High-Reliability Ceramic Capacitors to Enable Extreme Power Density Improvements

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Project ID: elt222

Overview

Timeline

- Start – FY19
- End – FY23
- 30% complete

Goals/Barriers

- Drive System Power Density = 33 kW/L
  - Power Electronics Density = 100 kW/L
    Motor/Generator Density = 50 kW/L
- Power target > 100 kW
- Cost target for drive system ($6/kW)
- Operational life of drive system = 300k miles

Budget

- Total project funding
  - DOE share – 100%
- Funding received in FY19: $75K
- Funding for FY20: $100K

Partners

- ORNL, NREL, Ames Lab
- Project lead: Sandia Labs
  - Greg Pickrell, Todd Monson, Jason Neely, Bob Kaplar

Oak Ridge National Laboratory
NREL NATIONAL RENEWABLE ENERGY LABORATORY
Sandia National Laboratories

Relevance and Objectives

- Achieving power electronics density will require improvements in all aspects of drive train (switches, passives, etc.)

- Ceramic dielectric capacitors preferred to achieve high power density systems
  - High energy density and reliability
  - Achieving cost metric requires base metal electrodes (reliability issues)
    - Achieving high performance/long lifetime at high T has been elusive

- Instead of addressing performance/reliability through material composition
  - Develop innovative bipolar switching strategy
  - Periodically clear a build-up of oxygen vacancies at electrode surfaces
  - The dynamics of this strategy will be explored and optimized
- Survey current state-of-the-art ceramic capacitors and identify technology gaps

<u>Power Electronics and Drive Train Goals</u>

- Power Electronics Density = 100 kW/L
- Power Electronics target > 100 kW (~1.2kV/100 A)
- Power Density target for drive system = 33kW/L
- Cost target for drive system ($6/kW)
- Operational life of drive system = 300k miles

FY19/20/21 Milestones

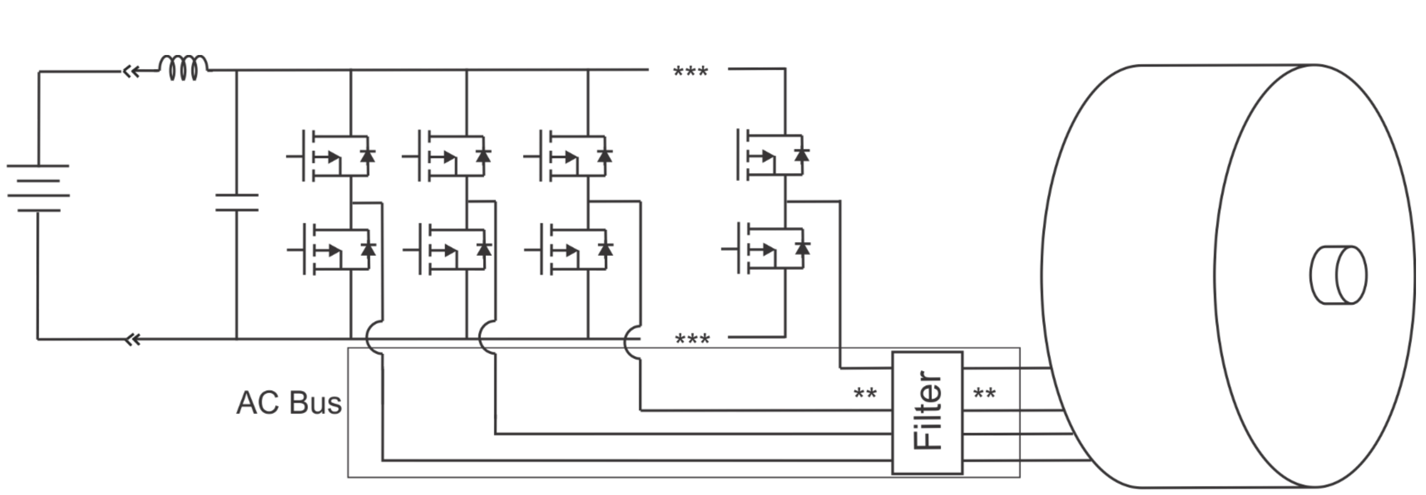
Milestone	Date	Status
Evaluate state-of-the-art ceramic capacitor components and identify gaps	4/2019	Completed
Develop bipolar switching strategy allowing ceramic dielectrics to exhibit long lifetime at high temperature.	10/2019	Completed
Build a custom AC Highly Accelerated Lifetime Test (HALT) system and initiate frequency-dependent HALT characterization of ceramic capacitors	10/2020	In Progress
Find acceleration factors for voltage and temperature for ceramic capacitors. Determine how those factors depend on frequency	10/2021	Not started

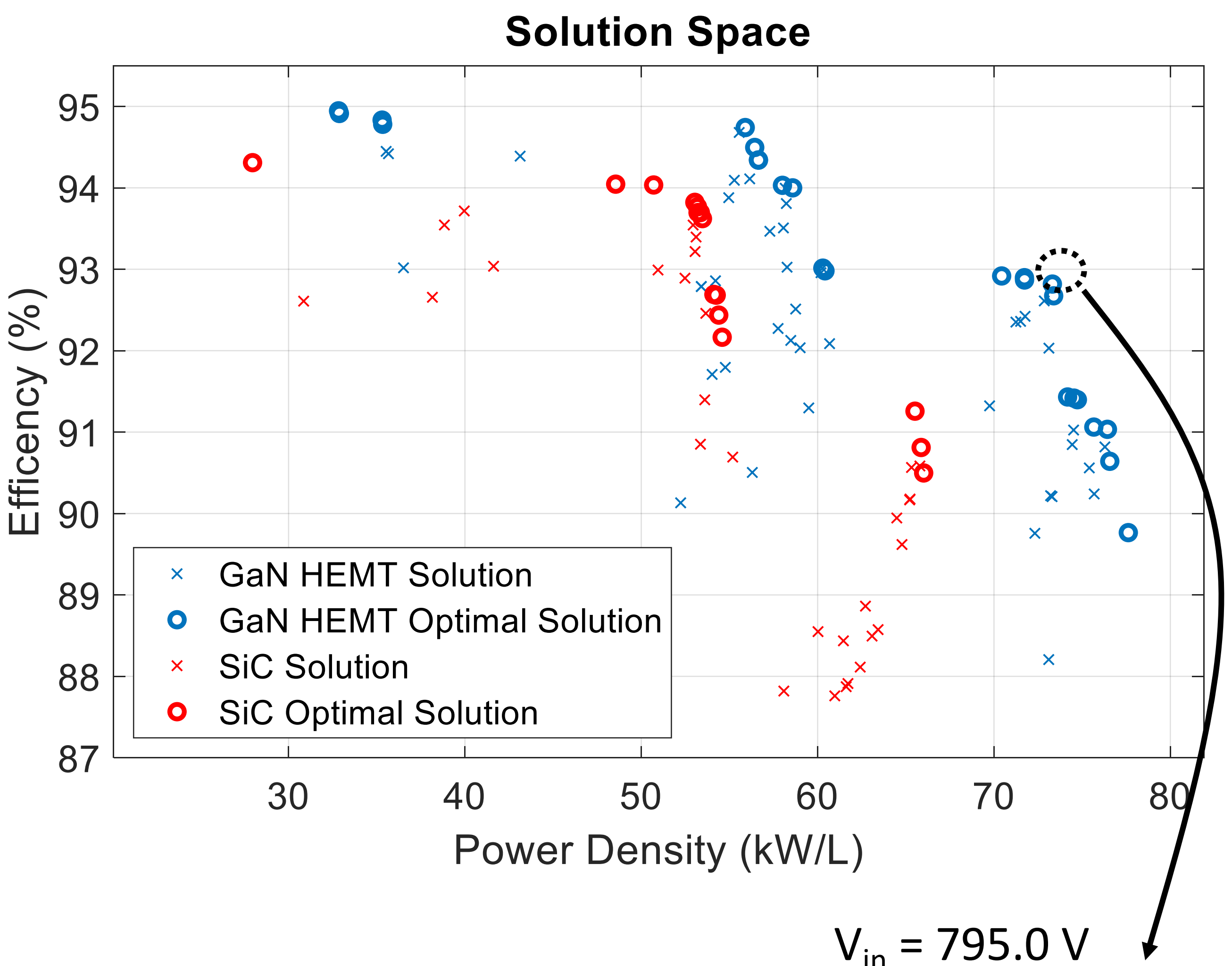
Any proposed future work is subject to change based on funding levels

