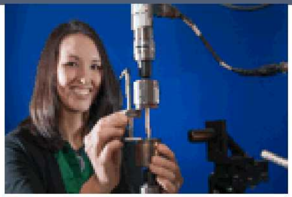
SAND2019-10838C

Reliability of Components that Contain Brittle Materials



PRESENTED BY

Kevin Strong and Scott Grutzik

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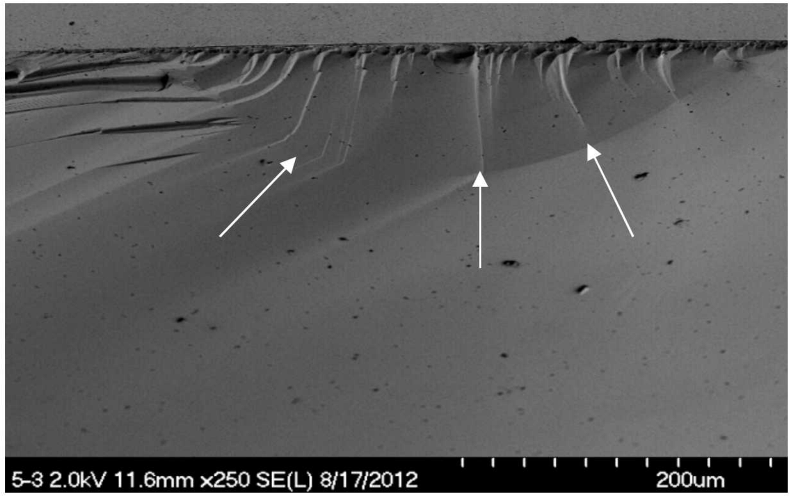
Outline

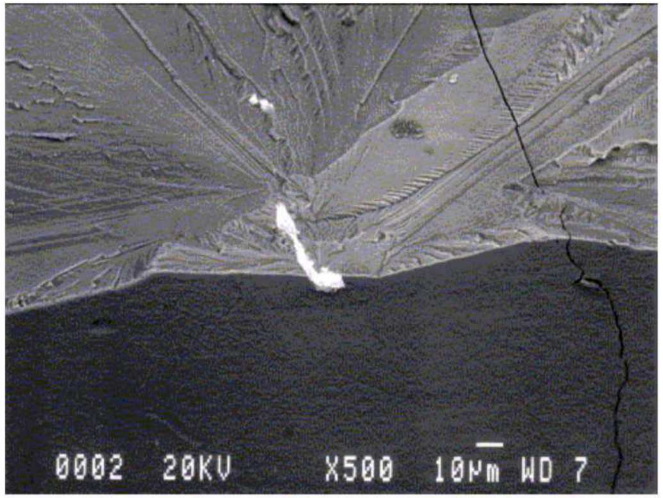
- Background
  - Failure Modes of Brittle Materials
  - Strength Size Scaling
  - Environmentally Enhanced Crack Growth
- Material Measurements
- FEA predictions
- Summary

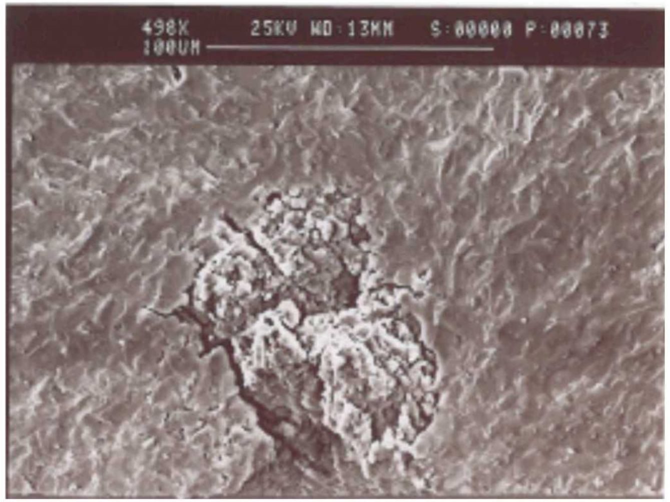
Failure Modes

I. Fast (brittle) fracture due over load w/scale effect.

- For glasses and single X'tals, occurs from imperfections (scratches, checks, and infrequent pores and inclusion).
- Polycrystals: inclusions, coarse grains, agglomerates, pores and damage.





