Reliability Issues with Polymer and MnO2 Tantalum Capacitors for Space Applications

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List of Acronyms

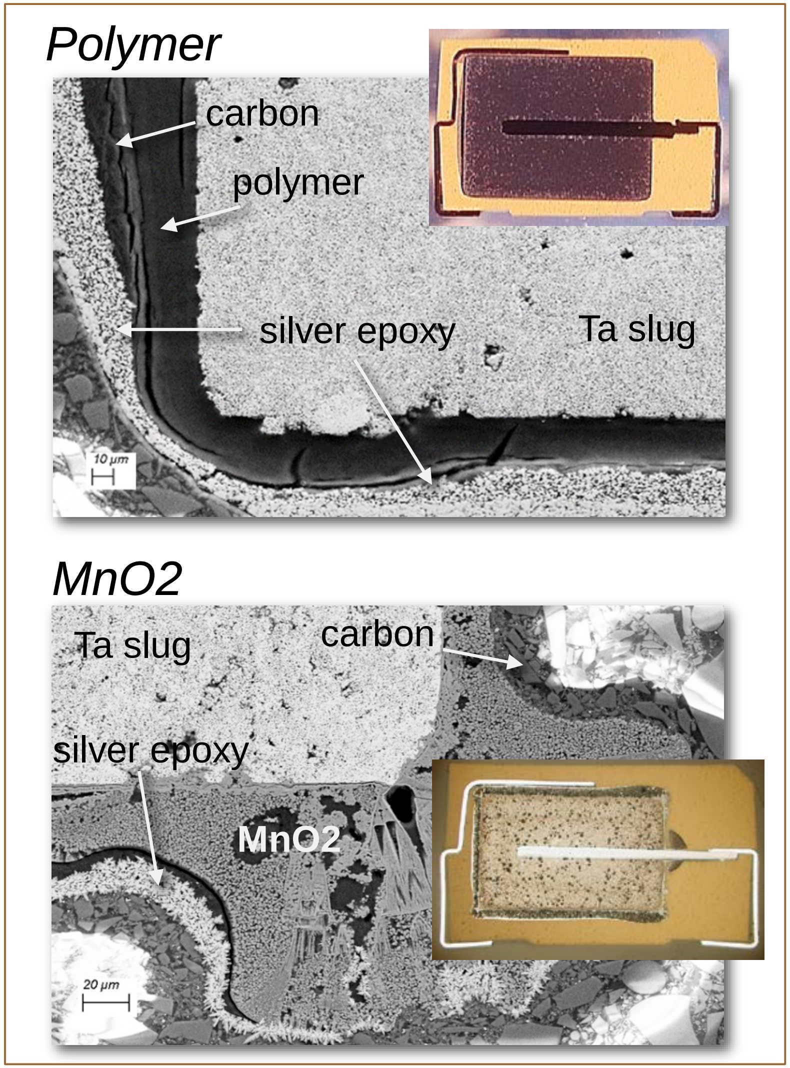
AC	alternating current	FR	failure rate
AF	accelerating facor	HTS	high temperature storage
AT	anomalous transients	LT	life test
C	capacitance	MSL	moisture sensitivity level
CCS	constant current stress	PEDOT: PSS	Poly(3,4-ethylenedioxythiophene)-poly(styrenesulfonate)
CPTC	chip polymer tantalum capacitor	S&Q	screening and qualification
DC	direct current	SCT	surge current stress
DCL	direct current leakage	T	temperature
DF	dissipation factor	TS	thermal shock
ER	established reliability	VBR	voltage breakdown
ESR	Equivalent series resistance	VR	voltage rating

Abstract

This work gives a comparative analysis of degradation processes, failure modes and mechanisms in MnO_2 and polymer technology capacitors. Analyzed conditions include effects of vacuum and radiation, soldering (pop-corning), long-term storage and operation at high temperatures, stability at low and high temperatures, and anomalous transients. Screening and qualification procedures to assure space-grade quality of CPTCs are suggested.

Outline

- Effect of moisture.
- Effect of soldering.
- Effect of vacuum.
- Stability at low and high temp.
- Effect of storage at high temp.
- Life testing.
- Scintillation breakdown.
- Anomalous transients.
- Quality assurance for space applications.
- Summary.



Capacitors have similar design but differ in cathode materials

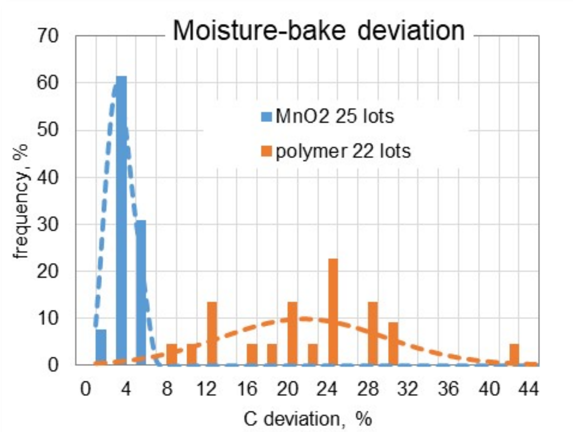
Advantages and Disadvantages of CPTCs for Space Applications

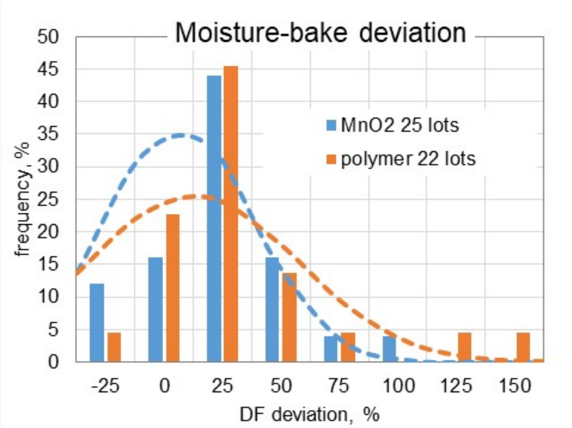
- Advantages:
  - Better volumetric efficiency (smaller case sizes);
  - Higher operating voltages (up to 125V);
  - Lower ESR (milliohm range);
  - A relatively safe failure mode (no ignition);
  - Radiation hardness is similar to MnO2 parts (up to 5 Mrad Si).
- Disadvantages:
  - Variety of materials and processes for cathode formation;
  - Desorption of moisture in vacuum can be a benefit or a hazard;
  - S&Q system developed for MnO2 capacitors is not sufficient due to new failure and degradation mechanisms;
  - Intrinsic ESR degradation processes at high temperatures;
  - A new phenomena: anomalous transients.