Approach: Capacitors for Power Electronics

Detailed Genetic Algorithm topology optimization [1] for the vehicle Electric Traction Drive (EDT) synchronous boost and inverter is being carried out

- Candidate Designs from pareto frontiers have been identified for SiC and GaN based semiconductor switches that achieve large ***power densities***
- However, these optimal designs are enabled only through the use of high energy density of multilayer ceramic capacitors (MLCCs)
    - Large distributed architecture of many (~250), small value MLCCs





V_{in} = 795.0 V
f_{sw} = 327.4 kHz
N_{caps} = 248
N_{phase} = 9

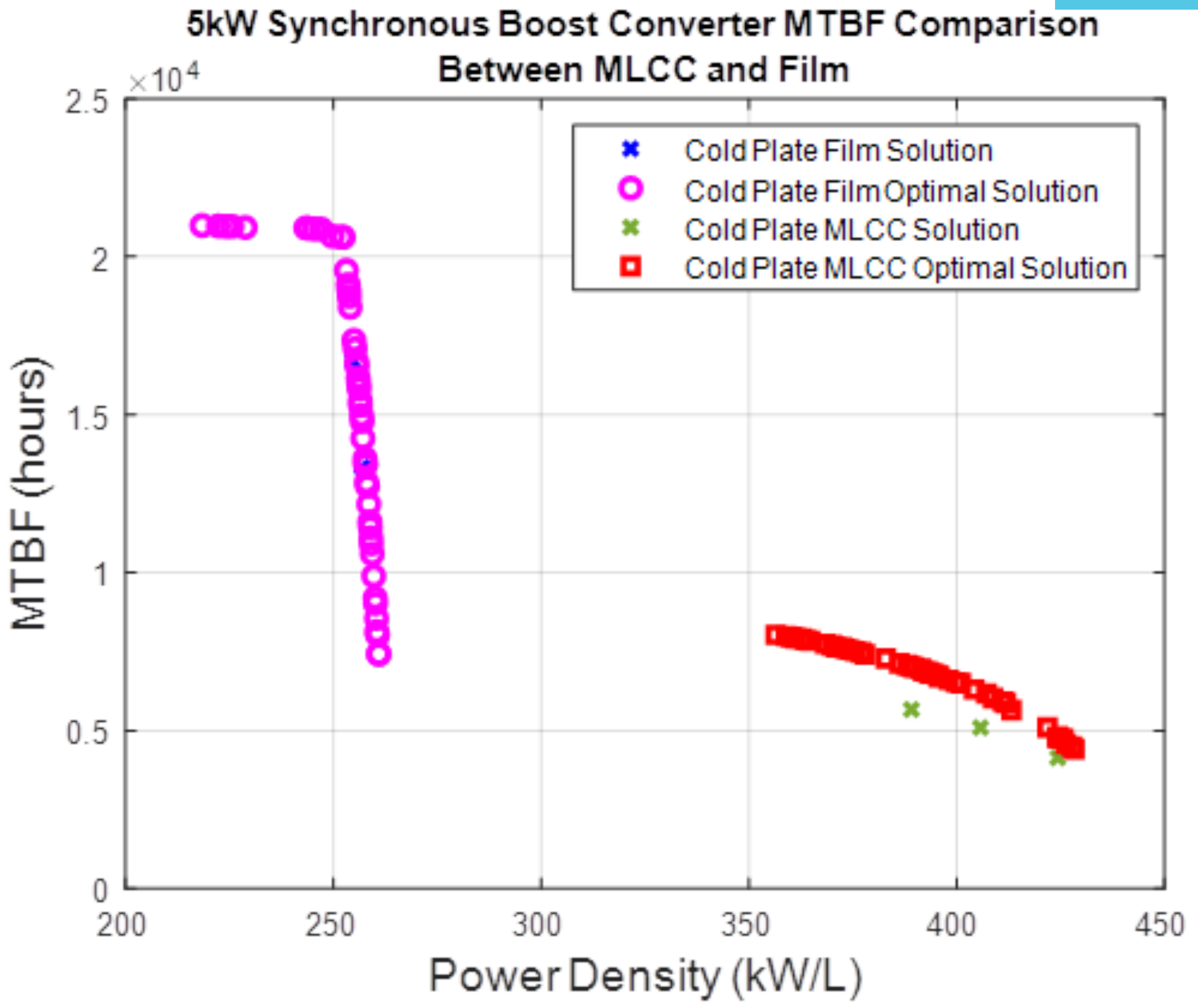
Component	Volume (L)	% of total	Loss (kW)	% of total
Module	0.025174	1.7721	5.1435	63.8379
Capacitor	0.1501494	10.5713	-	-
Input inductor	4.46e-6	0.0031	0.6135267	7.6147
Filter inductor	1.0607	74.6799	2.3001	28.54746
Cooling system	0.1842649	12.9733	N/A	N/A

