Rating and Derating for Low-Voltage Multilayer Ceramic Capacitors (MLCCs)

Alexander Teverovsky

Dell Services Federal Government, Inc.

work performed for Code 562, GSFC

Alexander.A.Teverovsky@nasa.gov

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List of Acronyms

MLCC	Multilayer ceramic capacitor
BME	Base metal electrode
PME	Precious metal electrode
DWV	Dielectric withstanding voltage
IR	Insulation resistance
EMR	Electromechanical resonance
VBR	Breakdown voltage
CCS	Constant current stress
STD	Standard deviation
HAST	Highly accelerated stress testing
HALT	Highly accelerated life testing
VR	Rated voltage

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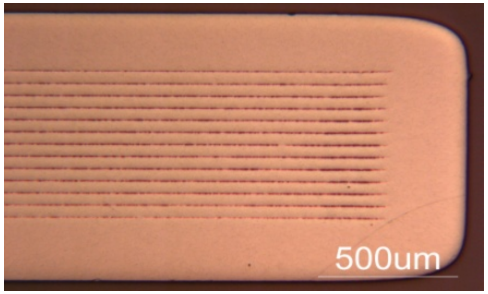
Rated Voltages and Derating for MLCCs

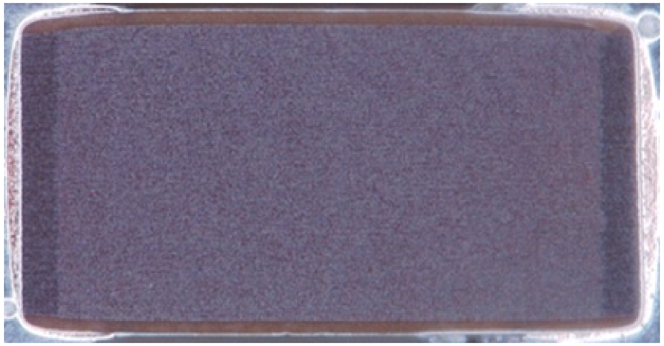
Scope:

Class II MLCCs rated to voltages ≤ 100V.



Outline:

- Breakdown voltages in BME and PME.
- Effect of voltage on capacitance.
- How performance of MLCCs is affected by voltage?
  - Dielectric withstanding voltage (DWV)
  - Insulation resistance (IR)
  - Electromechanical resonance (EMR)
  - Voltage conditioning and life test.
- How the parts are rated?
- Derating requirements.
- Where derating does not work?
- Conclusion



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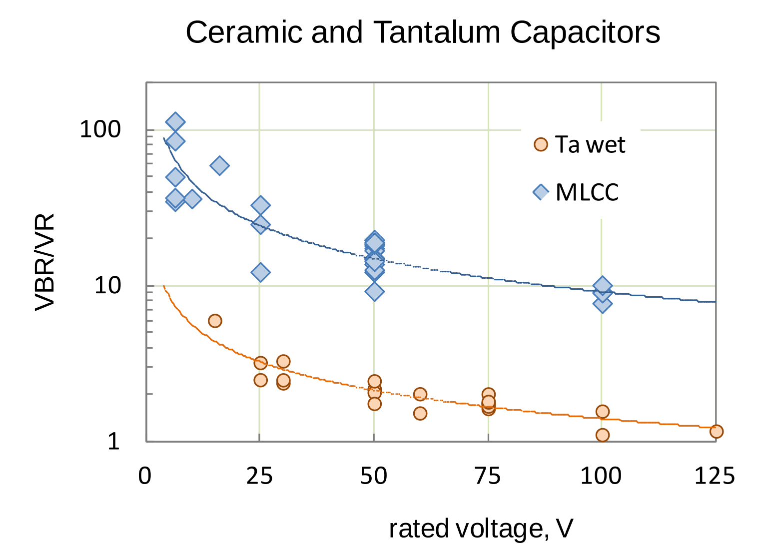
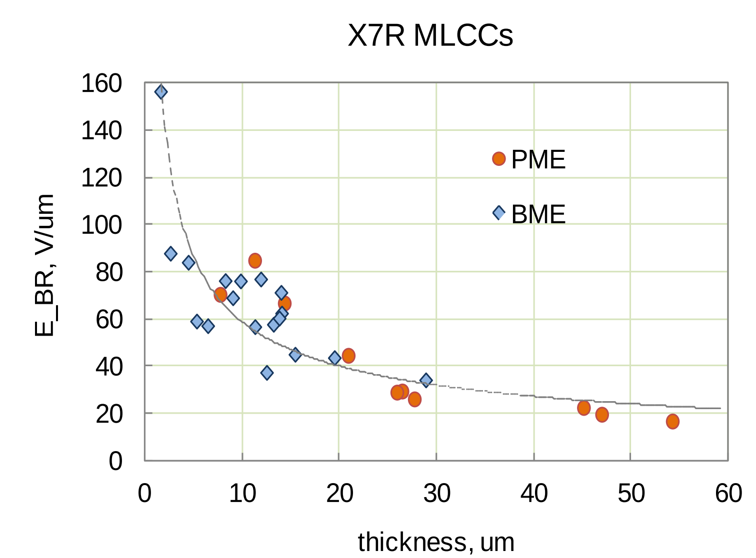
Breakdown Voltage in Capacitors

- VBR seems to be the most natural limit to VR:
  VR = VBR - margin
- How much margin is necessary?





