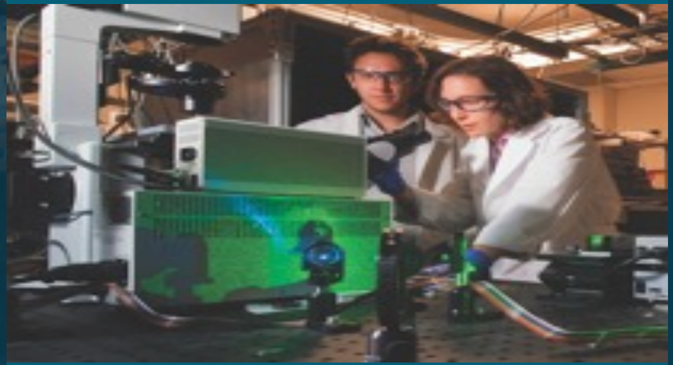
High-Reliability Ceramic Capacitors to Enable Extreme Power Density Improvements



Jack Flicker

Sandia National Laboratories

June 25, 2021

Project ID: elt222

Overview

Timeline

- Start – FY19
- End – FY23
- 50% 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
- Funding for FY21: $70k

Partners

- ORNL, NREL, Ames Lab
- Project lead: Sandia Labs
  - Andrew Binder, 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

Power Electronics and Drive Train Goals

- 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

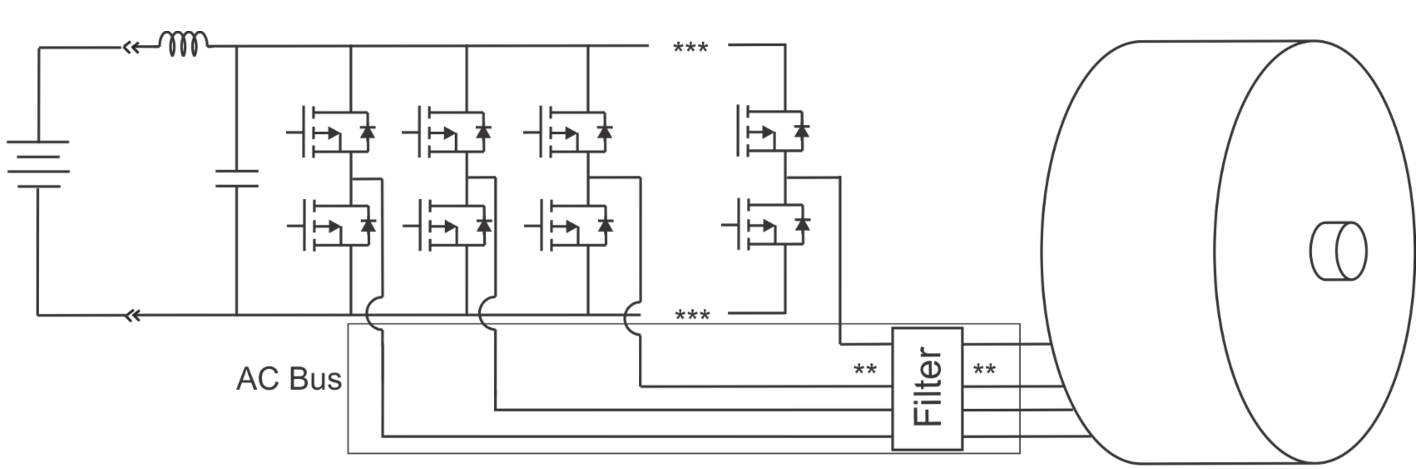
Milestone	Date	Status
Evaluate state-of-the-art ceramic capacitor components and identify gaps	4/2019	Completed
Develop bipolar switching strategy allowing ceramic dielectrics to exhibit long lifetime at high temperature.	10/2019	Completed
Build a custom AC Highly Accelerated Lifetime Test (HALT) system and initiate frequency-dependent HALT characterization of ceramic capacitors	10/2020	Completed
Find acceleration factors for voltage and temperature for ceramic capacitors. Determine how those factors depend on frequency	10/2021	In Progress

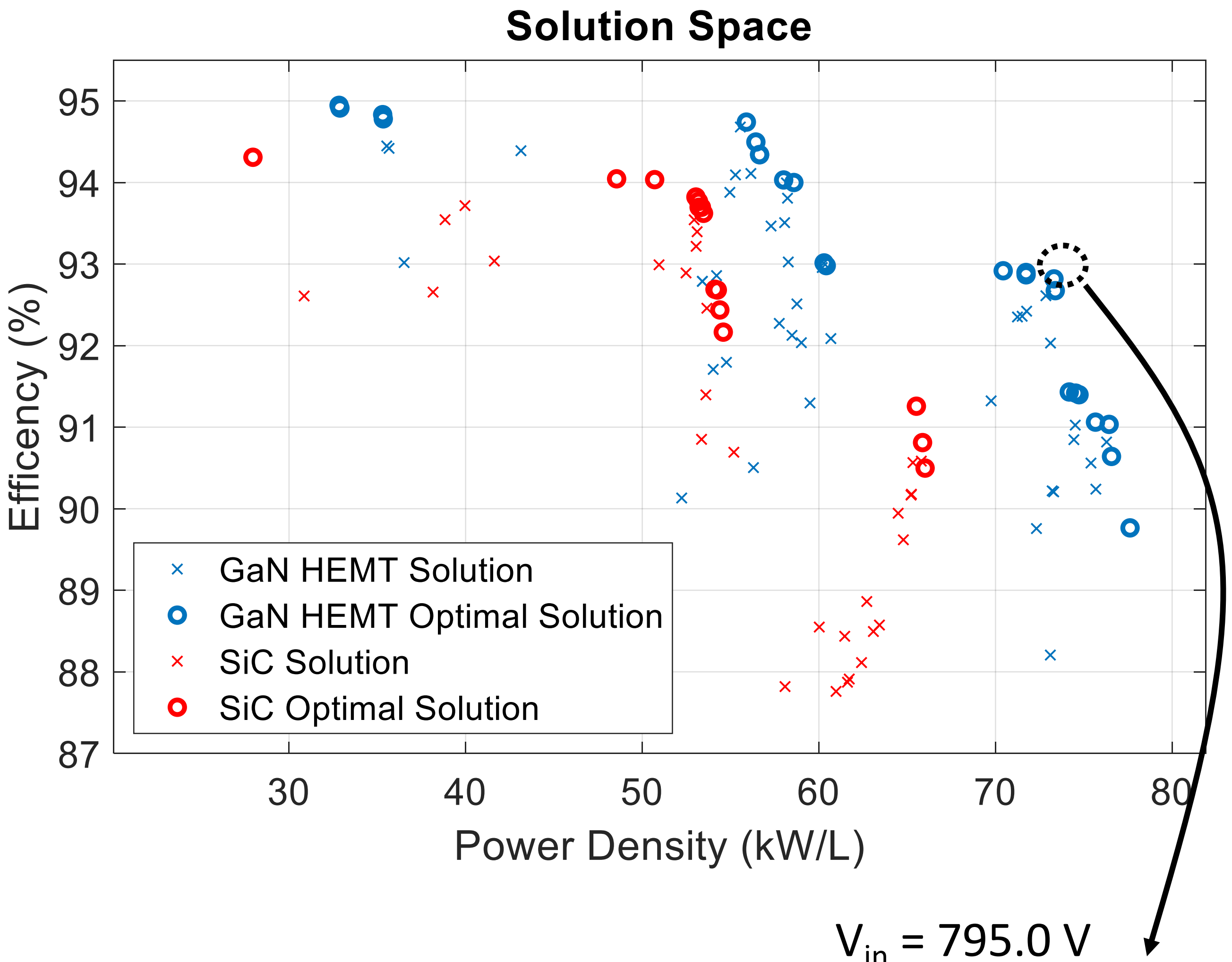
Any proposed future work is subject to change based on funding levels