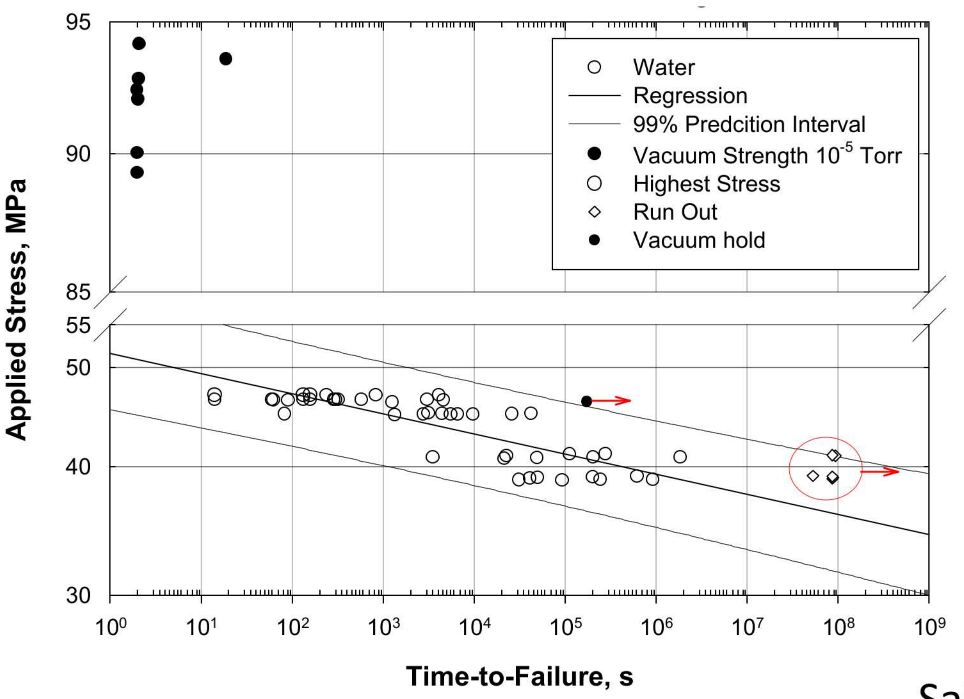


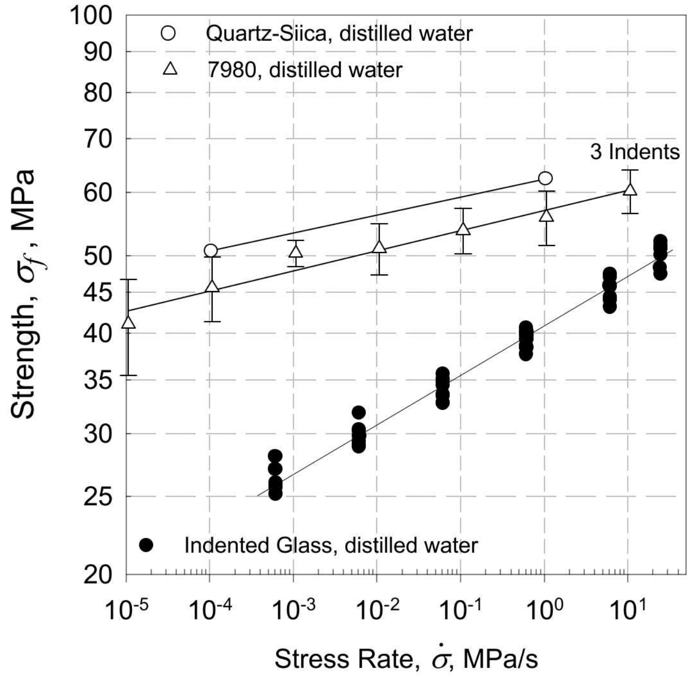
- Handling damage is surface distributed; pores are volume distributed.

Quinn, Fractography of glass and ceramics

Failure Modes

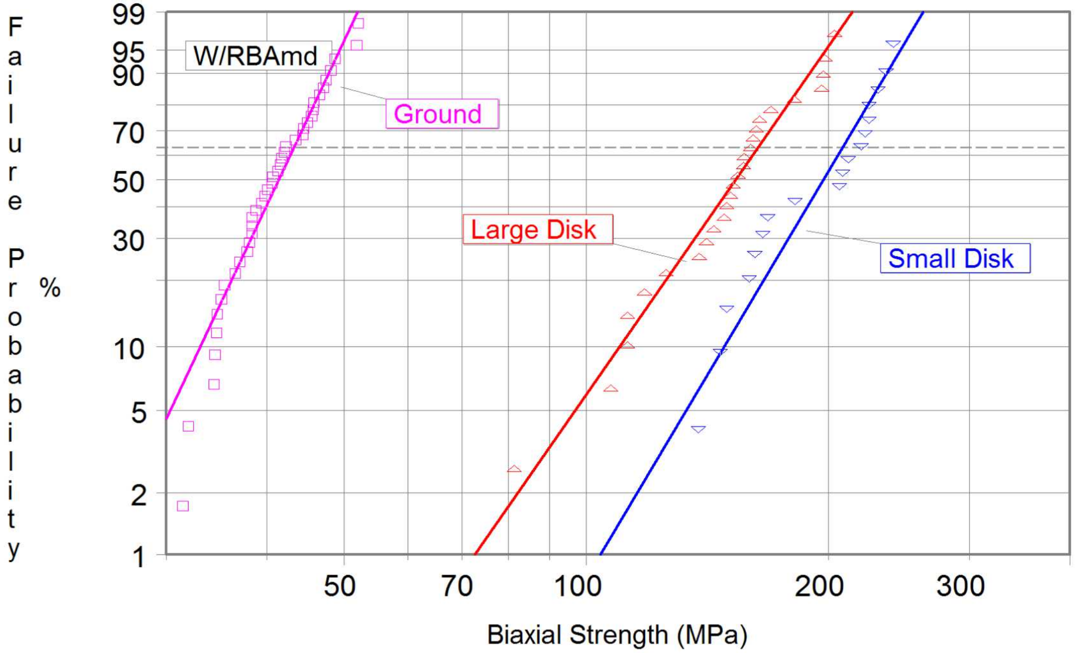
II. Slow crack growth (SCG) or "static fatigue." Strength decreases with time under static load:





Salem-NASA

Size Effects and Multiple Flaw Populations



Weakest Link Behavior:

- Structure is analogous to a chain with many links of differing strength
- Catastrophic failure occurs when the weakest link is broken

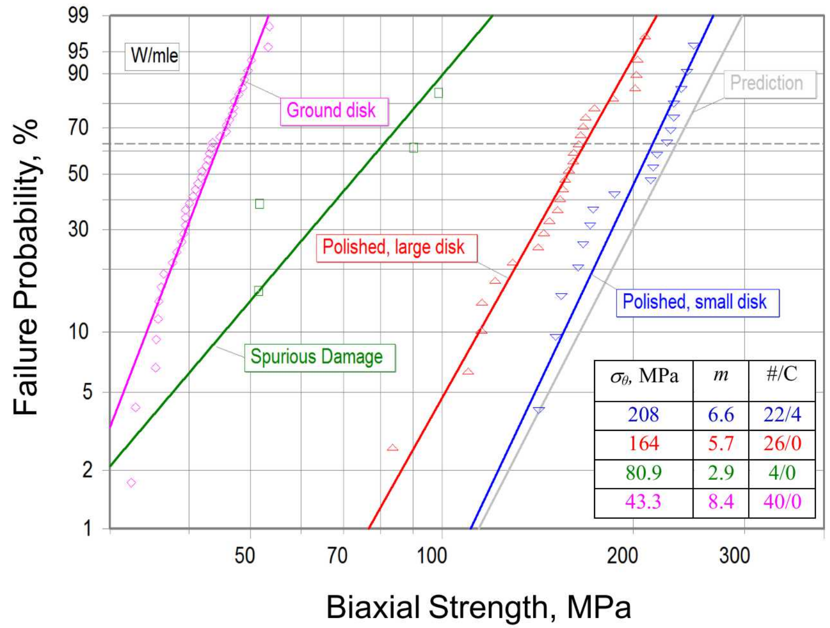
$$P_f = 1 - \exp[-(\sigma/\sigma_0)^\rho]$$

- Flaw population can change significantly, and strength is size dependent.
- Strength is *a variable*; not the inherent property. *Fracture toughness* is the inherent property: Strength results from the fracture toughness and flaw size present.
- Spurious damage lowers Weibull modulus and strength.
- Grinding distribution appear to be curved in 2-parameter Weibull space……

