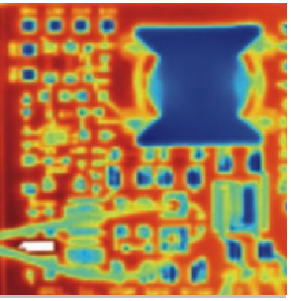

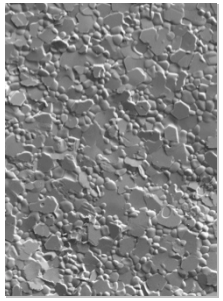

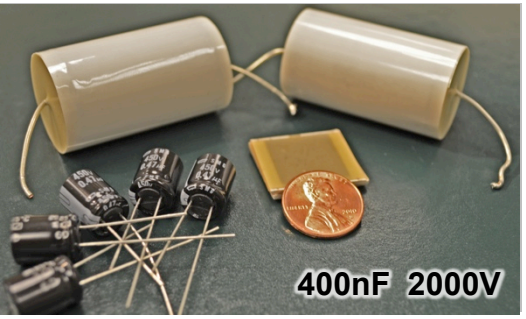

Sandia National Laboratories

Exceptional service in the national interest

Novel High Energy Density Dielectrics for Scalable Capacitor Needs

27 September 2012

Geoff Brennecka

The author gratefully acknowledges the support of Dr. Imre Gyuk and the Department of Energy's Office of Electricity Delivery and Energy Reliability.

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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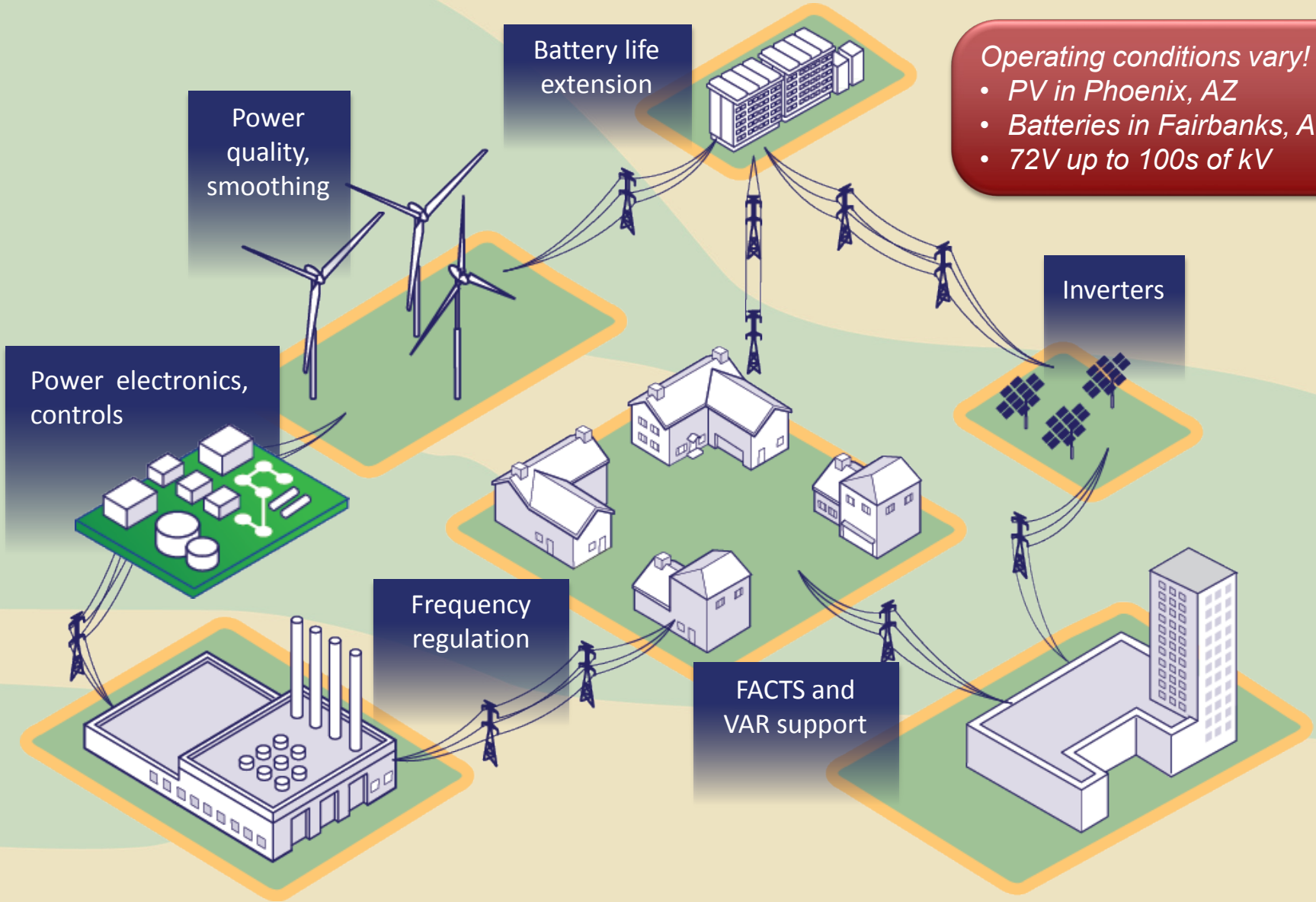
Project

- Currently-available capacitor options force undesired choices:
  - (power, capacitance) vs. reliability
  - performance vs. (temperature, voltage) stability
  - *Capacitors are often not deployed where they could be beneficial, or are deployed and fail (or are severely derated)*