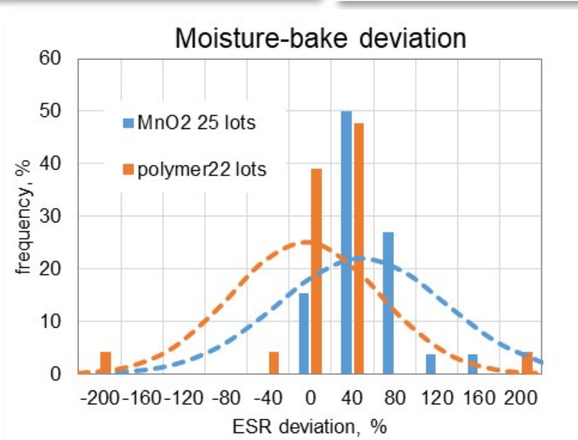
Breakdown failures in MnO2 and CPTC

Effect of Moisture

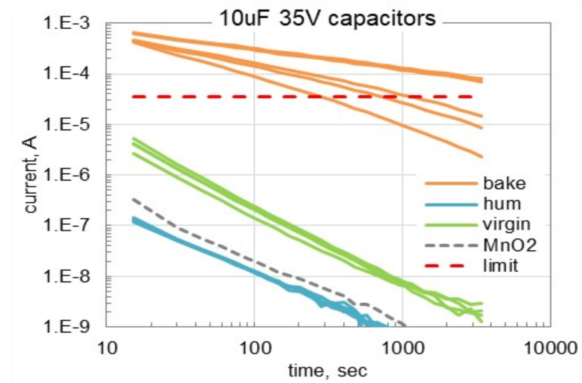
Distributions of deviations (wet-dry) of AC characteristics

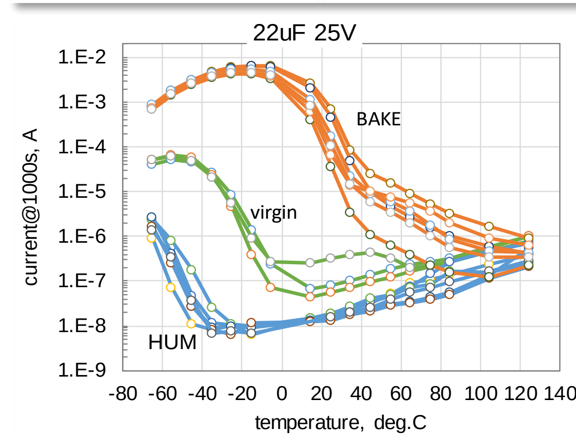






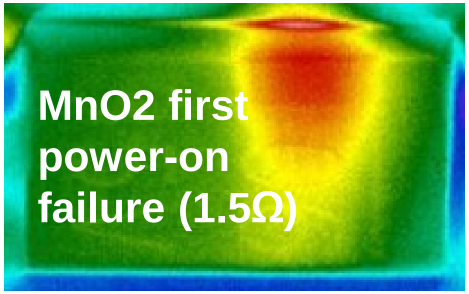
Leakage currents





- ✓ CPTCs are more sensitive to moisture compared to MnO2 caps.
- ✓ Capacitance variations can reach 40% and DCL >10^4 times.

Failures after Soldering



- Pop-corning due to the presence of moisture increases delamination, introduces cracks in package and might cause damage to Ta2O5.
- Cracks in packages facilitate penetration of oxygen that increases the rate of ESR degradation in CPTCs.
- Damage to dielectric causes first power-on failures in MnO_2 capacitors. The effect has not been observed yet in CPTCs.

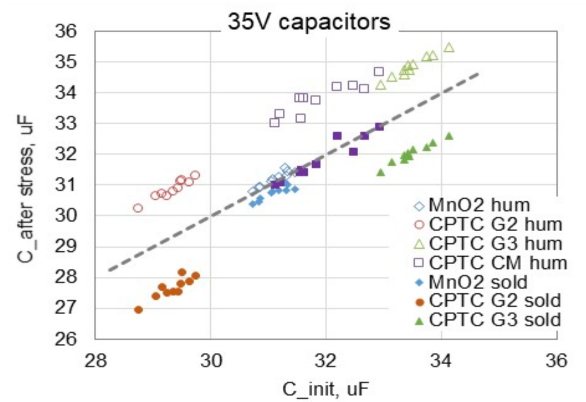
Test	CWR29, 10uF 35V		
	as is	Bake	Moisture
AC testing	0/20	0/20	0/20
SCT at 15V	2/20	0/20	9/20
SCT at 35V	1/18	0/20	8/11

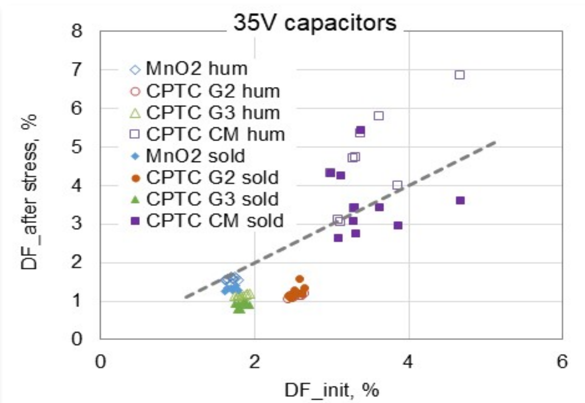
- ✓ Damage caused by soldering is lot-related.
- ✓ Pop-corning issues can be resolved by baking.
- ✓ Requirements for MSL testing should include measurements of ESR and surge current testing.

