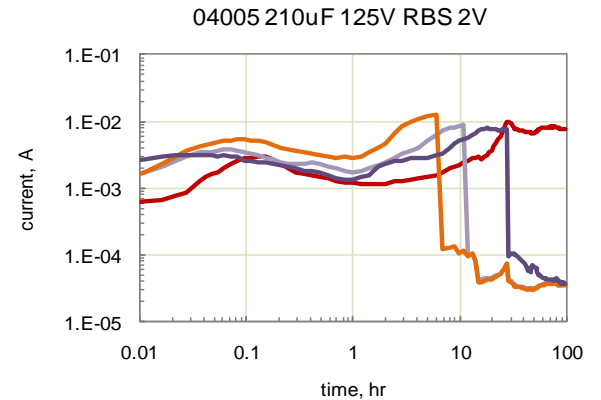
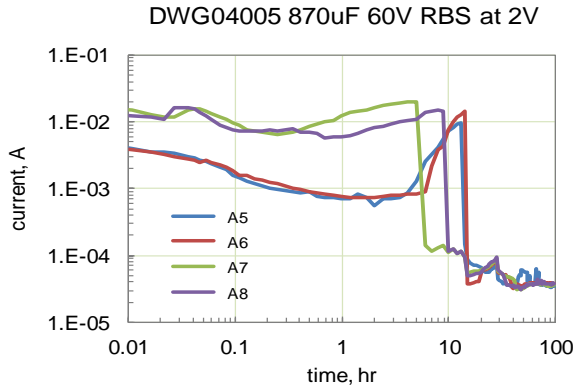
470uF 75V part failed RBS 100hr 2V due to lead fall-off caused by electrolyte leak.



Radiographic views of a normal (top picture) and bulged (bottom picture) capacitors

- ✓ Pressure deforms the case, forces electrolyte above the Teflon bushing, and causes corrosion of the weld.

Failures of #04005 Capacitors



- ✓ A sharp decrease in RB current and open circuit failure mode.
- ✓ At RT 2V time-to-failure ~10hr; at 1.5V ~ 100hr; at 1V ~ 1000hr?

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- ❑ Random vibration testing.
- ❑ Recommendations.

Introduction

- ❑ Ripple-current-induced heating affects the failure rate of capacitors.
- ❑ Typical requirements for temperature derating: 70 °C at 60% of VR to 110 °C at 40% VR.
- ❑ There is no derating requirement for ripple currents (effect of vacuum?).
- ❑ Self-heating caused by ripple current can be calculated as:

$$\Delta T = I_r^2 \times ESR(T, f) \times R_{th}(T, case_size, envir.)$$

This requires knowledge ESR(T, f), and thermal resistance, Rth.

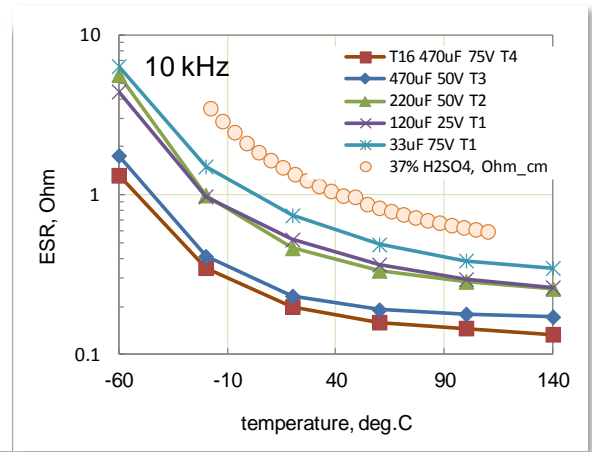
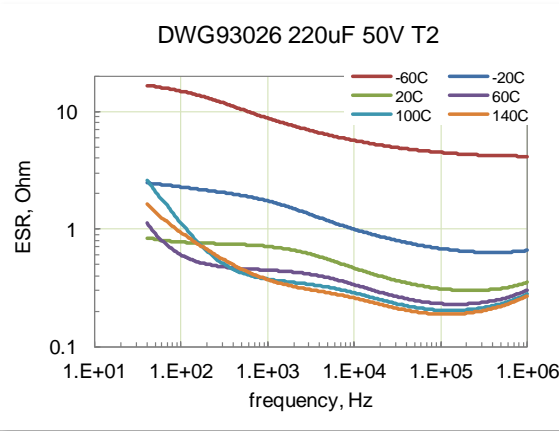
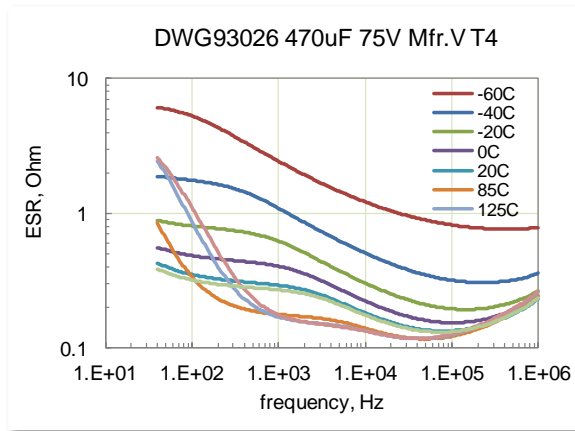
- ❑ A complex character of DT dependence on a variety of external and internal parameters explains difficulties with I_{rm} specification.
- ❑ Case-to-ambient thermal resistance:
$$R_{th} = (1/R_{conv} + 1/R_{rad} + 1/R_{cond})^{-1}$$
- ❑ Analysis shows that R_{conv} , R_{rad} , and R_{cond} , have comparable values.

