NASA Electronic Parts and Packaging Program

NEPP Task: Quality and Reliability of Advanced Wet and Solid Tantalum Capacitors

Part II. Evaluation of Advanced Wet Tantalum Capacitors

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Alexander Teverovsky

Dell Services Federal Government, Inc.

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Alexander.A.Teverovsky@nasa.gov

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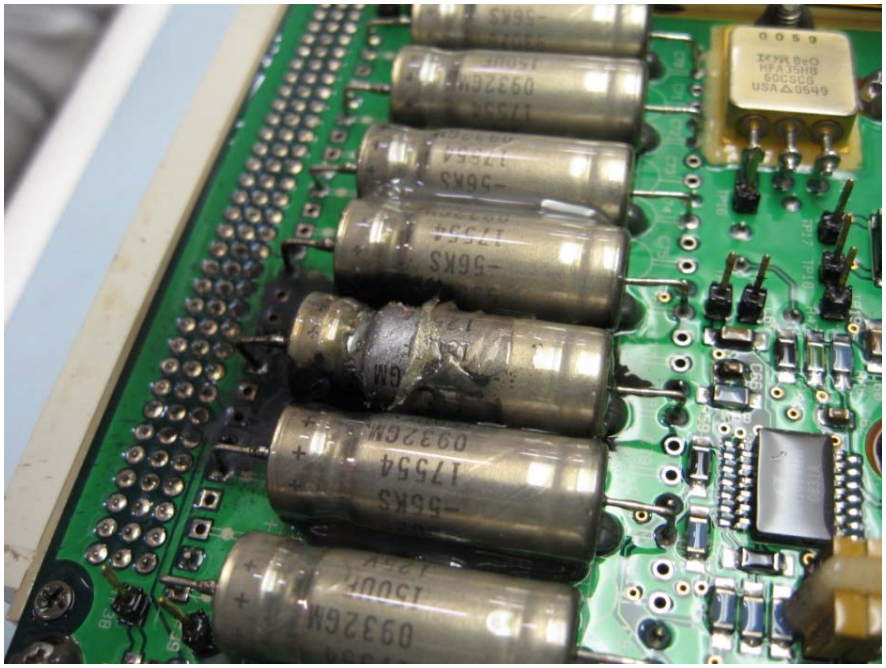
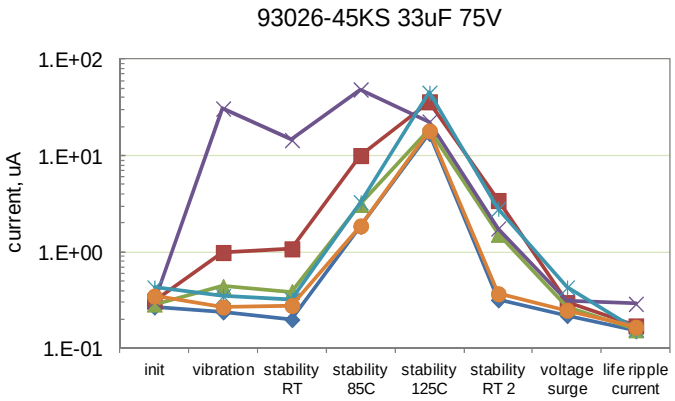
Outline

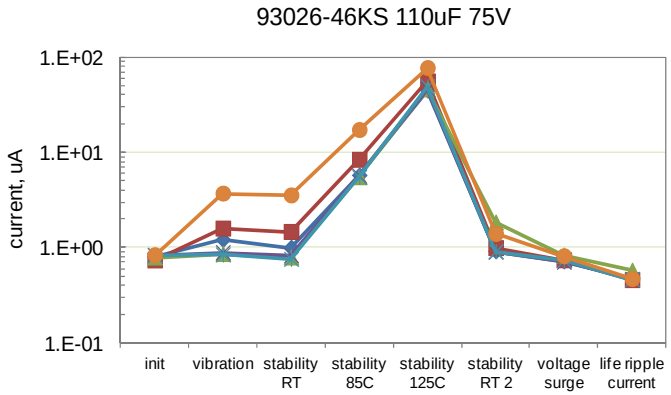
- Specifics of wet tantalum capacitors (WTC).
- New design.
- Reverse bias operation.
- Failure mechanisms at reverse bias.
- Random vibration testing.
- Failure modes and mechanisms during vibration testing.
- Conclusion and recommendations.



Resilience of WTC

Variation of leakage currents through the testing





PN	C, µF	VR, V	Vibration test (80 g), F/Qty.	Voltage surge test, 1000 cycles, F/Qty.	Ripple current life testing, 85C 1000hr, F/Qty.
93026-39KS	470	50	3/3	0/3	0/3
93026-45KS	33	75	12/12	0/12	0/12
93026-46KS	110	75	12/12	0/12	0/12
93026-50KS	68	100	3/6	0/6	0/6
93026-38KS	220	50	6/6	0/6	0/6

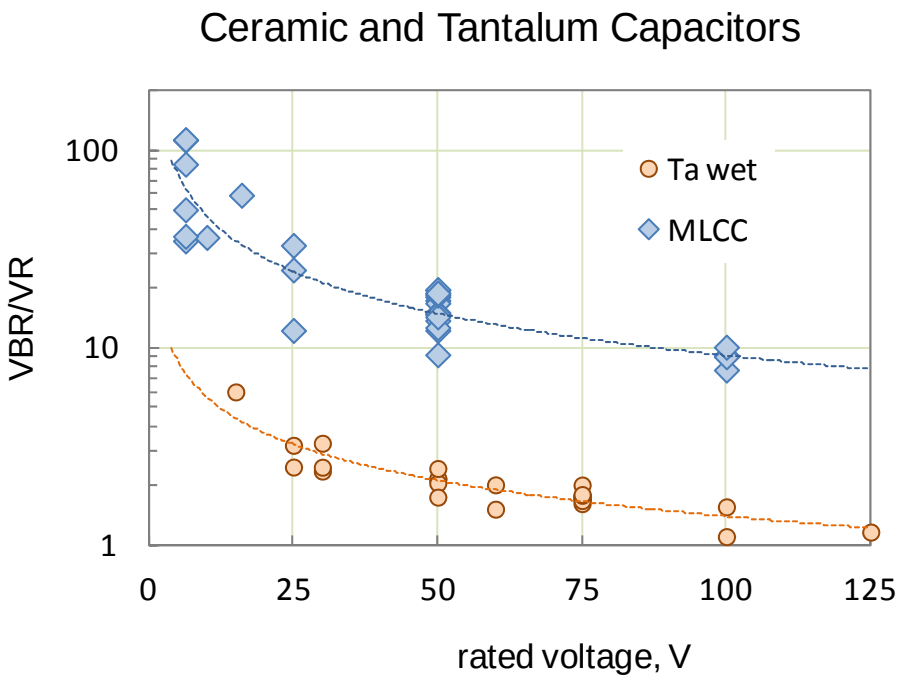
WTCs damaged by vibration can recover during the following tests.

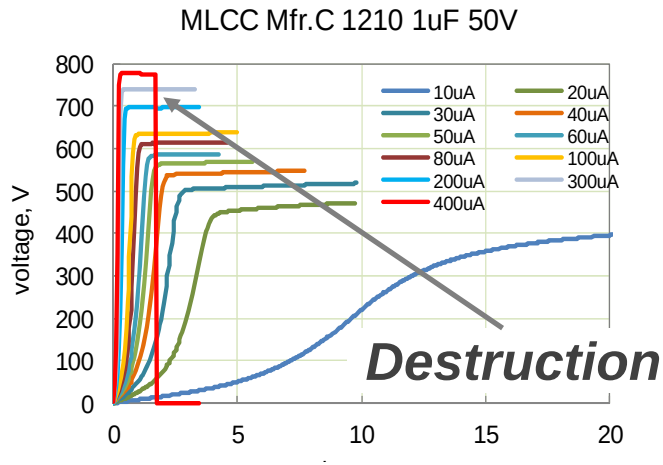
History of Use of Advanced WTC

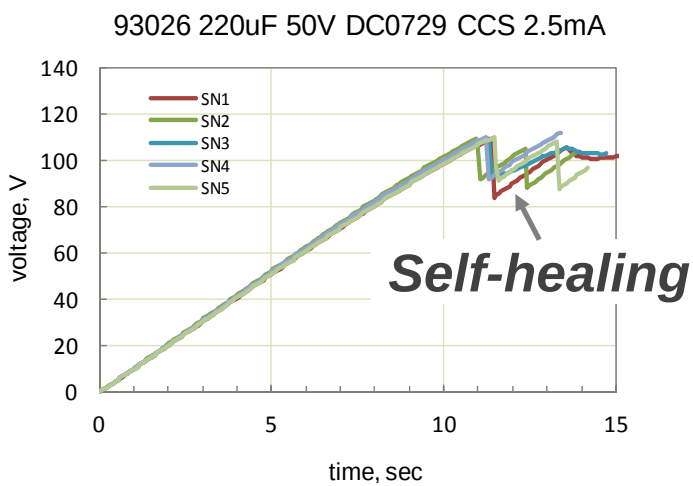
- Reportedly:
  - The part has been successfully used in military applications;
  - Failures due to vibration testing on lots before 2007(?)
  - Anomalies related to loose cathode coating flakes before 2006(?).
- 9 lots of different SuperTan-style capacitors have been used in three projects since 2007.
- 7 lots used in two projects (2008).
- System-level failures due to RB in 2010 and due to mechanical stress in 2011.
- Anomaly during thermal vacuum testing in 2012.

Are these parts qualified for space applications, how the existing system of S&Q guarantees reliability, and what can be done to reduce the risk of failures?

Specifics of Wet Tantalum Capacitors

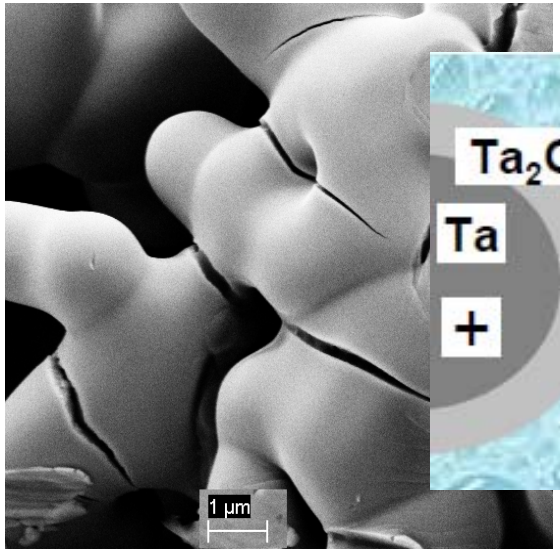


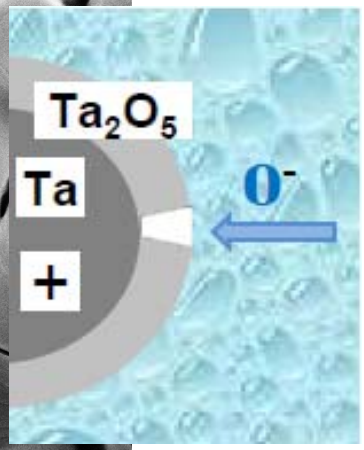


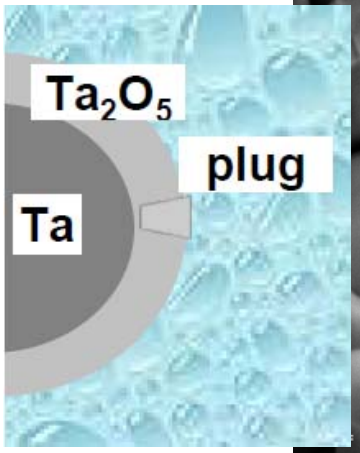


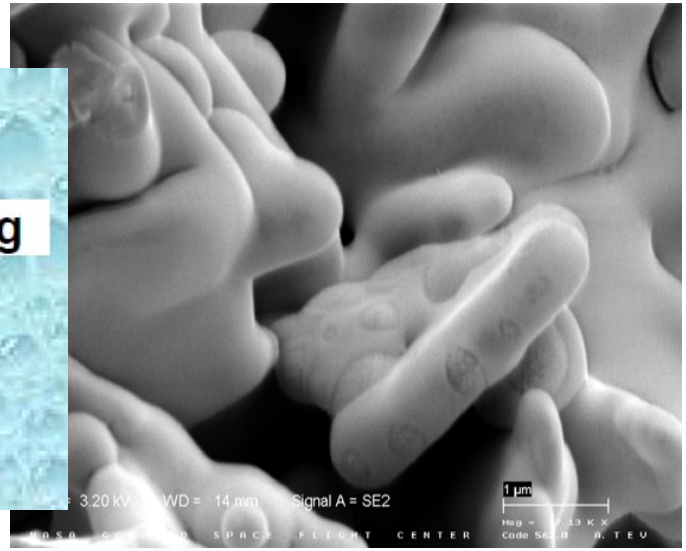
- Breakdown voltages (VBR) in ceramic capacitors are ~ 10 times of WTC.
- Rated voltages of WTC are much closer to VBR than for MLCCs.
- Why do we have similar derating requirements?

