Insulation Resistance and Leakage Currents in Ceramic Capacitors with Cracks

Alexander Teverovsky

Parts, Packaging, and Assembly Technologies Office, Code 562 GSFC/ASRC Federal Space and Defense

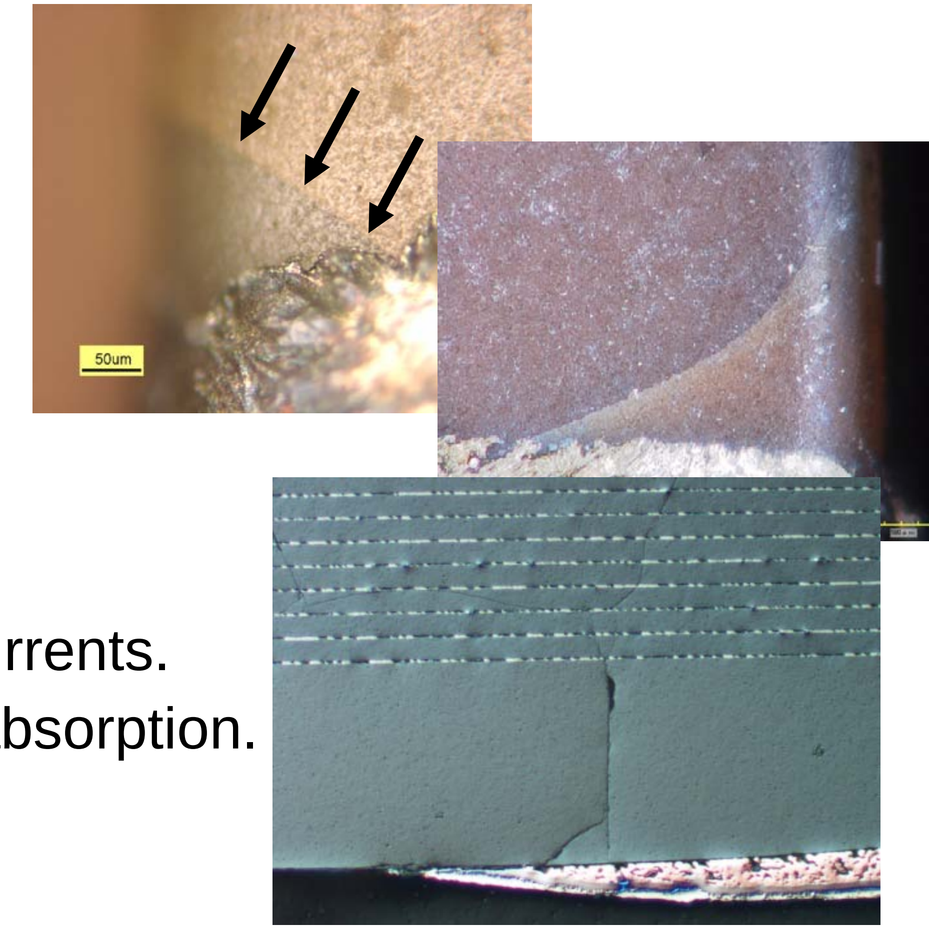
Alexander.A.Teverovsky@nasa.gov

Introduction

<u>Purpose</u>: Can measurements of insulation resistance (IR) reveal low-voltage MLCCs with cracks?

<u>Outline</u>:

- Absorption and intrinsic leakage currents.
  - Effect of size.
  - Effect of capacitance.
  - Effect of voltage.
  - Effect of temperature.
  - Effect of cracking.
- Absorption capacitance.
- Modeling of absorption currents.
- IR measured by voltage absorption.
- Conclusion.



Requirements for IR

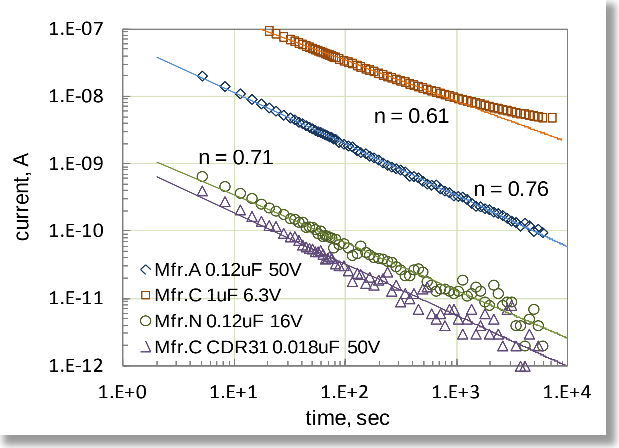
- $IR = V_R/I(t)$, where V_R is the rated voltage, and $t \le 2$ min.
- Limits for military MLCCs:
  $IR > 10^{11}$ Ω or 10^3 MΩ-μF, whichever is less, at +25°C,
  $IR > 10^{10}$ Ω or 10^2 MΩ-μF, whichever is less, at +125°C.
- Requirements for commercial capacitors are two times less.
- *IR* is inversely proportional to the value of capacitance and do not depend on VR and size (thickness of the dielectric)

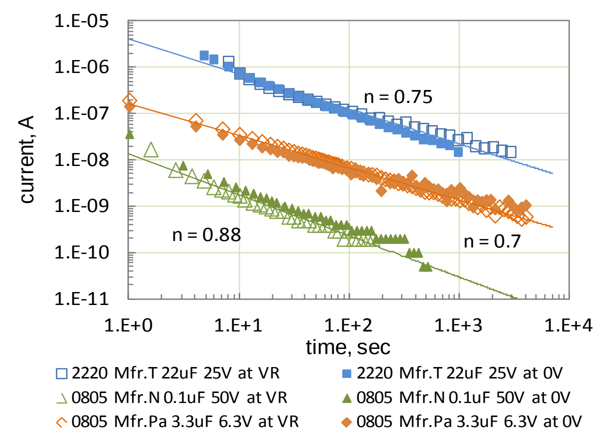
$$C = \frac{\varepsilon\varepsilon_0 S}{H} \qquad IR = \frac{\rho H}{S} \qquad IR = \frac{\rho\varepsilon\varepsilon_0}{C}$$

- However, ρ is not constant, and Schottky conduction increases exponentially with $E = V/H$.
- A decrease of IR_{limit} with temperature corresponds to activation energy of ~0.3 eV, which is much lower than the values reported for conductivity of ceramic materials.