Existing Ripple Current Requirements

- ❑ MIL-PRF-39006 specifications have tables with maximum ripple current, I_{rm} , at standard conditions: 40 kHz, 2/3VR, still air, $T_{amb} = 85^{\circ}\text{C}$.
“The ripple current listed in table represents a rating calculated by using a maximum internal temperature rise (ΔT) at 50°C at 40 kHz at 85°C ambient temperature, with a maximum peak rated voltage of 66.67 percent of the 85°C peak voltage rating.”
- ❑ To account for different frequencies, voltages, and temperature conditions current multiplying factors (CM) are suggested.
- ❑ No details on selection of CM are given, but It is assumed that maximum internal temperature should be less than 135°C .
- ❑ A method to determine I_{rm} is not specified, and MIL-PRF-39006 does not require temperature rise measurements.
- ❑ The specified values of I_{rm} are based on historic data that are adjusted for the frequency dependence of ESR for new capacitors; however, the method of the adjustment is not specified and different manufacturers might use different techniques.

ESR(T, f)

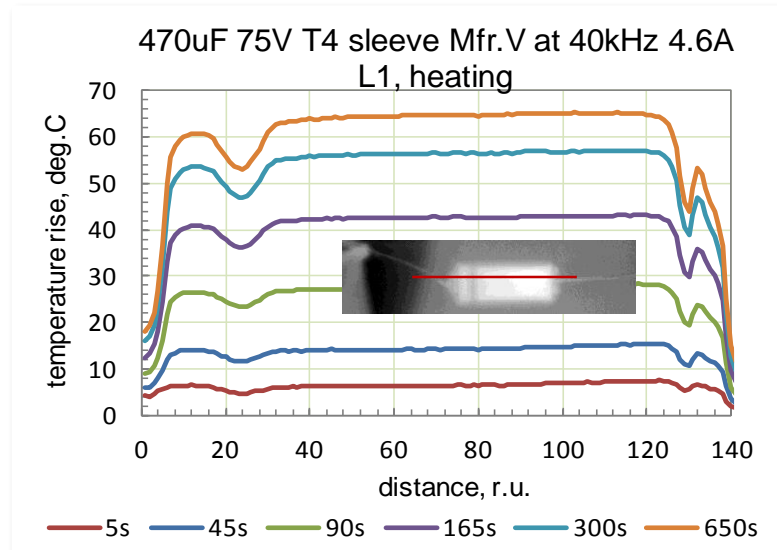
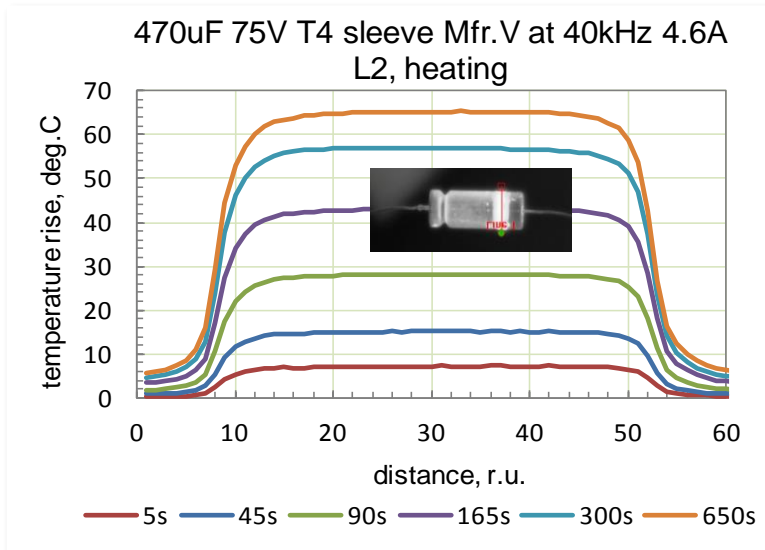
- ❑ ESR is a complex function of T and f .
- ❑ Power dissipation depends on the value of $ESR(T, f)$: $P = I_r^2 \times ESR(T, f)$



- ✓ ESR is decreasing with temperature at high frequencies (HF), but is rising at low frequencies (LF).
- ✓ There is a risk of thermal run-away at LF, typically below ~ 1 kHz.
- ✓ $ESR(T)$ at HF (> 1 kHz) corresponds to the temperature dependence of resistance of sulfuric acid. $ESR(f)$ at LF is determined by the AC resistance of Ta_2O_5 layer, but at HF - by resistance of the electrolyte.