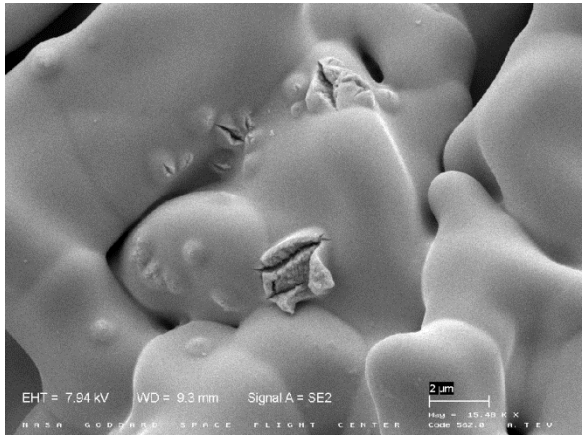
Self-Healing in Wet Tantalum Capacitors





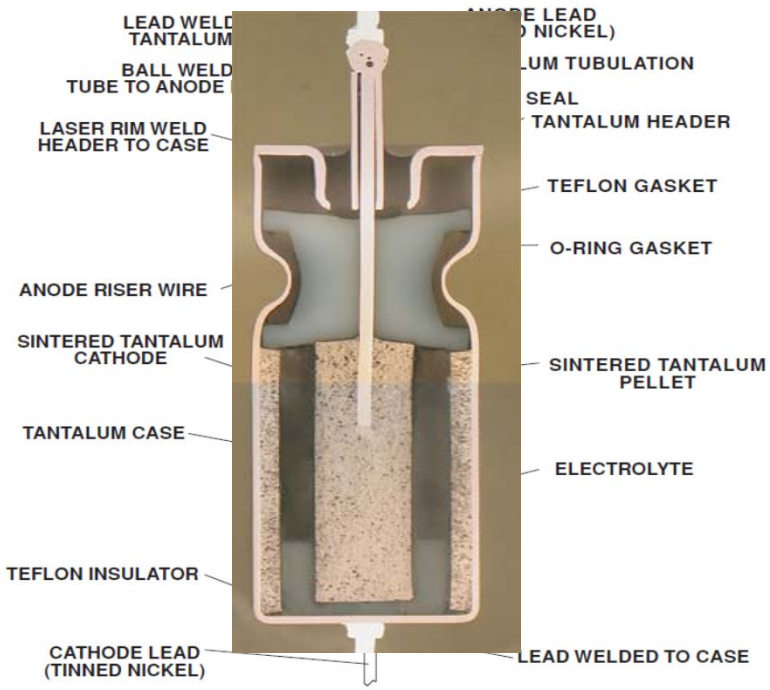


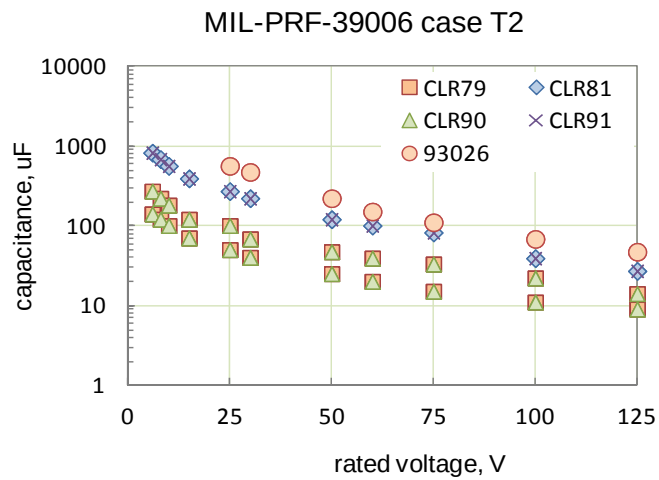


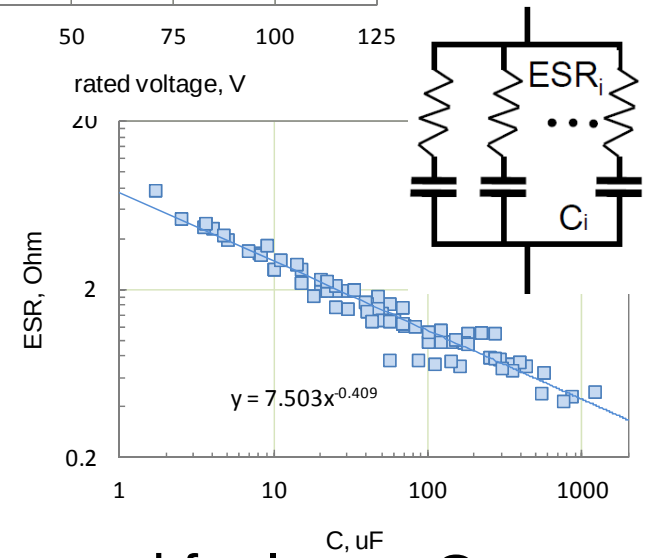


- If Ta2O5 is damaged (cracks or crystal growth), anodic oxidation continues under normal, forward bias conditions resulting in oxide growth thus effectively eliminating the defect.
- Self-healing contributes substantially to the reliability of WTC – is it a panacea?

Design and Performance of M39006 Wet Tantalum Capacitors



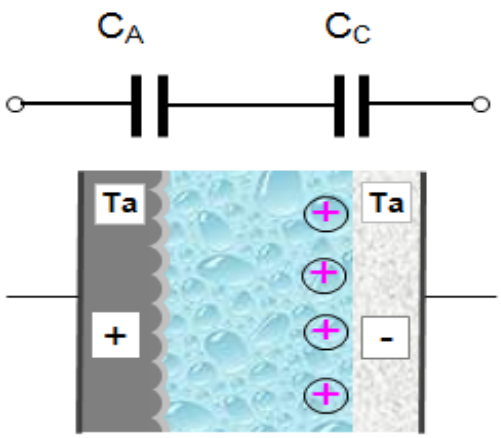




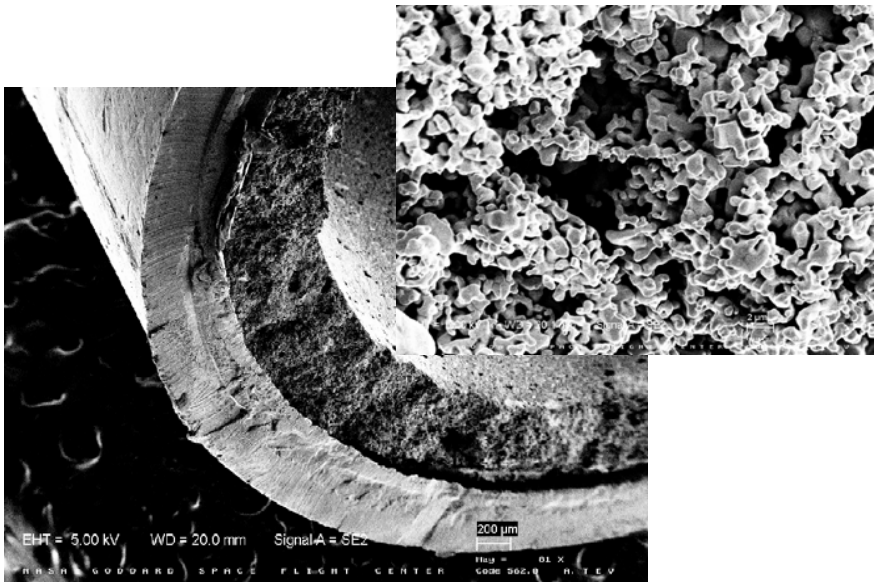
Better performance means:

- ❑ Smaller volume and larger voltage.
- ❑ More capacitance to deliver more energy.
- ❑ Smaller ESR to reduce ripple currents => a need for <u>larger C</u> is due to a close correlation between ESR and capacitance.

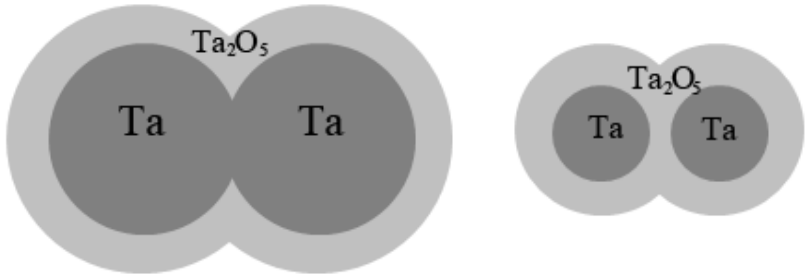
What Limits Performance of M39006 Capacitors?



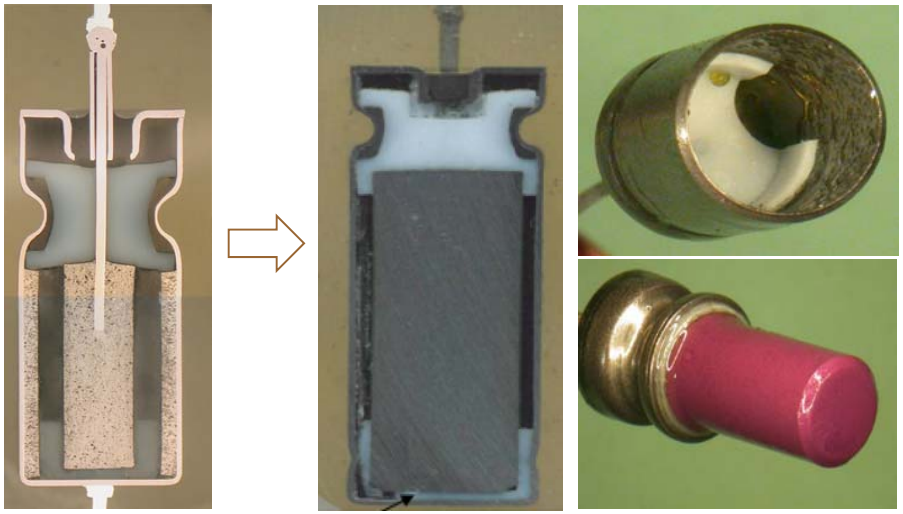
- Capacitance of the double layer at the electrolyte/case interface limits capacitance.
- C of metal/electrolyte interface is 20 to 50 uF/cm^2.
- Surface of anode ~ 100 times greater than the cathode case => a need for porous cathode.

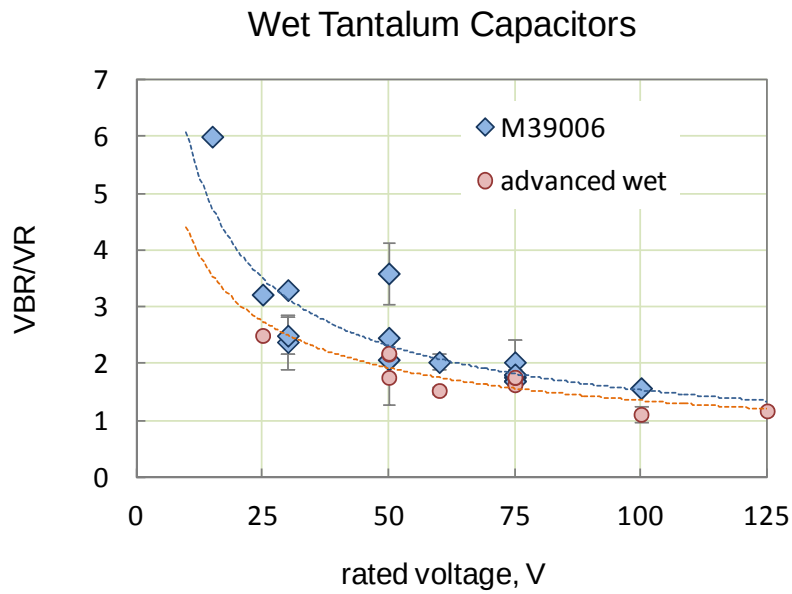


- Porous cathode layers occupy a substantial portion of the case.
- The larger VR the thicker the dielectric and the greater powder size is needed.



High Volumetric Efficiency WTC

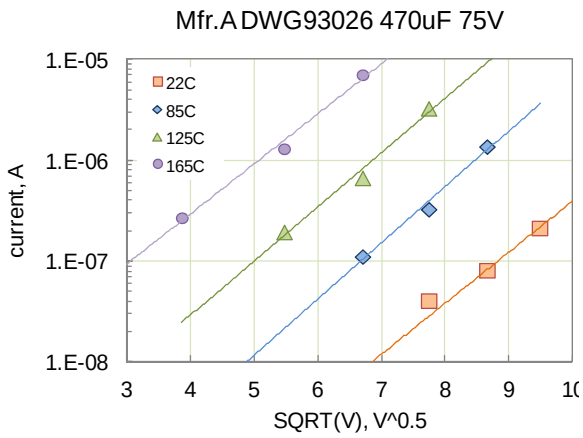


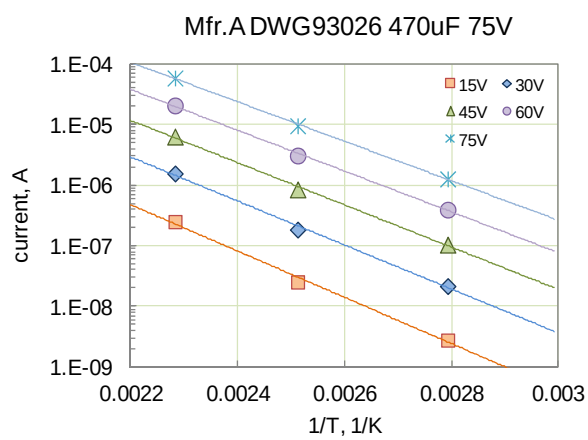


- Better performance of advanced WTC is achieved by reducing the thickness of the cathode layer, increasing the size of the slug, and using powder with a higher CV. => lower VBR.
- Different manufacturers are using different cathode materials: AVX: act.C/NbO-based; Vishay: Pd-based; Evans: RuO2-based.
- **Effect of new design on reliability**: reverse bias and vibration.

