Effect of Defect Dynamics on Reliability of X7R Multilayer Ceramic Capacitors

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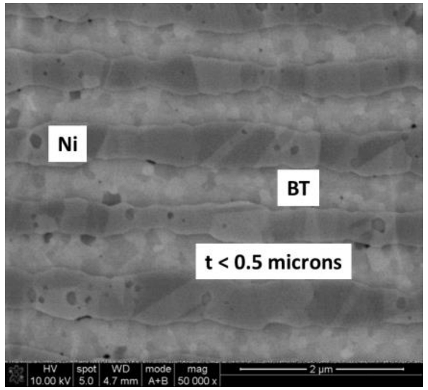
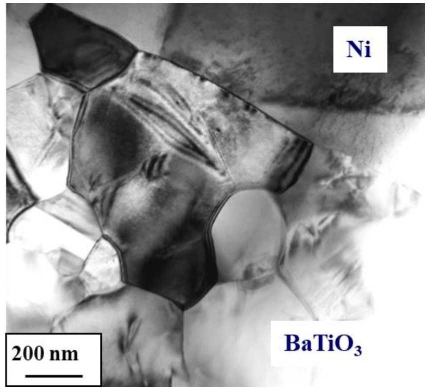
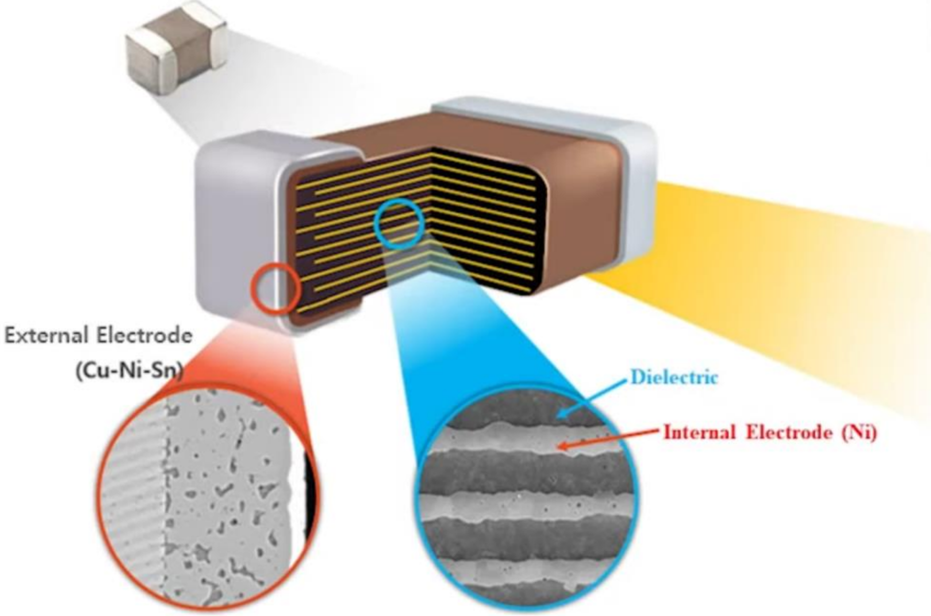
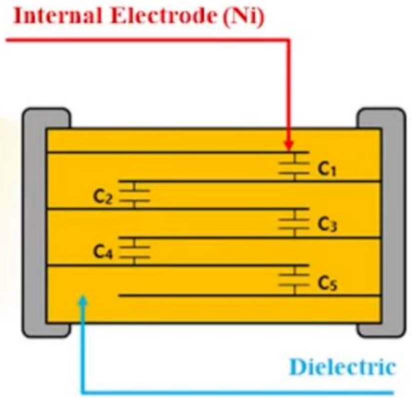
Multilayer Ceramic Capacitors (MLCCs)

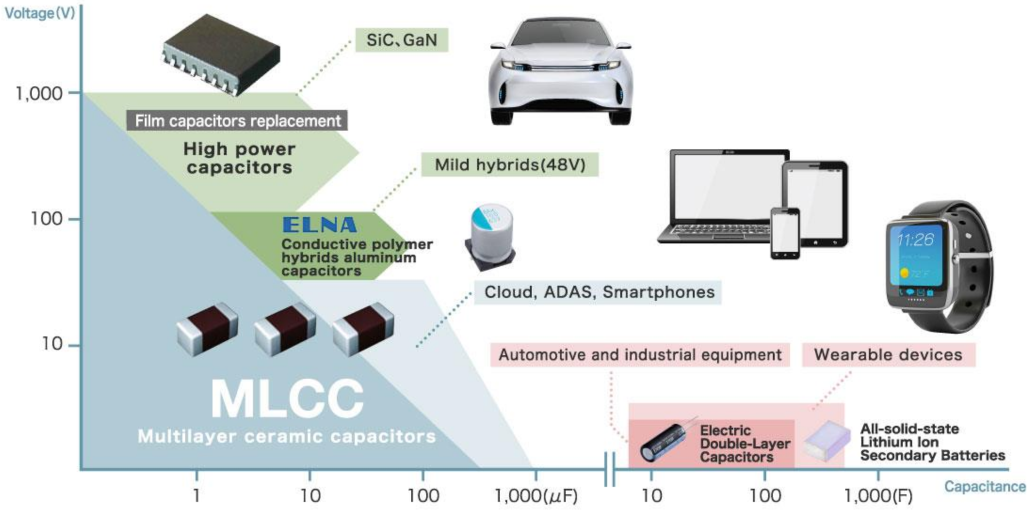


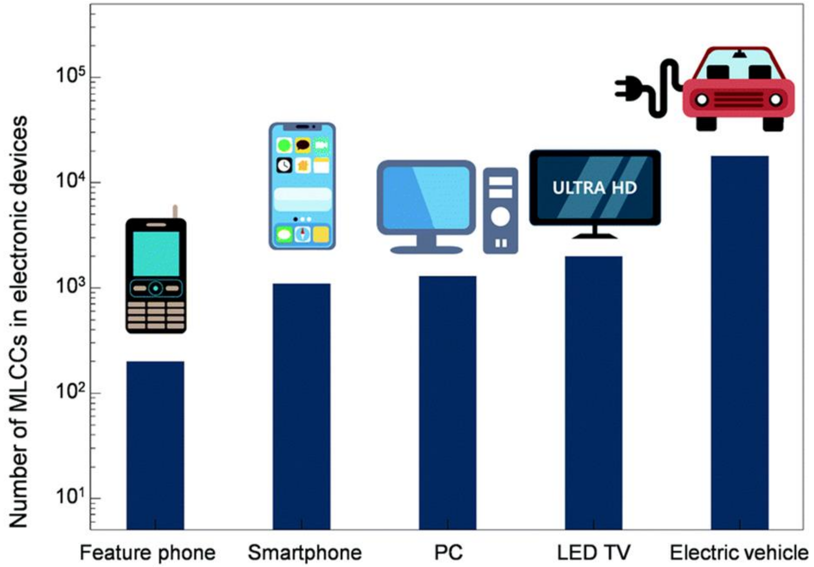






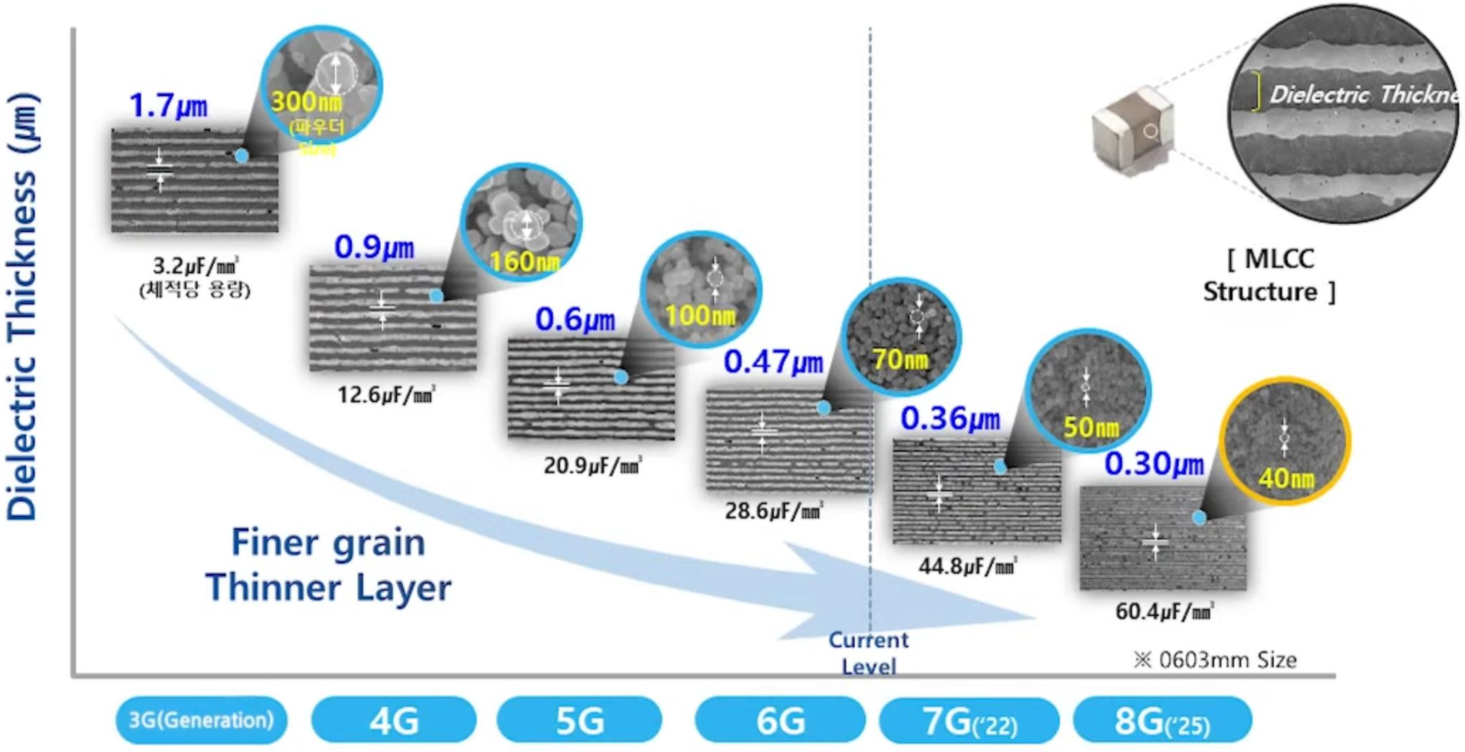
$$C_{total} = C_1 + C_2 + C_3 + C_4 + C_5$$





