Analysis of Accelerated Life Test for BME Capacitors

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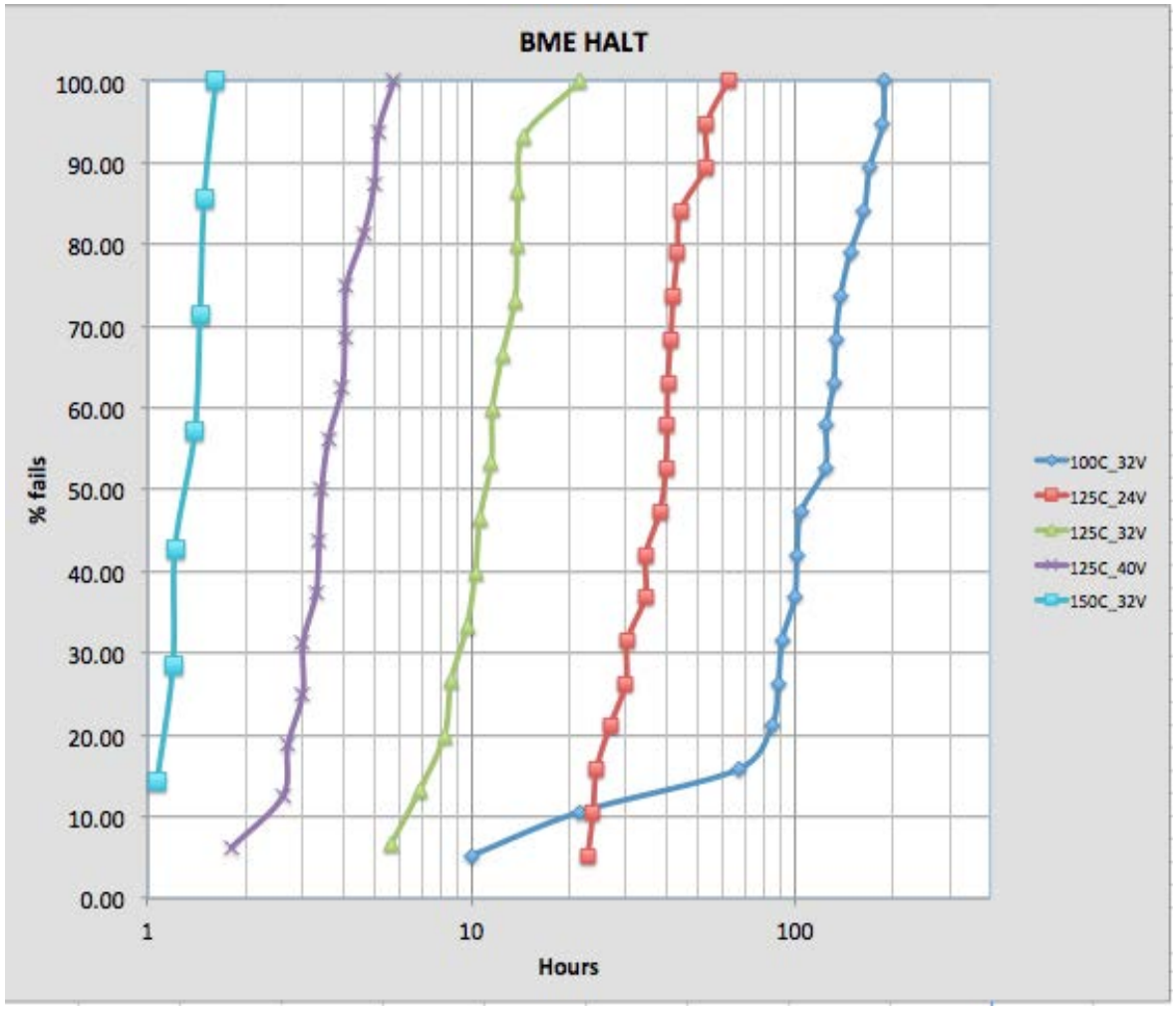
Issues with Accelerated Testing