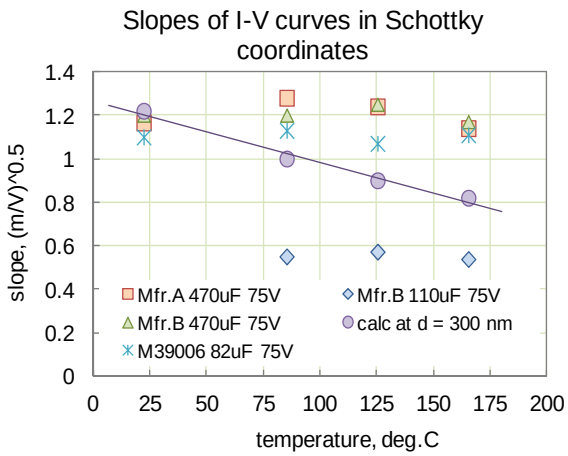
Characteristics of DWG#93026 WTC

Typical voltage and temperature dependencies of DCL

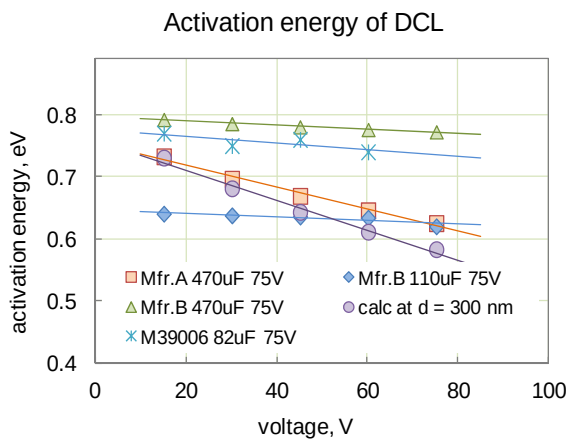




Variations of slopes with temperature

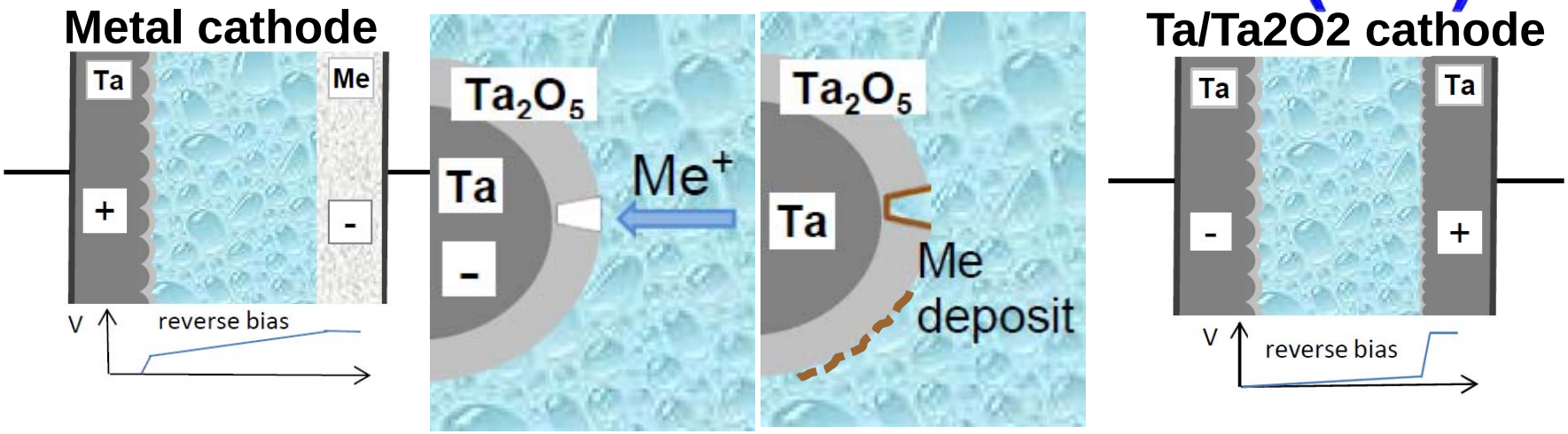


Variations of E_a with voltage



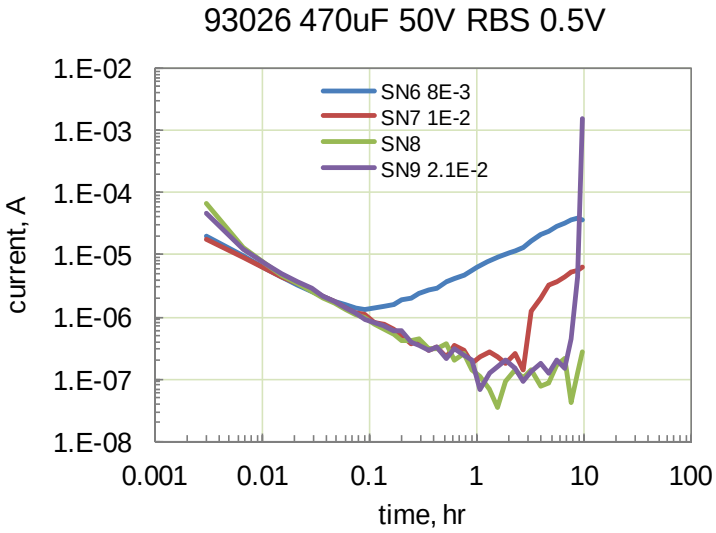
- Forward characteristics depends mostly on the anode structure and for this reason are similar to M39006 parts.
- Forward currents are likely controlled by the Schottky emission.
- Currents exponentially increase with temperature.
- The activation energy is in the range from 0.65 eV to 0.8 eV and decreases with voltage.

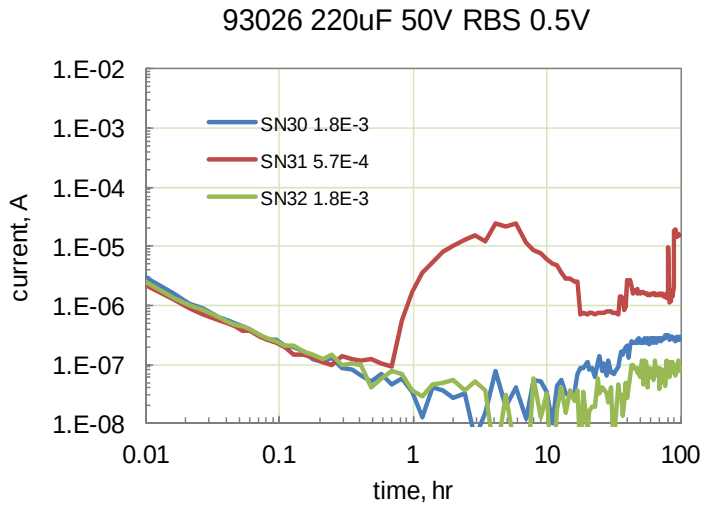
WTC are Unipolar Devices. Should we Care about Reverse Bias (RB)?

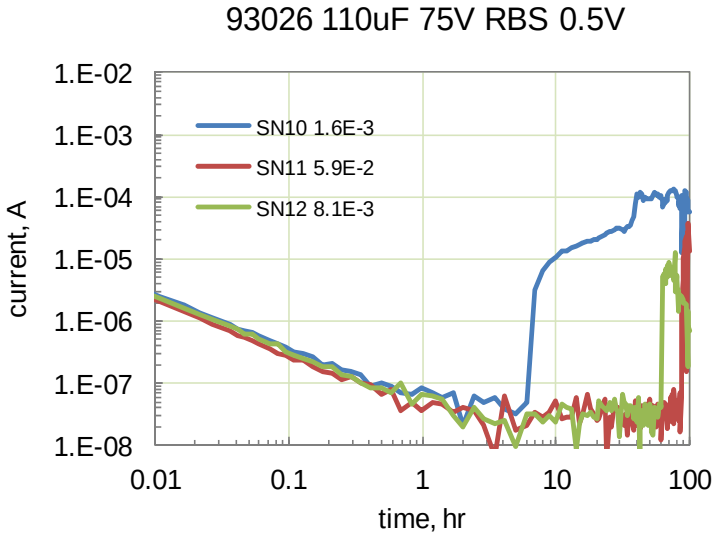


- Robustness to RB is needed to get additional margin for testing conditions and unforeseen events.
- First tantalum capacitors in silver case had failures under low RB due to silver electrodepositing and dendrite growth.
- The use of a tantalum case and oxidized sintered Ta powder improved substantially the robustness against RB.
- M39006 capacitors (except for 125V?) are approved for space applications. Are DWG93026 and DWG04005/3 qualified?

DWG#93026 RB Degradation at 0.5V

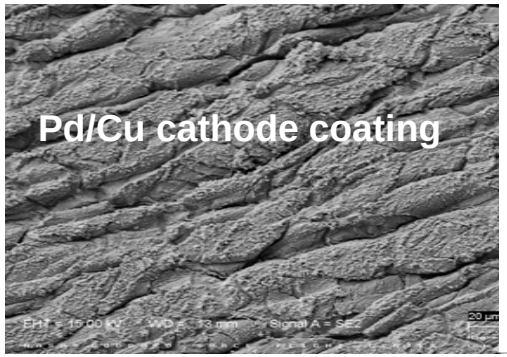


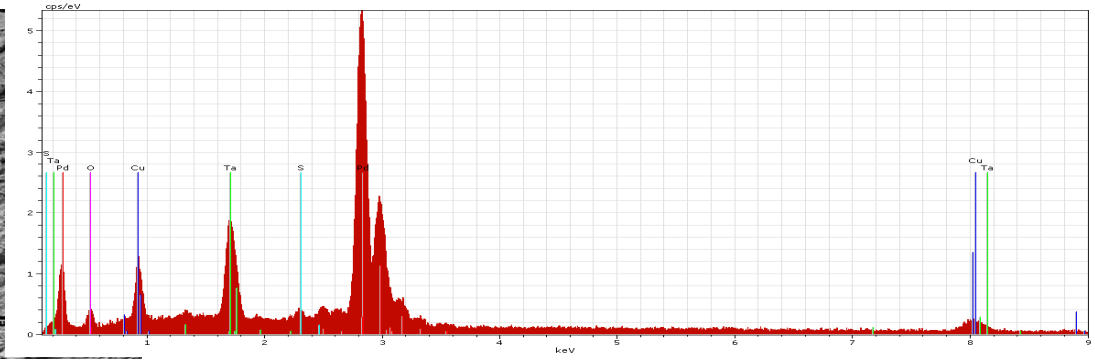




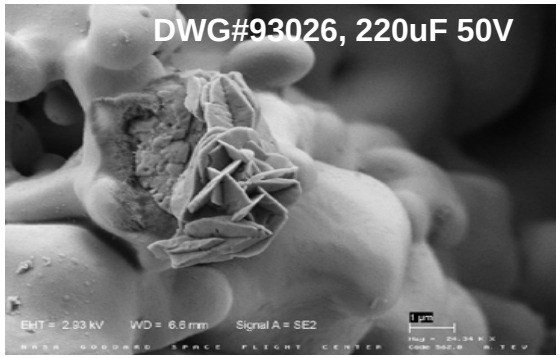
- In most cases the transfer charge is below the specified value of 0.05C.
- Time to failure varies from part-to part substantially.
- Failures might happen even at voltages as low as ~0.1V