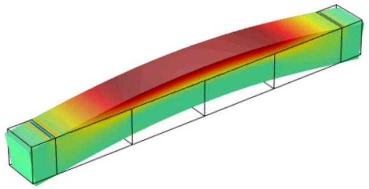
Accounting for Scale Effects - Effective Area

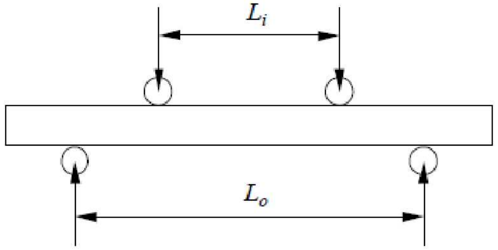
- General effective area solution:

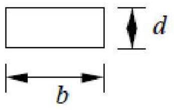
$$A^s_{eff} = \int_{A^s} \left(\frac{\sigma}{\sigma_{max}}\right)^{m_A}$$



- Closed form solution for Effective Area of 4 Pt. Bend Bar:

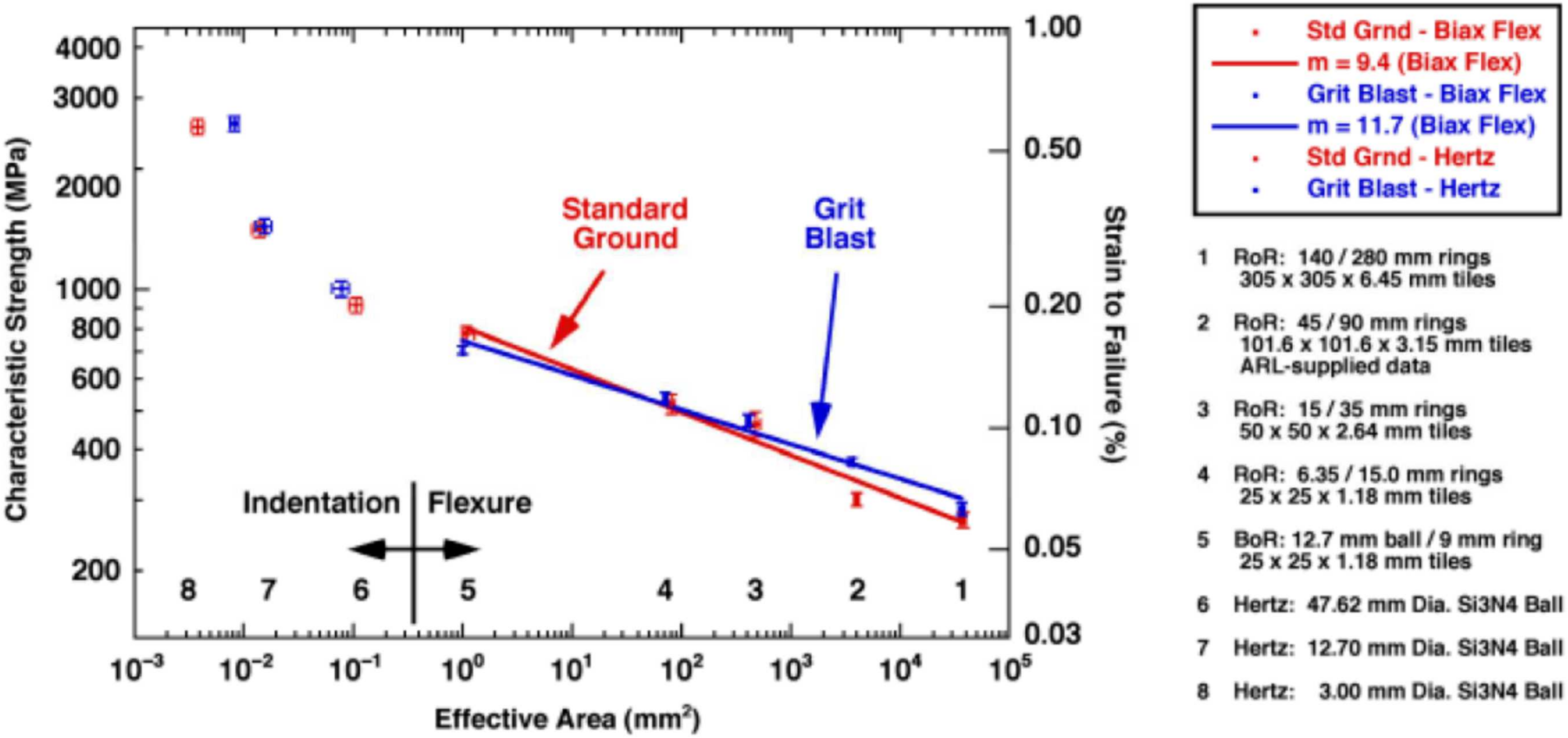






$$A_{eff} = L_o\left[\left(\frac{d}{WM+1}\right)+b\right]\left[\frac{\frac{L_i}{L_o}WM+1}{WM+1}\right]$$

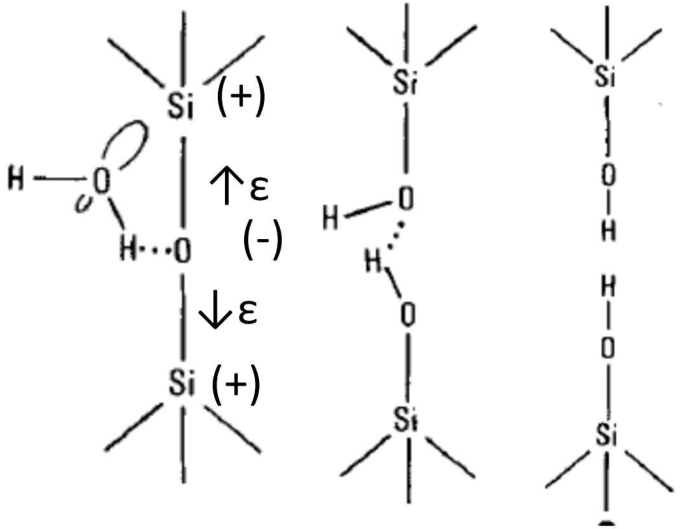
Accounting for Scale Effects - Effective Area