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

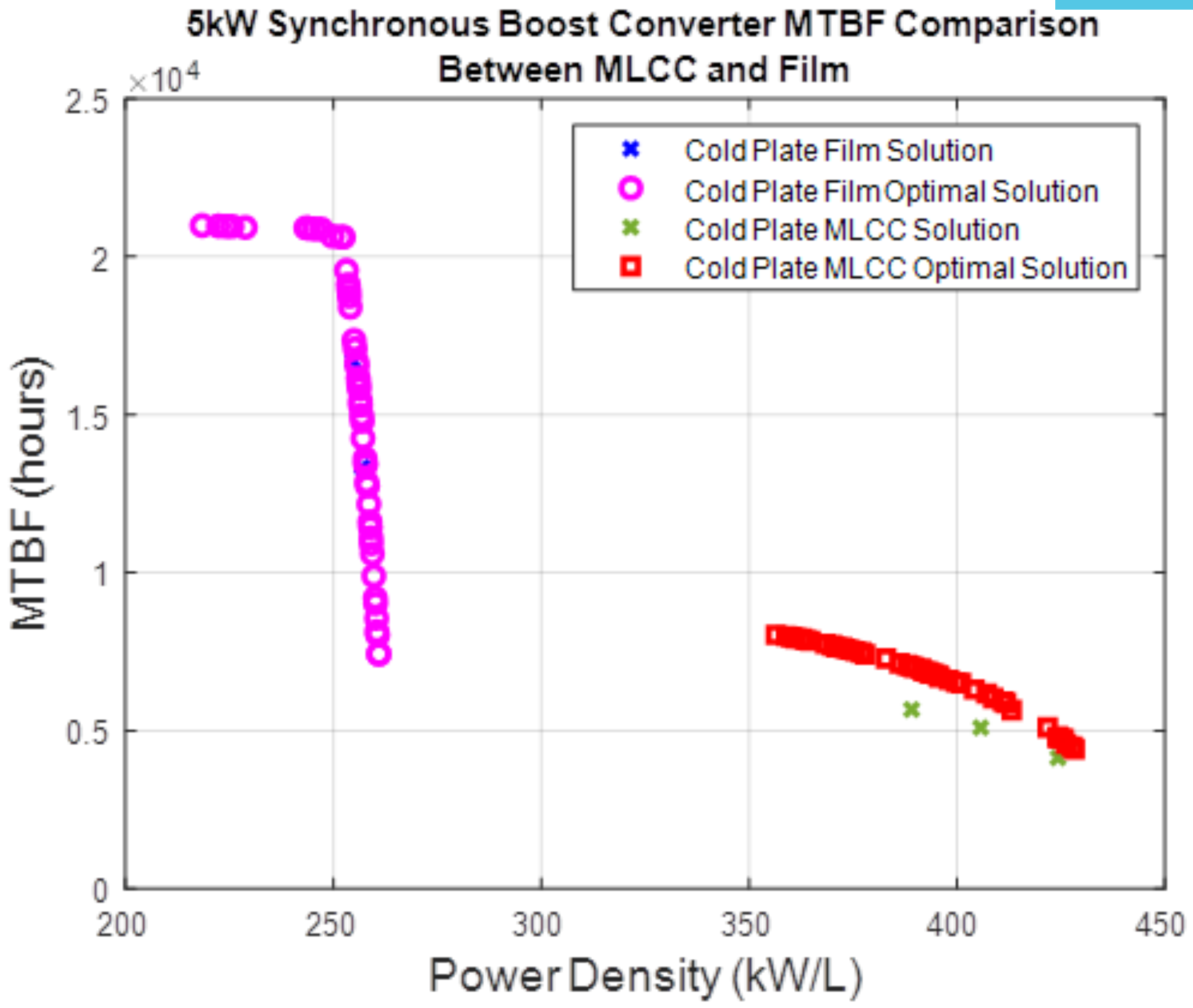
Component	Volume (L)	% of total	Loss (kW)	% of total
Module	0.025174	1.7721	5.1435	63.8379
Capacitor	0.1501494	10.5713	-	-
Input inductor	4.46e-6	0.0031	0.6135267	7.6147
Filter inductor	1.0607	74.6799	2.3001	28.54746
Cooling system	0.1842649	12.9733	N/A	N/A

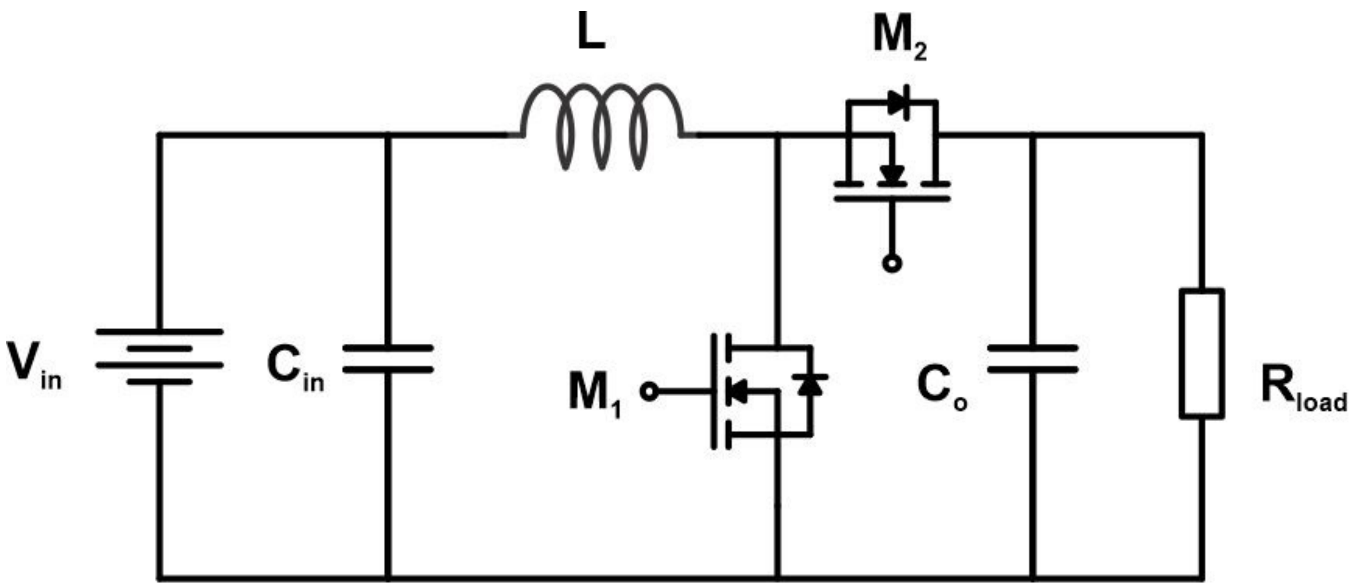
[1] "Co-Optimization of Boost Converter Reliability and Volumetric Power Density Using Genetic Algorithm". 2020 IEEE Energy Conversion Congress and Exposition (ECCE). Detroit, MI. October 2020. (Accepted)