- ✓ VBR does not limit VR for low-voltage MLCCs.
- ✓ Margin decreases as VR increases.
- ✓ There appears no difference in VBR for PME and BME.

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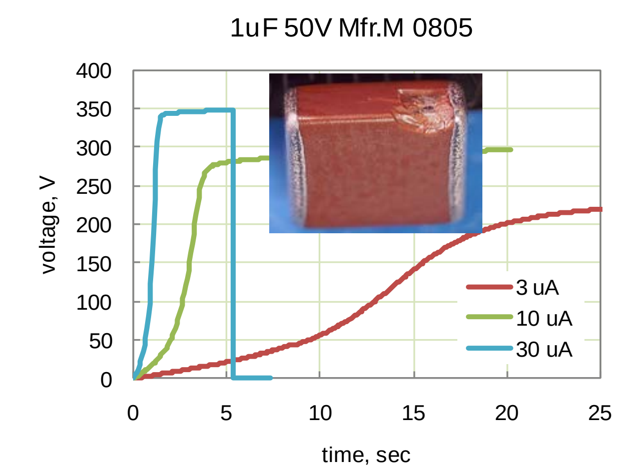
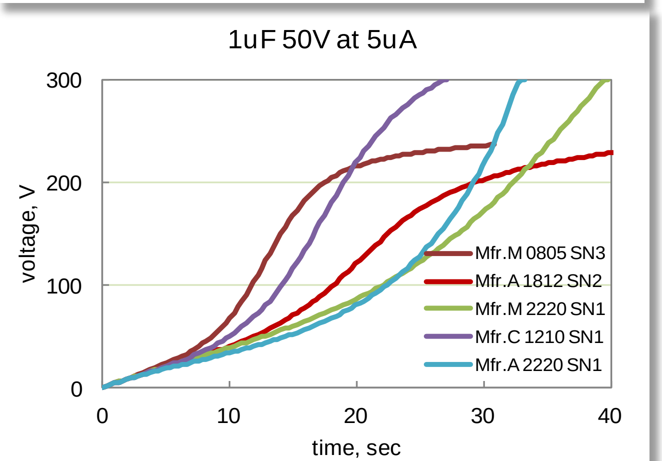
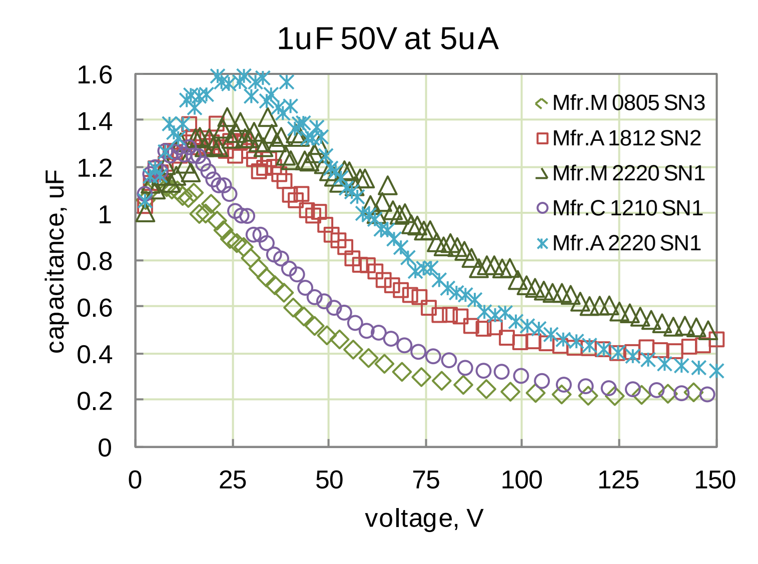
Constant Current Stress Testing

- CCS is a useful tool to test for VBR and quasi-static capacitance:

$$V(t)=\frac{1}{C}\times\int_0^t\left[I_{ch}-I_L(t)\right]\times dt \qquad C(V)=I_{ch}\frac{dV}{dt}$$







- ✓ Non-linearity of *V-t* characteristics is due to *C(V)* and *I(V)* variations.
- ✓ At *V* > *VR* capacitance drops substantially.

