Effects of Joint Geometry and Materials on the Failure Probability of Ceramic Joints

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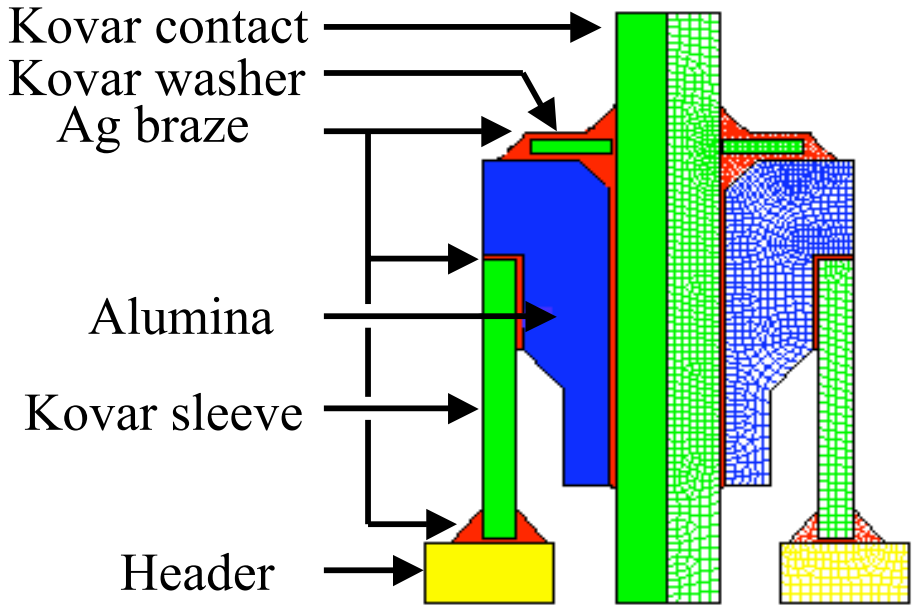
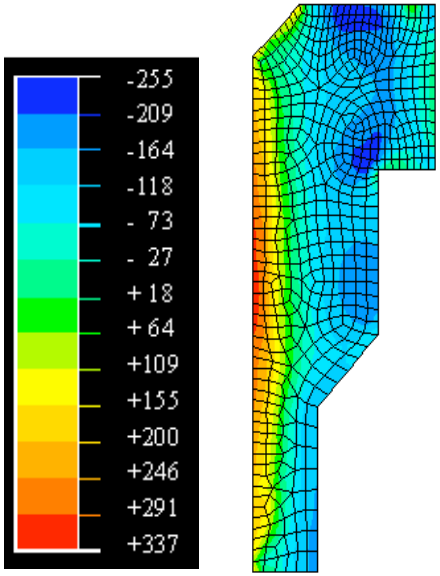
Ceramic-Containing Components Designed using Rules of Thumb

- Compare maximum principal stress from FEA to material strength (Al_2O_3 σ_f= 350 MPa, 51 ksi)
- Tailor design to keep stresses below 0.25 x σ_f





max. principal stress (MPa)

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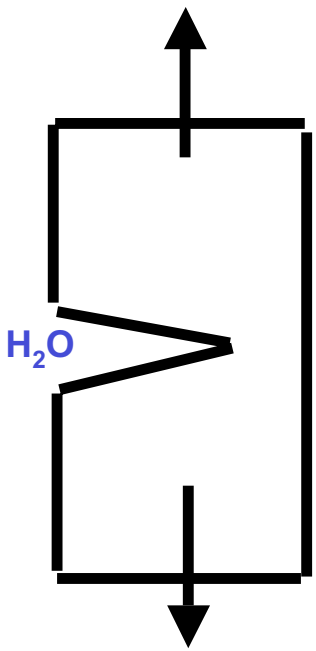
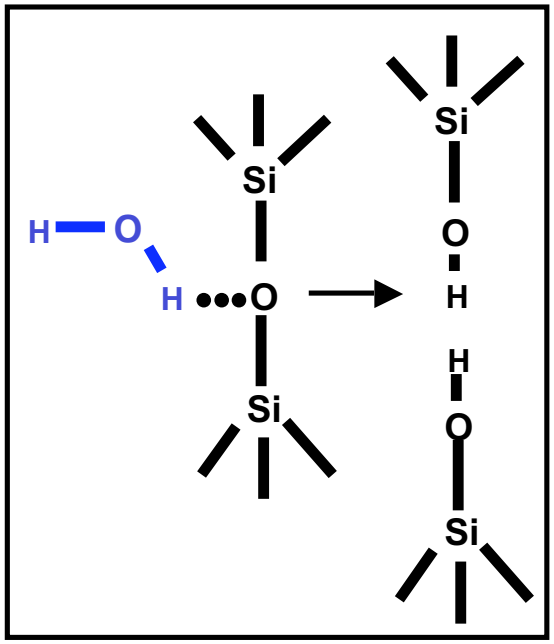
Large Population of Small Flaws under Stress with Subcritical Crack Growth