IR Imaging

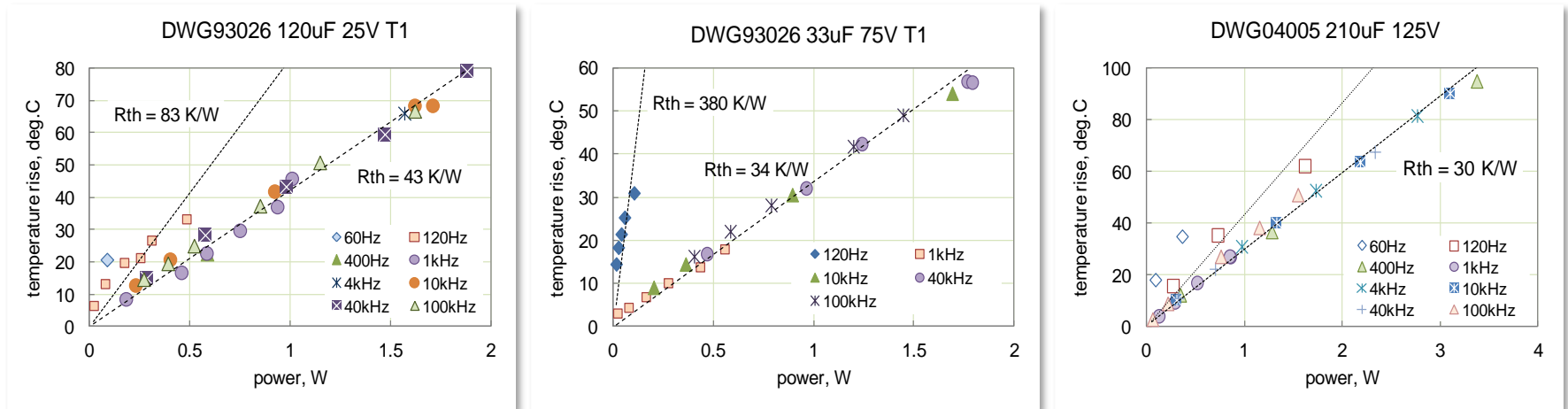
- IR images were recorded with time during heating and cooling of the parts to check for a possible formation of hot spots.



- ✓ Analysis of temperature distributions did not reveal hot spots in any of the parts.
- ✓ Temperature distributions corresponded to the location of the anode slug.

Effect of Power in Still Air

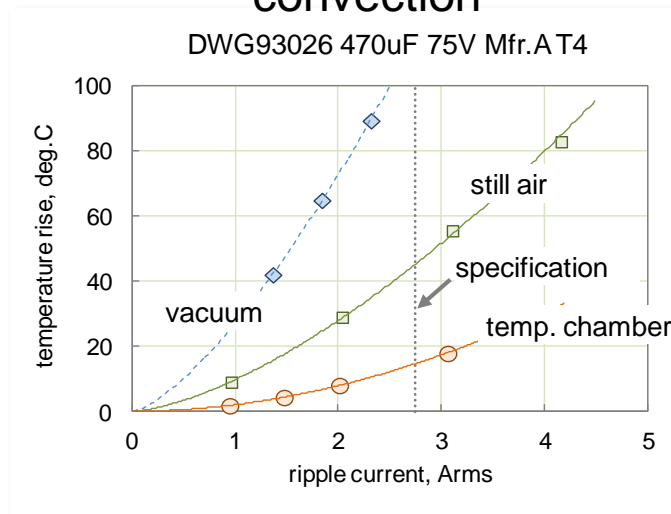
$\Delta T(P)$ at different frequencies and amplitudes of ripple currents



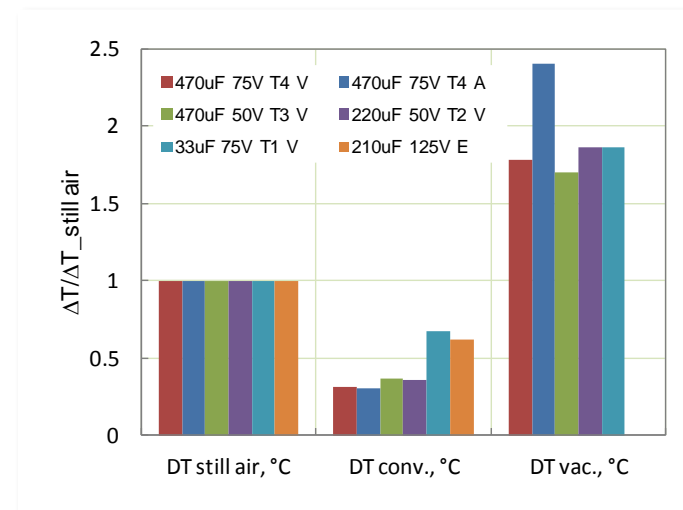
- ✓ At $f > 1$ kHz, R_{th} is frequency independent.
- ✓ At LF (60 Hz and 120 Hz), R_{th} is 2 to 10 times greater than at HF.
- ✓ The anomaly corresponds to much larger τ at LF, and is likely due to different temperature distributions in the capacitor.
- ✓ For low-size cases, contrary to the large-size cases, ΔT is noticeable at LF even at relatively low levels of the dissipated power.

Temperature Rise at Different Test Conditions

Variations of temperature rise with ripple current at 40 kHz in still air, vacuum, and a temperature chamber with forced air convection



Temperature rise normalized to still air conditions for different types of capacitors



- ✓ Temperature rise changes substantially depending on environments.
- ✓ Compared to still air, temperature rise in vacuum can be more than 2 times greater, and ~3 times less in the forced air convection temperature chamber.