[1] Samsung Electro-Mechanics
[2] https://www.yuden.co.jp/ap/solutions/mlcc/

MLCCs Reliability

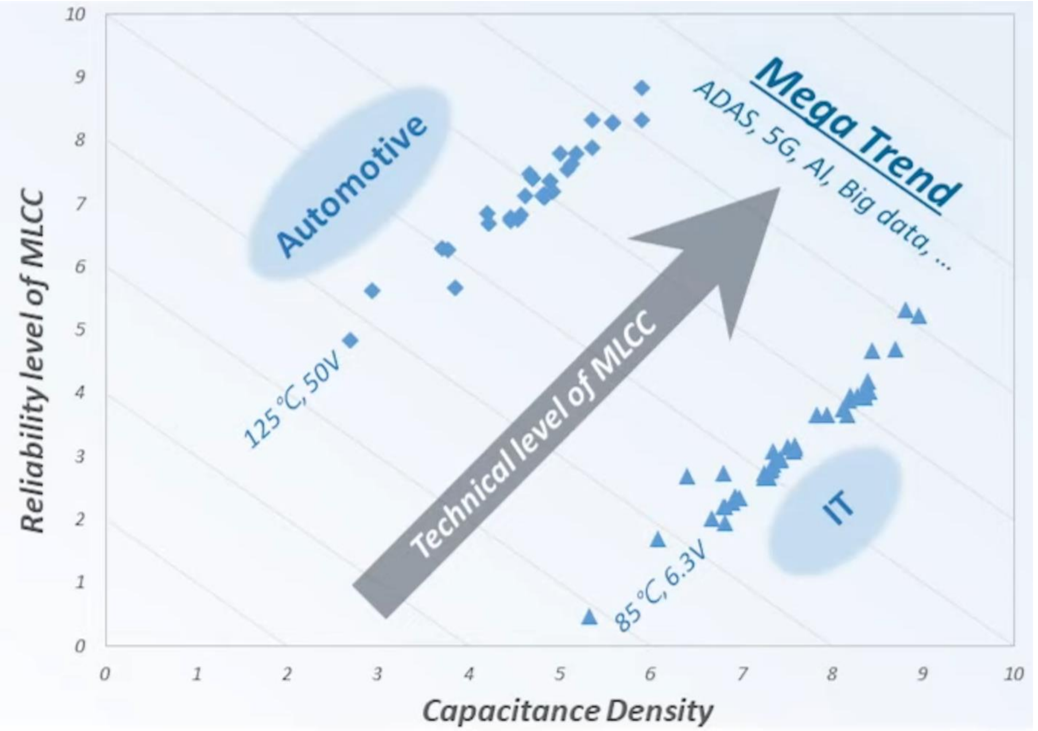


Faulty $5 Parts Cause 18-Month, $1 Billion Delay to Navy, Air Force Nuclear Upgrades

By: Ben Werner
September 25, 2019 4:46 PM

Replacement capacitors are being produced but will cost about $75 per unit, compared with the $5 per unit cost of the off-the-shelf capacitors that failed stress testing.

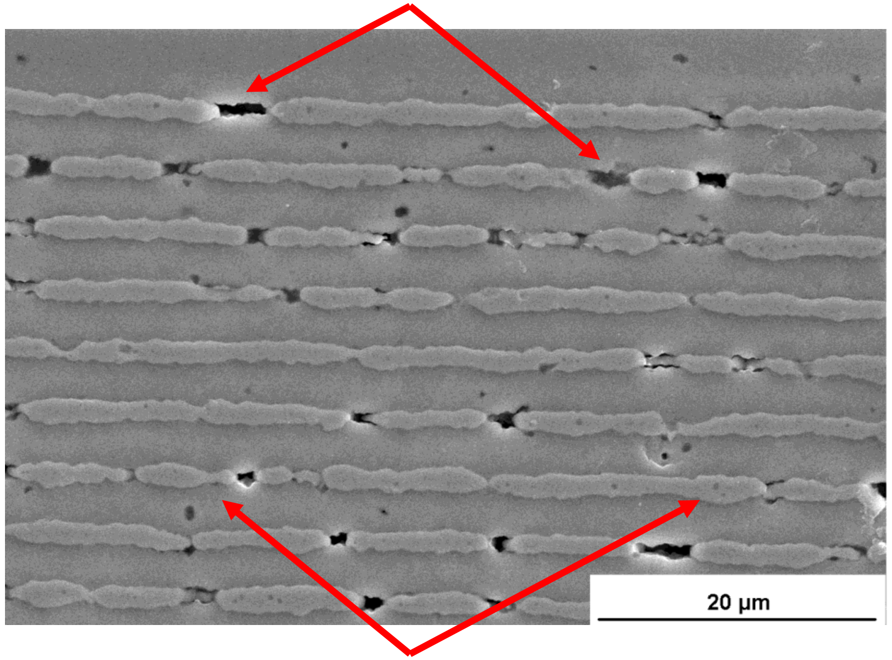
"The use of commercial-off-the-shelf electric components needs to be improved to reduce future COTS-related risk," Verdon said.



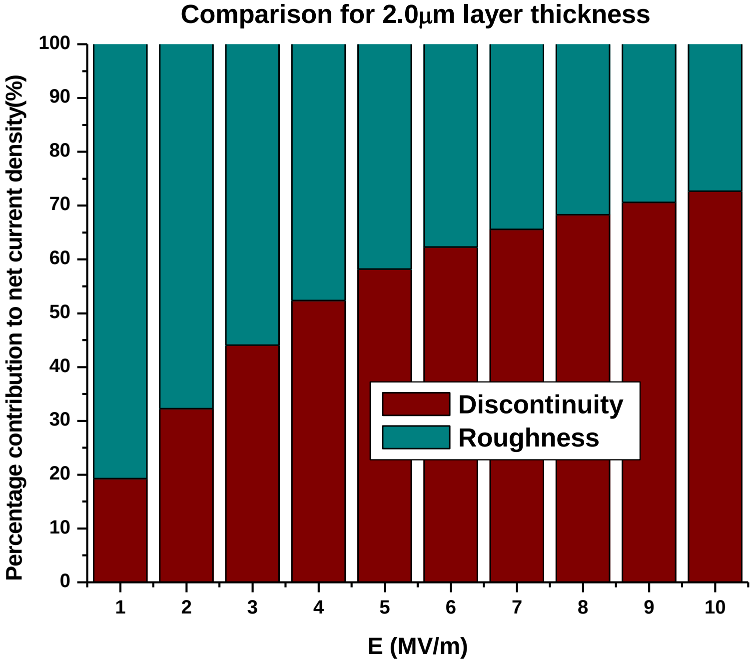
[1] SAMSUNG ELECTRO-MECHANICS
[2] https://news.usni.org/2019/09/25/faulty-5-parts-cause-18-month-1-billion-delay-to-navy-air-force-nuclear-upgrades

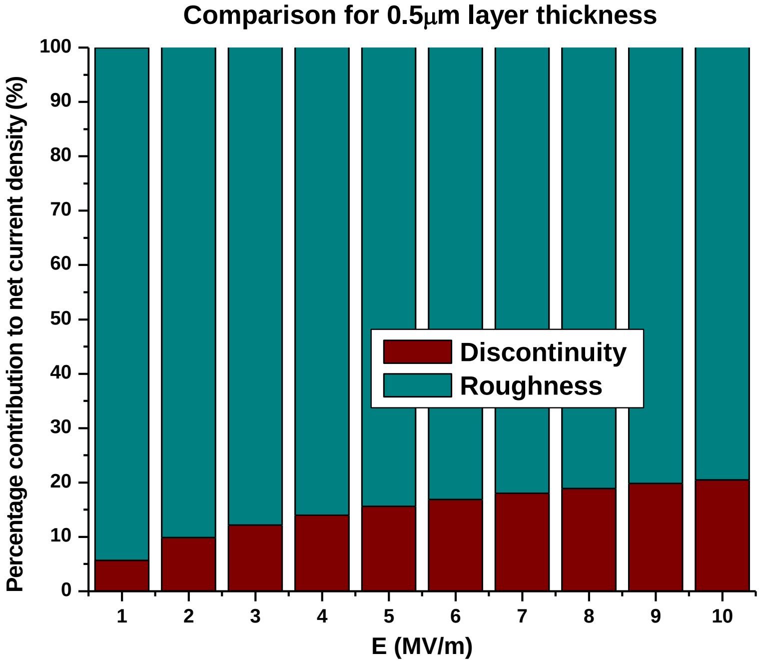
MLCCs' Reliability

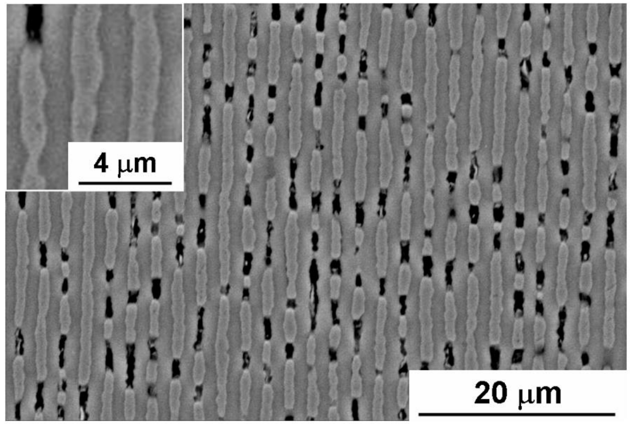
<u>Electrode discontinuities:</u>
Lower volumetric capacitance and electric field enhancement



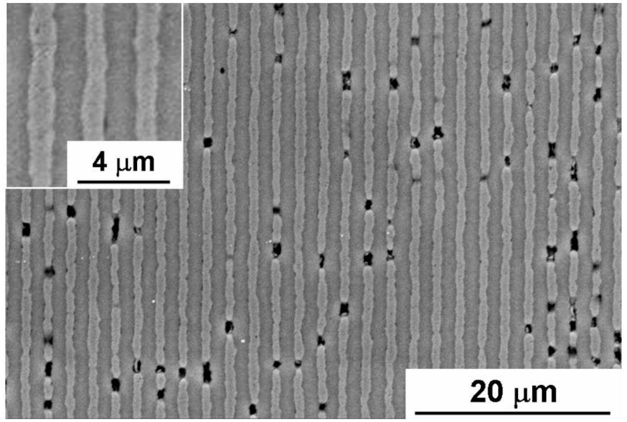
<u>Rough interfaces</u>: Lead to electric field enhancement and thus, higher leakage current