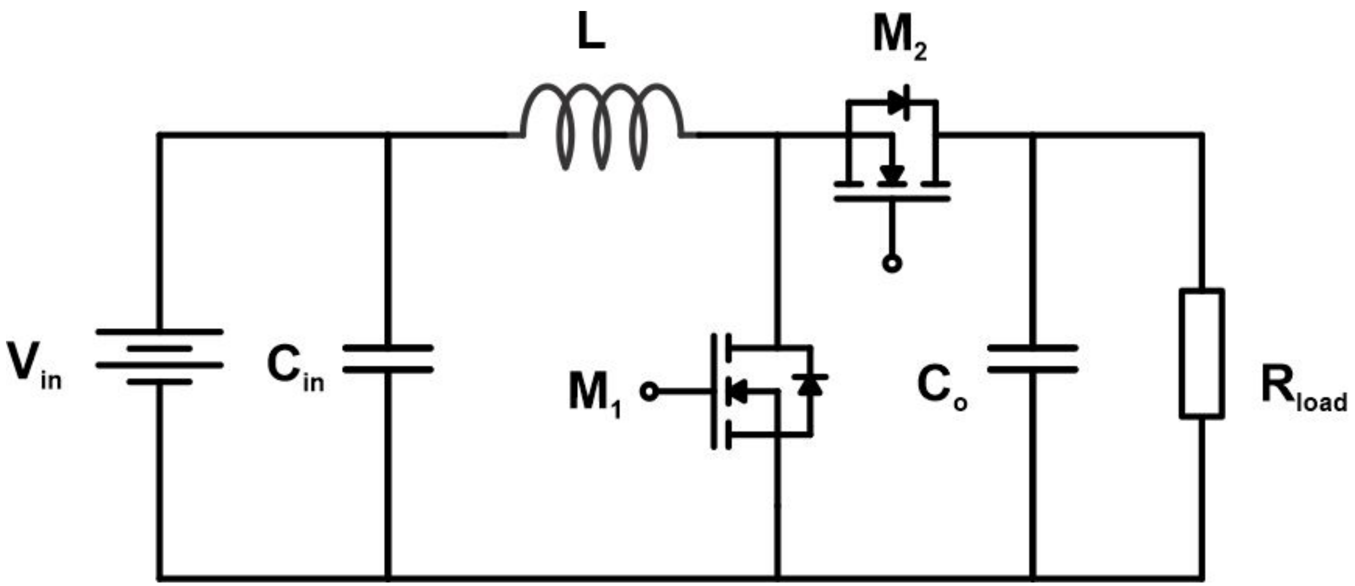
[1] "Co-Optimization of Boost Converter Reliability and Volumetric Power Density Using Genetic Algorithm". 2020 IEEE Energy Conversion Congress and Exposition (ECCE). Detroit, MI. October 2020. (Accepted)

Approach: Capacitors for Power Electronics

- Use of distributed, small MLCC capacitors on DC bus enables significant gains in system power density

- However, use of many discrete units has a detrimental effect on system-level mean time to failure (MTTF)
    - To achieve system-level power density and cost requirements, it will be necessary to ***significantly increase*** MTTF of MLCCs



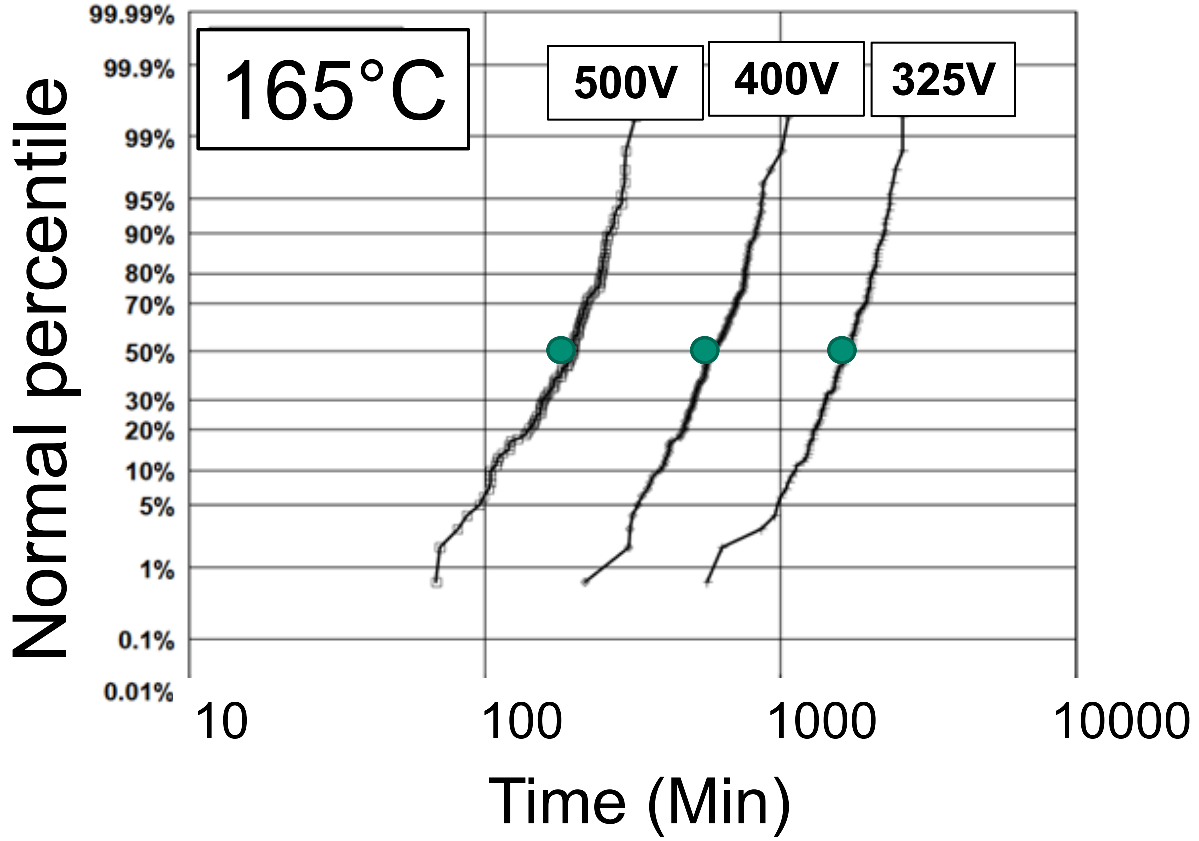


**154.07 kHz (f_{sw}),
400 V (V_{in}),
500.2 V (V_o),
1.0407 % ($I_{L_{pk2pk}}$),
195.5292 (T_j)**

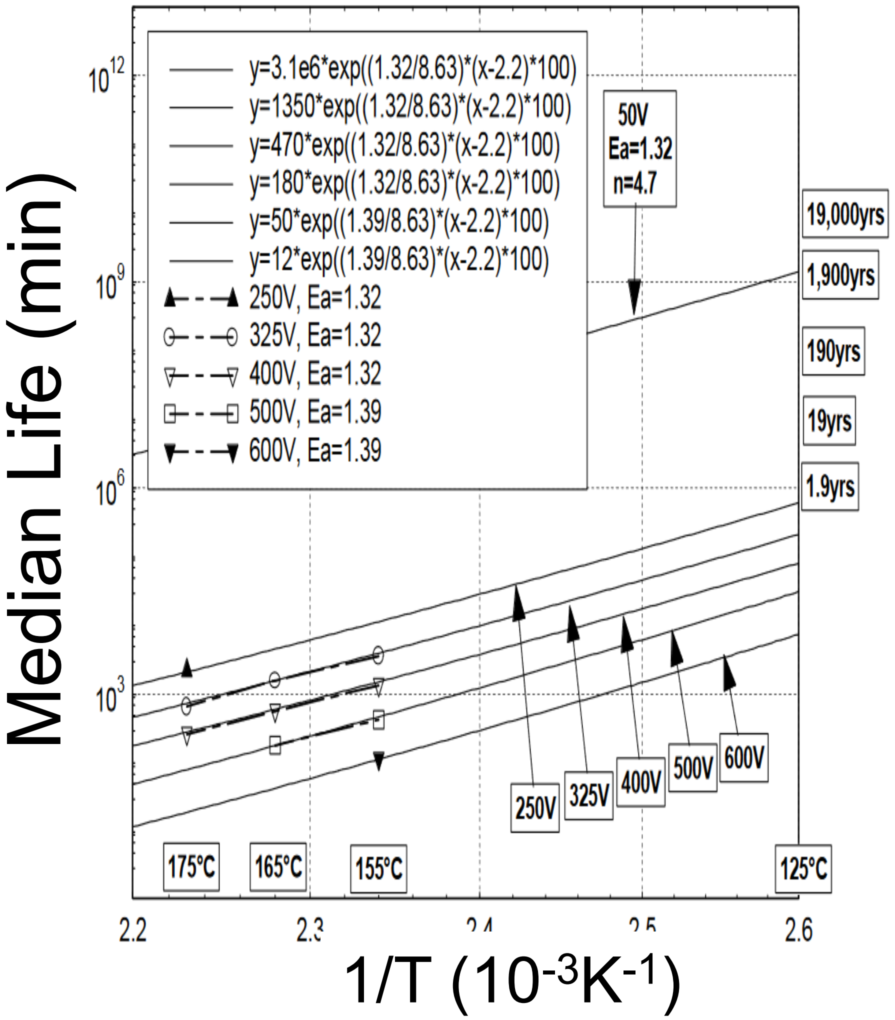
Approach: Capacitors for Power Electronics