Flaw

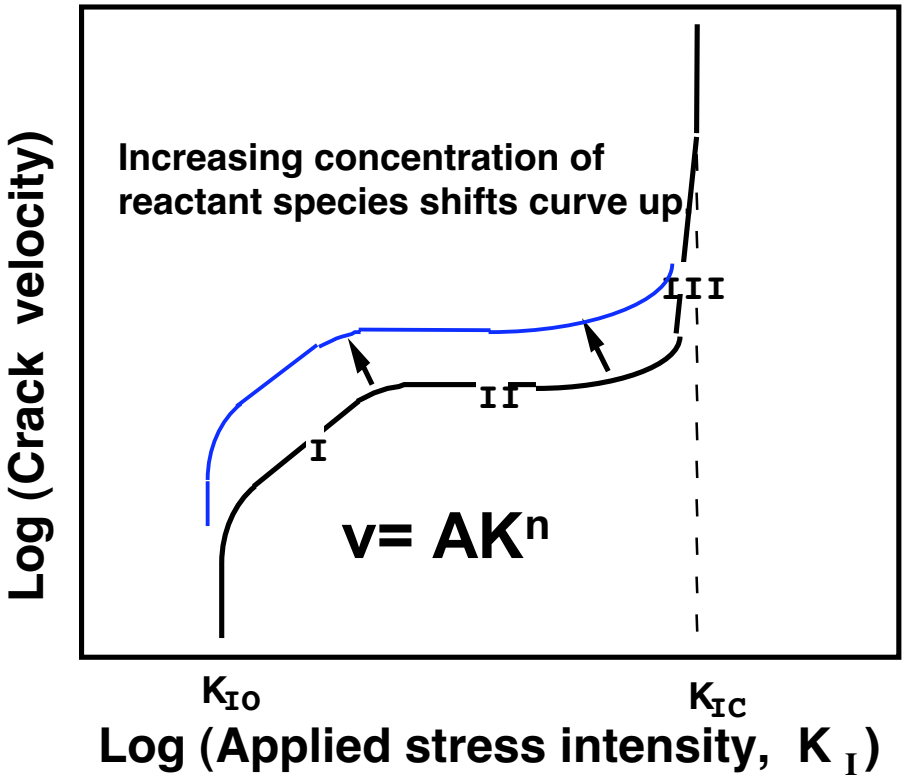


Applied & Residual Stresses

Mechanism



Effect



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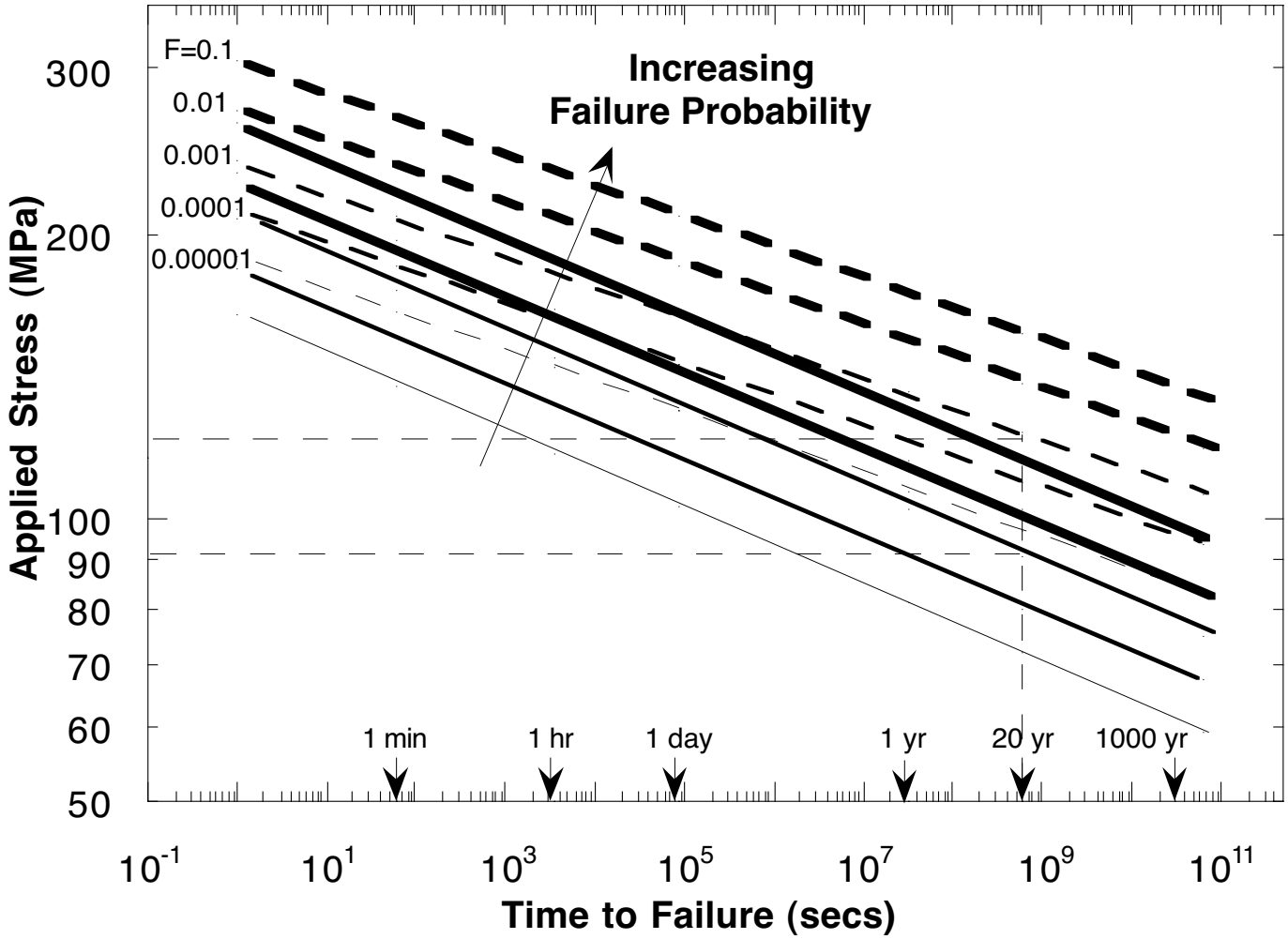
Stress-Failure Probability-Time to Failure Plots for 94% Alumina