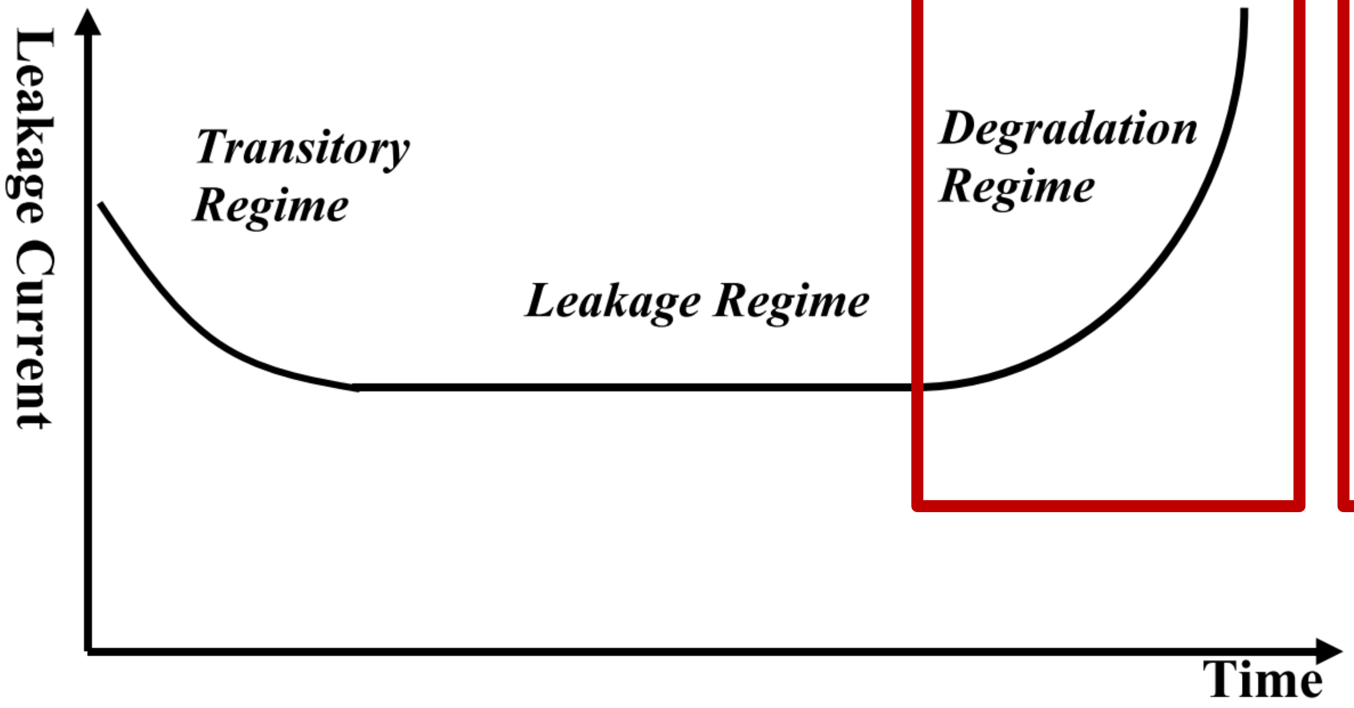
250˚C/min to 1300C

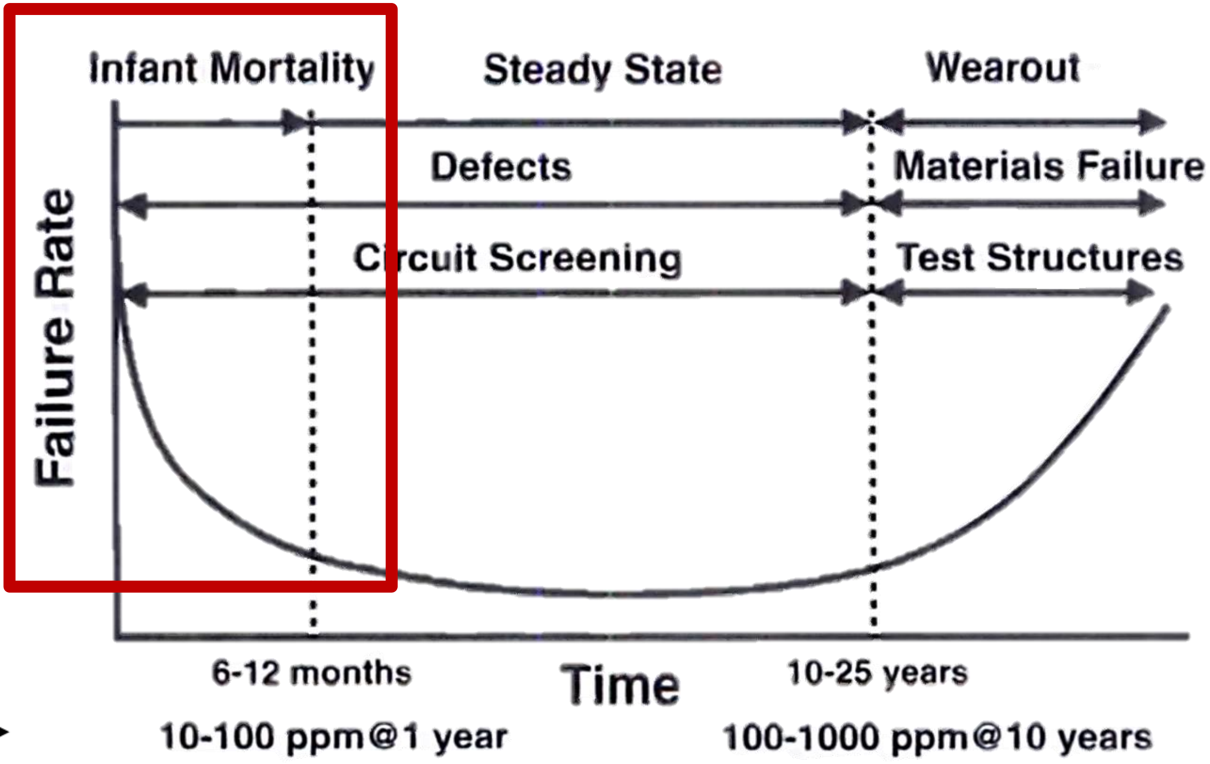


3000˚C/min to 1300C

[1] Polotai, Anton V., et al. *Journal of the American Ceramic Society* 90.12 (2007): 3811-3817.
[2] Samantaray, Malay M., et al. *Journal of the American Ceramic Society* 95.1 (2012): 264-268.

Quality Control & Lifetime Predictions



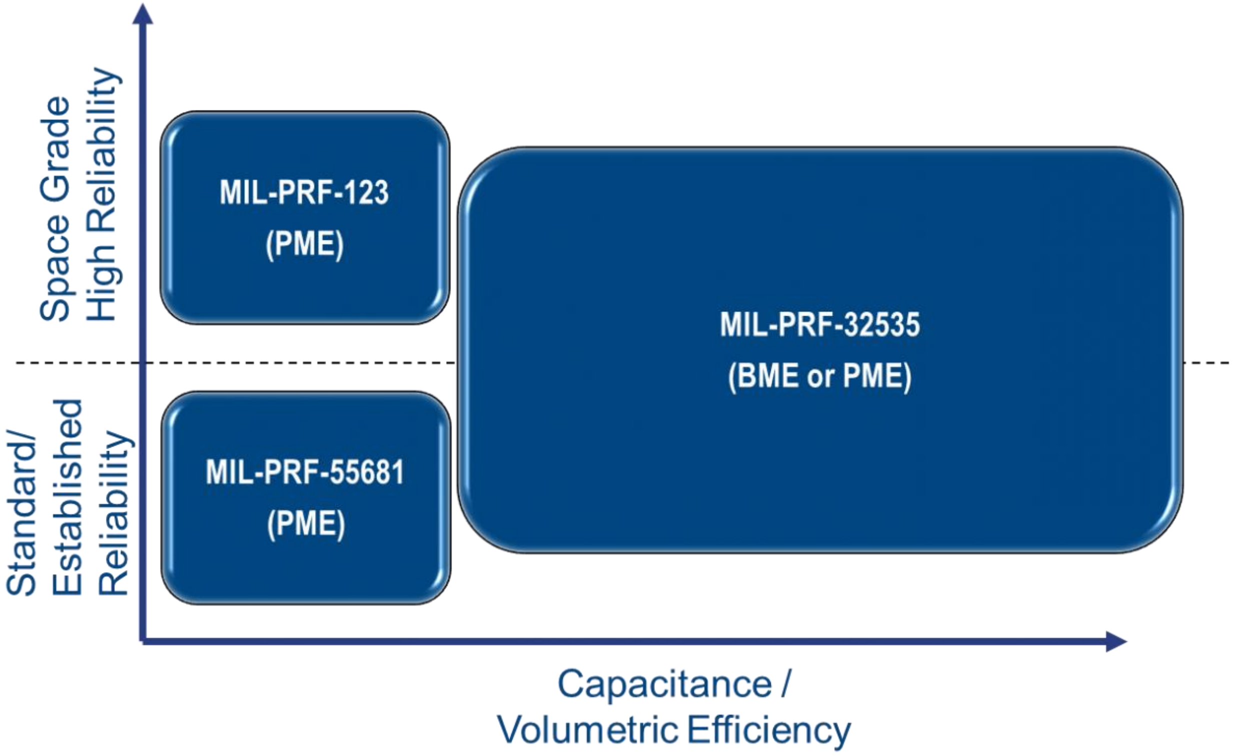


[1] Hnatek, Eugene R. Practical reliability of electronic equipment and products. CRC press, 2002.
[2] W.-E. Liu, The Pennsylvania State University, 2009.

Burn-in Test

MIL-PRF-32535A:

- "Voltage conditioning shall consist of applying twice the rated voltage to the units at the maximum rated temperature of +125°C +4°C, -0°C for a minimum of 168 hours and a maximum of 264 hours."



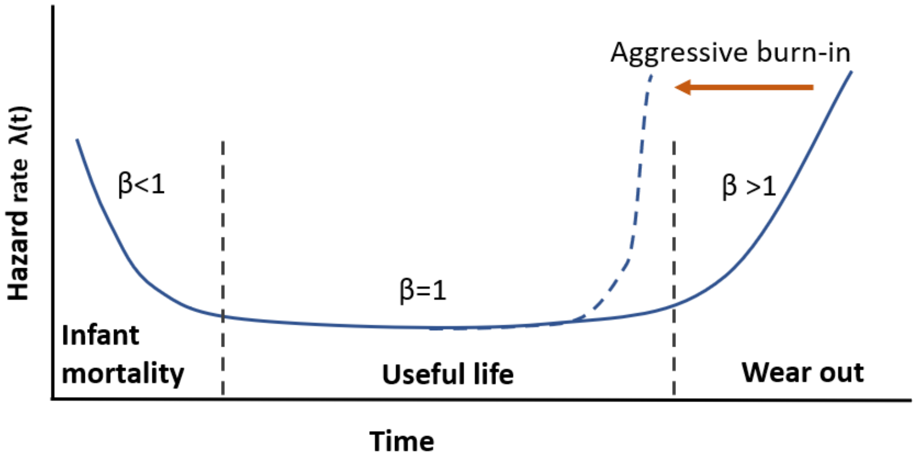
Burn-in Conditions

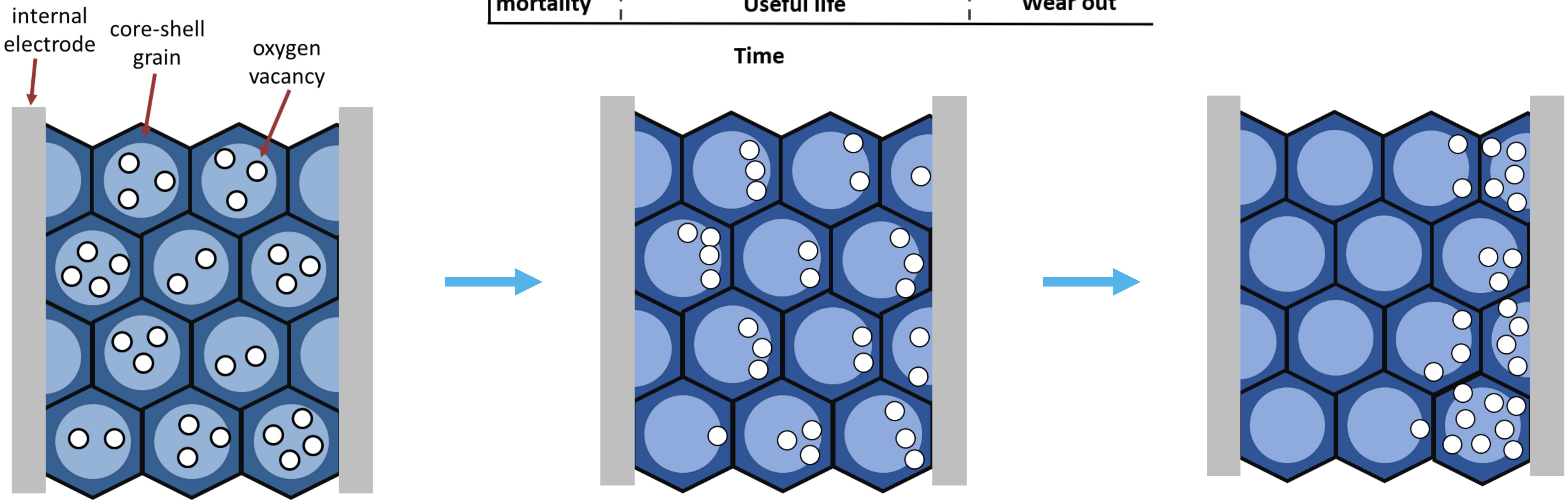
Long	$T_{test} = 125\ °C$ $V_{test} = 2 \times V_{rated}$ $t_{test} = 168\ hr = 7\ days$
Short	$T_{test} = 125\ °C$ $V_{test} = 4 \times V_{rated}$ $t_{test} = 21\ hr$

