SAND2016-10146C

Making the Most of Our Failures

28th Annual Rio Grande Symposium on Advanced Materials

Oct. 4, 2016

S. Jill Glass
Power Sources Component Development Dept.
Sandia National Labs
Albuquerque, NM 87185

sjglass@sandia.gov

Fractography and Glass

To introduce these articles, it is appropriate to briefly discuss **fractography** and to also address the issue of why glass is the focus of these articles and this monograph. Perhaps part of the reason is because fractography is concerned with the phenomenon of fracture, and glass, having one of the lowest fracture toughness values (resistance to fracture) of all materials, is particularly prone to fracture or break. **Of course, glass has been prone to breakage ever since the first glasses were produced many centuries ago.**

The word fractography does not appear in Webster's finest. It probably originates from a combination of the two terms: fracture and topography, deriving from the Latin frangere and topographye.

Fractography is the study of the relief features or surface structure of fractured surfaces, usually from an after-the-fracture or post mortem perspective. **Most modern fractography has been pursued from the perspective of examining the broken or fractured artifact, to attempt to reconstruct the manner and to identify the reason why the object fractured.**

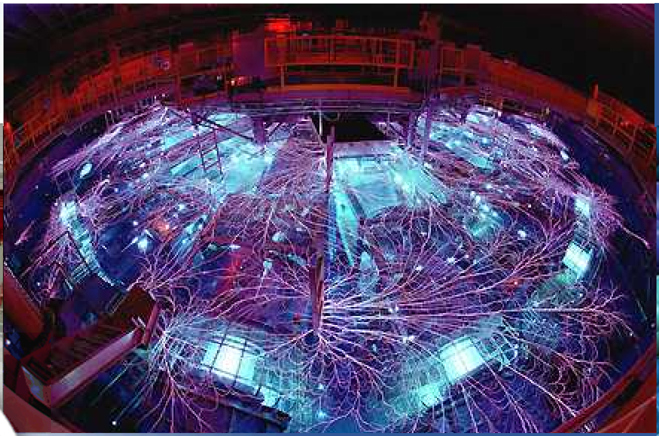
Fractography of Glass, Edited by Richard C. Bradt and Richard E. Tressler, 1994

Outline

- Failure Ingredients
- Failure Examples
- Making the Most of Our Failures

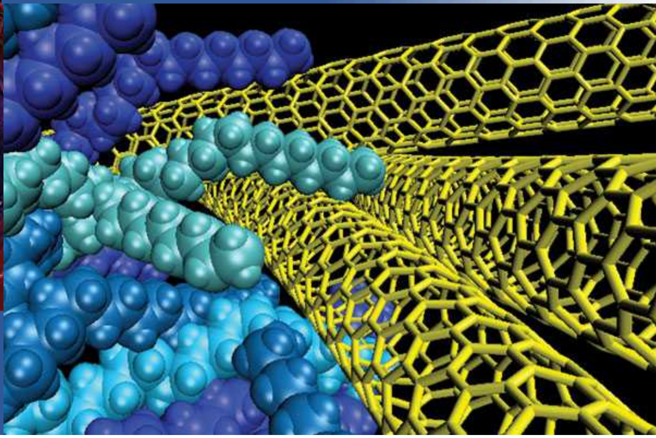
Sandia's Science and Technology Framework

Computing & Information Sciences

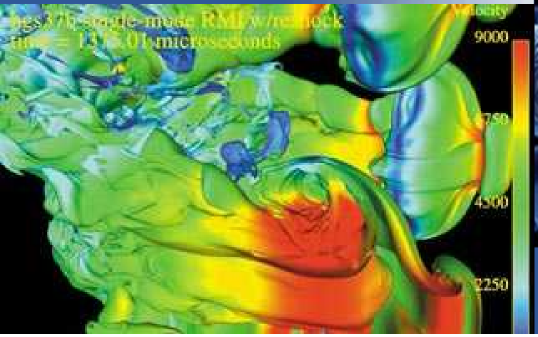


Radiation Effects & High Energy Density Science

Materials Sciences

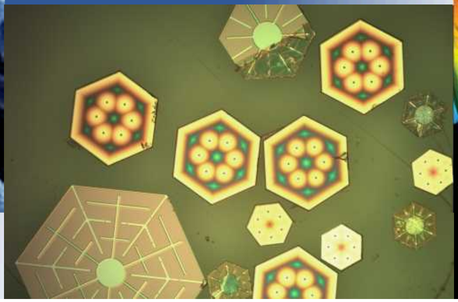


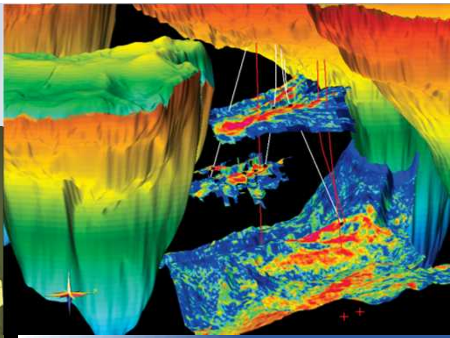
Engineering Sciences



Bioscience

Nanodevices & Microsystems



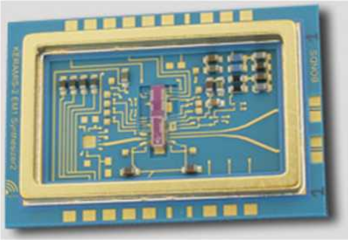


Geoscience

Brittle Material Containing Components

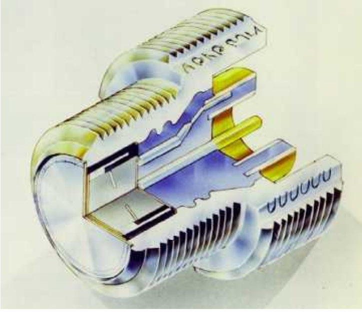
Materials

- 94% and 96% Al_2O_3
- Mo - Al_2O_3 Cermets
- Bulk Glasses and Glass Ceramics
- Glass Fibers
- Ceramic Ferrites
- PZT (lead zirconate titanate)
- PMN-PT (lead magnesium niobate - zirconate titanate)
- Barium Titanate
- Polysilicon
- ZnO Varistors
- **LTCC (low temp co-fired ceramic)**



Components (Sandia and Externally Produced)