Solid lines = 95% RH, Dashed lines = 0-3% RH

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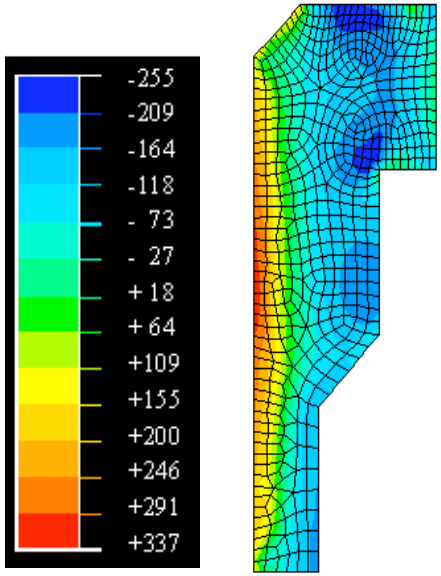
Lifetime and Stress Predictions for 94% Alumina for P_f=0.001

% Relative Humidity	σ_{max} for t_f=20 yr
0-3	116 MPa
95	92 MPa



max. prin. stress (MPa)

Comparison to Rule of Thumb:

- Compare maximum principal stress to strength (Al_2O_3 σ_f= 350 MPa, 51 ksi)
- Tailor design to keep stresses below 0.25 x σ_f

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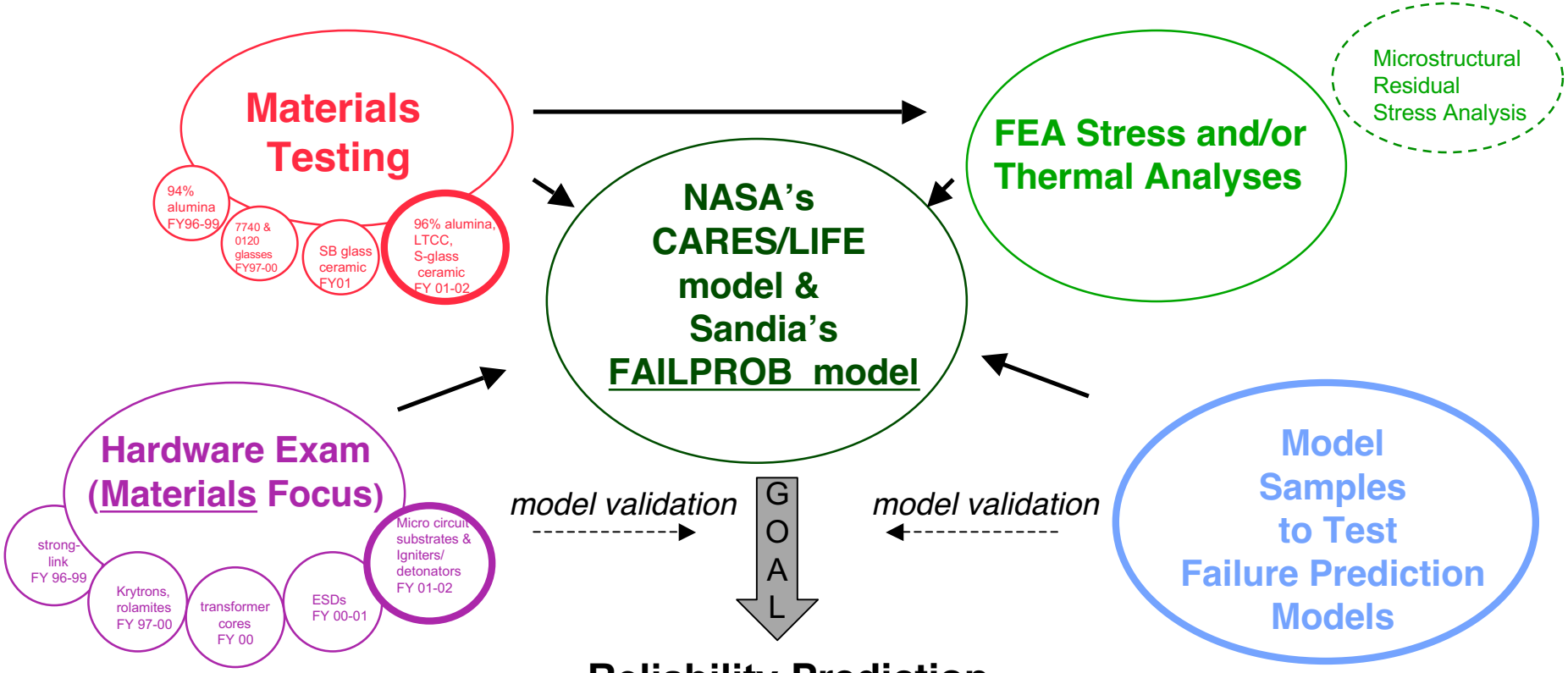
Sandia's Methodology to Predict Ceramic Component Reliability

