Durability and Reliability of Solid Oxide Fuel Cells

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SECA CTP Review
Tampa, FL January 2005

Outline

- Background
- Stresses in SOFCs
- Reliability Predictions
- Validation of methods to predict reliability
- Summary

- Other
- Creep-resistance of Ni-YSZ

Acknowledgments

ORNL

Miladin Radovic, Claire Luttrell, Rosa M. Trejo, Chris Cofer, Tom Watkins, Claudia Walls

GaTech

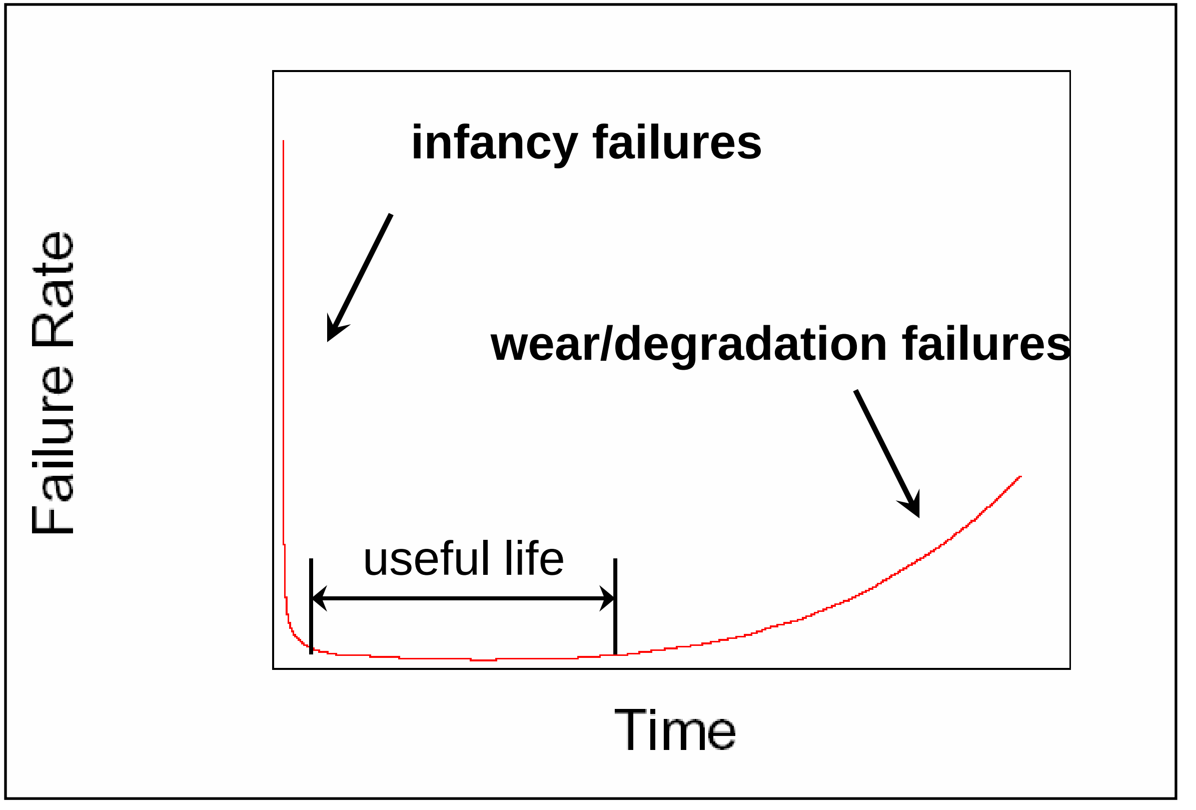
Jianmin Qu, Wenning Liu

PNNL

John Deibler and Kurt Recknagle

Failure of Systems

The failure rate of complex systems can be described by the bathtub curve



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Failure of Systems

- Mechanical failure is determined by the spectrum of mechanical loads and the distribution of strengths for materials that exhibit stochastic strength.
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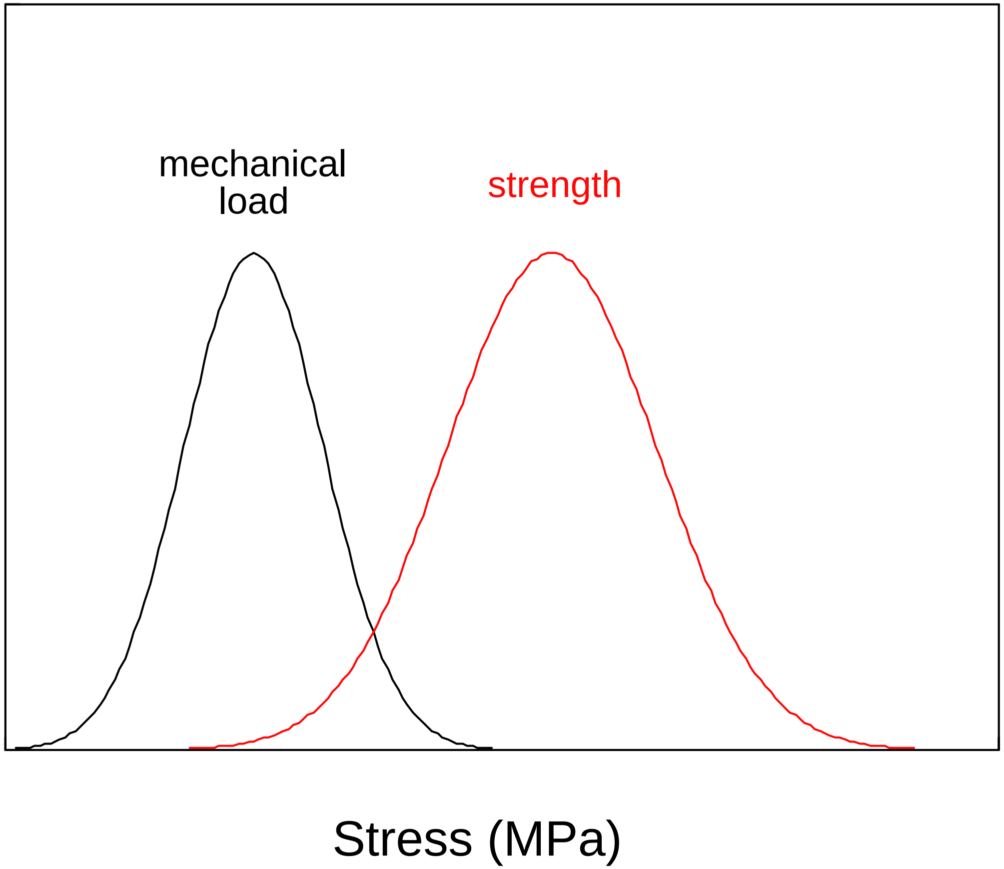

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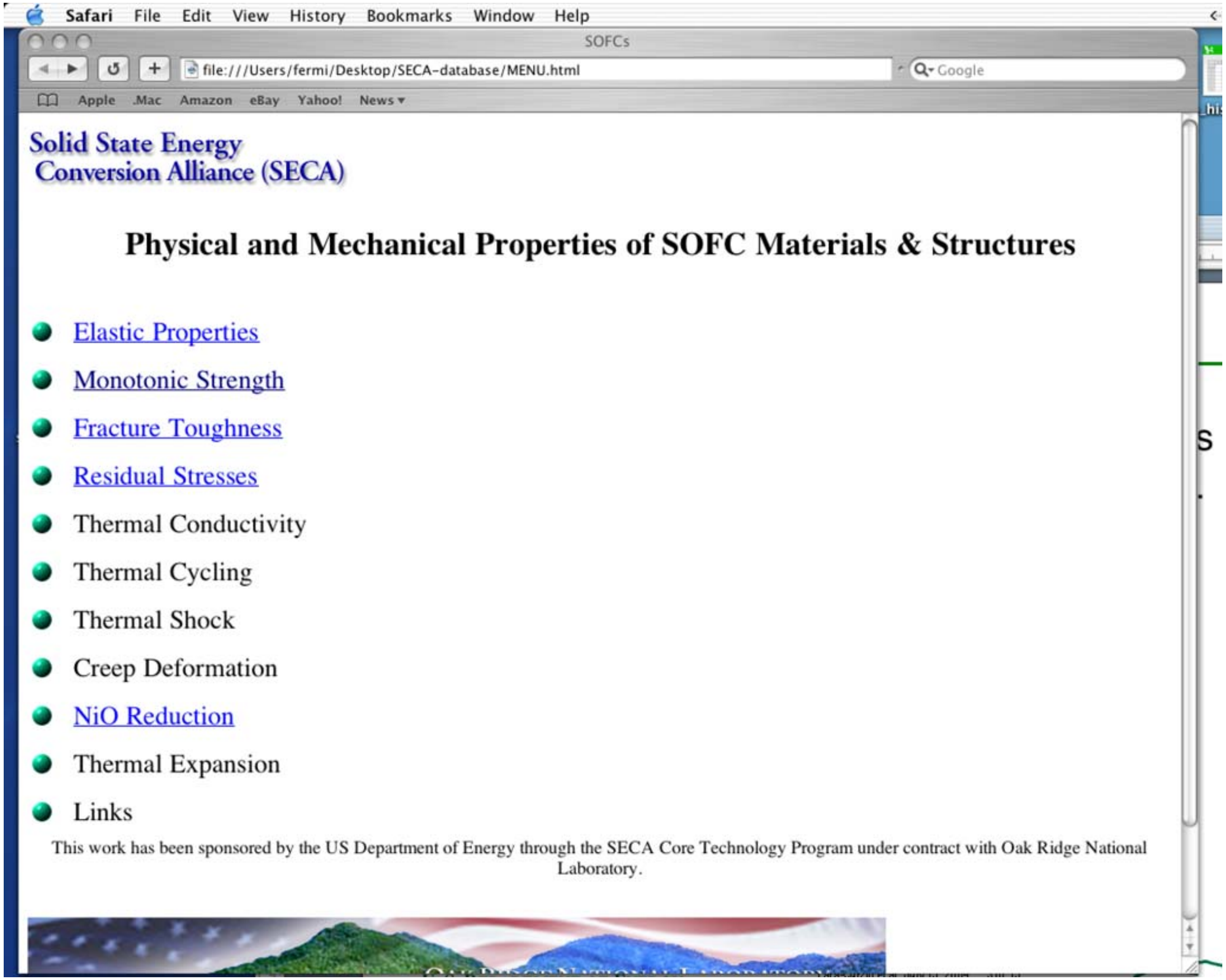
Evaluation of SOFC Materials

Data Base



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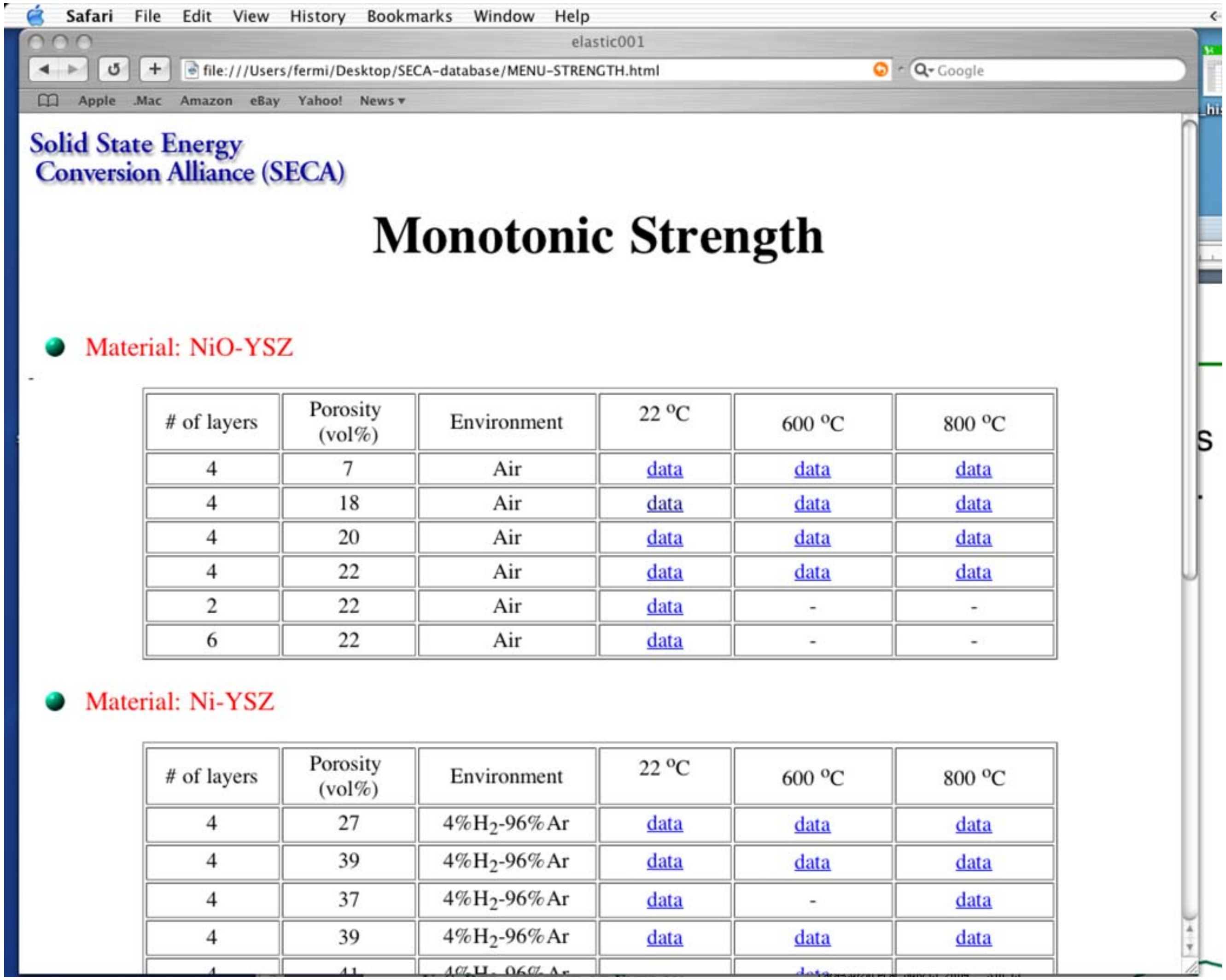
Data Base