0.1 hrs @ 100C

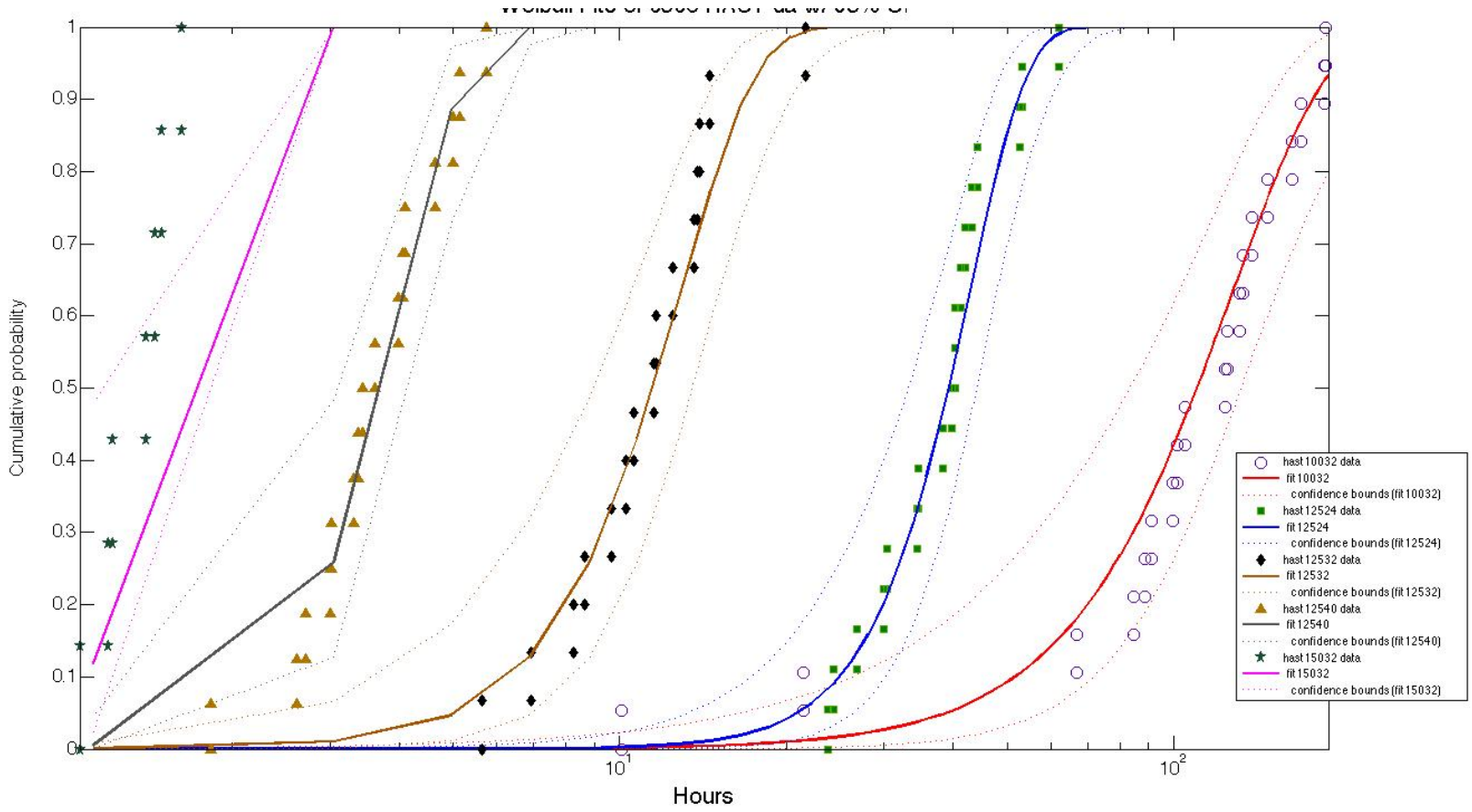
480 hrs @ 40C

BME HALT – Probability Plot



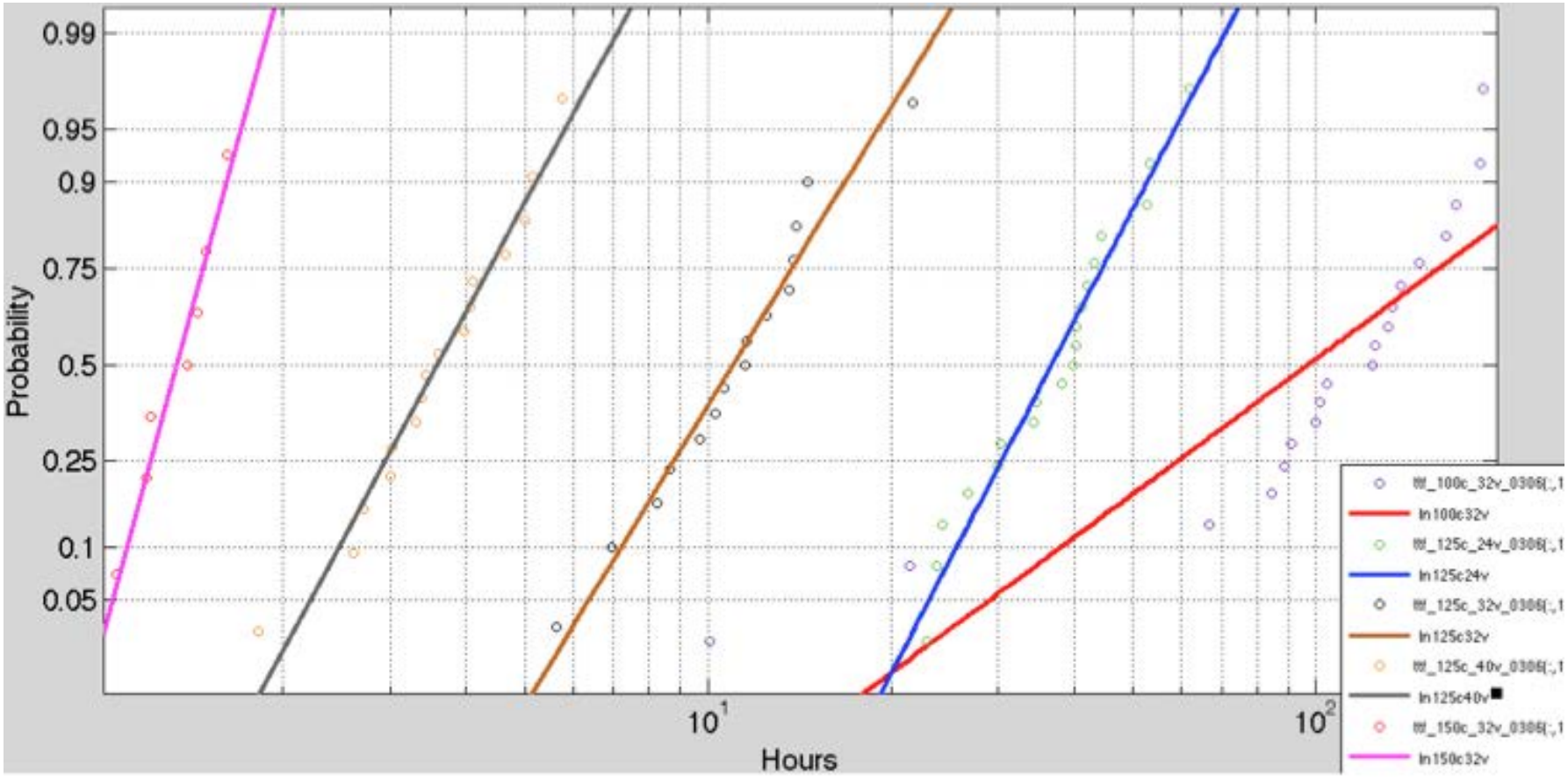
- Single lot, one capacitor size
- One distribution has a bi-modal component
- Different distribution appears to be excessively highly accelerated

Weibull Analysis of BME HALT



- Highly accelerated split does not fit Weibull
- Other split does not have same slope
- Historical acceleration methodology cannot be applied to entire data set