Expected MTTF is determinable via highly accelerated lifetime testing (HALT) testing

Problem: Current AEC-Q200 capacitors can handle many under-hood applications, but increasing usage temperature and voltage lead to *significantly* shorter lifetimes. Ceramic capacitor lifetime may not be sufficient to meet system-level lifetime metrics



Ex: 50V 0.1uF X7R MLCC



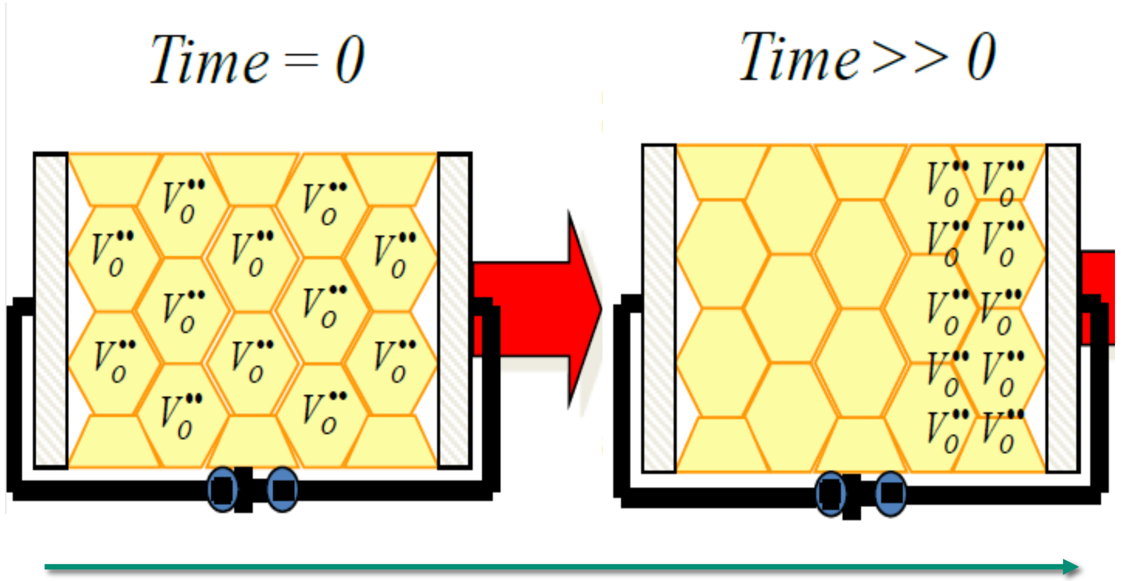
$$\frac{MTTF_1}{MTTF_2} = \left(\frac{V_2}{V_1}\right)^n exp\left[\frac{E_a}{k}\left(\frac{1}{T_1} - \frac{1}{T_2}\right)\right]$$

J. Paulsen, E. Reed, KEMET, CARTS Conf. 2001

Approach: Capacitors for Power Electronics

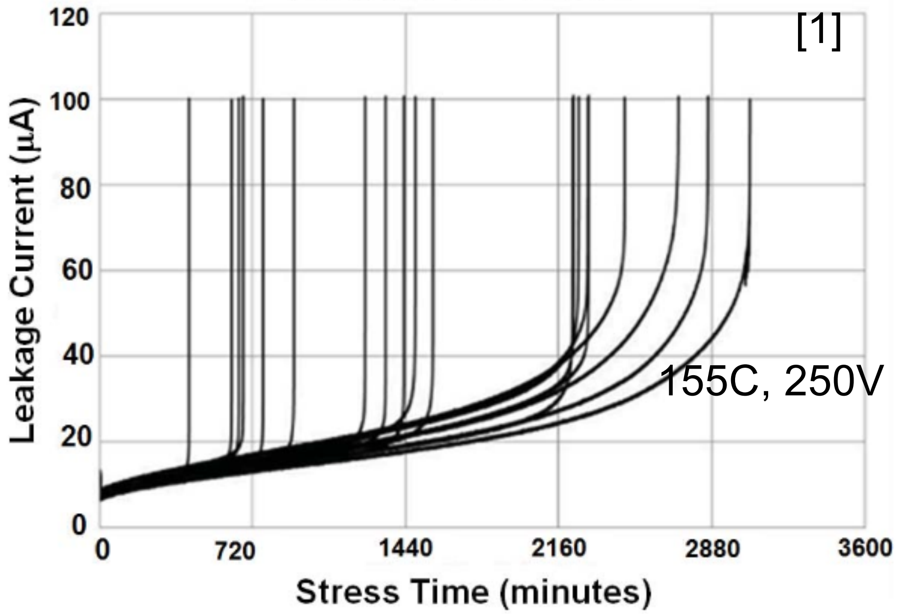
One significant failure mechanism at high voltage and temperature is DC Failure (Short) caused by Electromigration of Defects

- Under applied voltage and temperature oxygen vacancies migrate and gather at the cathode
  - Oxygen vacancies lower Schottky barriers at cathode and grain boundaries
  - Results in loss of insulation resistance (IR) → high DC leakage
  - Increased leakage raises operational temperature and field, further accelerating failure.