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



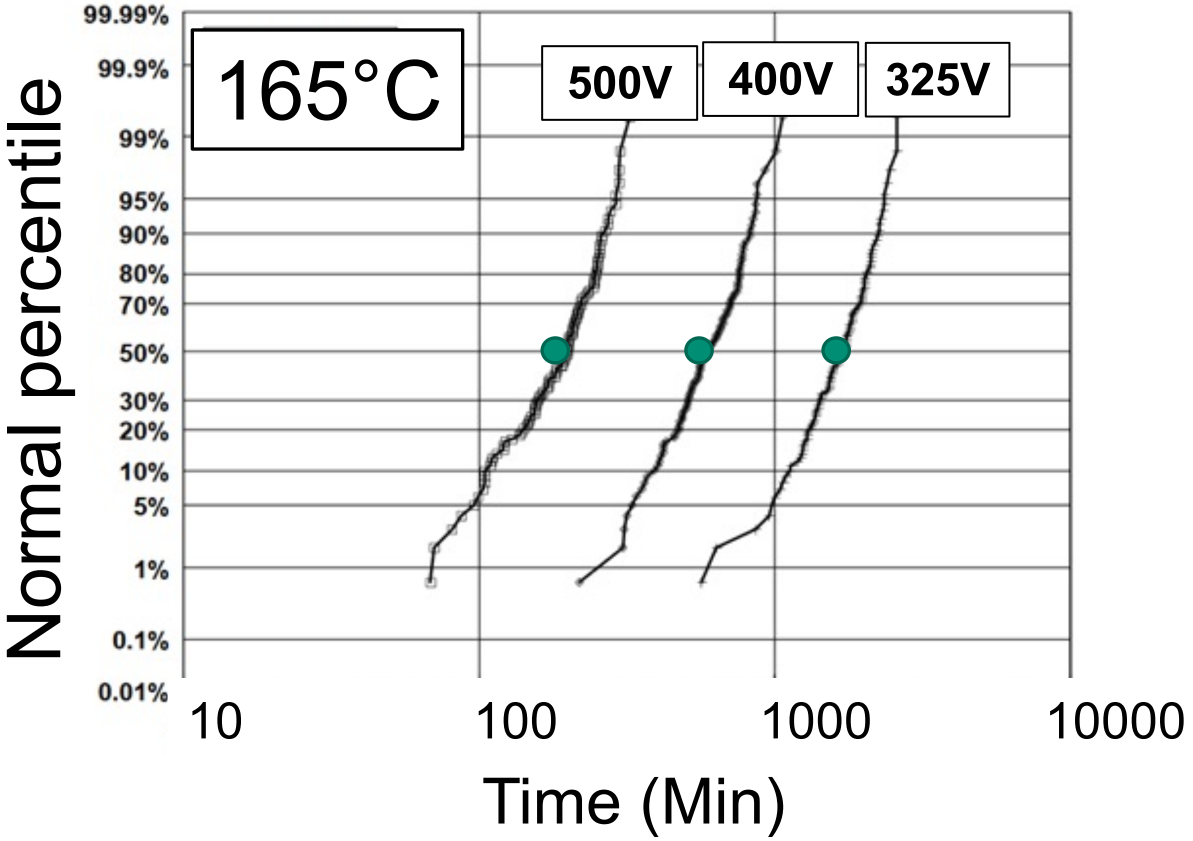


154.07 kHz (f_{sw}),
400 V (V_{in}),
500.2 V (V_o),
1.0407 % ($I_{L_{pk2pk}}$),
195.5292 (T_j)

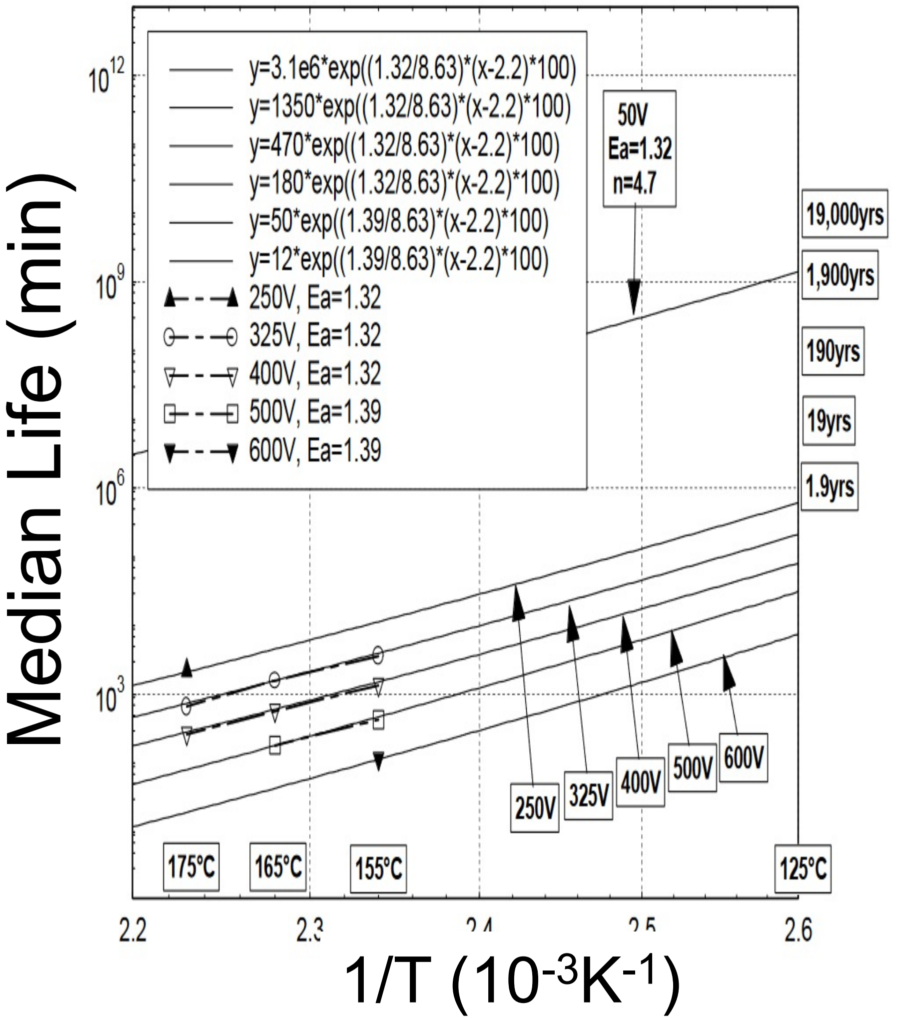
Approach: Capacitors for Power Electronics