Lognormal Analysis of BME HALT

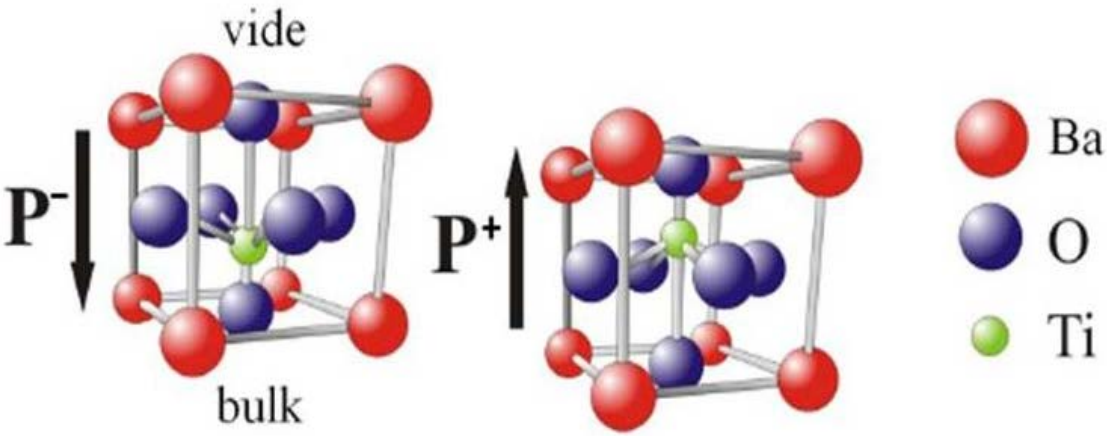


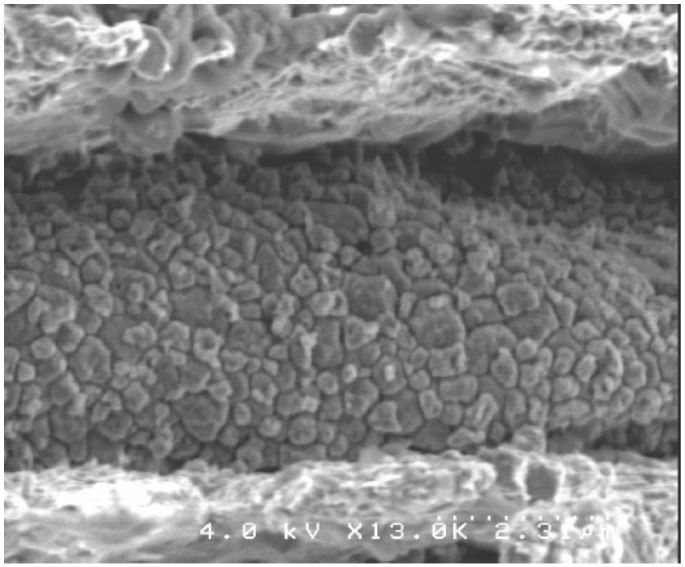
- Same concern, different distribution/test split

BME - Accelerated Stress Testing

- There is a need to have an understanding of the underlying physics of failure to properly construct and implement accelerated life tests
- Modern $BaTiO_3$ based BME capacitors represent a complex materials systems that will challenge historical approaches to accelerated testing
- Inconsistencies in accelerated testing need to be thoroughly understood for proper risk management and analysis
- Predictions for long term life can be over/under estimated, impacts mission approval/mitigation

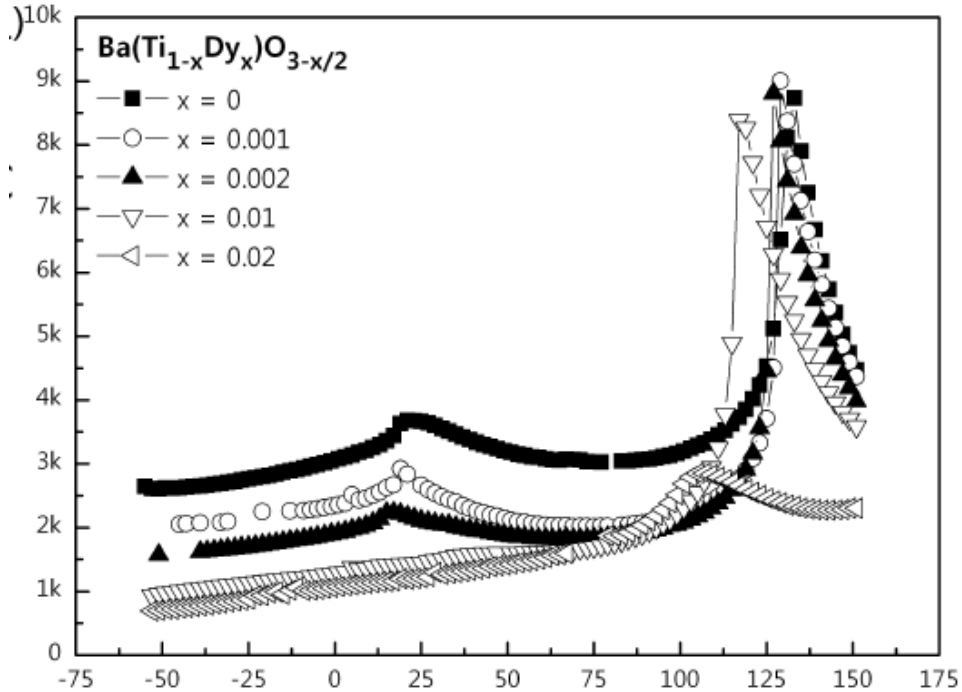
$BaTiO_3$





- Curie temperature ~ 120°C
- Tetragonal to cubic structure transformation and loss of spontaneous polarization.
- Spontaneous polarization is a driving force for oxygen vacancies
- Example of different physics occurring at different stress conditions
- Dielectric properties strongly dependent on doping and preparation

