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Sandia National Laboratories

SAND2022-XXXX C

ADVANCED FUZING TECHNOLOGY

High-Voltage Polymer Multi-Layer Capacitor Development, Characterization, Environmental Testing

HI-REL ELECTRONIC PRODUCTS

HIGH-RELIABILITY COMPONENTS - DELIVERED

Presented By:

Alex Robinson, Joshua Dye

(505) 844-9520, arobins@sandia.gov

(505) 844-8627, josdye@sandia.gov

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Compelling Long-Term Gaps, Needs, and Challenges

Needs:

Higher energy density firing systems for challenging environments

High-energy-density (HED) capacitor robust to wide-ranging environments.

Potential replacement for multi-layer ceramic capacitors (MLCC)

Approach:

Design high-voltage HED polymer multi-layer (PML) capacitors as replacements with potentially smaller footprint

Challenges:

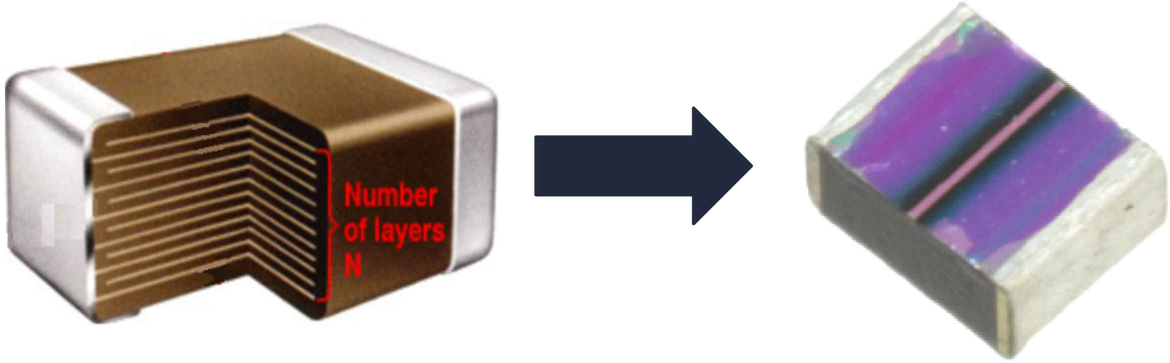
A drop-in PML replacement does not exist

High voltage PML capacitors are new

Next level - higher energy density dielectrics may reduce size with an acceptable trade-off of service lifetime.

Polymer Multi-Layer (PML) capacitors display advantageous characteristics worth pursuing

- High energy density
- Lightweight
- Robust
  - Self-healing
- Stable
  - Temperature
  - Voltage
  - Chemical
  - Humidity



$$C = \varepsilon_0 \varepsilon_r \frac{A}{d} N$$

C = capacitance

ε_0 = permittivity of a vacuum

ε_R = relative permittivity of dielectric

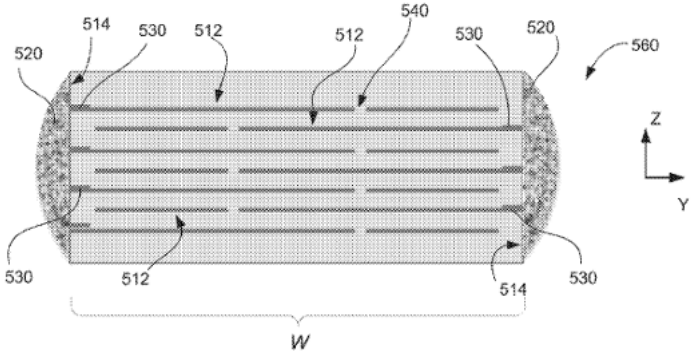
A = electrode square area

d = distance between each electrode

N = number of dielectric layers

Capacitor Construction

Internal serialization to achieve desired voltage rating



- An understanding of the physics guides the design to minimize energy dissipation (i.e. damage) during clearing events (better survivability)

$$E_{clearing} \ \alpha \ t^2 V^4 f(p)$$

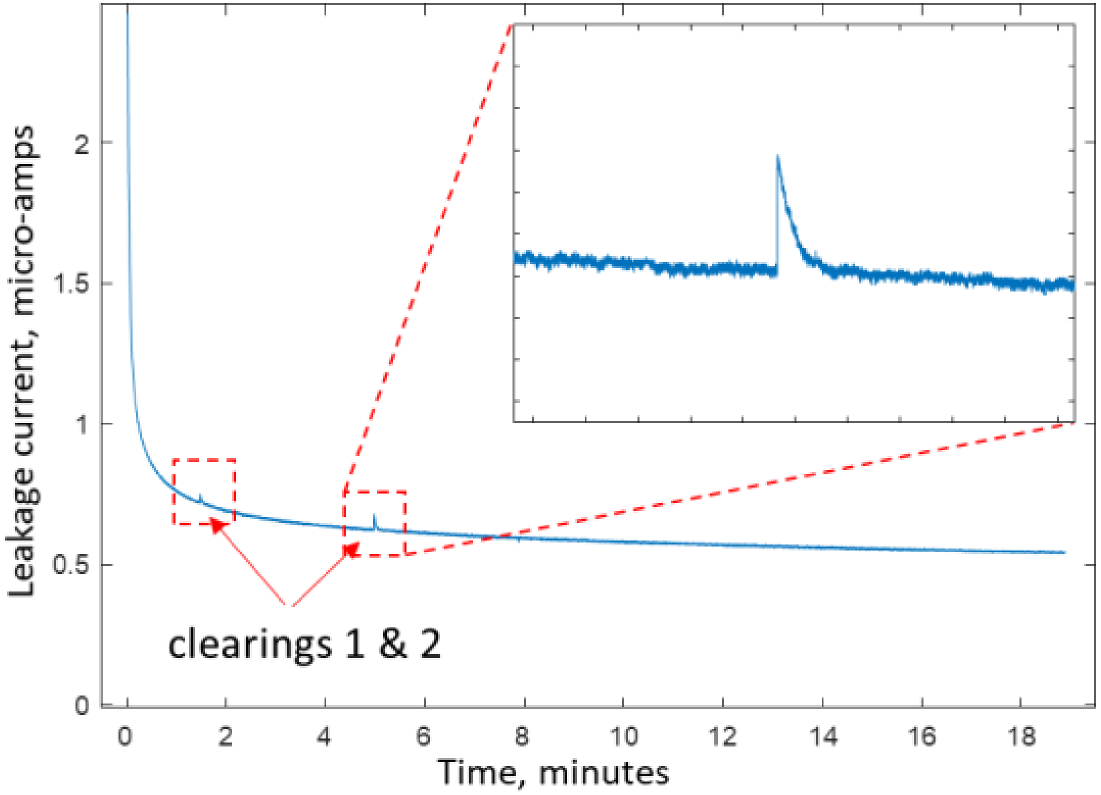
t = metallization thickness (minimize)
V = voltage across dielectric (minimize)
f(p) = inverse function of interlayer pressure

- Balancing the material composition facilitates defect clearing

$$Al_{(s)} + CHNO_{dielectric} \rightarrow Al_mO_n + CO, CO_2, C_xH_y$$

- A Yializis "Metallized Capacitors" chapter in the *Handbook of Solid state Batteries & Capacitors*, edited by M. Zafar A. Munshi (1995).
- A Yializis, "Polymeric Monolithic Capacitor," US Patent 10,102,974, (2018)
- NanoLam® technology