MLCC	BME X7R
Case	1206
$\mathbf{V_{rated}}$	50 V
C	1 µF

[1] Department of defense (2017) MIL-PRF-32535A.
[2] https://www.kemet.com/en/us/technical-resources/new-options-when-failure-is-not-an-option.html

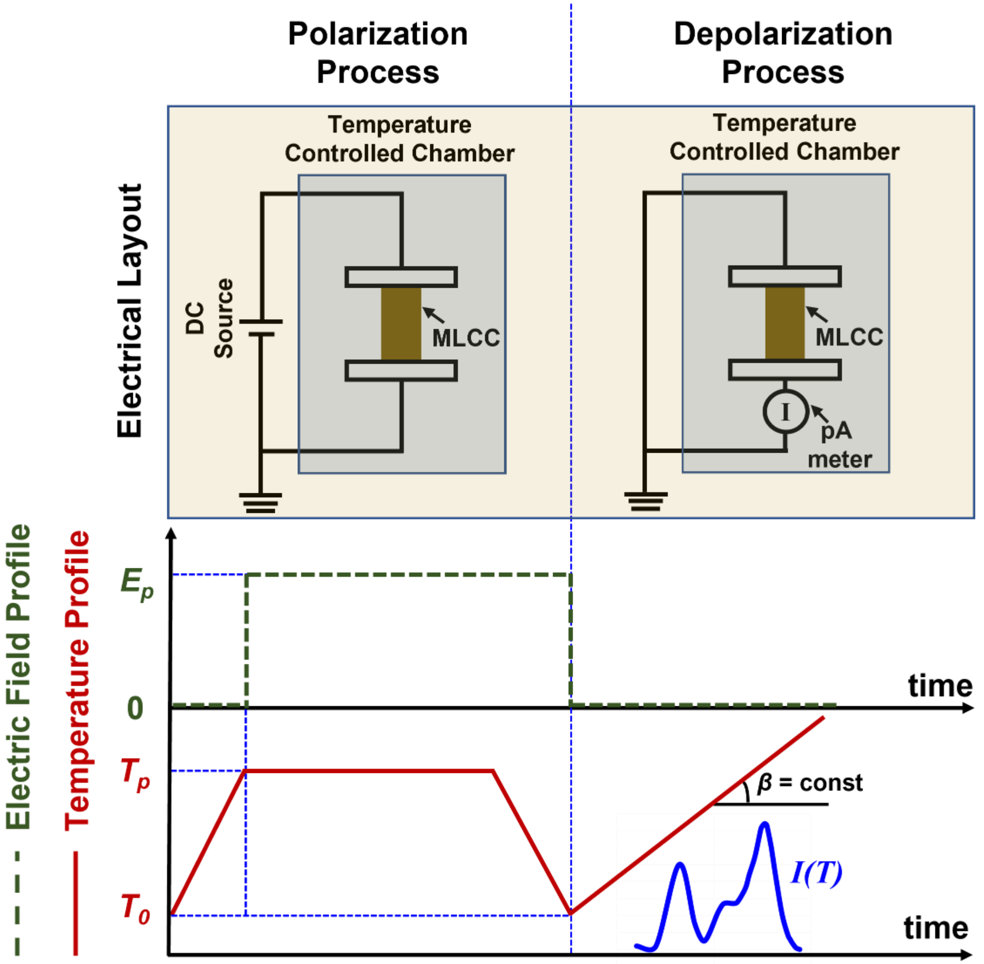
Hazard Rate Curve

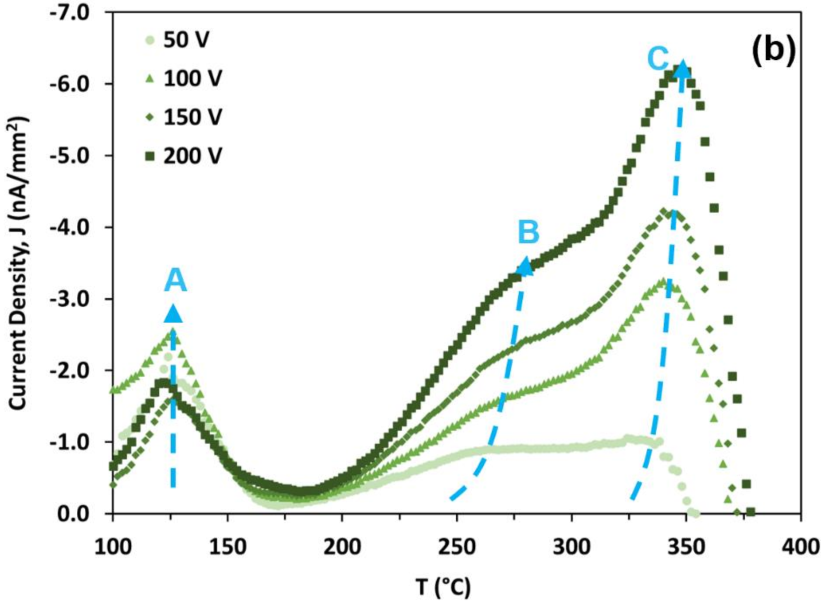


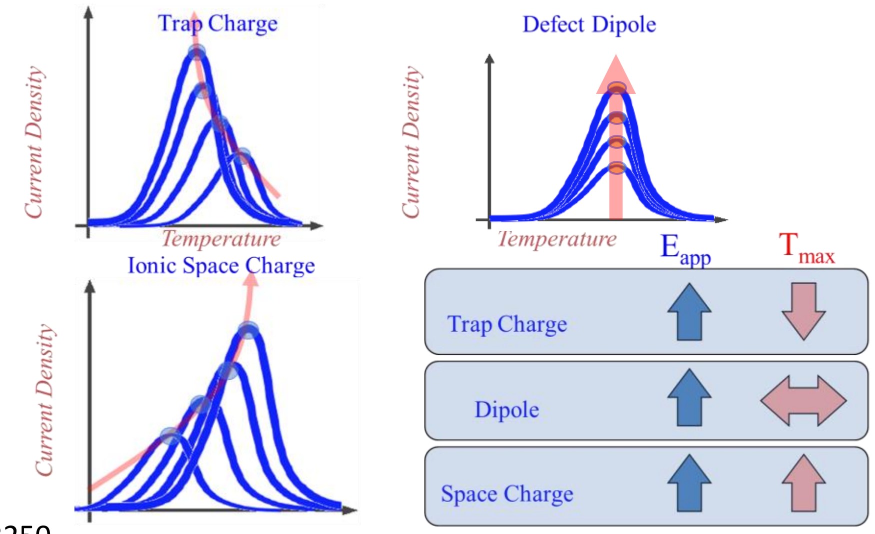


Aggressive Burn-in May Cause an Irreversible Damage to Grain Boundary Barriers

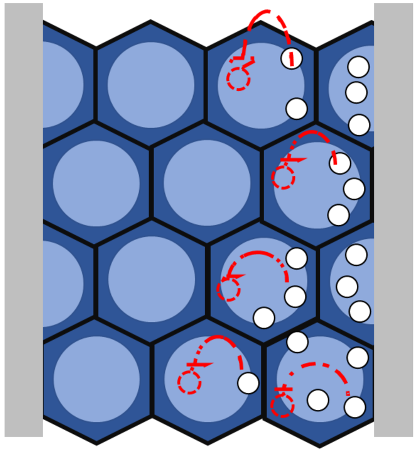
Thermally Stimulated Depolarization Current (TSDC)