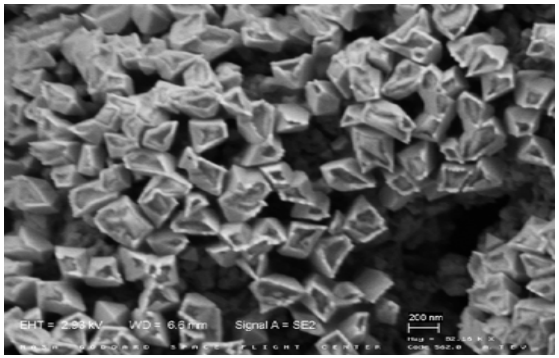
Failure Mechanisms DWG93026 Mfr.B

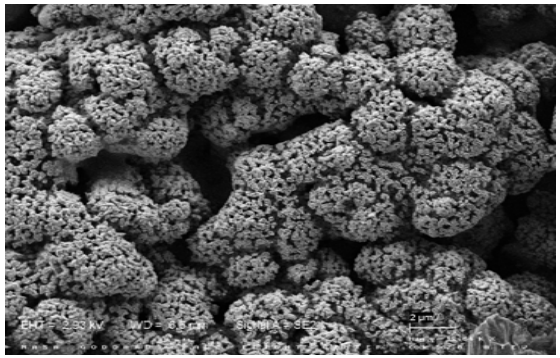




Surface of anode slug after RB testing covered with PD deposits

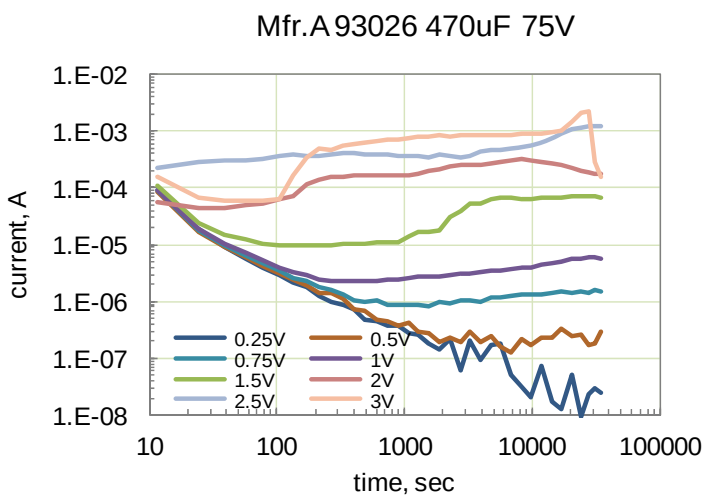


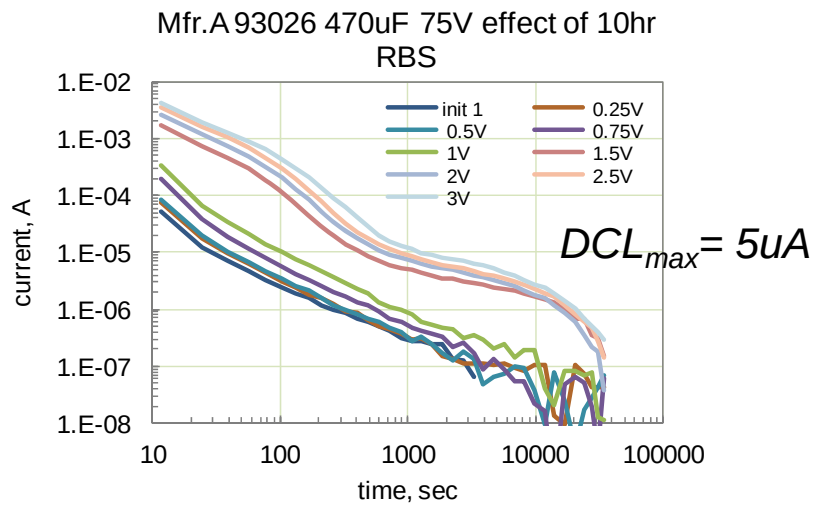


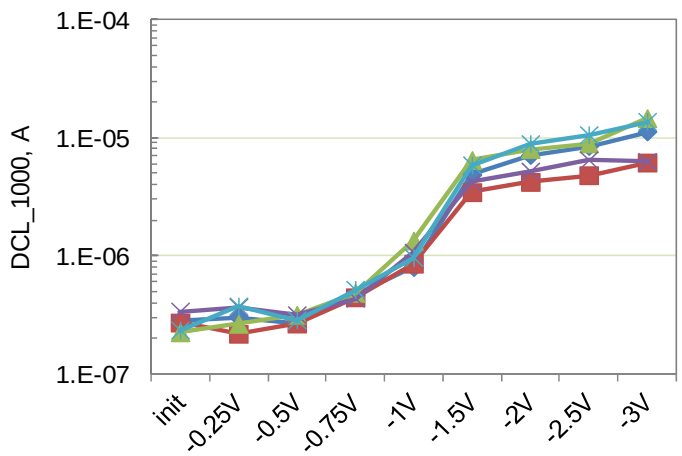


- Pd deposition on the surface of Ta2O5 reduces the barrier height and increases forward leakage currents.
- Electrodeposition at defects prevents self-healing.
- Degradation is reversible only partially.

DWG93026 470uF 75V Mfr.A, 10hr Reverse Bias Stress (RBS)

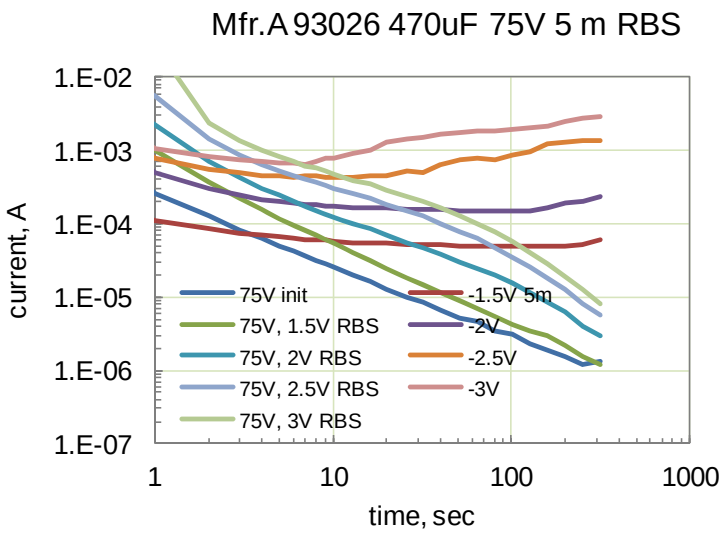


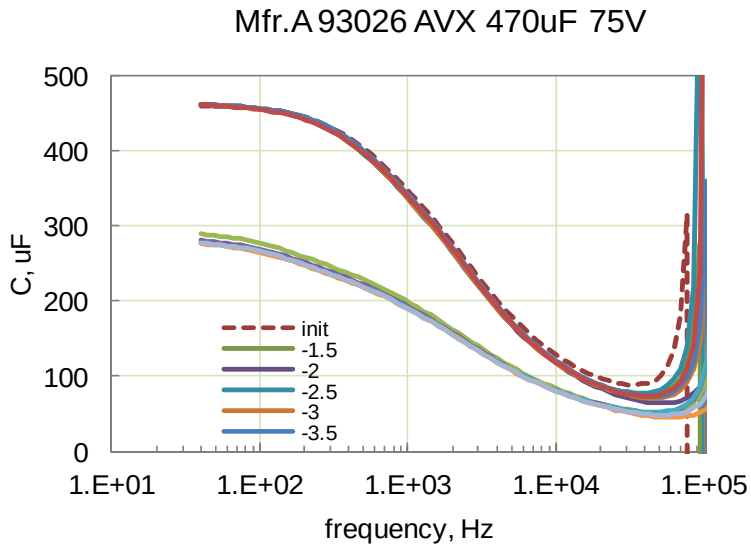




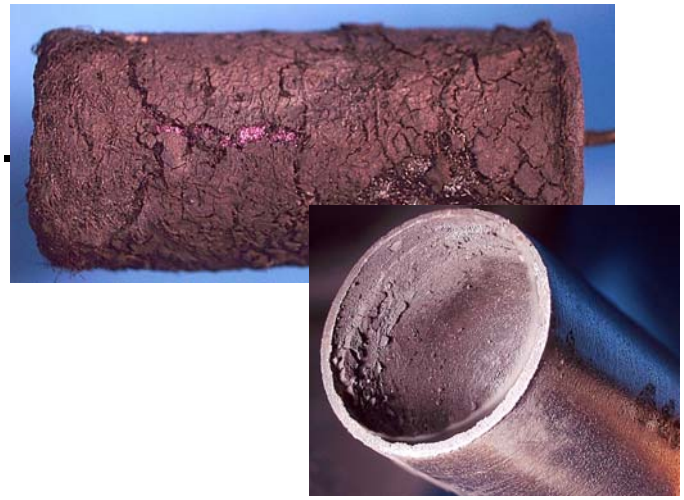
- No sharp increase of leakage current with time under RB.
- FB leakage currents increase ~ 40 times at RBS 1.5V and then stabilize.
- Forward currents appear to recover after 10 hr at rated voltages.
- RB currents increase substantially as the level of RBS increases.

DWG93026 470uF 75V Mfr.A, RBS





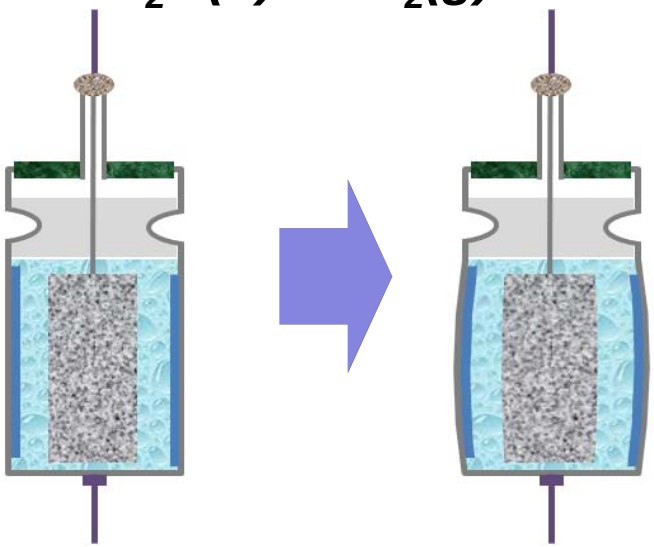
- RBS causes gradual degradation of RB and Forward Bias (FB) leakage currents.
- Capacitance decreases under RBS and then stabilizes.
- The loss of capacitance might be due to detachment of the cathode layer.

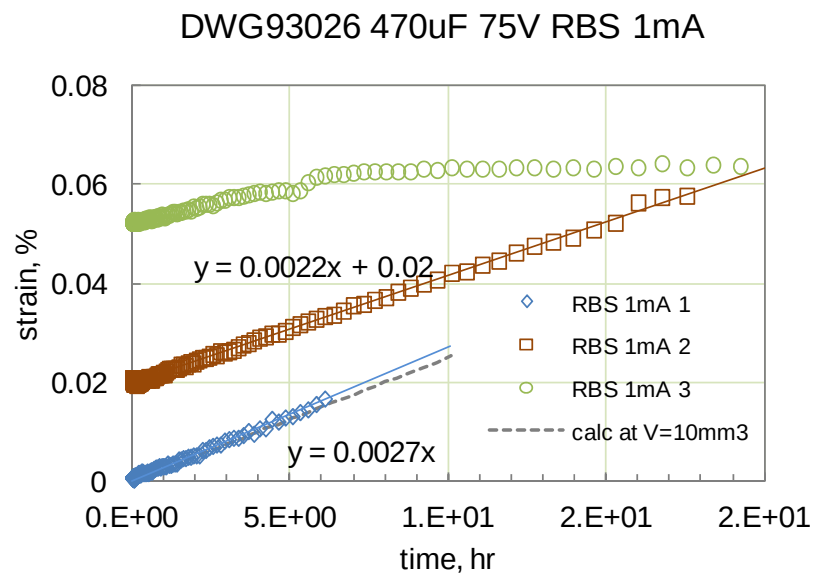


DWG93026 Bulging

H_2 generation at cathode:

$2e^- + 2H_2O(L) \Rightarrow H_2(g) + 2OH^-(aq)$



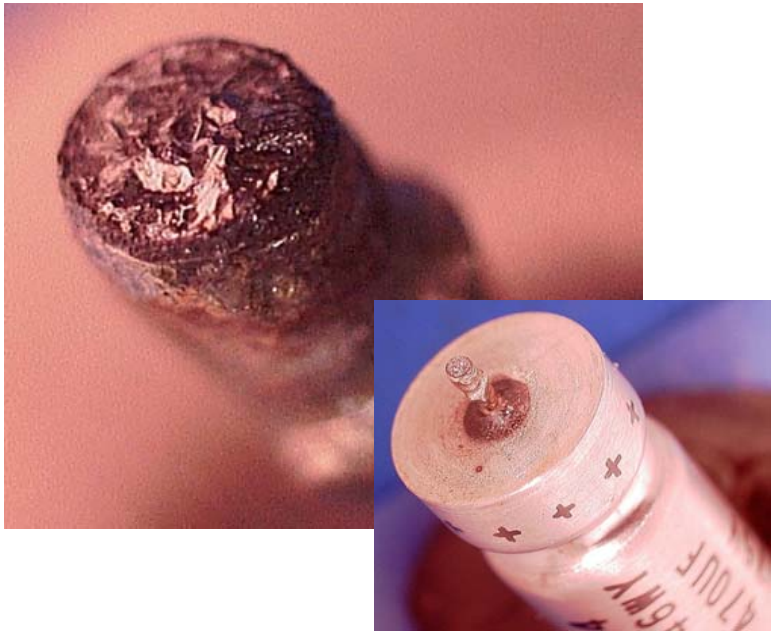


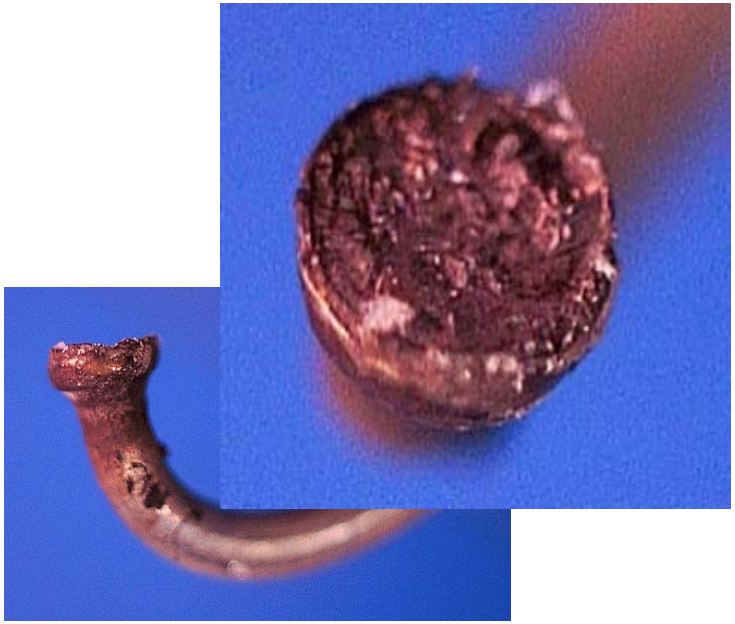
$$n = \frac{I \times t}{z \times F} \quad P = n \times \frac{RT}{V} \quad \varepsilon = \frac{P \times r}{E \times h}$$

- Temperature and deformation of the case were measured using flexible sensors.
- Strain increases linearly with time due to the pressure building up.
- Strain ~0.07% corresponds to a pressure of dozens of atm.
- The process can be simulated using Faraday and gas laws.