R_{th} and ΔT at Different Environments

- ❑ Average R_{th} values were calculated using two test methods.
- ❑ Temperature rise, ΔT , was calculated for standard conditions: 40 kHz and specified values of I_{rm} .

| Part | R_{th} still air, K/W | R_{th} conv., K/W | R_{th} vac., K/W | ΔT still air, °C | ΔT conv., °C | ΔT vac., °C |
|----------------|-------------------------|---------------------|--------------------|--------------------------|----------------------|---------------------|
| 470uF 75V T4 V | 30.4 | 12.2 | 70.7 | 28.8 | 9.1 | 51.3 |
| 470uF 75V T4 A | 31.9 | 11.8 | 111 | 47.5 | 14.6 | 114.3 |
| 470uF 50V T3 V | 36.2 | 17.4 | 89 | 22.5 | 8.2 | 38.2 |
| 220uF 50V T2 V | 37.3 | 18.2 | 113.3 | 43.4 | 15.6 | 81 |
| 120uF 25V T1 V | 40.9 | 27.1 | | 21 | | |
| 33uF 75V T1 V | 34.8 | 30.4 | 130.4 | 27.9 | 18.9 | 52 |
| 210uF 125V E | 24.3 | 14.1 | | 50.9 | 31.3 | |

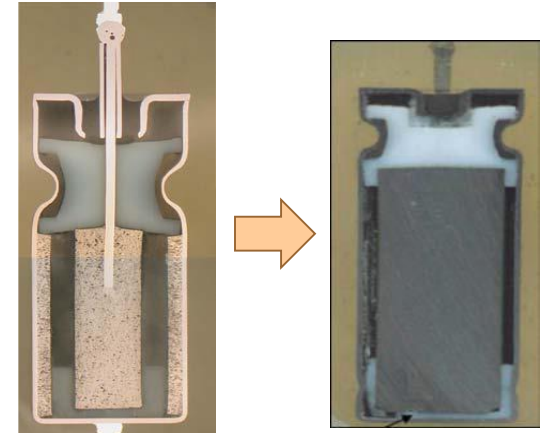
- ✓ Four out of 7 part types had low rated currents, $\Delta T \ll 50$ °C.
- ✓ In a convection chamber temperature rise decreases by 40% to 60% compared to still air conditions.
- ✓ Temperature rise increases by 60% to 140% in vacuum and can exceed 100 °C.

How Stressful is Ripple Current Testing?

- ❑ Experience shows that ripple life testing does not generate more failures compared to a regular, DC bias only, life testing.
 - ❑ At ripple life test conditions for M39006/33 capacitors (85°C, 40kHz, I_{rm} , 2/3VR), the temperature rise is from 10 °C to 20 °C only.
 - ❑ Assuming acceleration factors for reliability testing for solid and wet capacitors are similar, AF can be expressed as:
where $B = 10$ to 20 , $E_a = 0.7$ to 2 eV.
$$AF = \exp \left[B \left(\frac{V}{VR} - 1 \right) \right] \times \exp \left[- \frac{E_a}{k} \left(\frac{1}{T_2} - \frac{1}{T_1} \right) \right]$$
 - ❑ At $T = 85$ °C, an increase in the case temperature by 10 to 20 °C would increase FR in 2 to 34 times; however, a decrease in DC bias from VR to 2/3VR would decrease FR in 30 to 785 times.
- ✓ The level of stress during ripple life testing is typically below the level of stress during regular life testing at 85°C and VR.

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- ❑ Leakage currents.
- ❑ Hermeticity.
- ❑ Gas generation and internal pressure.
- ❑ Effect of reverse bias.
- ❑ Ripple currents.
- ❑ **Random vibration testing.**
- ❑ Recommendations.

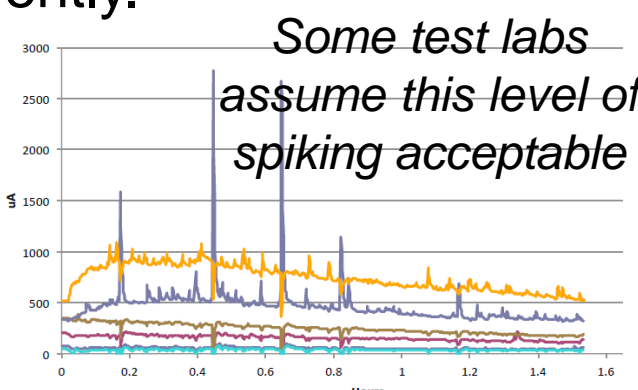
Introduction to RVT



- ❑ History of RVT failures.
- ❑ During RVT larger anodes in advanced WTCs experience greater stress than MIL capacitors, and are more susceptible to damage.
- ❑ Requirements for space modules: typical range of RVT is from 4.5 to 12.9 g rms.
- ❑ General Environmental Verification Specification (GEVS): an overall qualification level for testing is 14.1 g rms.
- ❑ Assuming a 3dB margin to the system-level, capacitors should sustain 19.64 g rms (condition II-E per MIL-STD-202, TM214).
- ❑ RVT cannot be replaced with sinusoidal testing. Peak accelerations during RVT are up to 4-5 times of the rms value.
- ❑ Capacitors per DLA DWG#93026 are not specified for RVT.