Solid State Energy Conversion Alliance (SECA)

Monotonic Strength

- Material: NiO-YSZ

# of layers	Porosity (vol%)	Environment	22 °C	600 °C	800 °C
4	7	Air	data	data	data
4	18	Air	data	data	data
4	20	Air	data	data	data
4	22	Air	data	data	data
2	22	Air	data	-	-
6	22	Air	data	-	-

- Material: Ni-YSZ

# of layers	Porosity (vol%)	Environment	22 °C	600 °C	800 °C
4	27	4%H_2-96%Ar	data	data	data
4	39	4%H_2-96%Ar	data	data	data
4	37	4%H_2-96%Ar	data	-	data
4	39	4%H_2-96%Ar	data	data	data

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Data Base

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file:///Users/fermi/Desktop/SECA-database/NIOYSZS2.html

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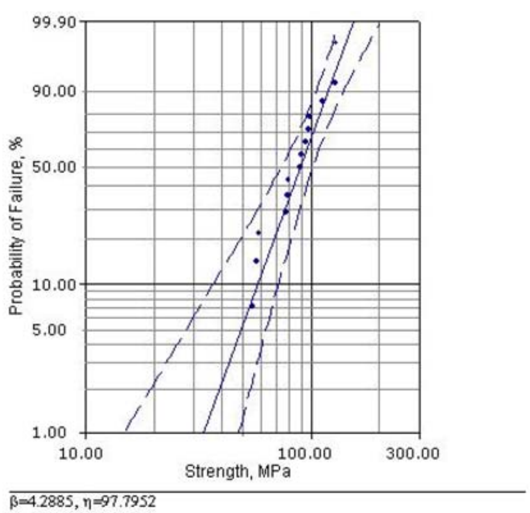
- Biaxial Strength
- Material: NiO-YSZ



DATA FILE

Samples were prepared from a powder mixture of 75% mol NiO (J.T.Baker, Phillipsburg, NJ) and 25% ZrO_2 stabilized with 8 mol% Y_2O_3 (TOSOH Corp., Grove City, OH).

Different amounts of organic pore former (rice starch, ICN Biomedicals, Inc Irvine, CA) were added to obtain samples with different levels of porosity. Green samples were prepared by tape casting 250-mm thick single layers. Four green tapes were subsequently laminated. Discs with nominal diameter of 25.4 mm were hot-knifed from the assembled green tapes and sintered at 1400 °C in air for 2 hours.

Biaxial strengths were determined using Ring-on-Ring test.

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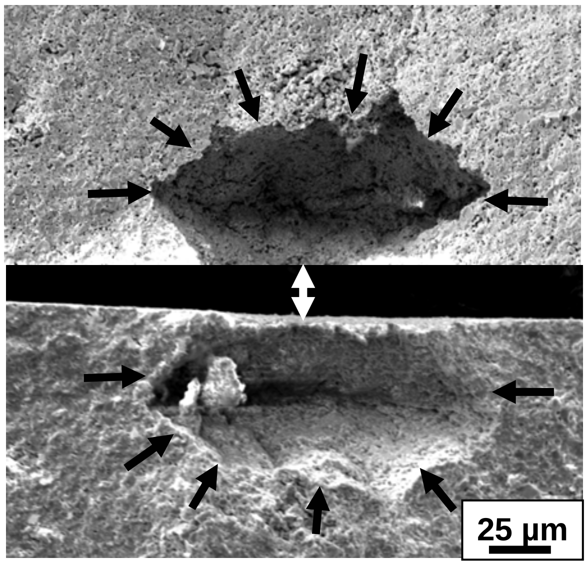
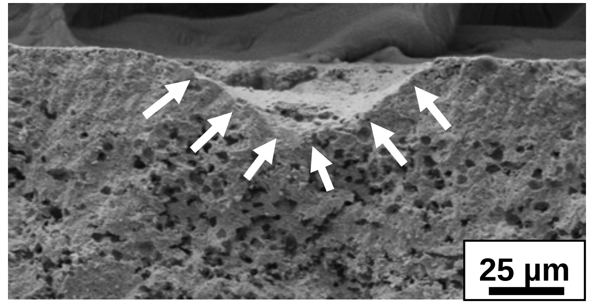
Biaxial Strength - Fractography

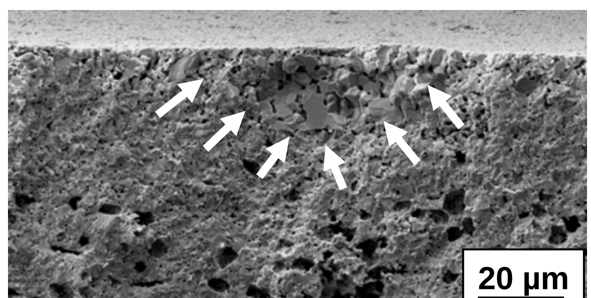


Large cavity close to tensile surface, NiO-YSZ with ≈6.6 vol% porosity

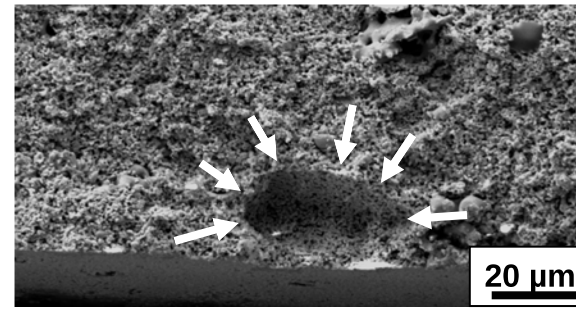


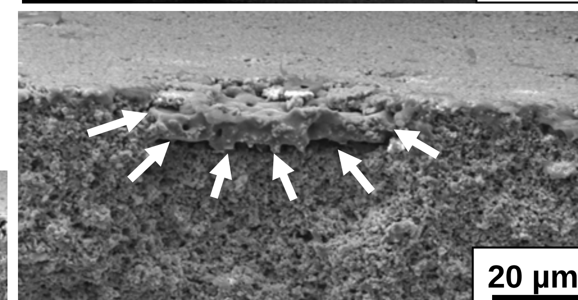
Surface dimple, NiO-YSZ with 21.9 vol% porosity

Cluster of YSZ grains on the tensile surface, NiO-YSZ with 21.9 vol% porosity



Cavity close to tensile surface, Ni-YSZ with ≈27.3 vol% porosity





Cluster of Ni grains on tensile surface, Ni-YSZ with ≈27.3 vol% porosity.

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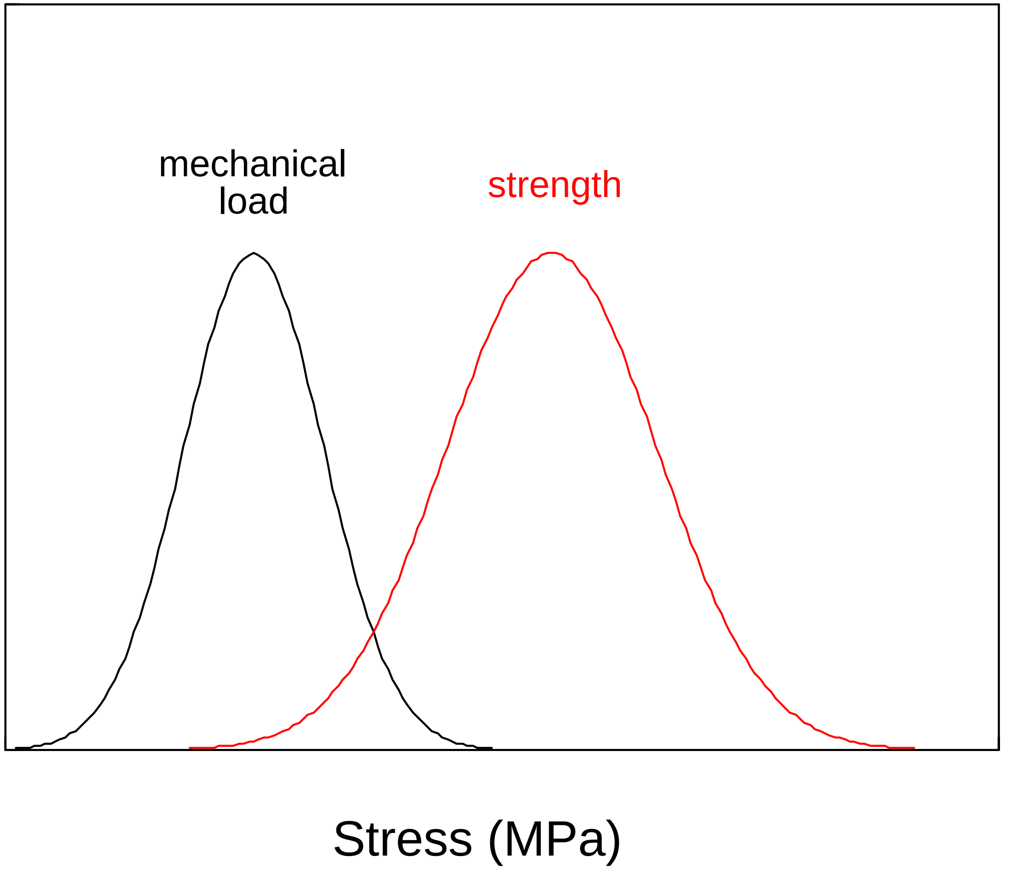

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Stresses in SOFCs

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Stresses in SOFCs: residual and "reduction" stresses

anode-supported cell

sintering

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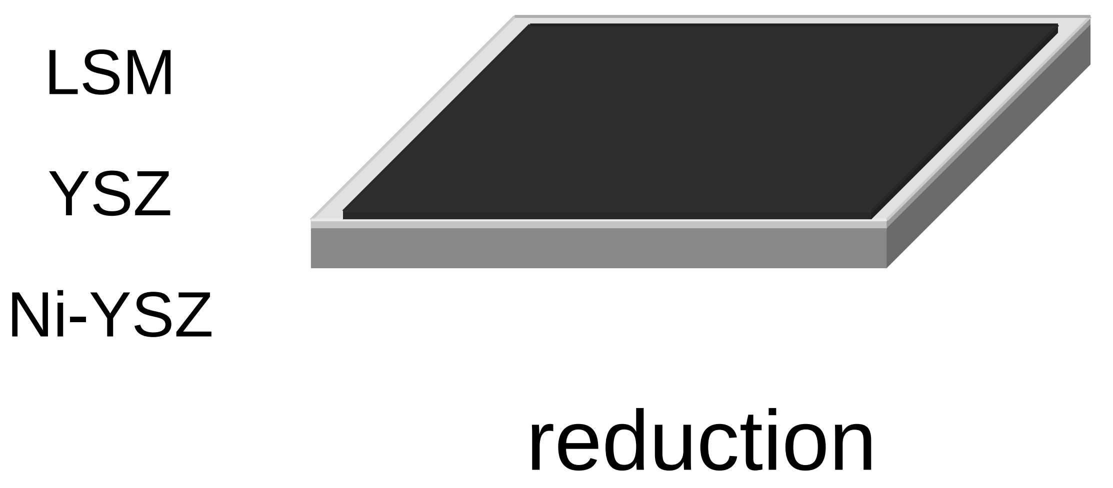
Stresses in SOFCs: residual and “reduction” stresses