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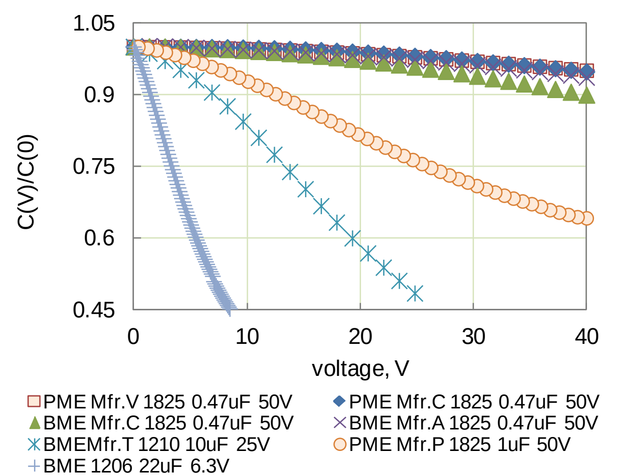
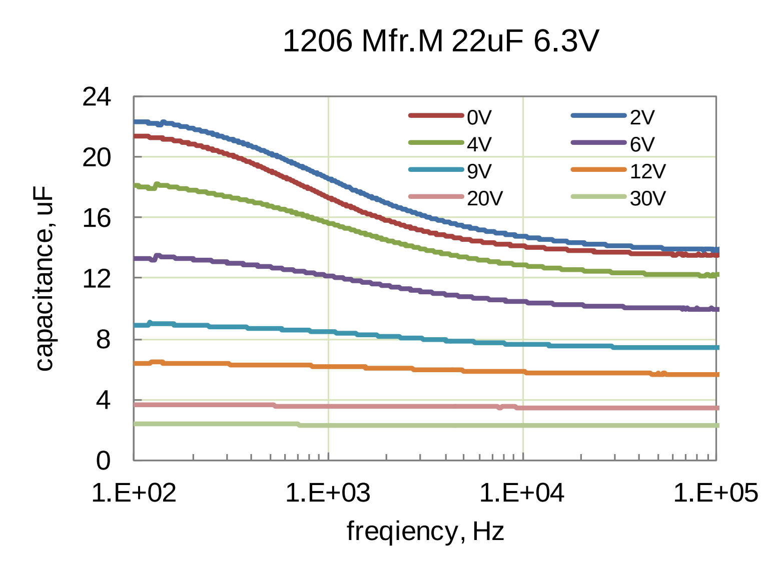
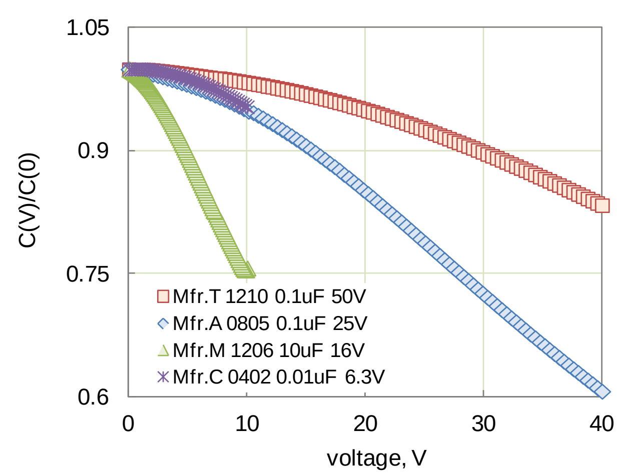
Effect of Voltage on Capacitance

- Standard measurements of capacitance at 1 kHz.







- ✓ Decrease of *C* with voltage is greater for high volumetric efficiency parts.
- ✓ Do we need limiting the voltage effect on *C* similar to MIL-PRF-55681 or leave the decision to the designer?

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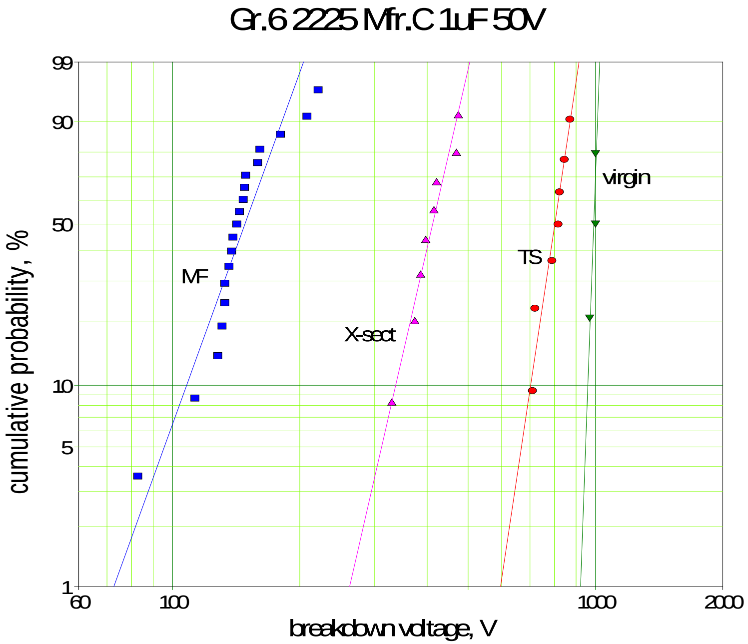
Effectiveness of DWV Test