Existing Requirements and Practice

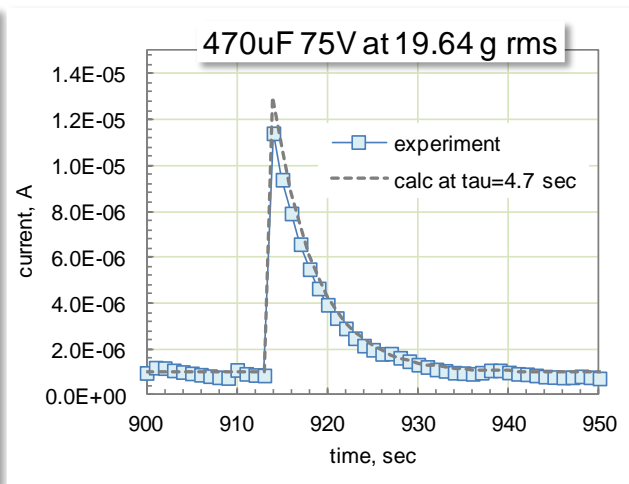
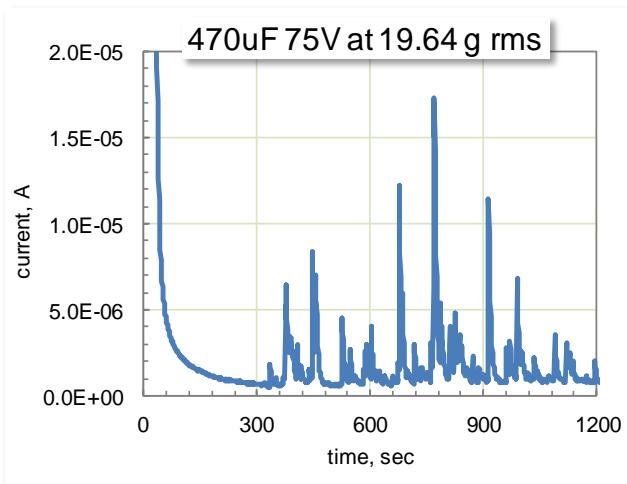
- ❑ MIL-PRF-39006: up to 53.8 g rms; 1.5hr in 3 directions; last 30 min by monitoring every 0.5 msec “to determine intermittent open-circuiting or short-circuiting”. $DCL_{\text{post test}} = 125\% \text{ of } DCL_{\text{init}}$.
 - ❑ Test techniques and failure criteria are not specified allowing different test labs to carry out testing differently.
 - ❑ Intermittent open circuit can be relatively easily detected during AC measurements.
 - ❑ Intermittent shorts result in spiking during DC measurements and require establishing critical levels.
 - ❑ Used circuits vary substantially, e.g limiting resistors from ohms to dozens of kohms, and failure criteria vary from 5% to 90% of VR.
- Some test labs assume this level of spiking acceptable*


- ✓ Different set-ups have different sensitivity to short-circuiting.
 - ✓ Different failure criteria cause inconsistency in test results.
 - ✓ A single scintillation event is sufficient to cause lot failure.

Experiment

- ❑ 24 types of military and DLA DWG#93026 capacitors from 4 manufacturers. 4 to 5 samples in a group.
- ❑ Step stress RVT: from 10.76 g rms (Cond. II-C) to 53.79 g rms (Cond. II-K) consequentially for 15 min.
- ❑ DCL were monitored every 100 msec through 10k resistors.
- ❑ Vibration started after 5 min of electrification.

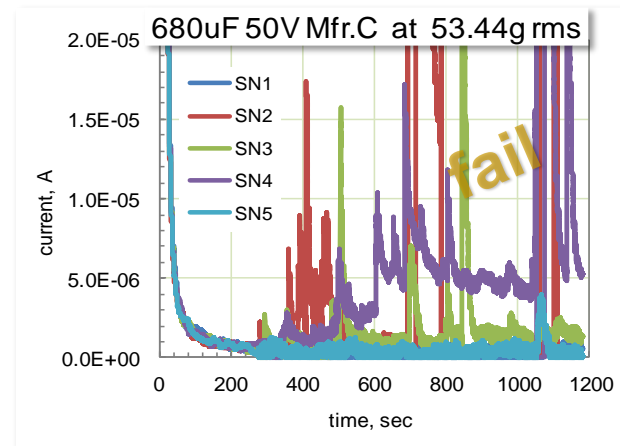
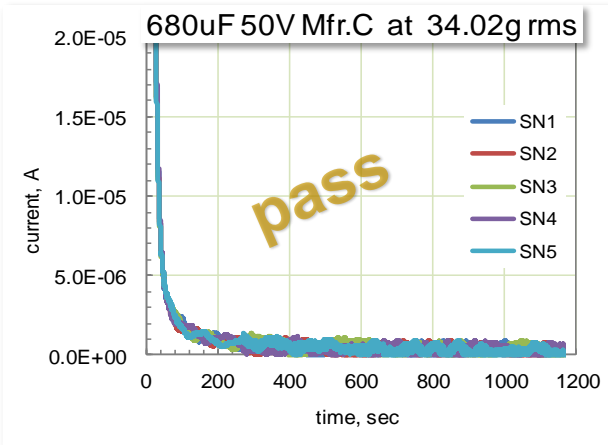
Typical results of RVT



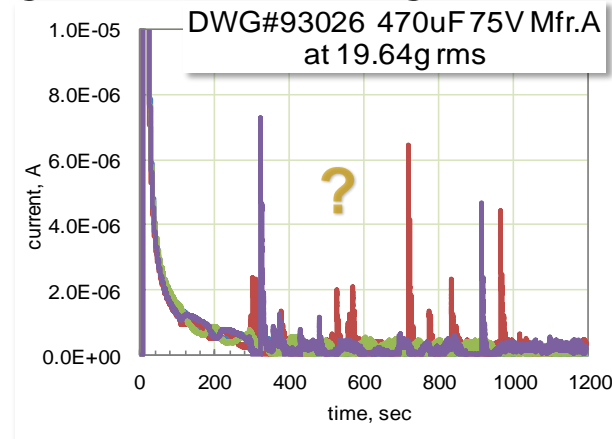
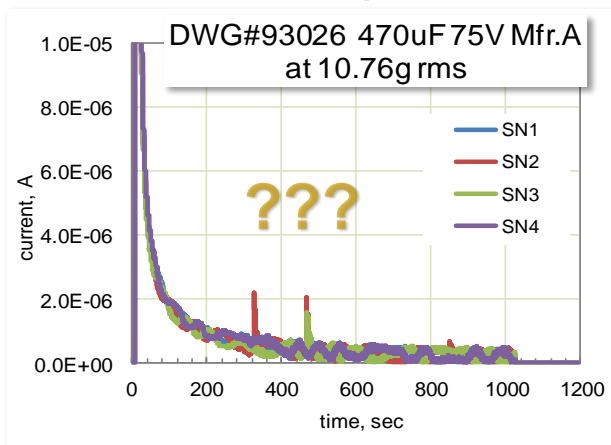
✓ The rise time is below 0.1 sec and the decay had a characteristic time of 4.7 sec (= $470 \mu\text{F} \times 10 \text{ k}\Omega$) that corresponds to the model.