anode-supported cell



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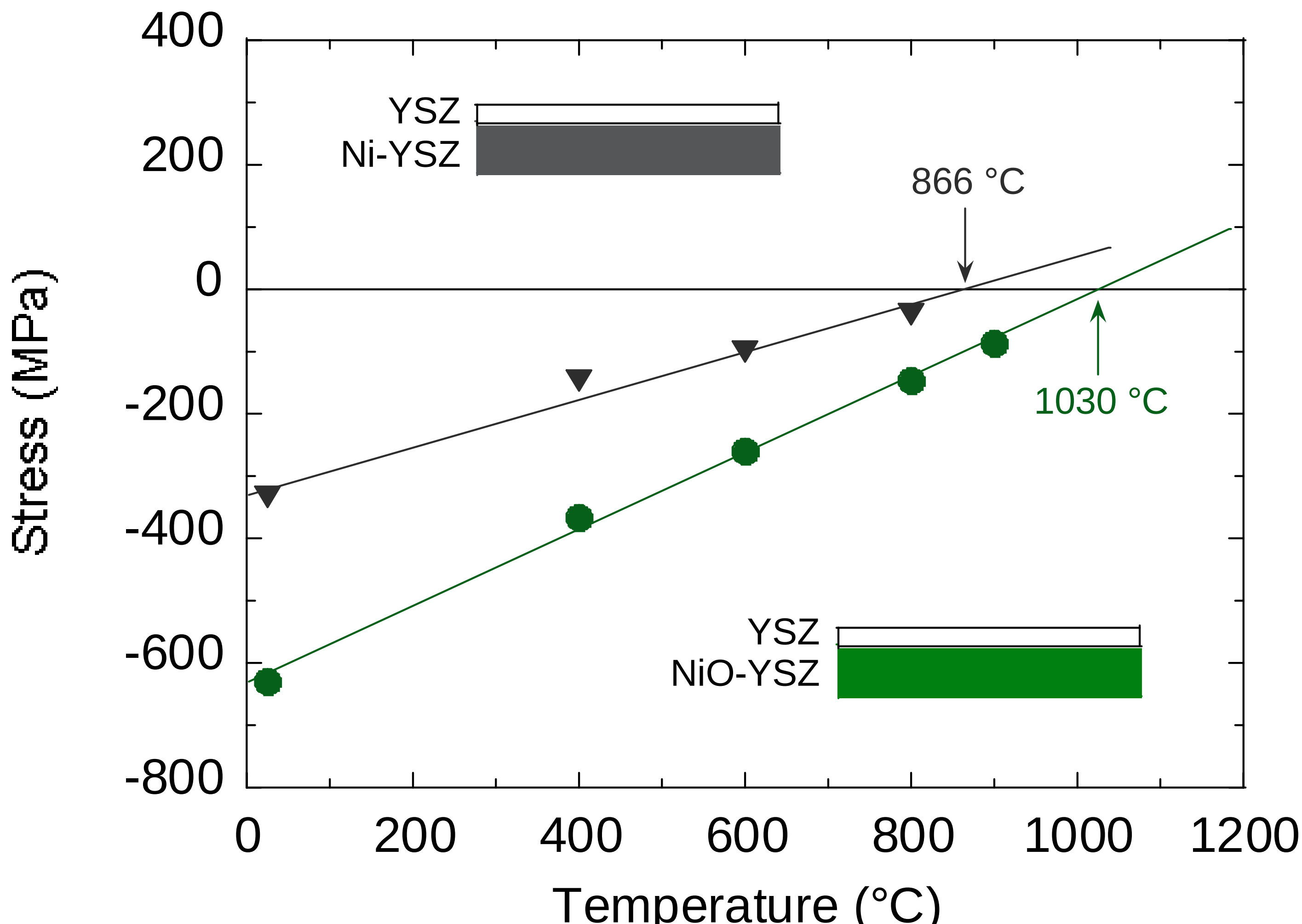
Residual and "Reduction" Stresses (X-ray diffraction)

800 °C Reduction in 4%H_2-96%Ar



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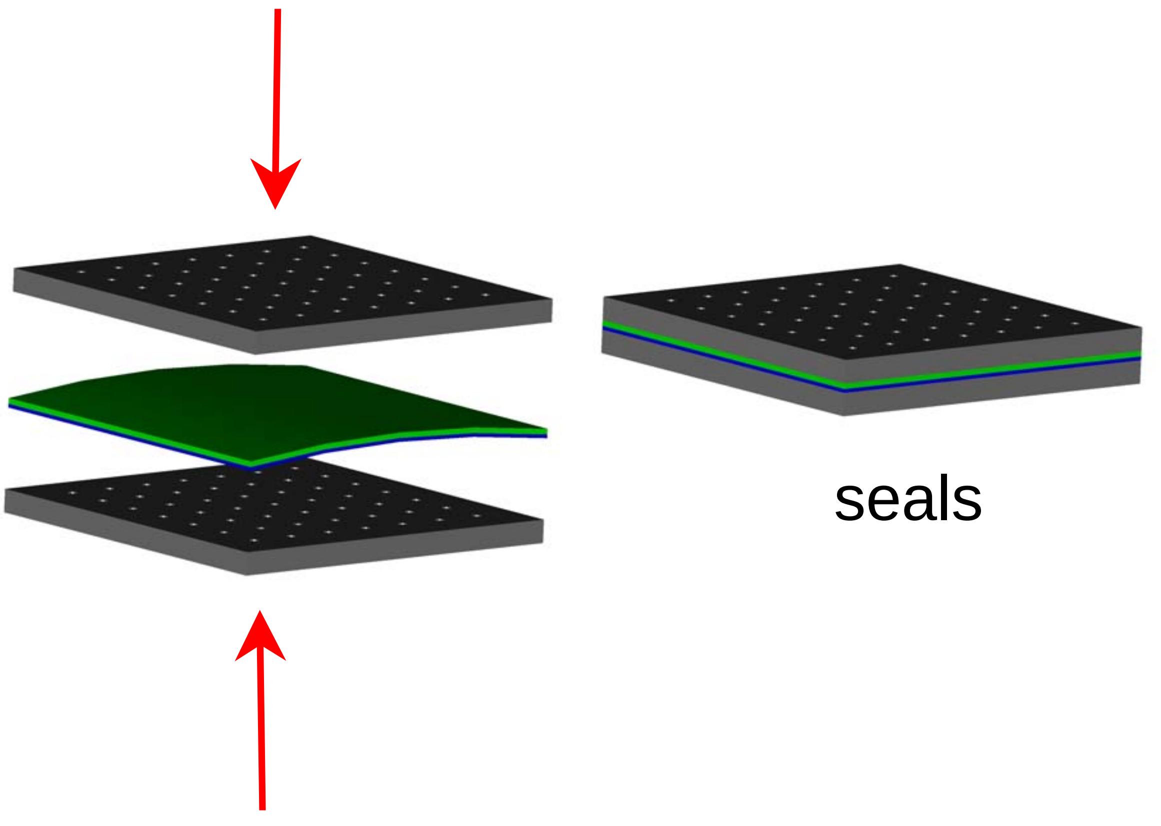
Stresses in SOFCs: Manufacturing stresses



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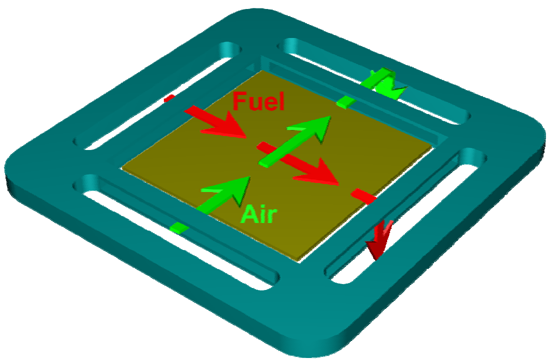
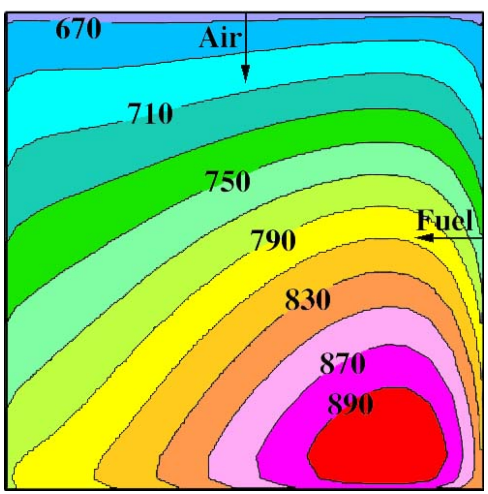
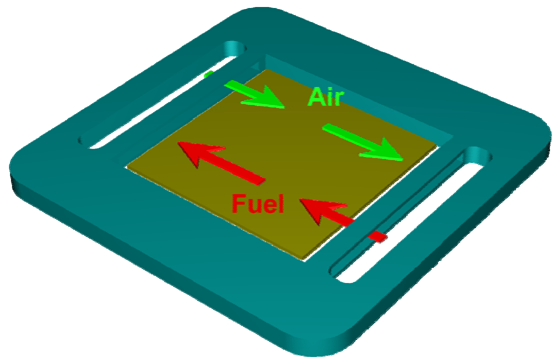
Stresses in SOFCs: Operation-induced Stresses

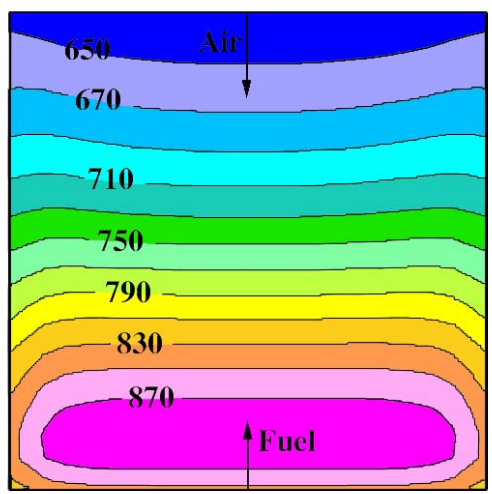


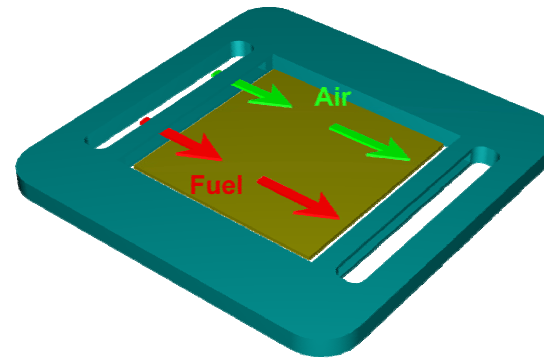
Cross-Flow



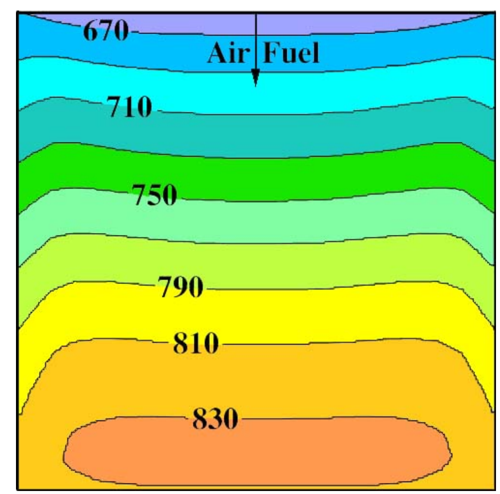


Counter-Flow





Co-Flow



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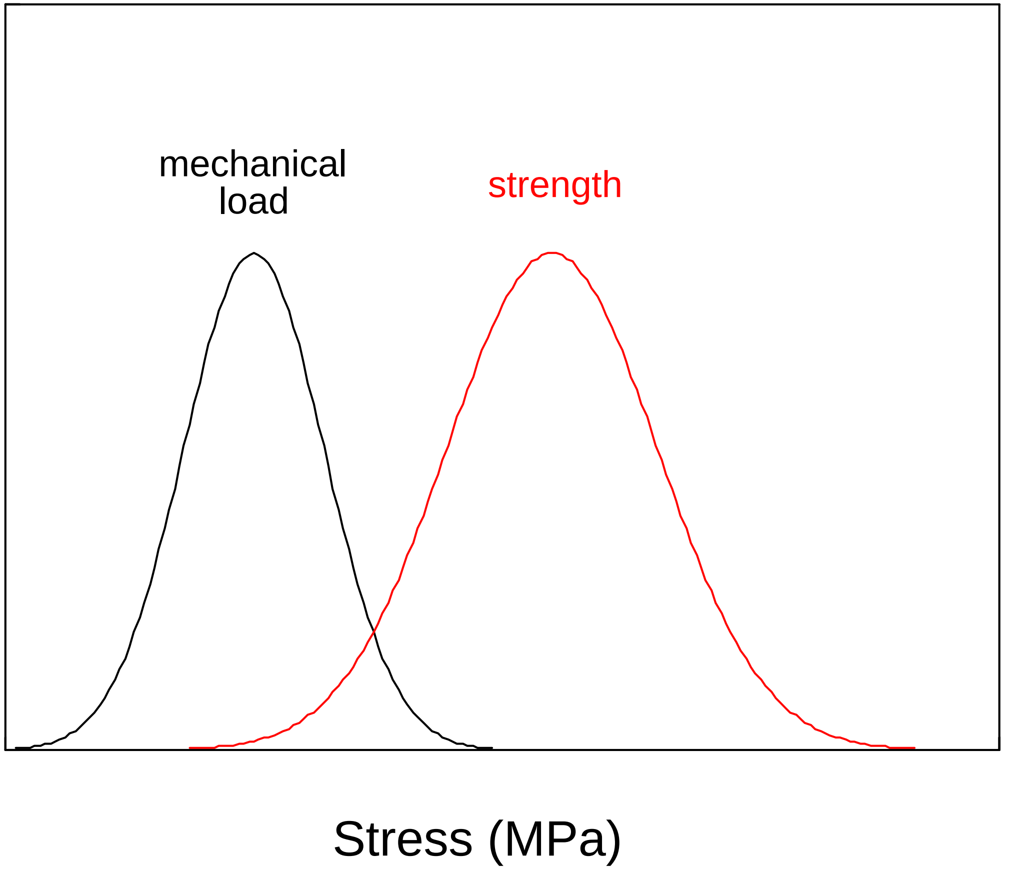