Materials Testing, Hardware Exam, FEA Stress Models,
Failure (Brittle Fracture) Prediction Models, Model Samples



Reliability Prediction

Material in component good for x years!

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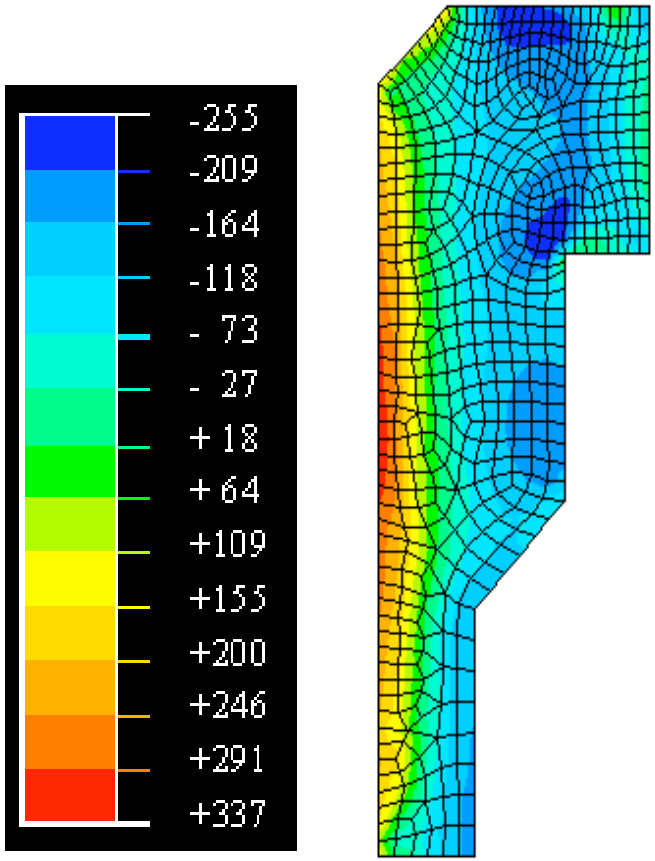
Ceramic Component Failure Probability for Various Times

Maximum Principal stress
In Ceramic (MPa)



Time (sec)	10^1	10^3	10^5 (27.7 hrs)
Failure Probability	0.01	0.07	0.99

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Limitations of Ceramic Reliability (Fracture Probability) Models

- When stress gradient is high a crack may grow out of this region and arrest
- FEA mesh dependencies and singularities at crack tips and bonded interfaces
- Weibull statistics are used to represent strength distribution (flaw size distribution cut-off?)

- Do models work for small volumes of ceramic that are highly stressed?

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Motivation - Validated Predictions of Ceramic Component Reliability

- FAILPROB* reliability predictions for small volumes of ceramic under high stress or high stress gradients
- Model sample geometries
- Probability of failure vs. load for model samples
- Measured vs. predicted strength distributions
- Fracture surface exams to identify failure location, origin type and microstructural differences

** FAILPROB - A Computer Program to Compute the Probability of Failure of a Brittle Component. G. W. Wellman, SAND2002-0409, Feb. 2002.*

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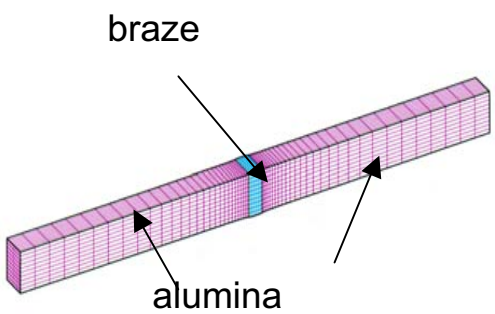
Three Model Sample Configurations for Failure Prediction Model Validation

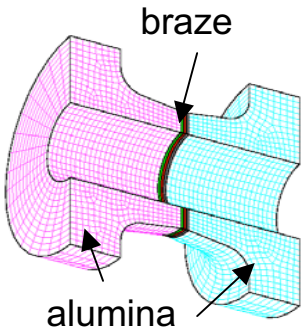
MODEL #1

- **94% Al_2O_3 bend bar joined with 50/50 Au-Cu braze (t=50 & 150 μm)**
- **Distributed stress in ceramic**