Results of Step Stress Testing

Example of a part passing RVT at 34 g rms and failing at 53.44 g rms

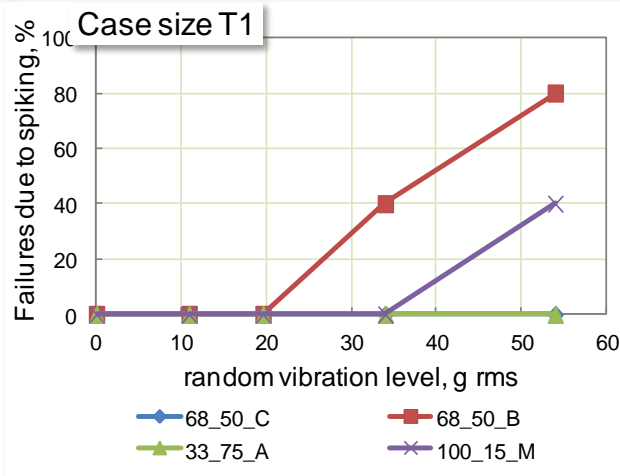
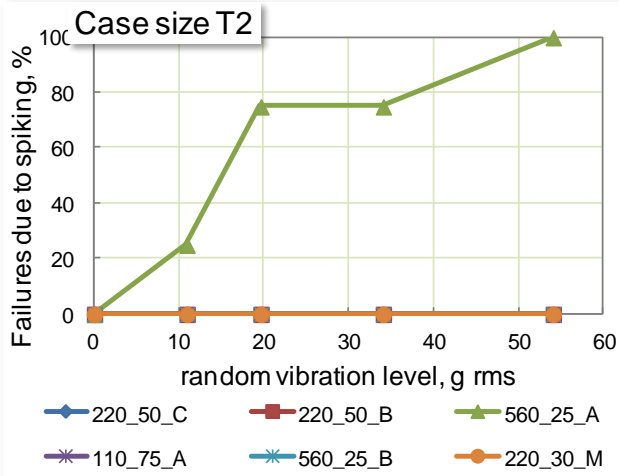
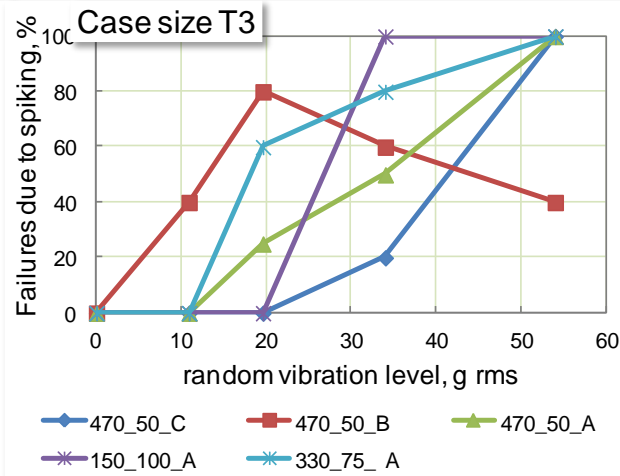
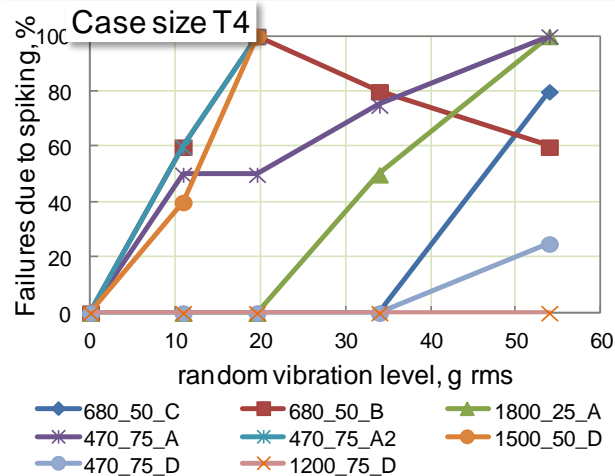


Did this part fail at 10.76 g rms, at 19.64 g rms?