Absorption Currents

- Currents decrease with time according to an empirical Curie-von Schveindler law: $$I(t) = I_0 \times t^{-n}$$, where *n* ~ 1.
- Current relaxation: charges are “absorbed” in the dielectric.

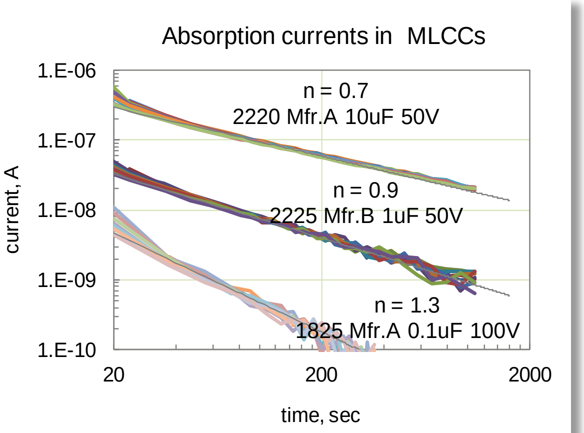


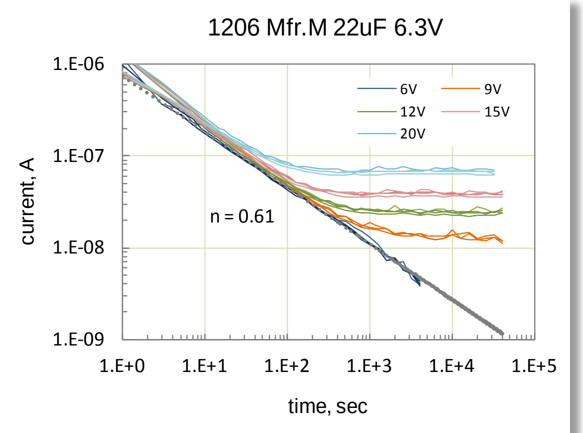


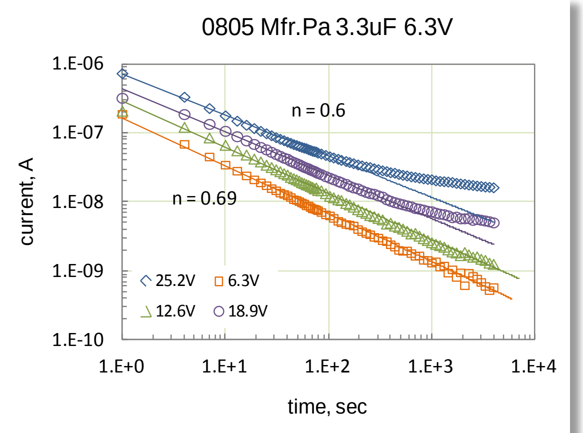
- ✓ Experimental data for different MLCCs: $0.6 < n < 1.1$.
- ✓ Depolarization, or desorption currents are flowing in the opposite direction in a short-circuited capacitor.
- ✓ Depolarization currents have similar value and follow the same power law.

Absorption and Intrinsic Leakage Currents

- Absorption currents, I_{abs}, and intrinsic leakage currents, I_{il}, are reproducible from sample to sample.
- I_{abs} reduces with time, while I_{il} remains constant.



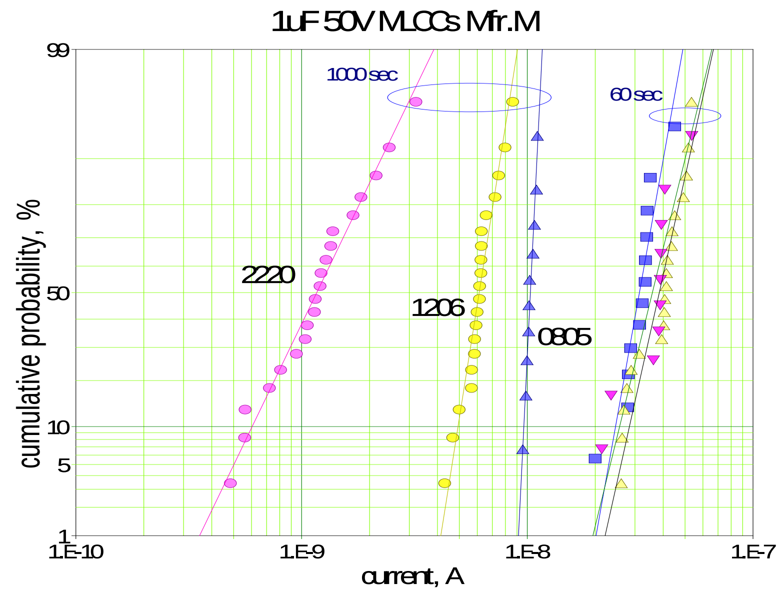




- ✓ Absorption currents prevail at initial moments of electrification.
- ✓ At room temperature and V_R intrinsic leakage currents are relatively small, but might be observed at $V>>V_R$ within minutes of electrification.