Application of DC field over time

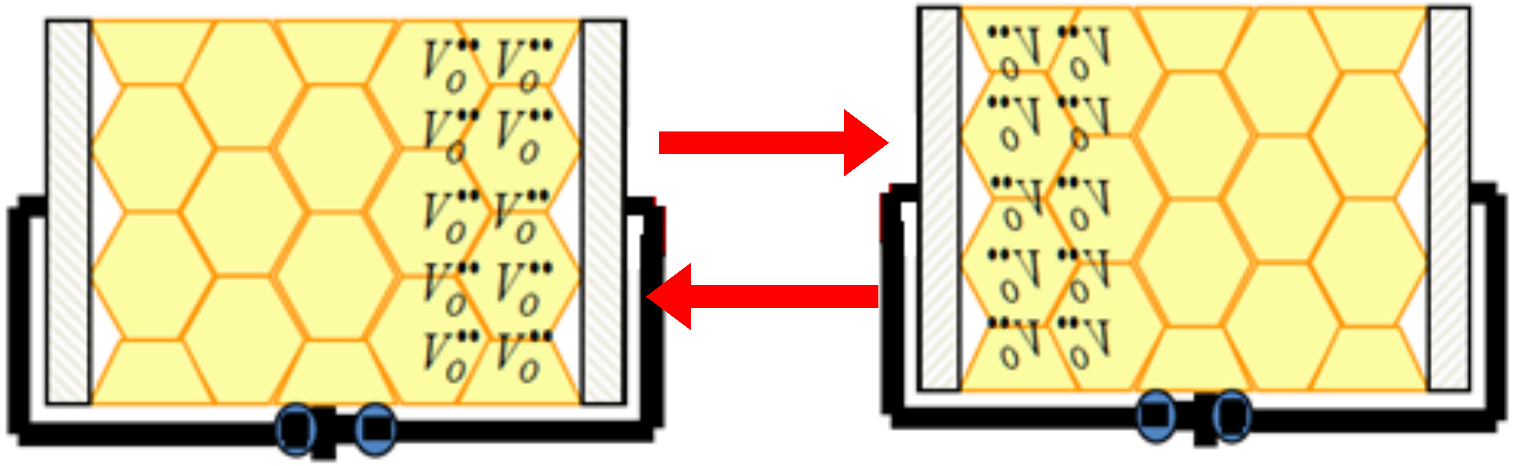
HALT Test; 50V 0.47uF 0805 AEC-Q200 X7R Cap



Leakage current increases leading to thermal runaway and short

Approach: Capacitors for Power Electronics

Bipolar actuation should ‘bounce’ defects between electrodes



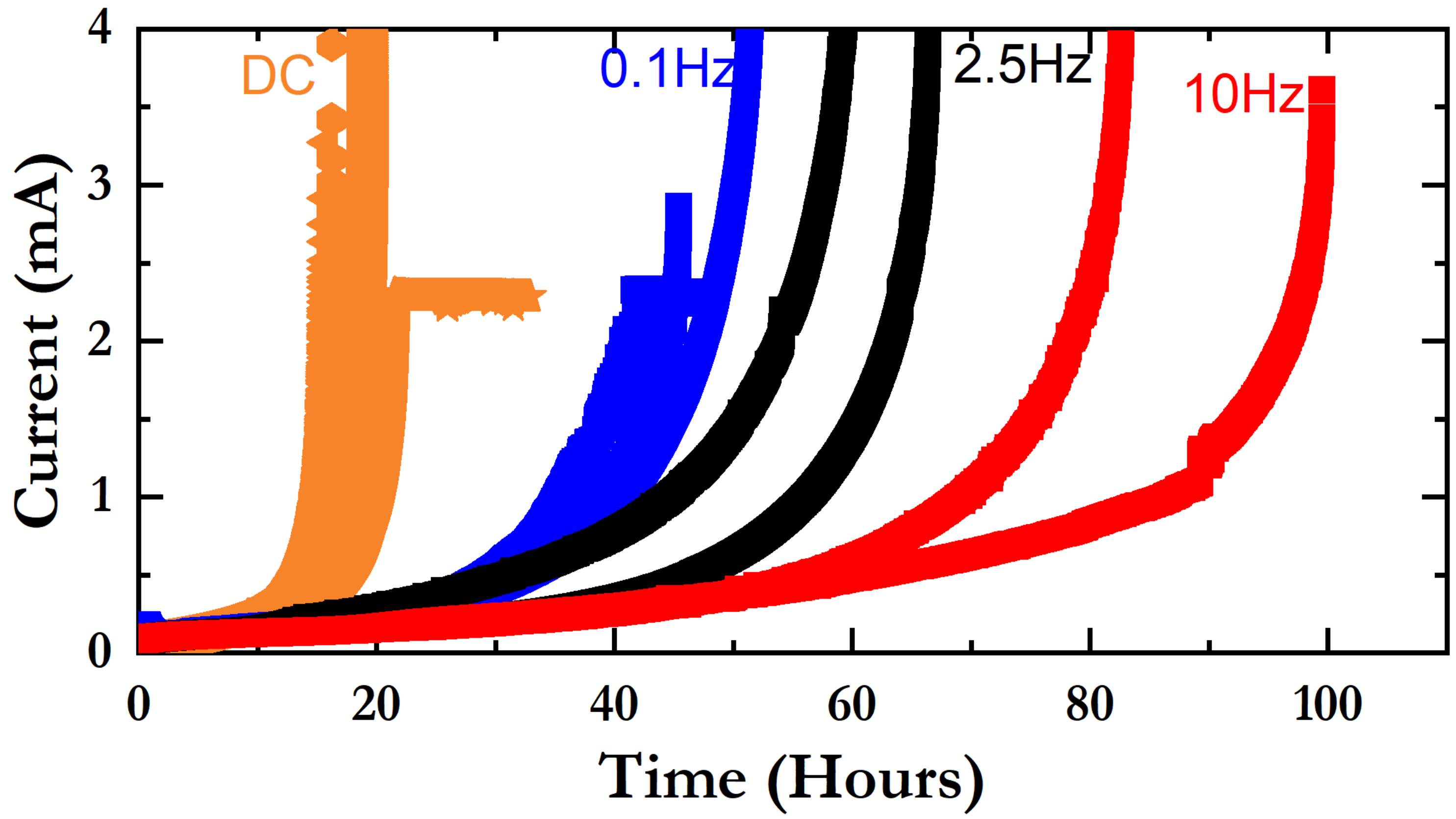
Application of AC field over time

- Instead of altering fabrication or materials properties
  - Targeting oxygen vacancy transport to electrodes
  - By altering the electric field from a DC field to an AC field, we can periodically “flush” oxygen vacancies at electrodes

- Exploring the development of a bipolar switching technique to periodically alter direction of oxygen vacancy travel
  - Testing to identify possible gains in ceramic capacitor reliability
  - Evaluating possible usage in electric drive

Technical Accomplishments and Progress-Passives

- Carried out preliminary bipolar switching testing
  - Tested capacitor degradation at DC bias, and bipolar switching of 0.1, 2.5 Hz, and 10Hz
  - Applied ~10x V_{rated} at 125°C **above** T_{rated}
    - Very high acceleration needed to shorten test length for high frequency samples



- Initial results show that AC extends lifetime as expected

- What frequencies are needed under unaccelerated conditions?
  - **Can practical 'healing cycle' frequencies be used (~<μHz)?**