Oxygen Vacancy Generation



Park 2010

$$2BaO + Dy_2O_3 \rightarrow 2Ba_{Ba} + 2Dy'_{Ti} + 5O_O + V_O^{\bullet\bullet}.$$

- Rare earth impurities (Dy, Yb, La, etc.) can be used as donors or acceptors in $BaTiO_3$
- Depending upon ionic radii size, both the Ba and Ti can be replaced by rare earth ion
- Replacement of the Ti will produce a corresponding number of oxygen vacancies

Oxygen Vacancies

- Oxygen vacancies provide a large concentration of electron in the conduction band.
- These act as free carriers and contribute to leakage current
- Movement is along grain boundaries
- The rate of diffusion along grain boundaries is much higher than that for volume diffusion => two different activation energies

Reliability Physics and Accelerated Life Testing

- First principals approach to derive accelerated life parameters from underlying physics
- Define materials degradation (end of life) in a formal mathematical context.
- Goal is to provide insight into possible causes of over/under accelerated life testing conditions

Reliability Physics

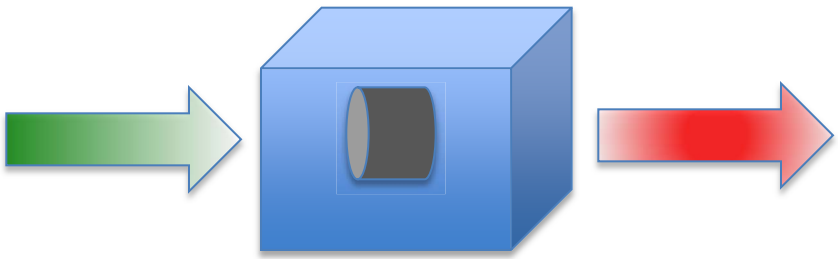
$$\frac{\partial f}{\partial p} + \frac{\vec{p}}{m} \cdot \nabla f + F \cdot \frac{\partial f}{\partial \vec{p}} = \left(\frac{\partial f}{\partial t} \right)_{coll}$$

- Boltzmann transport equation
- Describes statistical behavior of a thermodynamic system that is not in thermal equilibrium
- Force(s), collisions, diffusion are terms effecting particle distributions in thermodynamic systems

$$J(x,t) = \mu \rho(x,t) F - D \frac{\partial \rho(x,t)}{\partial x}$$

- Fick's law for transport
- Particle mobility, particle density, driving force and diffusivity
- Flux ~ conductivity X Driving force

Flux divergence and time to failure



- Number of particles moving in to area ≠ number moving out
- Electromigration of aluminum, oxygen vacancy movement in $BaTiO_3$
- Use Fick's law to describe flux divergence (McPherson 1986)

$$\nabla \cdot J(x,t) = -\frac{\partial \rho(x,t)}{\partial t}$$

- Integrate over both sides using divergence theorem

$$\int J \cdot dA = -\frac{dN(t)}{dt}$$

- N(t) is the total number of particles in the volume V bounded by A

Flux divergence and time to fail

$$\frac{dN(t)}{dt} = -k(t)N(t)$$

- First order reaction rate equation
- Voiding/accumulation is a change per time

$$k(t) = \frac{\int J(x,t) \cdot dA}{N(t)}$$

- Reaction rate constant, k(t), is a degradation rate constant
- Degradation is proportional to net flux of particles across an area A
- Flux divergence is needed to cause material degradation
- General solution to equation is:

$$\int_{N(0)}^{N(t)} \frac{dN}{N} = -\int_0^t k(t)dt$$

$$\frac{N(t)}{N(0)} = \exp\left[-\int_0^t k(t)dt\right]$$

Flux divergence and time to fail

- Failure occurs at t=TF
- A critical fraction of particles is required, f_{crit}

$$f_{crit} = \frac{N(TF)}{N(0)} = \exp\left[-\frac{\int_0^{TF} k(t)\,dt}{\int_0^{TF} dt} TF \right]$$

$$TF = \frac{\ln(1/f_{crit})}{\left\langle \frac{\int J(x,t)\cdot dA}{N(t)} \right\rangle}$$