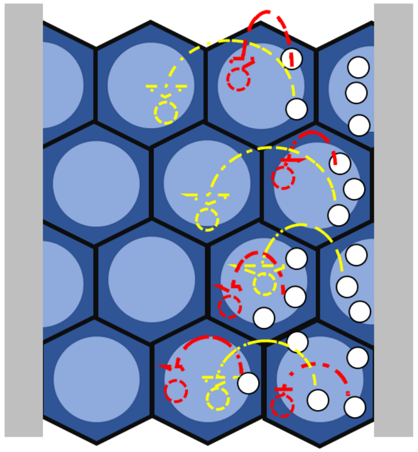




Intragranular Relaxation



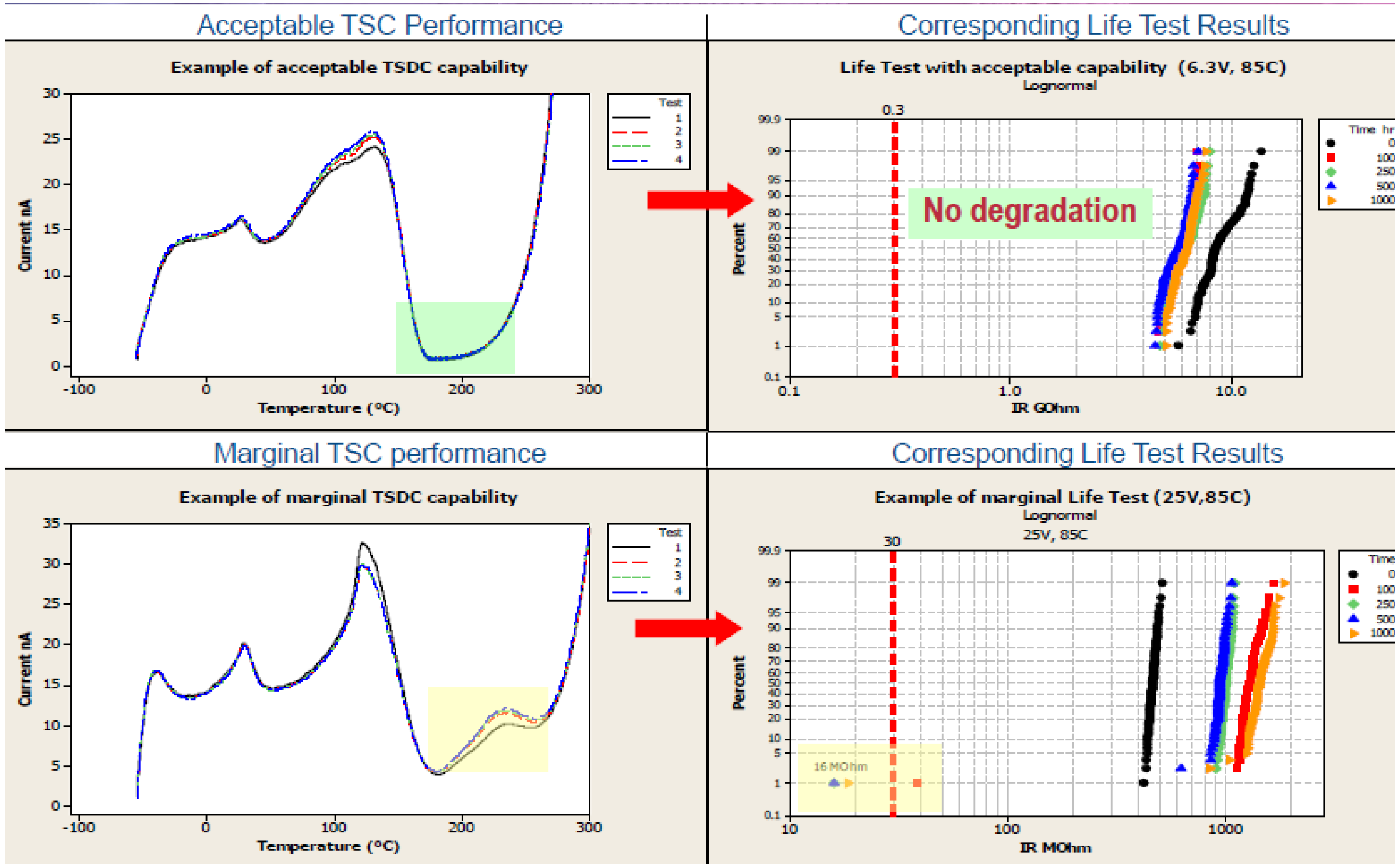
Transgranular Relaxation



[1] Yousefian P., et al. *Applied Physics Letters* 122.11 (2023): 112902.
[2] Liu W., et al. *Journal of the American Ceramic Society* 91.10 (2008): 3245-3250.

TSDC as a Screening Tool for MLCCs

- TSDC is being used as a screening method to detect infant failures
- Some companies now use it as an acceptance screen for lots where high reliability is required



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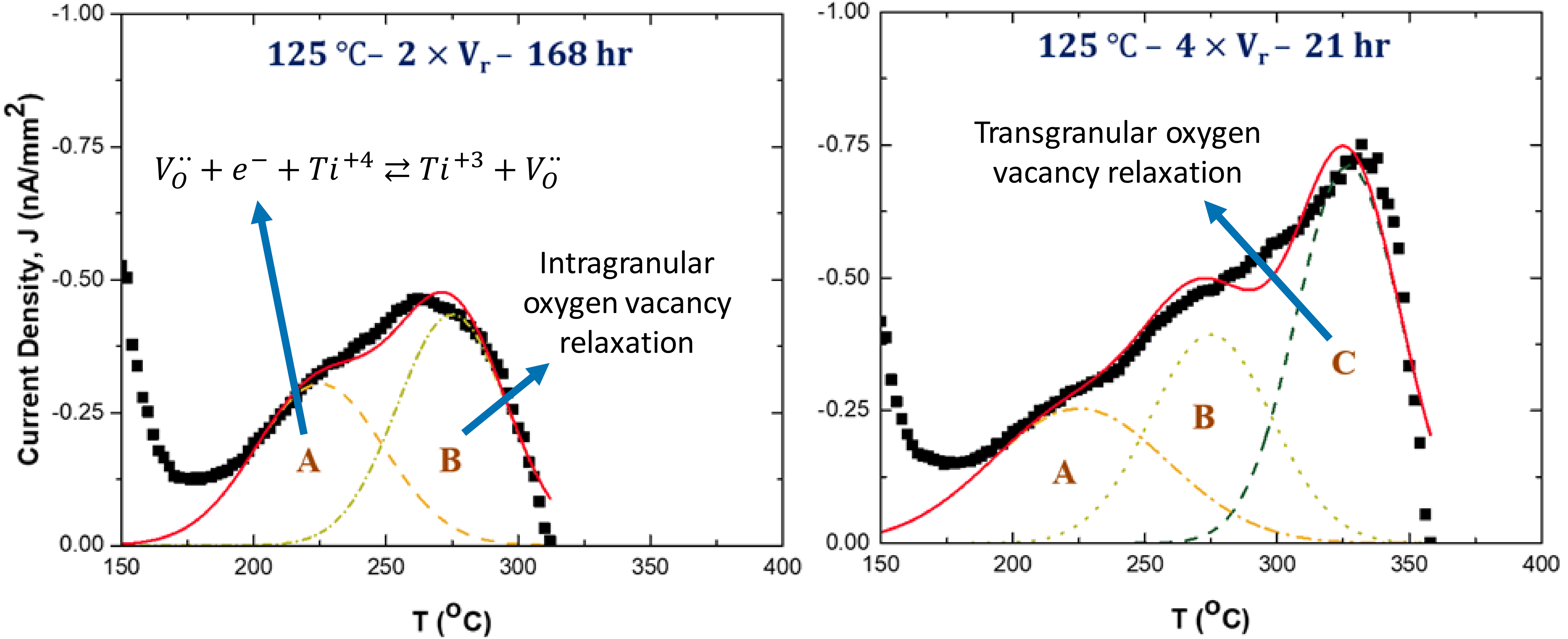
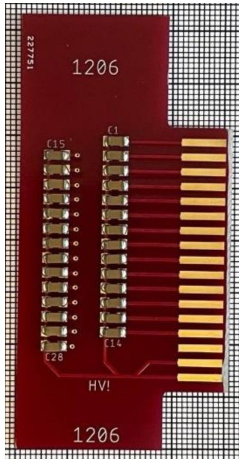
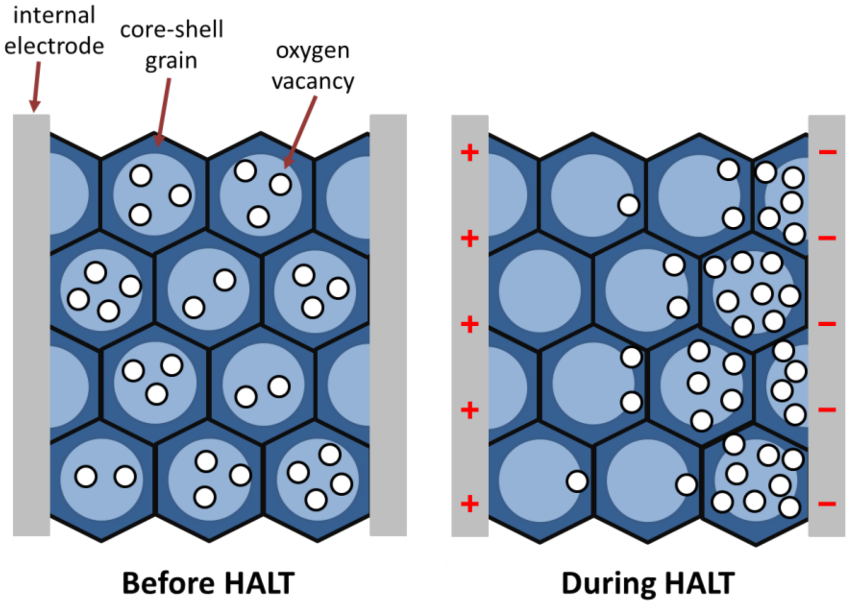
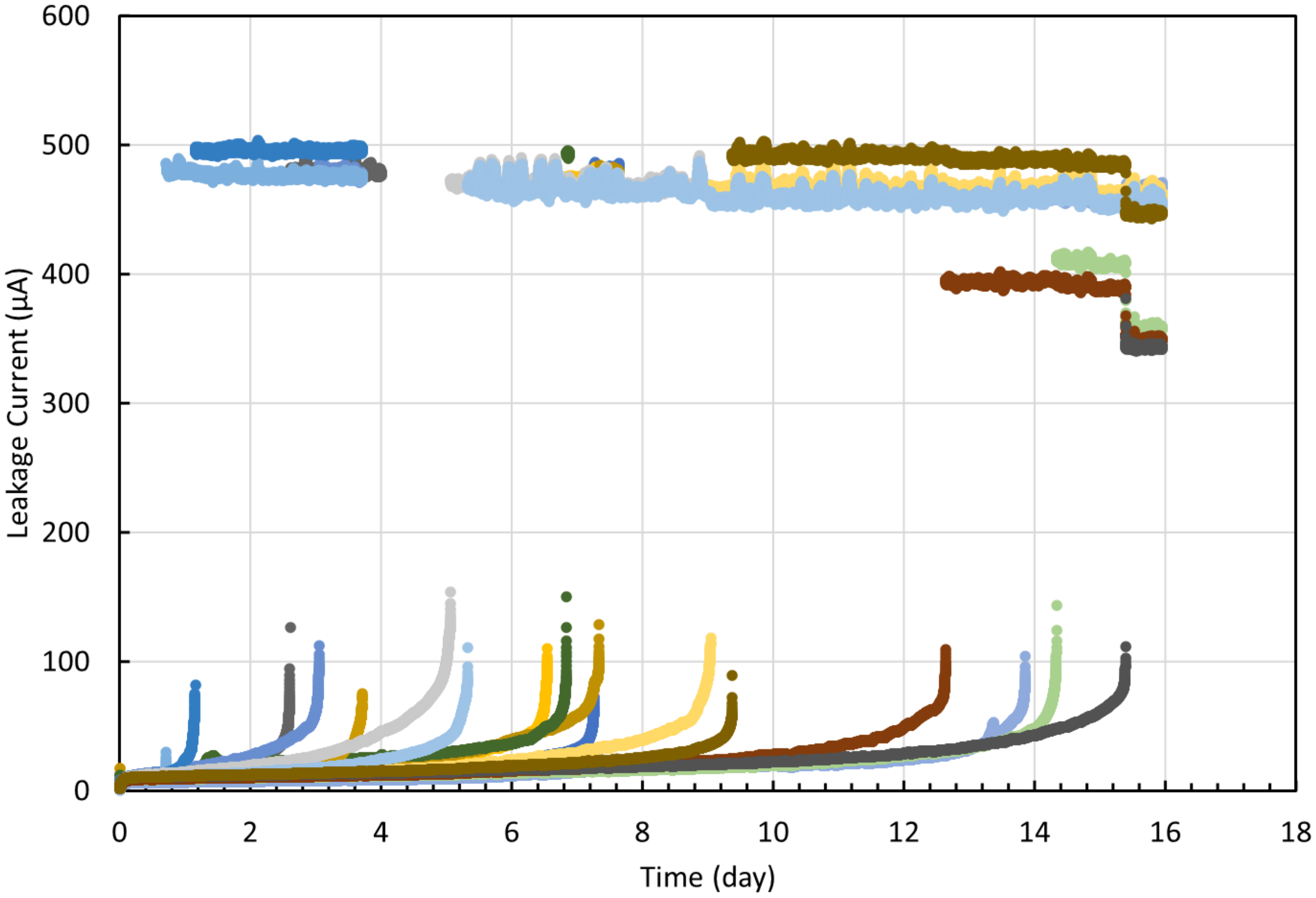


[1] Yousefian P., and C. A. Randall, *Journal of Materials Science* 57.33 (2022): 15913-15918.