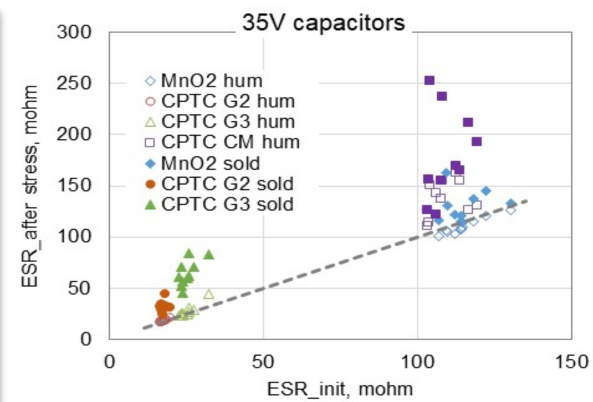
Effect of Soldering on Characteristics

Variations of capacitance in 35V capacitors during MSL1 testing

	MnO2 G1	Polym G2	Polym G3	Polym GM	Polym A1	Polym A2	Polym AQ
$\Delta C_{sold}/C_{init}$, %	1.4	10.9	8.4	6.2	13.1	18.8	8.3
$\Delta C_{max}/C_{init}$,%	2.3	11.8	9.8	6.9	21.5	26	16.6
$\Delta C_{sold}/\Delta C_{max}$, %	63	93	86	89	61	72	50



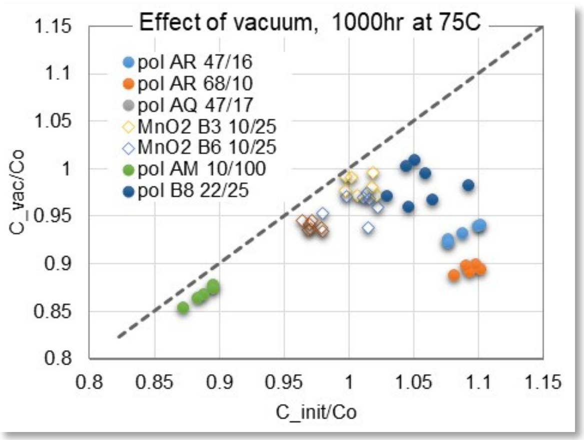


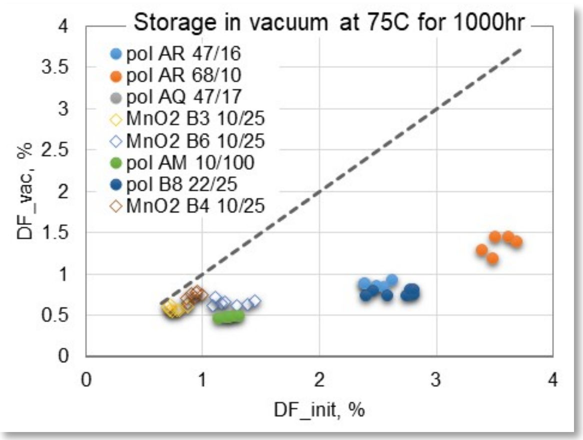


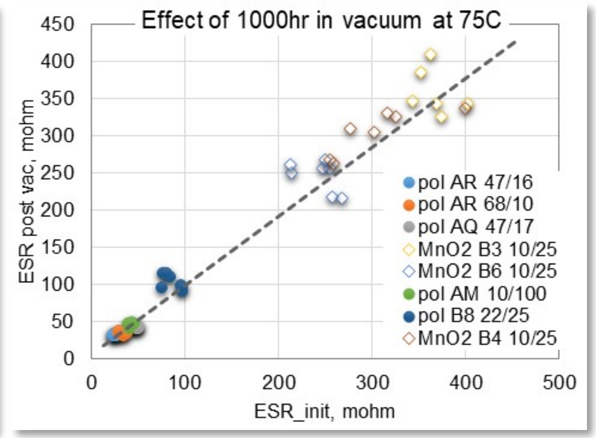
- ✓ Soldering results in drying off capacitors by 50 to 93%.
- ✓ Decrease of C in CPTCs is greater than in MnO2 capacitors.
- ✓ Soldering increases ESR in most types of capacitors, but the level of variations is lot-related.

Effect of Vacuum

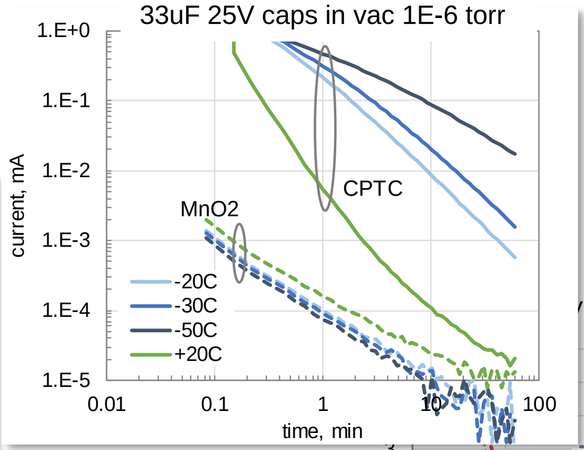
Variations of C, DF, and ESR after 1000hr at 75C, 1E-6 torr