Effect of Size

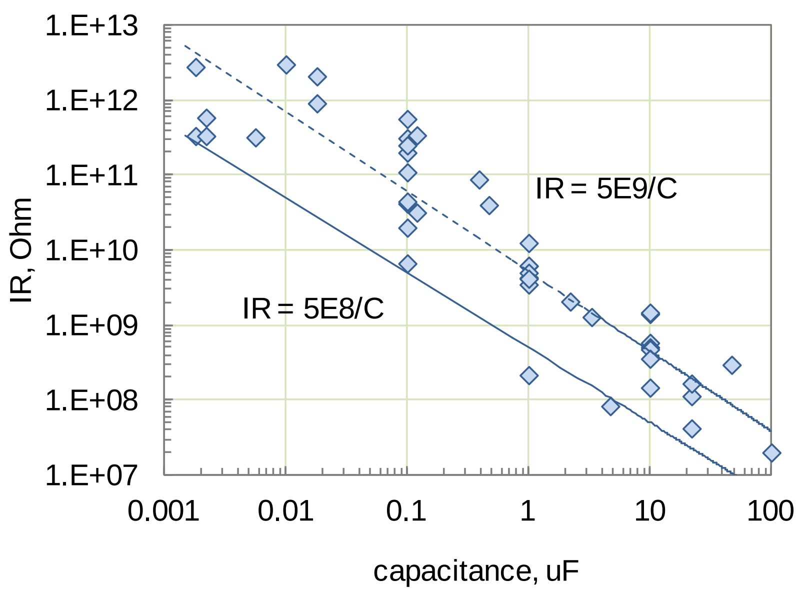
- Three types of 1 μF 50V capacitors were from the same manufacturer, but had different case sizes.
- The thickness of the dielectric was 19.4 μm, 8.9 μm, and 4.3 μm for case sizes 2220, 1206, and 0805, respectively.
- No substantial difference in currents and IR for the 60-sec measurements.
- The 1000-sec measurements were ~10X less for 2220 parts compared to 0805 capacitors.
- Currents measured after 1000 sec. have a substantial component related to the intrinsic leakage currents, while 60-sec currents were due to absorption.



✓ IR does not depend on the case size when absorption currents prevail.

Effect of Capacitance

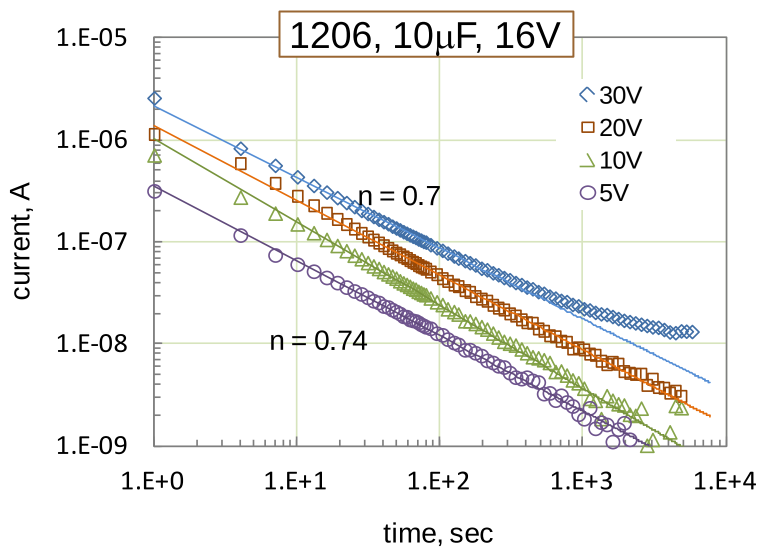
- X7R capacitors with EIA case sizes from 0402 to 2225, voltage rating from 6.3 V to 100 V, and capacitance from 1500 pF to 100 μF.
- Correlation between the values of IR measured by a standard technique and capacitance for 40 different part types:
  IR = 5×10^9/C, where C is in μF and IR is in Ω.

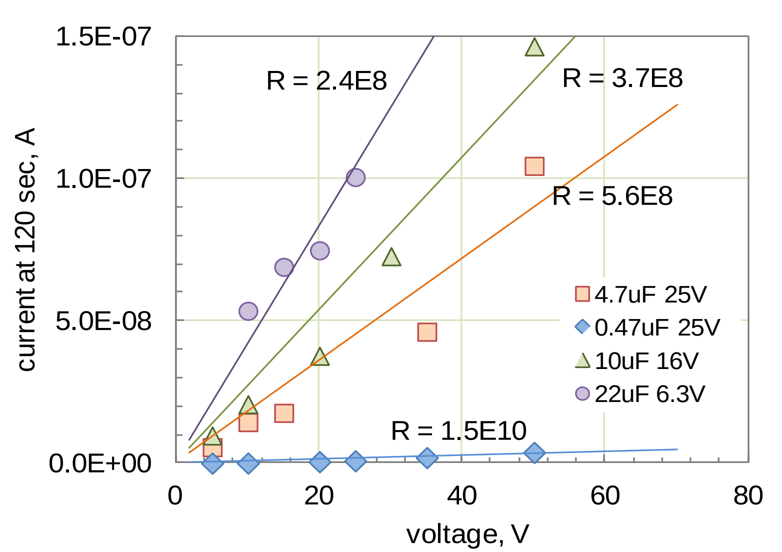


- ✓ The results are in agreement with the limit used by manufacturers of low-voltage, high-value MLCCs: IR = 5×10^8/C.
- ✓ On average, the margin between the actual IR values and the limit is ~ 10 times.