- DWV test requires 2.5VR.
- Only ~20% of parts with gross defects failed DWV test.
- 19 out of 30 (63%) lots of parts damaged by X-sect and TS had the probability of DWV test failure of less than 1%.
- Some Mfr. testing parts at 5VR, JAXA - 30VR?

✓ VBR is sensitive to the presence of defects and reflects quality of the lot.

✓ The effectiveness of the existing DWV testing is low.

✓ Guidelines: $VBR_{cr} = 0.5 \times (VBR_{avr} - 2 \times \sigma)$ - (5% level)/2

✓ Average VBR and STD should be provided by manufacturers.

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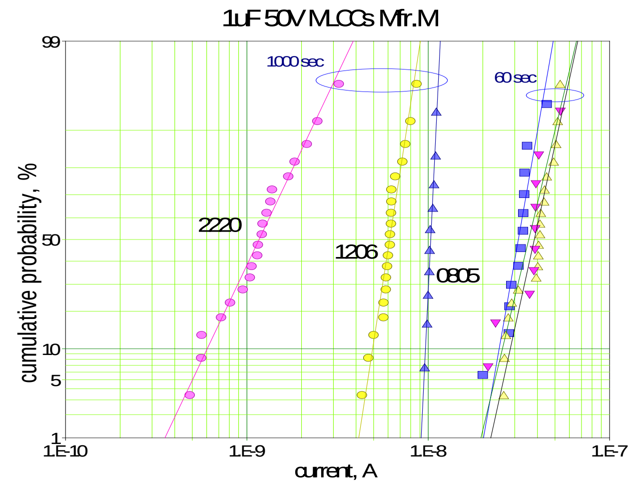
Effect of Voltage on IR

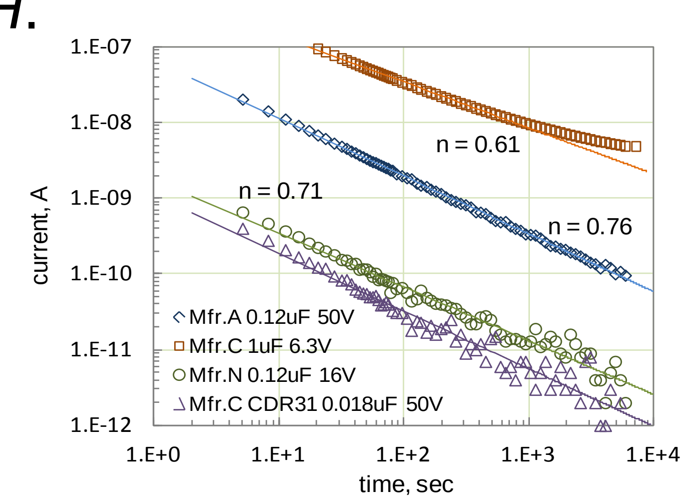


- IR requirements for BMEs are relaxed vs. MIL parts. Does it mean they are worse?
- Does voltage affect IR?
- According to spec, IR does not depend H and V, but depends on the value of C:

$$C = \frac{\varepsilon\varepsilon_0 S}{H} \qquad IR = \frac{\rho H}{S} \qquad IR = \frac{\rho\varepsilon\varepsilon_0}{C}$$

- However, ρ is not constant, and due to Schottky conduction IR should decrease exponentially with *V/H*.
- Currents in MLCCs follow Curie von Schweidler law:

$$I(t) = I_0 \times t^{-n}$$



- Will an increase in voltage reduce IR?
- What currents are measured during first 120 sec of electrification?