DWG93026 470uF 75V Mfr.A RBS Failure

A part failed after 100 hr at 2 V RB due to lead fell-off caused by electrolyte leak**.**

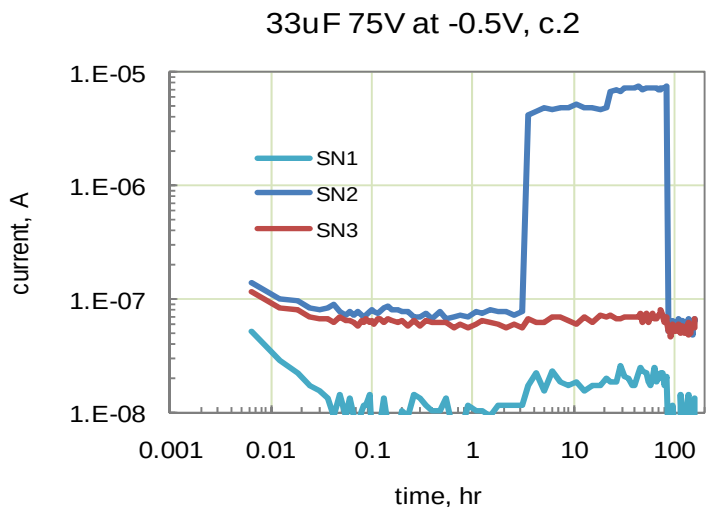


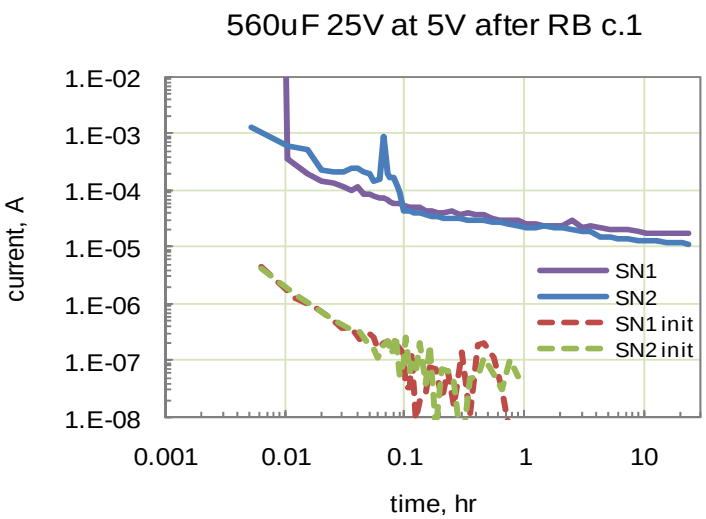


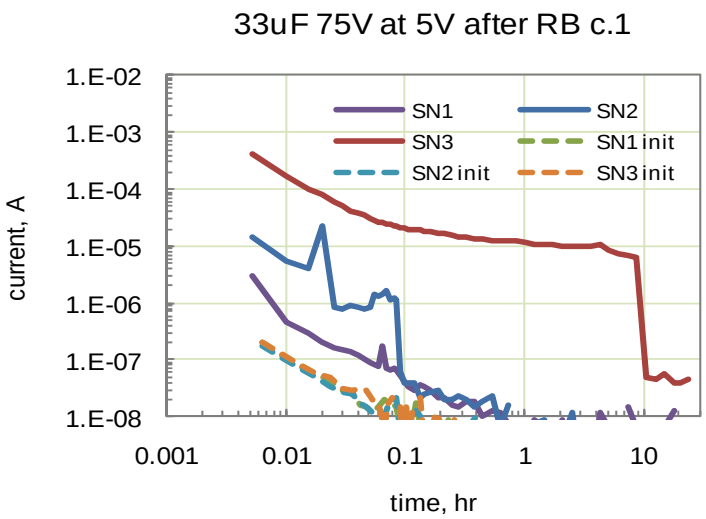
Pressure deforms the case, forces electrolyte above the Teflon bushing, and causes corrosion of the weld.

DWG93026 RB Failure. A History Case.

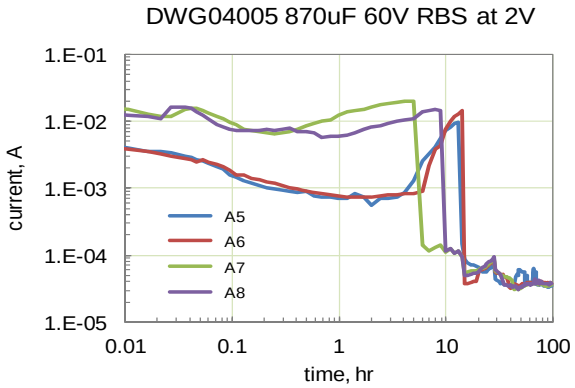
- Anomalies in one of the SC modules that due to unforeseen events had WTC operating for 1wk periodically at 0.5 V RB and 5 V FB.
- Testing showed substantial degradation of forward currents and increased probability of current spikes

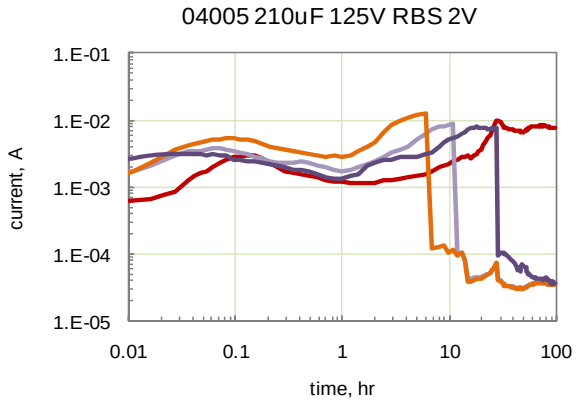


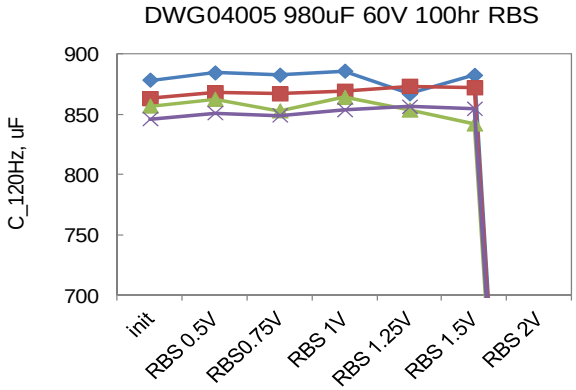


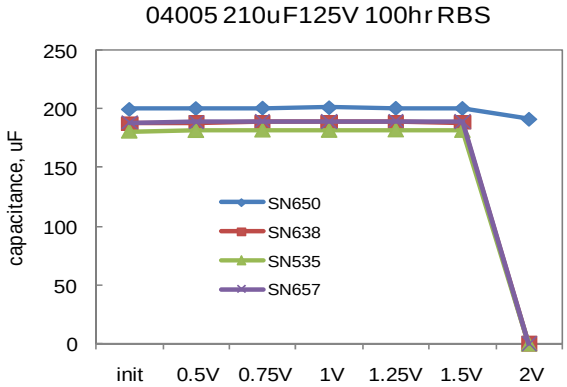


RBS in Button-Style Capacitors



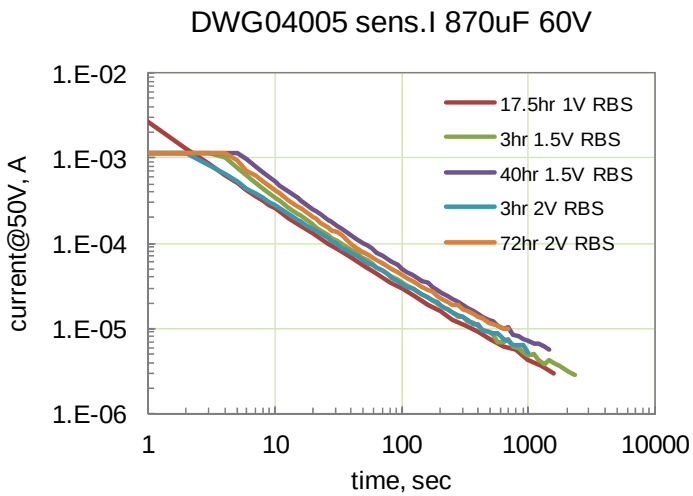


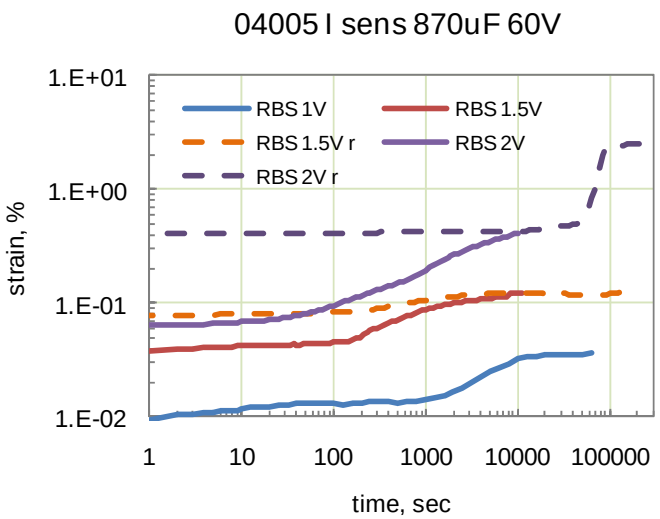


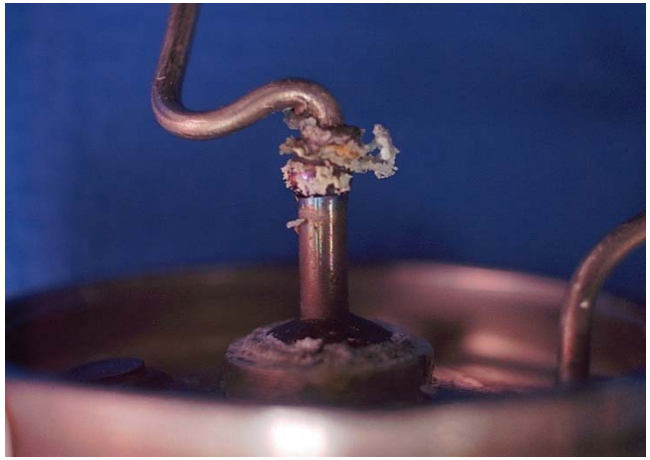


DWG04005 capacitors feature a sharp decrease in RB current with time and an open circuit failure mode.

Strain in DWG04005 980uF 60V, RBS

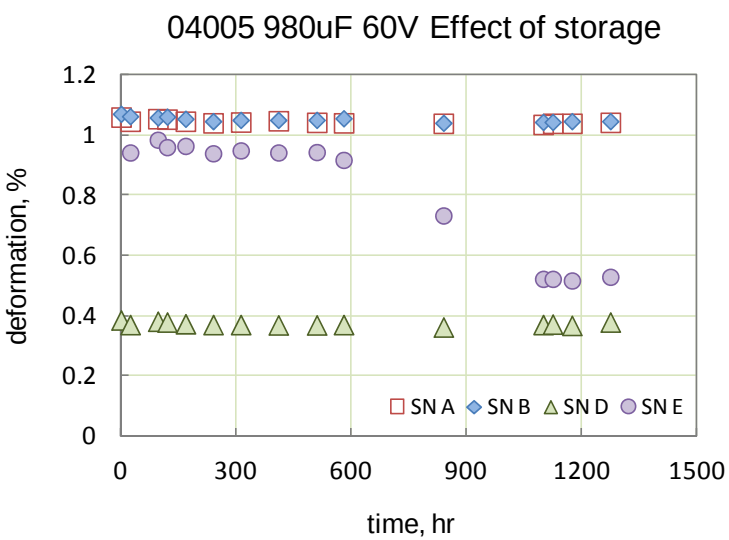






- Pressure starts building up after a few seconds at 1V.
- Pressure in the case remains when parts are unbiased and can cause electrolyte leak and corrosion.
- DCL did not degrade after 100hr at 2V RBS; whereas C and ESR fail.
- Strain ~3% corresponds to pressures up to 50 atm.