Effect of Voltage

- An increase in the applied voltage leads to an increase in the absorption currents, I_{abs} ,whereas n remains the same.
- At V > $2V_R$ the current decay levels-off after 1000 seconds, due to increased I_{il}.
- Absorption currents increase with voltage linearly.

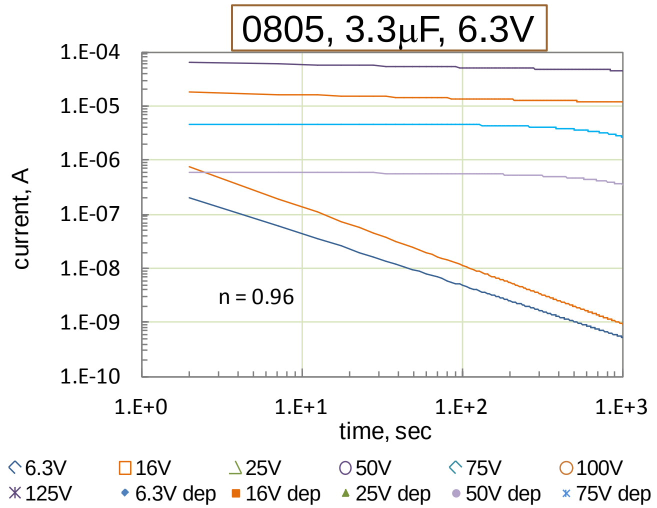


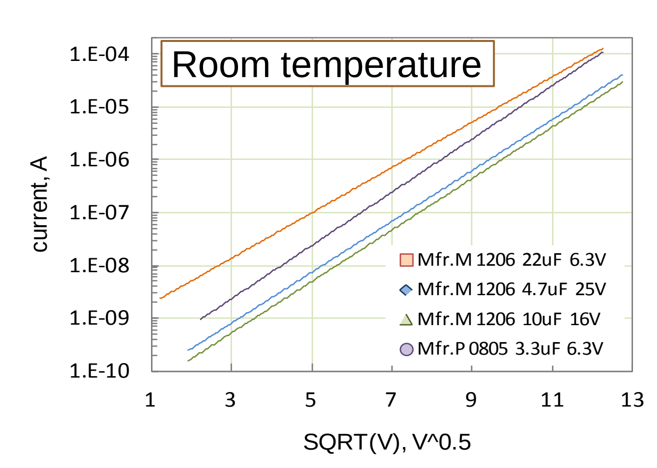


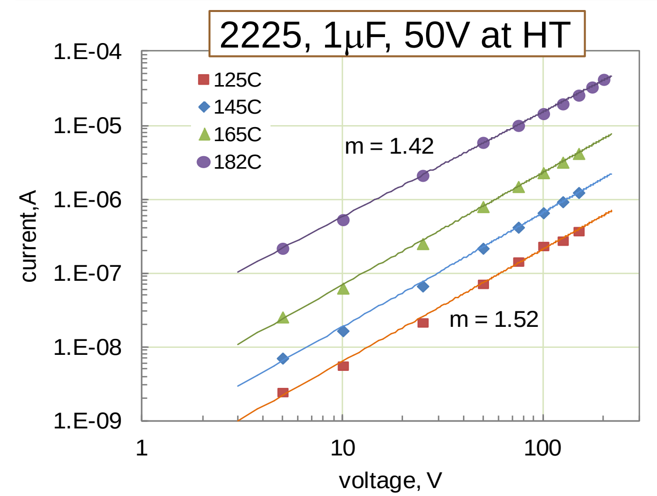
- ✓ Isochronic absorption currents increase with voltage linearly.
- ✓ IR does not depend on voltage.

Effect of Voltage, Cont'd

- ❑ Depolarization currents increase linearly to ~ $3V_R$, and then saturate with voltage.
- ❑ At high voltages, V >~ $3V_R$, intrinsic leakage currents prevail.



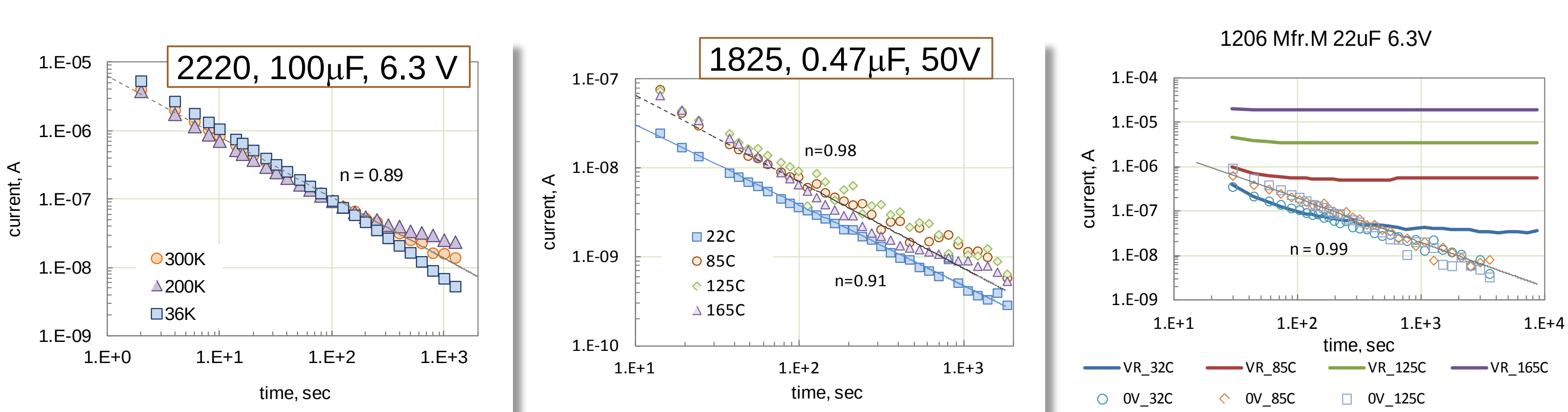




- ✓ Schottky-like *I-V* characteristics at room temperature: $ln(I) \sim V^{0.5}$.
- ✓ A 3/2 power law at 125 °C and higher: $I \sim V^m$, $m \approx 1.5$.