Highly Accelerated Life Test (HALT)







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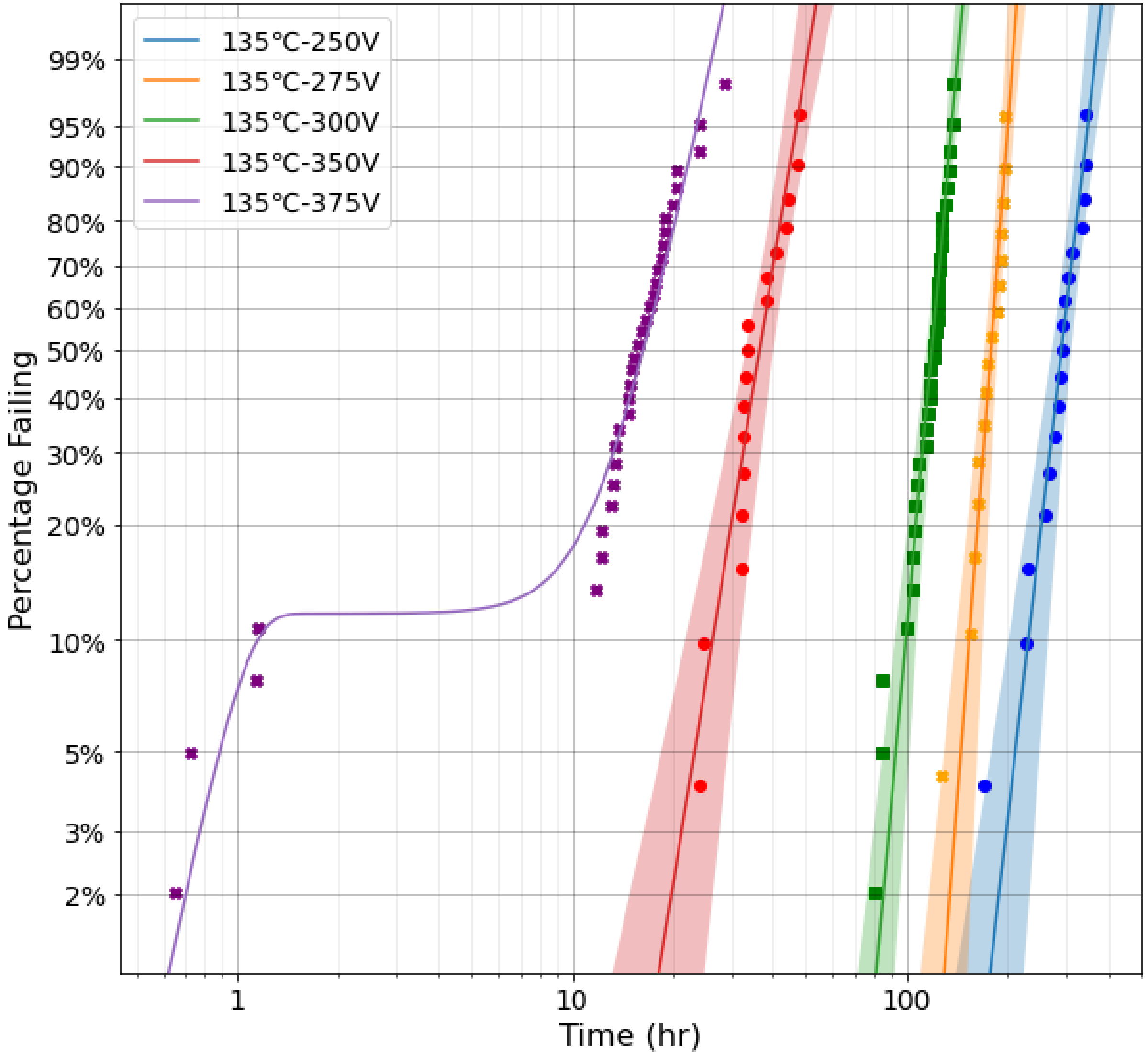


2-parameter Weibull Distribution

$$\text{PDF: } f(t) = \frac{\beta t^{\beta-1}}{\alpha^{\beta}} e^{-\left(\frac{t}{\alpha}\right)^{\beta}}$$

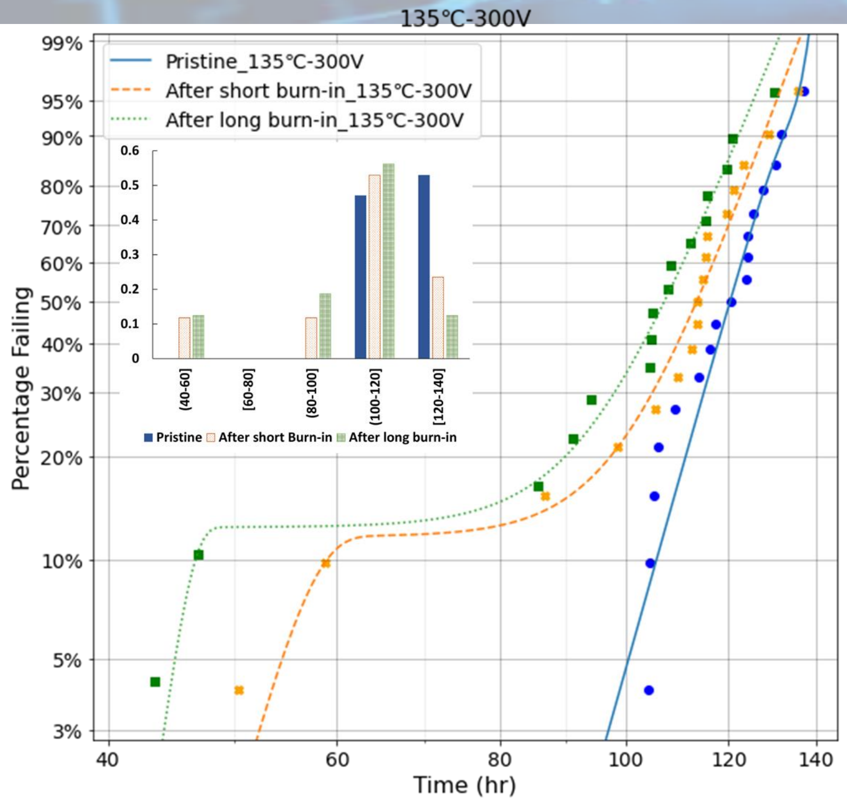
α: Scale parameter

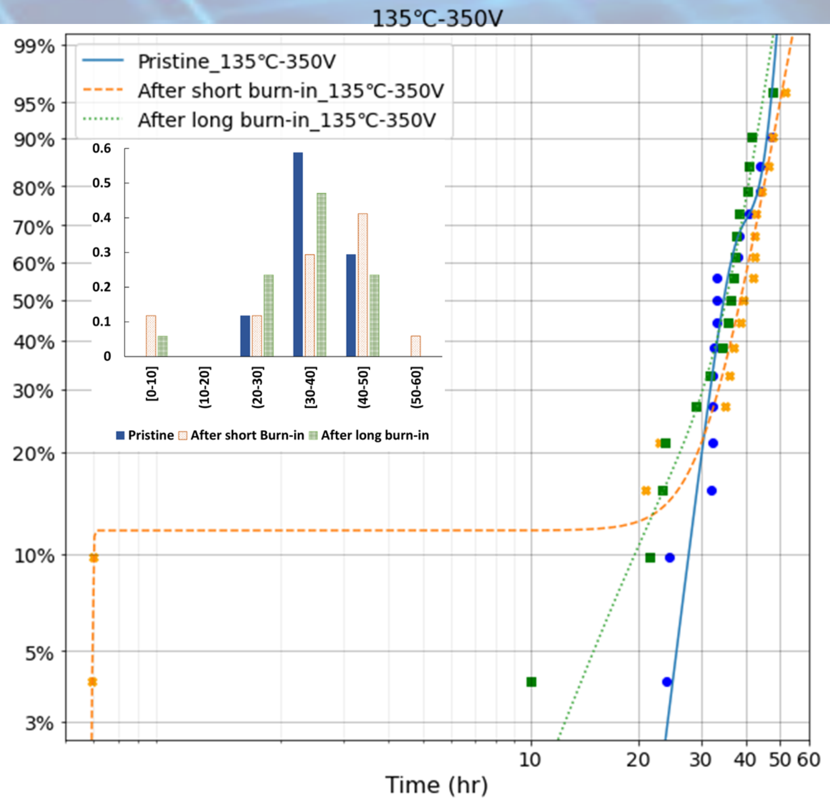
β: Shape parameter

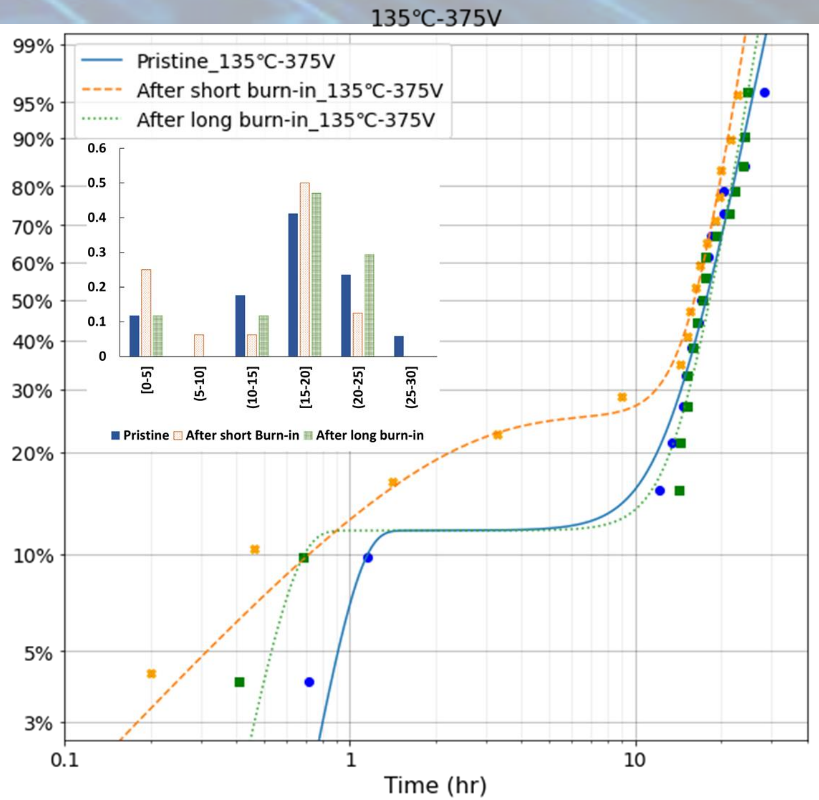
Weibull Mixture Model

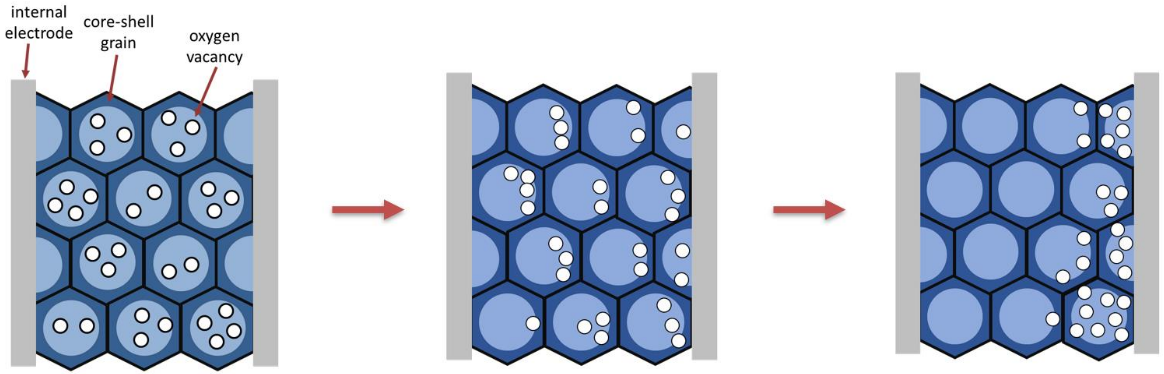
$$\text{PDF}_{\text{mixture}} = p \times \text{PDF}_1 + (1 - p) \times \text{PDF}_2$$

Effect of Burn-in Test









[1] Yousefian P., and C. A. Randall, *Journal of Materials Science* 57.33 (2022): 15913-15918.