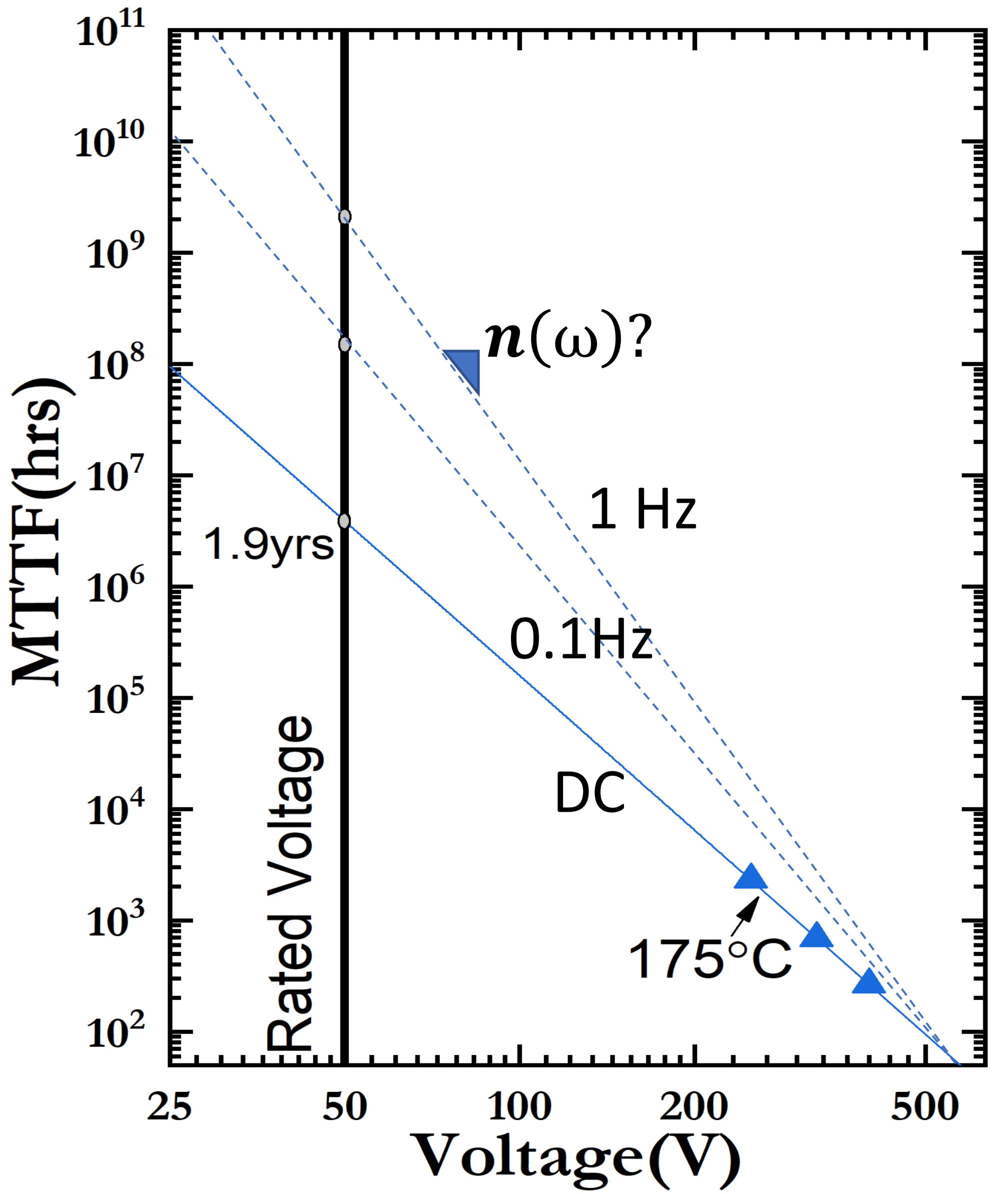
Technical Accomplishments and Progress-Passives

Full-scale HALT studies of AC degradation are needed for lifetime estimates

$$\frac{MTTF_1}{MTTF_2} = \boldsymbol{f}(\omega)\left(\frac{V_2}{V_1}\right)^{\boldsymbol{n}(\omega)} exp\left[\frac{\boldsymbol{E_a}(\omega)}{k}\left(\frac{1}{T_1} - \frac{1}{T_2}\right)\right]$$

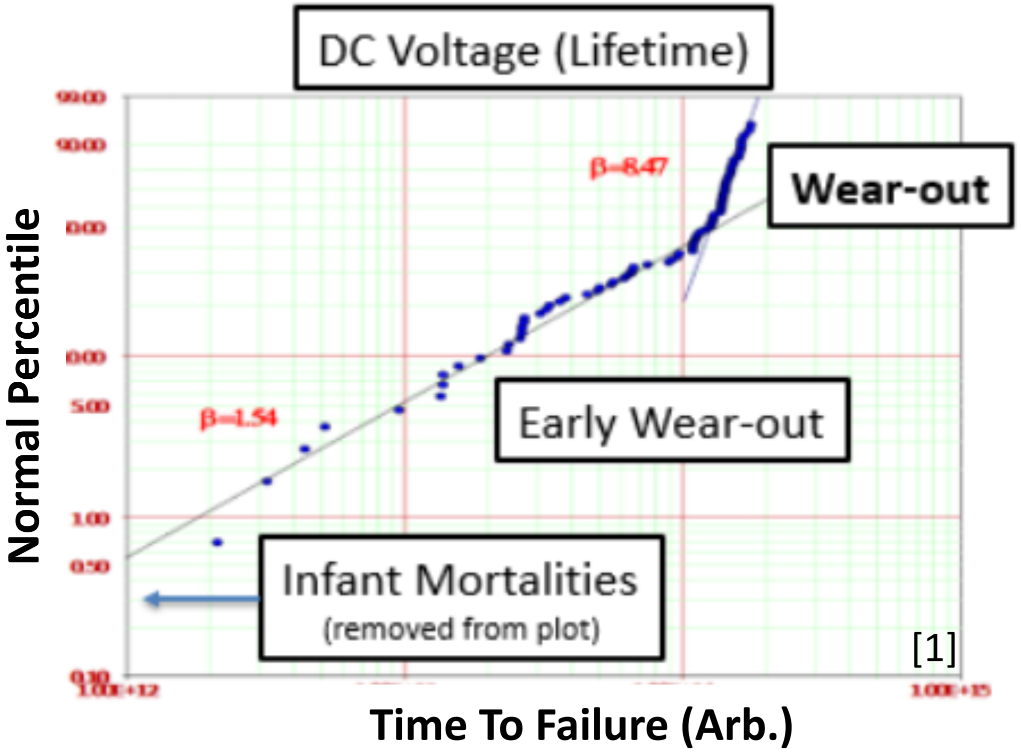
Open Questions

- Do Infant mortals and freak failures follow similar trends?
- Do **n** and **Ea** change with frequency?
  - A.k.a. are effects independent?
  - Likely not, how do we adjust equation?
- Is there a physical model to fit HALT equation to?
  - Relaxation of V_o^{**} ‘bouncing’ within a grain