Clearing Capability



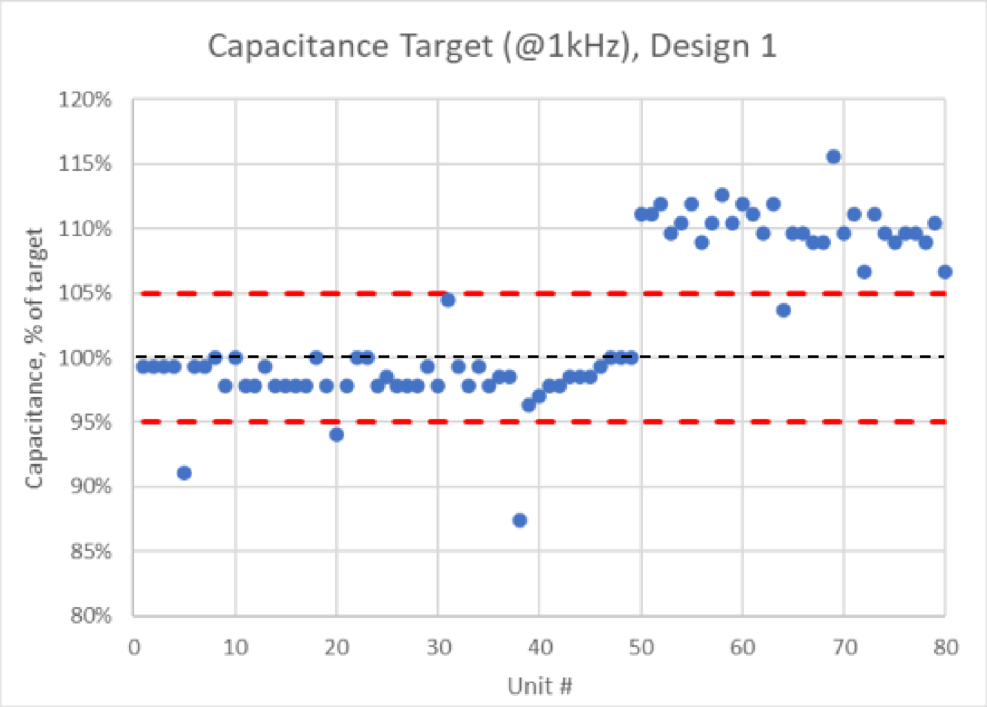
- Clearing events are difficult to detect. Voltage does not sag during a clearing.
- ΔC from a clearing is undetectable, but accumulates with progressive clearing events
- Three clearings captured over cumulative 6 hours of charge time on two units up to 130% rated voltage.

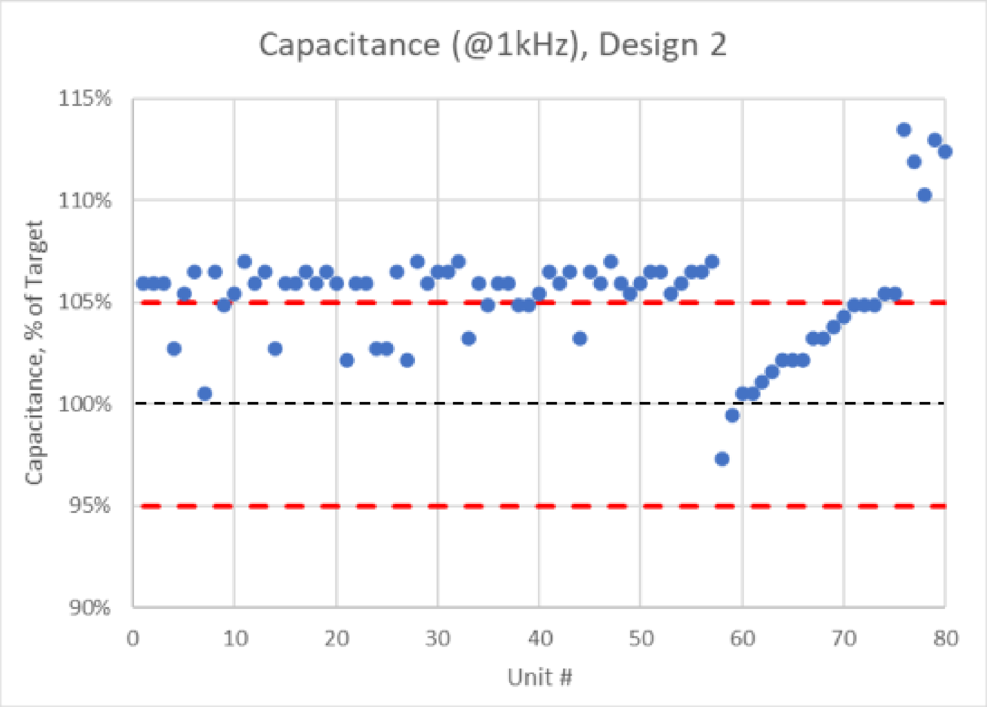
Clearing #1: ~100 mW
Clearing #2: ~290 mW

Baseline Characterization

Baseline characterization

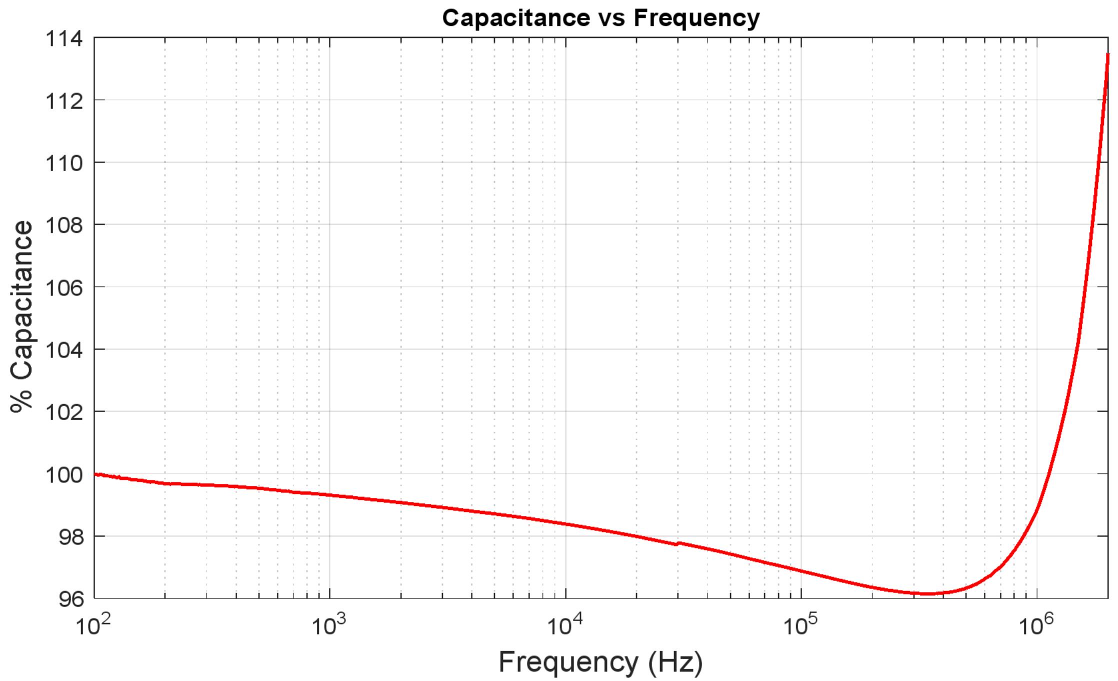
- Capacitance not easy to dial in for small batches, but good consistency within groups
- All but 5 units of Design 11 would be within ± 10% of target. Some capacitors spec'd at ± 20%