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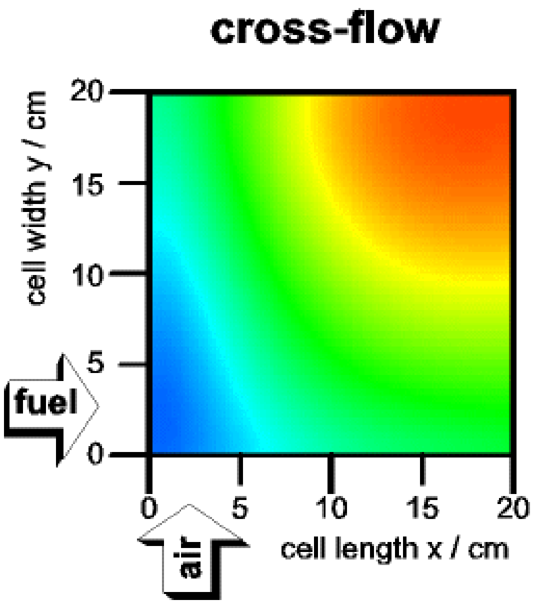
Reliability Predictions

FEM

Stress Distribution

+



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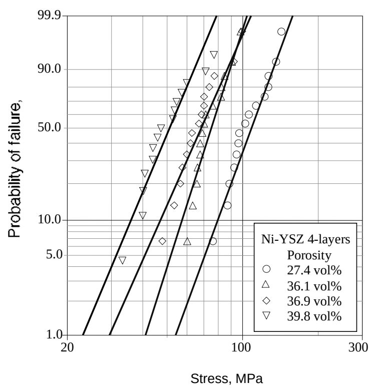

Strength Distributions

Residual Stresses

+

Manufacturing Stresses

CARES

Reliability

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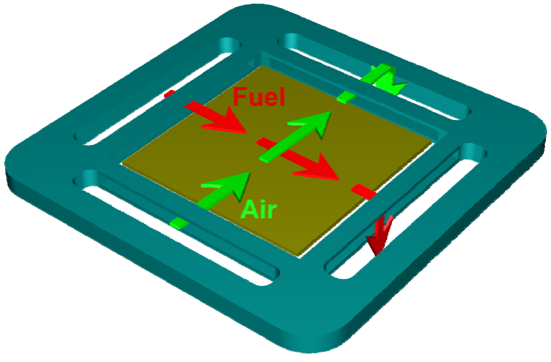
Stochastic nature of strength (CARES)

- In the 1980's DOE co-sponsored the development of CARES (Ceramics Analysis and Reliability Evaluation of Structures).
- CARES is a computer program, which coupled with a finite-element stress analysis, calculates the probability of failure (surface and volume) of ceramic components.
- The overall component reliability is the product of all the element survival probabilities.

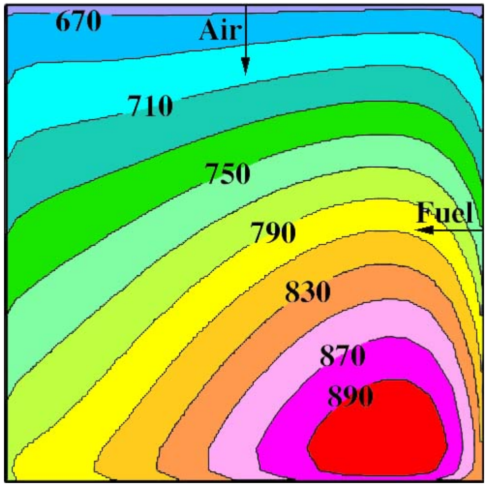
Stochastic nature of strength (CARES)

- The probabilistic nature of material strength is described using Weibull's cumulative distribution function.
- The effect of multiaxial stress on reliability is predicted by using the Principle of Independent Action (PIA)

Realiability of SOFCs



Cross-Flow



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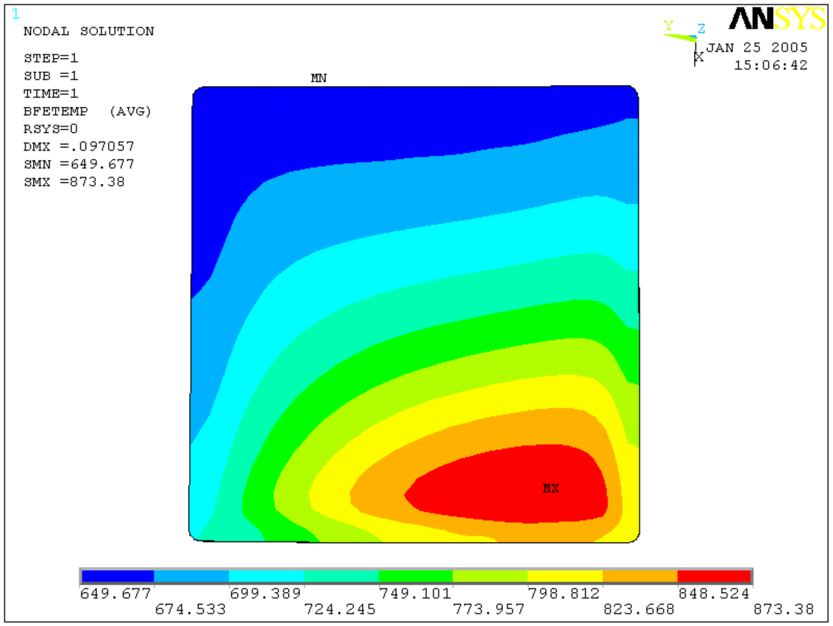
Cross-Flow configuration

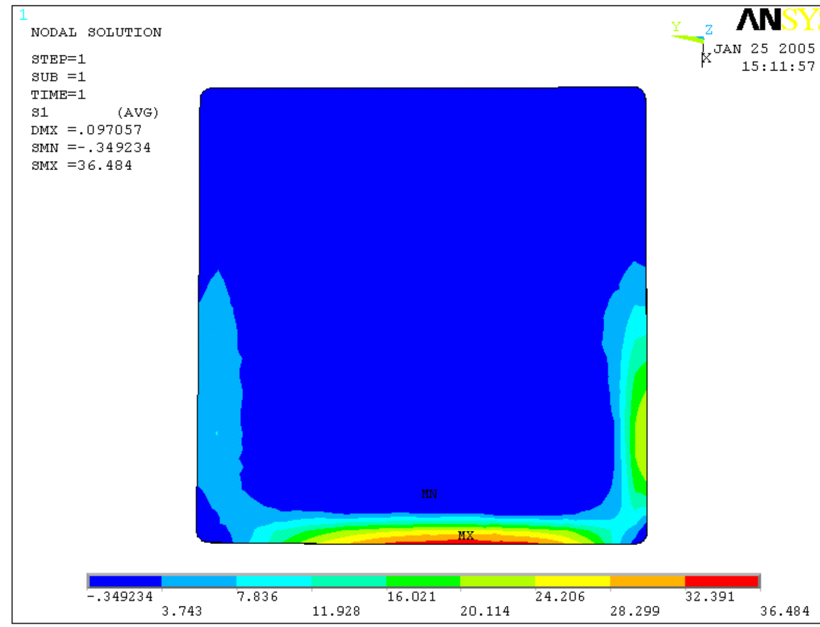
Temperature Distribution



-650°C 873°C

Stress Distribution

Maximum Principal Stress



-0.3 MPa 36 MPa

Courtesy: John Deibler & Kurt Recknagl, PNNL

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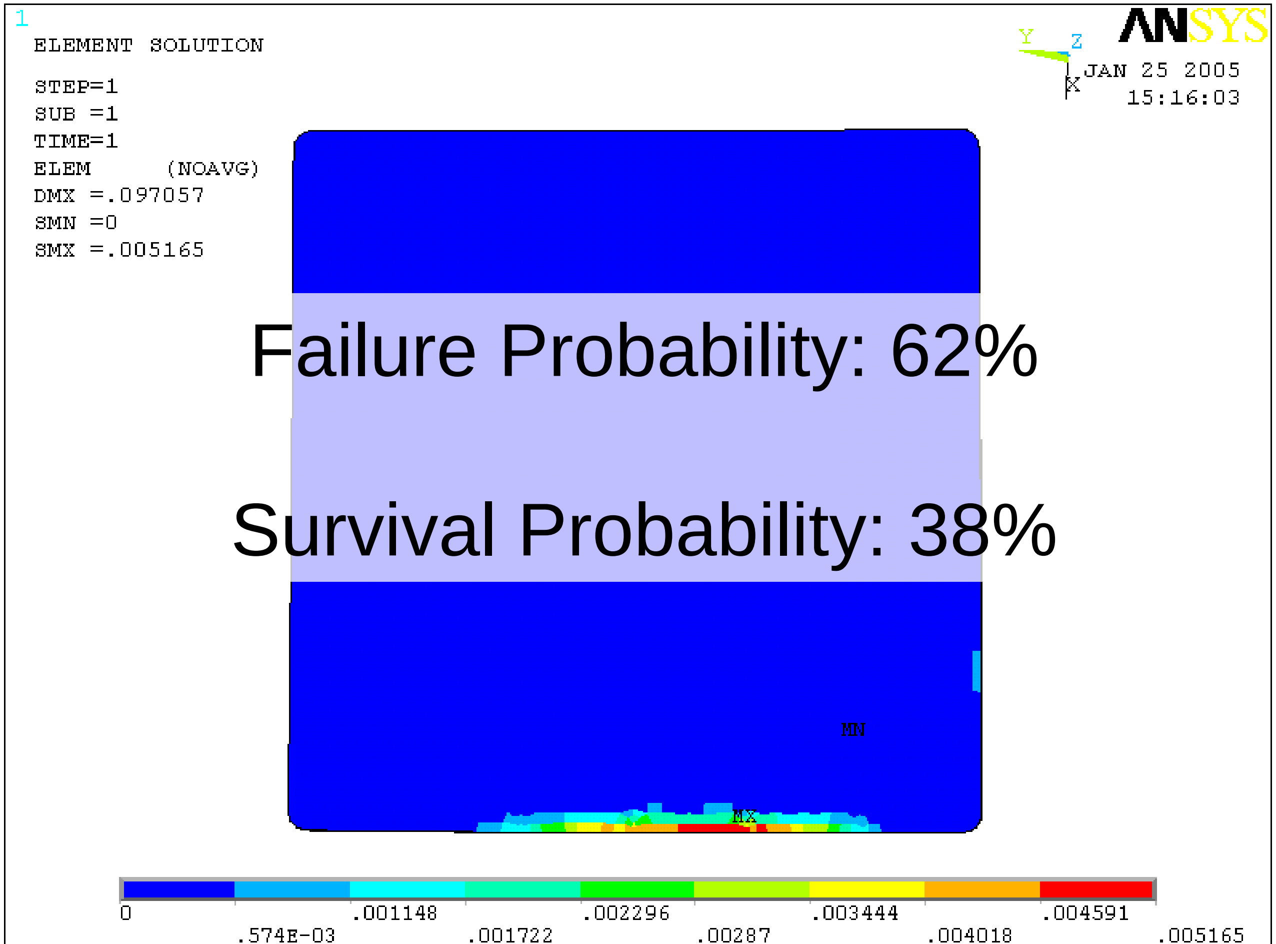
Cross-Flow configuration

