Dielectric Materials and Capacitor Reliability for Power Electronic and Pulse Power

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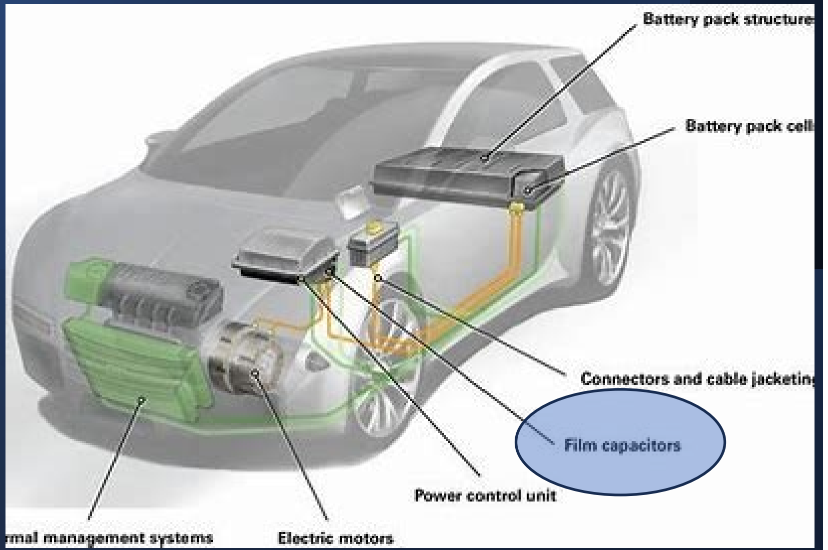
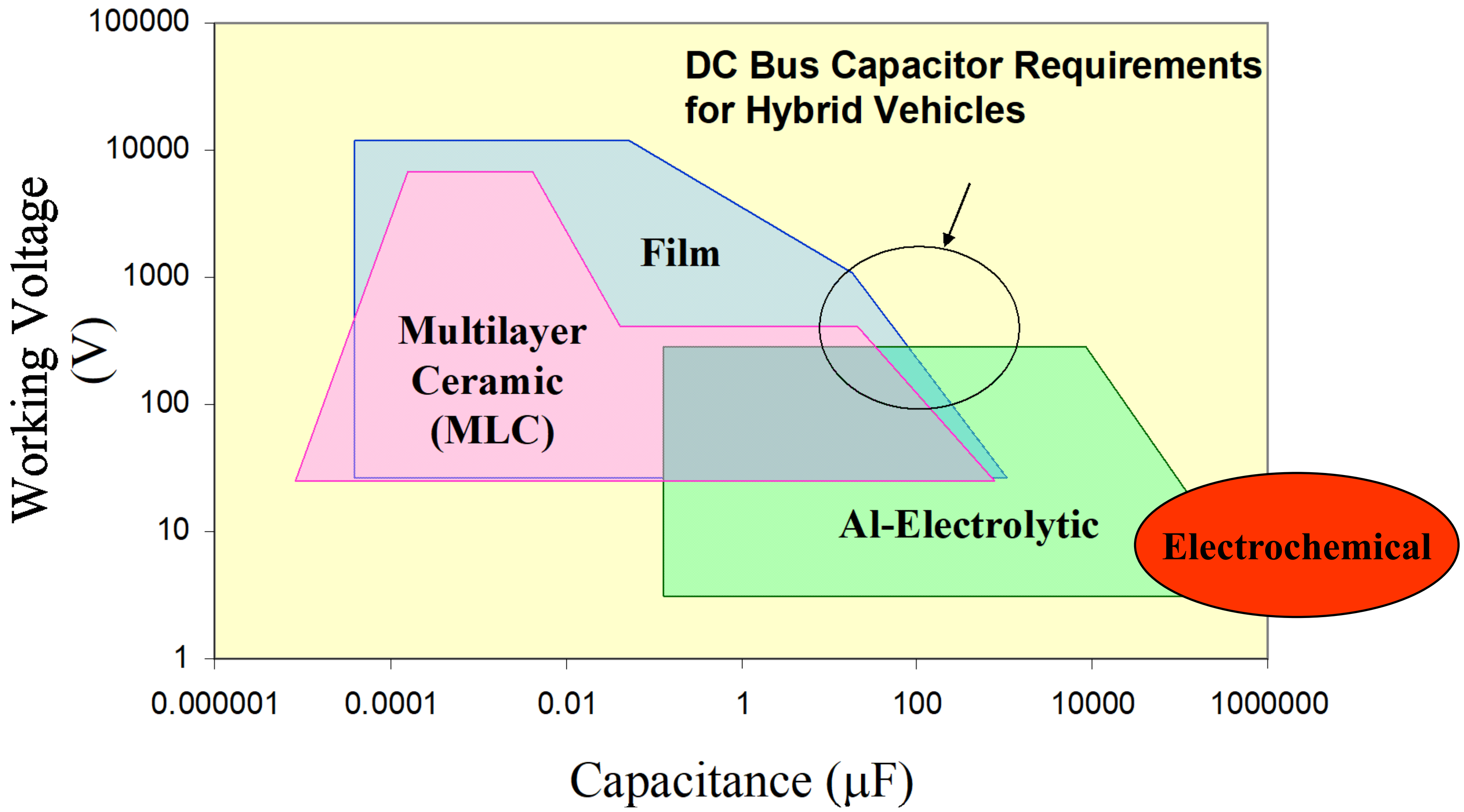
DOE Research on Capacitors for EVs



Commercial Capacitor Types

Multilayer Ceramic Capacitor

Commercial Capacitor Ranges



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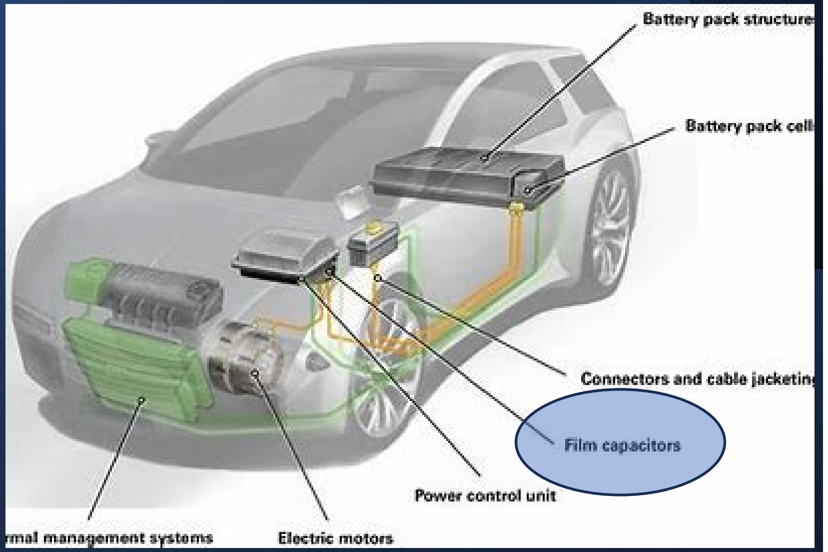
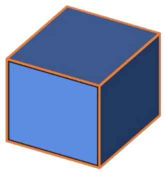


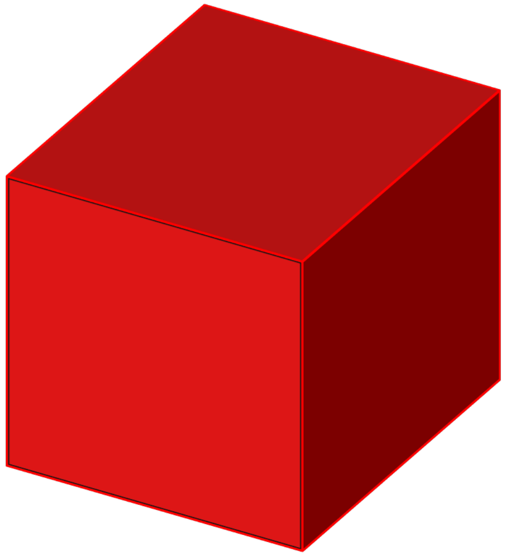
Volume of 1000 µF 600V capacitors in a Hybrid Electric Power Converter