Results of Step Stress Testing, Cont'd

Proportion of failures detected by current spiking for different case sizes

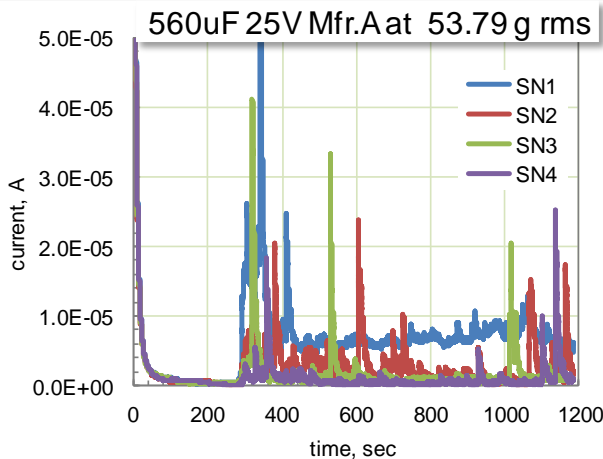


- ✓ Capacitors can fail at low stress levels (~10 g rms)
- ✓ Failures increase with the level of stress.
- ✓ Some parts are recovering at greater stresses.
- ✓ The probability of failure is greater for larger size capacitors.

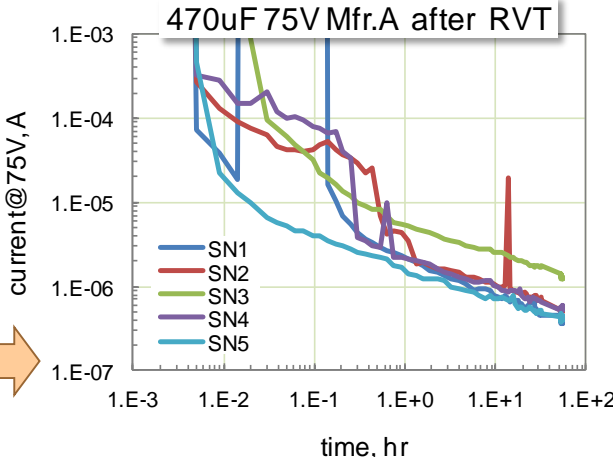
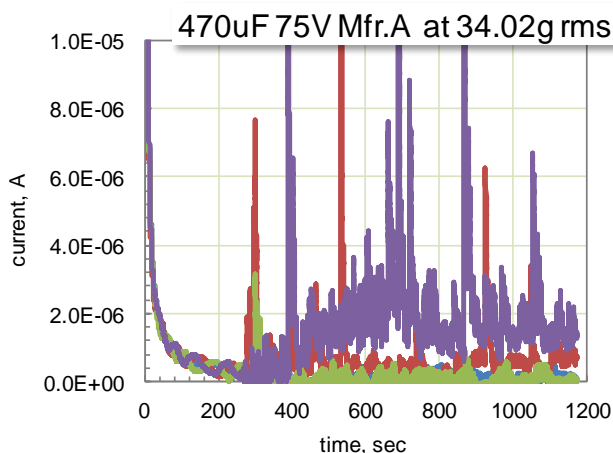
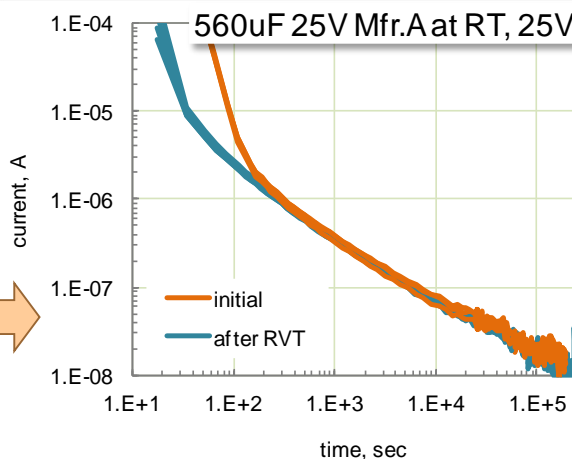
Post-RVT Leakage Currents

- Leakage currents were monitored with time under bias after RVT.

Currents during RVT



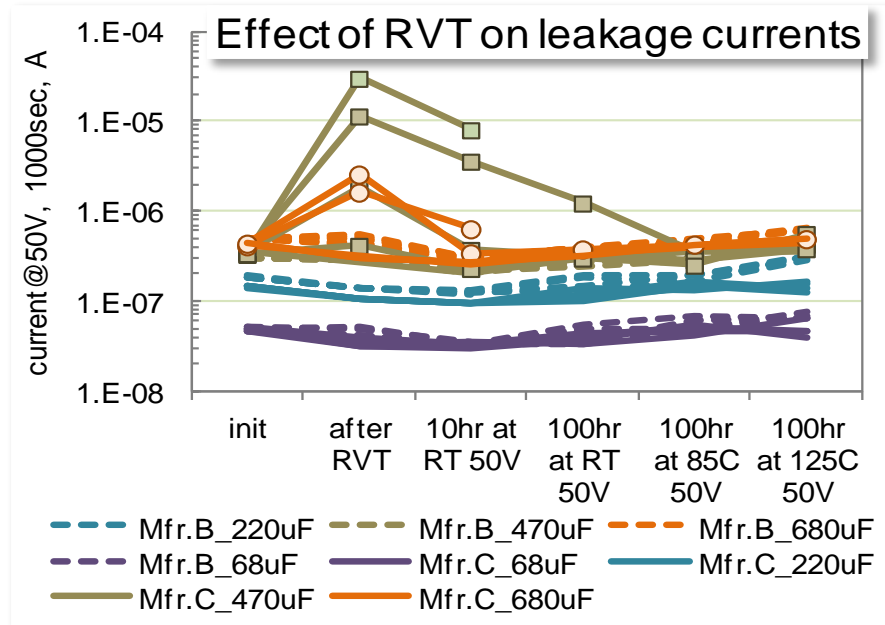
Currents after RVT



- ✓ Spiking during RVT might not result in DCL degradation after the testing.
- ✓ Capacitors that “fail” RVT at 53.8 g rms did not change DCL and passed HALT.
- ✓ Parts with excessive currents are recovering with time under bias.