- Batteries and other Power Sources
- Slim Loop Ferroelectrics
- Rolamite Switches
- Neutron Sources
- Safe Enable Wheels
- Stronglinks
- Voltage Bars
- Current Stacks
- Discoidal Capacitors
- Electronic Substrates
- Clocks
- Photo Diodes
- Connectors



Strength is Flaw Size Dependent for Brittle Material

When σ_a or σ_r > $\sigma_f = \frac{K_{IC}}{Y\sqrt{c}}$

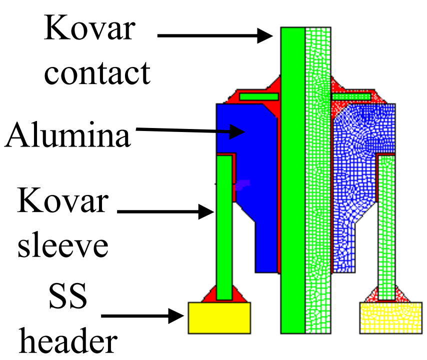
Where:

σ_f = fracture strength
K_{IC} = fracture toughness or critical stress intensity
c = flaw size
Y = geometrical factor

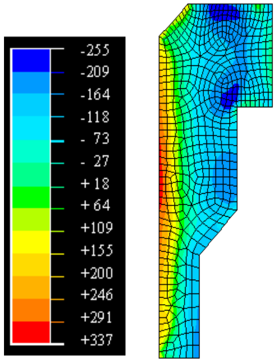
σ_a = applied stress
σ_r = residual stress

Ingredients for Brittle Material Failure

When $\sigma_{\text{applied or residual}} > \sigma_f = \dfrac{K_{IC}}{Y\sqrt{c}}$



- Poor Design - Excessive stress
  - Excessive applied/local stresses
  - Materials combinations and/or processing that lead to excessive residual stress
- Presence or introduction of defects
  - Intrinsic microstructural features
  - Processing related
  - Machining, in-service damage
- Material degradation
  - Environmental effects, decrease in K_{IC}
  - Increase in flaw size - subcritical crack growth



max. prin. stress (MPa) in alumina

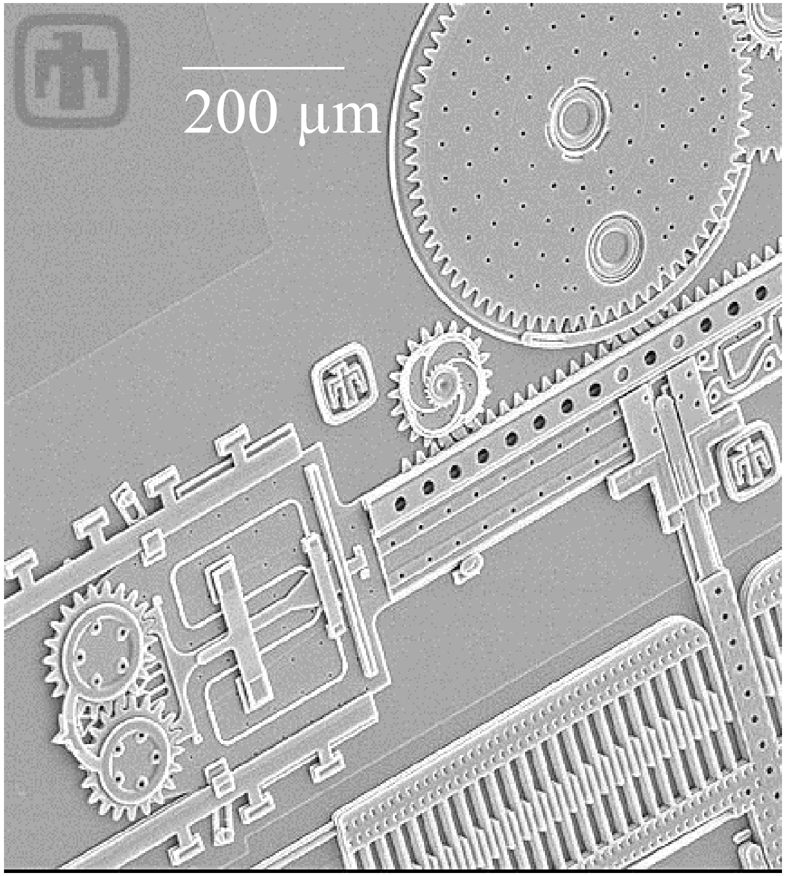
All of the above!

Brittle Materials Failure Examples

- Polysilicon Micro-Electromechanical Systems (MEMS) - Buchheit and Boyce
- Low Temperature Co-fired Ceramics (LTCC)strength samples - Tandon, Monroe, Newton, Roth
- ZnO varistors - Watson, Lockwood, and Diantonio
- Pressurized sulfuric acid tank from semiconductor industry - many

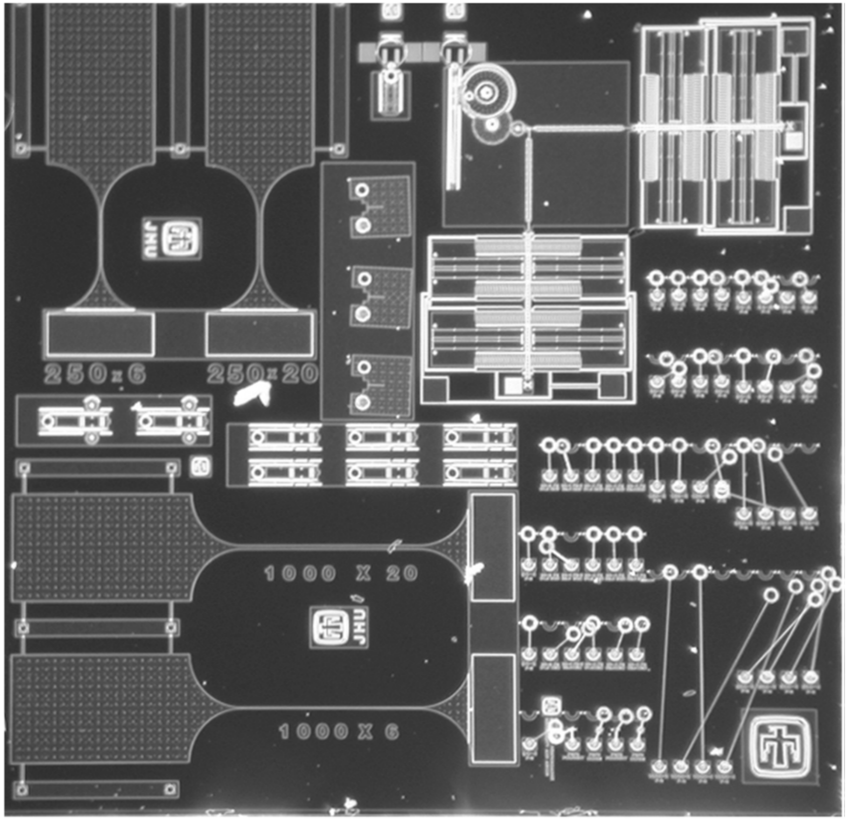
Fracture Strength Testing and Failure Origins for Polysilicon MEMS Materials

24-bit lock with 24-bit path, drive gears, anti-reversing gears, meshing gears, etc.