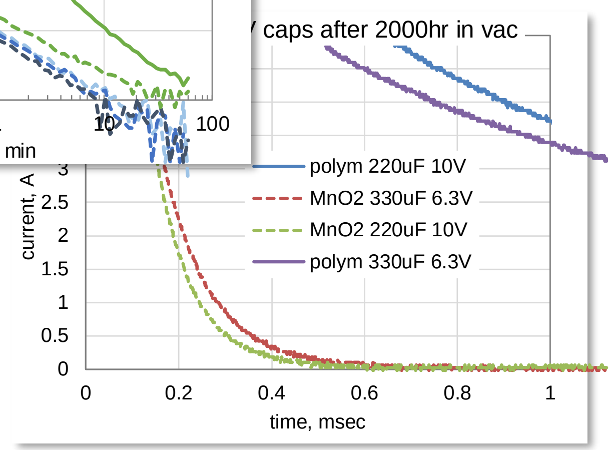




Relaxation of leakage currents



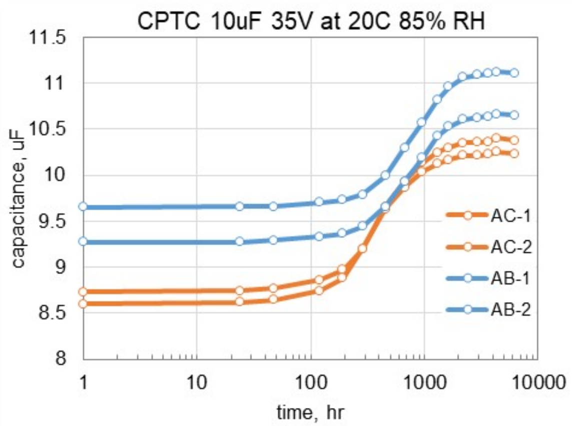
Surge current test

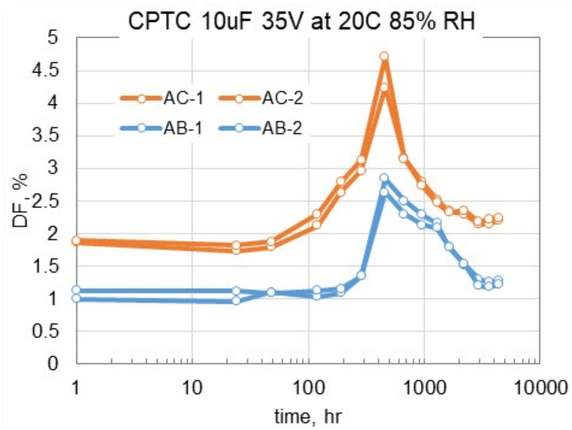


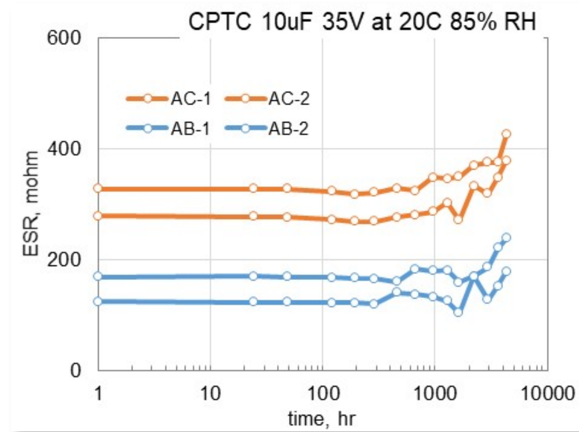
Drying in vacuum has a similar effect as drying in air:

- Decreasing of capacitance and DF;
- A relatively small changes in ESR;
- Variations of C and DF with V;
- Increasing of transient leakage currents, especially at low T.

Variations of AC Characteristics with in Time after Vacuum

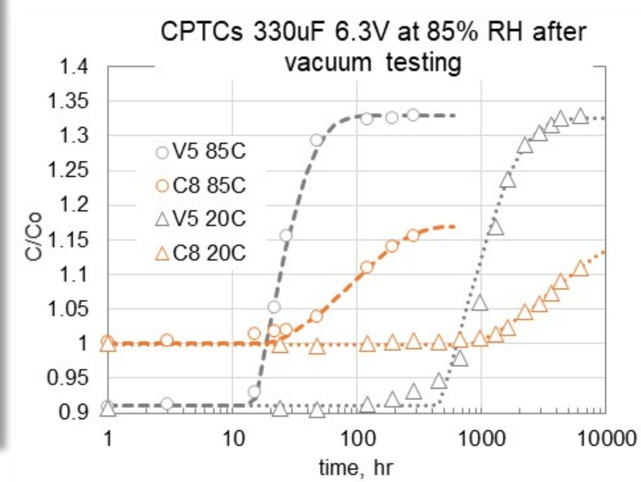






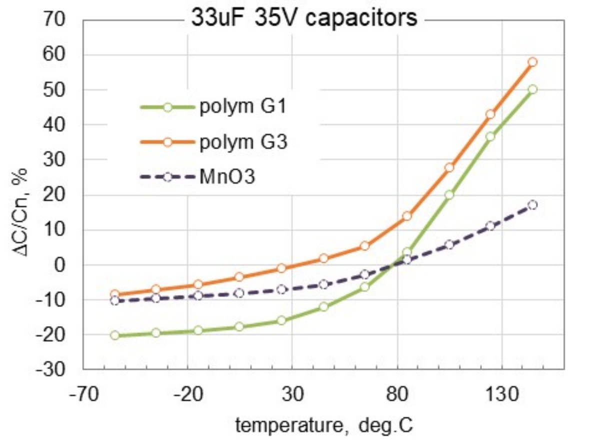
- Tantalum pellet can be used as a moisture sensor.
- Moisture sorption after vacuum testing results in extremal variations of DF.
- CPTCs remain dry and can be tested after vacuum for hundreds of hours at room conditions.