Current Capacitor
Wound polymer film
(polypropylene)



Volume = 1.4 Liters
85ºC Rating

Current High Temperature Capacitor
Wound polymer film capacitor



Volume = 21.6 Liters
125ºC Rating

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Energy Comparison of Capacitors and Dielectrics

Capacitance

$$\text{Energy} = \frac{1}{2} C V^2$$

Voltage

Units are Joules

Permittivity

$$\text{Energy Density} = \frac{1}{2} \varepsilon_0 \varepsilon_r E^2$$

Electric Field

$\frac{\text{Joules}}{\text{cm}^3}$

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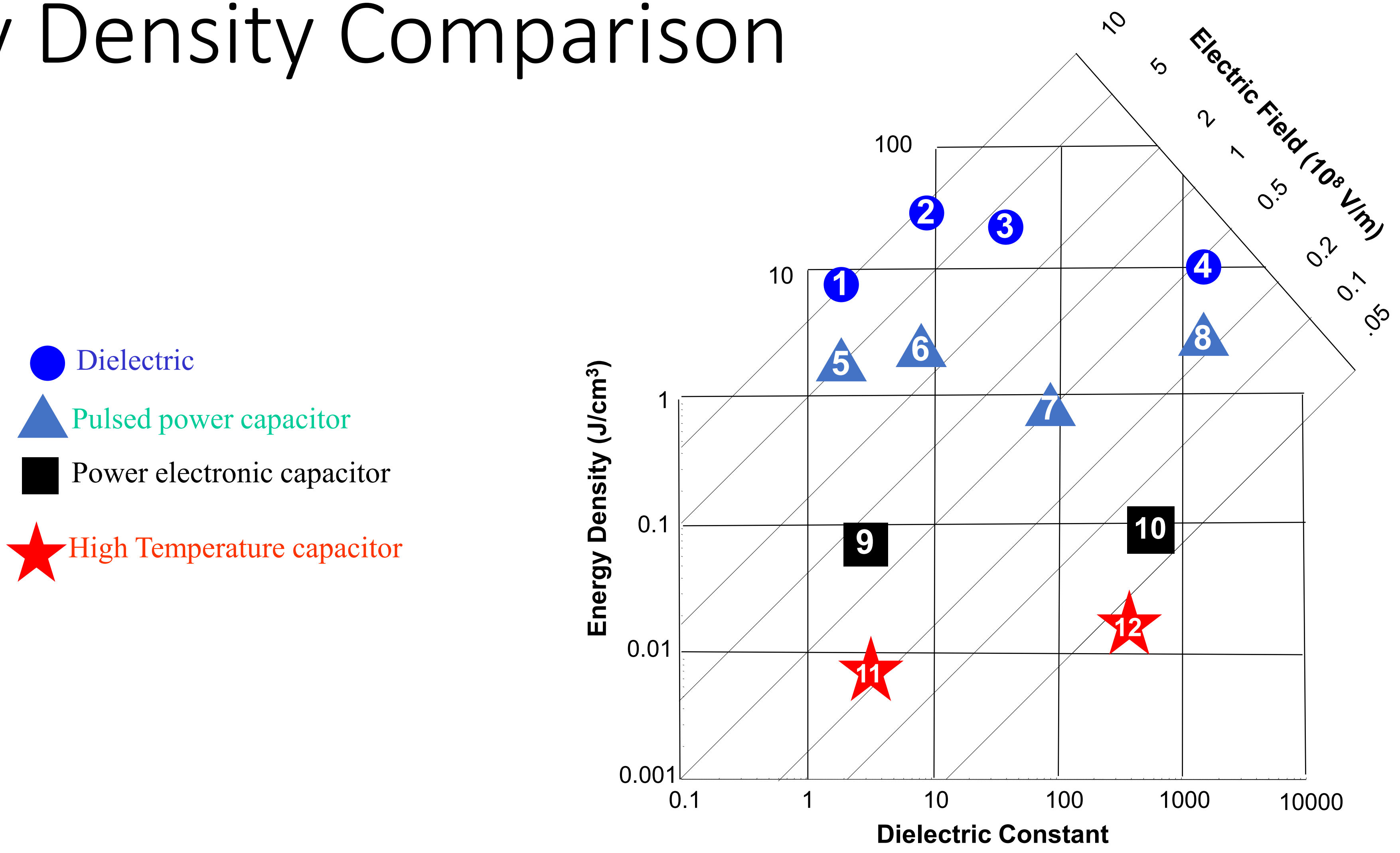
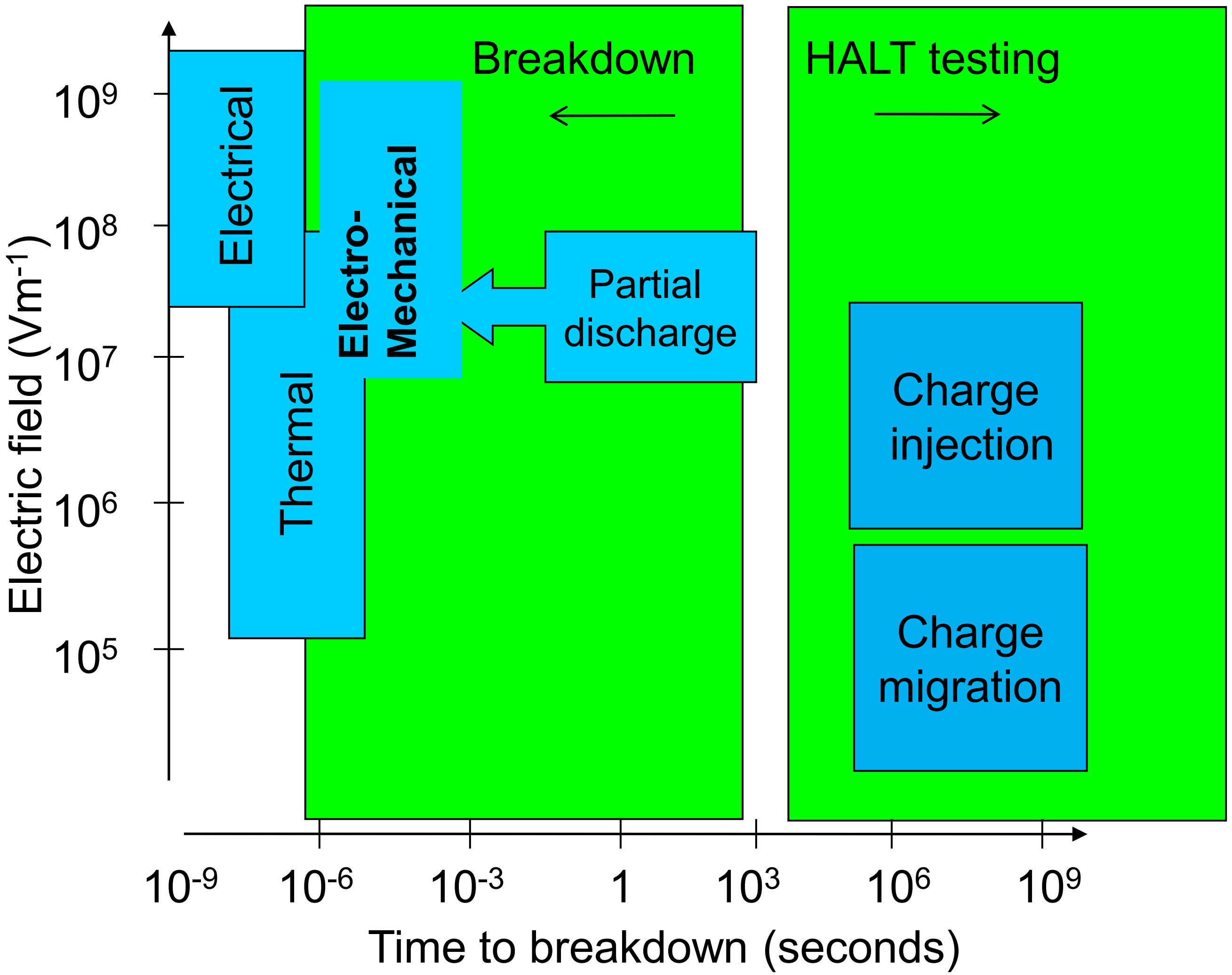
Energy Density Comparison