- Stationary storage and related applications can realize significant value via improved capacitor performance and reliability
  - Improve reliability and efficiency of high temperature power electronics
  - Distributed VAR support, power quality, and frequency regulation
  - Reduce power load on primary storage batteries
  - Other power control systems and beyond…

Capacitor Needs for ESS



Operating conditions vary!
- *PV in Phoenix, AZ*
- *Batteries in Fairbanks, AK*
- *72V up to 100s of kV*

Performance Space

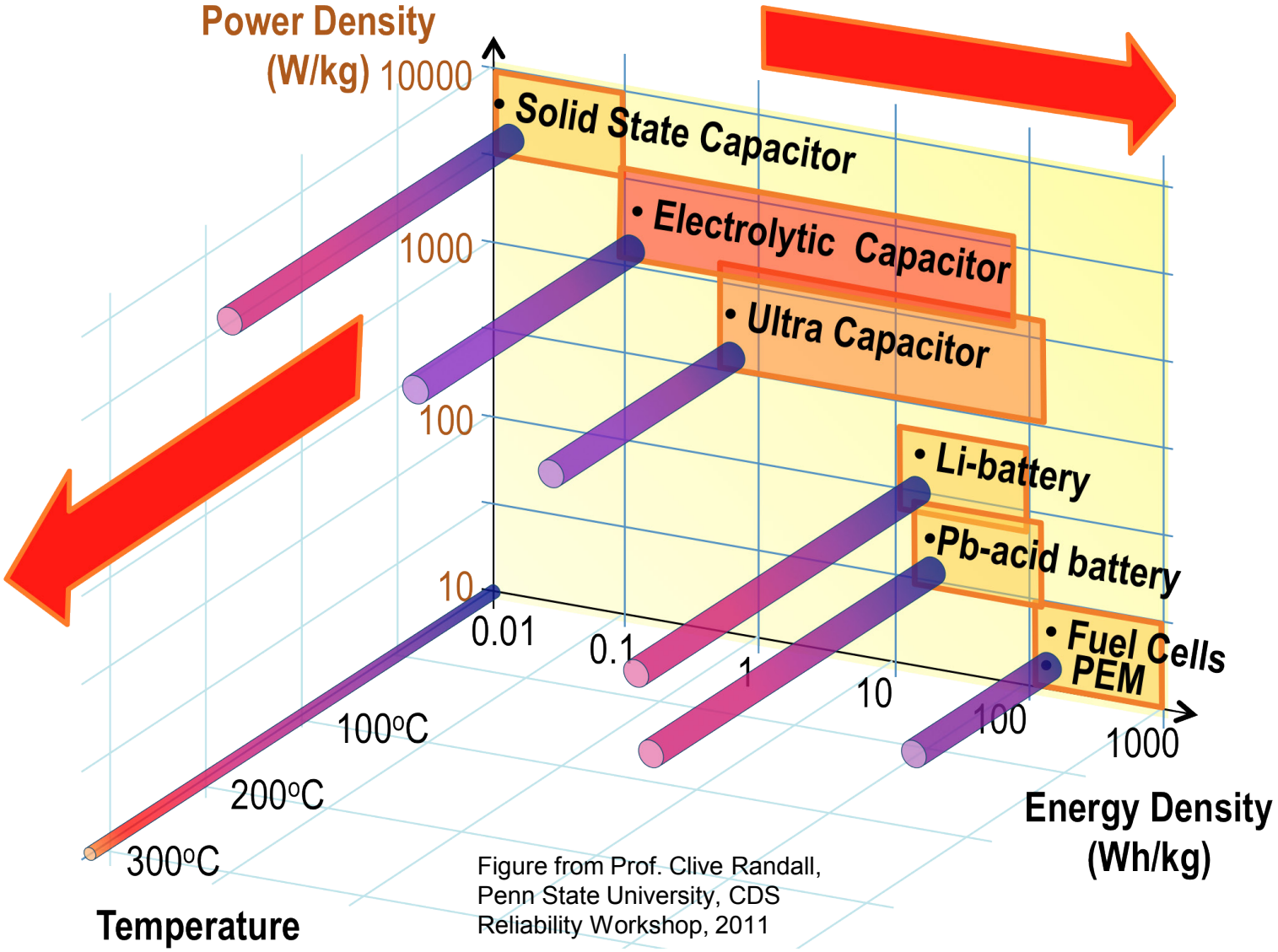
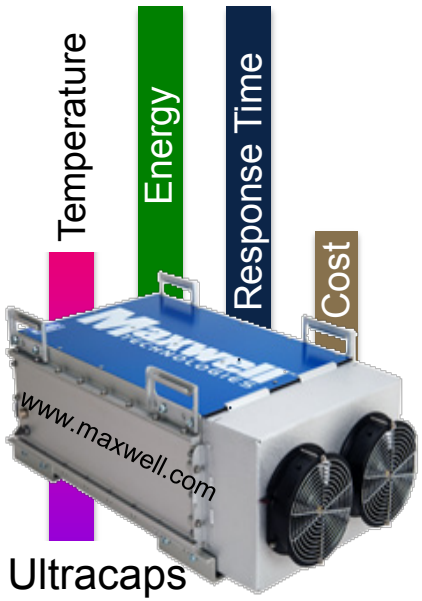