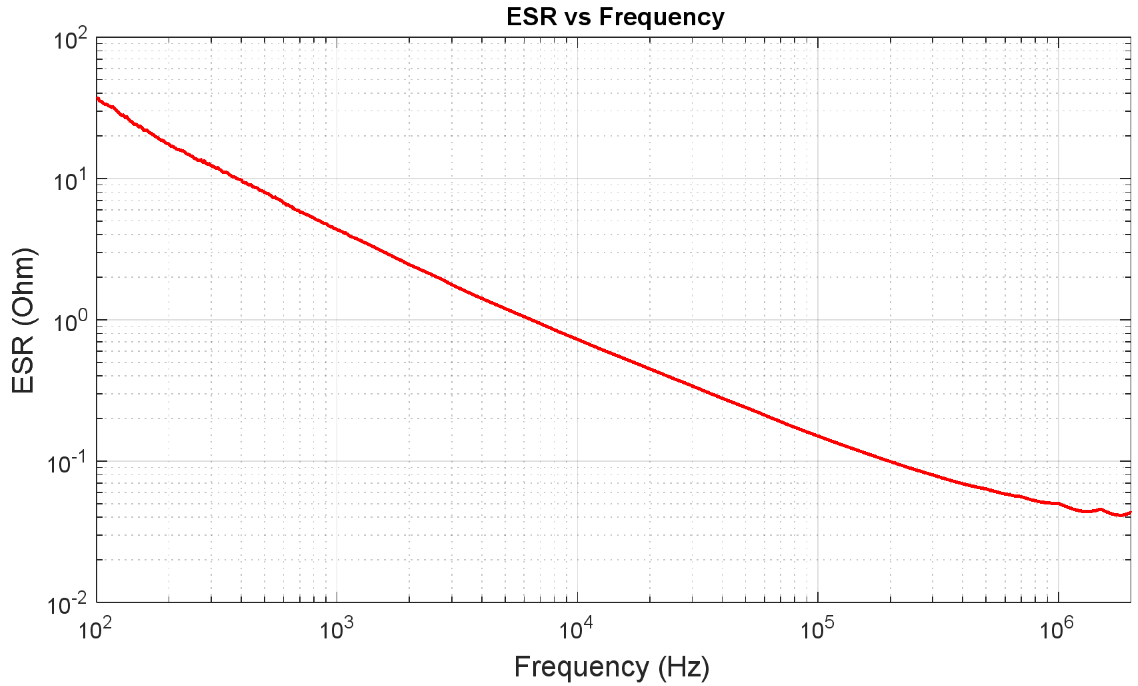




Low Voltage Characterization

- Capacitance higher than expected
- Dissipation factor: 0.6% (typical)
- Impedance: 25-40 mΩ @ 2.5 MHz (nominal discharge frequency)