(1) Polypropylene, (2) Alkali-free Barium Boroaluminosilicate Glass, (3) Fluoropolymer, (4) PZT Ceramics, (5) Polypropylene Capacitor (6) High-k Polymer Capacitor, (7) NPO MLCC, (8) X7R based MLCC , (9) Polypropylene film capacitor, (10) X7R MLCC, (11) High Temperature, 125ºC, Polymer Capacitor, (12) High Temperature, 200ºC, MLCC.

Randall, Clive A., Hideki Ogihara, Jeong-Ryeol Kim, Gai-Ying Yang, Craig S. Stringer, Susan Trolier-McKinstry, and Mike Lanagan. "High temperature and high energy density dielectric materials." In *2009 IEEE Pulsed Power Conference*, pp. 346-351. IEEE, 2009.

Reliability Regimes for Dielectric and Capacitors



Partially adopted from the book by Dissado and Fothergill “Electrical Degradation and Breakdown in Polymers”

Note: electromechanical breakdown originates commonly from Maxwell stress in polymers and electrostrictive strain in ceramics

Highly Accelerated Life Testing (HALT) Facility at Penn State Specializing in High Temperature

- Combine high temperature (500ºC) and high voltage (1 kV)
- 15 sample positions
- Monitor leakage current as a function of time
- Characterize impedance in-situ to monitor the degradation process

HALT system designed and built at Penn State University

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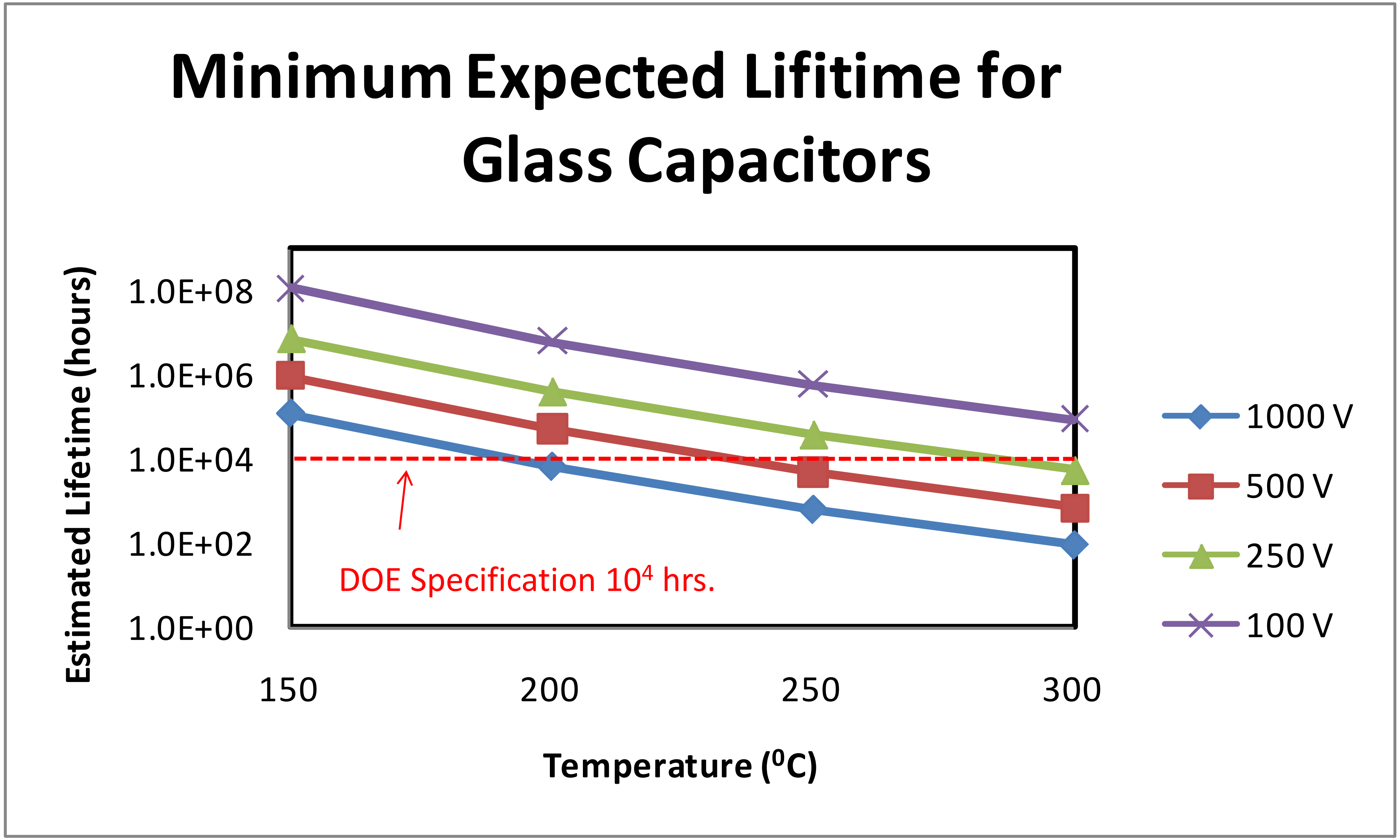
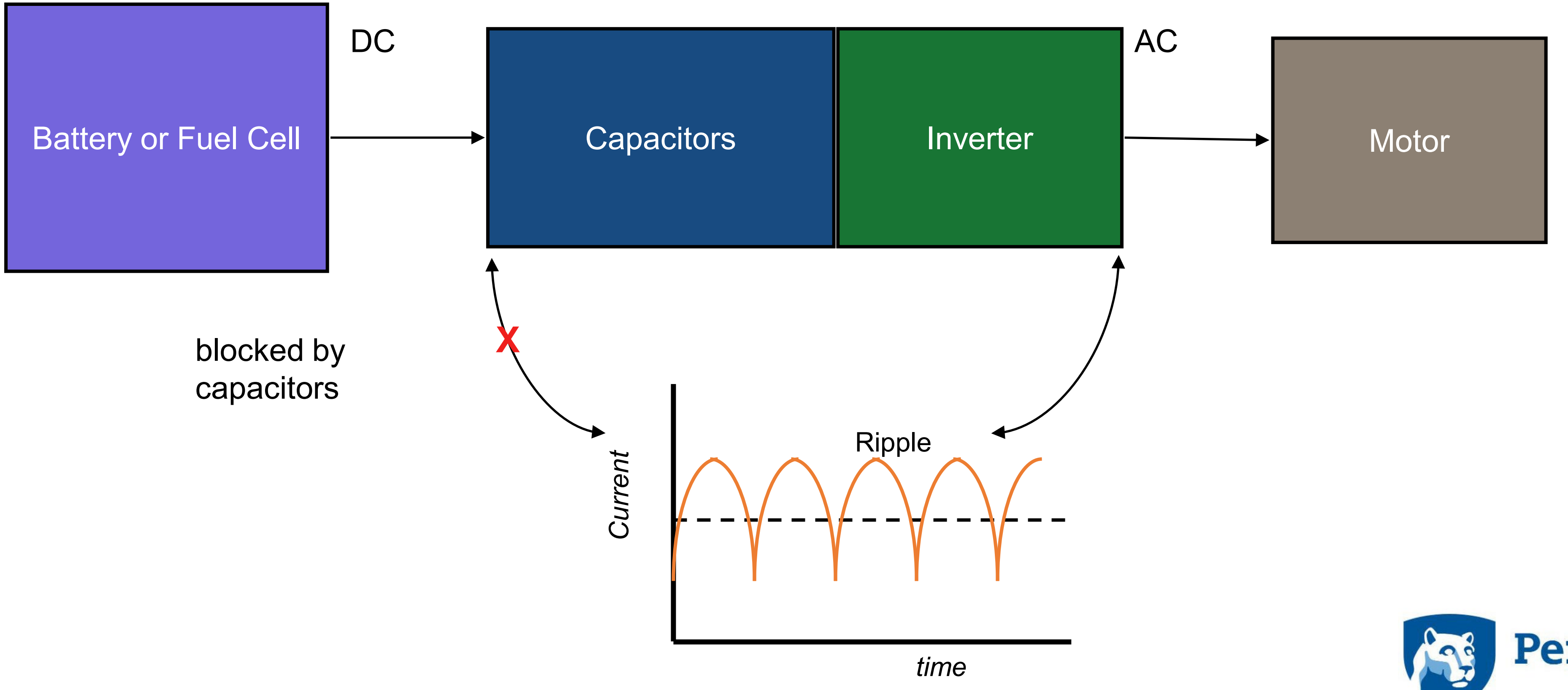