Effect of Temperature

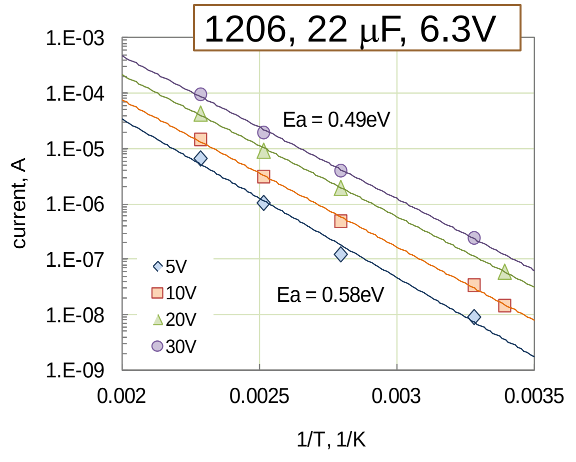
- Absorption currents at cryogenic and room temperatures remain the same.
- Temperature increase from 22°C to 165 °C result in a relatively small (less than 2 times) increase in I_{abs}.

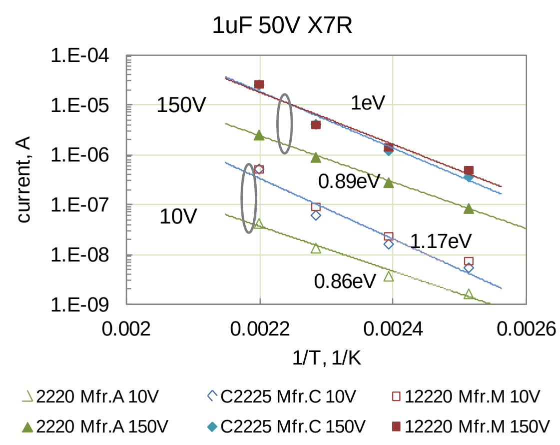


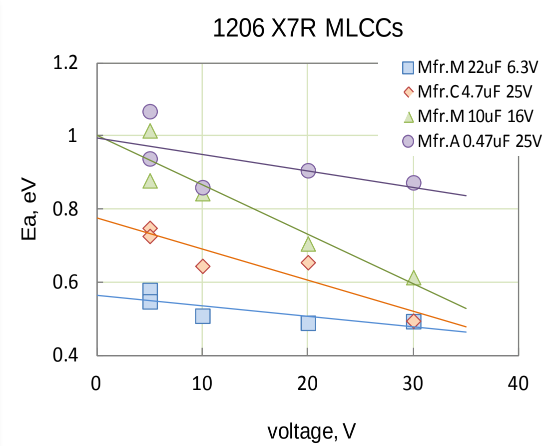
- ✓ Absorption currents have weak temperature dependence.
- ✓ Intrinsic leakage currents increase with temperature exponentially.

Effect of Temperature on Intrinsic DCL

- Temperature dependence of the intrinsic leakage currents follow Arrhenius law.
- Activation energy, E_a, decreases by 10% to 30% as the voltage increases from 0.5 V/VR to 5 V/V_R.