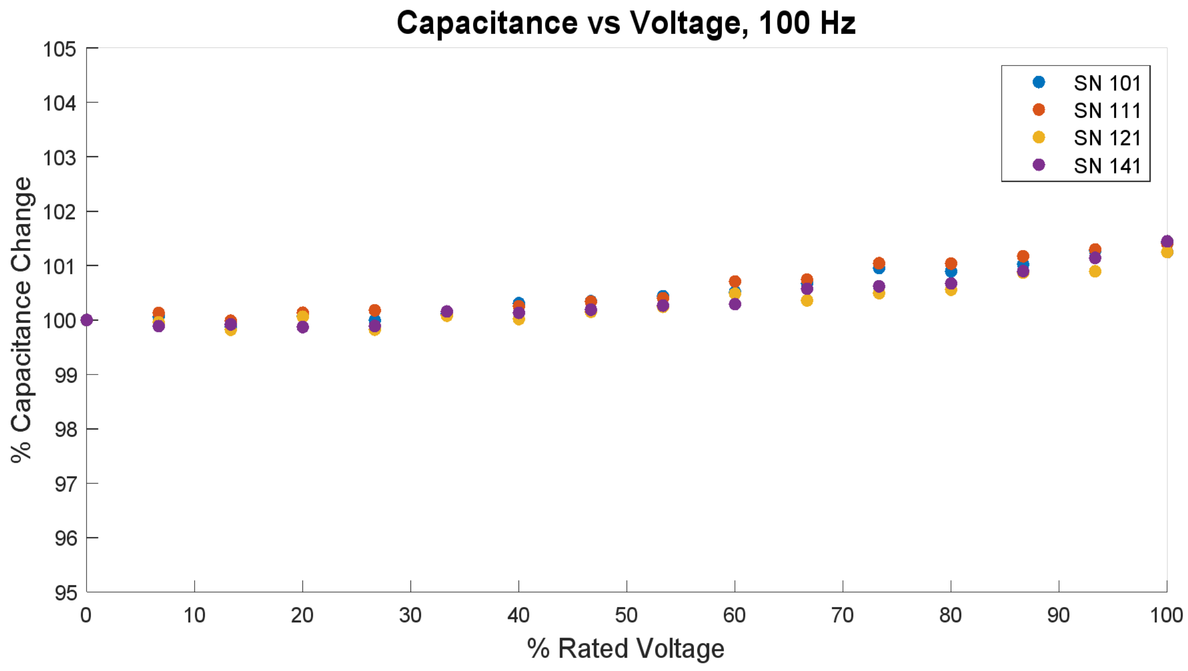


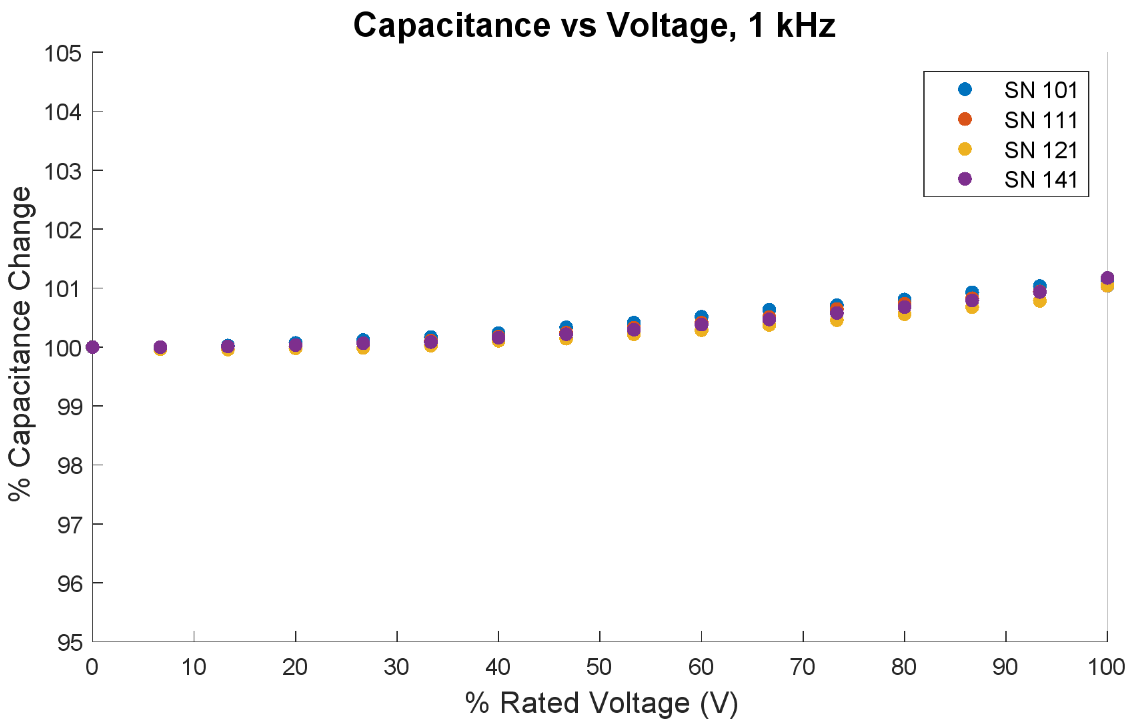


Capacitance vs Voltage

PML capacitors very stable across voltage

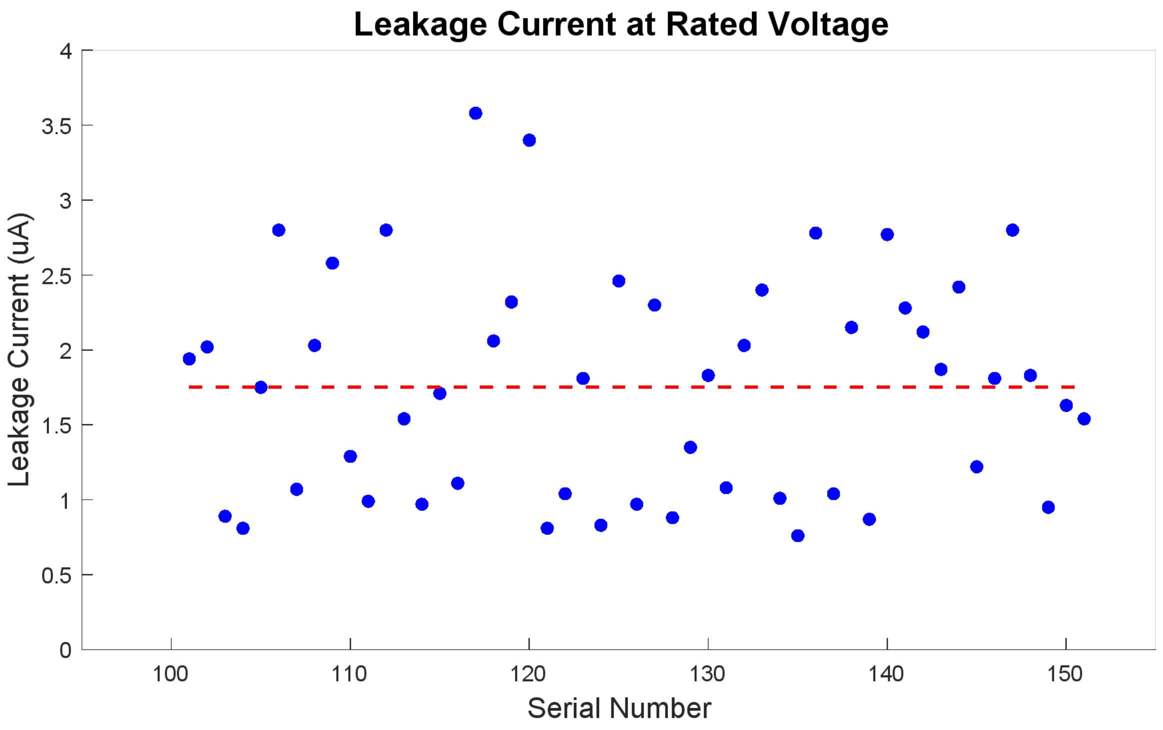
- < 2% variation through rated voltage

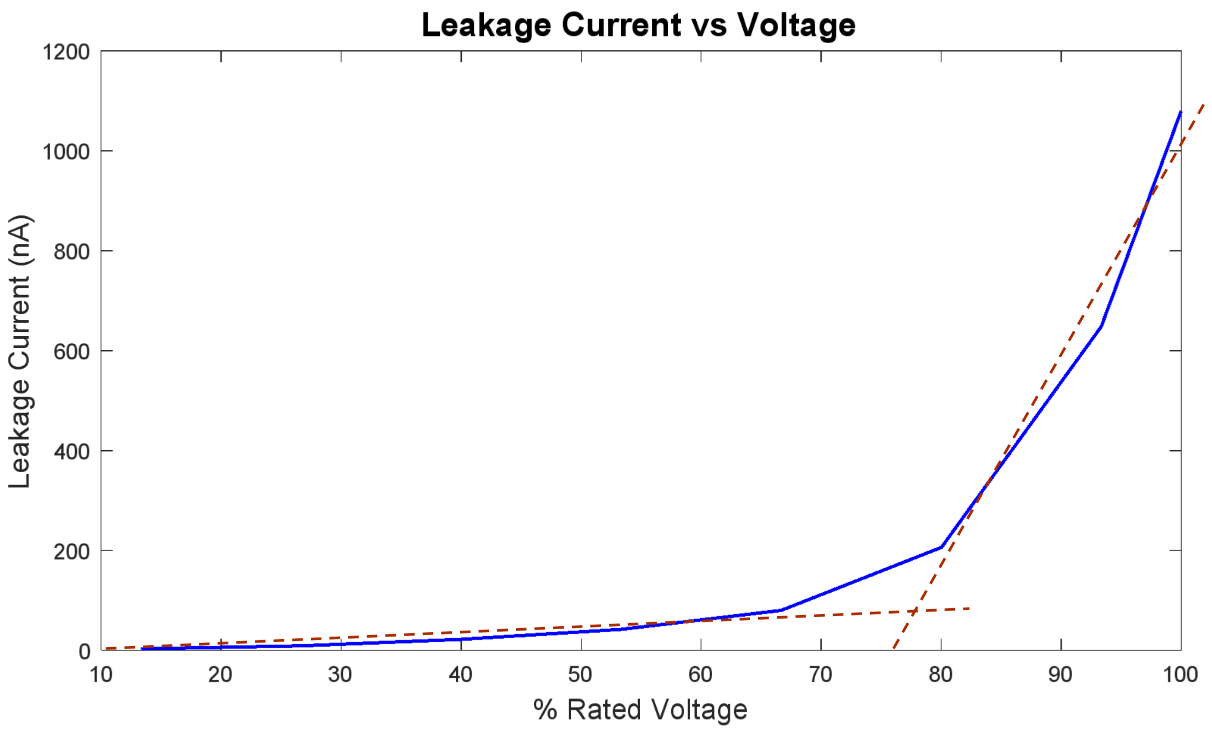




Leakage current at high voltage

- Leakage current higher than ceramic capacitors, but still low (micro-amps)
- Leakage current versus voltage demonstrates a behavior change > 80% rated voltage