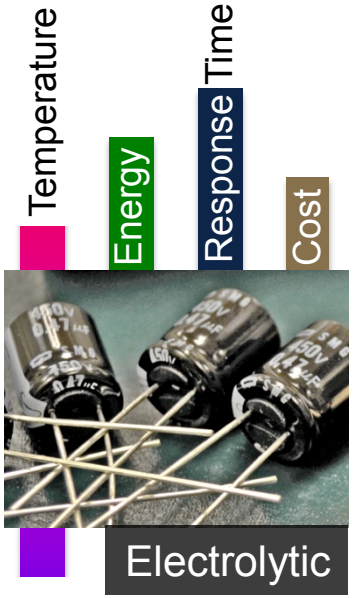
Figure from Prof. Clive Randall, Penn State University, CDS Reliability Workshop, 2011

Capacitor Comparison



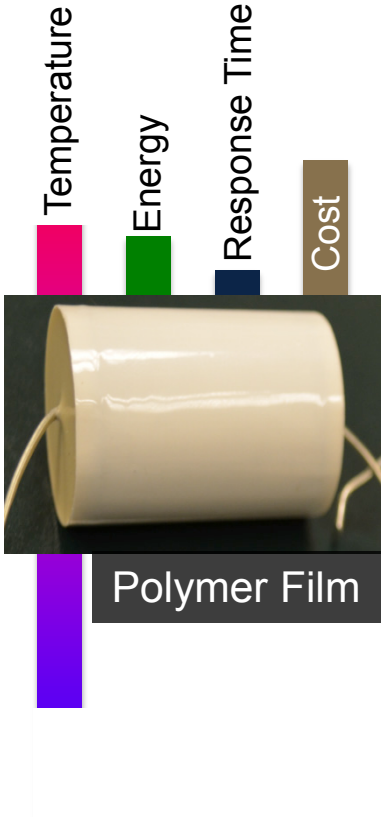
Ultracaps

10°C temperature increase = 50% lifetime reduction



Electrolytic

Polarity undesirable; poor ripple handling and reliability



Polymer Film

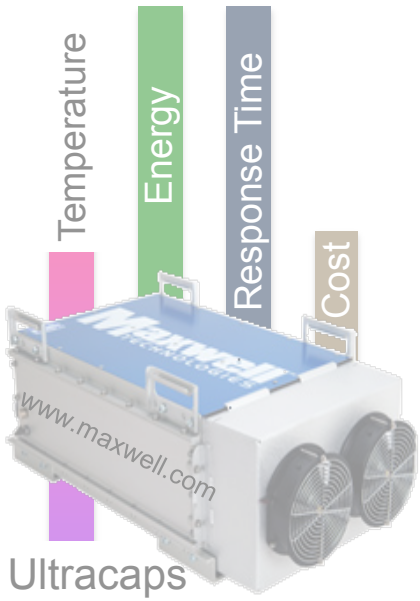
Temperature accelerates degradation; graceful failure

Ceramic

Handle ripple currents and temperature well; fail catastrophically

Capacitor Comparison

Sandia National Laboratories



Ultracaps

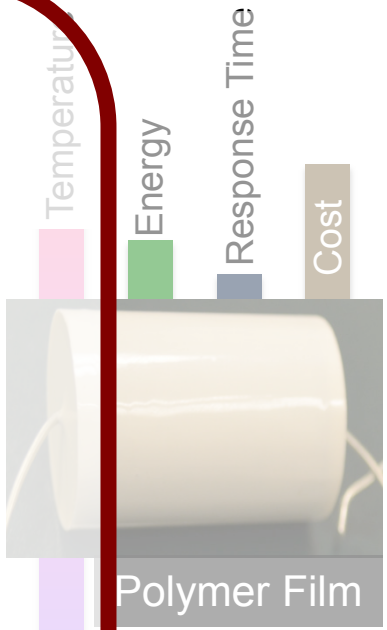
10°C temperature increase = 50% lifetime reduction

Electro ytic

Polarity unde
poor ripple ha
and reliability

New BZT-BT Ceramics

Improve upon strengths of ceramics (ripple, temperature) with higher energy density and greater reliability



Polymer Film

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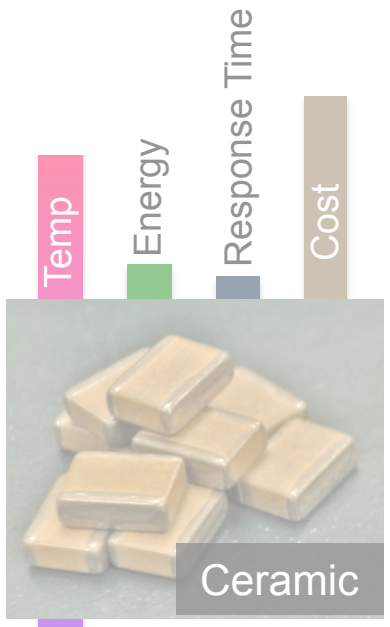
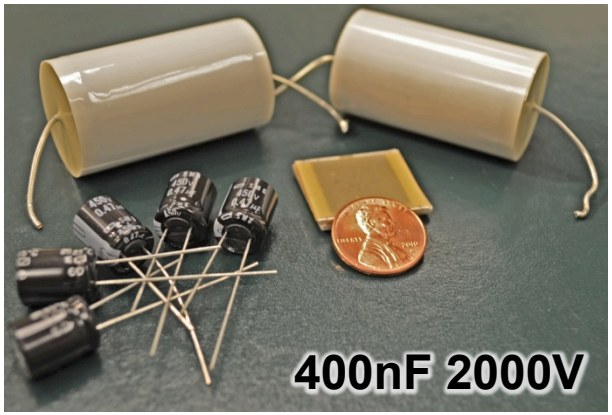