Minimum Expected Lifitime for Glass Capacitors
Estimated Lifetime (hours)
1.0E+08
1.0E+06
1.0E+04
1.0E+02
1.0E+00
150
200
250
300
Temperature (0C)
DOE Specification 10⁴ hrs.
1000 V
500 V
250 V
100 V

So far, we have discussed DC measurements, power electronics need AC assessment



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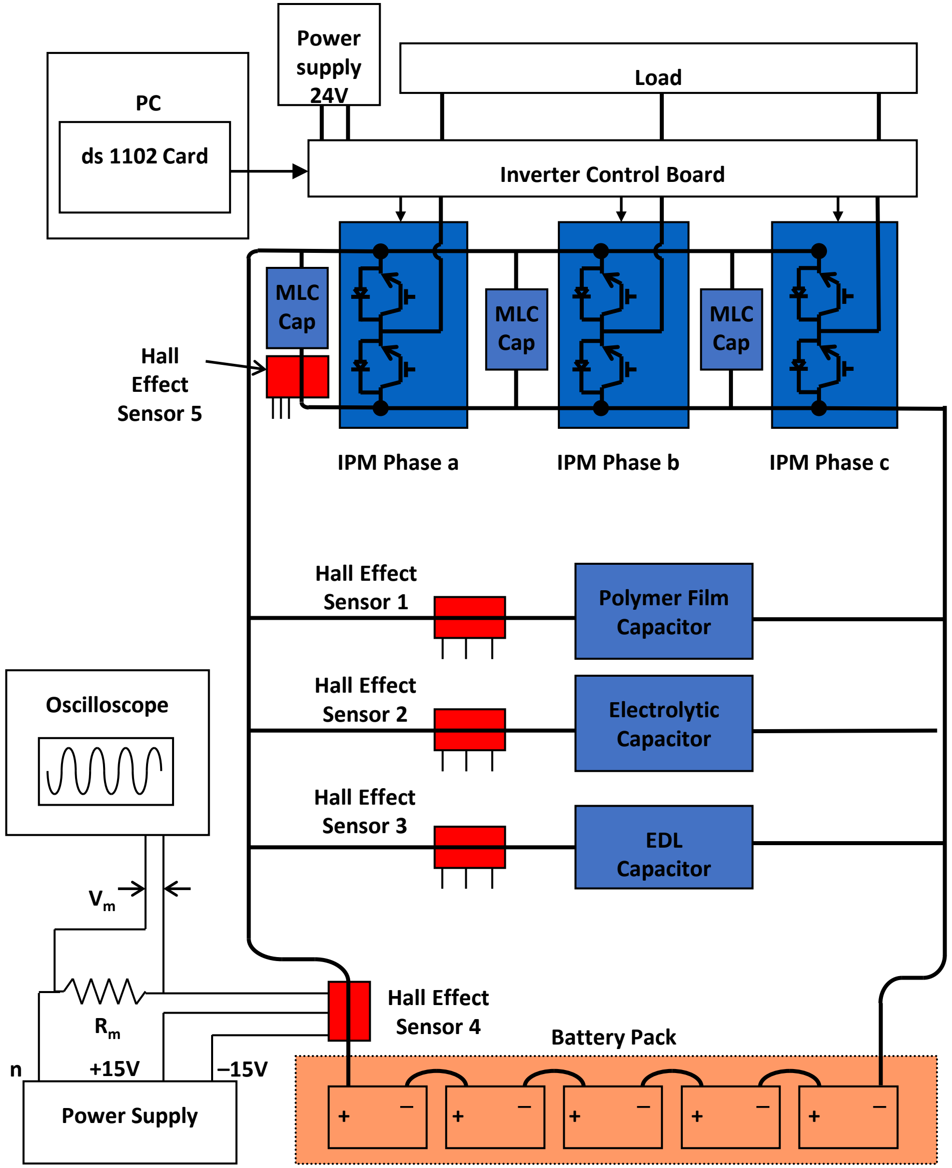
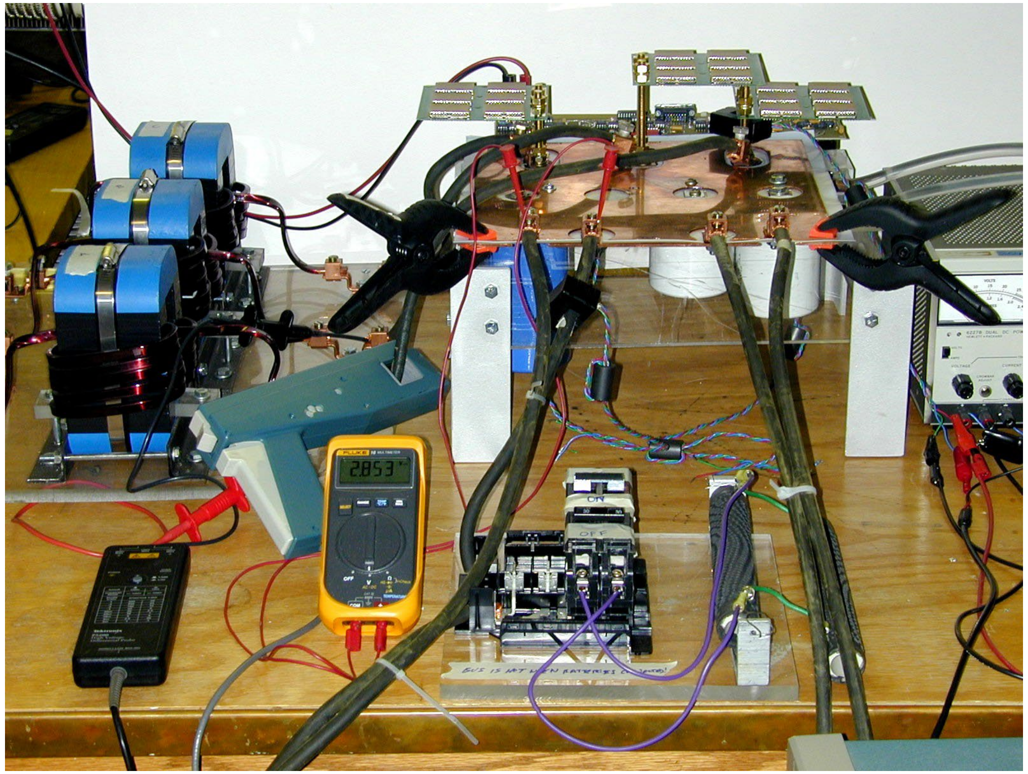
Experimental Setup to Characterize Capacitor Ripple Current