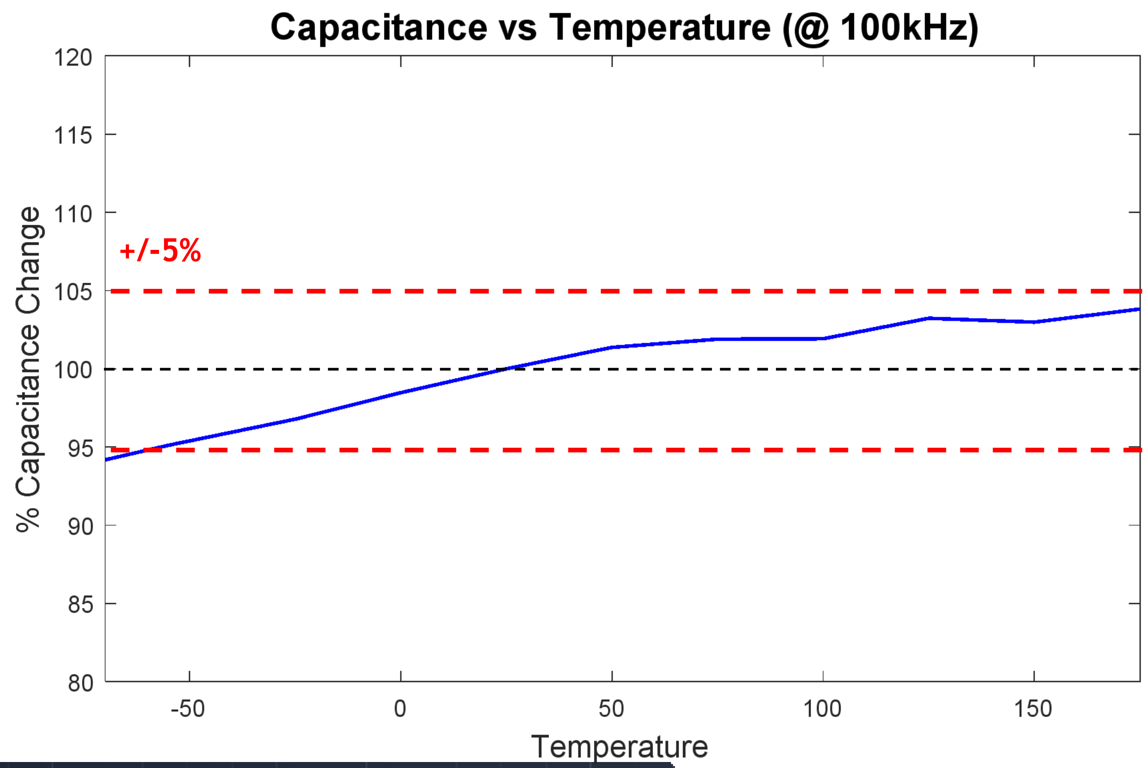


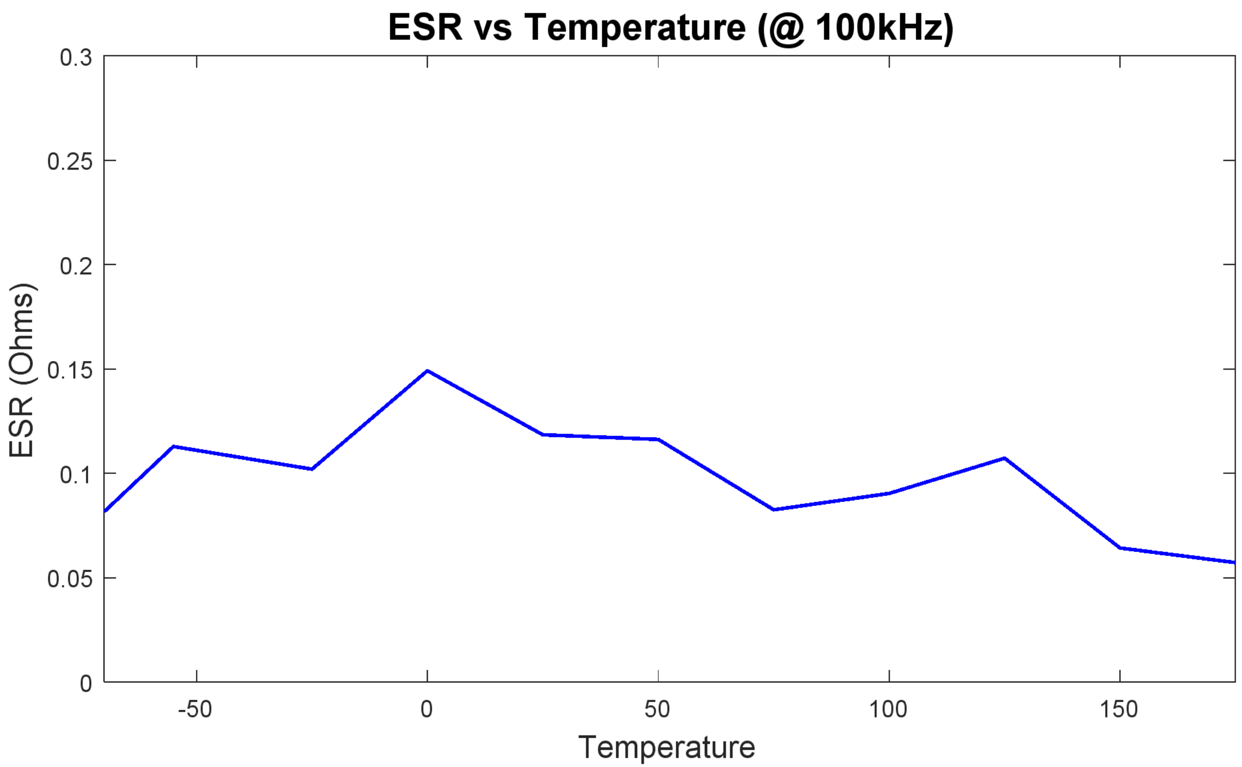


Thermal Characterization

Low voltage impedance measurement across temperature (-70°C to 175°C)

- Capacitance fairly flat
- ESR fairly flat (< 150 mΩ)

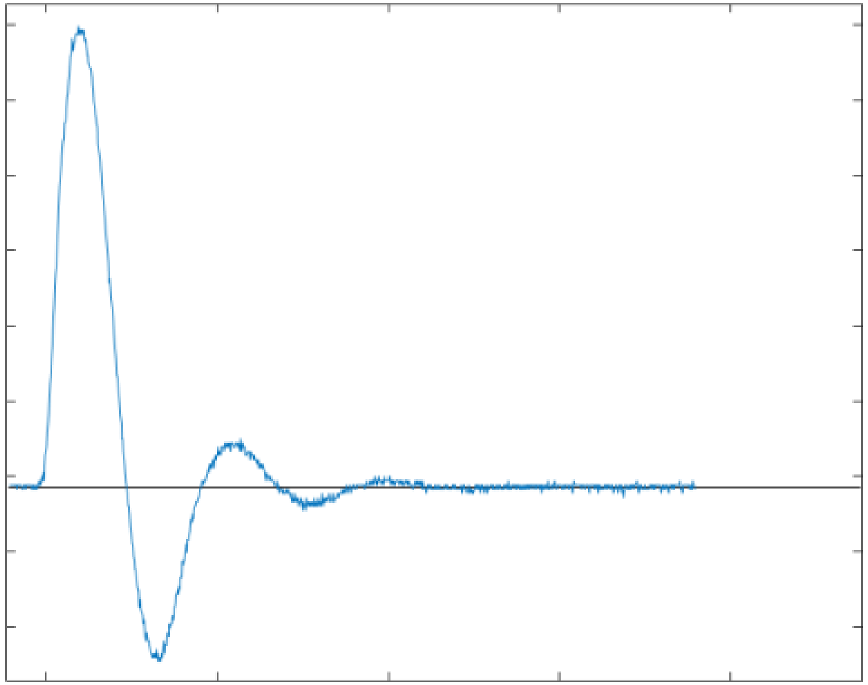


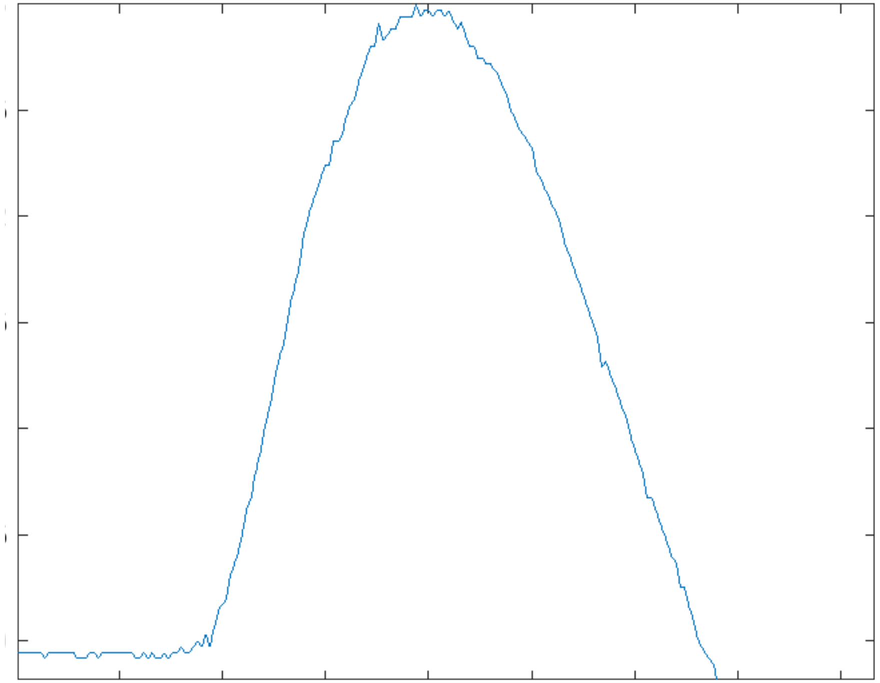


Pulse Discharge

Pulse discharge testing

- Pulse discharges across range of voltages up to 100%
- Characteristics very similar to legacy ceramic capacitor