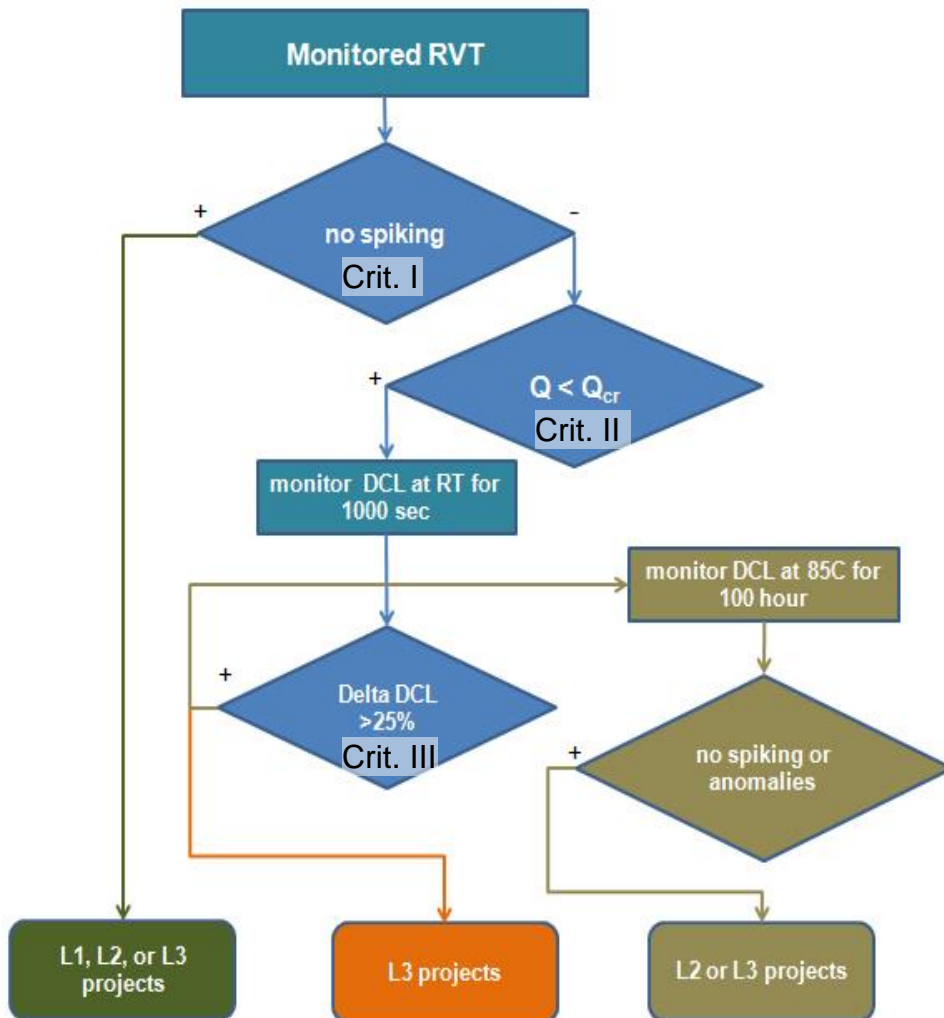
Post-RVT Leakage Currents, Cont'd

Variations of leakage currents at RT through the testing



- ✓ RT measurements of leakage currents might be more effective in revealing damage compared to high temperature measurements (Intrinsic DCL have a stronger temperature dependence compared to currents in damaged areas).
- ✓ The susceptibility to RVT failures is lot related.

Assessment of RVT Results



- ✓ Capacitors with minor spiking can self-heal and restore their performance and reliability.
- ✓ Different tests for different risk levels.
- ✓ Each lot should be tested.
- ✓ Typical testing:
 - 19.6 g rms , 6 samples.
 - 15 min in each direction.
 - DCL is monitored (10k, 0.1sec sampling).
 - Criterion I: $I_{sp} > 3 \times I_{300}$
 - Criterion II: $Q > Q_{cr}$
 - Criterion III:
 $I_{300_RVT} > 1.25 \times I_{300_init}$

- ❑ Introduction. Specific features of WTC.
- ❑ Design, DPA and CA.
- ❑ Parameters, their measurements and specifics.
- ❑ Leakage currents.
- ❑ Hermeticity.
- ❑ Gas generation and internal pressure.
- ❑ Effect of reverse bias.
- ❑ Ripple currents.
- ❑ Random vibration testing.
- ❑ **Recommendations.**

Recommendations

- ❑ Requirements for screening and qualification procedures for advanced WTCs are given in NASA Electronic Parts and Packaging (NEPP) Program reports (<https://nepp.nasa.gov/>):
 - “Leakage currents and gas generation in advanced wet tantalum capacitors”, 2015.
 - “Random Vibration Testing of Advanced Wet Tantalum Capacitors“, 2015.
 - “Ripple Current Testing and Derating for Wet Tantalum Capacitors”, 2013.
 - “Guidelines for Selection, Screening and Qualification of Advanced Wet Tantalum Capacitors Used for Space Programs”, rev.A - 2012, rev.B – 2016.