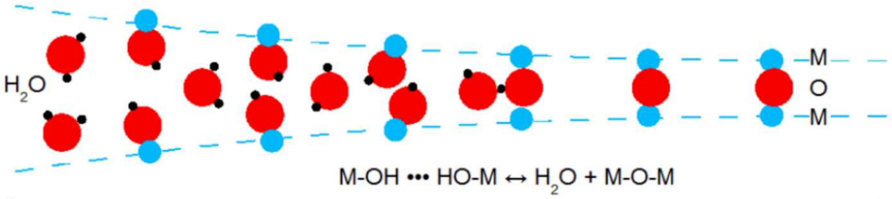


$$S_B = \left(\frac{k_{AA} \times A_A}{k_{AB} \times A_B}\right)^{1/m} S_A$$

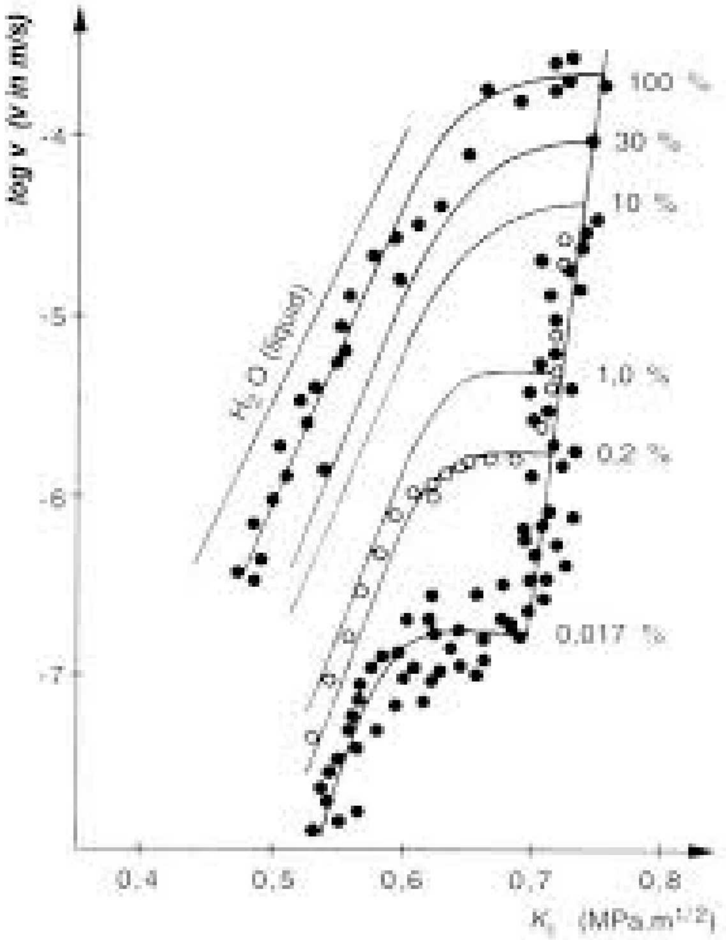
Mechanism - Environmentally Enhanced Crack Growth

Water causes intrinsic flaws (cracks) to slowly propagate at low stresses





Crack Propagation direction



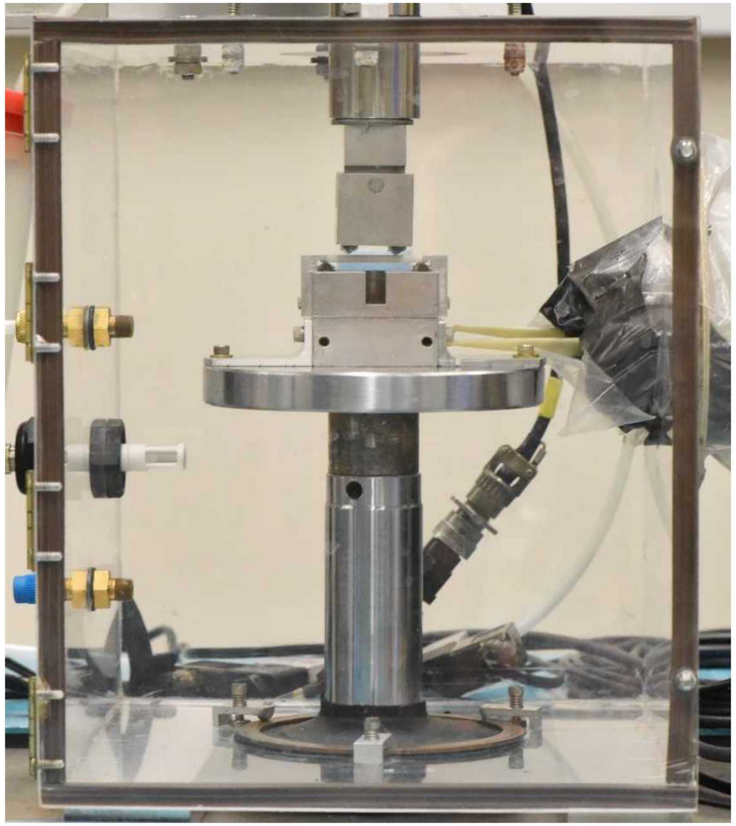
Weiderhorn (1967)

$$v = A_1 \left(\frac{K_I}{K_{IC}} \right)^{n_1}$$

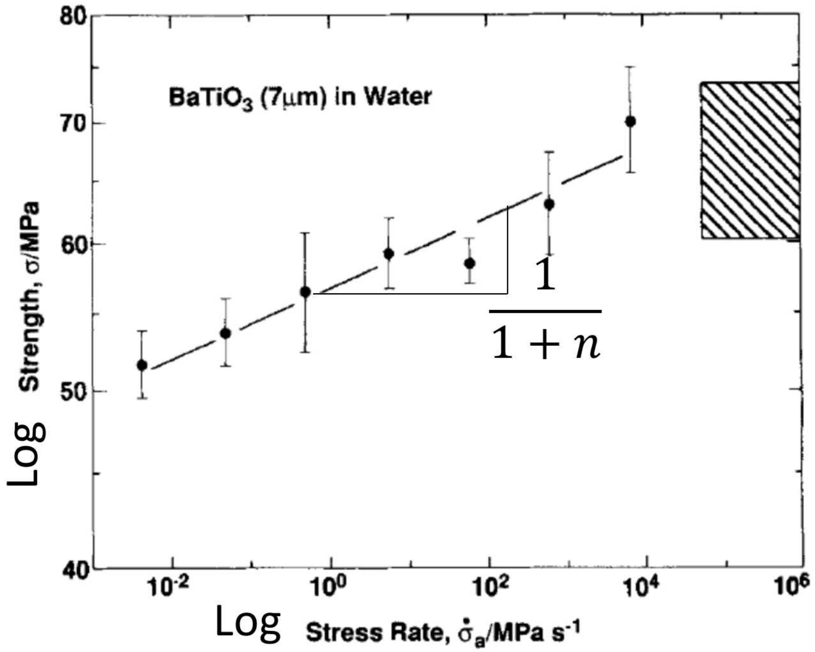
$$t_f = \frac{2}{Y^2 \sigma_a^2} \int_{K_{Ii}}^{K_{IC}} \frac{K_I}{v(K_I)} dK_I$$

ASTM C1368
Determination of Slow Crack Growth Parameters

Test Setup



Test Results



$$\log \sigma_f = \frac{1}{1+n} \log \dot{\sigma} + \log D$$

Environmental material parameters can be determined from laboratory experiments.