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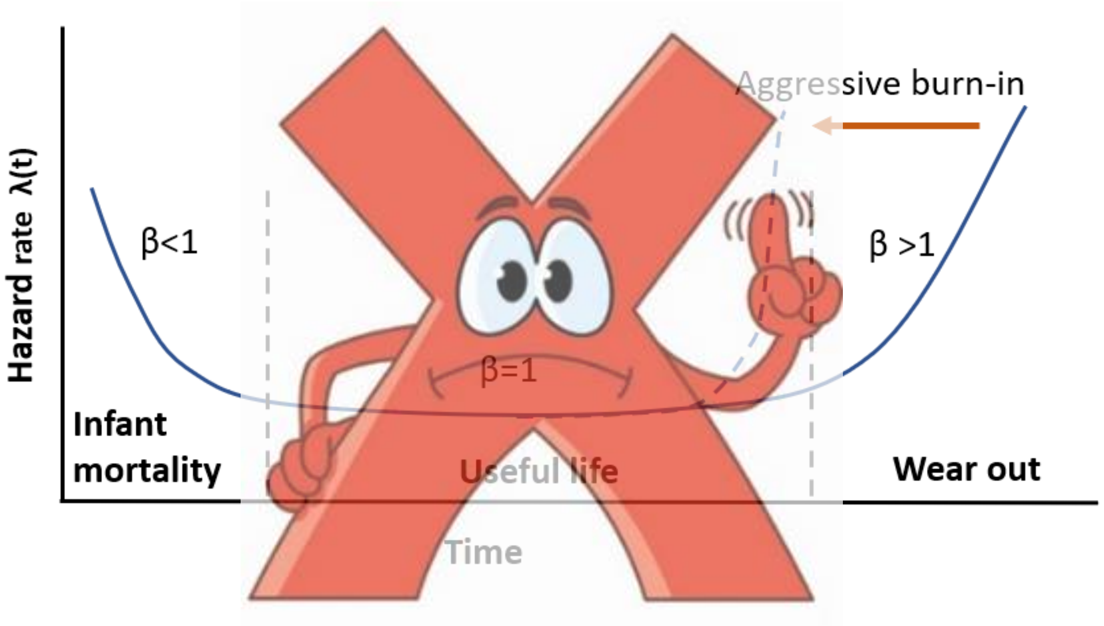
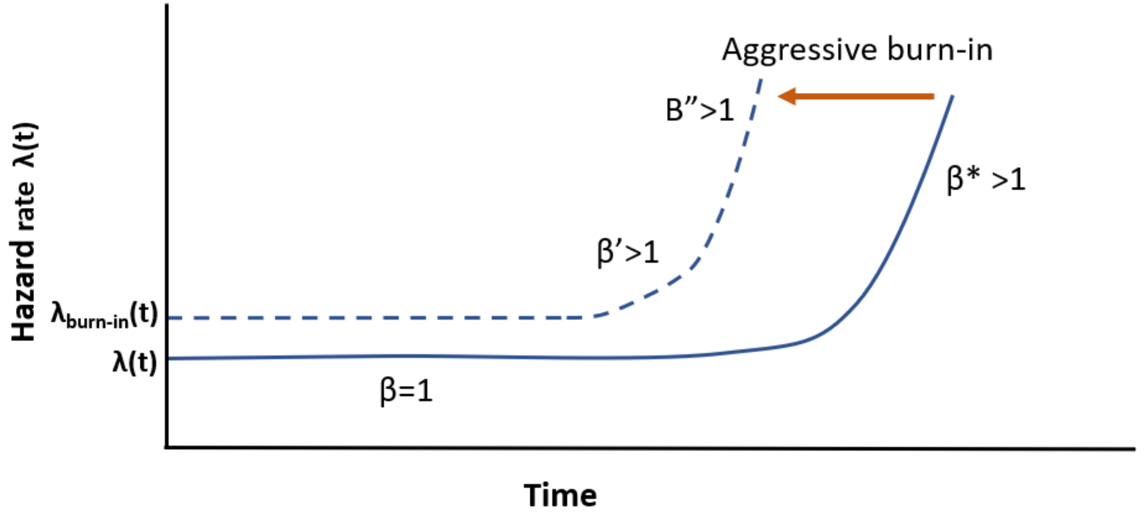




After Aggressive burn-in $\beta^* \rightarrow \beta' + \beta''$ &

$$\lambda(t) \rightarrow \lambda_{burn-in}(t)$$

$$\lambda_{burn-in}(t) > \lambda(t)$$

Aggressive Burn-in Cause an Irreversible Damage to Grain Boundary Barriers

[1] Yousefian P., and C. A. Randall, *Journal of Materials Science* 57.33 (2022): 15913-15918.

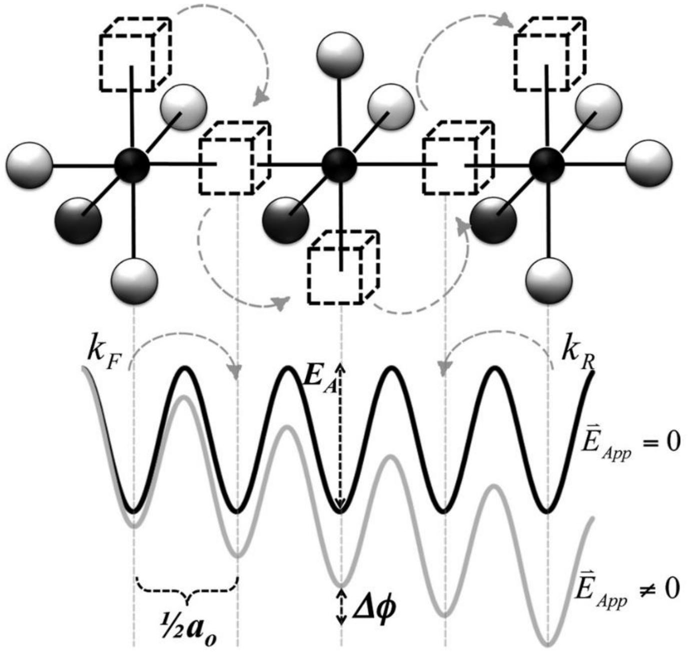
Lifetime Prediction Models

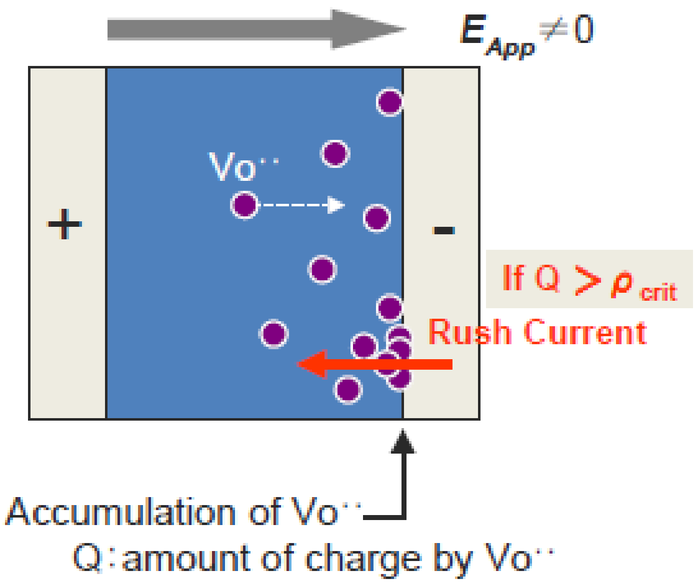
Empirical Models
Eyring Model

$$\frac{t_1}{t_2} = \left(\frac{V_2}{V_1}\right)^n \exp\left(\frac{E_A}{k_B}\left(\frac{1}{T_1} - \frac{1}{T_2}\right)\right)$$

n should be a constant and independent of V and T

Tipping Point Model





$$t_{crit} = \frac{\rho_{crit}}{a\vartheta Nq}\left[exp\left(-\frac{E_a}{k_B T}\right) sinh\left(\frac{qaE_{app}}{2k_B T}\right)\right]^{-1}$$

$$\ln(t) = C(T) - \ln\left(\sinh\left(\frac{\beta' E_{app}}{T}\right)\right)$$

[1] Randall, C. A., et al., *Journal of Applied Physics* 113.1 (2013): 014101.
[2] Morita, Koichiro, et al., *Japanese Journal of Applied Physics* 57.11S (2018): 11UC03.