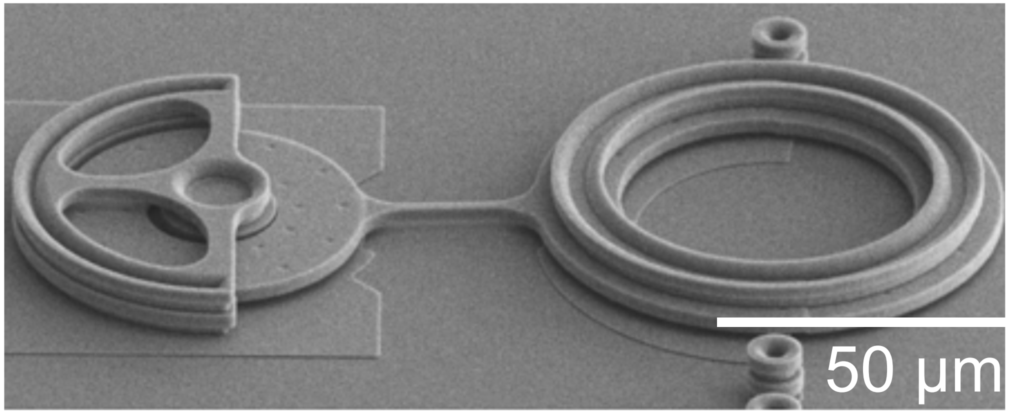


- Modest structural properties (K_{IC}=1.0-1.4 MPa√m)
- High degree of reactivity with oxygen, water and other reagents

Polysilicon Mechanical Testing Samples Fabricated Directly on the Die

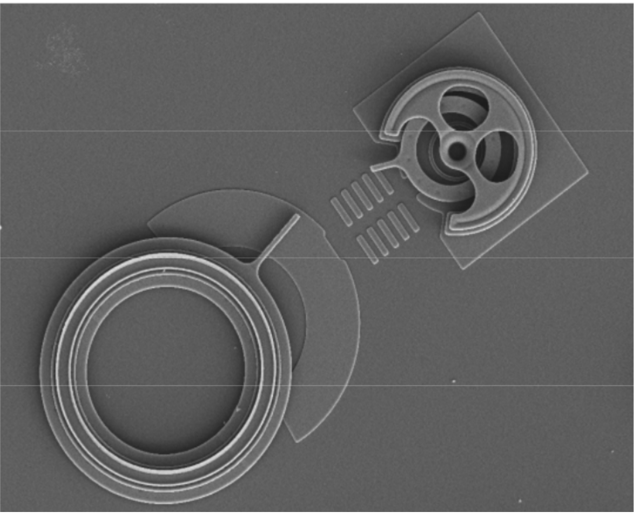


Pull-tab tensile strength sample.

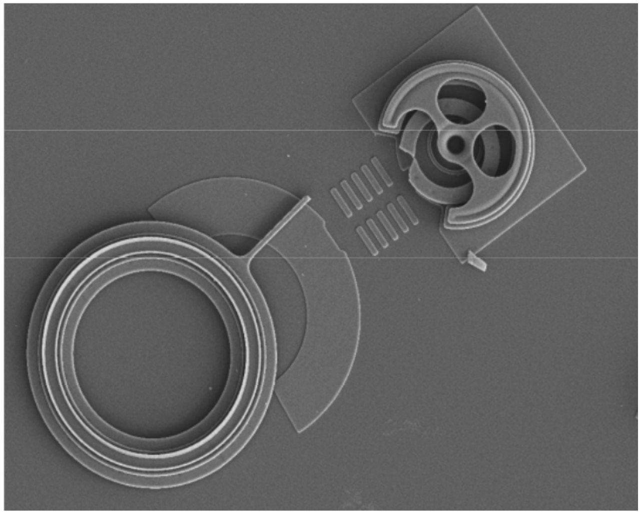


2 of 3 Failure Modes for 48 First Generation Polysilicon Samples Due to Pull-Tab Design