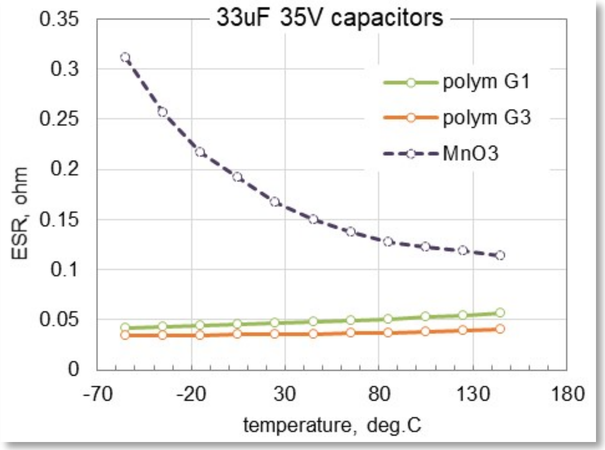
$$\frac{\Delta m}{\Delta m_{max}} = \frac{\Delta C}{\Delta C_{max}}$$



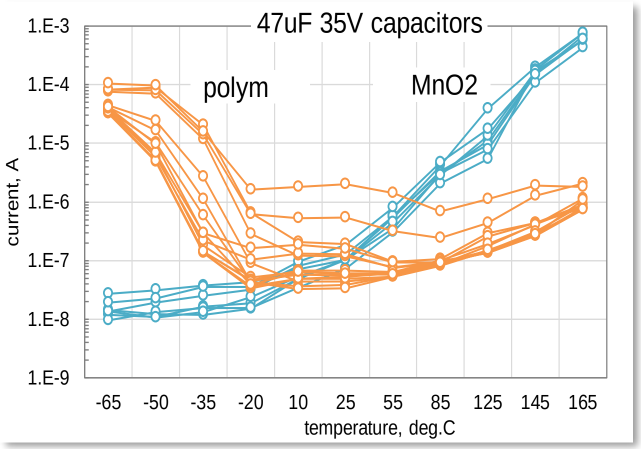
Stability of Characteristics at Low and High Temperatures

Variations of C and ESR with temperature





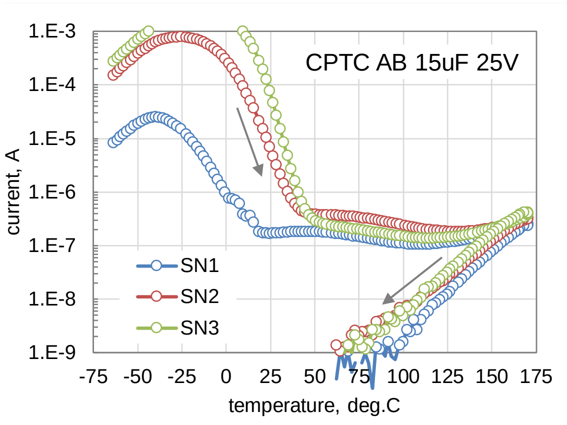
Variations of DCL with T

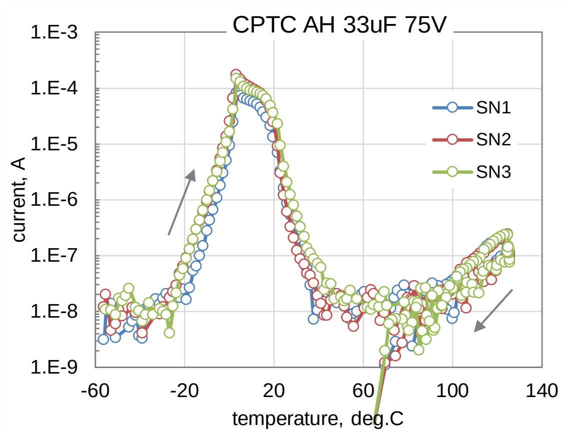


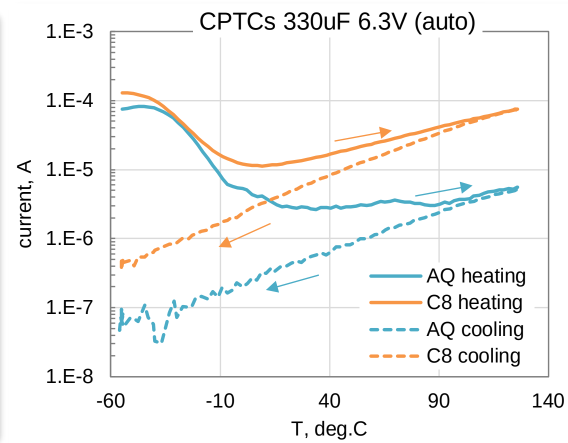
- ✓Capacitance in CPTCs increases with T to a greater degree than in MnO2, but ESR is much more stable.
- ✓CPTCs might be used for cryogenic applications.
- ✓Contrary to MnO2, DCL in CPTCs increases at low T and might exceed DCL_{max}.

Hysteresis of Leakage Currents during Temperature Variations

Leakage currents were measured in the process of heating and cooling at a rate 3 K/min without voltage interruptions