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



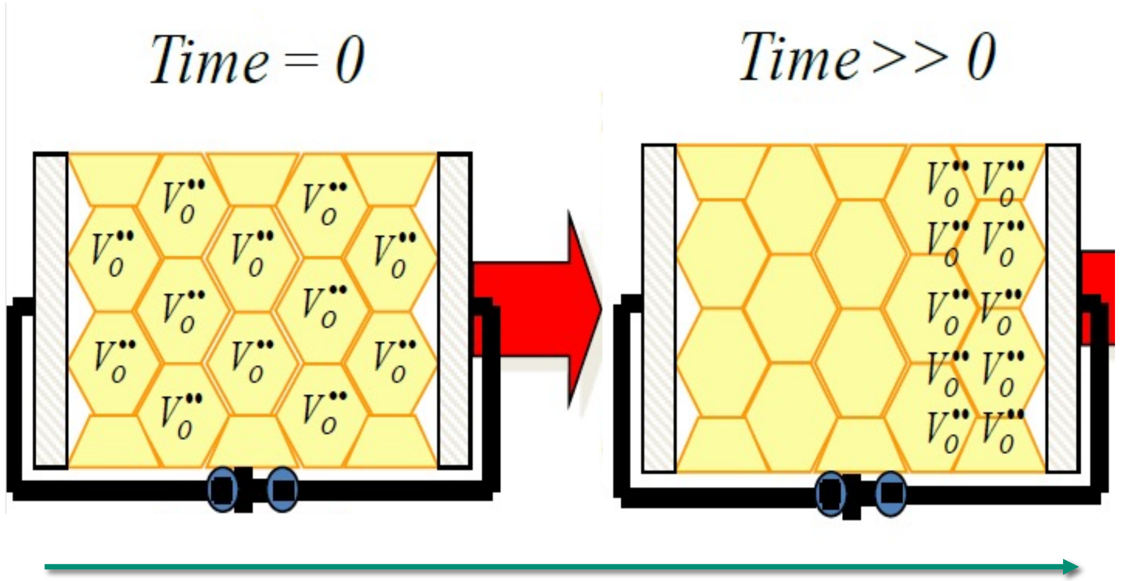
$$\frac{MTTF_1}{MTTF_2} = \left(\frac{V_2}{V_1}\right)^n exp\left[\frac{E_a}{k}\left(\frac{1}{T_1} - \frac{1}{T_2}\right)\right]$$

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

Approach: Capacitors for Power Electronics

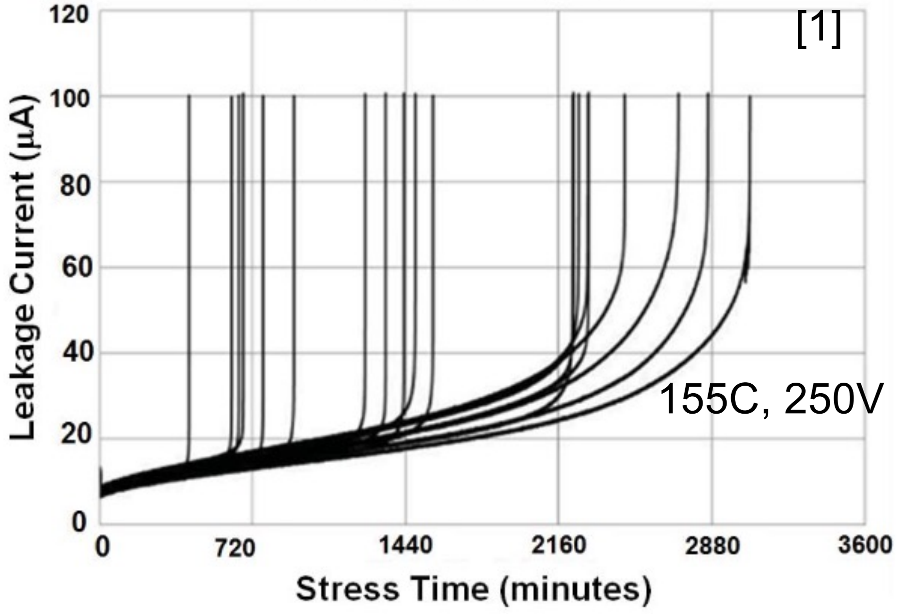
One significant failure mechanism at high voltage and temperature is DC Failure (Short) caused by Electromigration of Defects