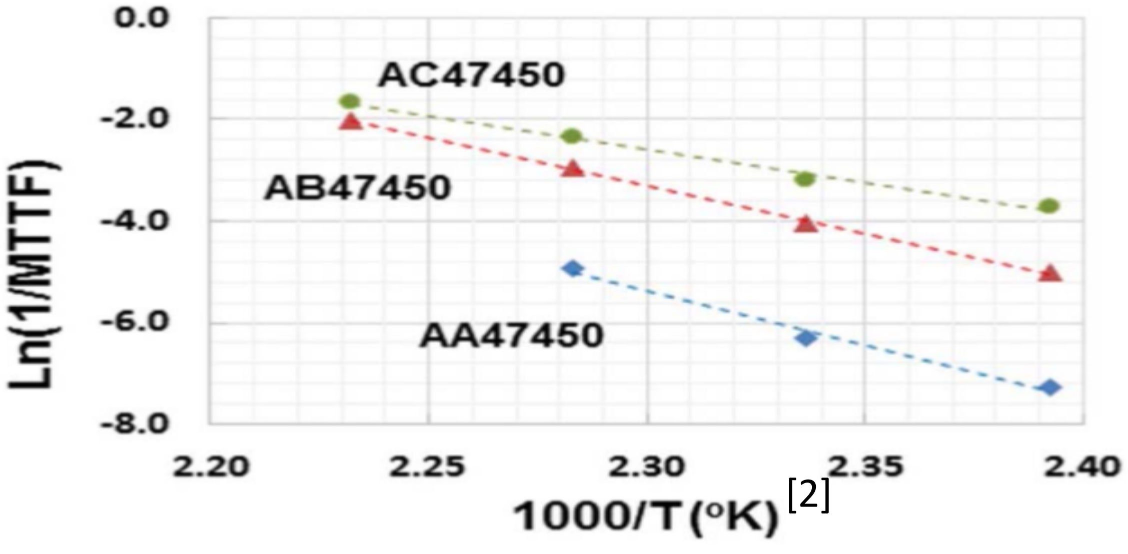
Technical Accomplishments and Progress-Passives

- **Challenge :** BME X7R Ceramic caps often exhibit freak failures and infant mortalities
  - Need full TTF data, not just MTTF…



- Infant mortals propensity is poorly described by MTTF data

- **Challenge :** n and E_a values vary significantly due to proprietary processing changes between Manufacturers



Capacitor ID	E_k (eV)
AA47450	1.65
AB47450	1.63
AC47450	1.11

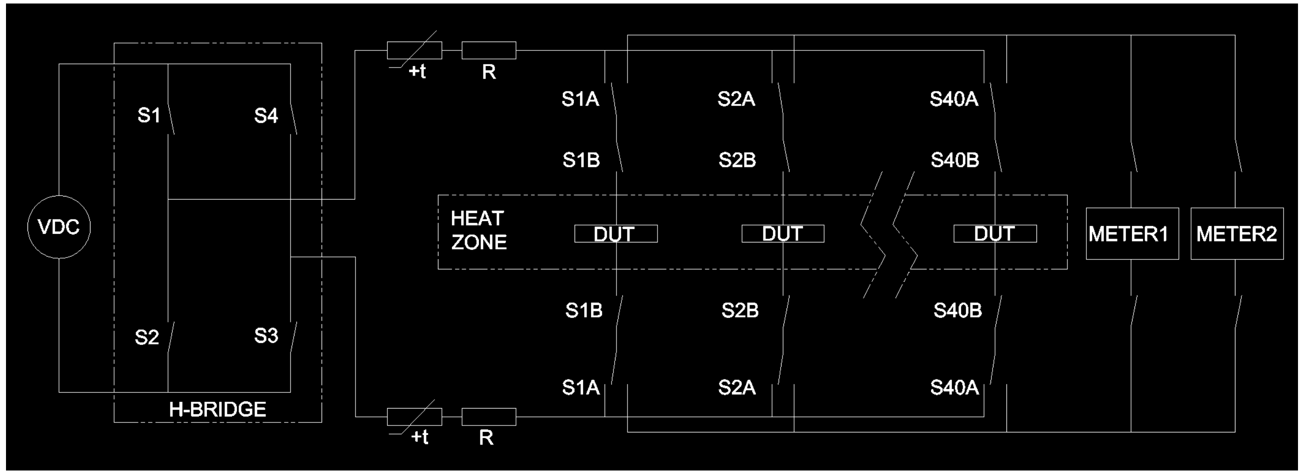
- Derating effectiveness is heavily influenced by n and E_a…

Capacitor Reliability Studies require large testing batches for lifetime determination - Scale up necessary

[1] A. Teverovsky, NASA NEPP Report, "The Significance of Breakdown Voltages for Qual. Assurance…"
[2] D. Liu, IEEE Trans. On Comp. and Manf. Tech. 5 (1) Jan 2015

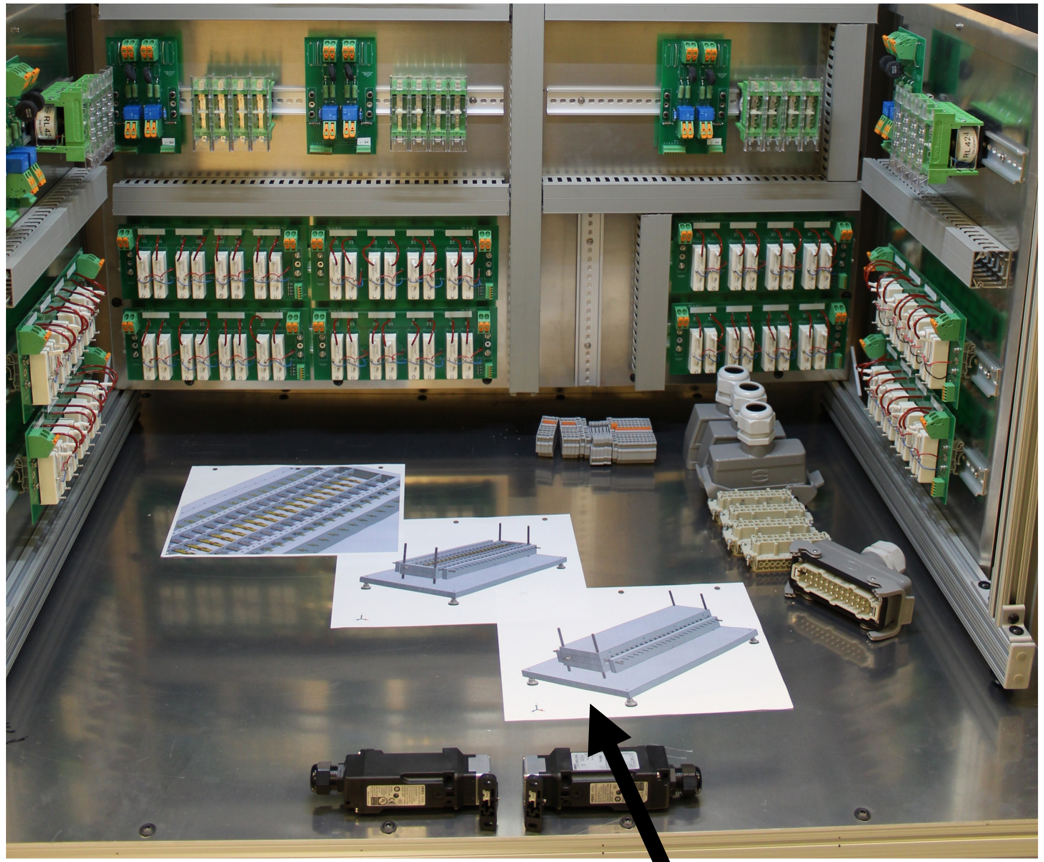
Technical Accomplishments and Progress-Passives