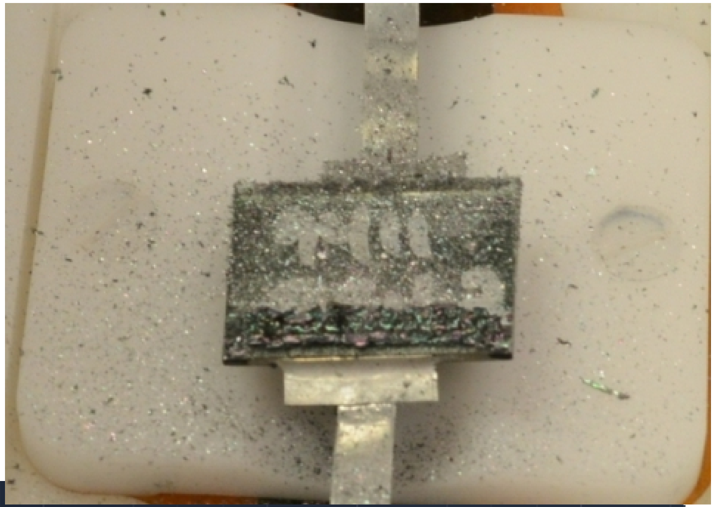
Repeated Pulse Discharge

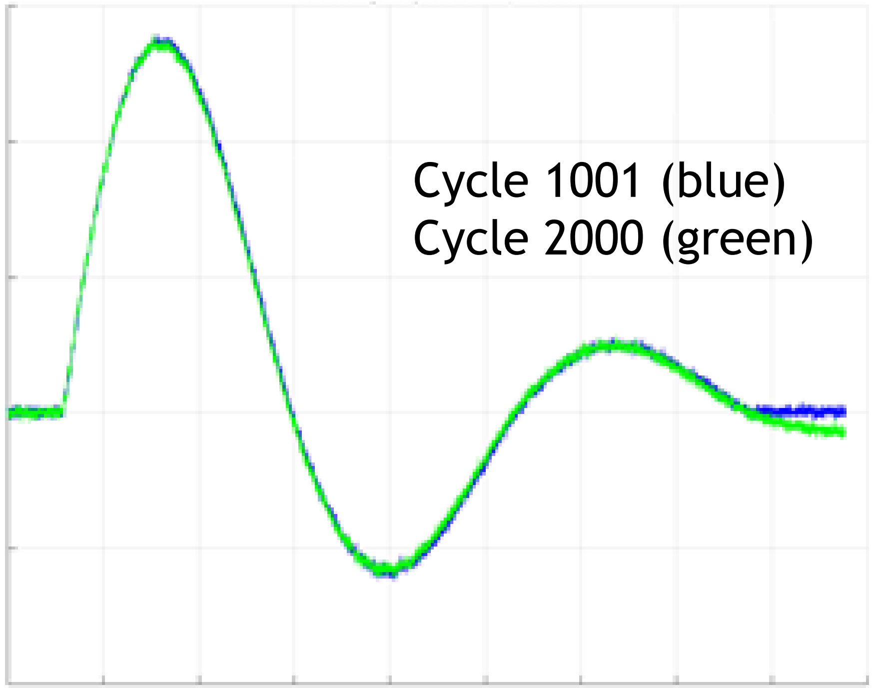
Pulse discharge tester, 5000 discharge cycles

- There was obvious erosion of the metallic end-spray on two units (worst one shown)

One unit after 5000 cycles

Another unit after 5000 cycles





Small losses in capacitance except end-of-life of Unit 1

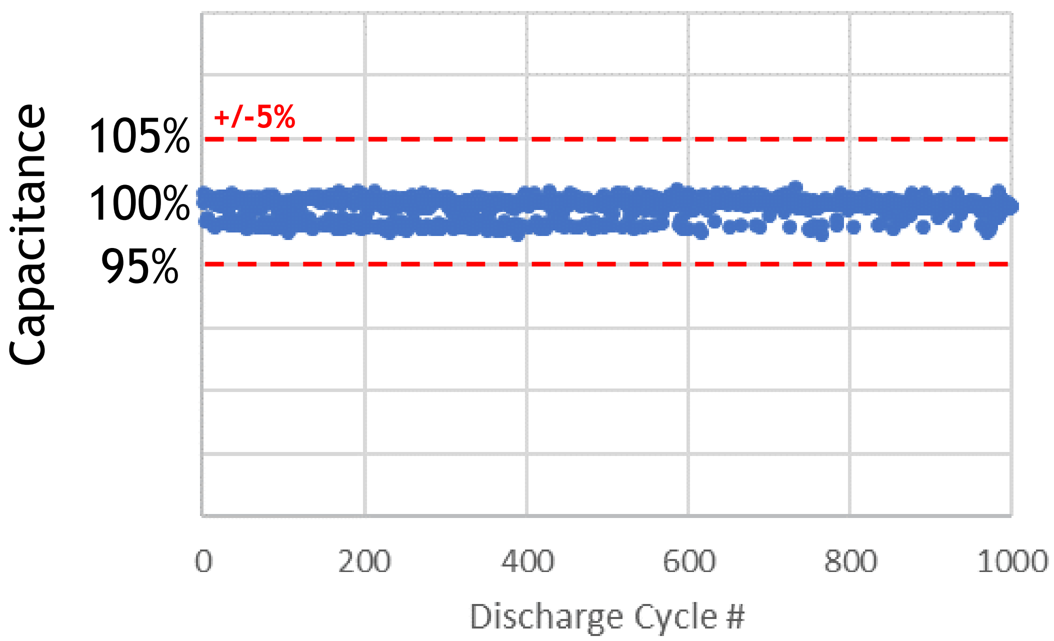
Unit	ΔC, %
1	-39%
2	-2.5%
3	-3.4%
4	-4.4%
5	-1.2%

Repeated Pulse Discharge

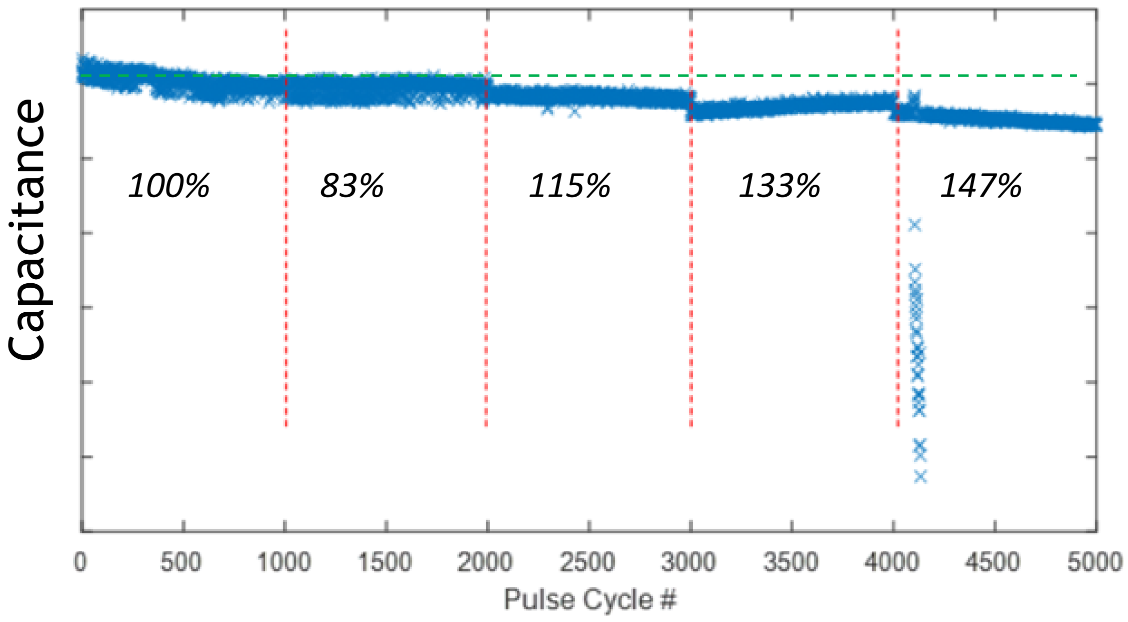
Pulse discharge tester, 5000 discharge cycles

- There was obvious erosion of the metallic end-spray on two units (worst one shown)