- 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

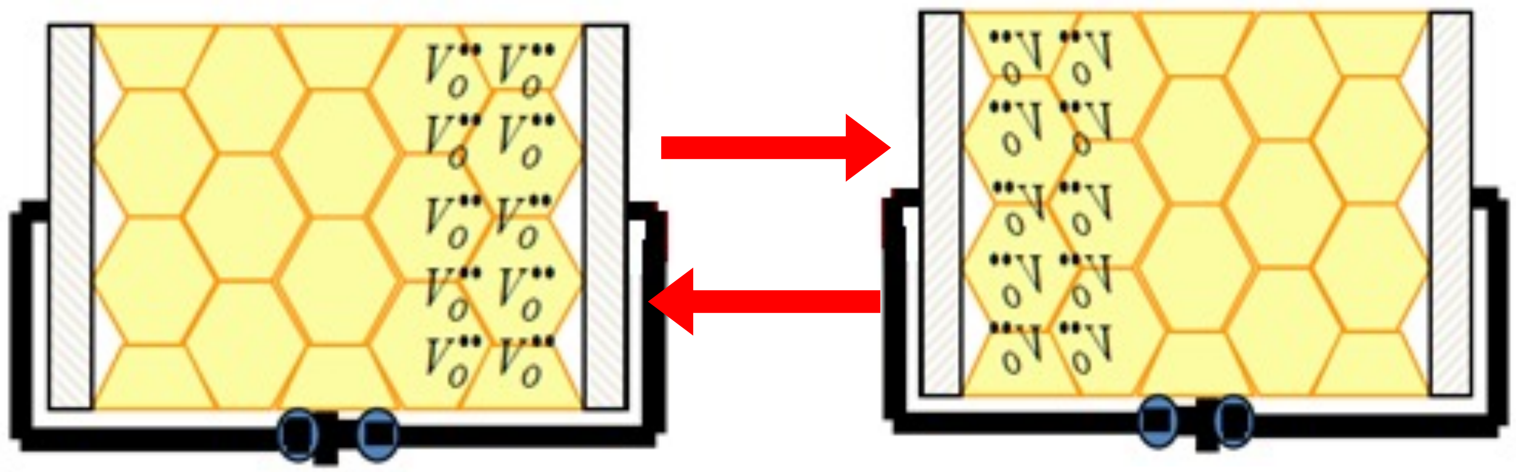


Leakage current increases leading to thermal runaway and short

[1] Evaluation of Commercial Automotive-Grade BME Capacitors", D. Liu, CARTS International, Santa Clara CA, 2014

Approach: Capacitors for Power Electronics

Bipolar actuation should 'bounce' defects between electrodes



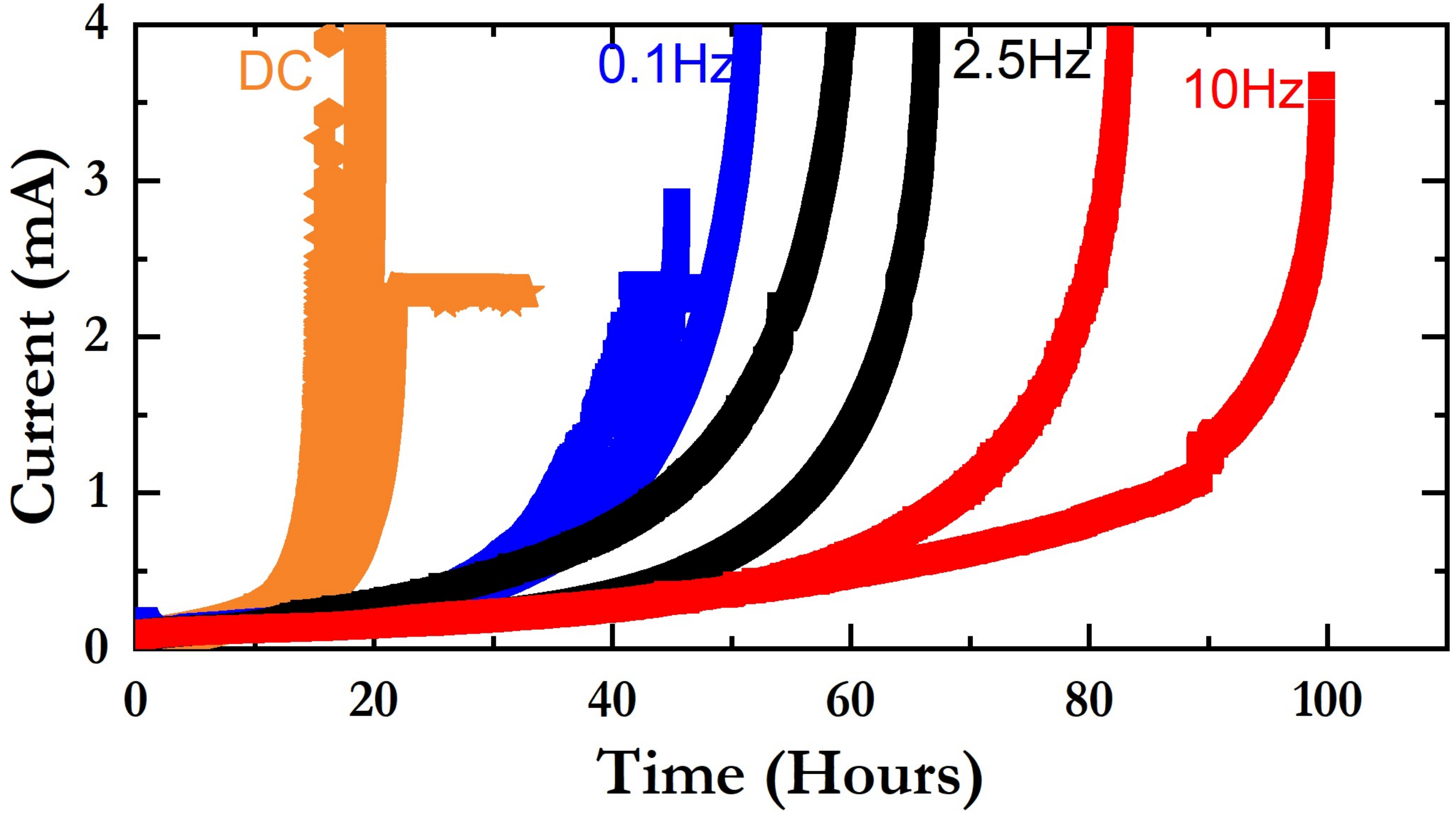
Application of AC field over time

- 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
  - Low voltage (6.3V) capacitors used in initial studies due to experimental setup limitations
    - Applied ~10x V_{rated} at 125°C **above** T_{rated}
  - Very high acceleration was 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)?**