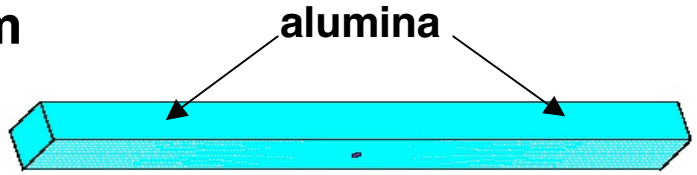
MODEL #3

- **Tensile button configuration with 94% Al_2O_3 and 50/50**
- **AuCu Braze produces strong stress singularity at joint**



MODEL #2

- **94% Al_2O_3 bend bar with 500 μm diameter Mo/Al_2O_3 cermet via**
- **High localized stress in Al_2O_3 near via**



cermet via

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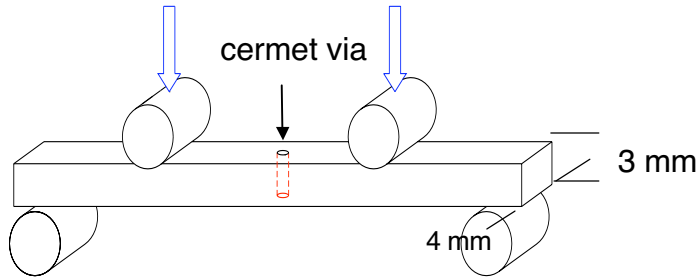
FAILPROB Inputs - FEA Stresses (Cool + 4-Pt. Bending) and Weibull Parameters

Material	Young's Modulus, GPa	Poisson's Ratio	CTE* (K^{-1}) (273–1473 K)
Sandi94 94% Al_2O_3	320	0.24	8.6 E-6
Cermet (27 vol% Mo, 73 vol% Al_2O_3)	309	0.256	7.9 E-6

Material	Quantity Tested	Average Strength, MPa (std. dev.)	Characteristic Strength, MPa	Weibull Modulus
Sandi94 94% Alumina	30	394 (23)	405	21



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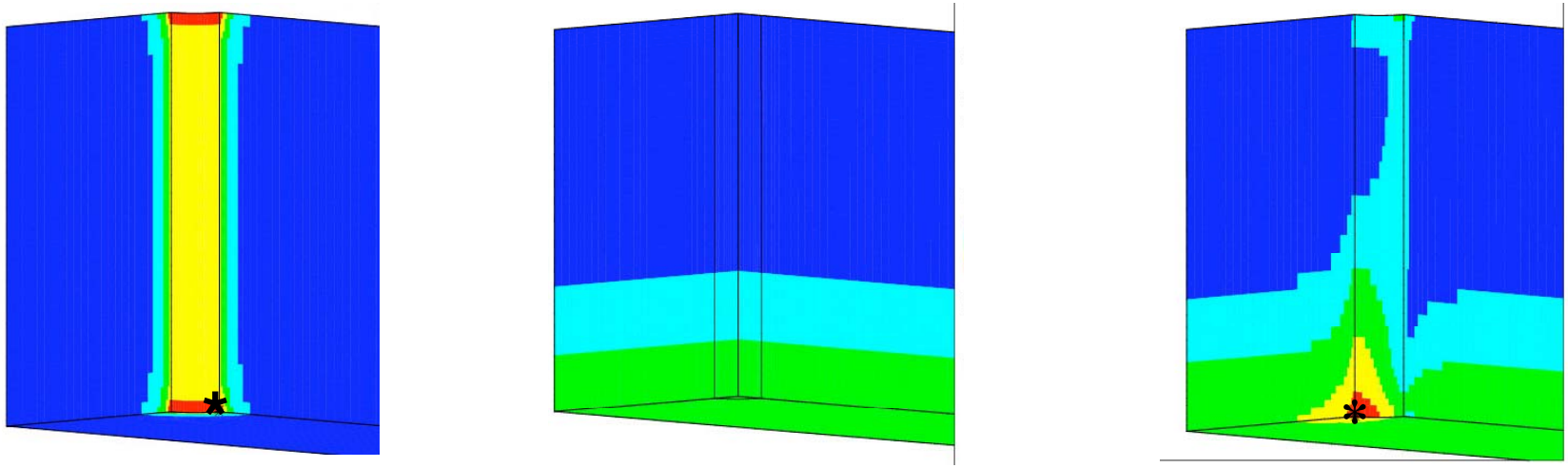
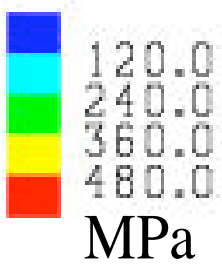
Model #2 - FEA Stresses in Al_2O_3 Near Cermet for Cooling + 410 N Bend Load



a) b) c)



a) Bar with cermet, no load, *=256 MPa
b) Loaded plain bar (no cermet), *=338 MPa
c) Loaded bar with cermet, *= 599 MPa