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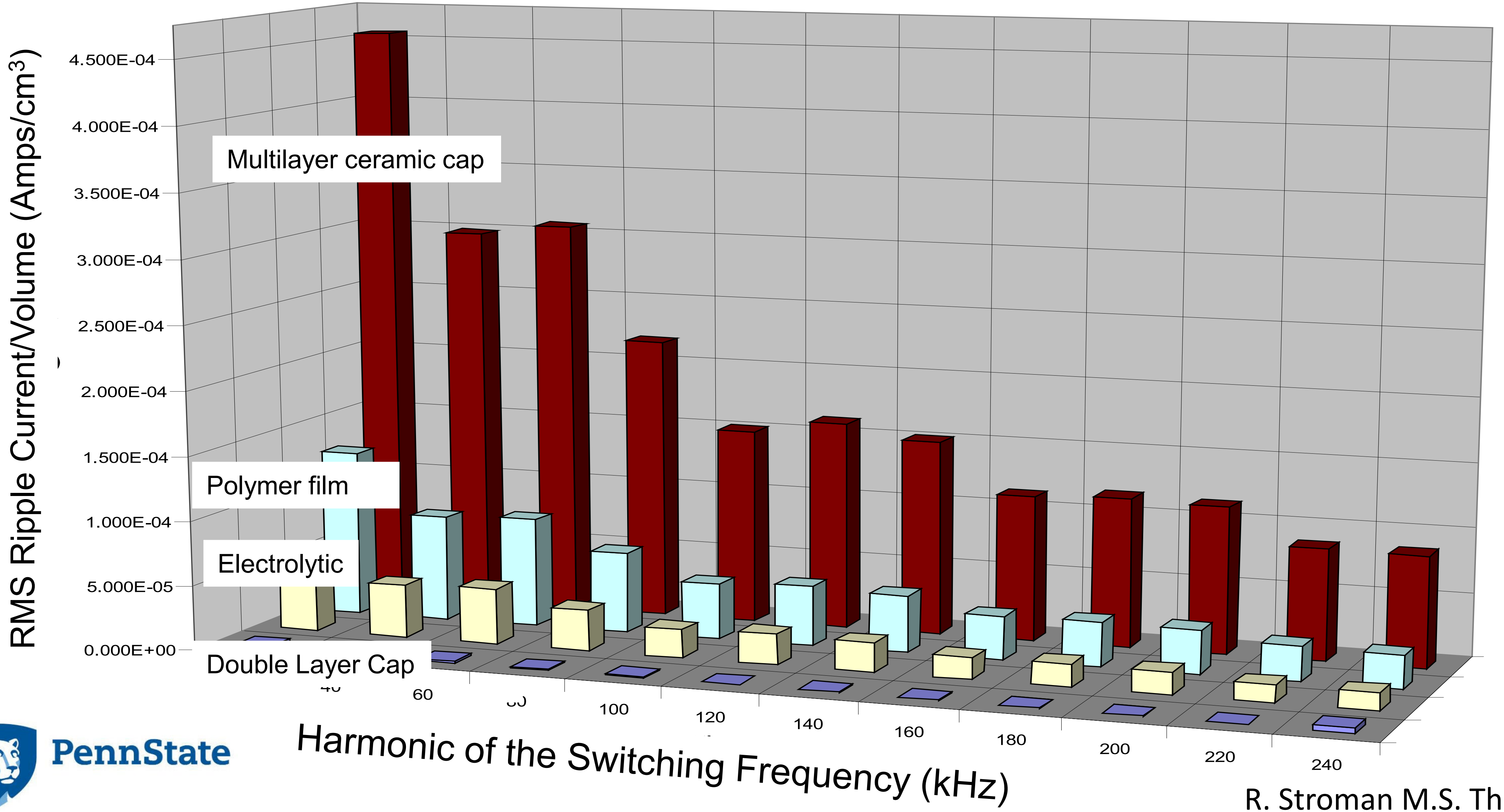
Capacitor Ripple Current Volumetric Efficiency



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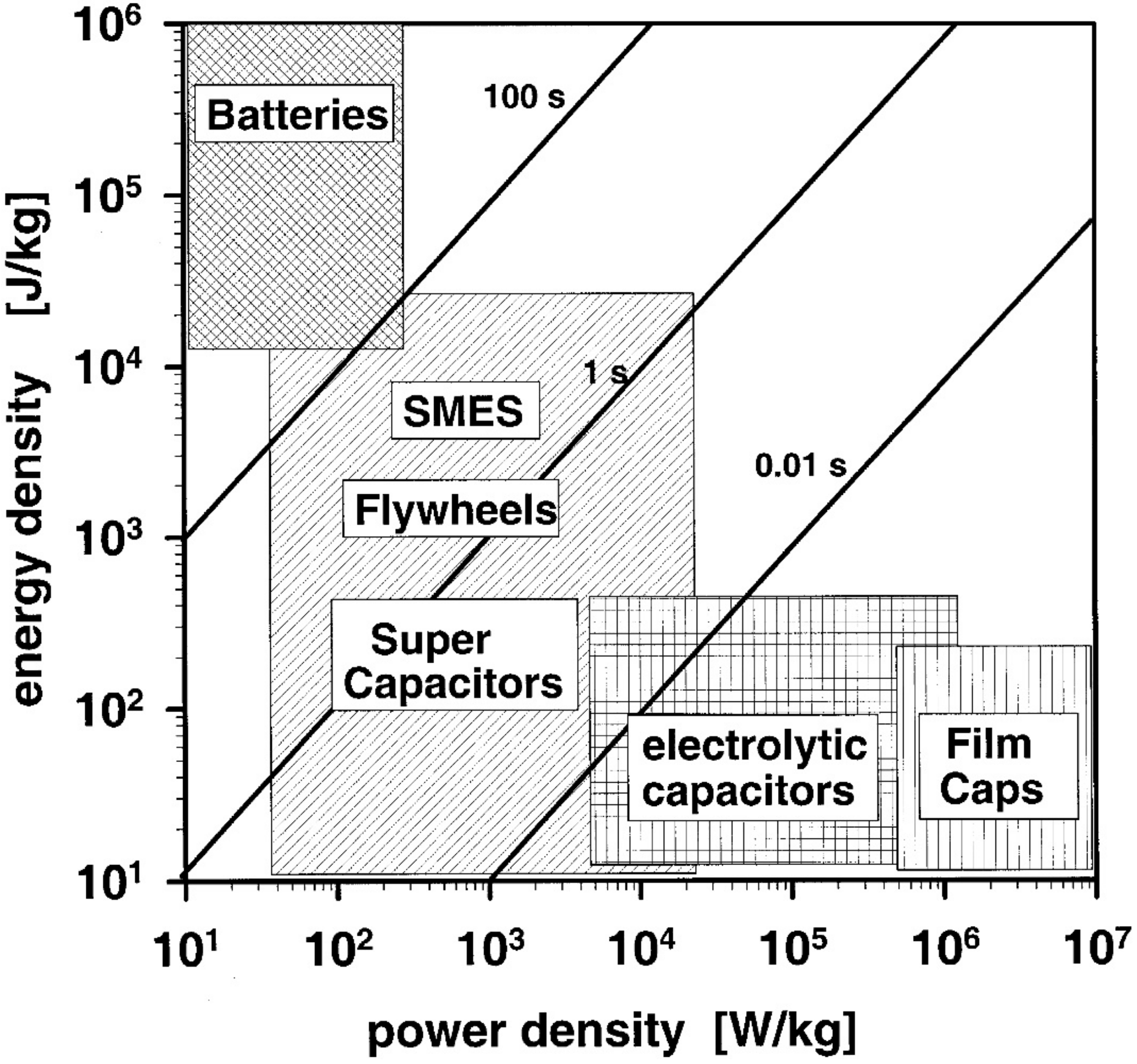
Both Energy and Power Density need to be considered for Capacitors