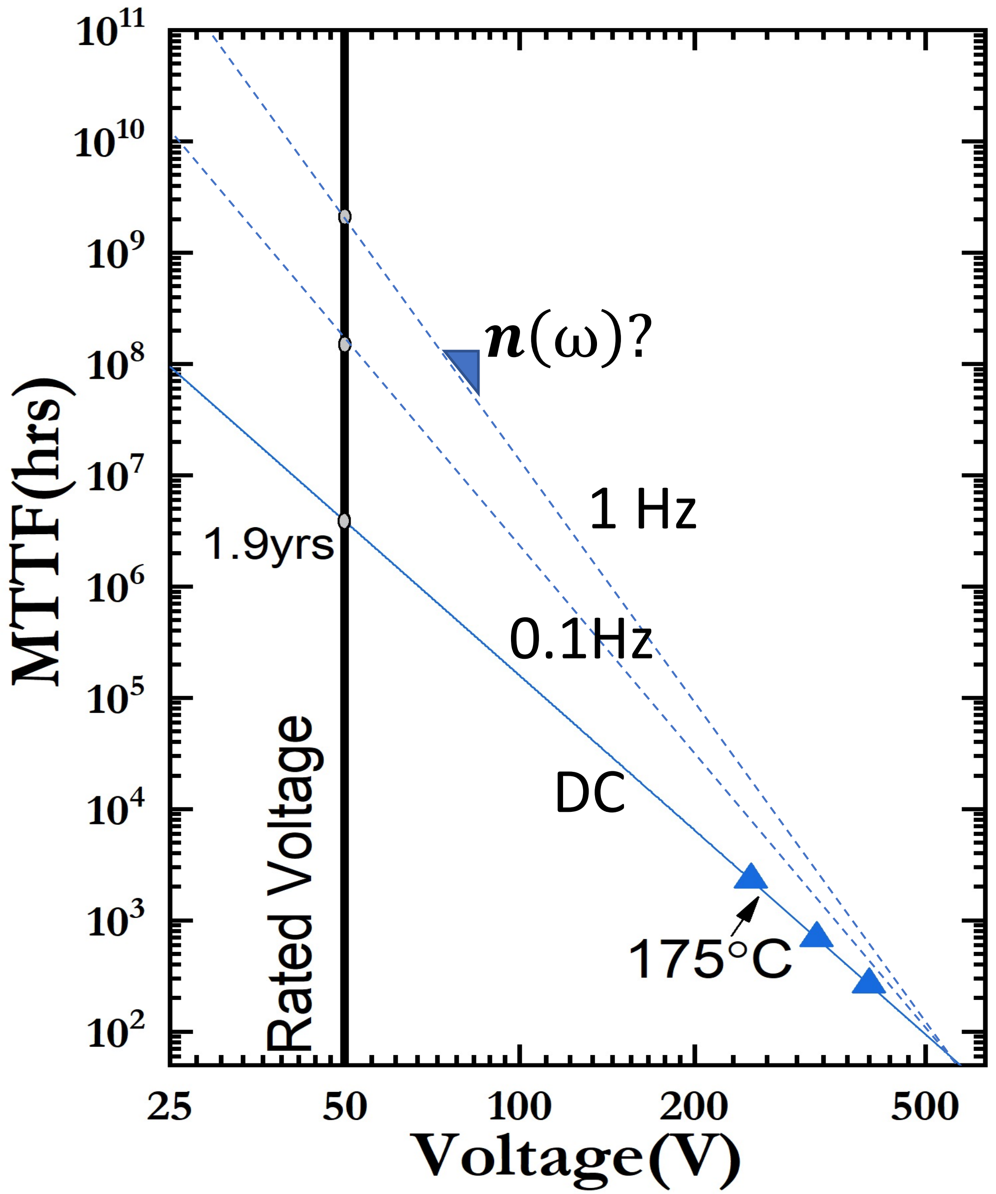
Technical Accomplishments and Progress-Passives

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

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

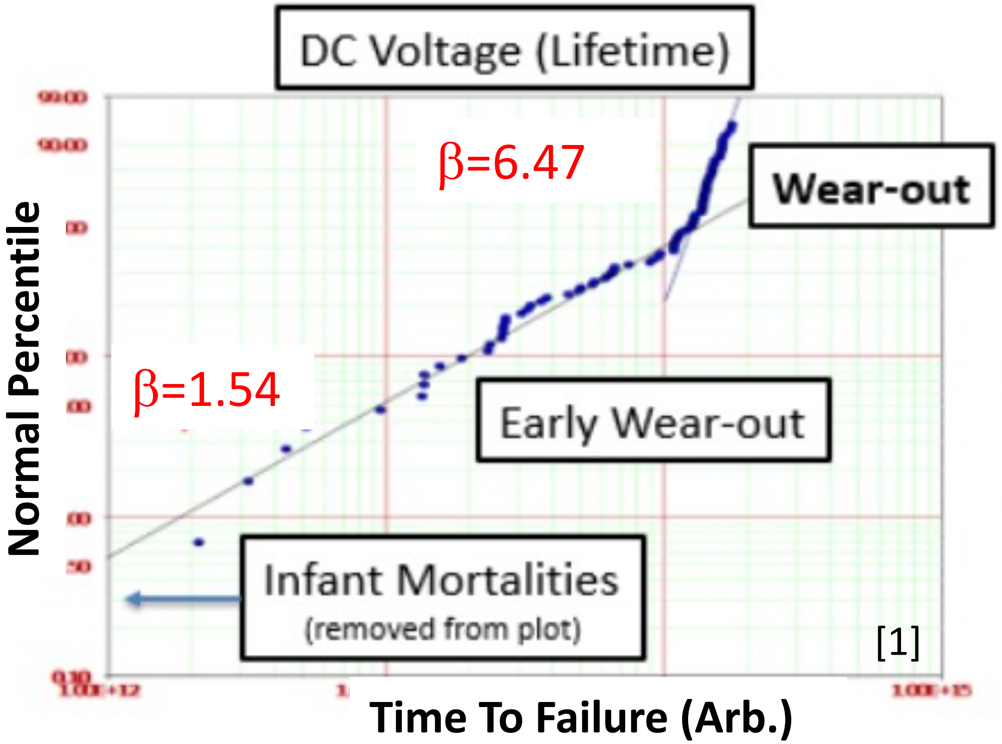
Open Questions

- Does HALT testing under AC conditions introduce a change in failure mechanism? i.e. is extrapolation of testing relevant to use conditions?
- 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



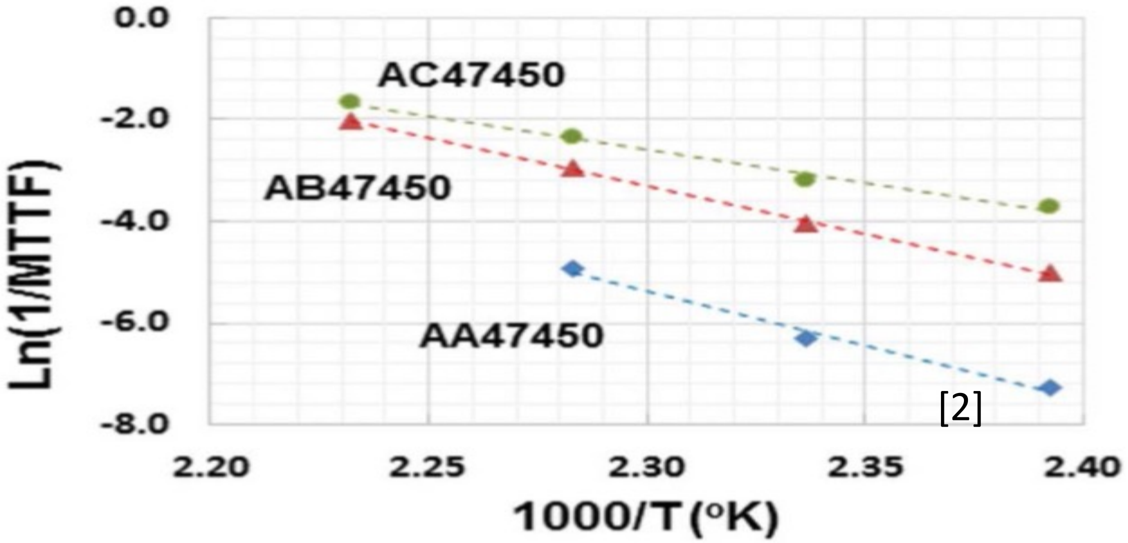
Technical Accomplishments and Progress-Passives