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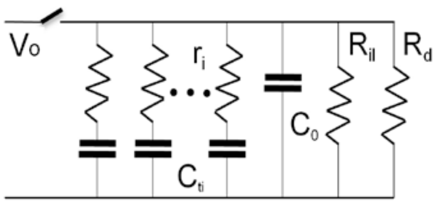
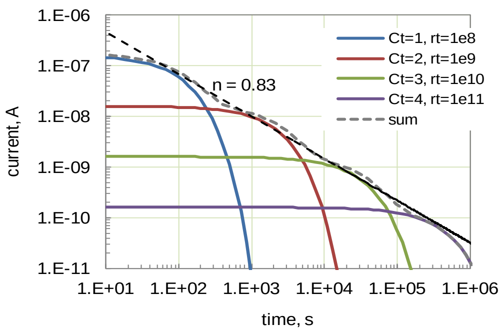
Leakage Currents in MLCCs

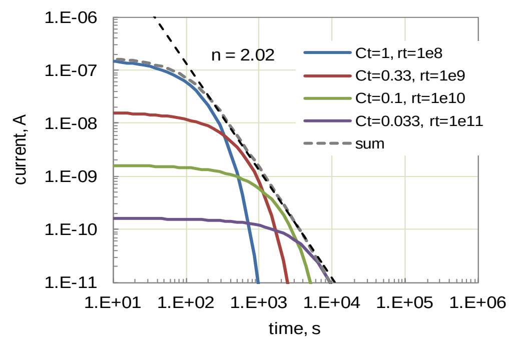
$$I(t,T,V) = I_{ch}(t,V) + I_{abs}(t,V) + I_{il}(T,V) + I_{dl}(T,V,RH)$$

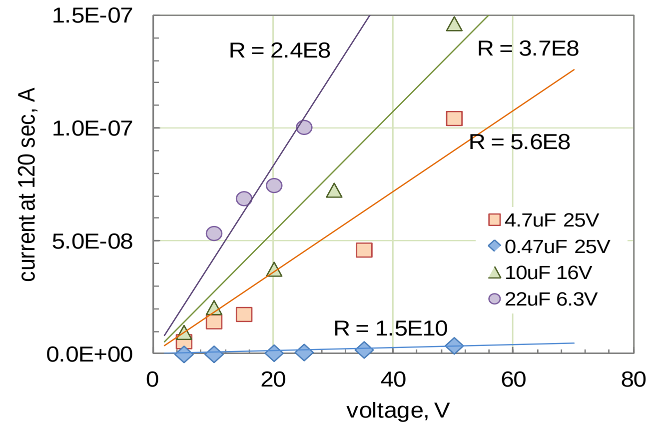
Capacitor with absorption

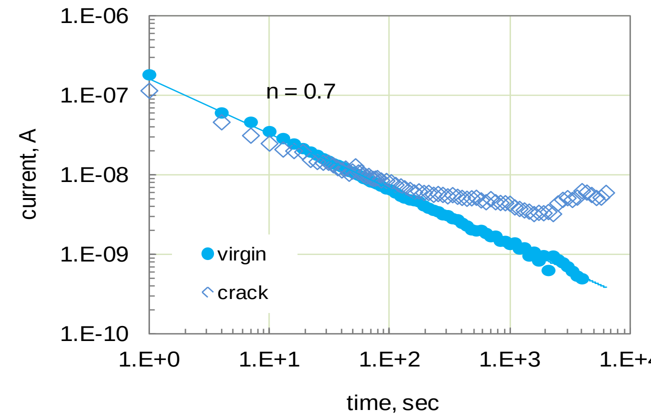


$$I(t) = \frac{V_0}{R_d} + \frac{V_0}{R_{il}} + \sum_i \frac{V_0}{r_i} \exp\left(-t/\tau_i\right)$$









- ✓ Absorption currents prevail up to several hours of electrification.
- ✓ I_{abs} increases linearly with voltage, hence IR does not depend on how accurately VR is determined.
- ✓ IR in high-C MLCCs is not sensitive to the presence of defects.

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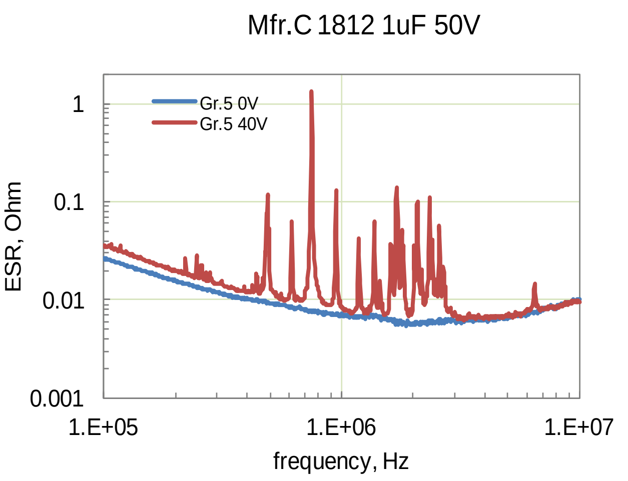
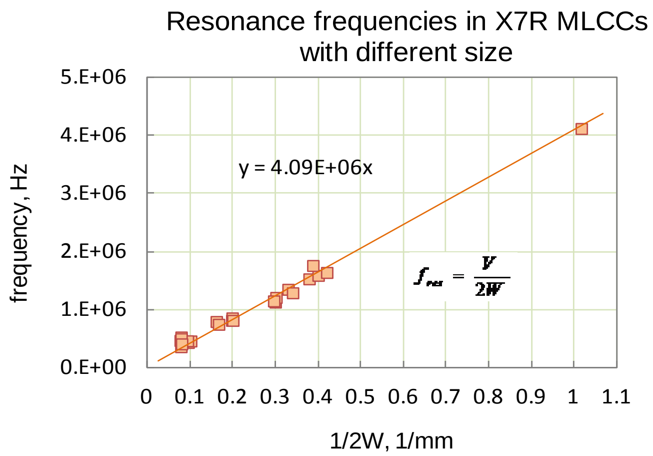
Effect of Voltage on EMR