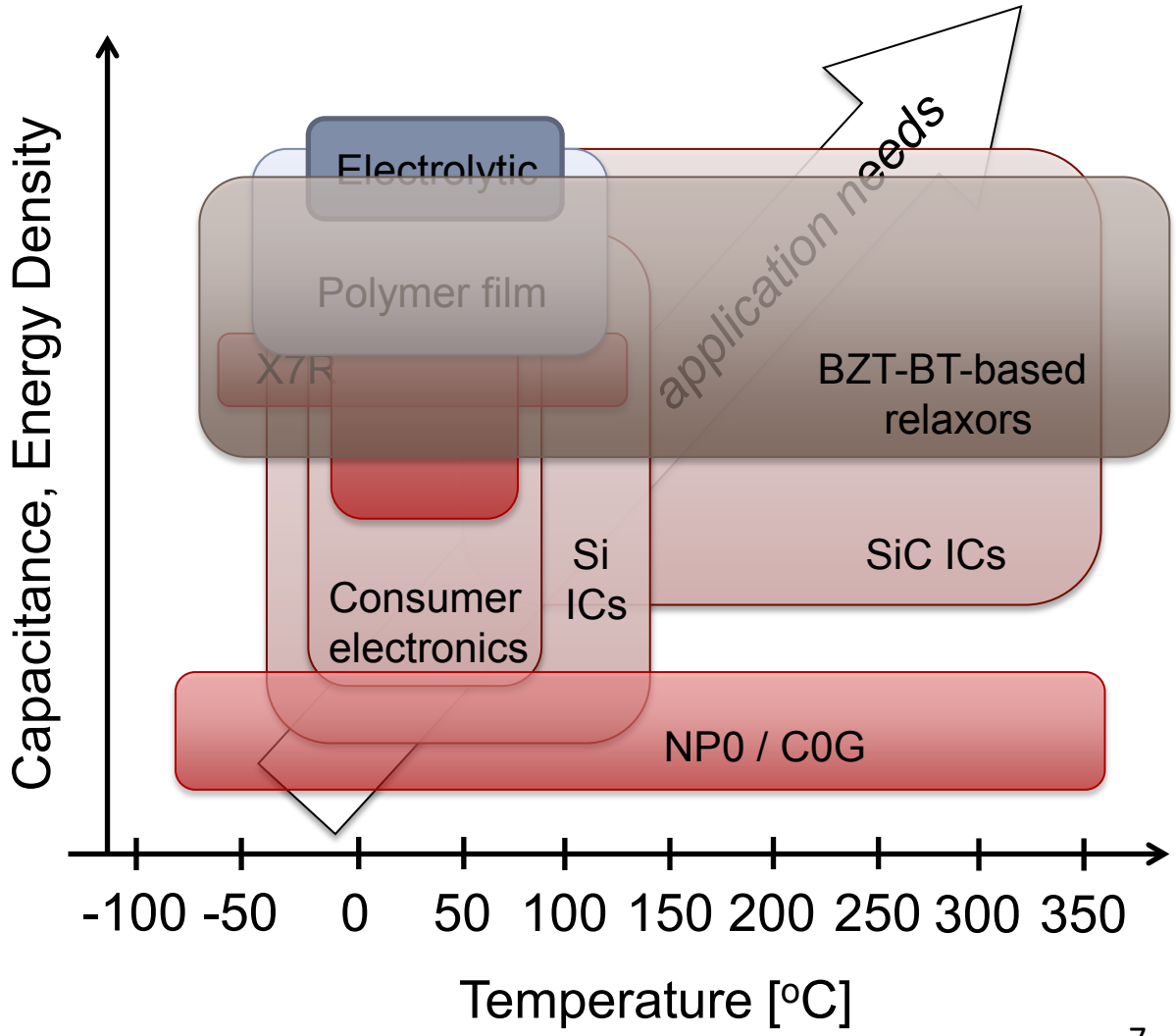
Ceramic

Handle ripple currents and temperature well; fail catastrophically

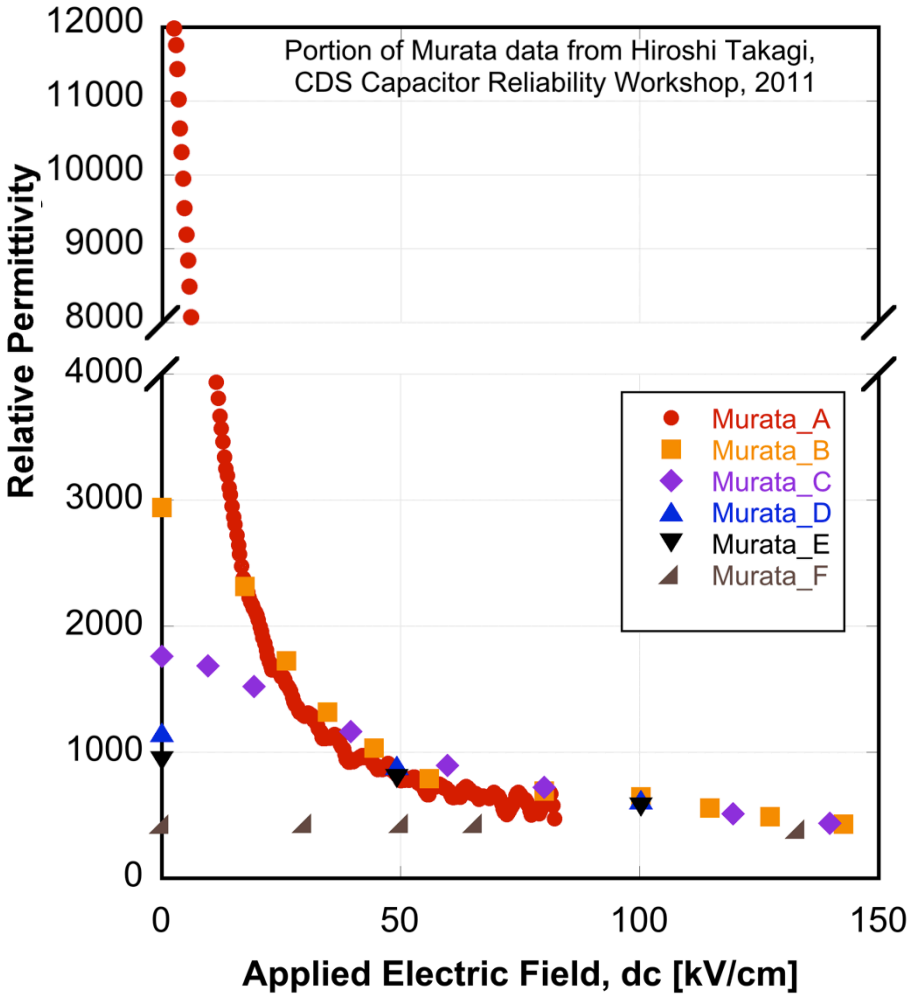
Application Space

- BZT-BT-based MLCCs offer comparable or better energy density, better ripple current handling, and significantly greater temperature stability