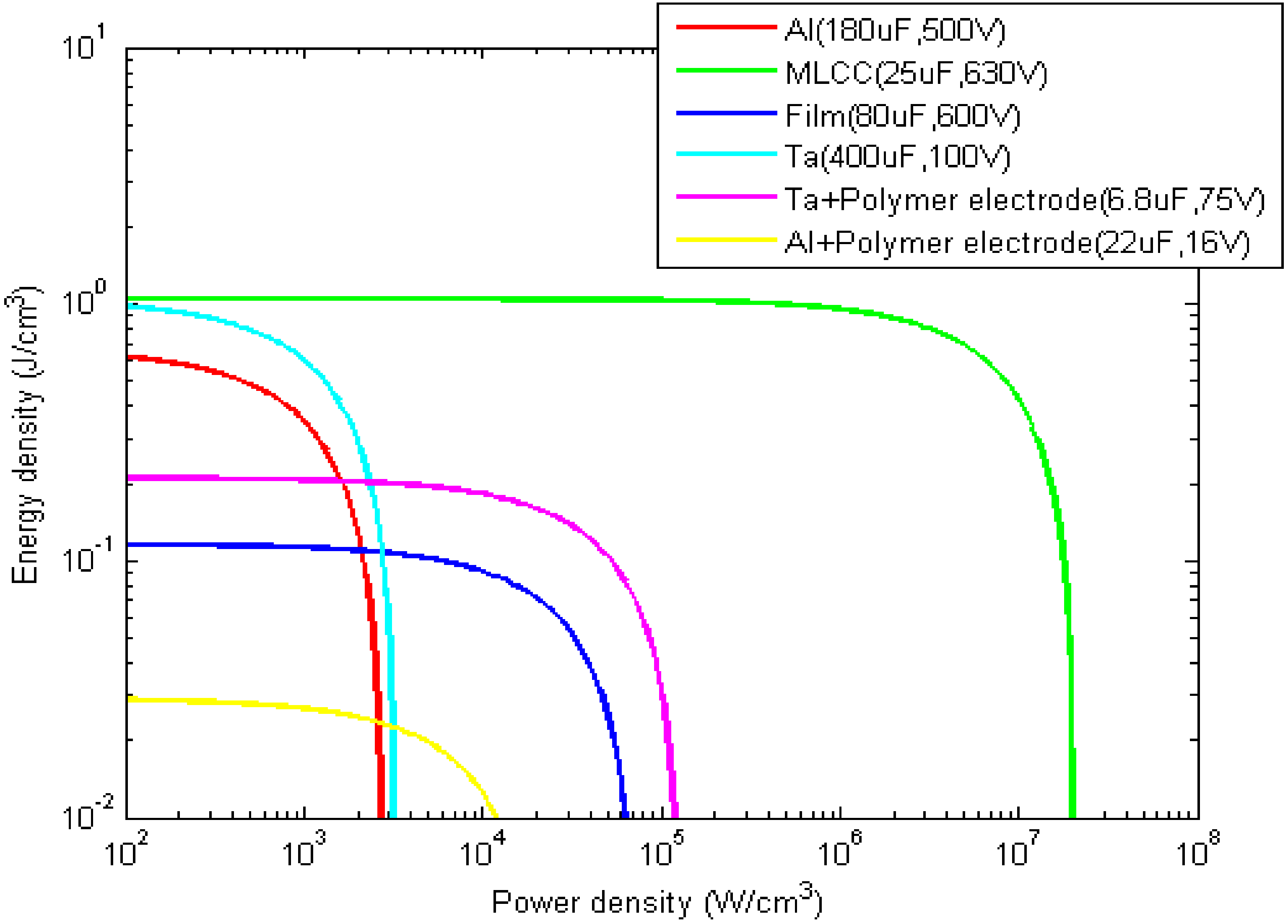
- Energy density is a function of voltage (or E-field) and capacitance (or permittivity)

- Power density is governed by energy loss which is quantified by resistance (or dielectric loss).



T. Christen and M. Carlen, J. Power Sources. 91, 210, (2000).

Comparison of Capacitor Technologies



Choi, Doo-Hyun, et al. "Energy and power densities of capacitors and dielectrics." *2015 IEEE International Workshop on Integrated Power Packaging (IWIPP)*. IEEE, 2015.

Figure of Merit for high temperature capacitors

- The “RC” figure-of-merit provides an “apples to apples” comparison for different capacitors.

Parallel Plate Capacitor

Device Resistance

$$R = \frac{\rho d}{A}$$

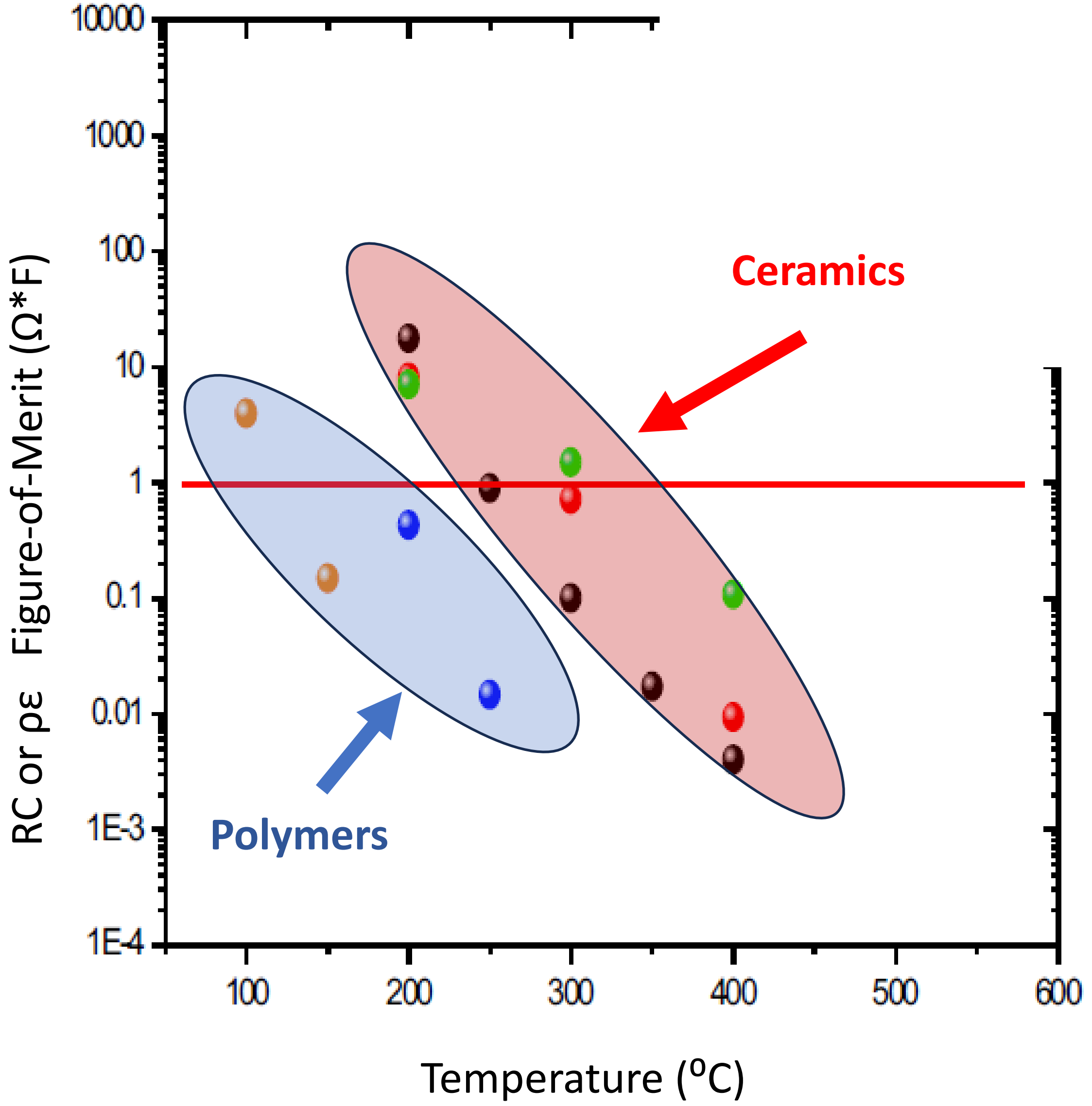
Device Capacitance

$$C = \frac{\varepsilon A}{d}$$

$$RC = \rho\varepsilon$$

→ Resistivity “ρ” and permittivity “ε” are fundamental dielectric material parameters without any capacitor dimensions.