- Inverse piezoelectric effect results in acoustic waives in polarized capacitors.
- Several resonance frequencies.
- The amplitude increases with V (=>VR).
- EMR results in excessive noise and might cause mechanical damage and failure.
- History case: a stacked capacitor failed in PS systems.





- ✓ The major f_{res} depends on the width, W, of the capacitor:

  $$f_{res} = v/(2W),$$ v is the sound velocity.
- ✓ For X7R materials $v \sim 4.1\times10^3$ m/sec.
- ✓ Guidelines: warning about EMR effect and impedance spectroscopy if necessary.

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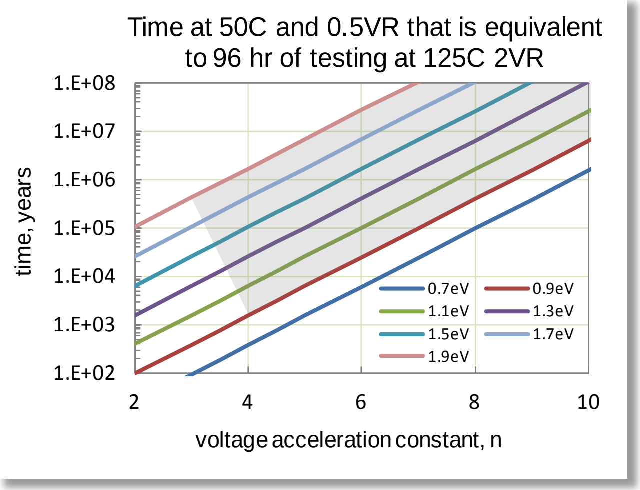
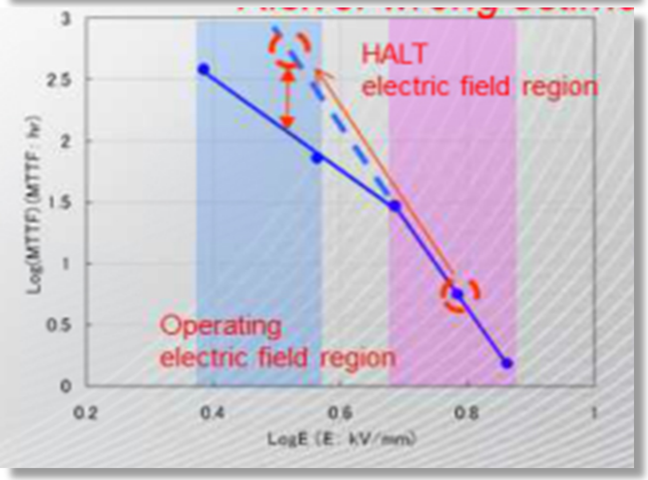
Effect of Voltage on Life Test

- Large VBR allows for extremely high voltage acceleration.
- IR degradation and failures due to V_O^{++} are observed mostly during HAST.

$$AF = \frac{\tau_1(V_1,T_1)}{\tau_2(V_2,T_2)} = \left(\frac{V_2}{V_1}\right)^n \times \exp\left[\frac{E_a}{k}\left(\frac{1}{T_1}-\frac{1}{T_2}\right)\right]$$

- Voltage conditioning at 125C, 2VR for 100 hr corresponds to thousands of years of operation at 50C and 0.5VR.
- Shiota (Murata, CARTS'13):
  - acceleration at HV might result in errors of extrapolation to operating conditions;
  - a stress by T acceleration instead of V.





✓ Derating is an effective means for reducing risk of failures caused by V_O^{++}.