- Brackets are the time-averaged values of the quantities inside
- Explicit relationship between particle divergence and failure
- Impact can be mitigated by number of particles in failing volume
- Wide conductors fail more slowly than narrow for example
  - Example: 1cm^3 of Al, constant flux divergence of 10^{14} atoms/sec, 50% loss of atoms => 9.5 years to fail

Time to failure and activation energy

$$TF = \frac{\ln(1/f_{crit})}{\left\langle \frac{\int J(x,t)\cdot dA}{N(t)} \right\rangle}$$

$$J(x,t) = \mu\rho(x,t)F - D\frac{\partial\rho(x,t)}{\partial x}$$

$$\mu = \frac{D}{k_B T} = \frac{D_0 \exp(-\frac{Q_{diffusion}}{k_B T})}{k_B T}$$

- Need to relate flux divergence to applied stress gradients (electrical, mechanical, chemical)
- Use exponential or power law dependence, ξ, is the generic stress

$$TF = A_0(\xi)^{-n}\exp(\frac{Q}{k_B T})$$

$$TF = B_0 \exp(-\gamma\cdot\xi)\exp\left(\frac{Q}{k_B T}\right)$$

Time to failure and activation energy

$$TF = A_0(\xi)^{-n}\exp\left(\frac{Q}{k_B T}\right)$$

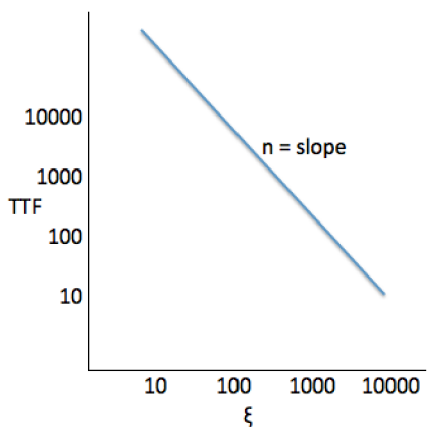
$$TF = B_0\exp(-\gamma\cdot\xi)\exp\left(\frac{Q}{k_B T}\right)$$

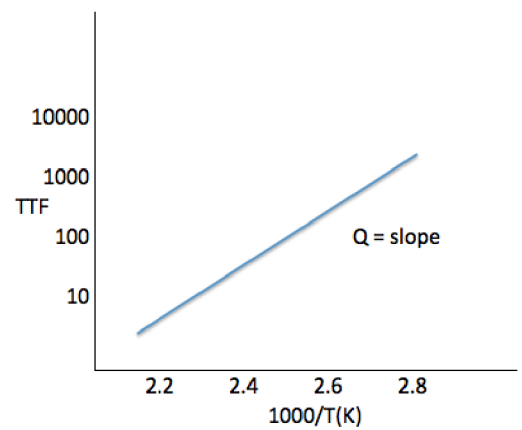
$$n = -\left[\frac{\partial \ln(TF)}{\partial \ln \xi}\right]_T$$

$$\gamma = -\left[\frac{\partial \ln(TF)}{\partial \xi}\right]_T$$

$$Q = k_B\left[\frac{\partial \ln(TF)}{\partial (1/T)}\right]_\xi$$

- Mathematical/physical derivation of standard stress parameters used in life test analysis