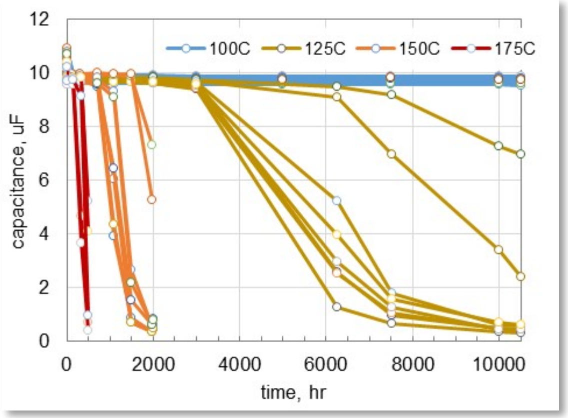


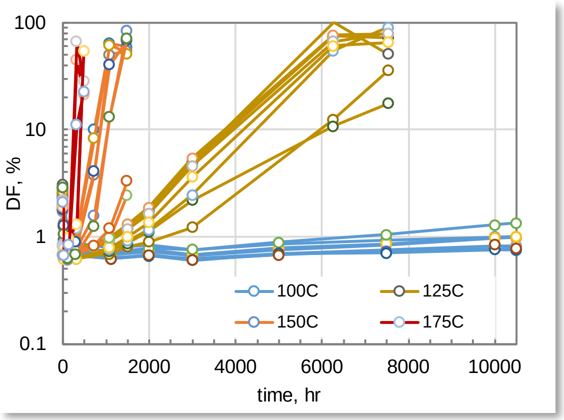


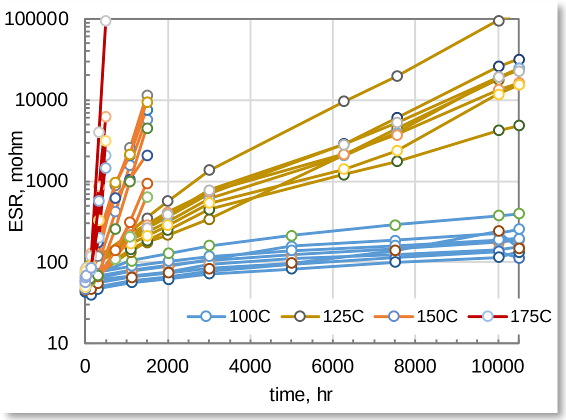
- ✓ Extremal variations of leakage currents in the process of heating.
- ✓ Maximum currents can be reached at temperatures from -65 ºC to 0 ºC and exceed the specified limit.
- ✓ Hysteresis can exceed 6 orders of magnitude and is one of manifestations of anomalous transients.

Effect of Ageing on AC Characteristics

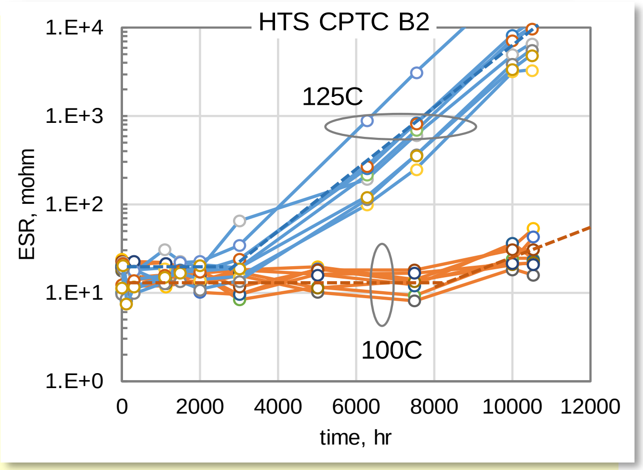
Degradation of C, DF, and ESR during HTS at 100, 125, 150, and 175 ºC for 10uF 25V CPTC





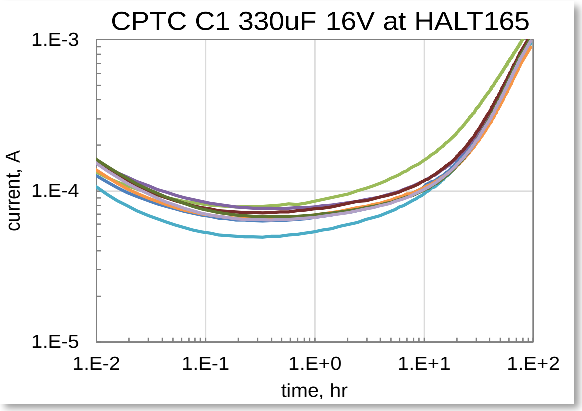


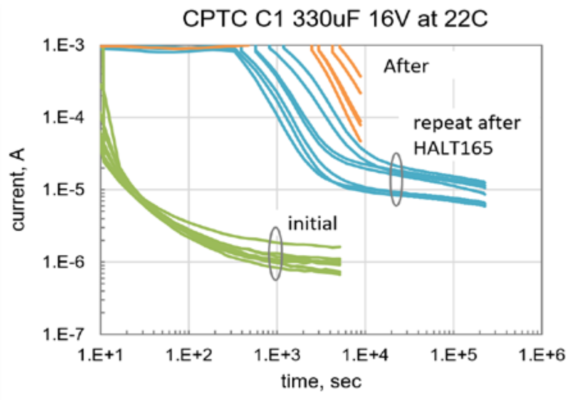
- ✓ Contrary to MnO_2, PEDOT:PSS is degrading with time of exposure to high T due to thermo-oxidative processes.
- ✓ ESR increases with time after a certain incubation period exponentially.
- ✓ Data in air: E_a = 0.62 eV ±0.17eV.
- ✓ In vacuum E_a *~2 eV*, so successful testing at 125 ºC for 1000hr might guarantee long-term stability of ESR in space.



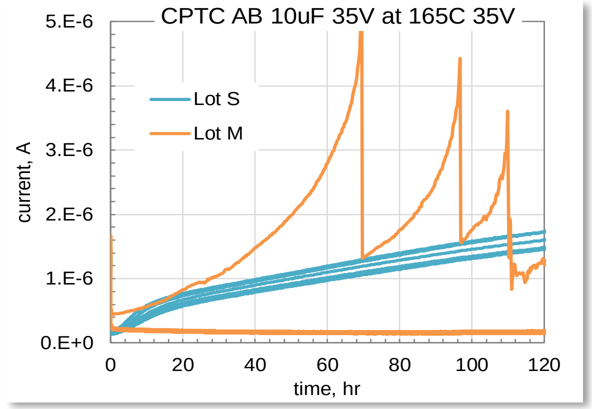
Life Testing

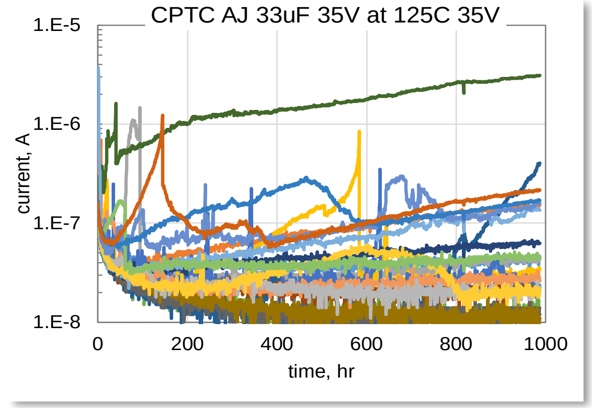
- Monitored 1000 hr life testing at VR:
  - 11 lots at 85C and 125C, 10 to 20 pcs in a group.
- Monitored step stress life testing at VR:
  - 12 lots consequently at 85, 105, 125, 145, and 165C.
  - 200hr steps, 10 to 20 pcs in a group.