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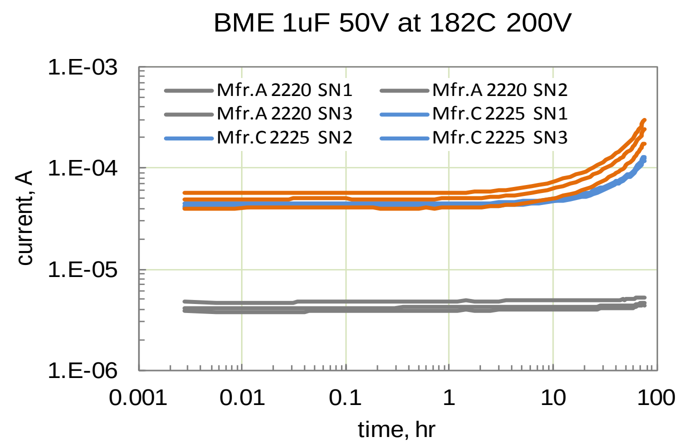
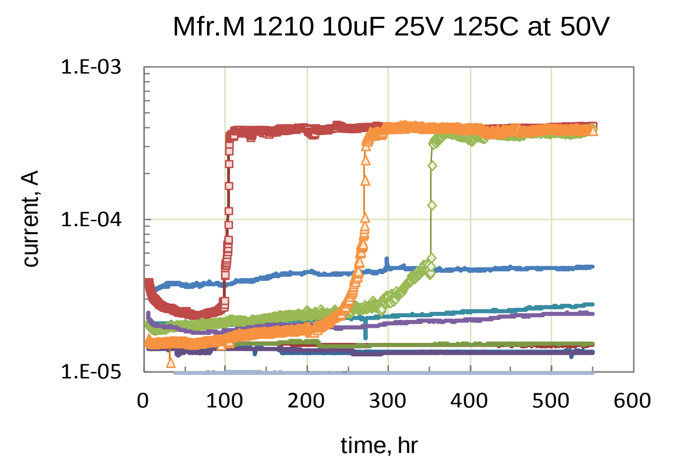
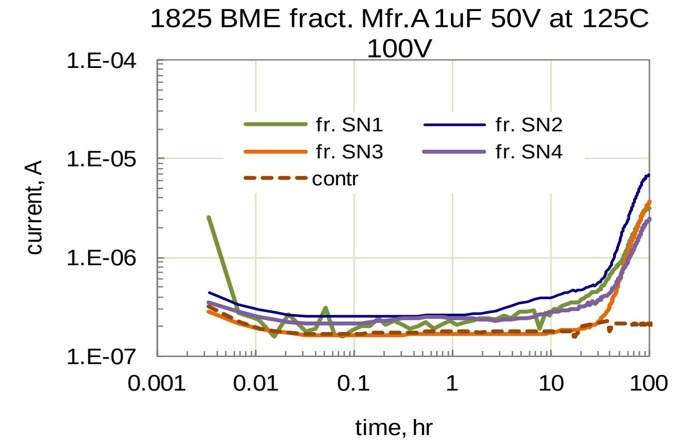
Early HALT Failures

- Are parts from Mfr.A better than from C?
- At E=1 eV, n=3 "failures" at 30hr 182C 200V correspond to >47,000 years at 25V and 55C.
- Early failures might be more important than wear-out failures.





Cracks might cause early HALT failures



Cracks might appear as IR degradation

✓ Early HALT failures and IR degradation might be due to cracks.

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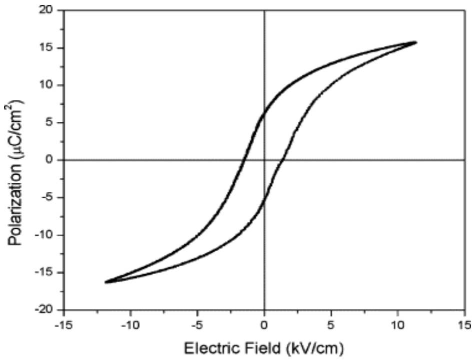
How Voltage for Capacitors is Rated?



- In ferroelectric materials the dielectric constant decreases with electric field.
- For BaTiO3 type materials $\varepsilon(E)$ function depends on the composition, structure of the dielectric, and is sensitive to the process conditions, and probably H => proprietary information.
- Based on the acceptable level of the $\varepsilon(E)$ variations, E_{max} can be selected.
- For a given thickness of the dielectric, *H*, the rated voltage is $VR = H \times E_{max} - margin\ (?)$

✓ VR in low-voltage MLCCs is controlled by polarization processes in the dielectric, and is not related to breakdown voltages.

✓ VR is a technical parameter chosen so that voltage dependent characteristics and reliability remain within the specified limits.

Guidelines for Derating Requirements

Part Type	Voltage derating factor 1/	Maximum operating temperature	Ripple current derating factor 2/
MIL	0.6	110 °C	NA
BME	**0.5**	**100 °C**	**0.75**

Notes:
1/ The derating factor applies to the sum of peak AC ripple and DC polarizing voltage.
2/ Ripple currents in power applications shall be derated to 75% of the manufacturers' recommendations. The frequency of ripple current should be outside the electromechanical resonance frequency for the part.