Liu Model of MLCC Reliability

$$R(t) = \varphi(N, d, \vec{r}, S) * AF(T, V) * \gamma(t)$$

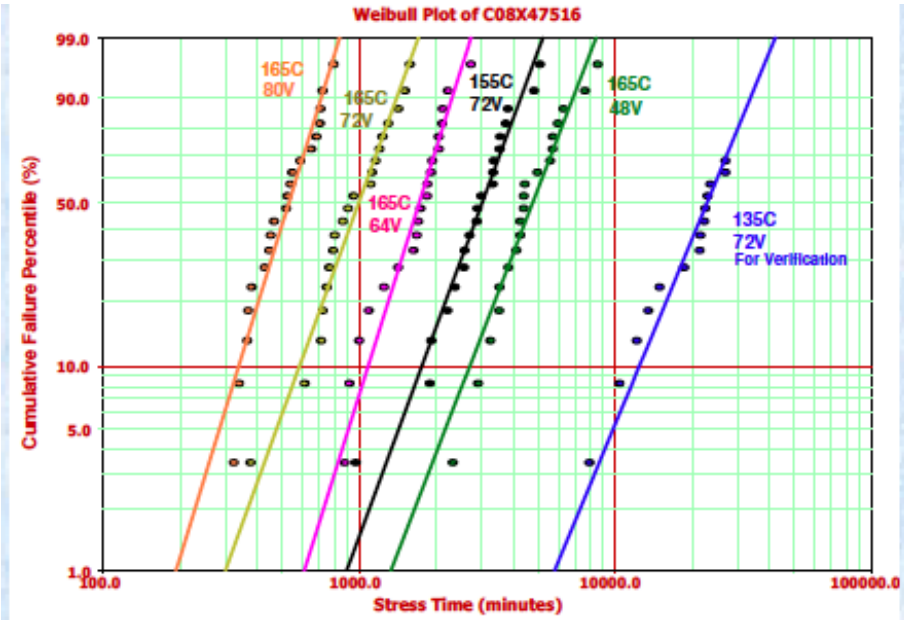
- $\varphi(N, d, \vec{r}, S)$ = Capacitor specific structure, construction effects
- $AF(V, T)$ = Function that responds to external stress
- $\gamma(t)$ = Statistical distribution of individual variation

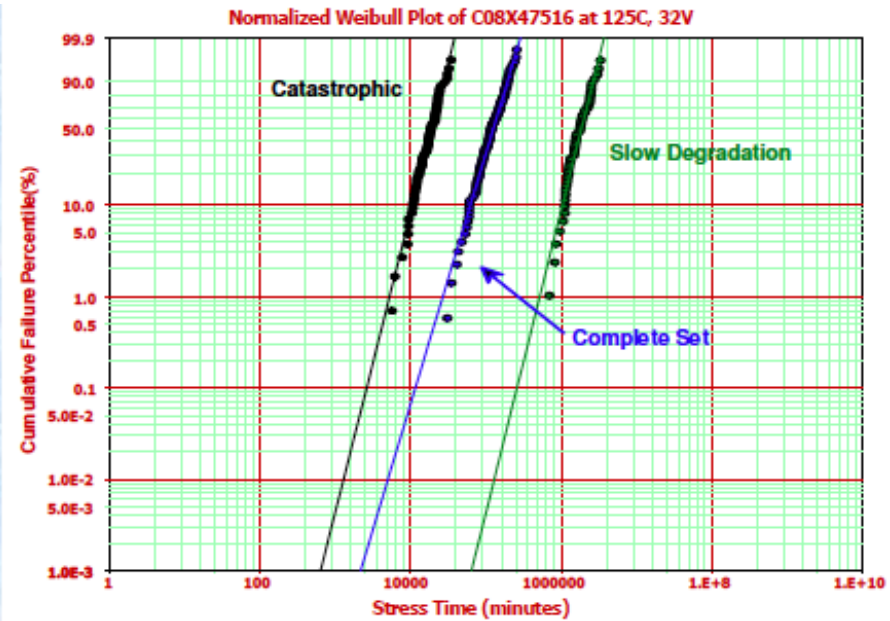
$$R(t) = \left[1 - \left(\frac{\bar{a}}{d}\right)^{\alpha}\right]^{N} \sum_{m=1}^{l} \exp\left(\frac{-t}{\eta_{m(E(V),T)}}\right)^{\beta_m}$$

Liu 2013

Liu Model

- Microstructure specific terms (average grain size, number of layers, average thickness)
- Ability to include low field and high field effects
- Activation energy that is function of field and temperature
- Slow and Catastrophic degradation modes defined through leakage current analysis
- Re-normalize Weibull analysis





Accelerated Life Test for BME Evolution

- The $BaTiO_3$ dielectric used in modern BME capacitors is a complicated materials system that requires an evolution in the implementation and analysis of accelerated life test experiments (HALT)
- The long term reliability of BME capacitors will be driven by oxygen vacancy generation and diffusion in the dielectric layers
- First principals derivation of diffusion mechanisms support activation energy “constants” that are in fact a function of electric field, temperature and materials conditions
- Successful and accurate long term reliability predictions of BME capacitors must include new modeling approaches
- A phenomenological model has been developed to address these concerns and should continue to be validated by other researchers