Freiman and Pohanka; *J. Am. Ceram. Soc., 1989*

Effect of atmosphere on aging of strength

- To predict the aging of the strength we assume that any flaws (small cracks) grow according to

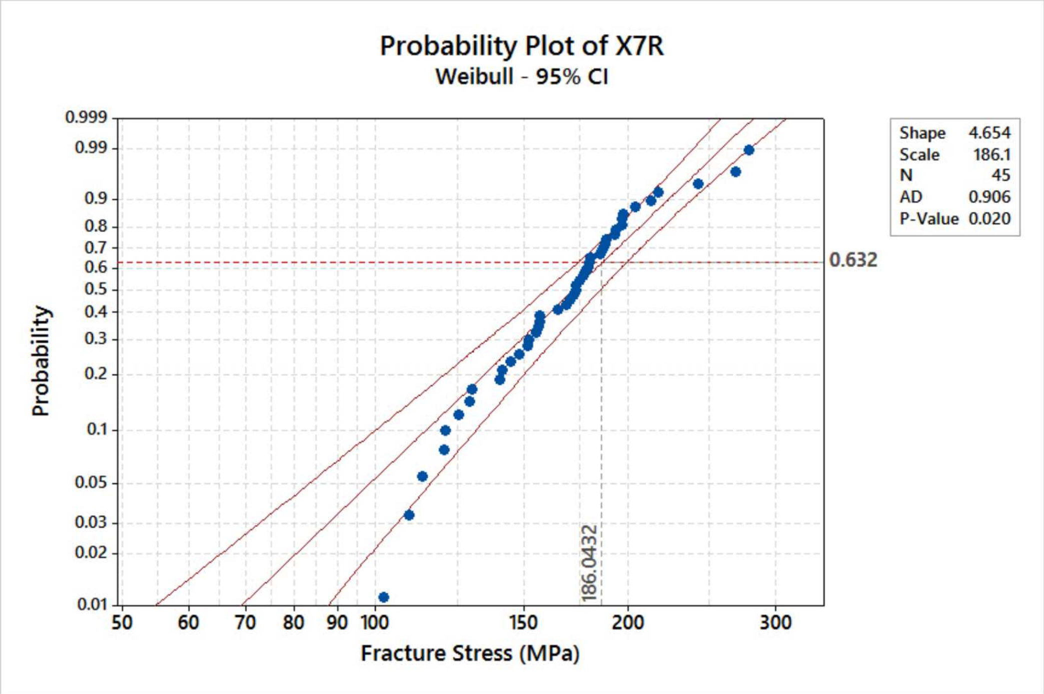
$$v = \dot{a} = A \cdot (K_I/K_{Ic})^n$$

- where a is crack length, K_I is mode I stress intensity factor from linear elastic fracture mechanics, K_{Ic} is fracture toughness, and A and n are fitting parameters
- At beginning of life, strength data is fit to the Weibull distribution, $P_{fail} = 1 - \exp\left[-\left(\frac{\sigma}{\sigma_0}\right)^{\rho}\right]$, which characterizes the flaws in the specimen
- Under a constant stress, σ_f, we assume the flaws grow according to the above velocity relation
- By integrating from an initial to a critical flaw size we predict that the aged strength distribution at some time t_f will be

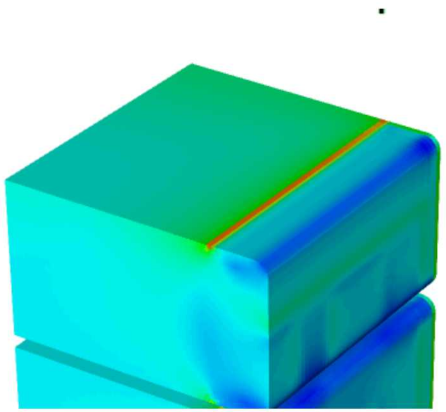
$$P_f = 1 - \exp\left(-\left\{\frac{\left[\frac{A(n-2)Y^2\sigma_f^2 t_f}{2K_{\mathrm{Ic}}^2}+1\right]^{\frac{1}{n-2}}\sigma_f}{\sigma_0}\right\}^{\rho}\right)$$

Stress predicted by model

- Max stress predicted in model is approximately 105 Mpa
- Weibull strength ASTM-B 4 point bend bars is 186 MPa
- Weibull strength is that which corresponds to 63.2% probability of failure (consider this a measure of the average strength of the specimen)
- We can use these Weibull parameters to predict probability of failure from an arbitrary geometry and stress state
- Max stress and Weibull strength are of the same order of magnitude → We expect a non-negligible but relatively small probability of failure
    - 0.14% Probability of Failure