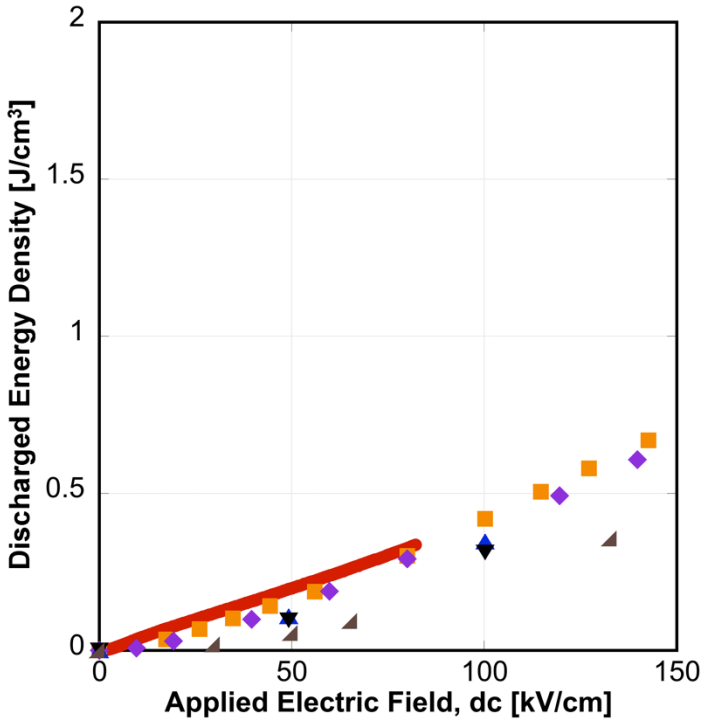




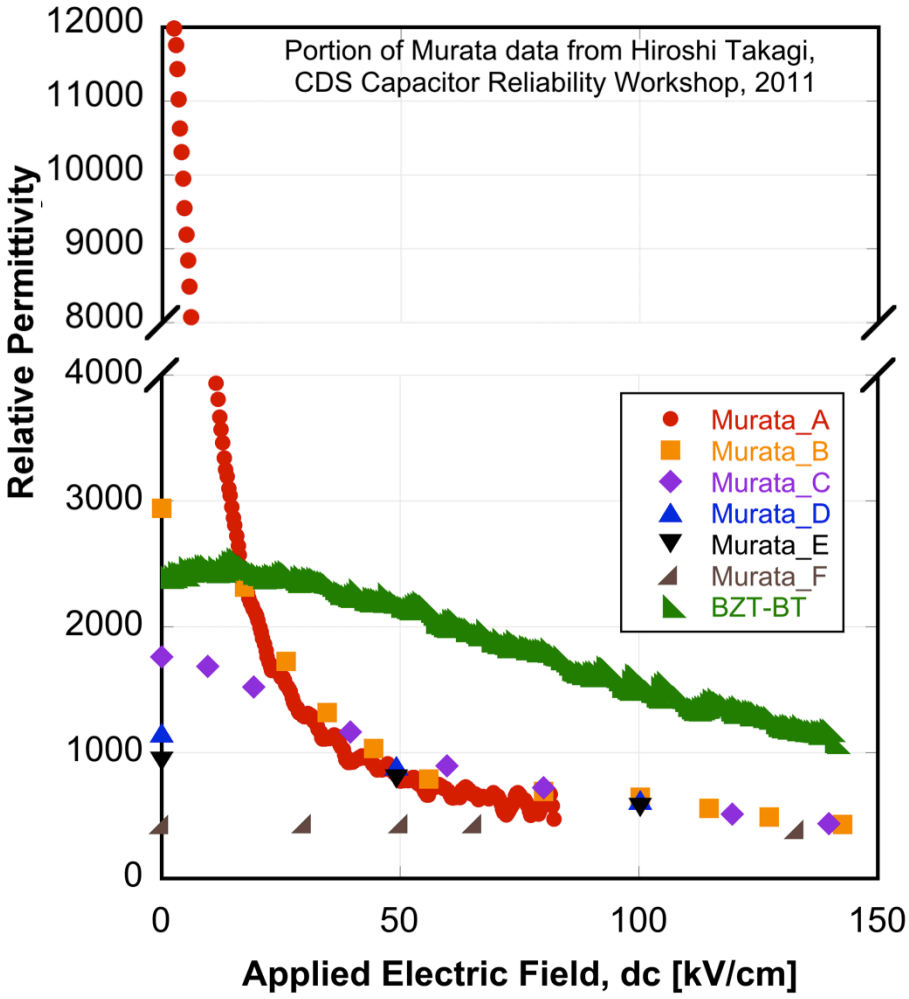
Minimize Voltage Tuning



- Voltage tuning and dielectric breakdown severely limit stored energy density