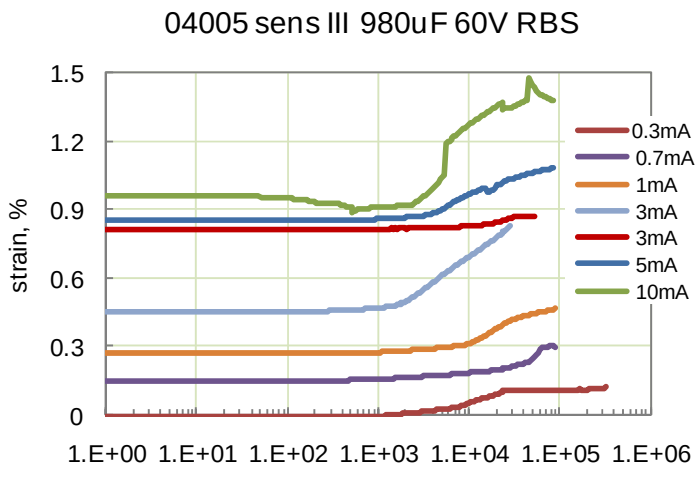
Strain in WTC during Storage

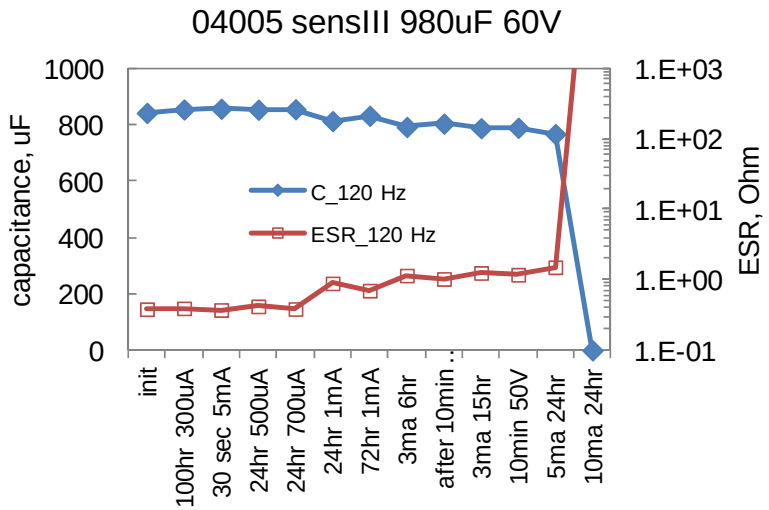


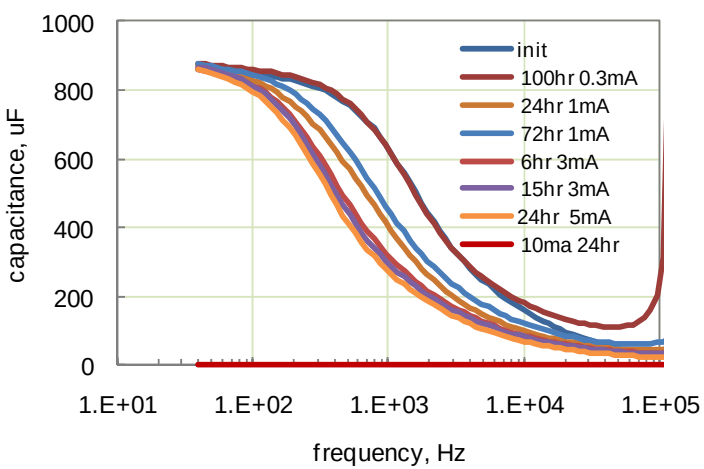
- Excessive pressure did not change substantially during 1500 hrs of storage in 3 out of 4 parts.
- Estimations show that the characteristic time of pressure relaxation is 1 to 6 years.
- Long-term hermeticity of capacitors operating under high internal gas pressure is critical to assure reliability of the parts.

- The robustness of the case can be verified by a high temperature storage life testing, HTSL. Testing at 150 °C 1000 hr, per JESD22-A103 Condition B, is recommended as a part of qualification testing for WTC.

Strain in DWG04005 980uF 60V at Constant Reverse Current

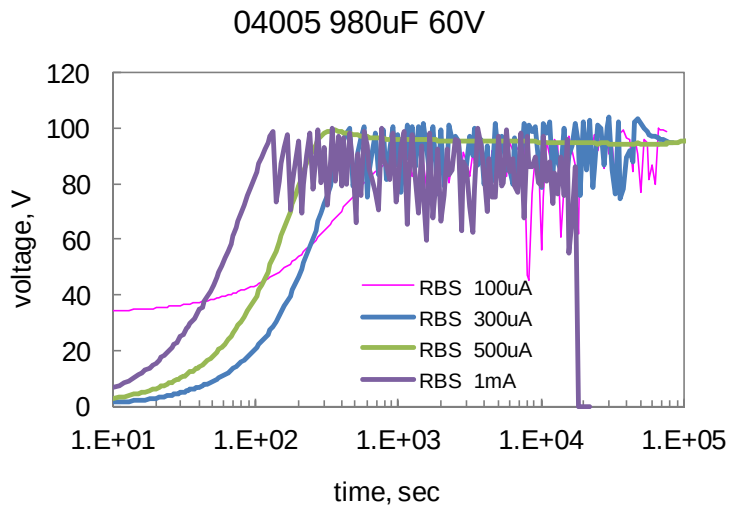


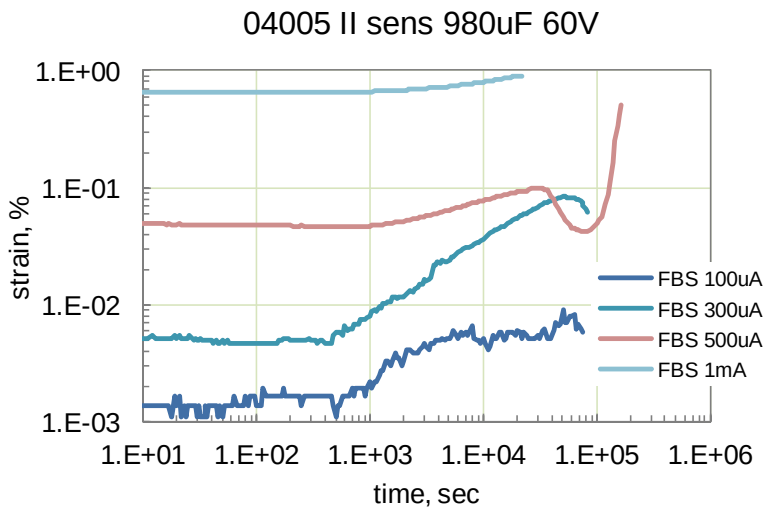




- Strain increases with each cycle.
- Stabilization of pressure with time at 0.3 mA is likely due to voltage drop below the threshold level, ~ 1 V.
- FB currents did not degrade substantially.
- Decrease of roll-off frequency with RBS is due to increase in ESR.
- A failure mode in all cases is open circuit.

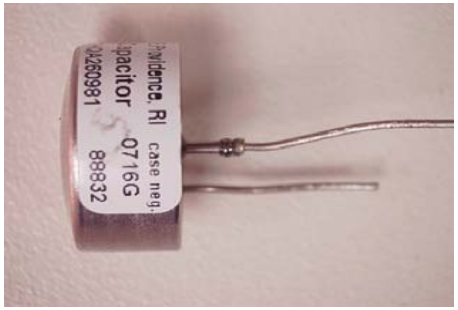
Strain in DWG04005 980uF 60V at Constant Forward Current

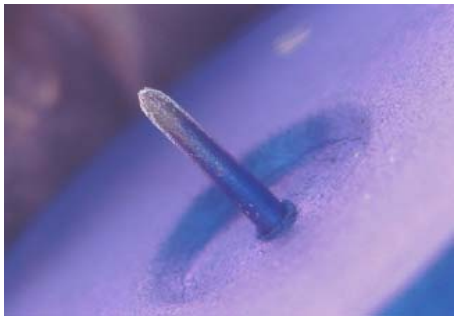


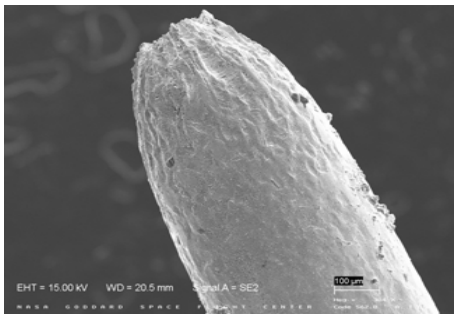


- To maintain constant breakdown current voltages were oscillating from 80V to 100V.
- Breakdown currents result in pressure build-up similar to reverse currents.

DWG04005 Failure Mechanism

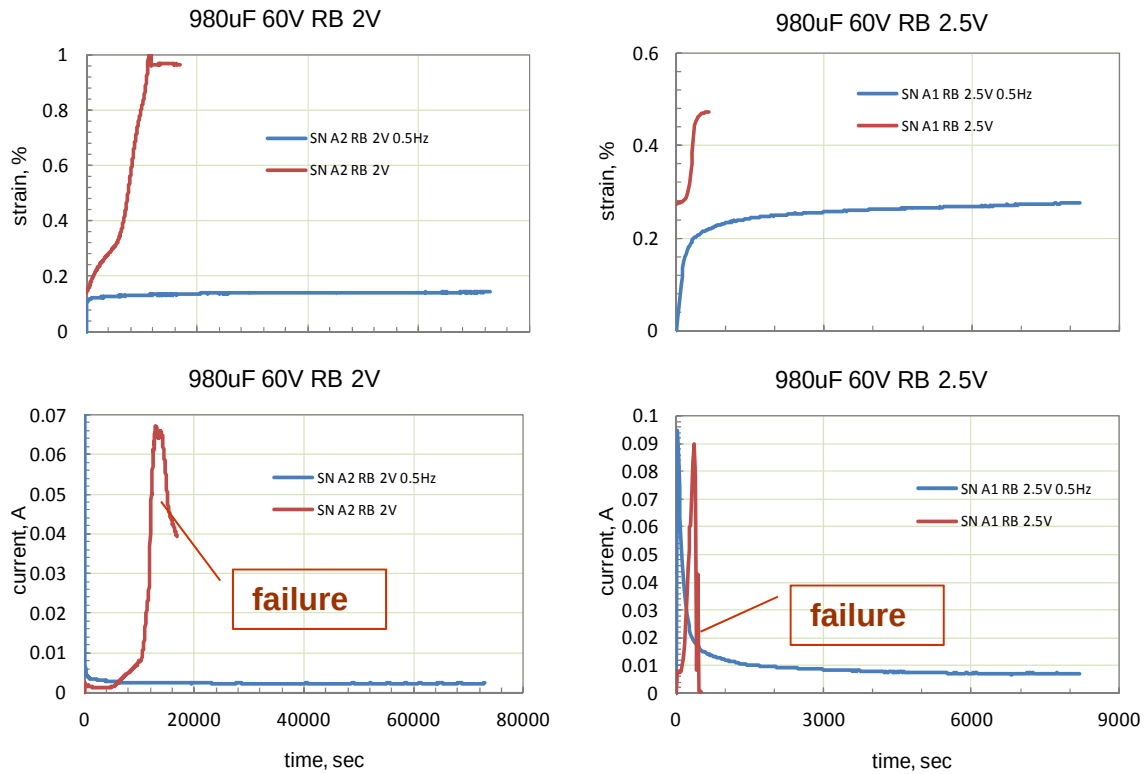






- Internal pressure causes bulging.
- Bulging strains the anode riser wire that fractures eventually. (max wire deformation is ~0.25 mm; deformation of a clamped 20 mil membrane at 50 atm is ~0.23 mm).
- The absence of a Teflon gasket facilitates electrolyte leakage.
- Wire fracture results in open circuit, and electrolyte leakage can cause corrosion of other elements on the board.

Operation at Steady-State and Pulsed RB

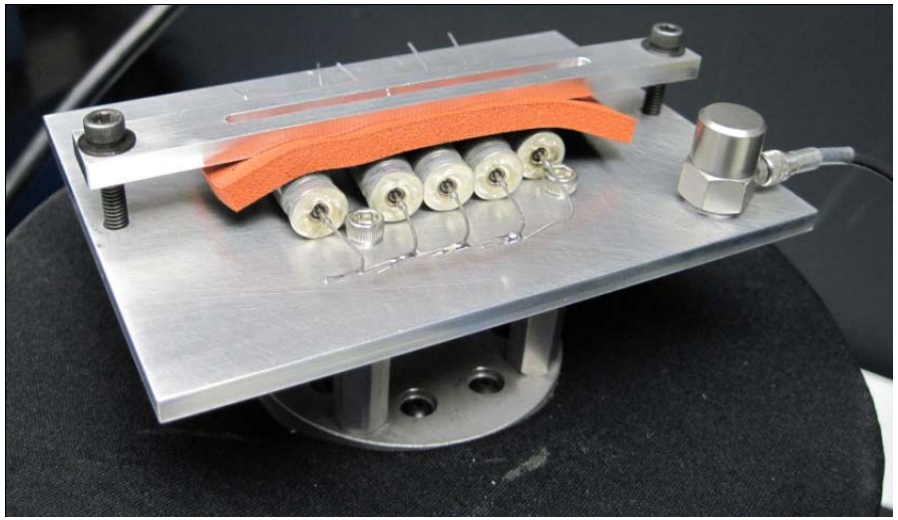


DWG04005 980uF 60V capacitors were tested at RB = 2V and 2.5V first at 0.5 Hz meander pulses (RB to 0V) till current and pressure stabilization, and then at a steady-state (SS) RB conditions till failure.

- Failures at constant voltage occur within a few min at 2.5V and a few hrs at 2V, but no failures for dozens of hours under RB pulses.
- RB currents are stabilizing under pulses at much lower levels.
- Transfer charge during pulsed testing can be greater than for SS.

Random Vibration Test

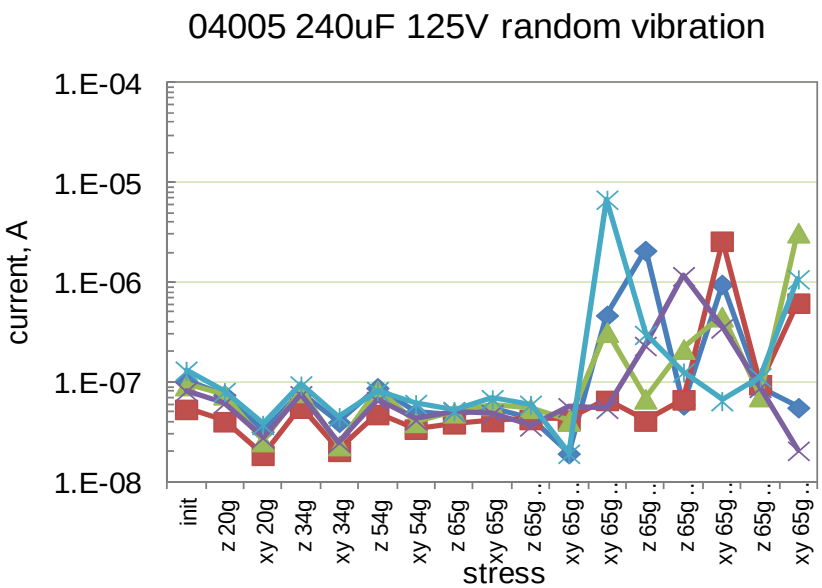
- Capacitors per DWG#93026 and #04005 are qualified to 20 g sin high frequency vibration only.
  - Sample size is not set (in some cases 2 samples only are tested).
  - Random vibration testing is not required and is performed only if specified by the purchase order.