Comparison of resistivity*permittivity Figure-of-Merit



Furman, Eugene, Shujun Zhang, Namchul Kim, Thomas R. Shrout, Heath Hofmann, Richard Stroman, and Michael Lanagan. "High-Temperature, High-Power Capacitors: the Assessment of Capabilities." *SAE International Journal of Aerospace* 1, no. 1 (2009): 822-831.

Dielectric Materials and Capacitor Summary

- Past R&D has focused on energy density
  - Breakdown strength and permittivity
- Future dielectric research needs to address
  - Power density
  - High temperature reliability
- Future capacitor development
  - Lower ESR and and ESL
  - Higher frequency and voltage

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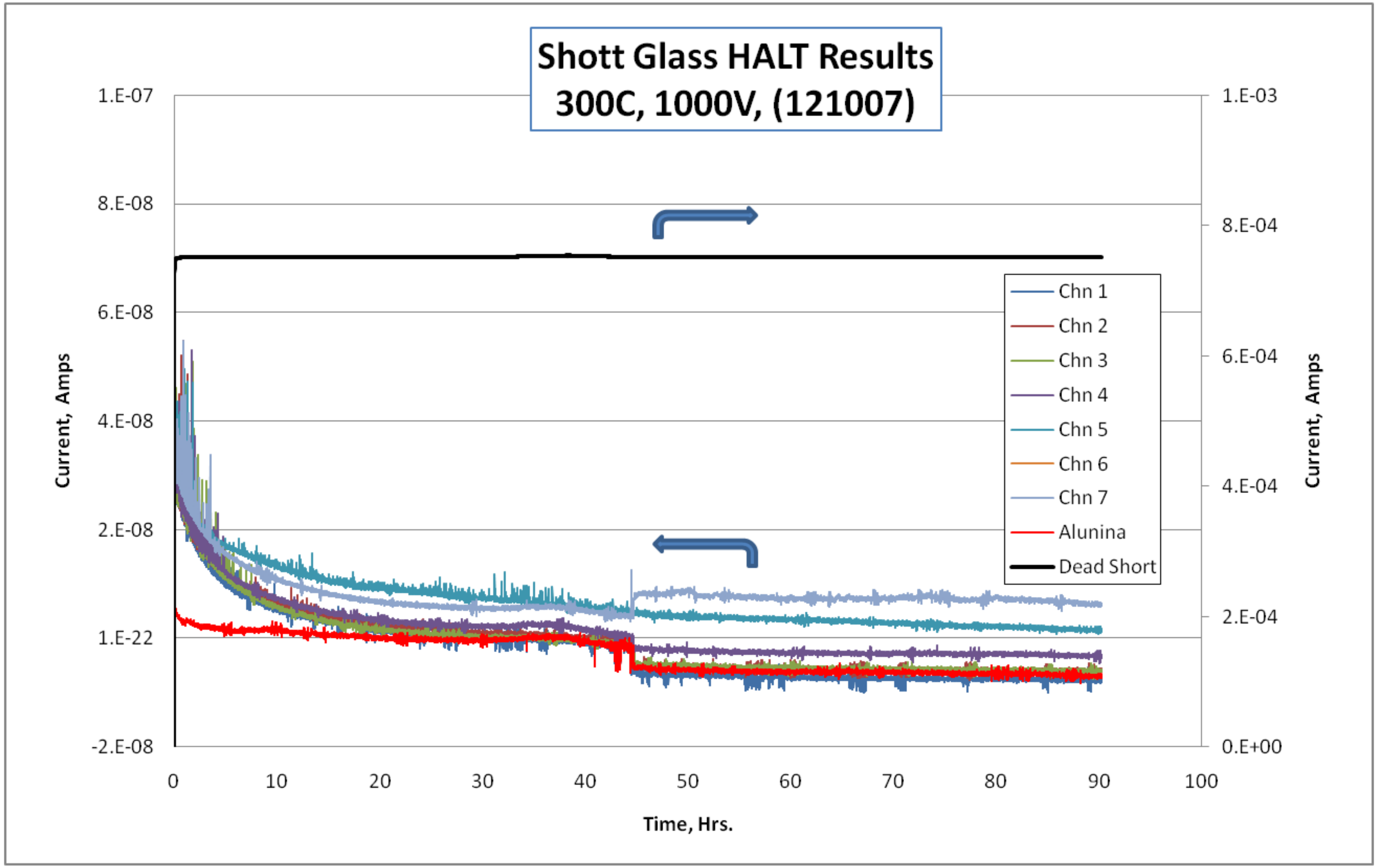
Supplementary Material

Example HALT Test



Isothermal Highly Accelerated Life Tests (HALT): Relationship between two conditions (1&2)

Acceleration Factor

Activation Energy

Time to Failure

$$\frac{t_1}{t_2} = \left[\frac{V_2}{V_1}\right]^n \exp\frac{E_A}{K}\left[\frac{1}{T_1} - \frac{1}{T_2}\right]$$

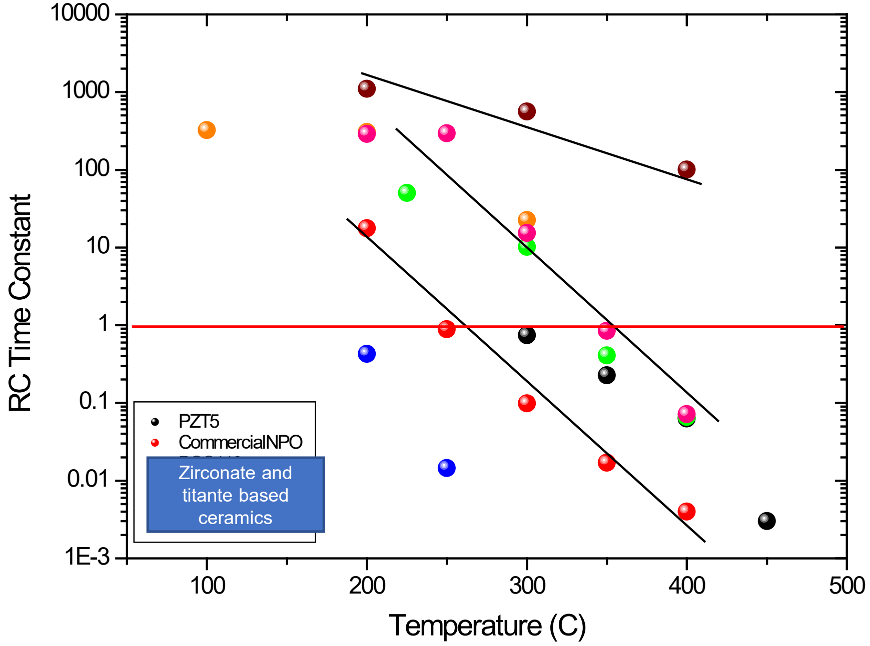
Voltage

Temperature

,

where the subscripts *1* and *2* describe the test conditions, *t* is the median time to failure, *V* is voltage, *n* is the voltage acceleration factor, E_A is the activation energy for failure, *K* is the Boltzmann constant, and *T* is absolute temperature. The acceleration factor, *n*, and activation energy, E_A, will be determined by performing HALT at different temperatures and voltages.