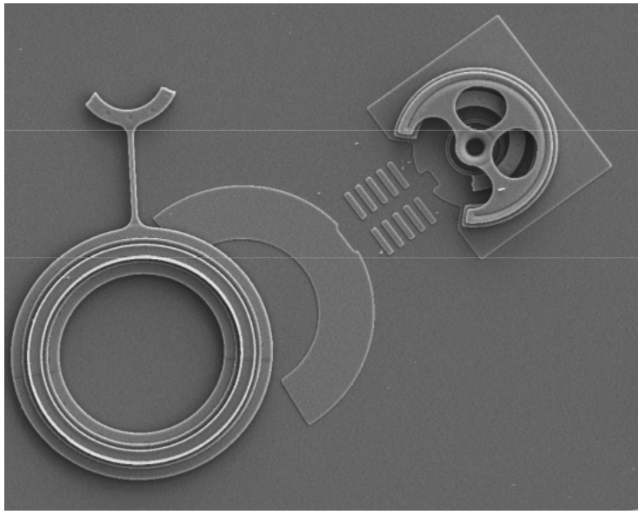
Average σ_f = 2.24 GPa ±0.35



7 Strongest

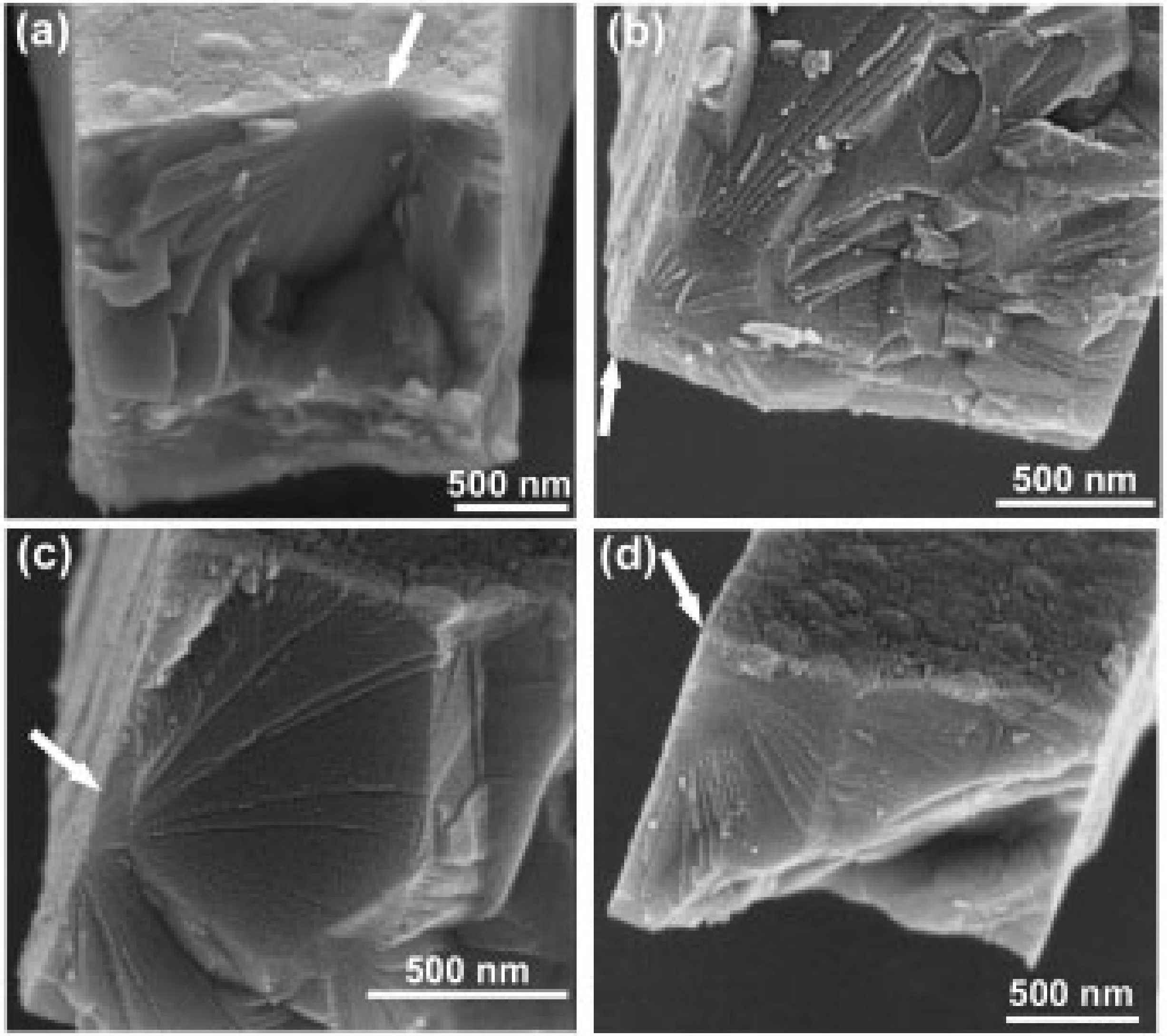


Intermediate Strength



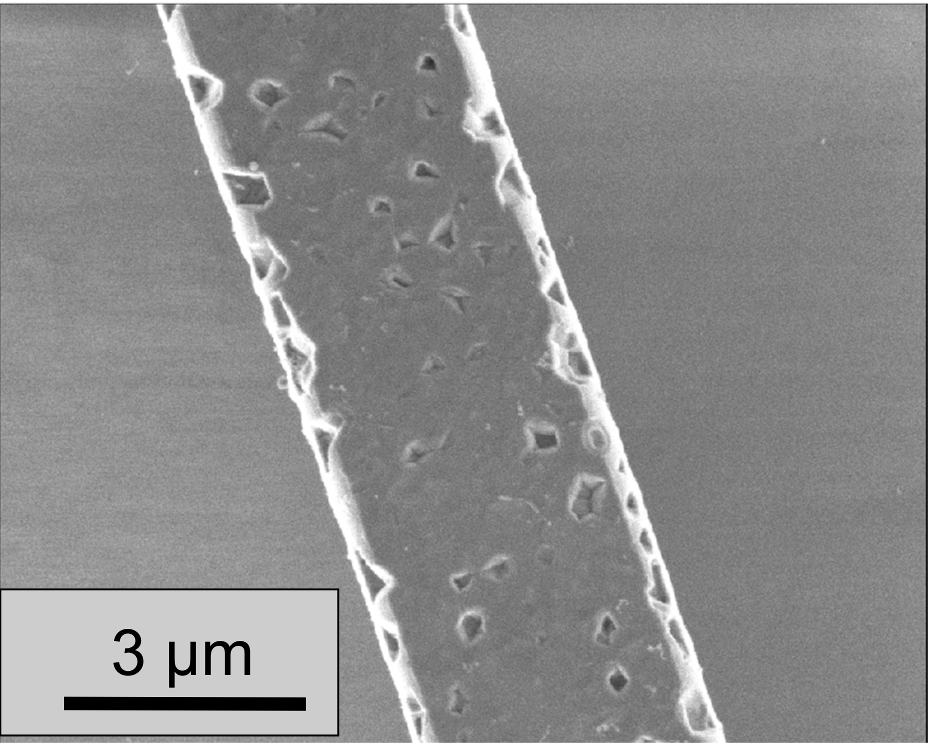
Weakest

Failures Due to Both Etching Flaws (a & c) and Corner Stress Concentrations (b &d)