Risk of Rupture Intensities



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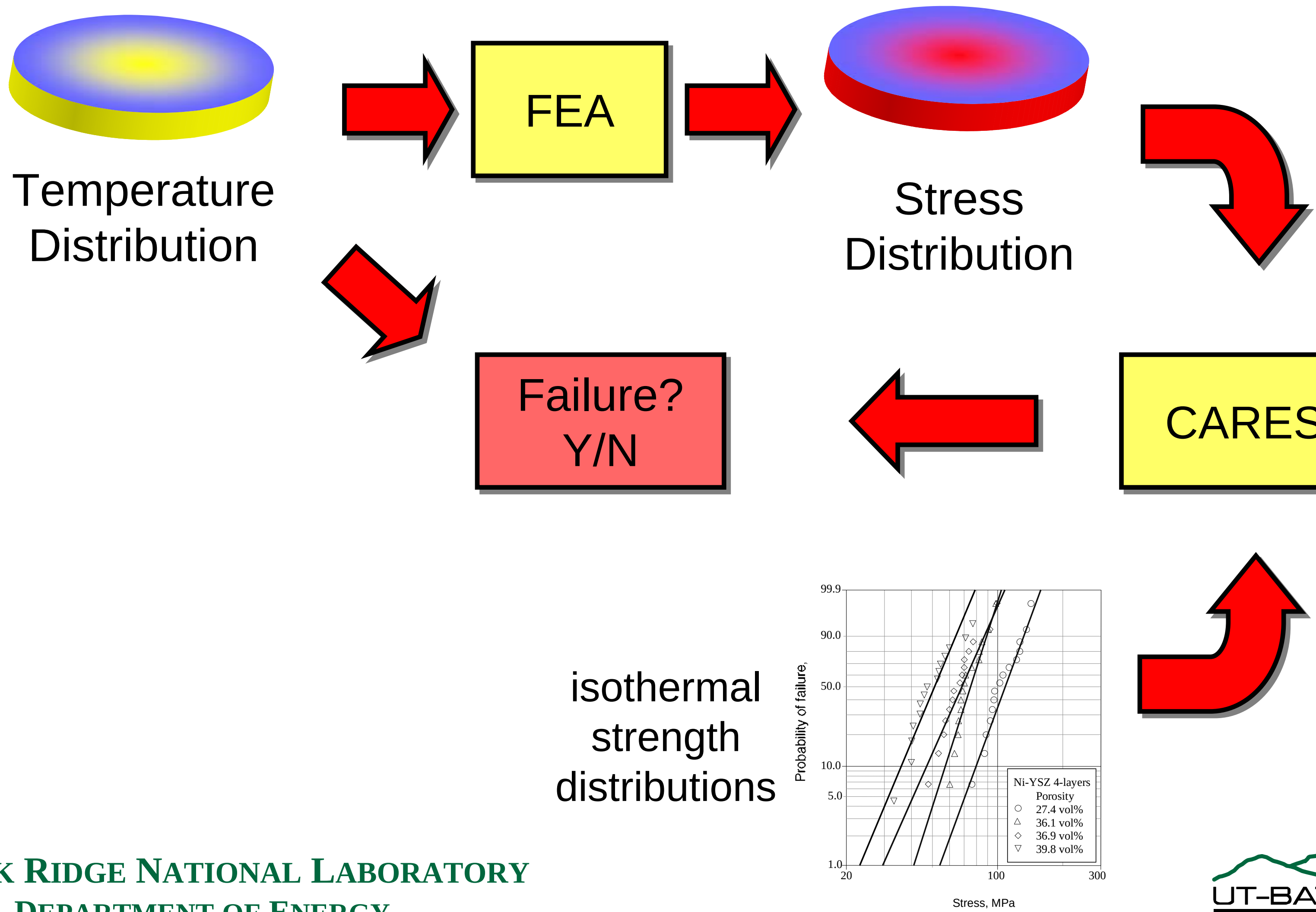
How do we verify that this methodology really works?

Strength evaluation of test specimens under a temperature gradient



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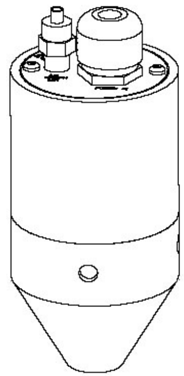
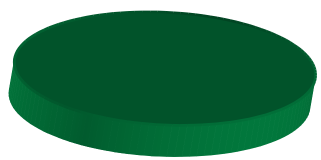
Strength evaluation under a temperature gradient

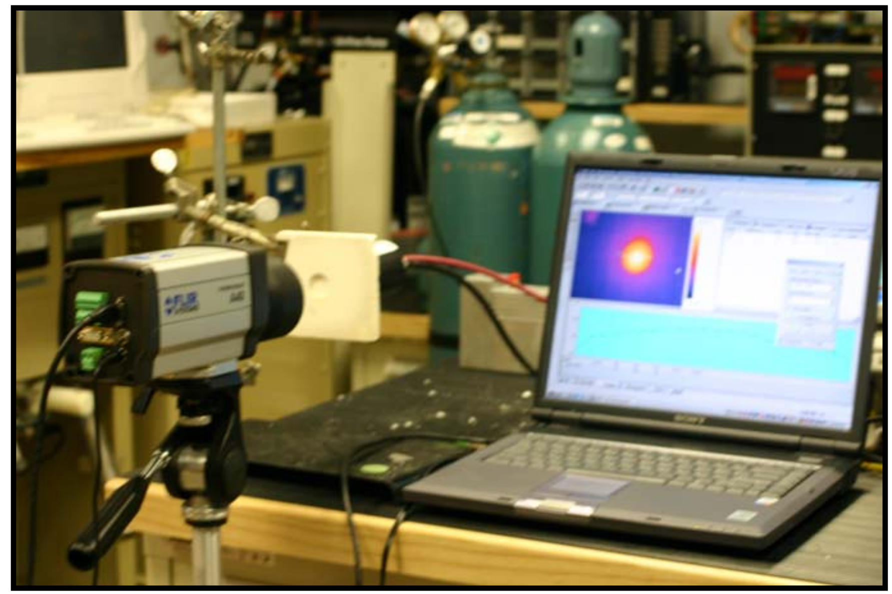
SpotIR® Heater



test specimen



Infrared Digital Camera



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Strength of Ni-YSZ under temperature gradient

QuickTime™ and a
Microsoft Video 1 decompressor
are needed to see this picture.

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Strength of Ni-YSZ under temperature gradient

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Microsoft Video 1 decompressor
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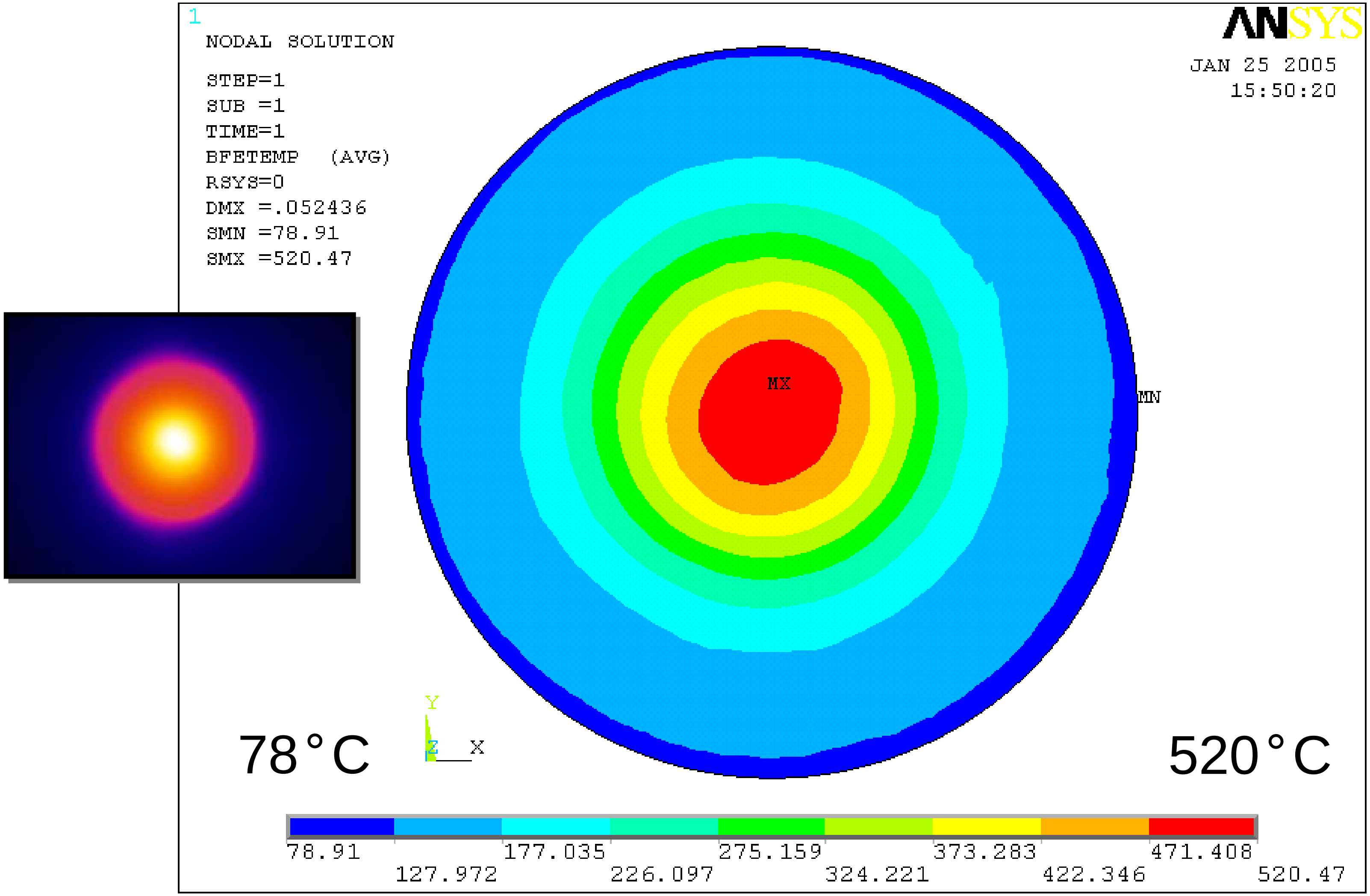
Sample A3-30-L4-06-23 – Temperature Distribution



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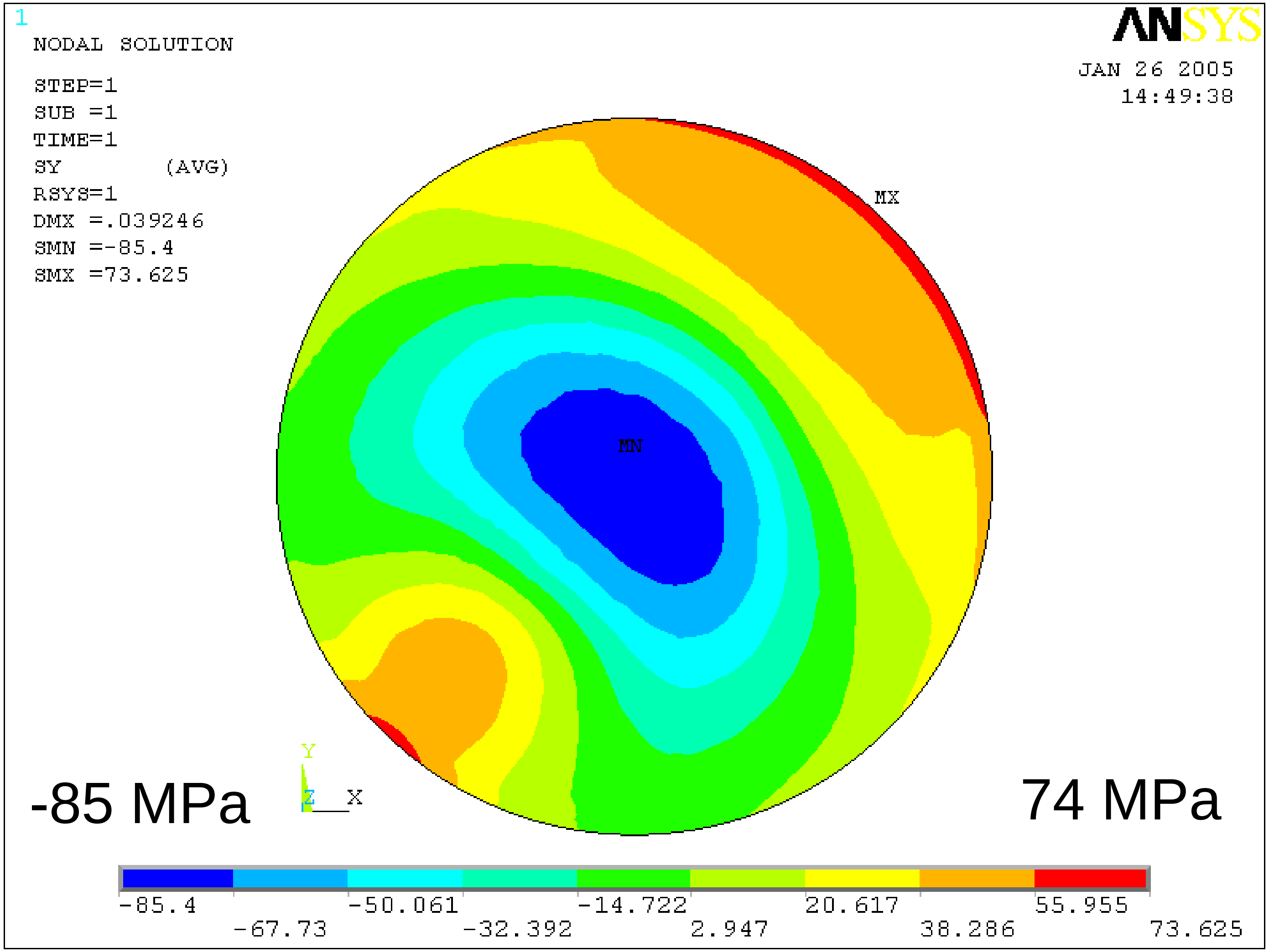
Sample A3-30-L4-06-23 – Tangential Stress