Minimize Voltage Tuning



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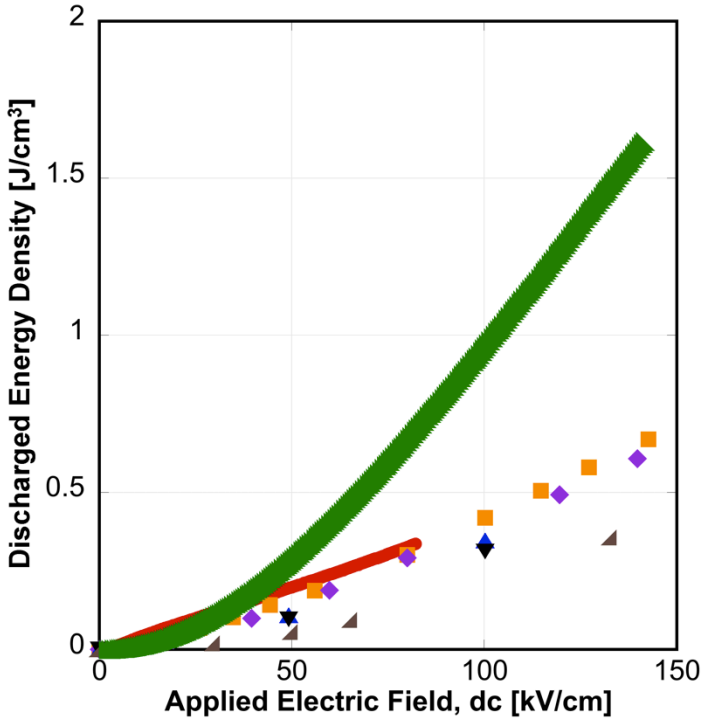
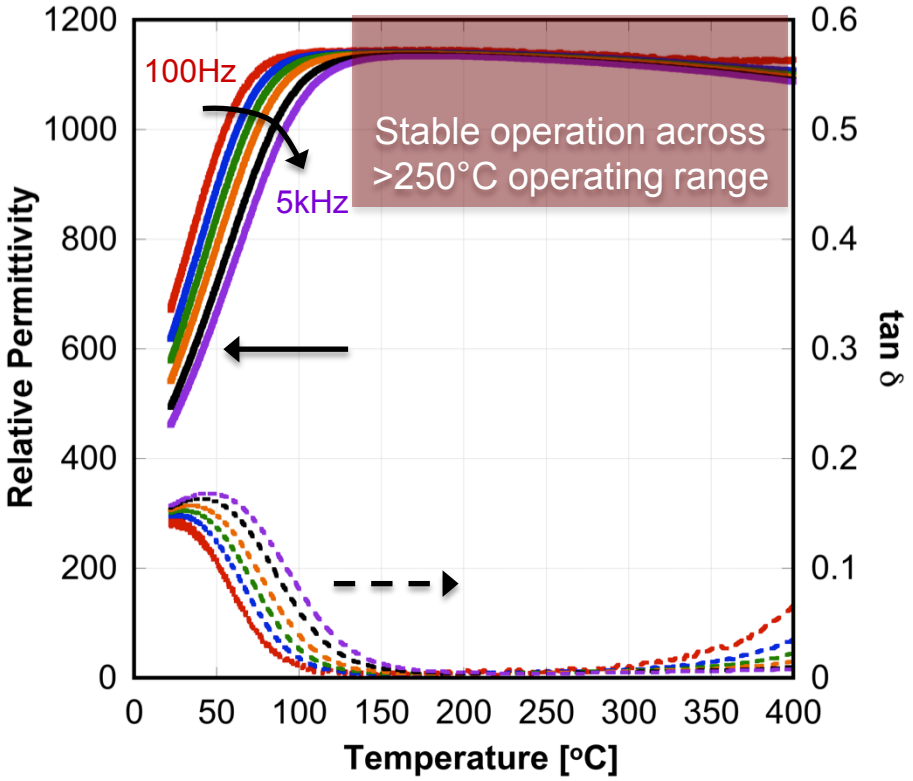
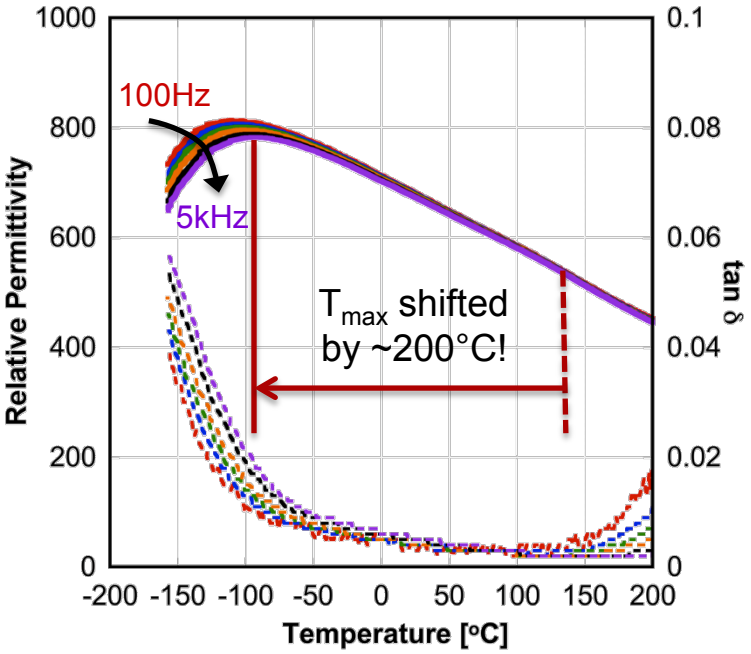