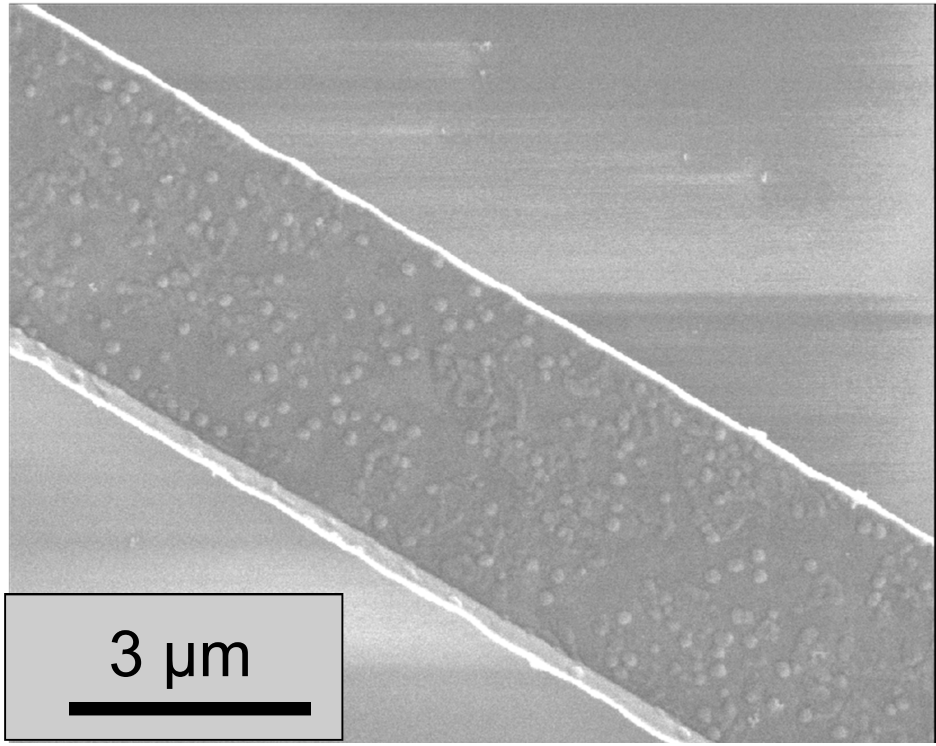


B. Boyce,
Sandia, 2005

Strengths Are Sensitive to Surface Condition (Etching Flaws) for Different Layers

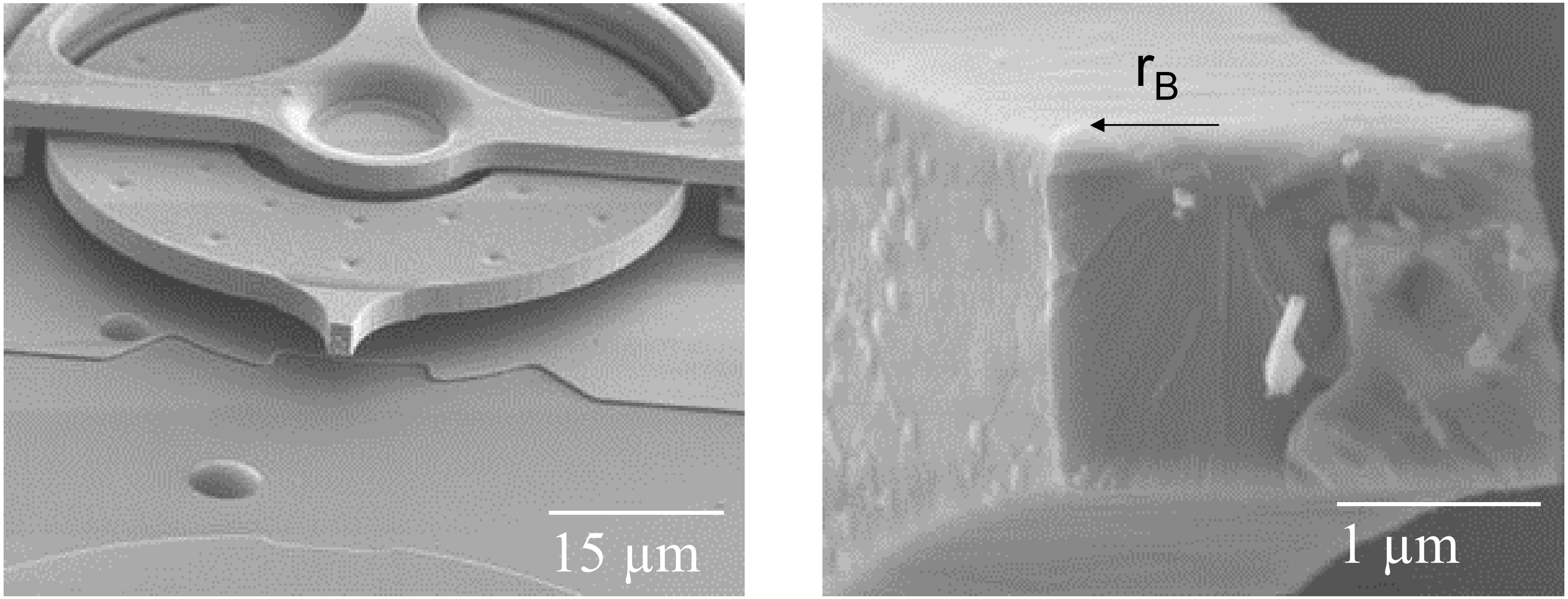


Weak



Strong

Strength Can be Estimated from Fracture Branching Boundaries on Fracture Surface



$$\sigma_f Y r_B^{1/2} = \text{constant} = K_B$$

K_B = 2.0 MPa√m
(Tsai & Mecholsky, 1992)

Therefore, $\sigma_f = 2.1$ GPa

Ingredients for Polysilicon Micro-Electromechanical Systems (MEMS) Failures

When $\sigma_{\substack{\text{applied} \\ \text{or residual}}} >$ $$\sigma_f = \frac{K_{IC}}{Y\sqrt{c}}$$

Poor Design - Excessive stress

- Excessive applied or **local stress concentrations**
- Materials combinations and/or processing that lead to excessive residual stress