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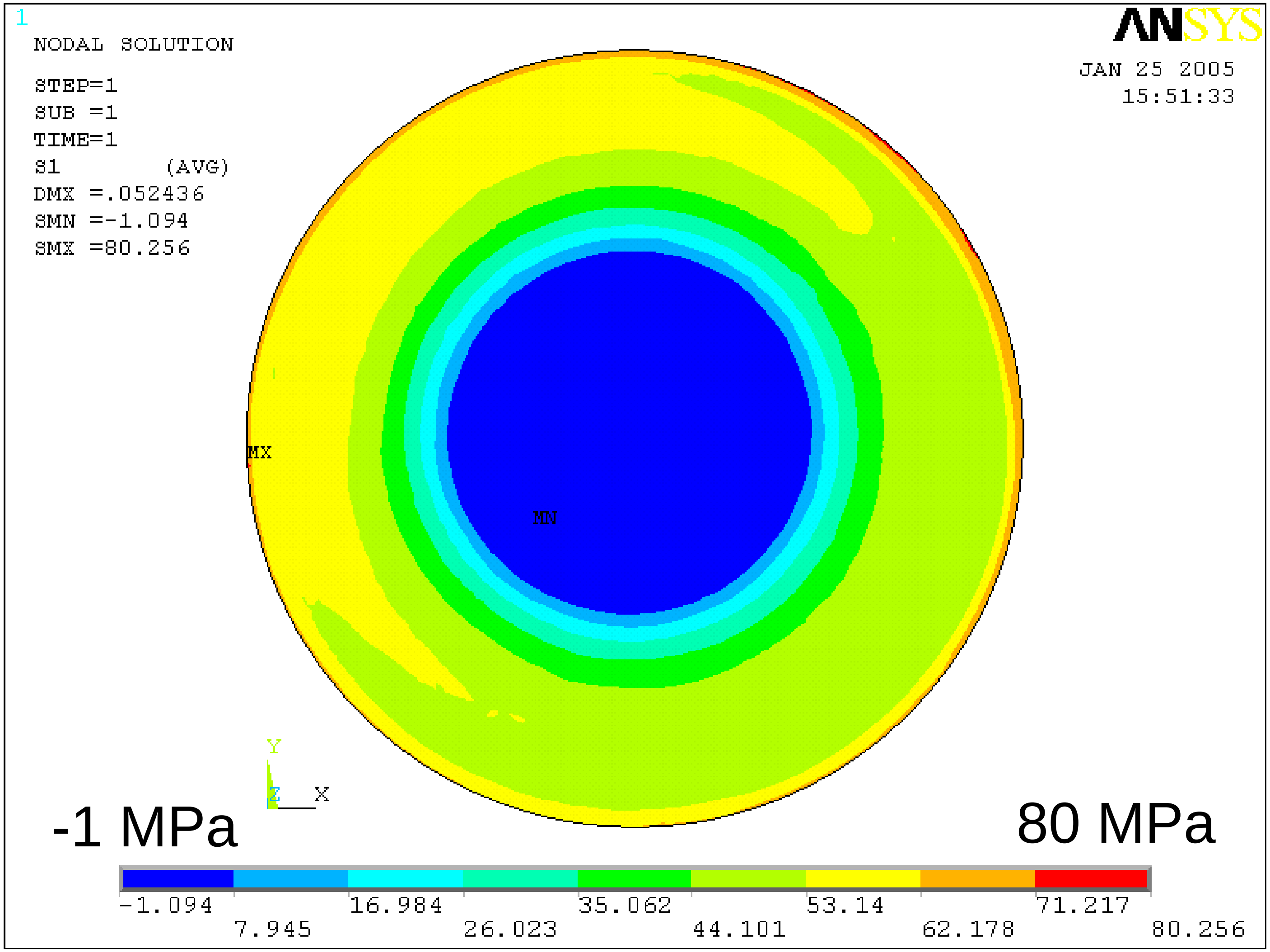
Sample A3-30-L4-06-23 – Max Principal Stress



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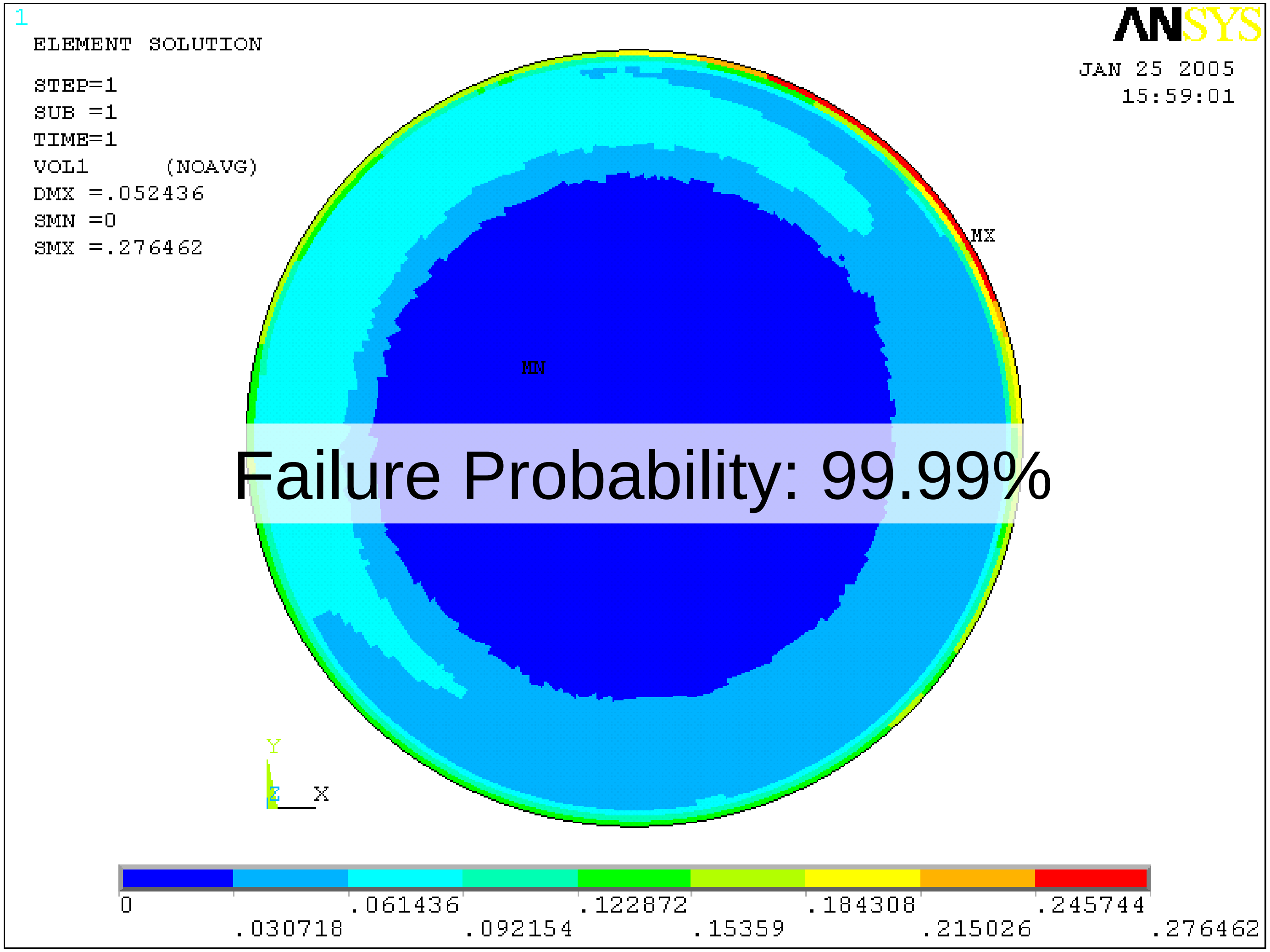
Sample A3-30-L4-06-23 – Risk of Rupture Intensity



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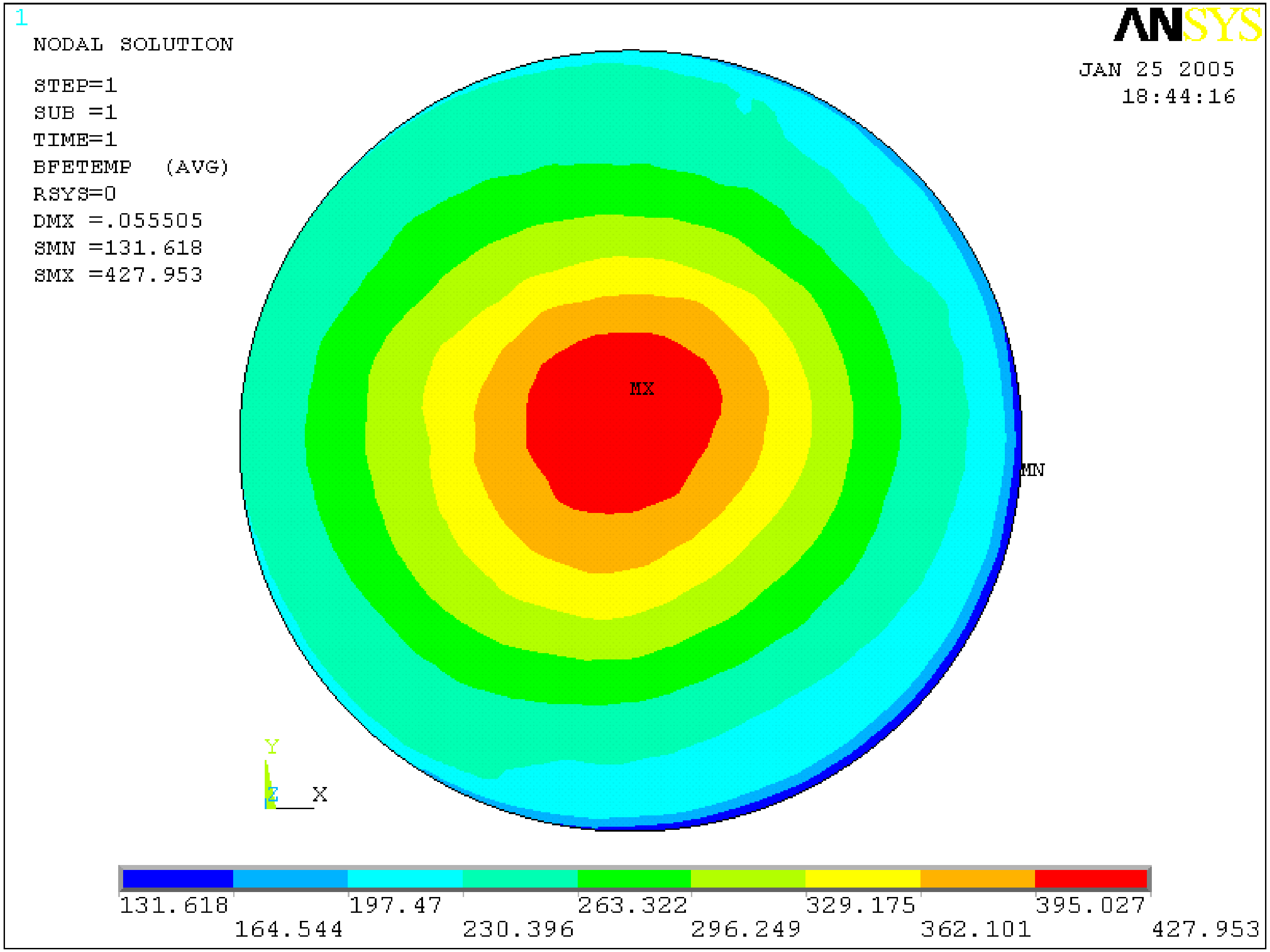
Sample A3-30-L4-06-10 – Temperature Distribution



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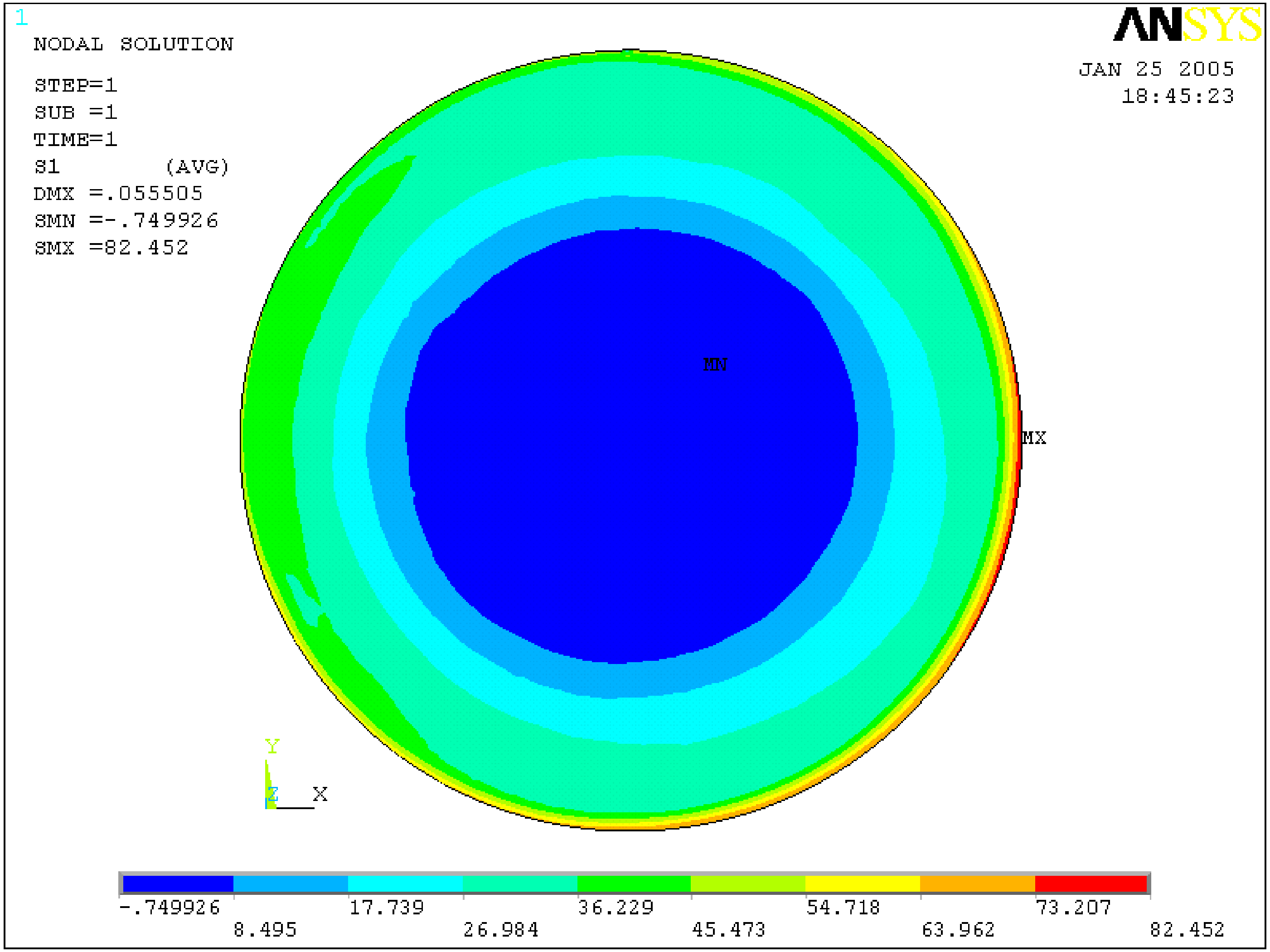
Sample A3-30-L4-06-10 – Maximum Principal Stress