Spiking of leakage currents

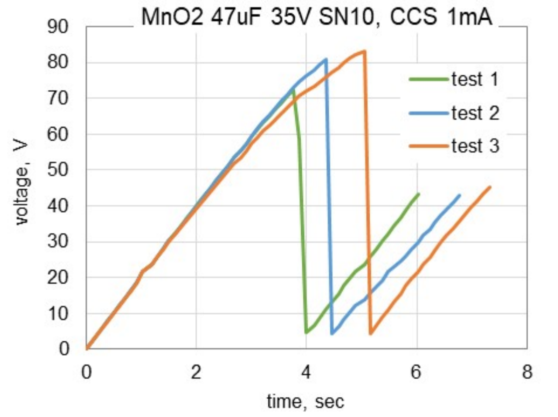


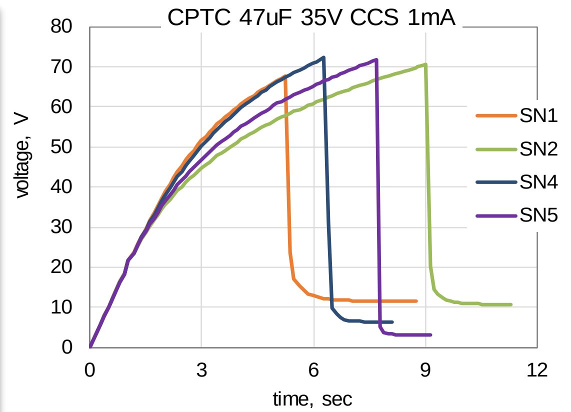


- ✓ No catastrophic failures during life testing and SSLT in 23 lots.
- ✓ Post-LT DCL exceeding the limit can be misjudged as LT failures.
- ✓ CPTCs can operate reliably at high T at steady-state conditions.
- ✓ Increasing of leakage currents with time is similar to MnO_2 caps.
- ✓ Erratic behavior of currents in some samples/lots.

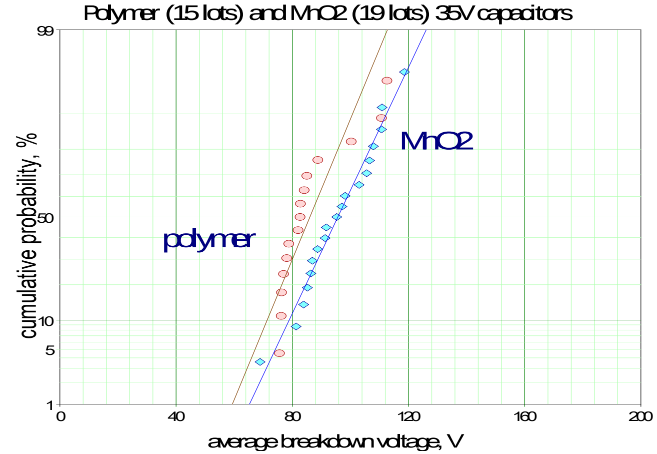
Scintillation Breakdowns

Typical results of CCS testing

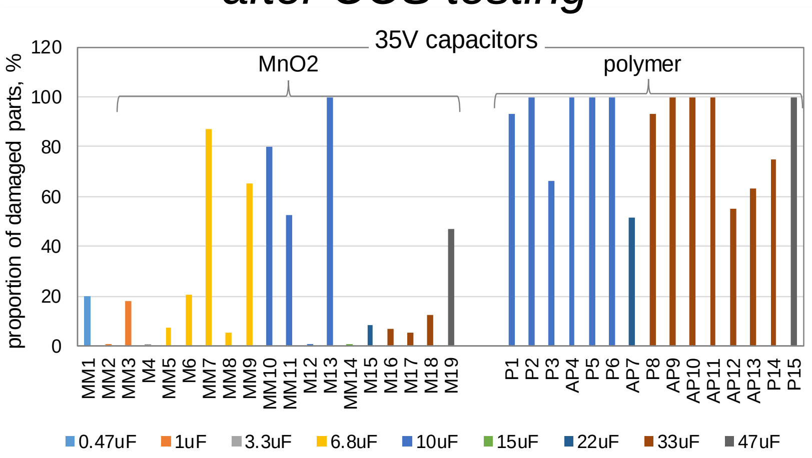




Distributions of VBR in different lots of 35V capacitors



Proportions of damaged capacitors after CCS testing

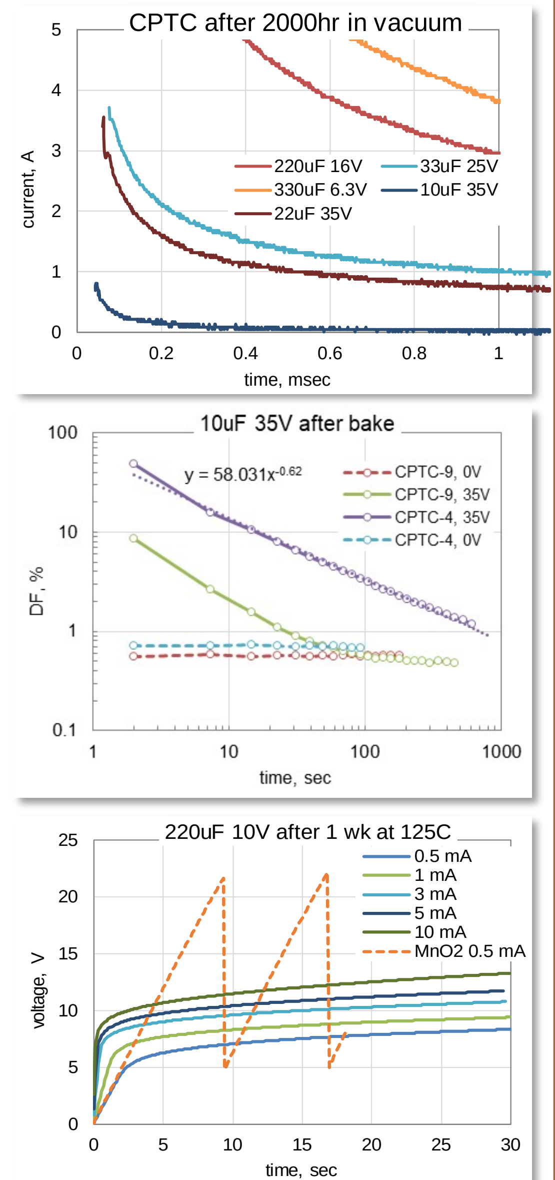


- ✓ Self-healing is less effective in CPTCs than in MnO2 capacitors.
- ✓ Breakdown voltages in the same ratings of MnO2 and polymer capacitors are similar.
- ✓ Mechanism of self-healing requires additional analysis.