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



- Infant mortal 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

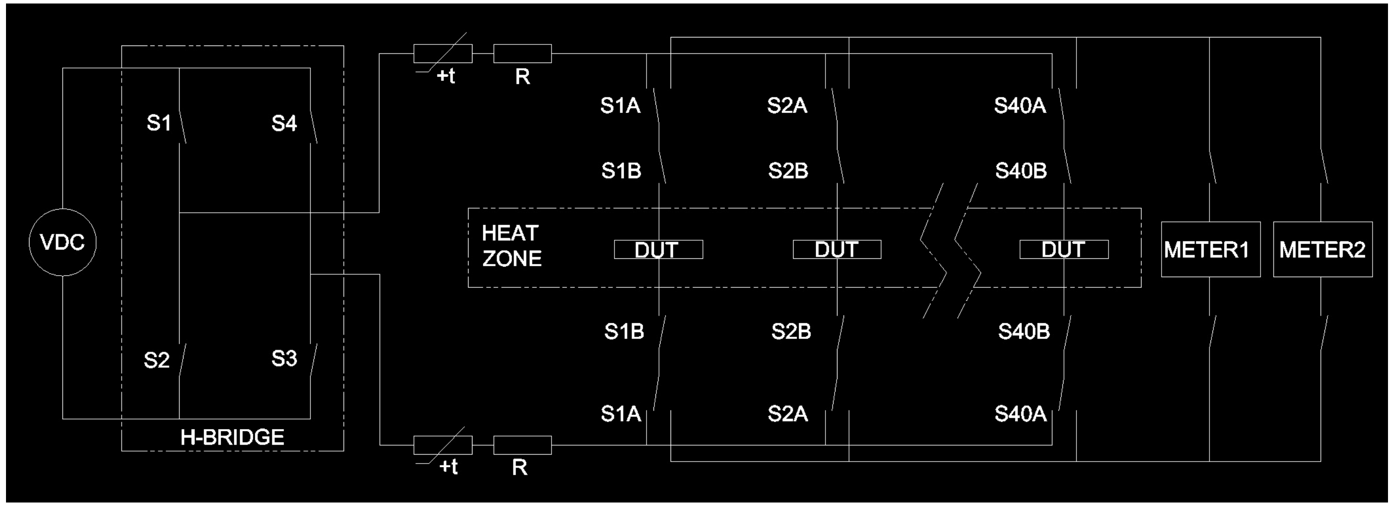
- Derating effectiveness is heavily influenced by n and E_a…

Capacitor Reliability Studies require large testing batches for lifetime determination - Scale up of testbed is 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 has been developed to allow for large-scale HALT studies



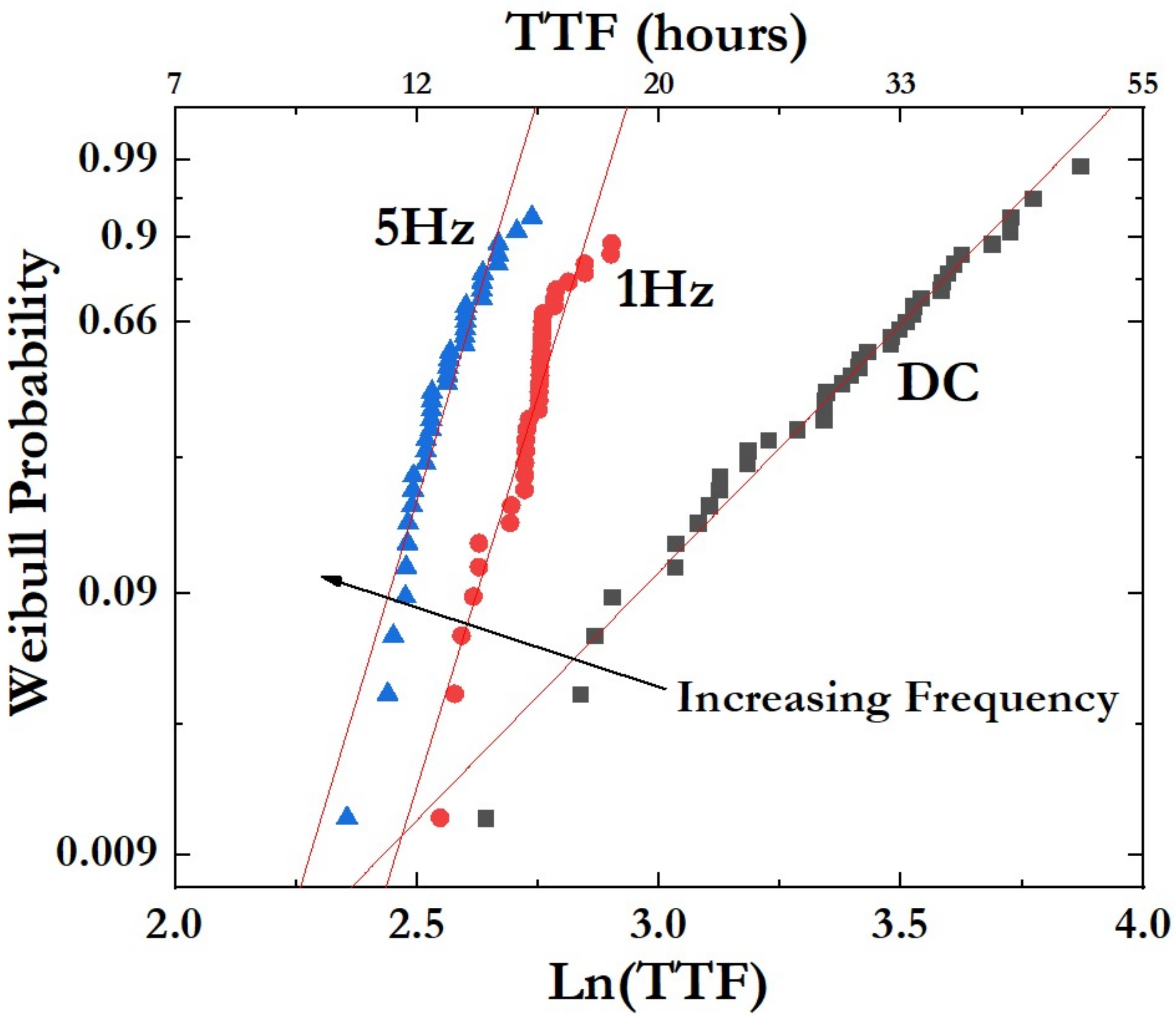
Power Bus/Measurement Bus Architecture

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)