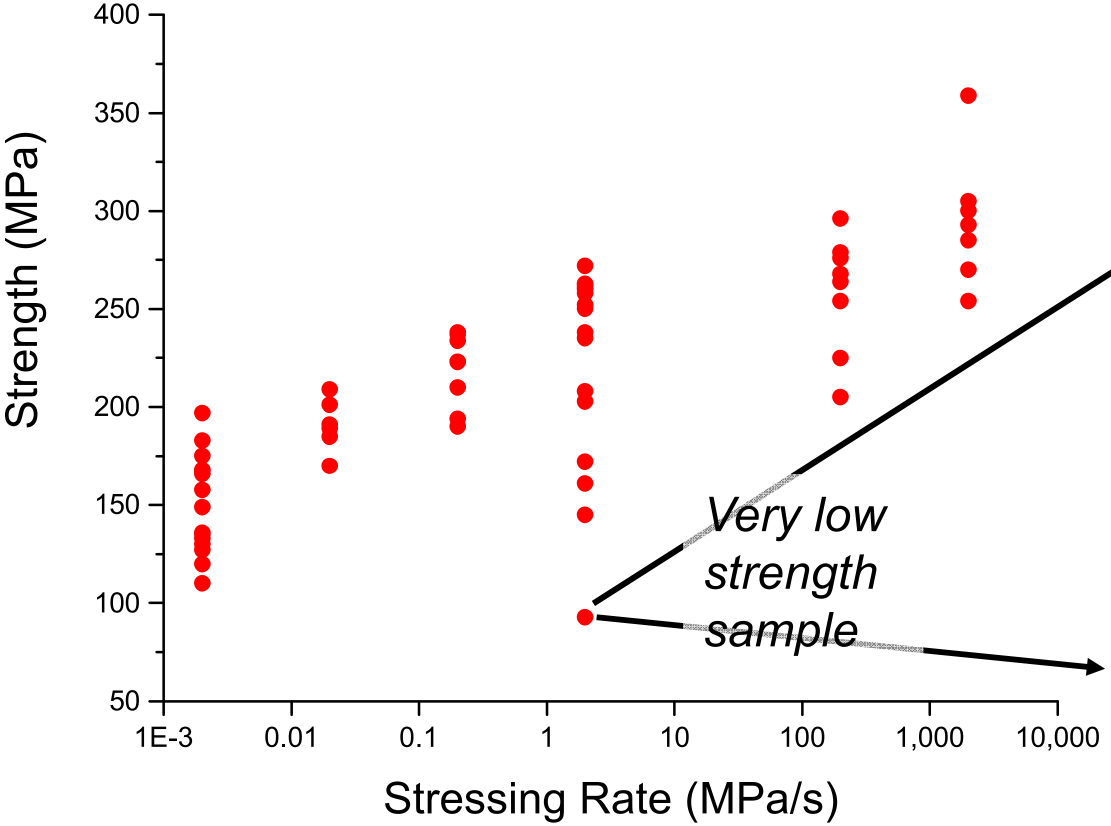
Presence or introduction of defects

- Intrinsic microstructural features
- ***Processing related***
- Handling or in-service damage

Material degradation (loss of strength)

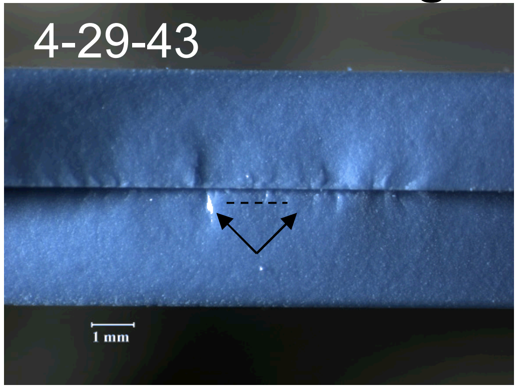
- Environmental effects, decrease in K_{IC}
- Increase in flaw size - subcritical crack growth

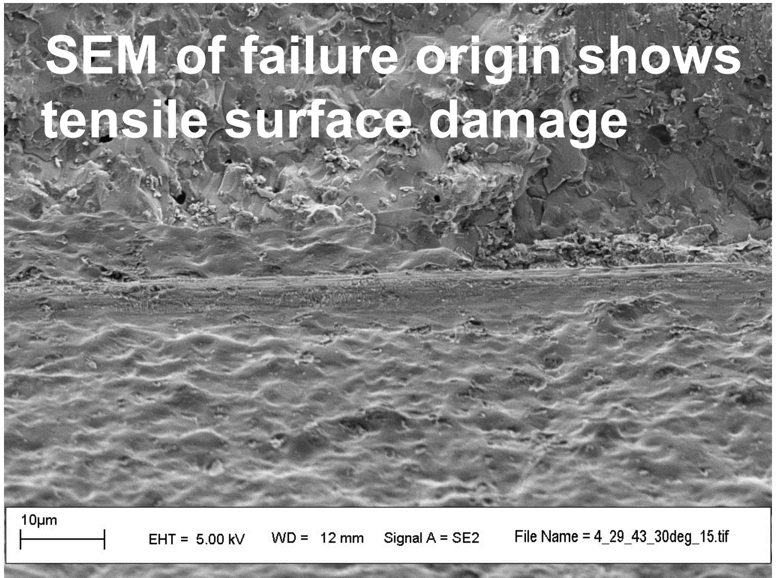
LTCC Subcritical Crack Growth Data Collected for Lifetime Predictions (crack velocity=AK^n)