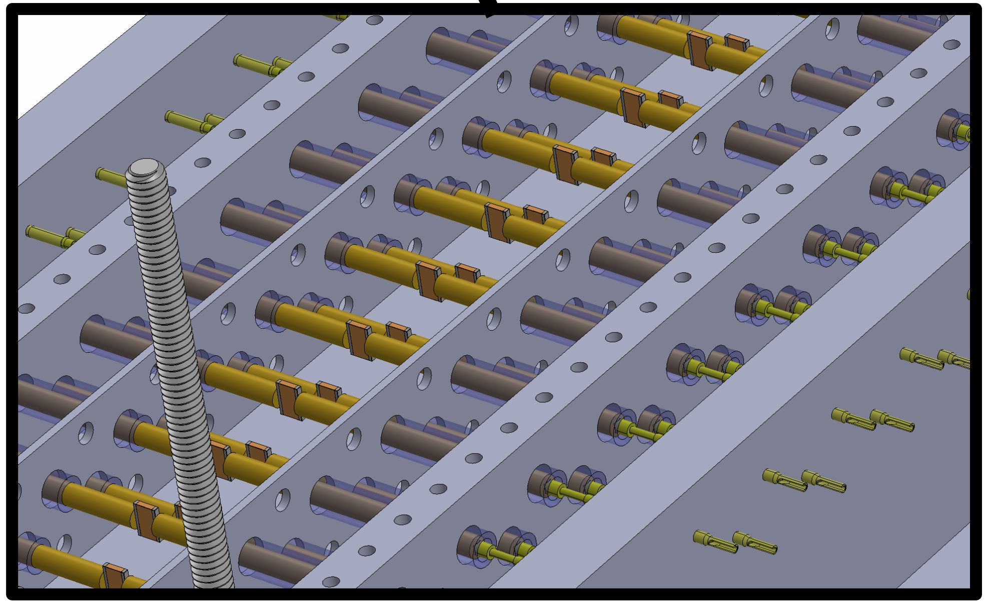
40-unit test and measure system is being developed to allow for large-scale HALT studies



Power Bus/Measurement Bus Architecture

Value	System Limit
Voltage	600V (power supply)
Temperature	300°C
Capacitors/DUT	40





- H-Bridge integrated into power bus for AC cycling of caps
- High Temperature and voltage for aggressive acceleration (Ceralink, KC-Link, High temp X9R)

Initial test to begin in June

Technical Accomplishments and Progress-Passives

Detailed Pictures of System

NI Controller

H-bridge

Power Bus and Measurement Bus switching relays

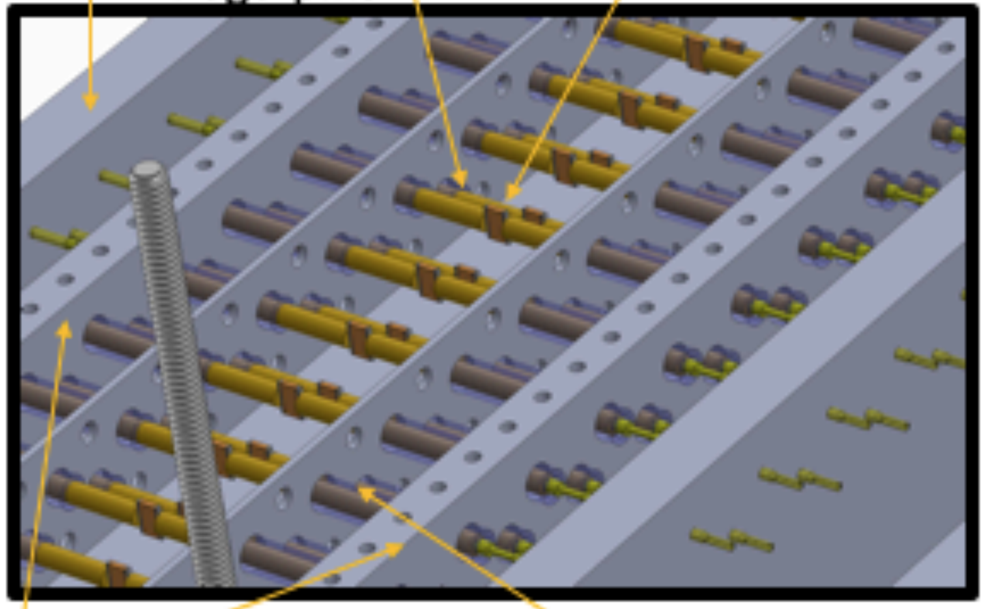
Relays for sample isolation
(Reusable fuses)

Sample fixture/Heater
(In manufacturing)

Ultem blocks hold pogo pins

High Temp
Pogo-pins

Caps (0805-2225)



Aluminum, both sides guarded

Quartz tubes for isolation

Top and bottom aluminum covers hold cartridge heaters for temperature control and provide low-noise measurement environment

Collaboration

NREL- Novel high density integration and thermal management

Oak Ridge – Implementation into traction drive

Proposed Future Research

- Survey current state-of-the-art ceramic capacitors and identify technology gaps
  - Currently focusing on X7R capacitors
  - KC-Link and Ceralink DC capacitors may have Ea, n that vary significantly from X7R

- Perform further experiments on bipolar switching
  - Longer term testing (less acceleration)
  - Determine frequency dependence of acceleration factors
  - Evaluate larger capacitor value

- Evaluate bipolar switching scheme compatibility with drive train technologies
  - *In situ* reversal of stress during operation may not be possible
  - Evaluate long term voltage reverse bias healing step when vehicle is not in operation

Any proposed future work is subject to change based on funding levels

Summary

- Carried out preliminary bipolar switching testing on ceramic capacitors
- Demonstrated ~4x lifetime increase with a 2.5 Hz bipolar switching scheme compared to DC
- Developing large-scale testbed for large population testing
  - Evaluation of failure statistics for HALT
  - Frequency dependence of acceleration factors

Technical Back-Up Slides

Responses to Previous Year Reviewers' Comments

"…without a full understanding of the application"

"take a step back and discuss with the OEM's what the requirements are for the DC link capacitor used in inverters today"

"has not looked deep enough to see what already has been done. It would be helpful if the problem could be better defined. In other words, for a given switching range and ripple voltage, what range of capacitance and equivalence series resistance (ESR) would be required."

"discuss the application with an OEM(s) or Tier 1 supplier to better understand the application requirements."

"needs to discuss requirements with the OEMs or others in automotive to"

- The principal investigator appreciates the thorough comments of the reviewers. Several reviewers raised concerns that a better understanding of the current state-of-the-art for capacitors in electric traction drives is needed for the project moving forward. The reviewers recommended discussions with OEMs or Tier 1 suppliers to understand application requirements as well as current capacitor solutions and how any proposed solution could be implemented in a traction drive. In response to this feedback, the project team has added additional capacitor subject matter experts to participate in the project. Additionally, the project team is now regularly participating in meetings with the VTO Electrical and Electronics Technical Team (EETT) to present interim results, get a better understanding of how the project fits into the overall application area, and further understand the needs and challenges of OEMs and other stakeholders.