Capacitance dropped 0.5% over second 1000 cycles



Capacitance dropped ~4.5% over 5000 cycles



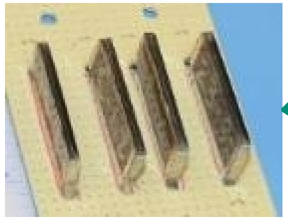
Thermal Accelerated Aging

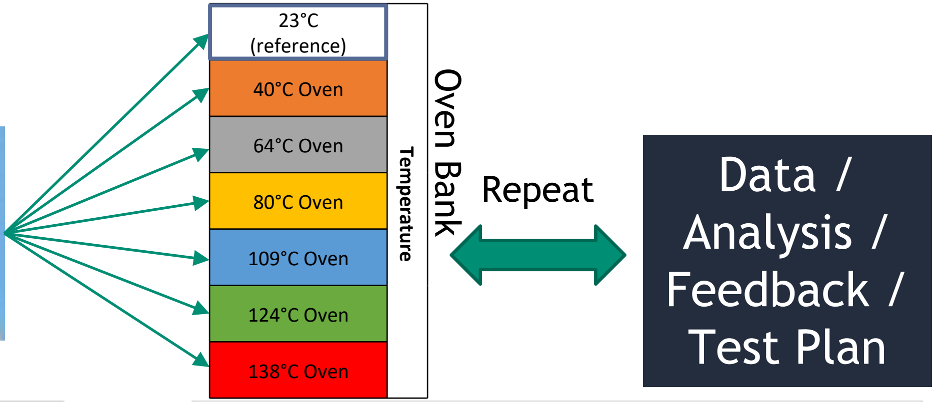
Bare capacitors up to 138°C

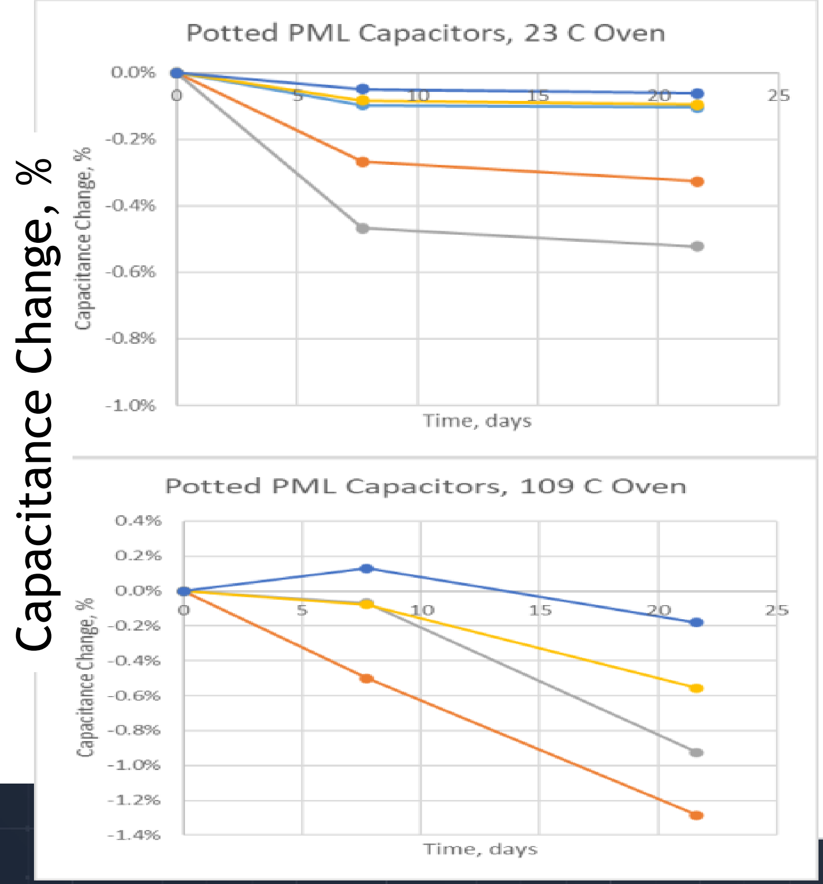
Potted capacitors up to 109°C

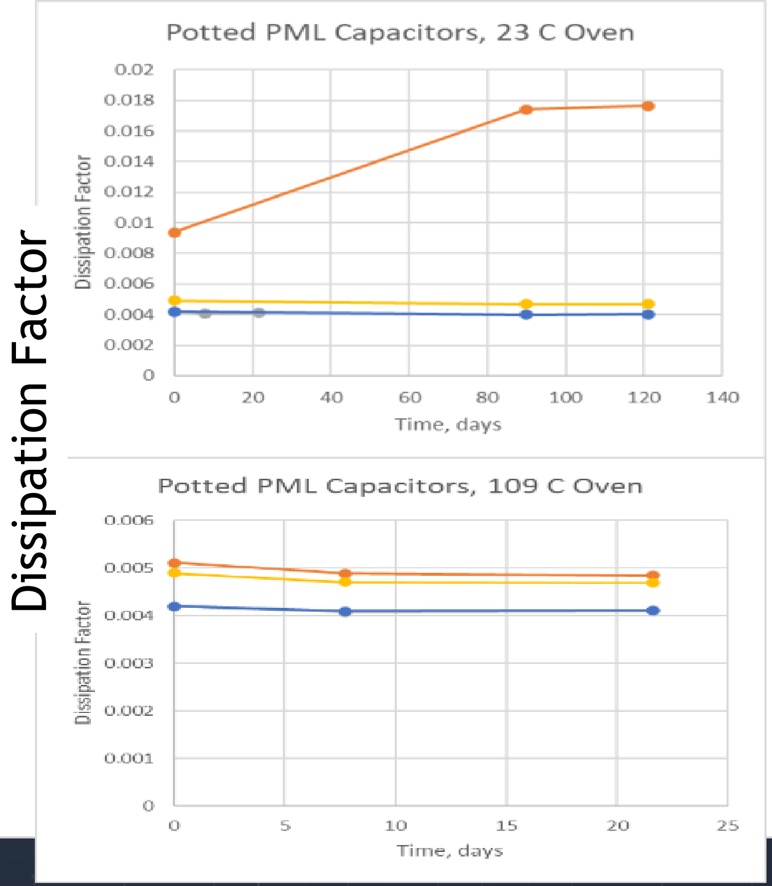
- Reduced leakage current and dissipation factor, likely from moisture removal
- Also 600 hours 95%RH/40°C. Moisture effects were reversed with 40°C drying (24 hrs)