Very low strength sample

Optical exam used to locate failure origin





SEM of failure origin shows tensile surface damage

Ingredients for Failure of Low Temp Co-Fired Ceramic (LTCC) Strength Samples

When σ_{applied} > $\sigma_{\text{f}} = \dfrac{K_{IC}}{Y\sqrt{c}}$

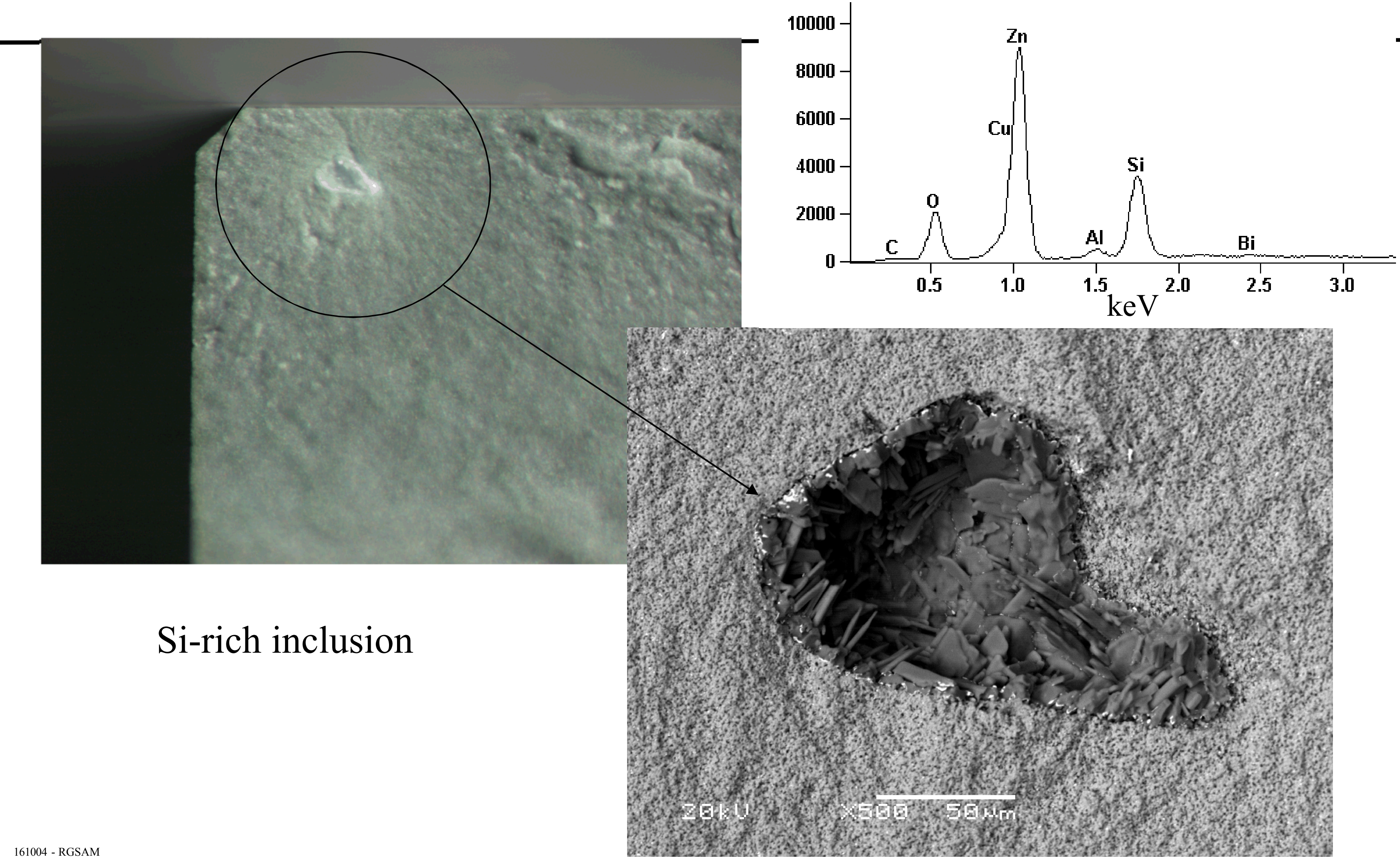
or residual

Excessive stress
- Excessive applied stress or macroscopic stress concentrations
- Materials combinations and/or processing that lead to excessive residual stress

Presence or introduction of defects
- Intrinsic microstructural features
- Processing related
- ***Machining, in-service damage***

Material degradation (loss of strength)
- Increase in flaw size due to subcritical crack growth
- Decrease in K_{IC}

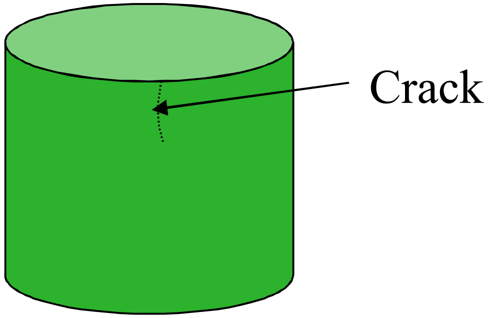
Fractography of ZnO Varistor Bend Bars Reveals that Contaminants Serve as Failure Origins

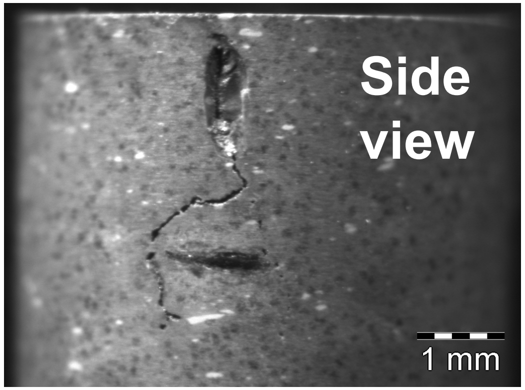


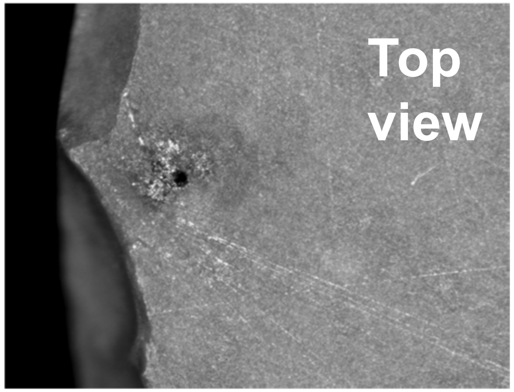
Si-rich inclusion

Surface Damage Studied to Determine How it Contributes to ZnO Electrical Breakdown