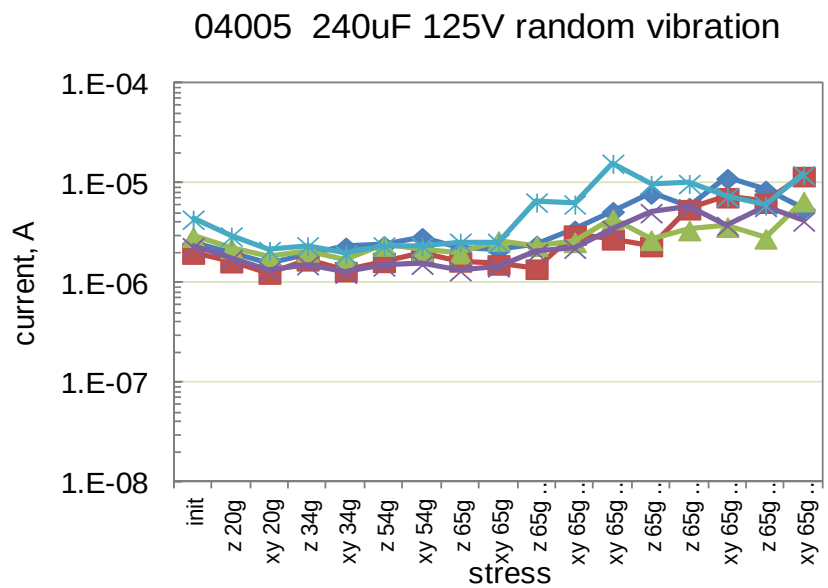
- Random vibration test is more appropriate for space applications than HF sinusoidal vibration, and MARs for most projects require box-level random vibration testing at 14.1 G_{rms}.
- Can WTC that are failing vibration test be used for space applications?

Post-Random-Vib-Test Measurements

DCL at 3 V

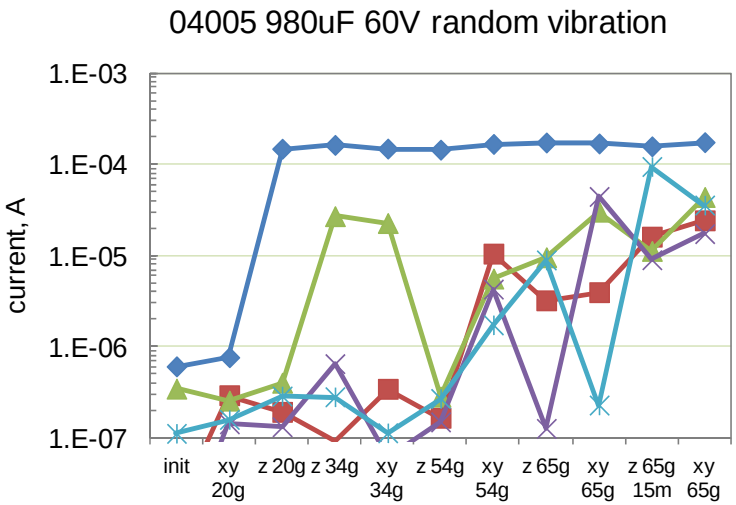


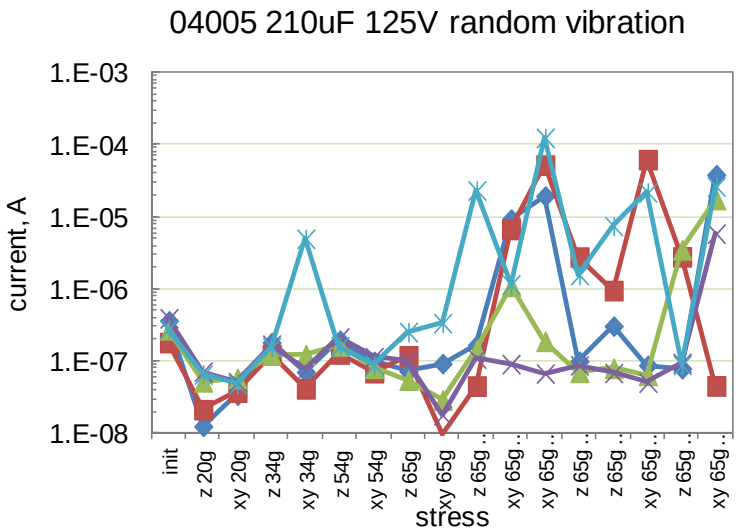
DCL at 125V

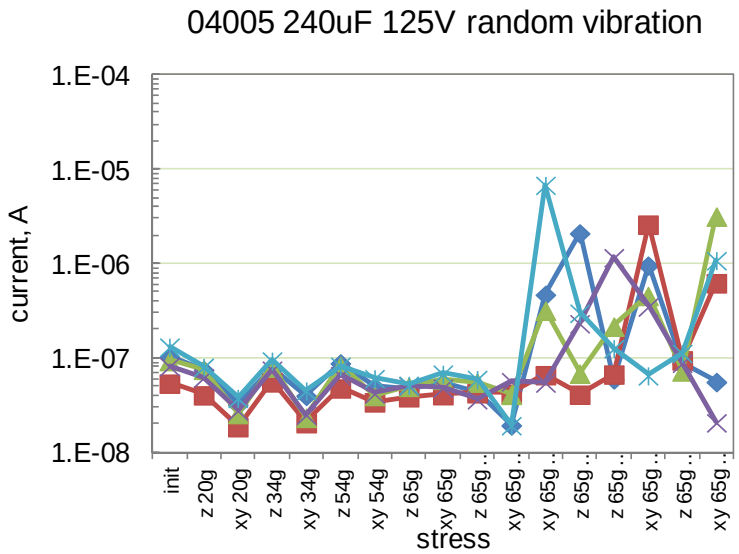


- DCL measurements at low voltages are more sensitive to damage caused by vibration.
- Absorption currents and self-healing are masking vibration-induced damage and degradation.

Susceptibility to Failures is Lot-Specific

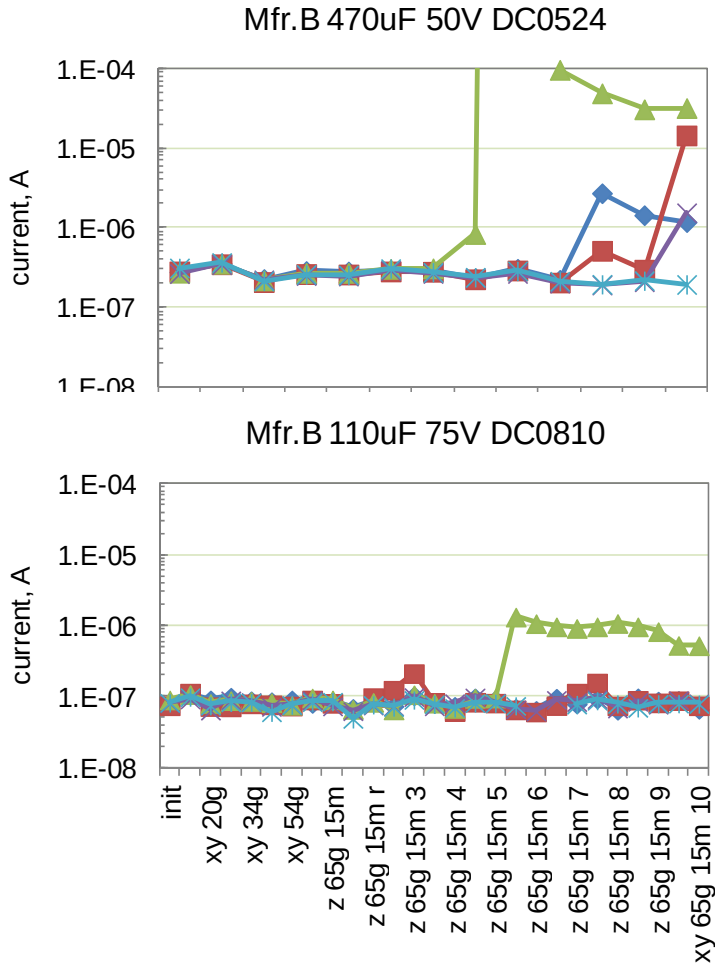


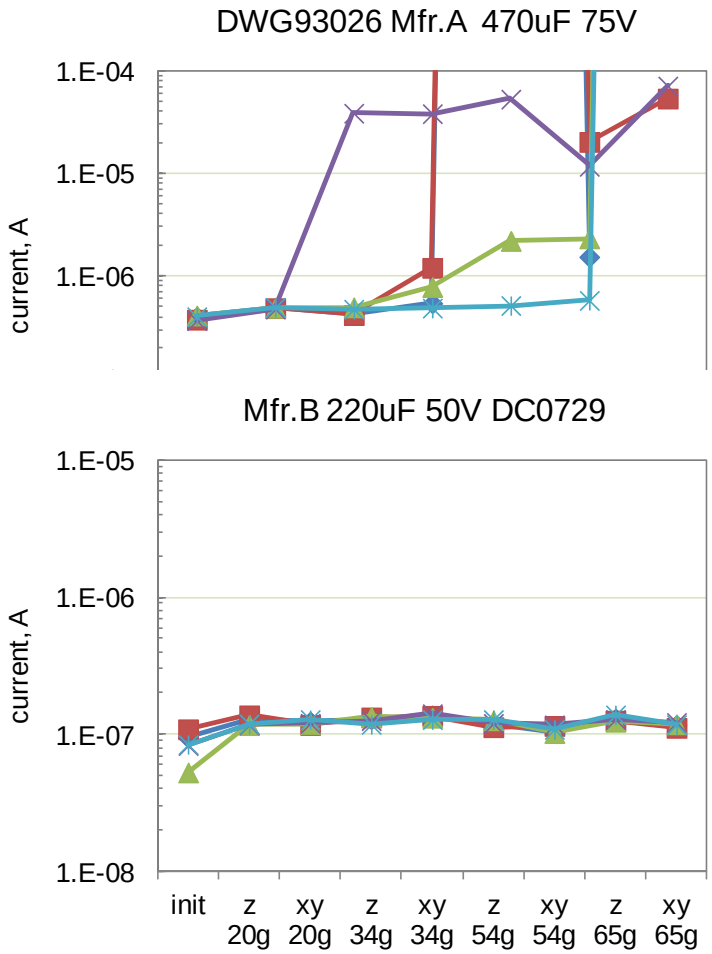




- 980 uF 60V parts have failures at 20 G_{rms}.
- 240uF 125V caps can withstand 54 G_{rms}.
- 210uF 125V caps had failures starting 34 G_{rms}.
- Parts might recover and pass repeat testing.

Random Vibration Step Stress Testing

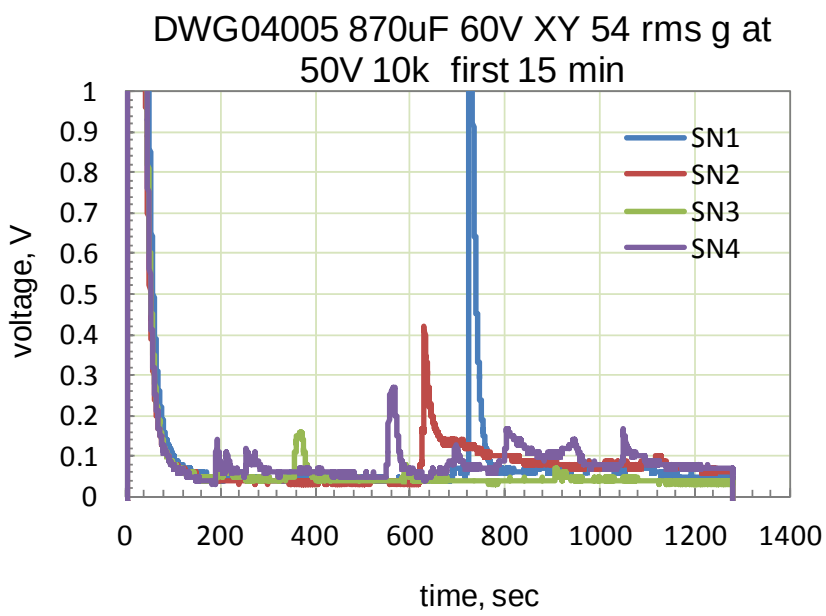


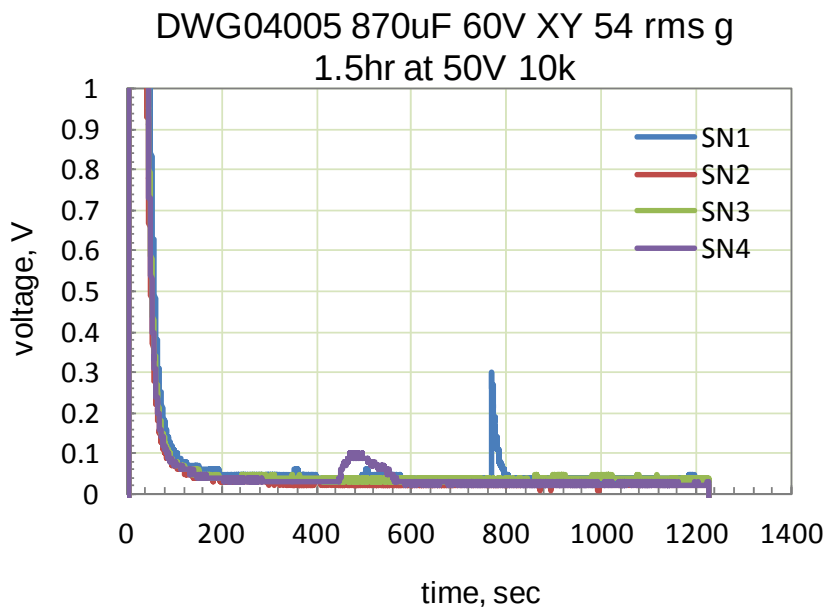


Different part types fail from 20 G_{rms} to more than 65 G_{rms}.