*** =Maximum Principal Stress**

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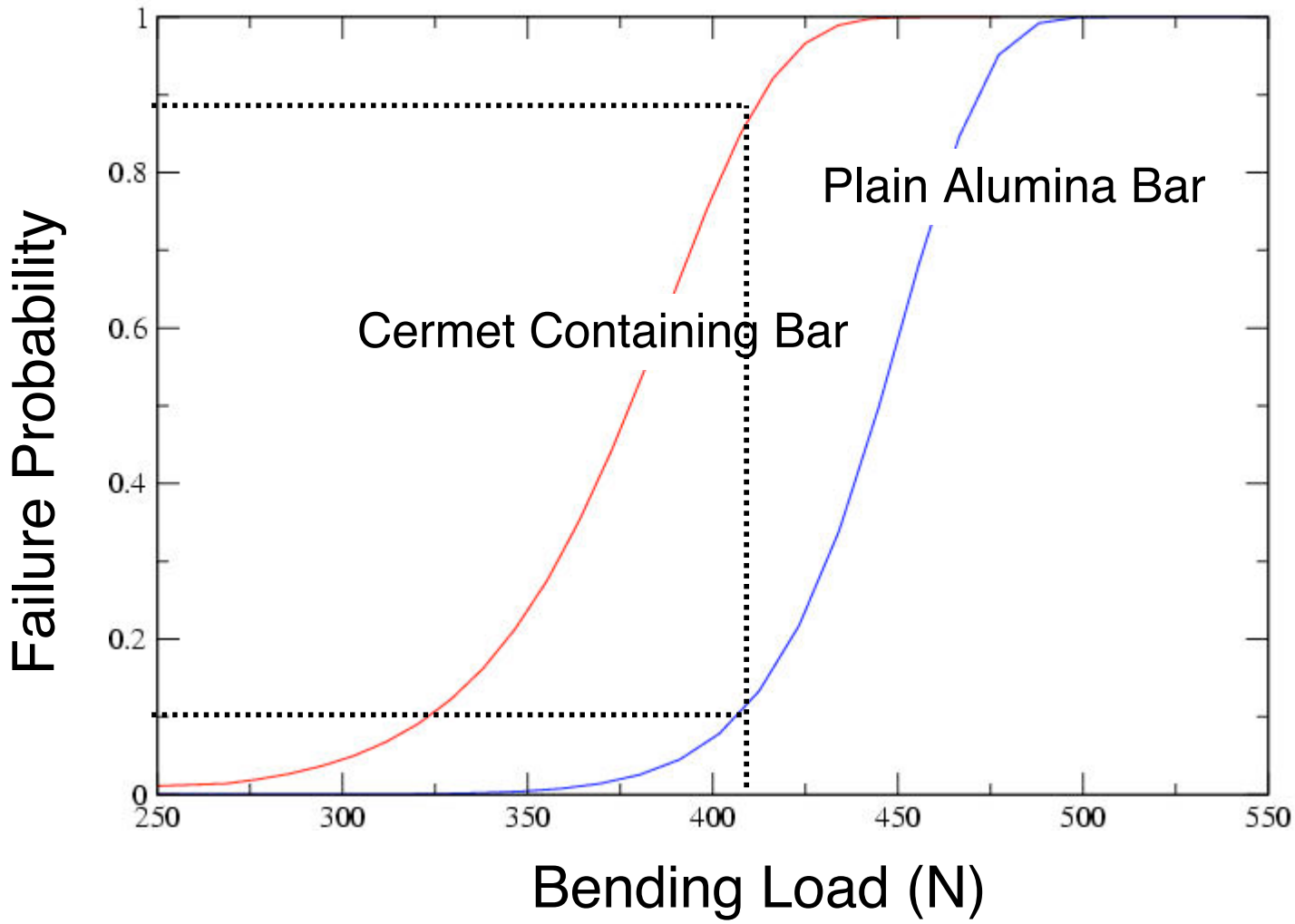
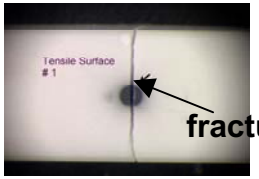
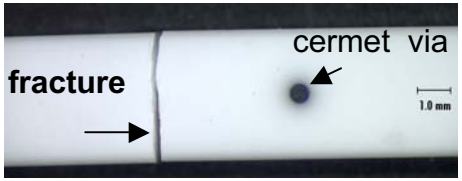
Cermet Via Should Dramatically Increase Failure Probability of Bar at a Given Load



Strength Parameters for Monolithic Bend Bars and Model #2 Samples

Material and Geometry	Weibull Modulus	Average Strength, MPa (std. dev.)	Quantity Tested	Comments
Sandi94 alumina	21	394 (23)	30	
Model #2 – Sandi94 alumina with cermet via	18	392 (25)	12	Failure in alumina near cermet
	23	402 (19)	11	Failure in bulk alumina
	21	397 (23)	23	Average for both failure modes