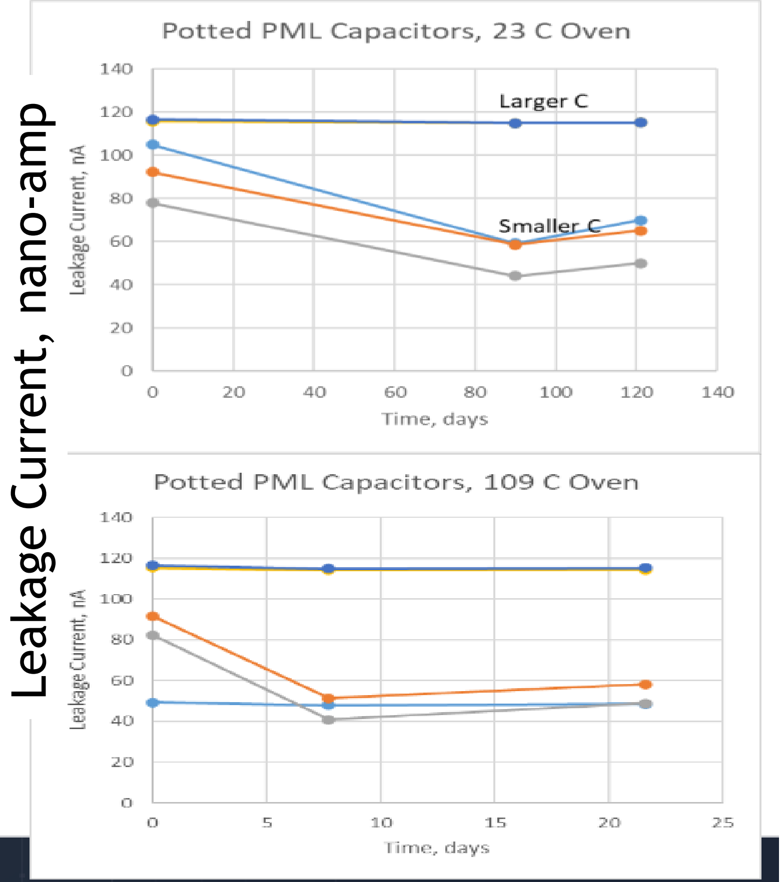
54x Bare PML Capacitors





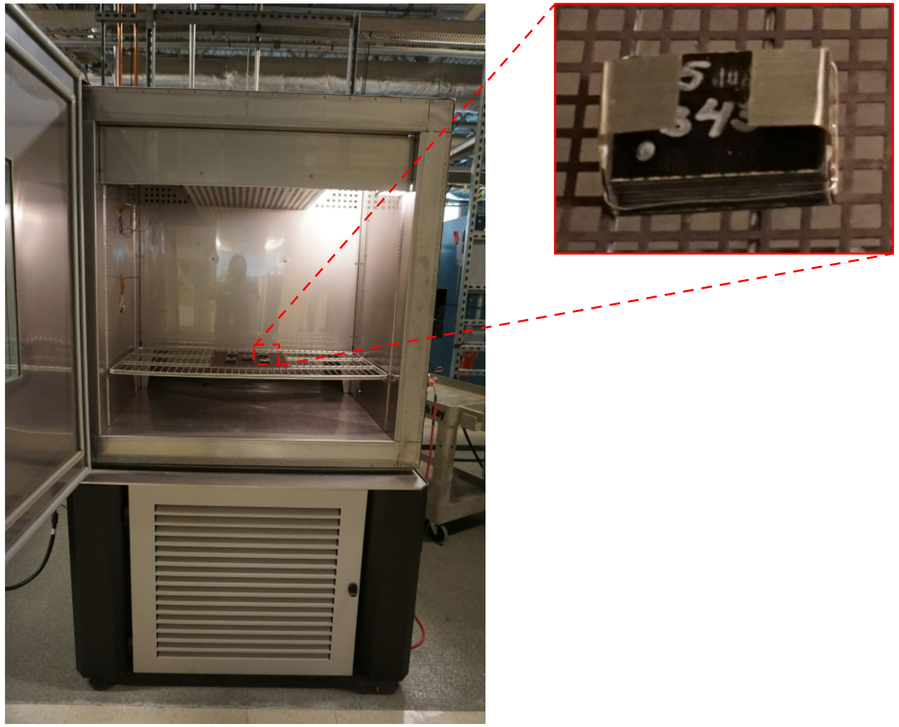






Humidity Accelerated Aging

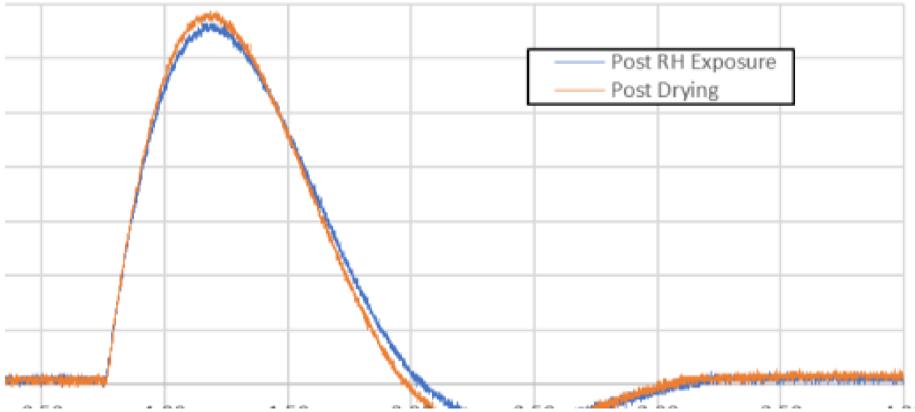
- *5 bare parts exposed to MIL-STD 202 Method 103B, test condition B*
  - *95% humidity, 40℃, 96 hours*
  - *Capacitance, leakage current, and dissipation factor all increased post-exposure*
  - *Drying period at 40℃ restored values, except for minor loss of capacitance (one unit lost >10% capacitance)*
  - *Pulse discharges had more energy when dry (lower dissipation factor)*



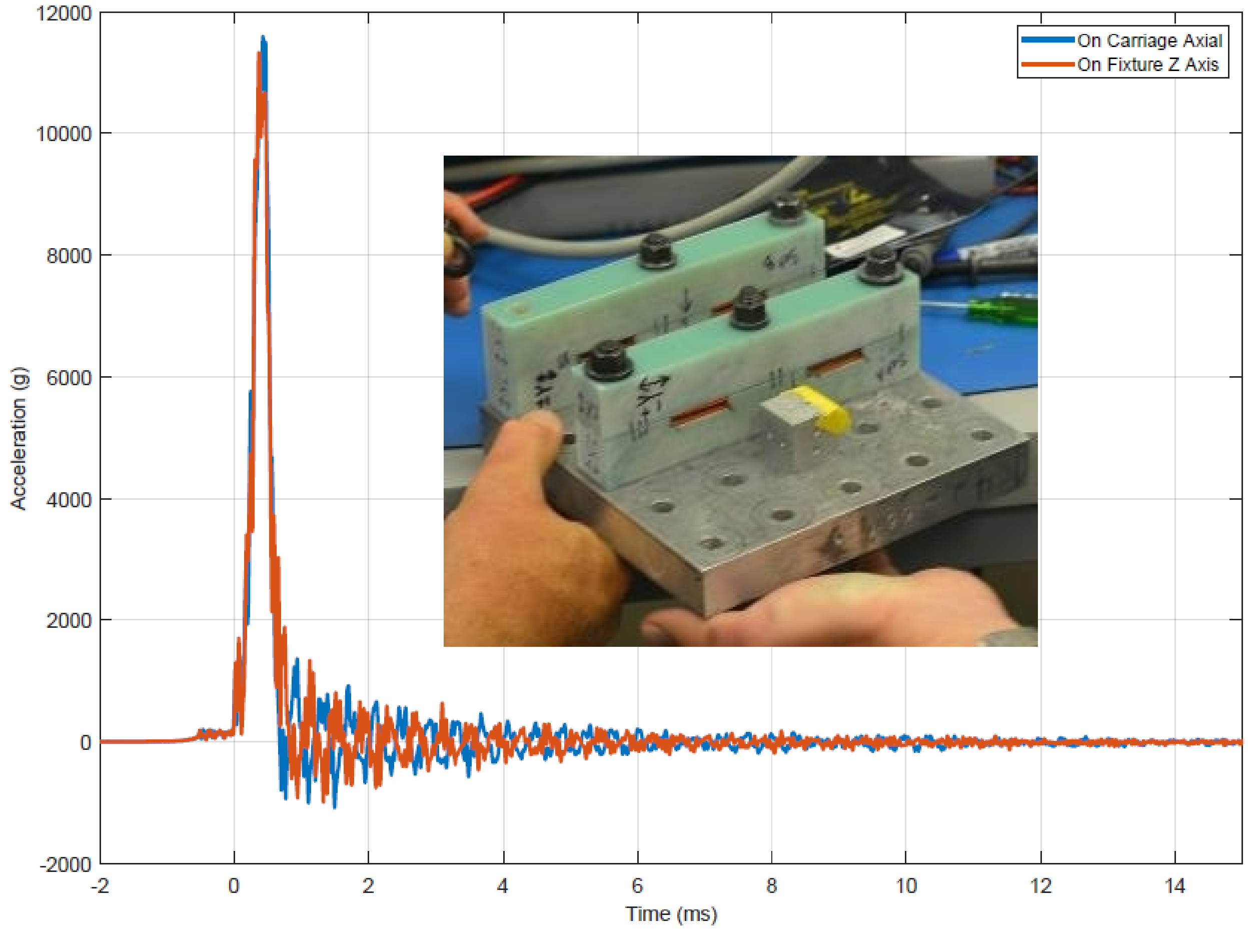
	Capacitance Change		
S/N	**as received**	**after RH exposure**	**post-dry**
B27	100%	108%	99.4%
B30	100%	108%	99.0%
B43	100%	109%	99.6%
B46	100%	108%	97.1%
B48	100%	107%	89.2%

Average DF 0.45% → 0.58% → 0.45%

Pulse Discharge Comparison (unit B46)



Mechanical Shock Testing



Testing:

- 200G (2 ms)
- 2000G (0.5 ms)
- 12,000G (0.5 ms)
- 5x in each orientation (X,Y,Z) at each level

Individual capacitor chips survived 200 and 2000 G shocks without change.*

*One unit lost ~30% capacitance, but it appeared to be related to the electrical connection. (Verification coming.)

Post-test data not been taken yet for 12,000G shocks.

Conclusions and Future Work

- Two prototype polymer-based multilayer capacitors have been developed
- The technology demonstrates good design versatility for capacitance and voltage
- Chemical, physical, and mechanical testing shows stable properties and broad use environments
- Mechanical impact shock testing and Sandia (12,000 G)
- Upcoming
  - Mechanical shock testing with AFRL coming (60,000 G expected)
  - High-voltage testing at temperature extremes
  - Modeling of impact dynamics, leading to…
  - Next generation design for improved survivability

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