Effect of Test Duration

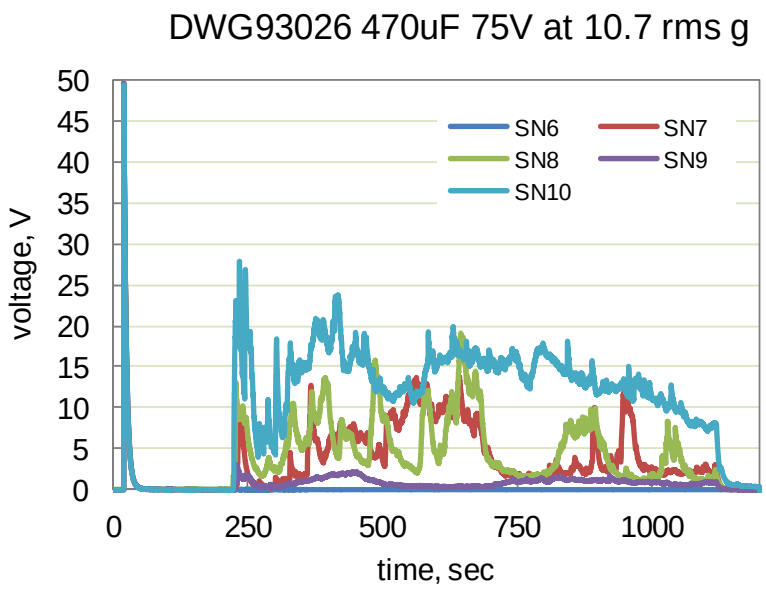
- Self-healing might occur during the testing, so after 1.5 hr of testing the level of noise can be less than initially.
- Testing at low voltages might be more effective and less risky.
- MIL-PRF-39006 does not specify bias conditions and failure criteria during vibration testing. Due to a large RC the required sampling frequency of 2 kHz is excessive.



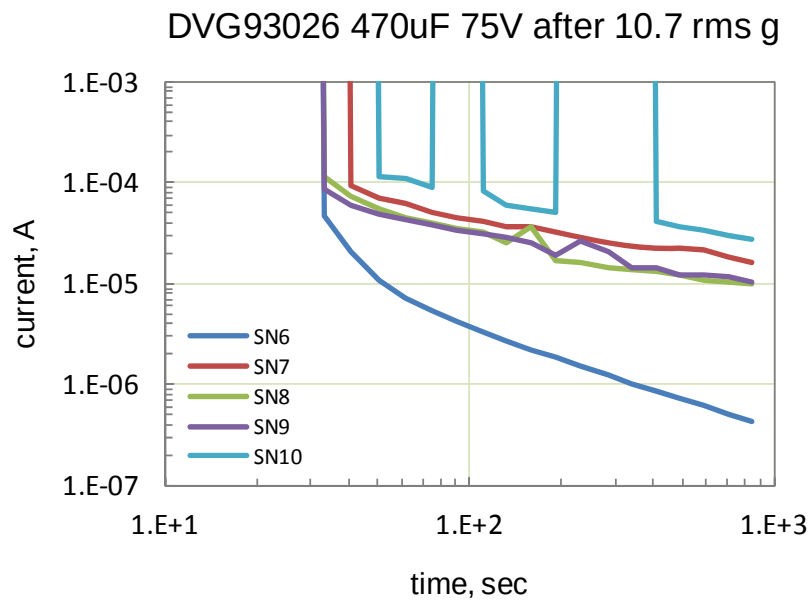


Failures DuringTesting at 10.7 G_{rms}

Current spiking during 15 min vib. testing



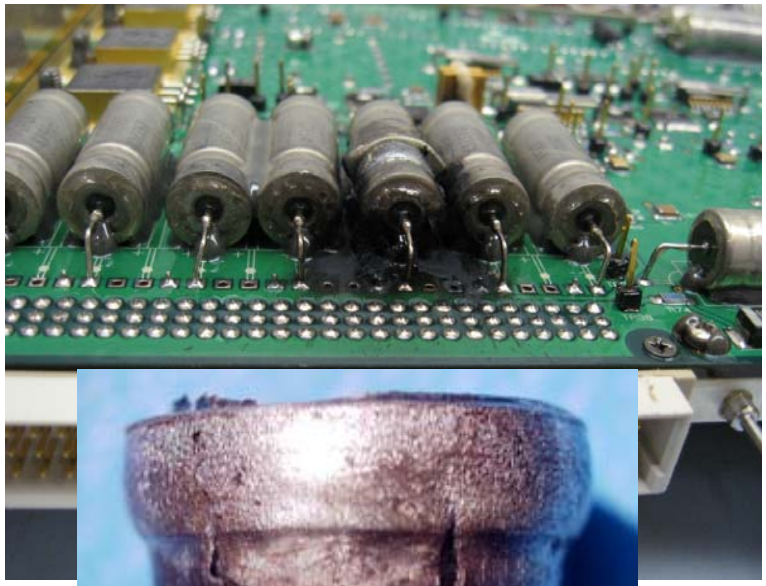
Excessive currents and spiking during post test DCL measurements

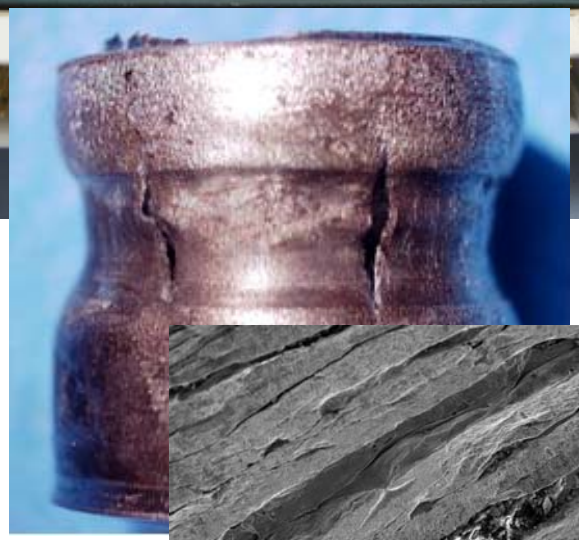


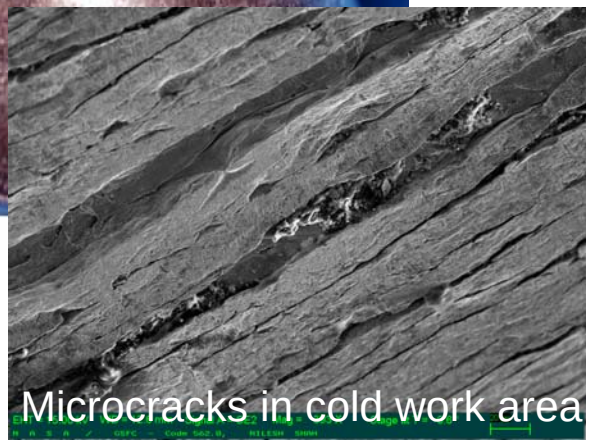
Some DWG#93026 parts can fail at vibration levels that are below typical MAR requirements.

A History Case

- Several anomalies have been observed during thermal vacuum testing. However, at the end of the testing the unit operated normally.
- Post-testing internal examinations revealed damaged sleeve, discoloration and charring of conformal coating around one of the WTCs.
- The cracks were due to stresses caused by the building-up of gas pressure in the case and hydrogen embrittlement of tantalum at cold work areas.



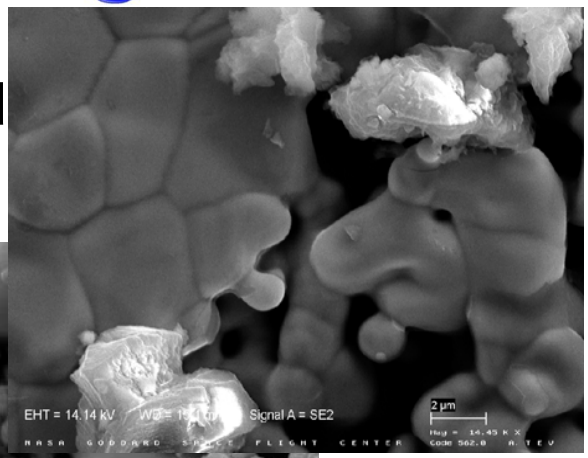


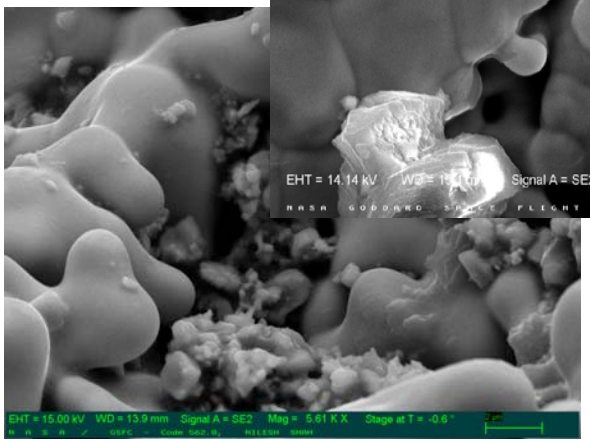


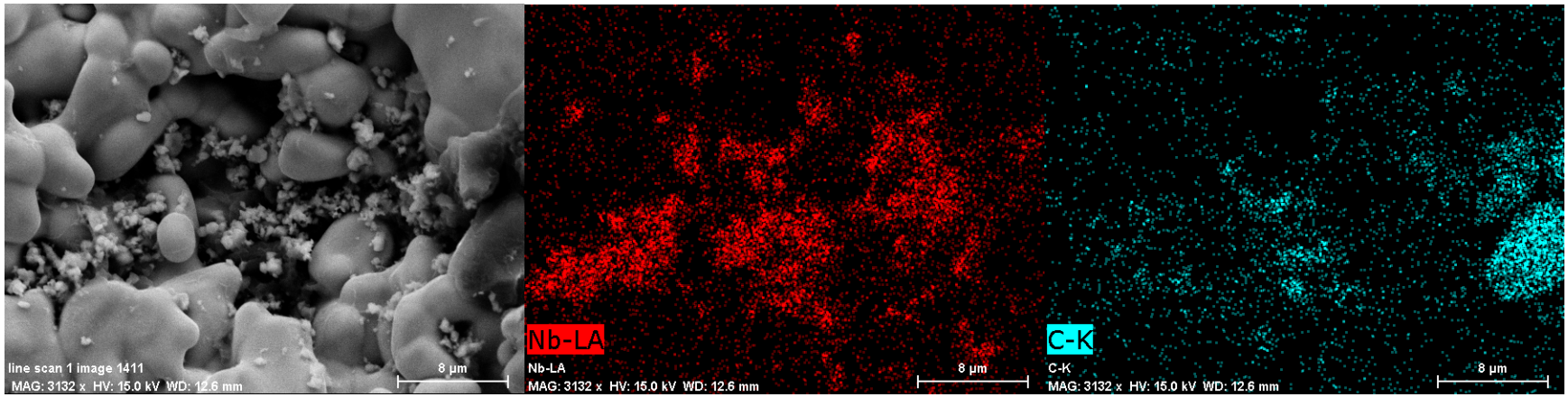
Microcracks in cold work area

Particles in the Slug

- Failures during vibration were likely caused by NbO and carbon particles penetrating inside the slug.
- Under mechanical testing wedged particles might create local stresses sufficient to cause damage to the dielectric and increase leakage current.







Conclusion

- Capacitors manufactured to DWG#93026 and #04005 might fail after exposure to low-voltage (0.5 V and less) reverse bias conditions and random vibration as low as 10.7 $G_{rms.}$
- Both, RB and vibration can result in increased leakage currents, internal gas pressure, case fractures, electrolyte leak, and corrosion.
- WTC can sustain a much greater transfer charge under reverse bias pulses compared to steady-state conditions.
- Parts with Pd-based cathode appeared to be more sensitive to RB, whereas parts with NbO-based cathode are more sensitive to vibration.
- Manufacturers are working on new designs to improve reliability.
- Advance WTCs are resilient to environmental stresses, but not to the degree of M39006 capacitors. They might operate reliably provided the robustness against mechanical stress (random vibration at 20 G_{rms}) and reverse bias (to 1.5V at 85C) are verified.
- Test conditions and failure criteria for vibration testing need refining.
- Guidelines for selection, screening and qualification of advanced WTC have been developed.