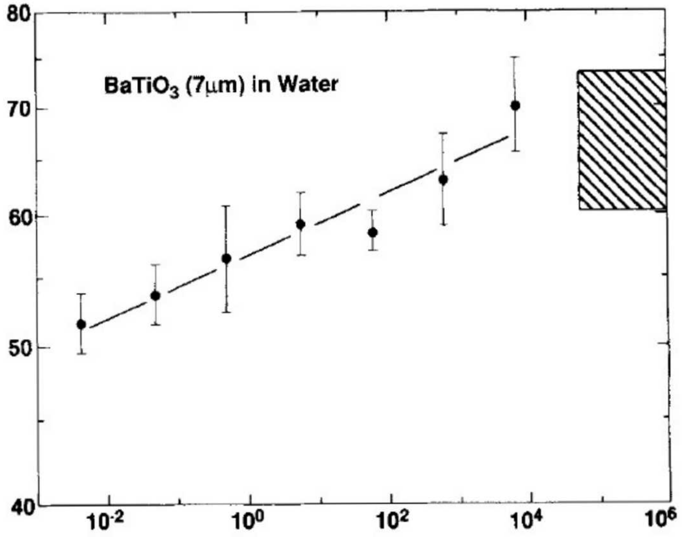


FEA Stress Analysis

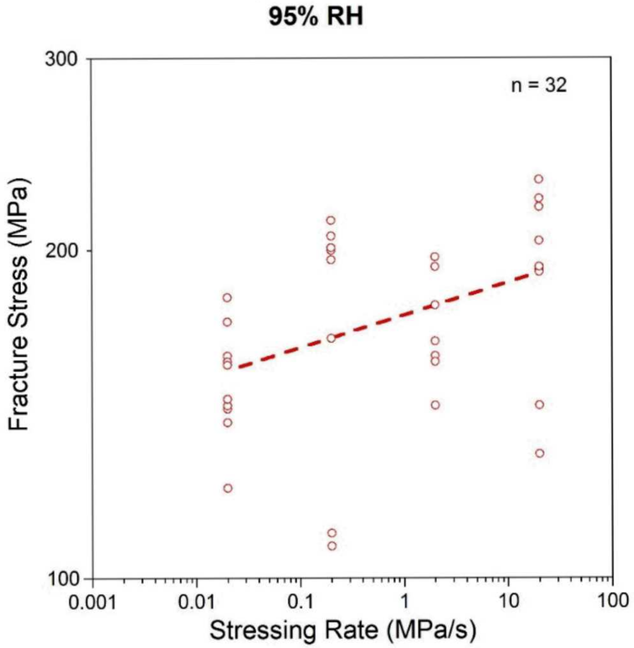


SCG Test Done

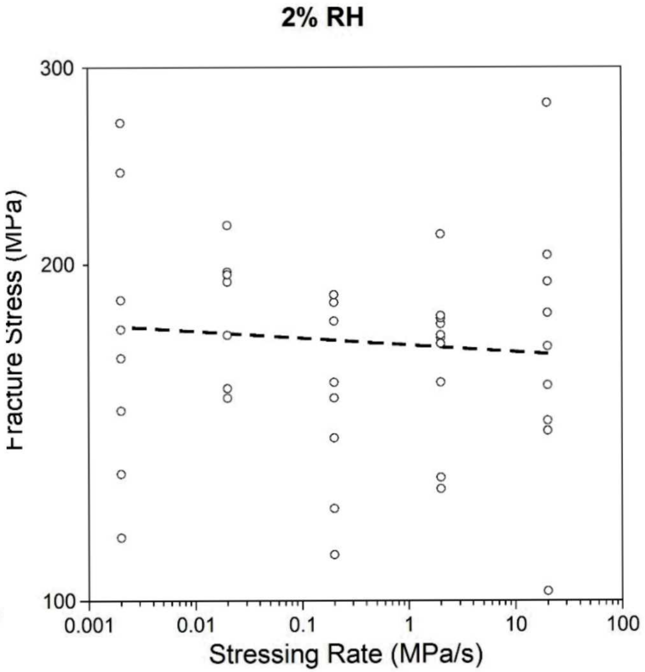
n = 49



n = 32



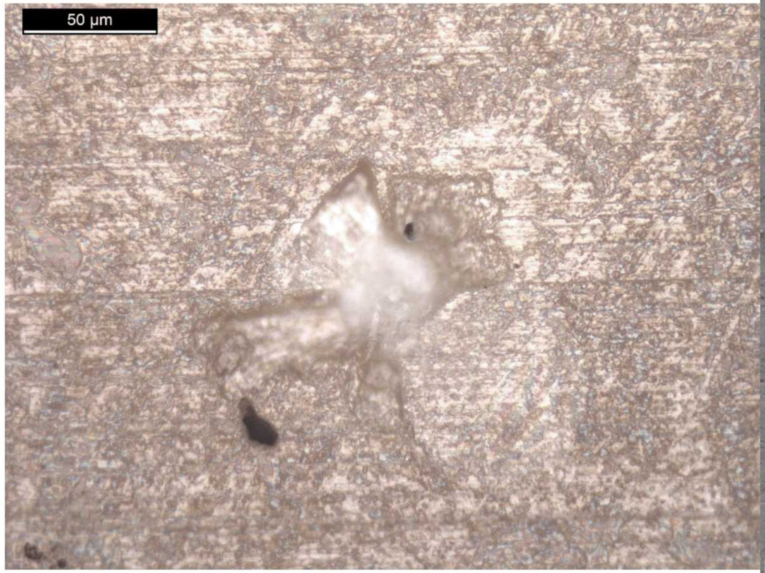
No slope

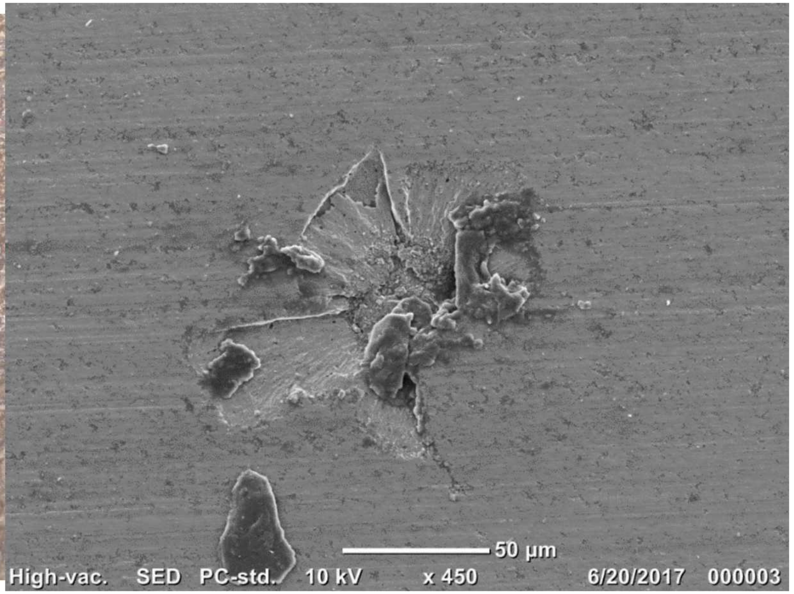


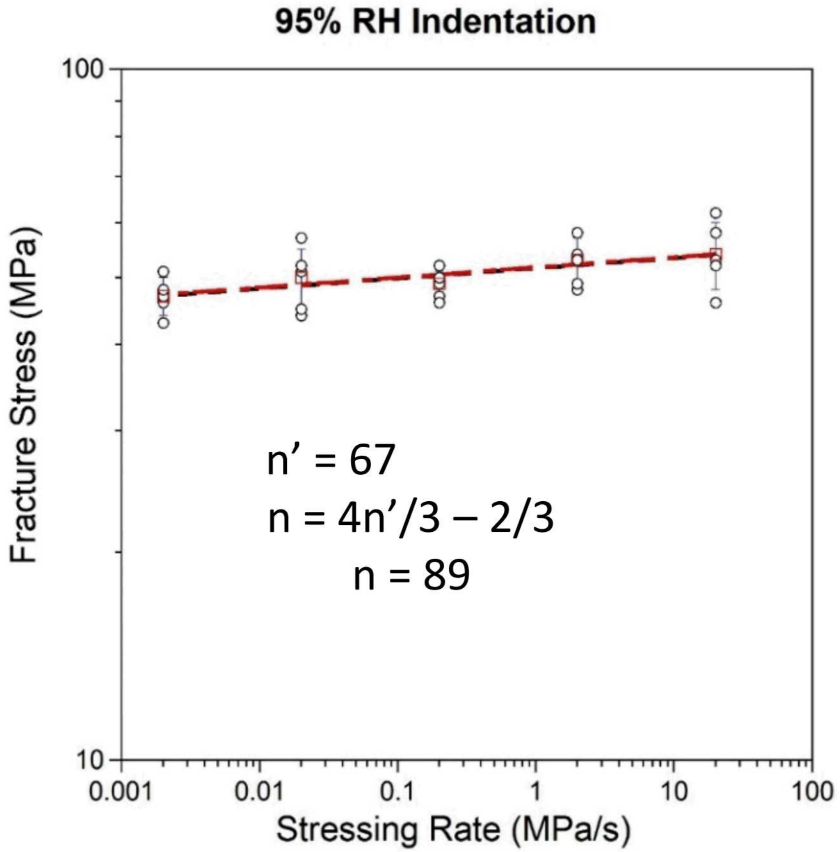