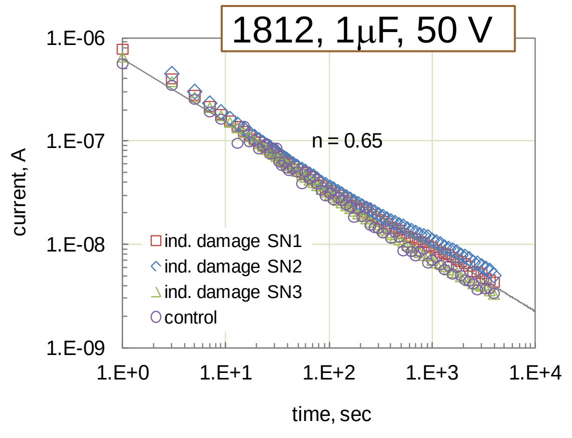


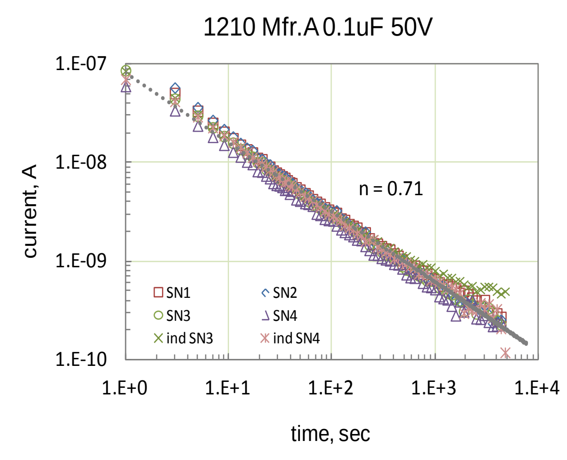


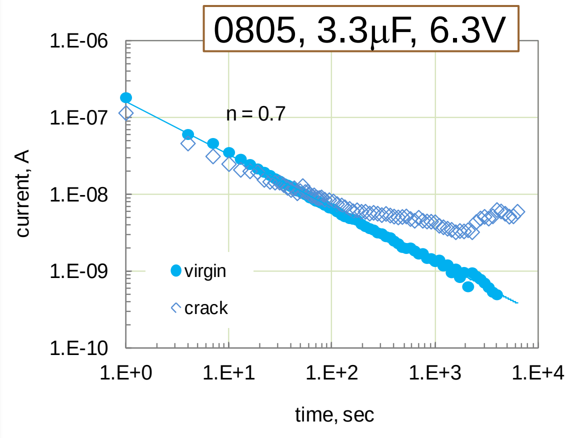
- ✓ At rated voltages intrinsic leakage currents, and the insulation resistance change with temperature exponentially.
- ✓ Activation energy is in the range from 0.6 to 1.3 eV and decreases with voltage.

Effect of Cracking

- No difference in I-t curves between normal quality parts and capacitors with cracks.
- For severely damaged parts the difference can be noticeable after ~ 100 sec.



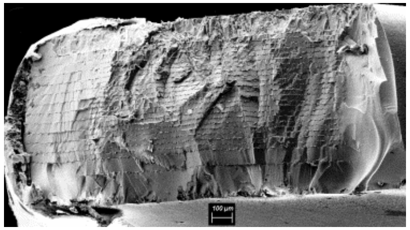


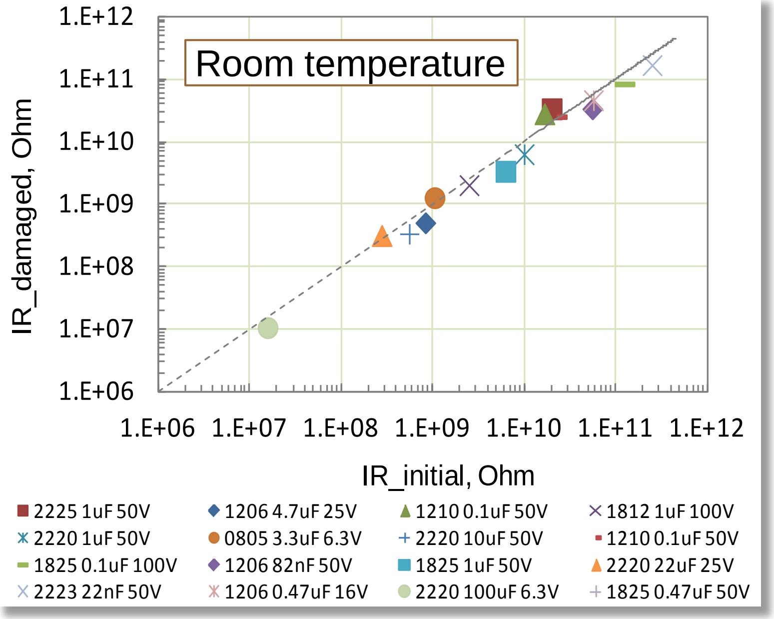


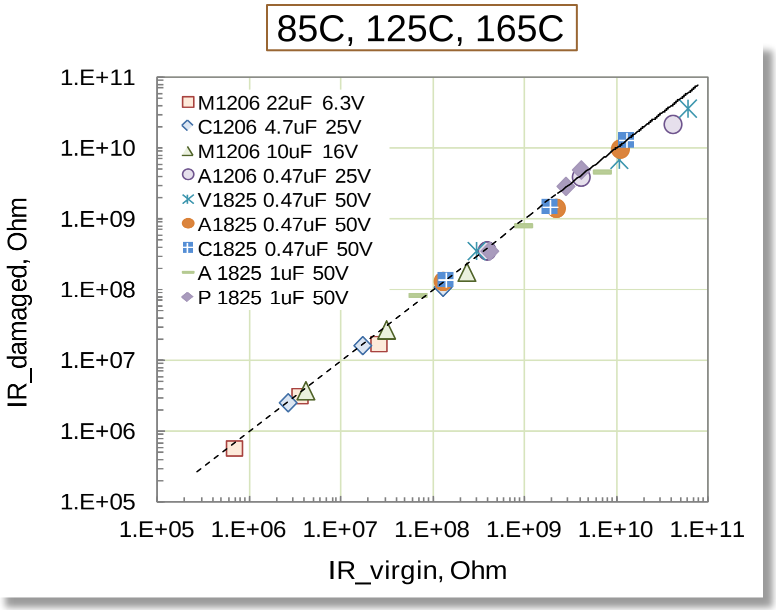
✓ At room temperature, absorption currents, hence IR, are not sensitive to the presence of cracks.

Effect of Cracking, Cont'd.

- IR values measured after 120 seconds for 15 types of virgin and fractured capacitors both, at room and high temperatures, were closely correlated.







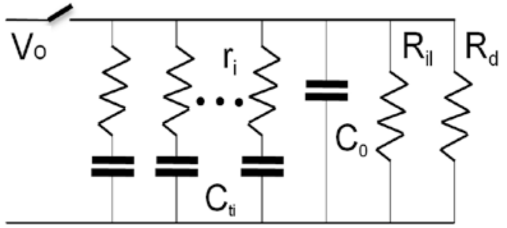
- ✓ Fractured parts can pass screening by standard IR measurements.
- ✓ High absorption currents at room temperature, and large intrinsic leakage currents at high temperatures mask the presence of cracks.