Prior to electrical pulse testing







- Cracks parallel to current flow produce early breakdowns

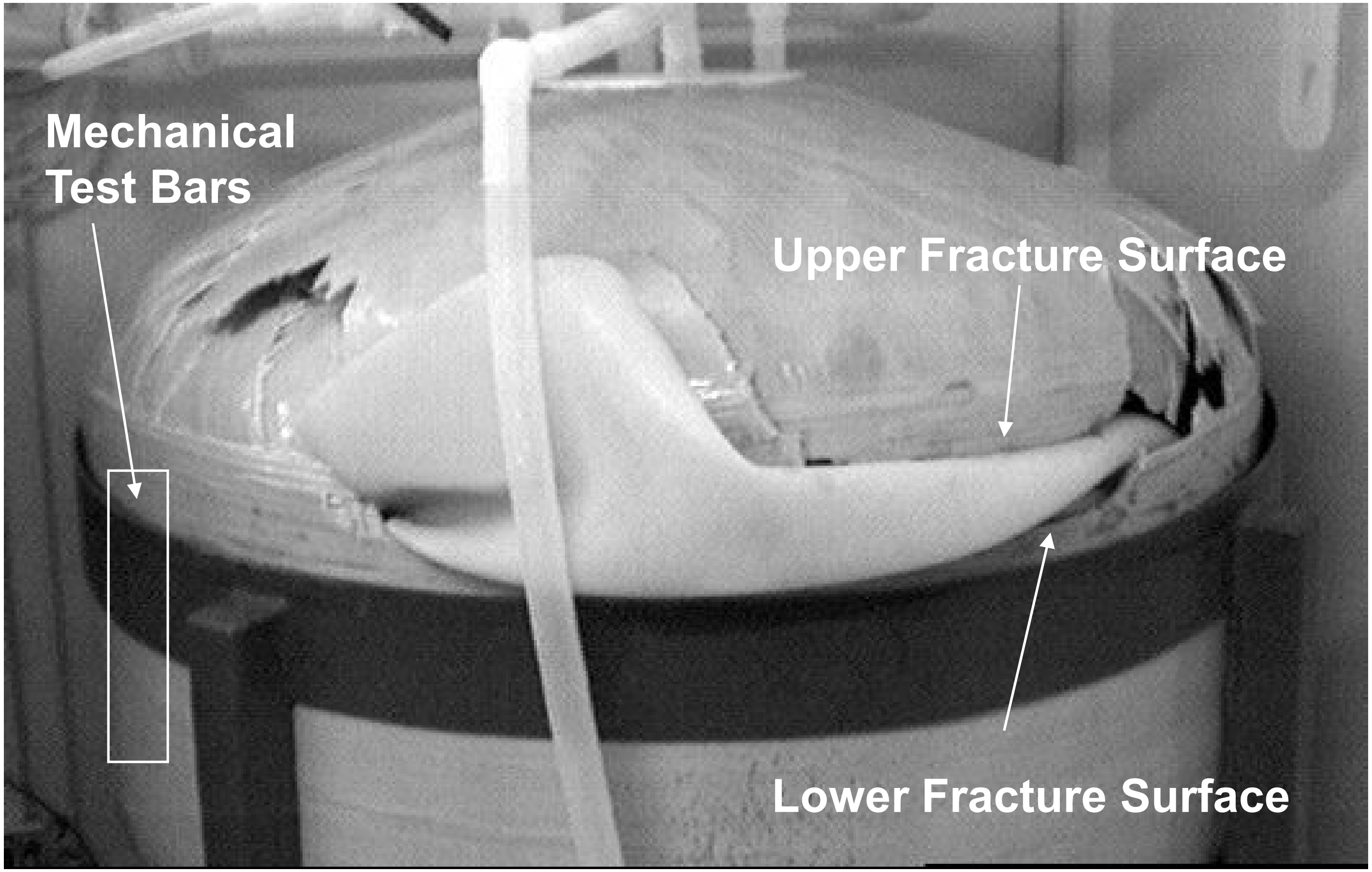
Ingredients for ZnO Varistor Failure (Mechanical and Electrical Breakdown Strength)

When $\sigma_{\text{applied or residual}} > \sigma_f = \dfrac{K_{IC}}{Y\sqrt{c}}$

- Excessive stress
  - Excessive applied stress or macroscopic stress concentrations
  - Materials combinations and/or processing that lead to excessive residual stress
- Presence or introduction of defects
  - Intrinsic microstructural features
  - ***Processing related***
  - ***Machining, in-service damage***
- Material degradation (loss of strength)
  - Increase in flaw size due to subcritical crack growth
  - Decrease in K_{IC}

Failure and Fractography of a Fiberglass Reinforced Composite (FRC) Acid Tank

A FRC tank containing sulfuric acid failed catastrophically during a pressurization cycle.



Tank Failure was Due to a Variety of Factors

- High tensile stress in of the circular wrap in the region just above the constraining cradle
- Cracking of epoxy in circular wraps exposed cross ply fibers
- Sulfuric acid was introduced into the cracks
- Fibers in the cross plies were severely degraded and weakened by acid
- Sequential failure of fibers in cross plies occurred during pressurization cycles until crack of critical dimensions produced
- Catastrophic crack propagation occurred

Ingredients for Failure of a Fiberglass Reinforced Composite (FRC) Tank

When $\sigma_{\text{applied or residual}}$ > $$\sigma_f = \frac{K_{IC}}{Y\sqrt{c}}$$

- Excessive stress
  - ***Excessive applied stress or macroscopic stress concentrations***
  - Materials combinations and/or processing that lead to excessive residual stress
- Presence or introduction of defects
  - Intrinsic microstructural features
  - Processing related
  - ***Machining, in-service damage***
- Material degradation (loss of strength)
  - ***Increase in flaw size due to subcritical crack growth***
  - ***Decrease in K_{IC}***

All of the above!

Making the Most of Our Failures

- Failure/survival depends on properties, flaws, design - loading (applied and residual), and environment

- Failure often due to a combination of factors

- We have valuable opportunities to improve our materials, processing, designs, and analyses by “*observing, measuring, and interpreting our failures.”* (Derek Hull)

Materials Failures and their Analyses as a Metaphor for Human Failure

FAMOUS FAILURES

ALBERT EINSTEIN
He wasn't able to speak until he was almost 4-years-old and his teachers said he would "never amount to much"

MICHAEL JORDAN
After being cut from his high school basketball team, he went home, locked himself in his room, and cried.

WALT DISNEY
Fired from a newspaper for "lacking imagination" and "having no original ideas."

STEVE JOBS
At 30-years-old he was left devastated and depressed after being unceremoniously removed from the company he started.

OPRAH WINFREY
Was demoted from her job as a news anchor because she "wasn't fit for television."

THE BEATLES
Rejected by Decca Recording Studios, who said "We don't like their sound—they have no future in show business."

104 TIMES
Albert Einstein didn't speak until he was four and didn't read till seven. He went on to win a Nobel Prize and became the face of modern physics.

12 TIMES
J.k Rowling was famously rejected by a mighty 12 publishers before Harry Potter and The Philosopher's Stone was accepted.

27 TIMES
Dr. Seuss's first book To Think That I Saw It on Mulberry Street was rejected by 27 different publishers.

302 TIMES
Legend has it Walt Disney was turned down 302 times before he got financing for creating Disneyland.

Thank you!

Favorite Failure Quotes

“Materials are a lot like people, imperfections control their behavior.” Rusty Gray

“All major weaknesses have been exposed, analyzed, and replaced with new weaknesses.” Bruce Leverett

“Failure is not an option. It comes bundled with your software.” Unattributed