Higher the n value, the <u>less</u> susceptible a material is to sub-critical crack growth.

Indentation Strength

1 kgf ~60um crack length







n′ = 67

n = 4n′/3 – 2/3

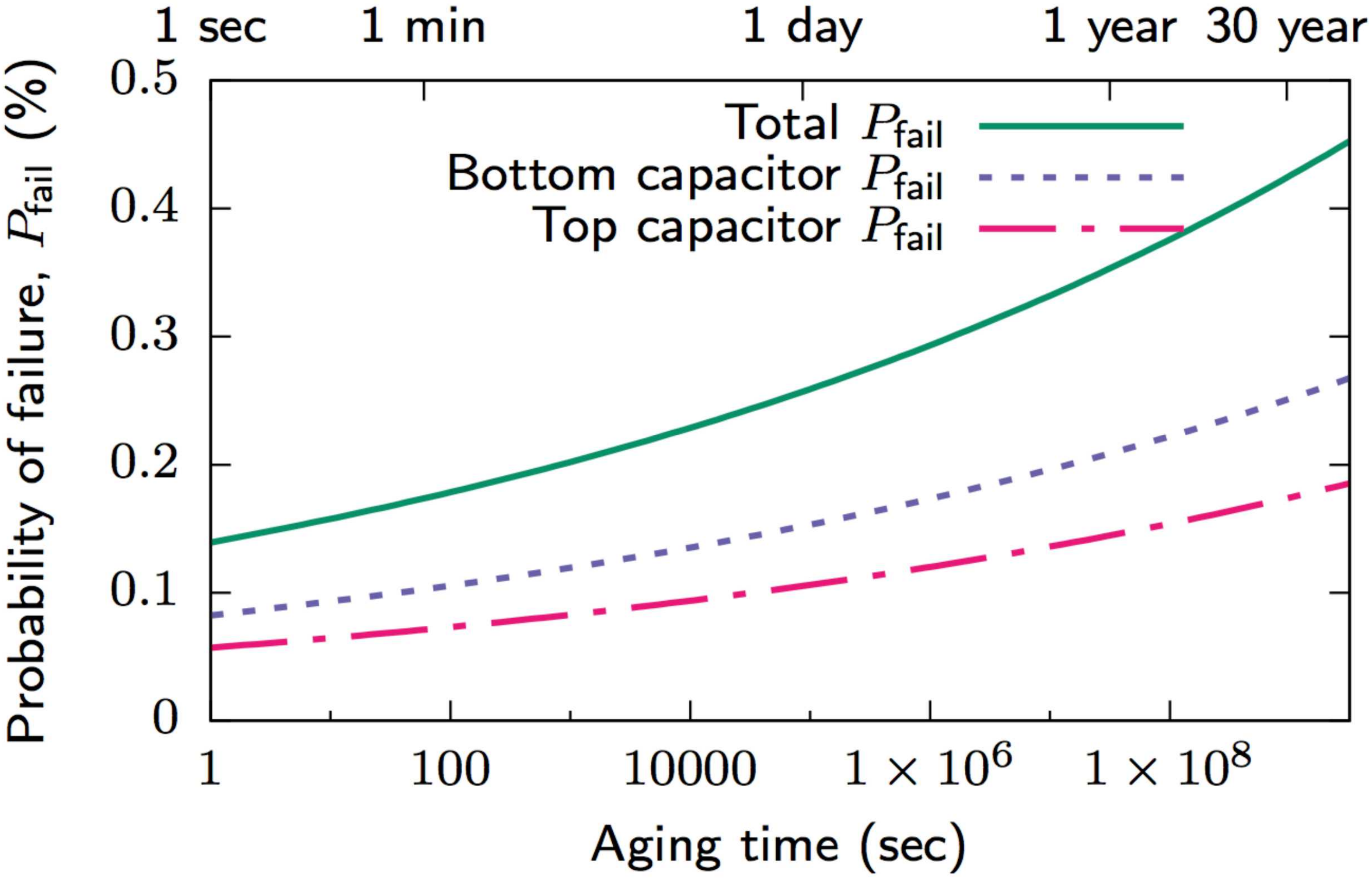
n = 89

Evolution of failure probability

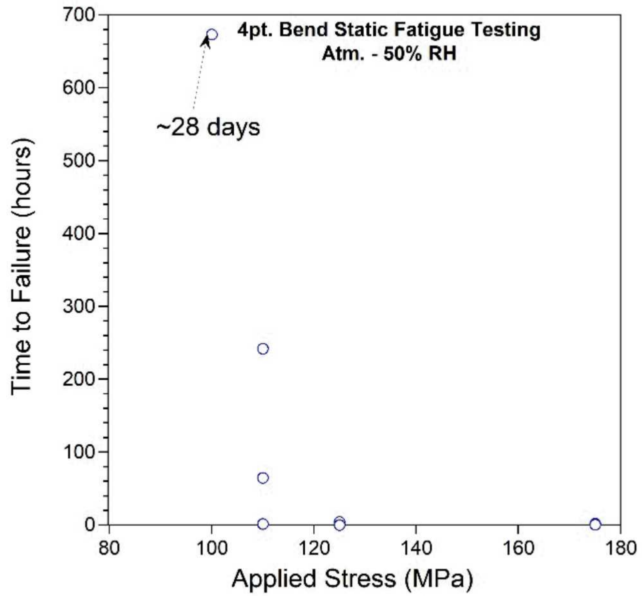
The relevant parameters in this case are:

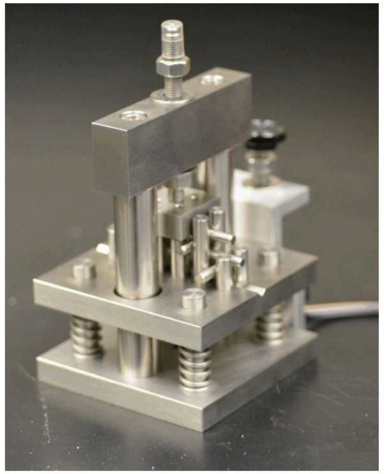
- σ_0=186 MPa
- ρ=4.654
- A=1.83·10^{-3} m/s
- n=90.7
- K_{Ic}=1.06 MPa m$^{1/2}$
- Geometry factor Y corresponding to a half penny surface flaw

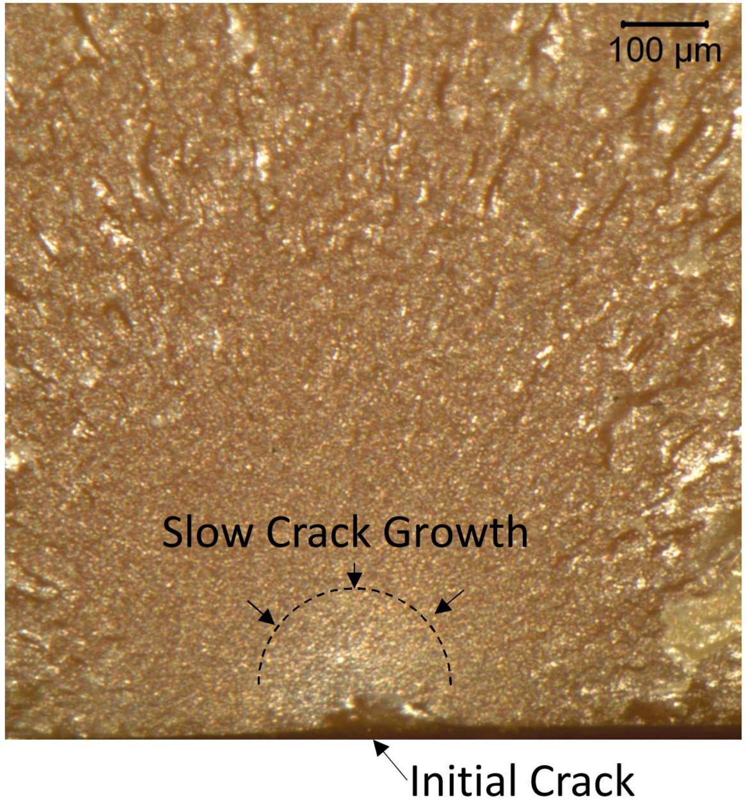
For both capacitors considered together, we predict an increase in probability of failure from 0.14% to 0.42% over 30 years

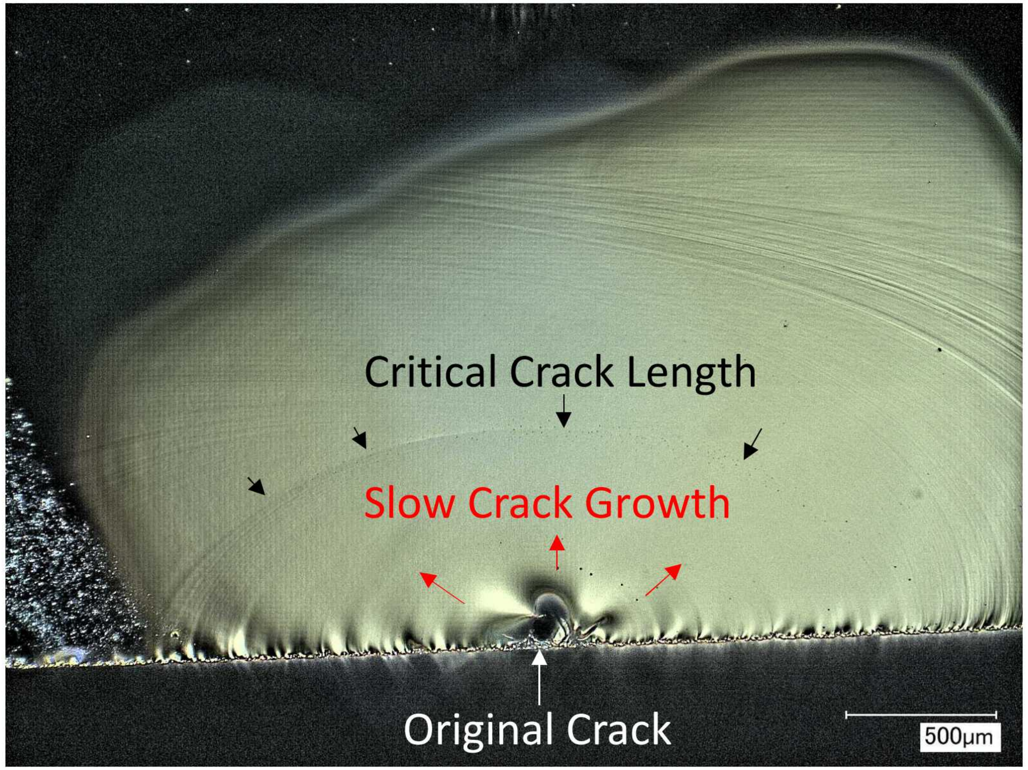


Delayed Failure Results to Validate Models









Summary

- Predictive models exist and can be implemented
  - Based on empirical fits -> Need physics based model that can be implemented

- Basic assumptions

  - stress state is well known
  - flaw populations are well know
  - flaw populations don't change except via SCG
  - similitude
  - reasonable extrapolations (scale effect breakdown).