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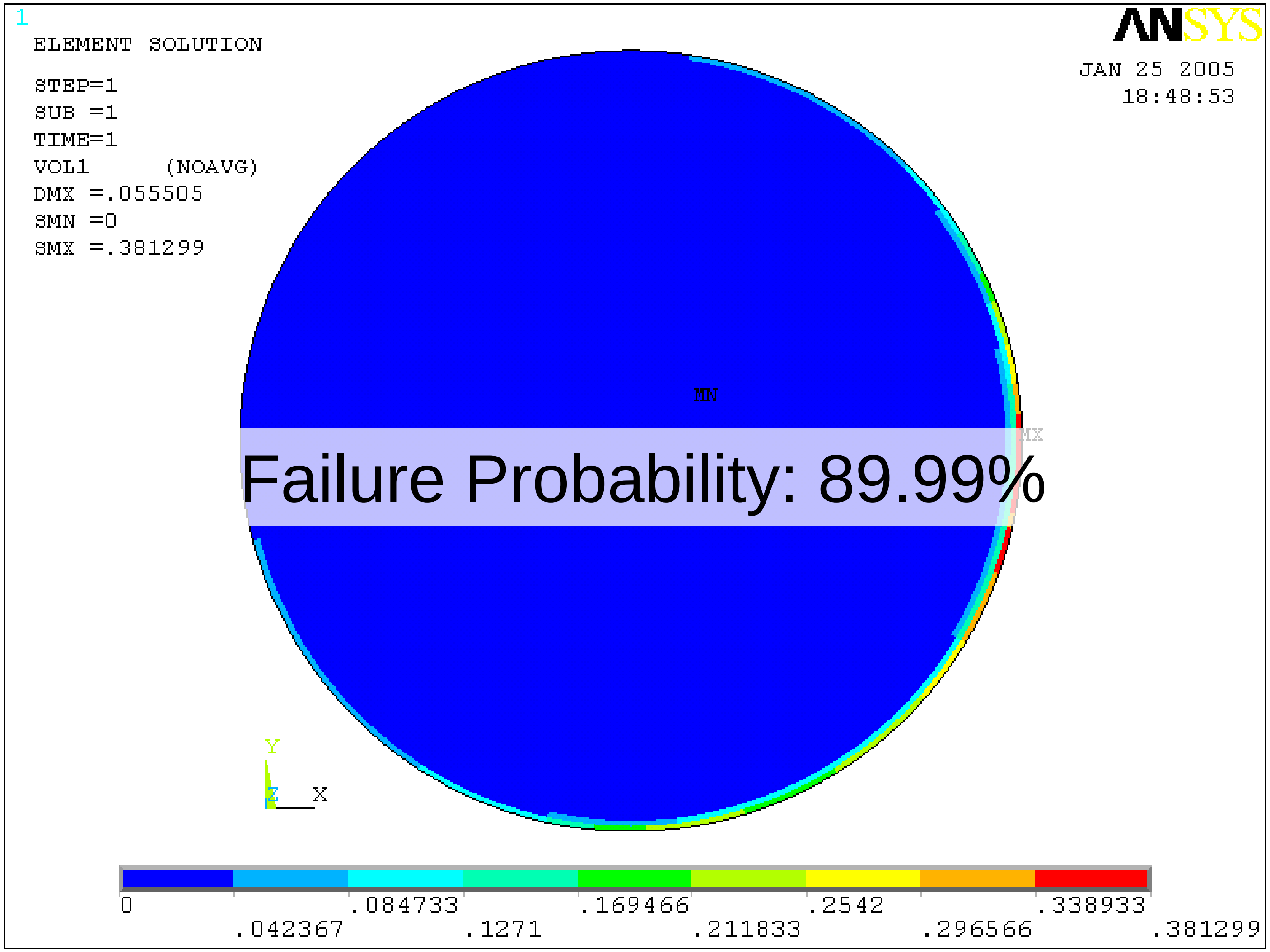
Sample A3-30-L4-06-10 – Risk of Rupture Intensity



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Strength evaluation under a temperature gradient

Temperature Gradient	Predicted Failure Rate	Actual Failure Rate
440 °C	84%	15/17 (88%)
300 °C	54%	7/17 (45%)

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Strength evaluation under a temperature gradient

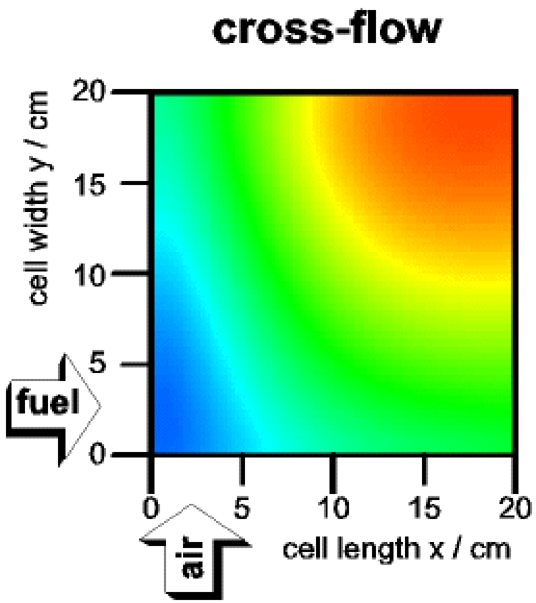
- Test specimens (25-mm diameter disks) were subjected to temperature gradients of different magnitude.
- The experimentally-determined failure rates are comparable to those predicted by combining isothermal strength results and the CARES analysis of the test specimen.
- These results are encouraging because they validate the applicability of probabilistic methods towards the design of reliable SOFCs.

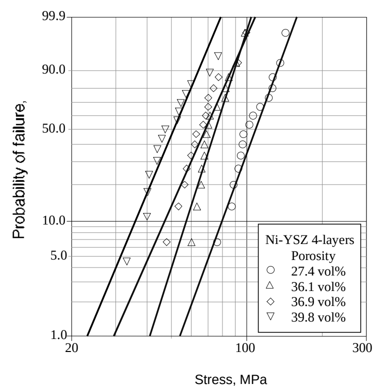
Reliability Predictions

FEM

Stress Distribution

FEM





Residual Stresses
+
Assembly Stresses

Strength Distributions

CARES

Reliability

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Creep behavior of Ni-YSZ

Does Ni-YSZ experience creep deformation at SOFC operating temperatures?

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Creep behavior of Ni-YSZ

- Short-term stress relaxation tests were carried-out at 800°C in 4%H2-96%Ar at different strains/stress to answer this question.
- The duration of the tests was 50 hours.
- The material examined was Ni-YSZ (40%)
- Tests specimens were beams 1.5-inches long, 0.15-inches wide, 0.04-inches thick

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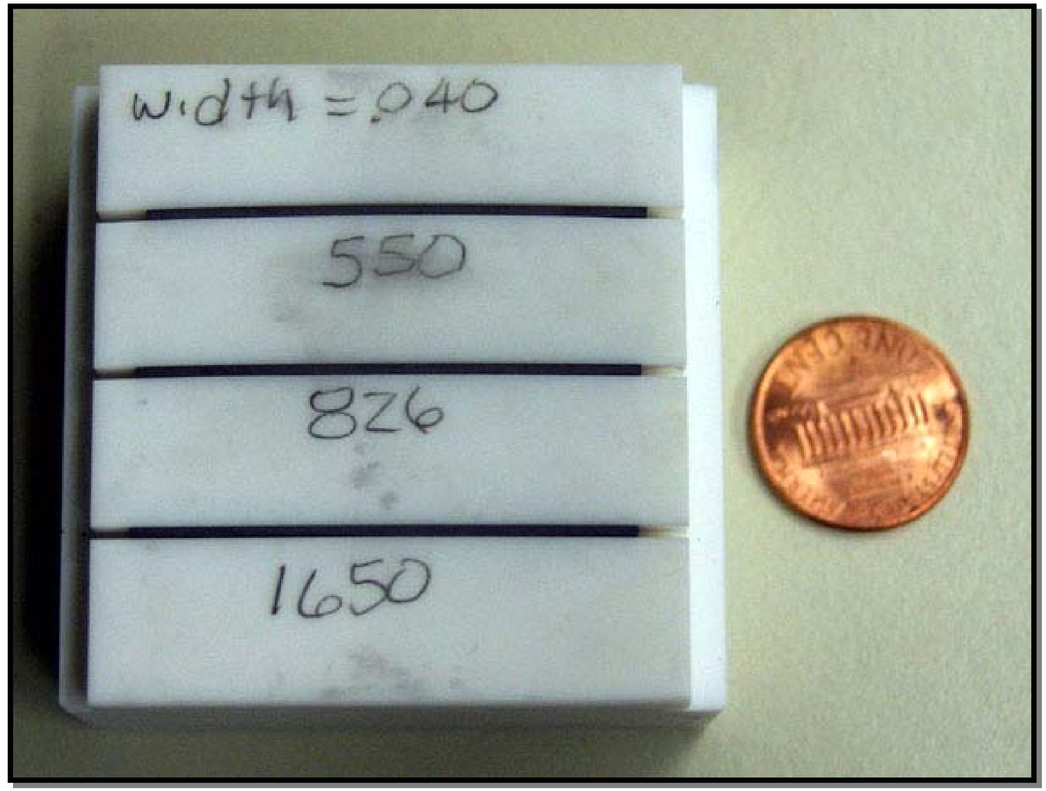
Creep behavior of Ni-YSZ

- Macor (glass-ceramic) block
- Channels with three different radii of curvature were machined.
- The curvature of the beams was determined before and after the tests by profilometry.



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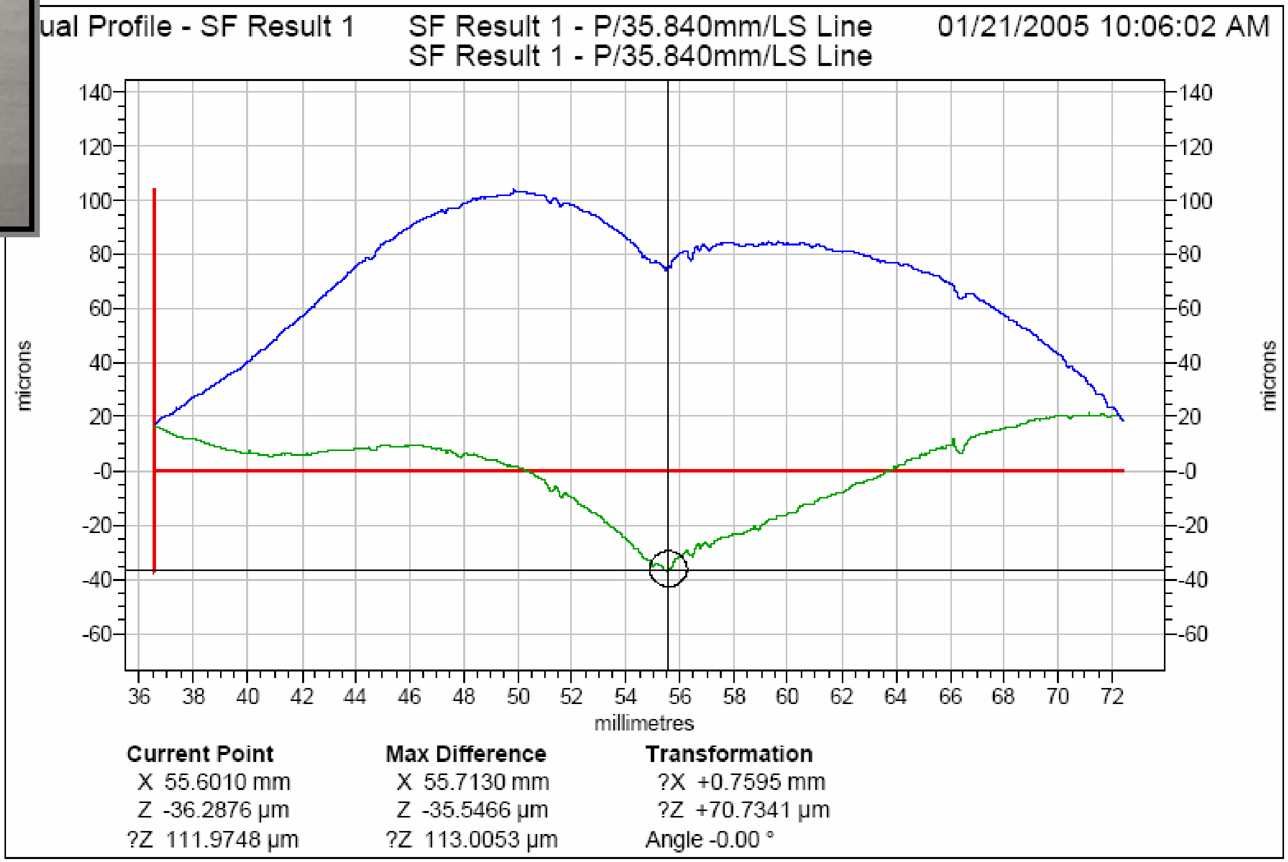
Creep behavior of Ni-YSZ