Improve Temperature Stability

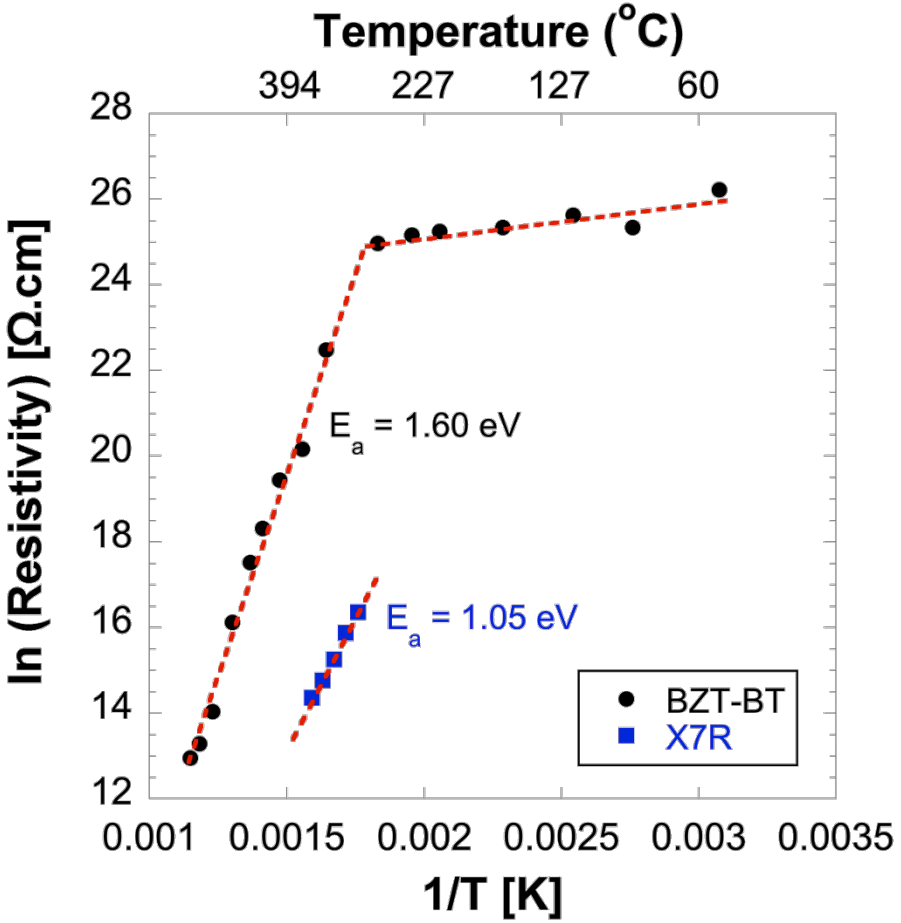


In collaboration with Prof. David Cann at Oregon State University

- Relaxor behavior induced by doping; can be shifted
  - Stable operation over broad temperature range desired
  - Reliable operation at high temps requires high resistivity



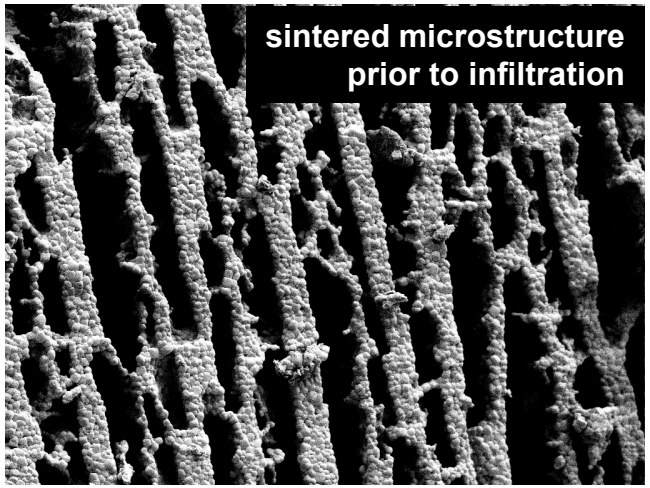
Defect Control for Reliability

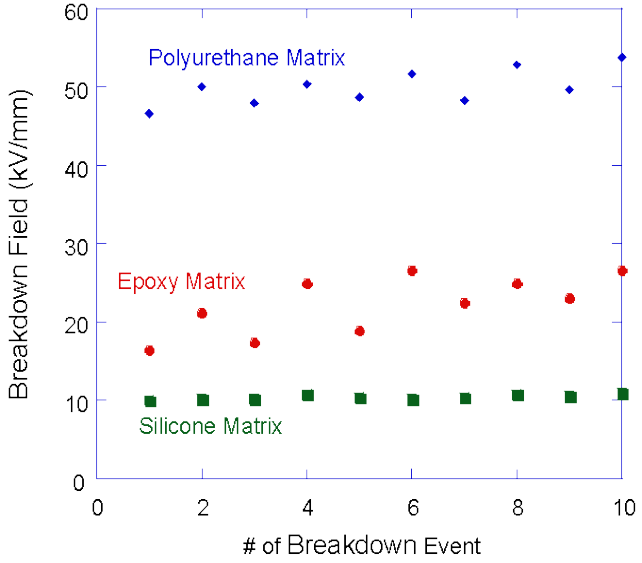


- Long-term reliability is directly correlated with high resistivity, particularly at elevated temperatures
  - Mobile defects lead to long-term degradation
  - Correlation of electrical activation energy with optical band gap measurements strongly suggests highly effective trapping of charged defects
  - In early stages of accelerated lifetime testing