- ✓ Derating = stress reduction => increase of reliability and mitigation of unforeseen events (e.g. EMR).
- ✓ Derating is based on history of applications and consensus.
- ✓ Danger of over-derating: larger parts weight more and might be more susceptible to fracturing.

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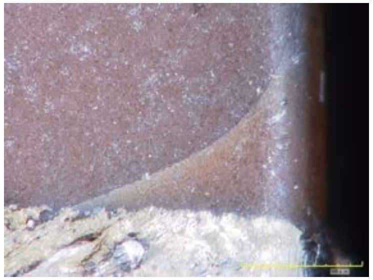
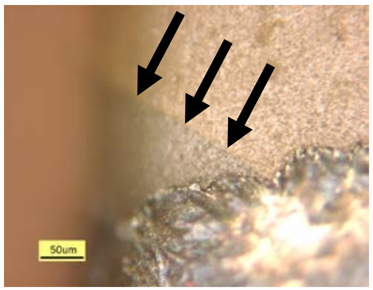
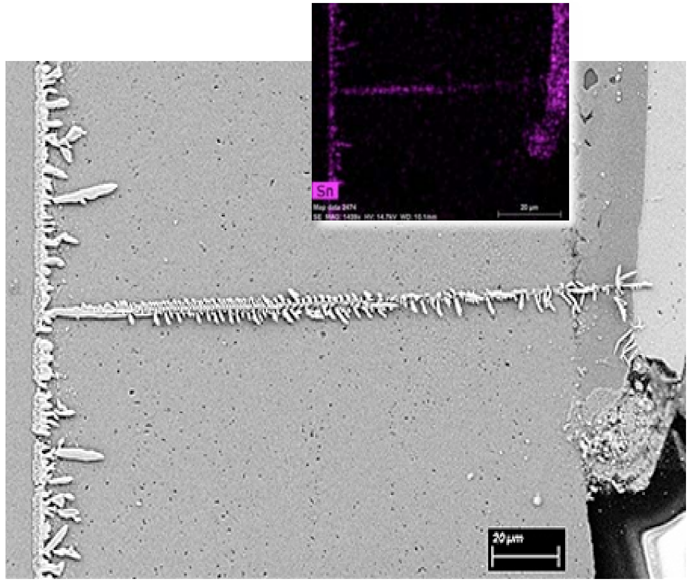
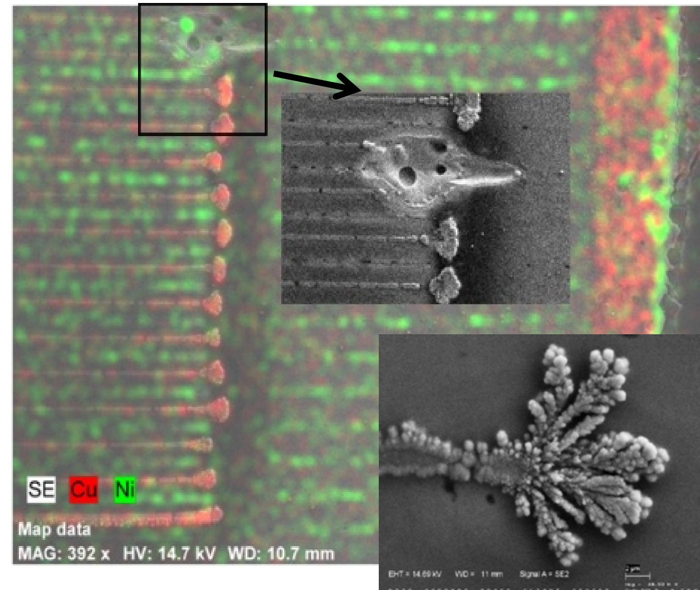
Where Derating Does not Work?





BME, WLT at 0.8V, 23 min





- ✓ Failures due to V_O^{++} are observed mostly during HAST and can be mitigated by derating.
- ✓ Failures due to the presence of cracks observed during box-level testing and operation at low voltages.
- ✓ <u>Bad news</u>: derating does not help for low-voltage failures.
- ✓ <u>Good news</u>: BMEs are less susceptible to low-voltage failures.

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Conclusion

- Rating of capacitors is a prerogative of manufacturers.
  - Manufacturers should assure and demonstrate reliability of their product at rated conditions. (For Hi-Rel parts the requirements and test conditions are set by users.)
  - Manufacturers should also provide acceleration factors and methods used for their calculation. (Standardization of HAST?)
- Derating is an efficient means for users to reduce risks of IR degradation and failures caused by V_o^{++} ; it might also work for cracking related failures.
- A 50% voltage derating seems reasonable.
- An open issue: should we limit a decrease of capacitance at rated voltages. (Derating might be sufficient to take care of the problem if manufacturers specify C at VR.)

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