Anomalous Transients

- AT are caused by increased conductivity of Ta2O5 in discharged polymer capacitors.
- AT is more significant in dry CPTCs and at low temperatures.
- The conductivity gradually (hours) decreases with time under bias.
- The phenomena manifests as:
  - Increased 10x DCL limits compared to MnO2 capacitors;
  - Parametric SCT failures;
  - Variations of C and DF with voltage and time under bias;
  - Increasing leakage currents at low T;
  - Anomalous charging currents (ACC);
  - Failures during power cycling.

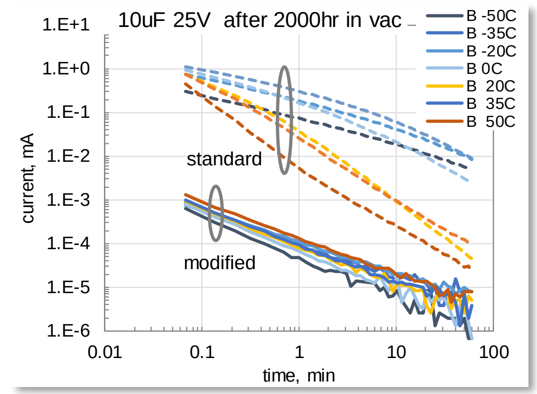
Examples of AT



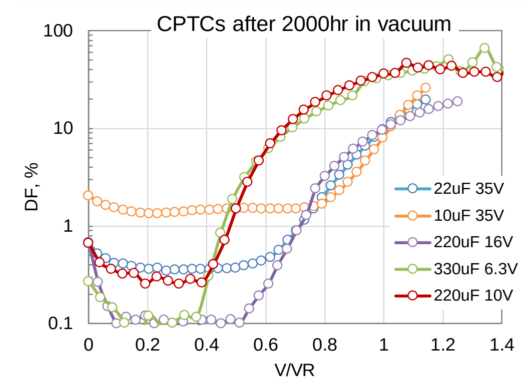
Mitigation of AT and Derating Requirements

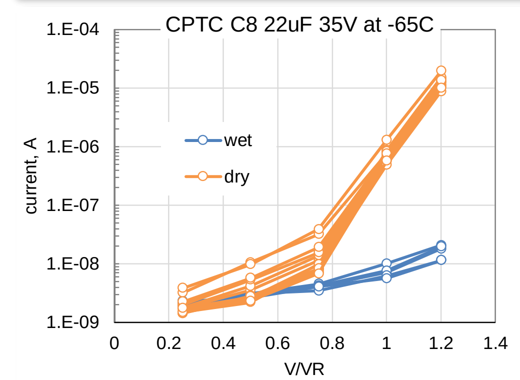
- Effects related to AT can be mitigated by:
  - Modification of polymer materials.
    - might result in increasing of ESR.
  - Using special S&Q procedures.
    - e.g. testing after bake for SCT, DCL at low T, *C-V* and *DF-V*, power cycling, etc.
  - Analysis of application conditions.
    - operations at low T, especially cold start-ups.
  - Voltage derating to 30 - 50% of VR.
- Due to thermo-oxidative degradation in CPTCs, T_{max} should be limited to 100 ºC.

Effect of polymer modification



Effect of voltage





Recommendations for S&Q

- General
  - CPTCs should be preconditioned before qualification testing.
  - Life testing, HTS, and TS should be carried out using capacitors soldered per specified MSL.
  - Testing for FR is not necessary for the following reasons:
    - Field failures rarely happen at life test conditions;
    - Uncertainty in AFs creates orders of magnitude errors in FR;
    - Due to derating, actual FRs are orders of magnitude below mission requirements;
    - Good experience with using microcircuits that are typically non-ER components.
- Screening (Gr.A) should include:
  - Surge current testing. The existing MIL-PRF-55365 requirements limiting maximum current after 1 msec can be used for CPTCs.
  - Burning-in at 105 ºC 1.1VR for 40 hours.

Recommendations for S&Q, Cont'd

- LAT (or gr. B qualification test) should include:
  - Life testing at 105 ºC, 1.1VR for 1000 hr.
  - High temperature storage test, 1000 hr at 125 ºC.
  - Thermal shock, 100 cycles between -55 and +125 ºC.
  - Testing after baking at 125 ºC for 168 hours:
    - Surge current test at -55 ºC, 25 ºC, and +85 ºC.
    - Stability at low and high temperatures (including DCL at low temperatures).
    - Power cycling 100 cycles at RT and 0.75VR (5 sec ON/OFF using a power supply capable of rising voltage in less than 1 msec).

Summary

- Specific features of polymer compared to MnO2 capacitors include:
  - Greater sensitivity to absence of moisture.
  - Less effective self-healing mechanism.
  - Intrinsic mechanism of ESR degradation during high T storage or operation in presence of oxygen.
  - Anomalous transient phenomena.
  - Smaller probability of catastrophic, short circuit failures.
  - Increased probability of noisy behavior.
- Space systems would benefit from using CPTCs if:
  - Selected parts pass space-level screening and qualification testing.
  - Operating voltage is derated to 50% VR.
  - Application conditions are analyzed regarding operations at low T (special testing is necessary for missions requiring cold start-ups).