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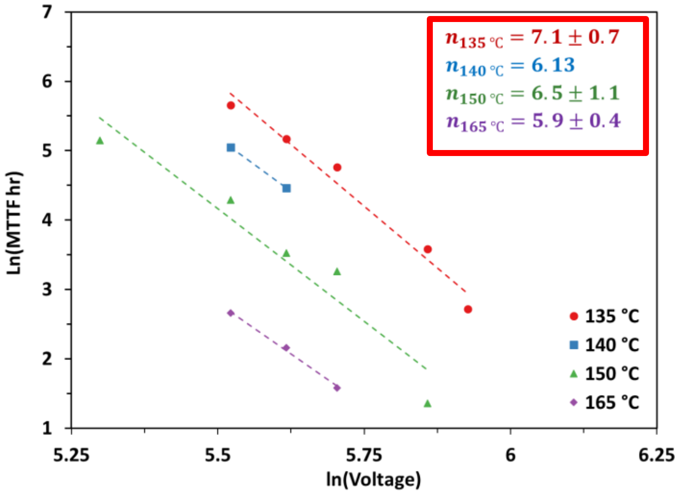
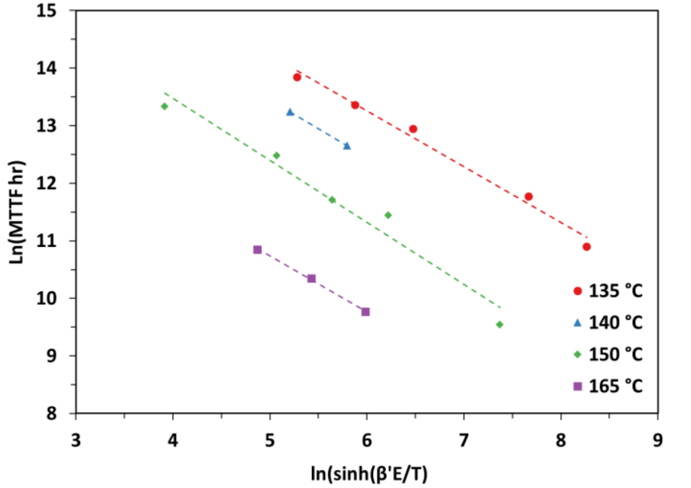
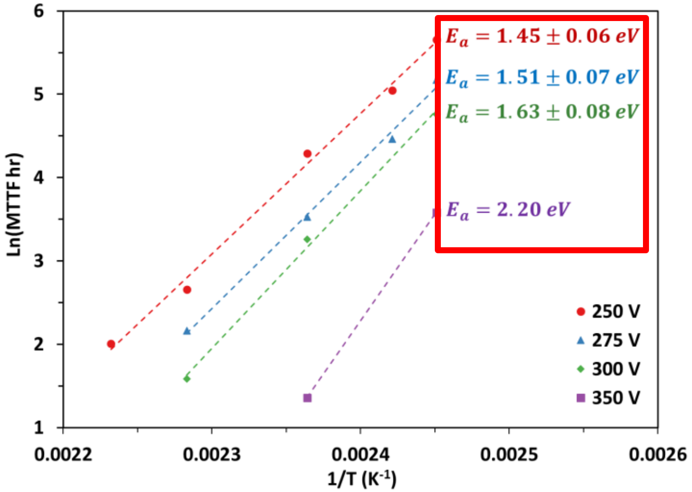
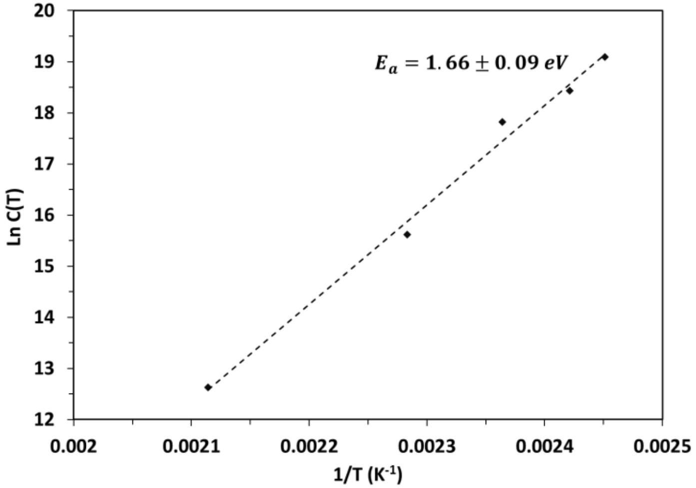




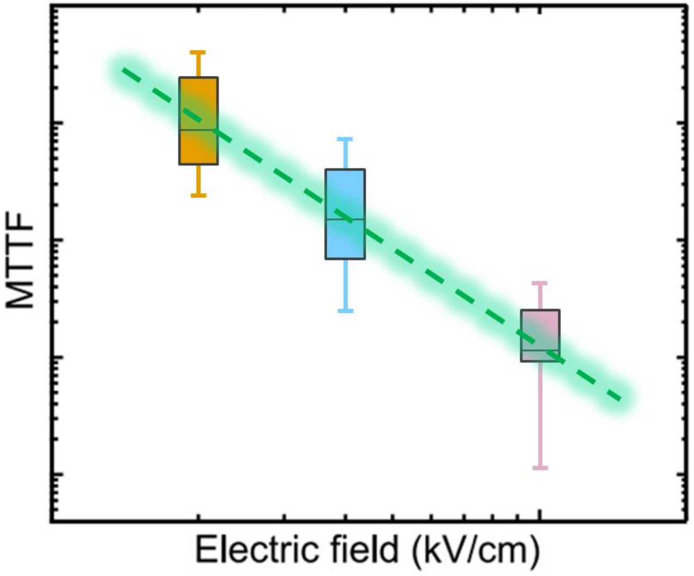




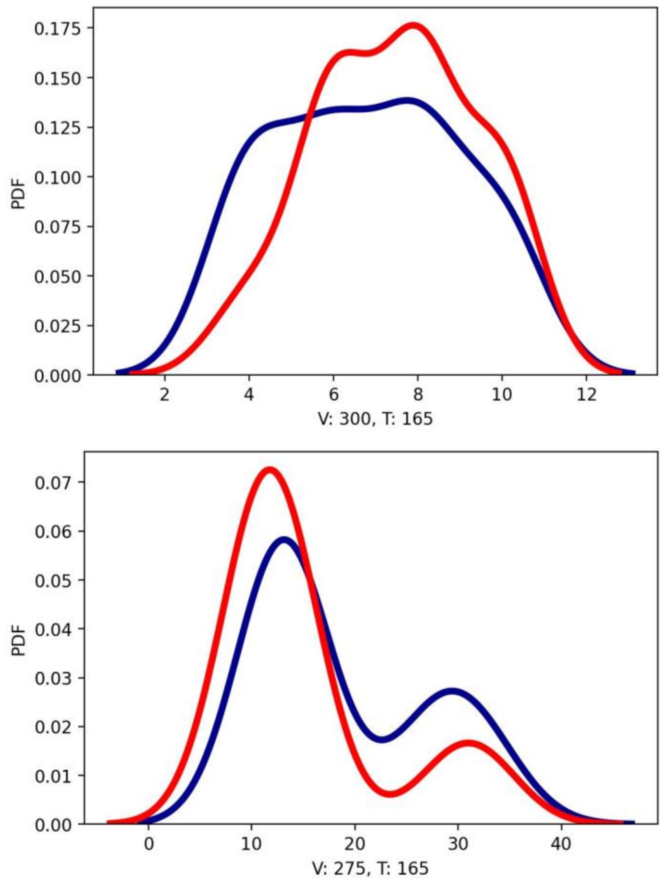
[1] Yousefian P., et al. *Applied Physics Letters* 122.11 (2023): 112902.

What is Next?

MTTF Limitations



Machine Learning-Based Lifetime Prediction Model

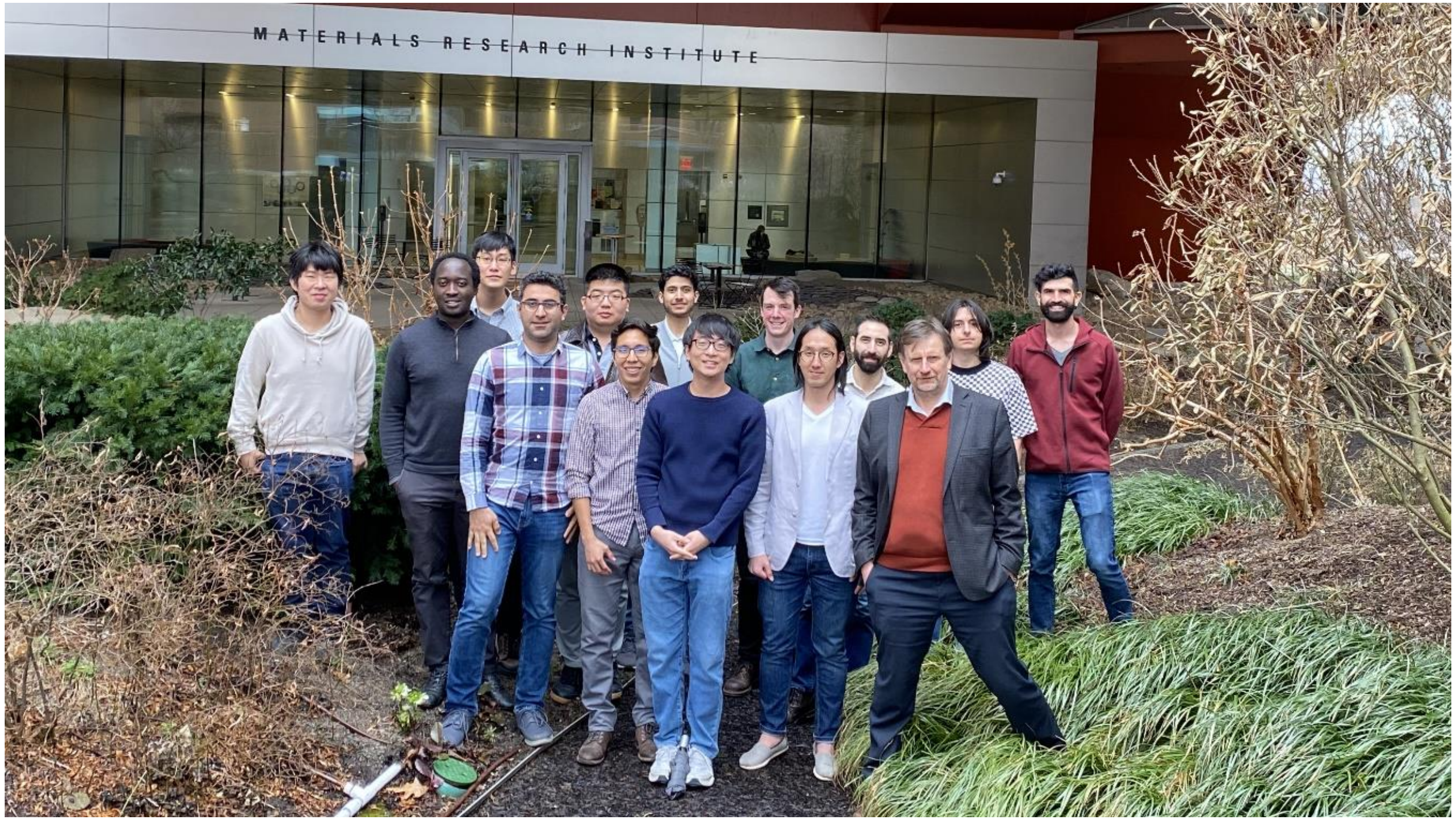


Summary

- ✓ We demonstrated that TSDC is a powerful technique for MLCCs' screening
- ✓ Intragranular and transgranular electromigration of oxygen vacancies after burn-in test was observed. and reduction of lifetime in screened MLCCs.
- ✓ Determined the effect of Burn in conditions on the distribution of MLCC's failure time.
- ✓ We quantified a freak population of failures in MLCCs after short burn-in process.
- ✓ Limitation of Eyring model on predicting lifetime of MLCCs was demonstrated.
- ✓ The tipping point model appears to be more systematic and predictable across all testing conditions
- ✓ We are investigating AI methods for predicting not only MTTF but also failure times data distribution.

Acknowledgments

- This work is supported by the National Science Foundation, as part of the Center for Dielectrics and Piezoelectrics under Grant Nos. IIP-1841453 and IIP-1841466”.
- Materials Characterization Lab staff
- Jeff Long, Steve Perini, and Mike Norrell



CDP center for dielectrics and piezoelectrics

NSF

PennState Materials Research Institute


thank
you