In collaboration with Prof. David Cann at Oregon State University

Engineering Benign Failure

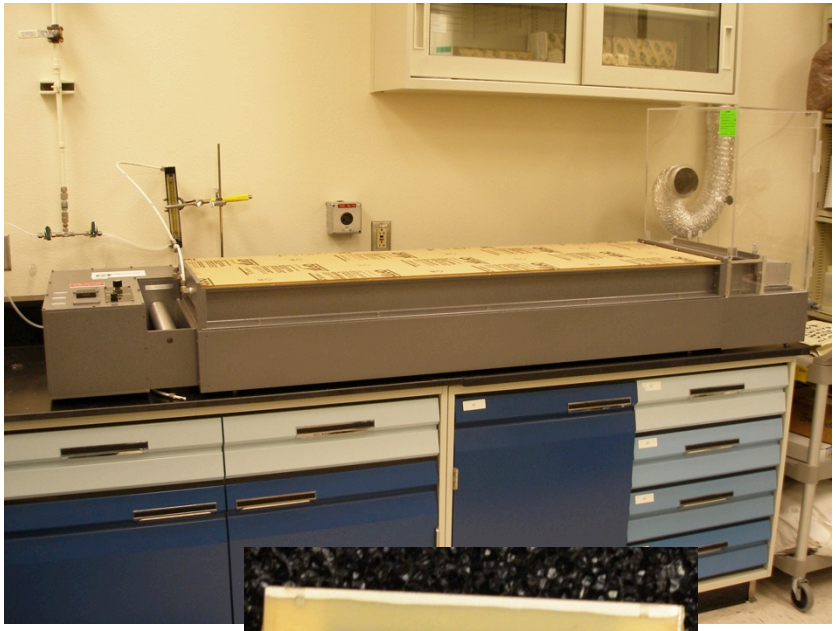




- Ceramics (typically) fail catastrophically
  - Achieving graceful failure would drastically reduce derating
- Freeze cast composites
  - Parallel composite structure maintains (much of) the high permittivity of the ceramic but isolates breakdown evens
  - Polymer infiltration introduces temperature limitations, but as long as the polymer retains high resistivity, variations in other properties are less important

In collaboration with Dr. Ed Gorzkowski at the Naval Research Lab

Scale-Up and Cost Reduction



200nF 2000V MLCC

- Manufacturing-relevant process
  - Successfully scaled-up processing to lab-scale MLCCs using same tape casting approach that dominates commercial MLCC manufacturing
- Cost
  - Materials and processing costs of dielectric are equivalent to (marginally lower than) current commercial MLCCs
  - Cost of MLCCs is dominated by cost of electrodes; current efforts are to demonstrate co-firing with Cu or Ni

FY12 Summary

- FY12 Milestones:
  - Initial permittivity vs. field 'map' for BZT-BT-based compositions
    - ✓ Initiated; ongoing as planned as compositional optimization continues
  - Composition studies for shifting T_{max}
    - ✓ Initiated; optimization ongoing as planned
  - Thin films of BZT-BT-based materials demonstrated
    - ✓ Initiated; optimization ongoing as planned
  - Quantify stressed-volume sensitivity for dielectric breakdown for these vs. common commercial systems
    - ✓ Initiated; additional statistics continuously being added
  - Submit manuscript for publication in peer-reviewed journal
    - ✓ 3 papers already submitted, currently in press
      - N. Raengthon, T. Sebasian, D. Cumming, I.M. Reaney, and D.P. Cann, *J. Am. Ceram. Soc., in press* (2012)
      - N. Raengthon, V.J. DeRose, G.L. Brennecka, and D.P. Cann, *Appl. Phys. Lett., in press* (2012)
      - N. Raengthon, H.J. Brown-Shaklee, G.L. Brennecka, and D.P. Cann, *submitted to J. Mater. Sci. Comm.* (2012).

FY12 Summary

- Additional FY12 accomplishments
  - Successful scale-up from standard laboratory pellets to tape-cast MLCCs of baseline BZT-BT composition
  - Initial proof-of-concept demonstrations of graceful failure of high-permittivity parallel-structured BZT-BT – polymer composites
  - Mechanisms behind defect trapping for improved high temperature resistivity elucidated
  - Transient liquid phase approach successfully demonstrated for reduced-temperature processing

FY13 Milestones

- Investigate fundamental science underlying voltage and temperature stability (crystallographic and chemical studies)
- Pursue integration with low-cost electrodes
- Continue work on transient liquid phase processing for reduced processing temperatures and higher density, higher operating fields
- Perform accelerated lifetime and reliability testing
- Submit ≥2 manuscripts for publication in peer-reviewed journals
- Direct application testing of prototype capacitors
  - With batteries for lifetime extension
  - With inverter modules at elevated temperatures
- Explore partnership with commercial manufacturer(s)

Contact Information

- PI: Geoff Brennecka
  Sandia National Laboratories
  glbrenn@sandia.gov
  505-845-0105

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