Technical Accomplishments and Progress-Passives

- Measurements in new testbed have been started on 100V 1uF 0805 X7R capacitors
- DC HALT measurements found Ea~1.6eV in agreement with literature.
- First set of AC Measurements done at 100V and 200°C
  - **Increasing frequency shows decreasing lifetime**
  - Opposite from initial experiments
- Mechanism currently unclear
  - High dV/dT during switching may lead to cracking and subsequent field concentration at cracks.
  - AC cycling may lead to electrostrictive delamination of electrode and dielectric
  - ‘Pumping’ of oxygen vacancies to grain boundaries causing conductive pathway along grain boundaries

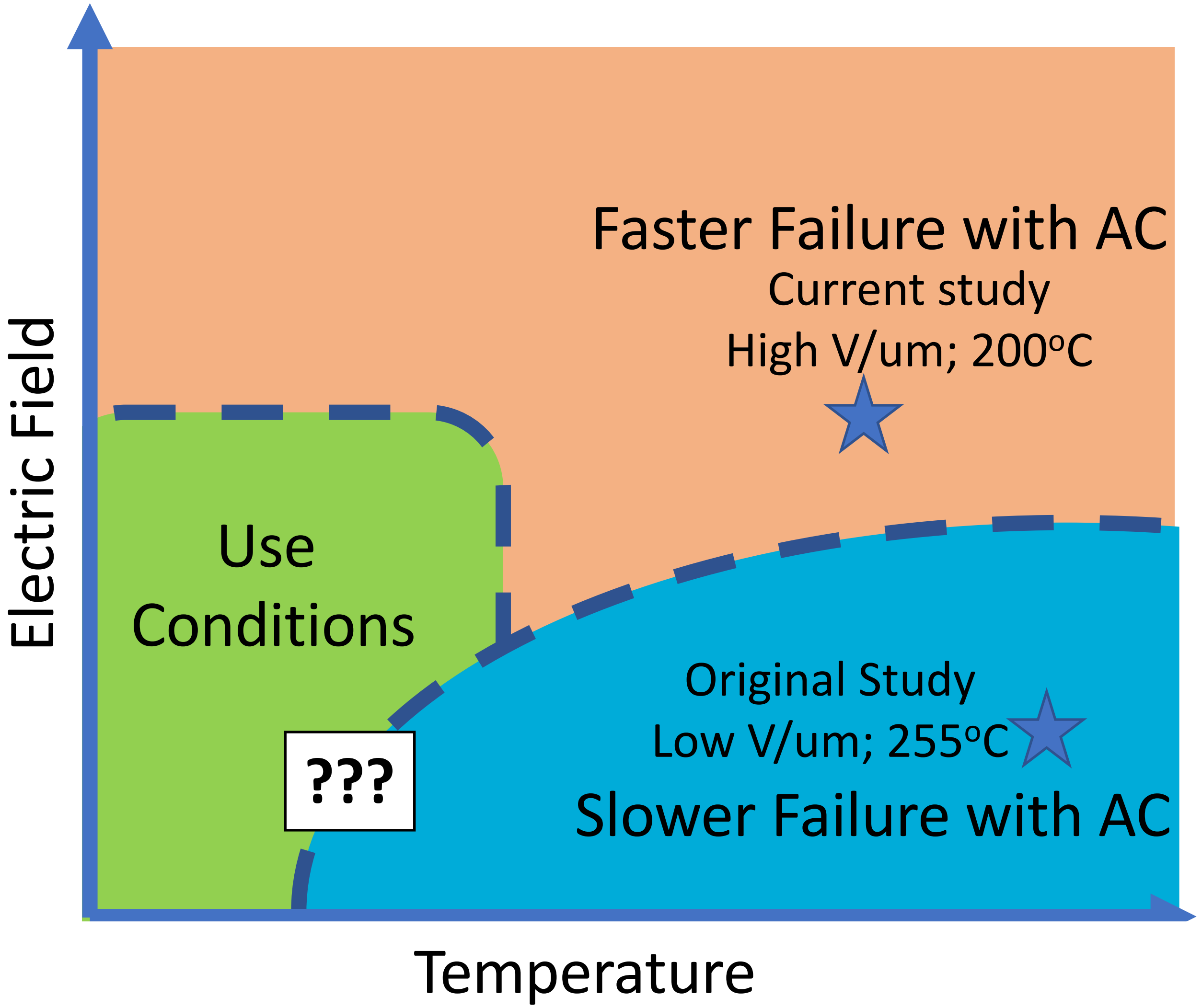


Technical Accomplishments and Progress-Passives

Under Bipolar Square Wave Conditions:

- Previous tests (Moderate E-field, Very High Temp) caused *slower failure* w/ increased frequency
- Current tests (High E-field, High Temp) caused *faster failure* w/ increased frequency
- Both sets of failures occurred via similar failure *mode*: degradation in insulation resistance.

- Specifics of the failure *mechanism* may be changing under different accelerated conditions, but ***more data*** is needed.



Need to measure the effect of frequency on lifetime over multiple voltage/temperature conditions to better understand if extrapolation to use conditions is justifiable

Responses to Previous Year Reviewers' Comments

"..the total time the capacitor is subject to voltage above a critical value dictates its failure. For DC voltage, this is the total test time; for AC voltage, it is a small fraction of the test time. Slide 10 could be misunderstood as the AC field extended lifetime."

The principal investigator appreciates the thorough comments of the reviewers. To date, all tests have been performed with 50% duty cycle in an *bipolar* AC fashion with no additional DC bias. That is, tests are stressed with a square wave between $+V_{test}$ and $-V_{test}$. As the reviewer pointed out, "Lifetime extension" would also be found when comparing between DC and cycling between 0 V and $+V_{test.}$ But, as the reviewer mentions, this would be misconstruing the test. The interesting aspect here is that lifetime extension comes from the reverse bias that is applied ($-V_{test}$), which would not be the case if it were only dependent on the magnitude of the field. We are attempting to determine the effectiveness of that reverse bias in 'healing' the capacitor by reversing the electromigration.

Collaboration

NREL- Novel high density integration and thermal management

Oak Ridge – Implementation into traction drive

Proposed Future Research

- Perform further experiments on bipolar switching
  - Determining frequency dependence of median time to failure at multiple voltage/temperature acceleration conditions
  - Determine frequency dependence of acceleration factors
  - Evaluate larger capacitor values

- 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
    - DC HALT of Ceralink capacitors funded in FY22 through separate DOE project

- 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 on lower voltage X7R MLCC's.

- Developed a large-scale testbed for large population testing and have recently started initial tests.
  - Initial experiments on higher voltage capacitors result in opposite result (lower lifetime under AC conditions)
  - More information needed to determine differences between high and low voltage capacitors and the applicability extrapolating current testing to use conditions.

Technical Back-Up Slides