Applied initial stress: 30MPa
Fixture radius: 826 mm



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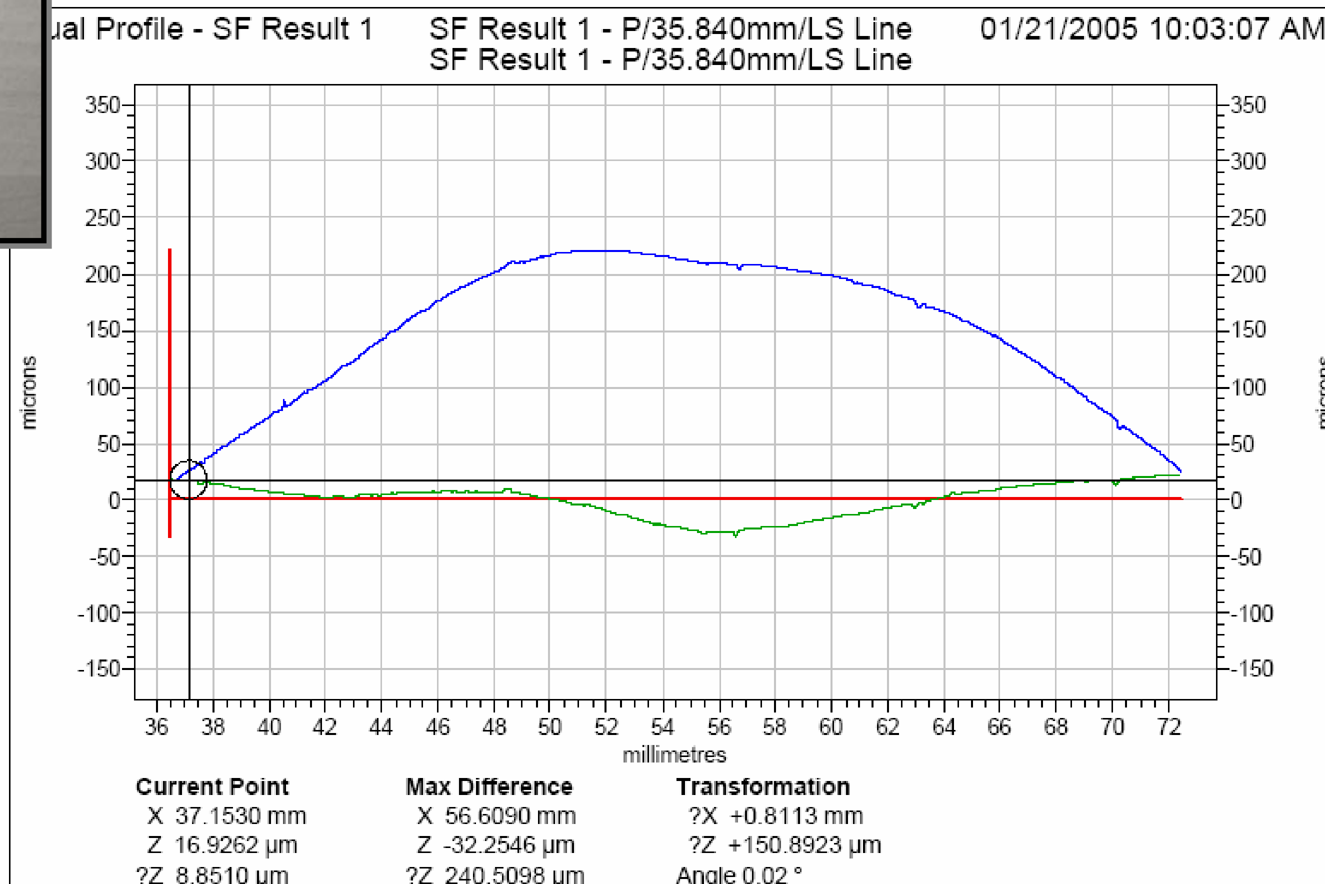
Creep behavior of Ni-YSZ

Applied initial stress: 45MPa
Fixture radius: 550 mm



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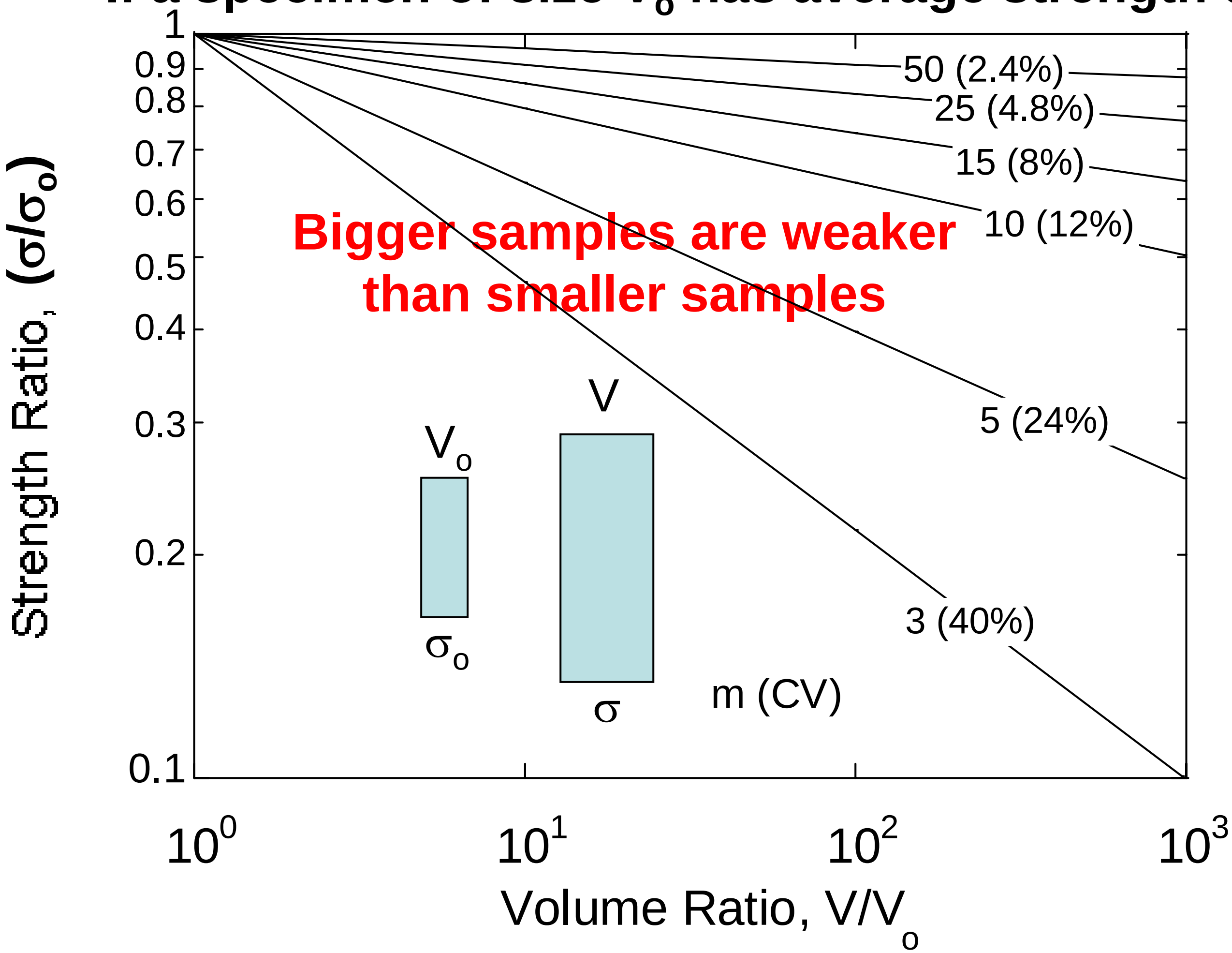
Creep behavior of Ni-YSZ

- Ni-YSZ does creep at 800 °C
- Subsequent creep measurements will be carried-out in coordination with Professor Qu's team at GaTech.

Implications of stochastic nature of strength

If a specimen of size V_o has average strength σ_o, then



$$\frac{\sigma_2}{\sigma_1} = \left(\frac{V_1}{V_2}\right)^{\frac{1}{m}}$$

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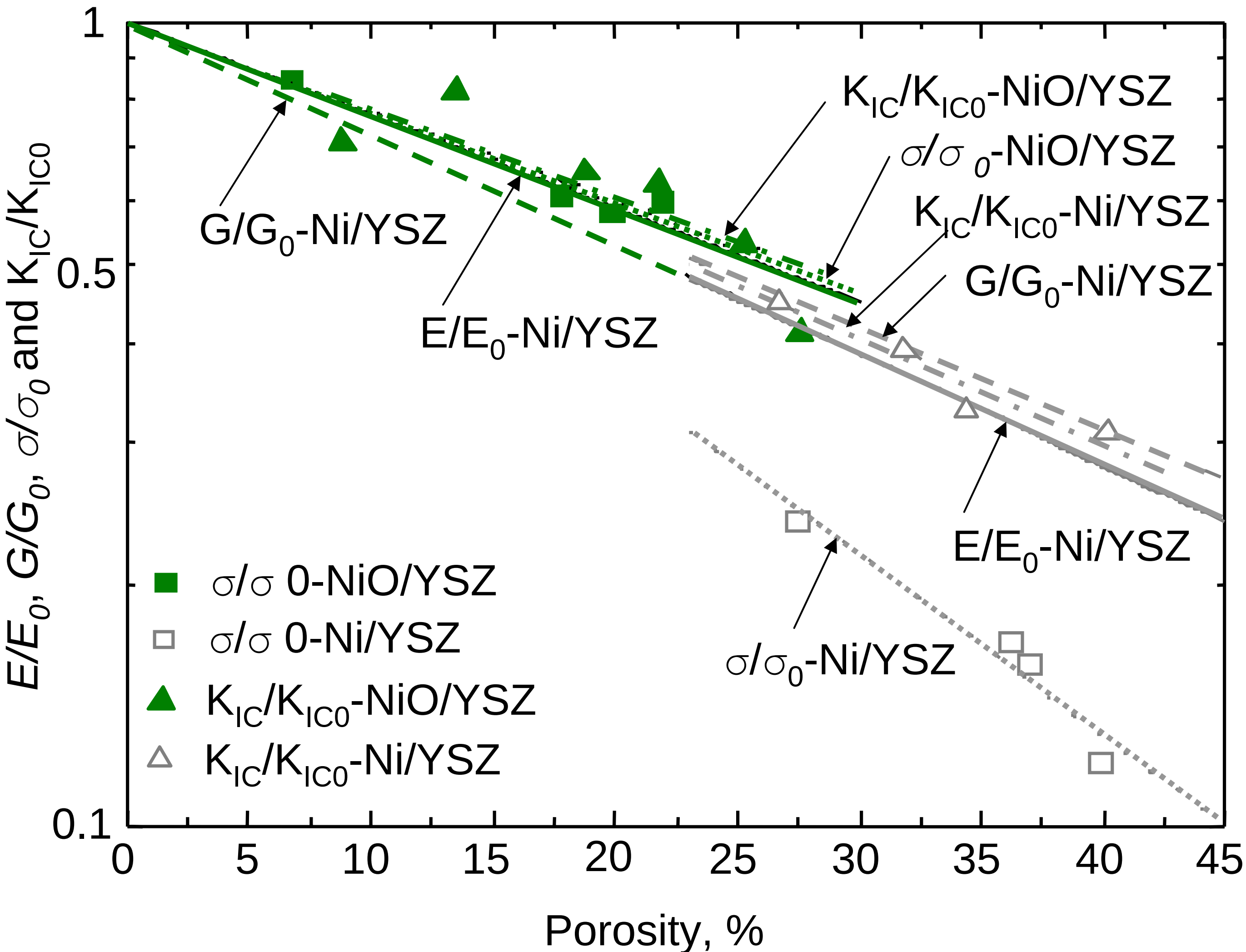
Comparison of Property-Porosity Trends



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