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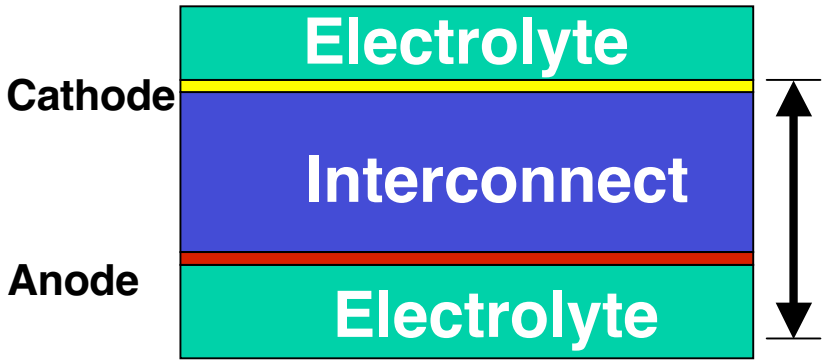
SOFC Joining Work at Sandia-
Residual Stresses due to CTE Mismatch



- Main components are oxide ceramics
- Metals are also present
- Different materials have different CTE's
- **Brittle materials with low strength cannot sustain high tensile stresses**

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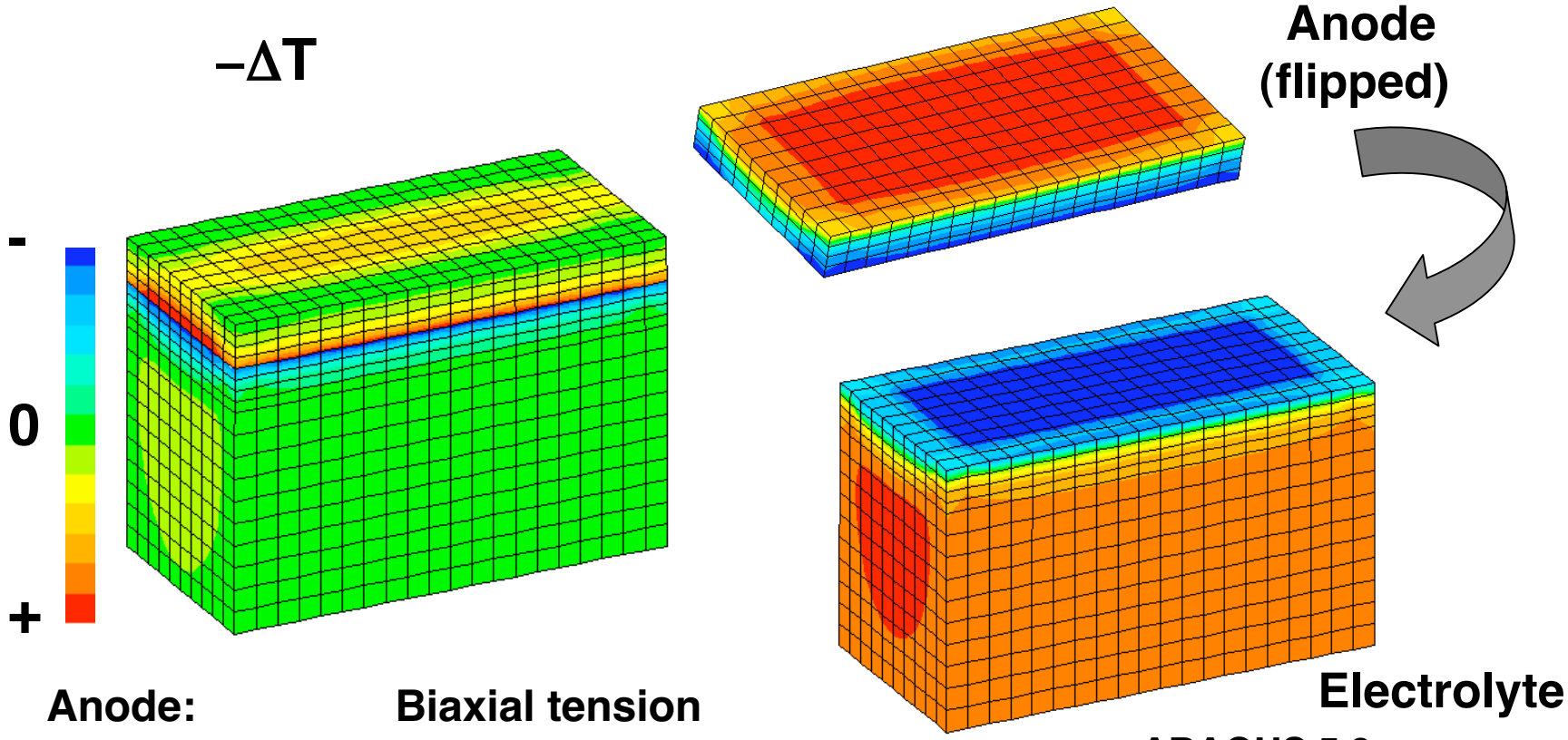
Anode and Electrolyte Stresses