Comparison of RC Figure-of-Merit



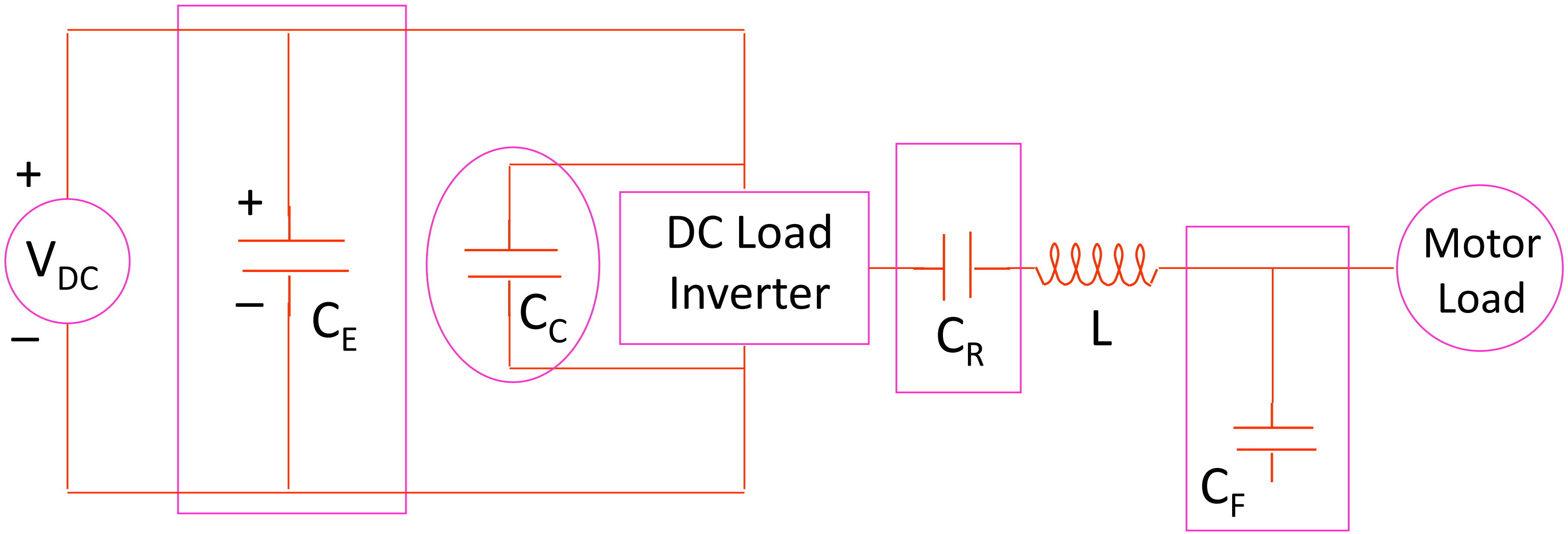
Material	200C	300C	400C
Com. NPO	17	0.09	0.004
PLZT	253	18.2	0.056
$DyScO_3$	50	10.1	0.066
Titanate and Zirconate based ceramics	0.426	0.005	-
	290	15.3	0.072
	1096	22	0.26
	1100	560	101

- High temperature Relaxor system can easily be tuned and designed for high temp dielectrics.
- Linear based dielectrics show very high RC values of several order higher than commercial NPO dielectrics.

See Rece CDP thesis by Dennis Shay for more high-temperature compositions

Furman, Eugene, Shujun Zhang, Namchul Kim, Thomas R. Shrout, Heath Hofmann, Richard Stroman, and Michael Lanagan. "High-Temperature, High-Power Capacitors: the Assessment of Capabilities." *SAE International Journal of Aerospace* 1, no. 1 (2009): 822-831.

Capacitor Functions



C_E - Energy storage and Voltage smoothing

C_C - Voltage clamping and Decoupling

C_R - Snubber and Resonant circuits

C_F - PWM ripple and Harmonics filtering

Theory of Ragone Plots

- Solution to 2nd order differential equation with unique charge conditions

$$L\ddot{Q} + R\dot{Q} + V(Q) = -\frac{P}{\dot{Q}}$$

Where Q = Charge

L = Inductance

R = Series Resistance

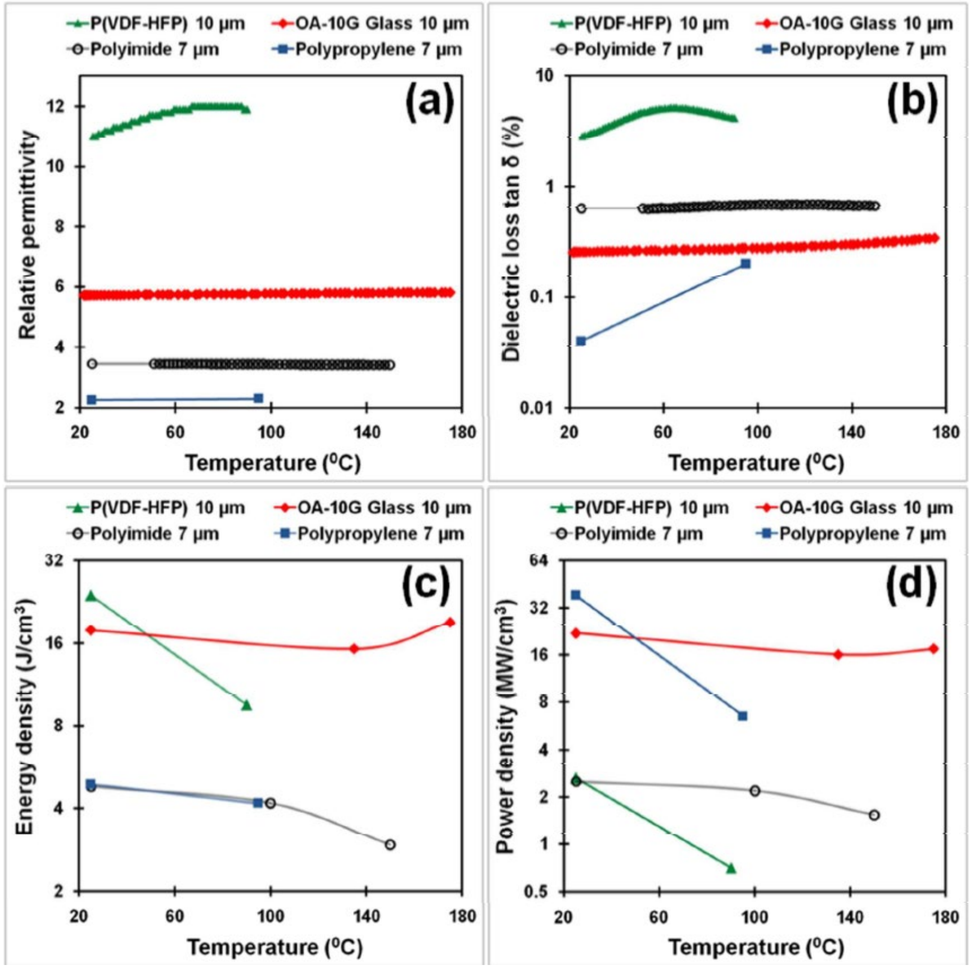
P = Power

V = Voltage

T. Christen and M. Carlen, J. Power Sources. 91, 210, (2000).

Energy and Power Density Comparison for Dielectrics

- PVDF based polymers have high energy density but poor power density.
- PP's power density decreases significantly with temperature.
- Flat panel display glass has the best combination of energy and power density at high temperature.



M. Manoharan, "Flexible Glass for High Temperature Energy Storage," Energy Technology