Modeling of Absorption Currents

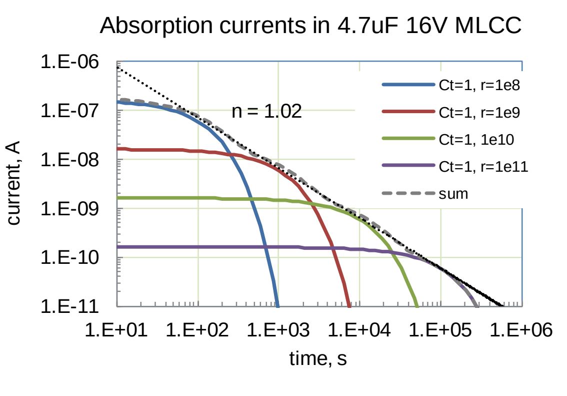
- Total current through a capacitor with defect:

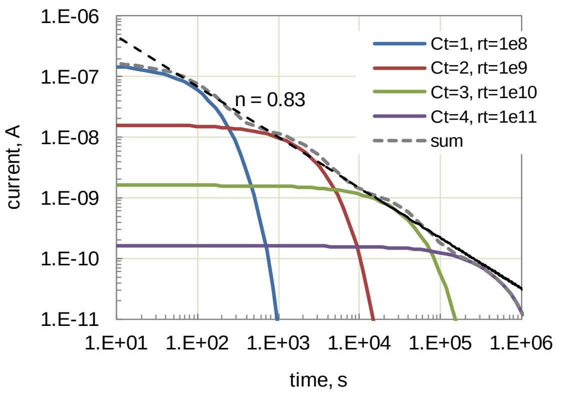
$$I(t,T,V,RH) = I_{abs}(t,V) + I_{il}(T,V) + I_{dl}(T,V,RH)$$

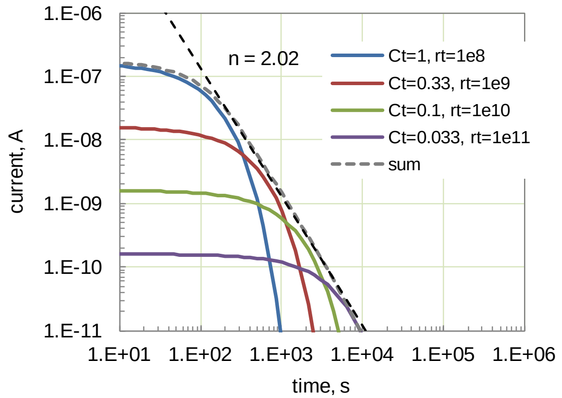
- Dow model for a capacitor with absorption:



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





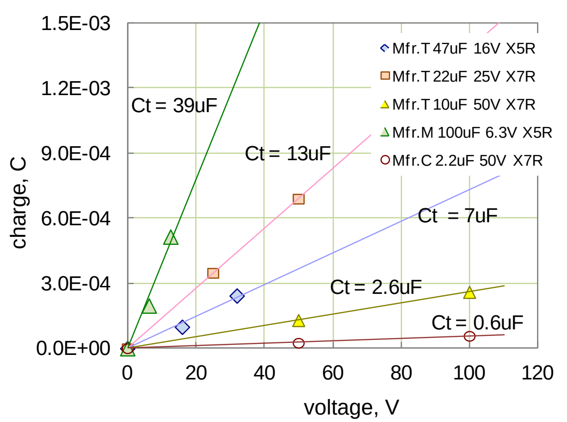


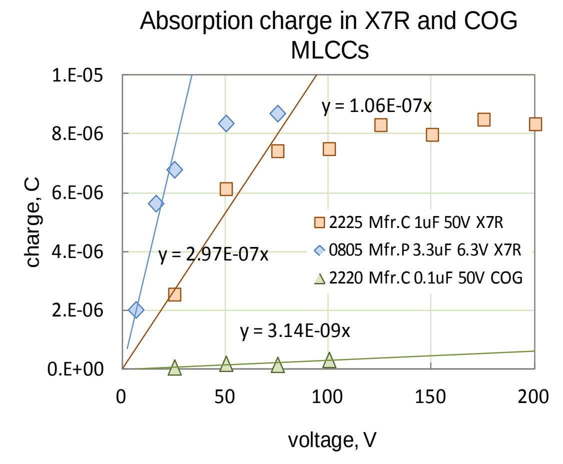
- ✓ Relaxation of I_{abs} in a wide range of times can be presented as a superposition of currents through a few r_i - C_{ti} relaxators.
- ✓ How large are C_{ti}?

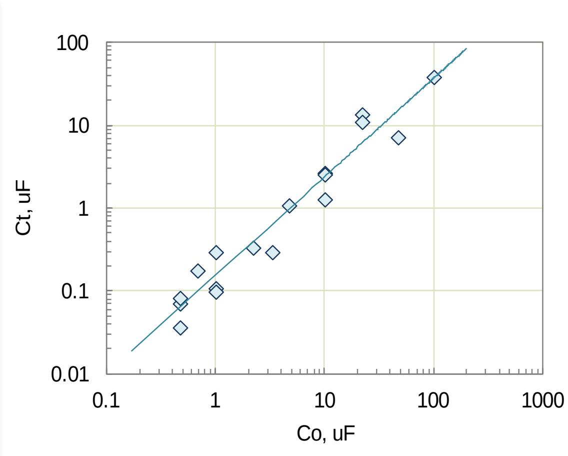
Absorption Capacitance

- Absorption charge, Q_t, increases with voltage linearly.
- The process can be described by a capacitance, C_t, that is determined as $C_t = Q_t/V$.

$$Q_t = \int_1^{1000} I_0 \times t^{-n} \times dt = \frac{I_0}{1-n} \times t^{1-n} \Big|_1^{1000}$$







- ✓ Q_t varies linearly at relatively low voltages and saturates at V >~ $3V_R$.
- ✓ Absorption capacitance increases with the nominal value of capacitors; on average, $C_t = 0.25 \times C_0$.