Anode: Biaxial tension
Electrolyte: Biaxial compression

ABAQUS 5.8

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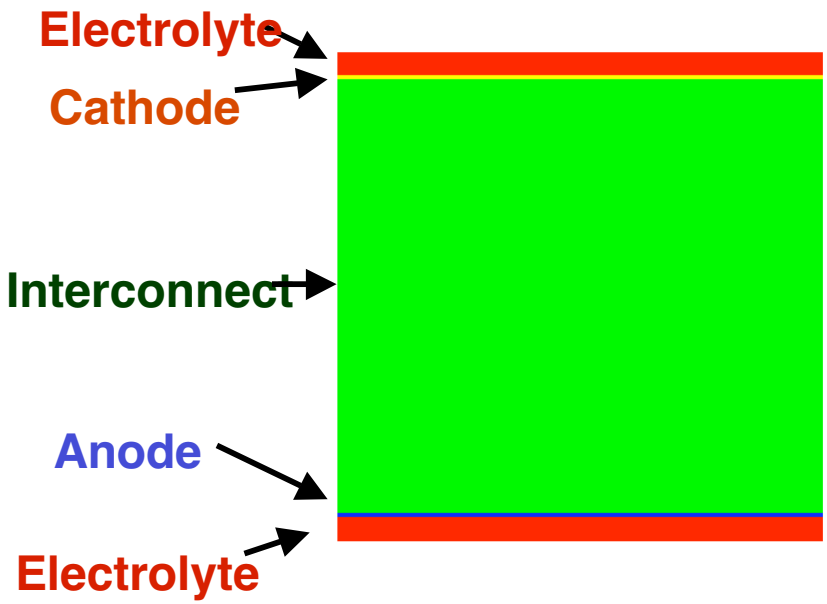
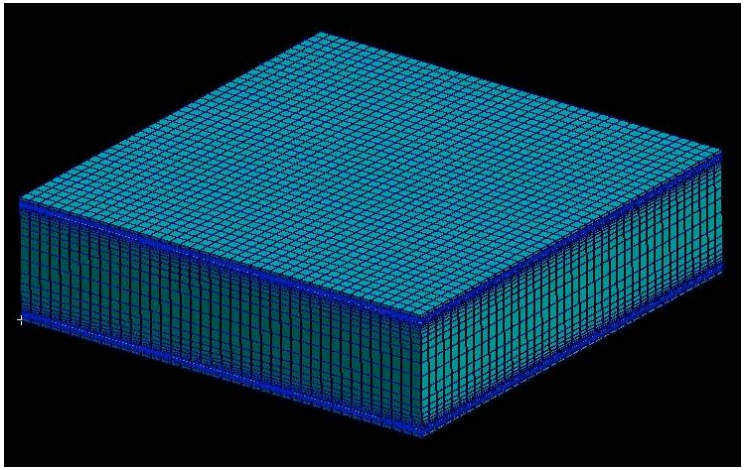
Stresses in SOFC Stack

- The interaction and constraints of all stack components are critical in assessing the stresses in the stack



2-D Stack



3-D Stack

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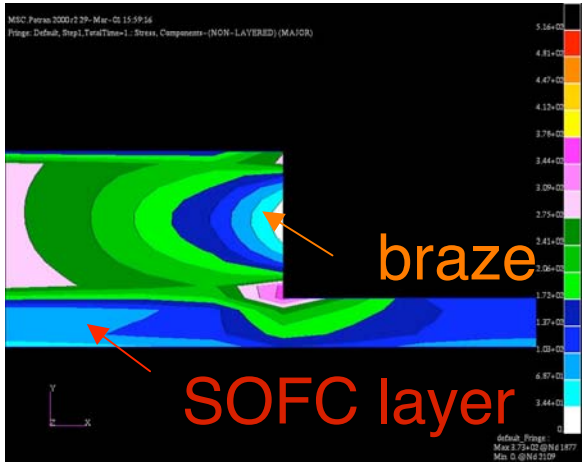
FEA of Braze and Joints

- Expertise in brazing, braze joint testing and braze joint analysis

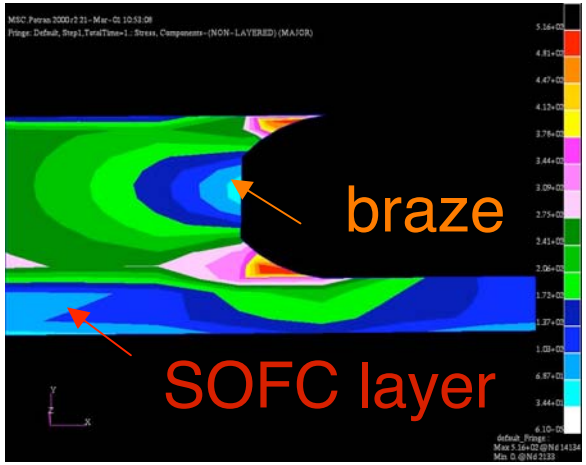


MPa, *ksi*

516, *75*

241, *35*

0



MPa, *ksi*

516, *75*

241, *35*

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Summary

- **Design and materials optimization based on <u>both</u> processing and reliability considerations**
- **<u>Outputs</u> of Sandia's sintering and joining models and simulations, along with mechanical properties <u>= inputs</u> for reliability and lifetime predictions**
- **Sandia has established methodology to predict short and long-term reliability - FEA stress models in conjunction with brittle failure prediction models (SNL and commercial)**

Stress and reliability analyses are the final part of Sandia's integrated approach to the optimization of SOFC design, processing, joining, and performance.

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