Modeling of Insulation Resistance

- Traps with concentration, N_t, are likely located at the metal-ceramic interface and are filled up at V >~3V_R

$$C_t = \frac{q \times N_t \times S}{3 \times VR} = \alpha \frac{\varepsilon \times \varepsilon_0 \times S}{d}$$

, where α ~0.25. In this case, 1.8×10^{13} cm^{-2} < N_t < 6×10^{13} cm^{-2}.

- $IR = V_R/I_{abs.}$ At $\tau = r\times C_t > \Delta t$ ~ 100 sec.

$$IR = \left(\frac{1}{R_d} + \frac{1}{R_{il}} + \frac{1}{r}\right)^{-1}$$

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

- At $r < R_d$, R_{il}, and $\tau > \Delta t$:

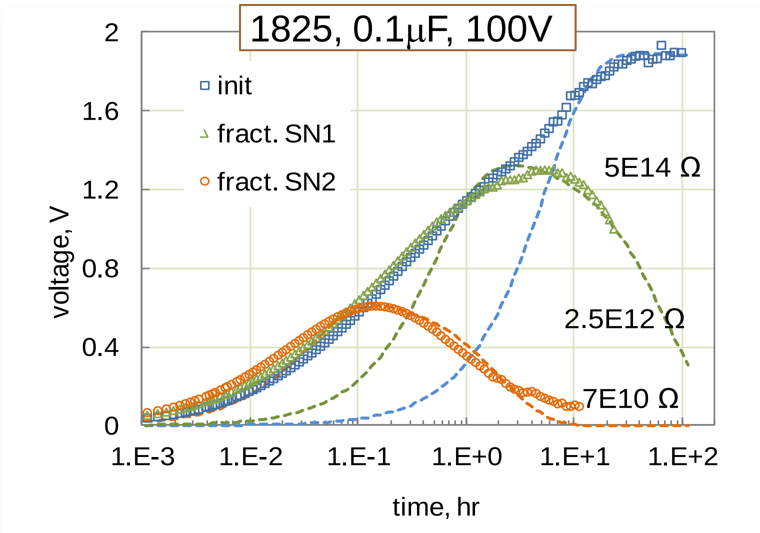
$$IR = r > \frac{100\times10^6}{0.25\times C_0} = \frac{4\times10^8}{C_0}$$

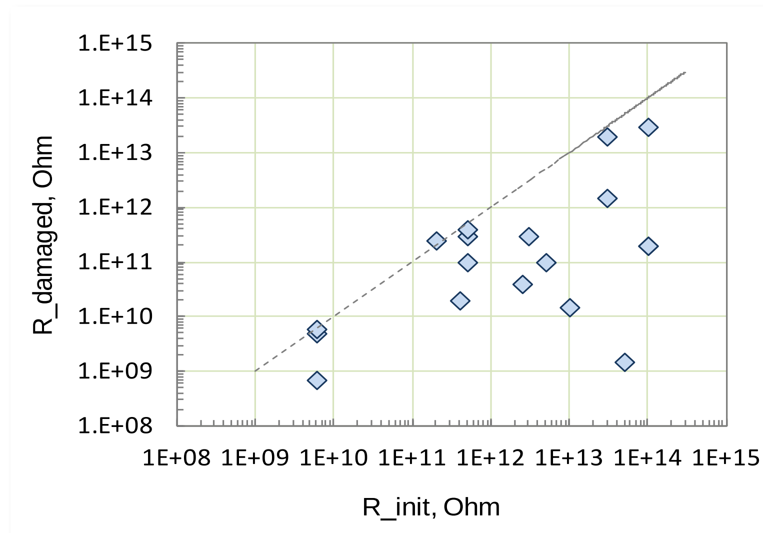
- The result is in a good agreement with the existing requirements for IR: $IR_{max} = 5\times10^8/C_0$

✓ The absorption model explains IR dependence on capacitance and is in a reasonable agreement with actual IR values.

Voltage Absorption in Capacitors with Cracks

- Measurements of variations of absorption voltages with time can be used to assess the value of resistance up to 10^{14} Ω.





- ✓ Resistance corresponding to intrinsic leakage currents is in the range from 5×10^{9} to 10^{14} Ω.
- ✓ Fracturing reduces resistance up to 5 orders of magnitude, but in many cases still remains within the specified limits.
- ✓ Both, test method and requirements need to be revised.

Conclusion

- Absorption currents prevail during standard measurements of IR at room temperature. Absorption currents depend on capacitance, have a weak dependence on temperature, and change linearly with voltage up to 2 - 3 times VR.
- Possible variations of IR for the parts with the same value of capacitance are likely due to some differences in timing during measurements, rather than to different quality of the parts.
- Absorption processes in MLCCs can be explained by electron trapping in states at the metal/ceramic interface, as a result of tunneling. Absorption capacitance increases with the nominal value of capacitance, and is on average ~25% of C_0.
- At relatively low temperatures, intrinsic leakage currents in MLCCs can be described using the Simmons model. At temperatures above 85°C, *I-V* characteristics follow a power law with the exponent close to 1.5. Activation energy of leakage currents for different types of X7R capacitors is in the range from 0.6 eV to 1.3 eV.
- Neither room temperature nor high temperature standard IR measurements are sensitive to the presence of cracks. Development of new, more effective testing methods to reveal capacitors with structural defects is necessary.