Thermoelectric Mechanical Reliability

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Oak Ridge National Laboratory

Overview

Timeline

- Project start: October 2006
- Project end date: March 2012
- Percent complete: 80%

Budget

- Total project funding
  - DOE: 100% pre Mar 2009
  - DOE: 67% post Mar 2009
  - Marlow (CRADA): 33% post Mar09

	FY08	FY09	FY10	FY11
DOE	$300K	$300K	$300K	$300K
Marlow Ind.		$75K	$150K	$150K

Barriers

- Barriers addressed
  - 2/3 chemical energy in automotive fuel is rejected to atmosphere as waste heat
  - Thermomechanical stresses must be managed and TE material strength improved to fully exploit TE devices
  - TE materials are inherently brittle and susceptible to thermal-induced fracture
- Targets*
  - 5000h life or 10 yr or 150k mile lifetime
  - Brittle bulk materials must survive thermal and mechanical stresses for life

Partners

- Marlow Industries (CRADA)
- General Motors (indirectly)

* "A Science-Based Approach to Development of Thermoelectric Materials for Transportation Applications, Office of FreedomCAR and Vehicle Technologies, August 8, 2007.

Objectives

- **Measure needed thermomechanical and thermophysical properties of candidate thermoelectric materials (TEMats) considered for waste heat recovery and cooling applications in vehicular applications.**
- **Combine measured data with established probabilistic reliability and design models to optimally design automotive and heavy vehicle thermoelectric devices (TEDs) for heat recovery and cooling.**

Milestones

- **FY10:**
  - **Generate thermoelastic and mechanical property database as a function of temperature on candidate p- and n-type skutterudites.**

- **FY11:**
  - **Generate thermoelastic and mechanical property database as a function of temperature on Marlow's next set of candidate p- and n-type TEMats.**
  - **Provide mechanical characterization of other material constituents used in the TEDs.**

Technical Approach

- **Measure Young's Modulus, Poisson's ratio, CTE, thermal conductivity, heat capacity, and strength as a function of temperature of candidate Marlow (and General Motors) TEMats.**
- **Perform fractography on strength specimens, identify failure initiation sites and strength-limiting flaw types, and recommend processing recommendations that will improve strength.**
- **Use probabilistic design and reliability methods with candidate and prototype TEDs.**
- **Provide mechanical evaluation of the other material constituents used in Marlow's TEDs.**

Technical Accomplishments – 1 of 11

Overview of FY10 results

- **Established a strength database two vintages of high-temperature-capable TEMats (skutterudites).**
- **High temperature strength test fixturing developed.**
- **Transport properties of those skutterudites were also evaluated.**
- **Neutron diffraction explored as a means to estimate residual stresses in thermoelectric legs in devices. Can enable correlation of predicted and measured stresses.**

Technical Accomplishments – 2 of 11

Why is mechanical strength important to TEMats?

$$R_{Therm} = \frac{S_{Tens}(1-\nu)\kappa}{CTE \bullet E}$$

Kingery, J. Am. Cer. Soc., 38:3-15 (1955).

R_{Therm} = Thermal resistance parameter (the larger the better)
S_{Tens} = Tensile stress or strength
ν = Poisson's ratio
κ = Thermal conductivity
CTE = Coefficient of thermal expansion
E = Elastic modulus

Griffith Criterion

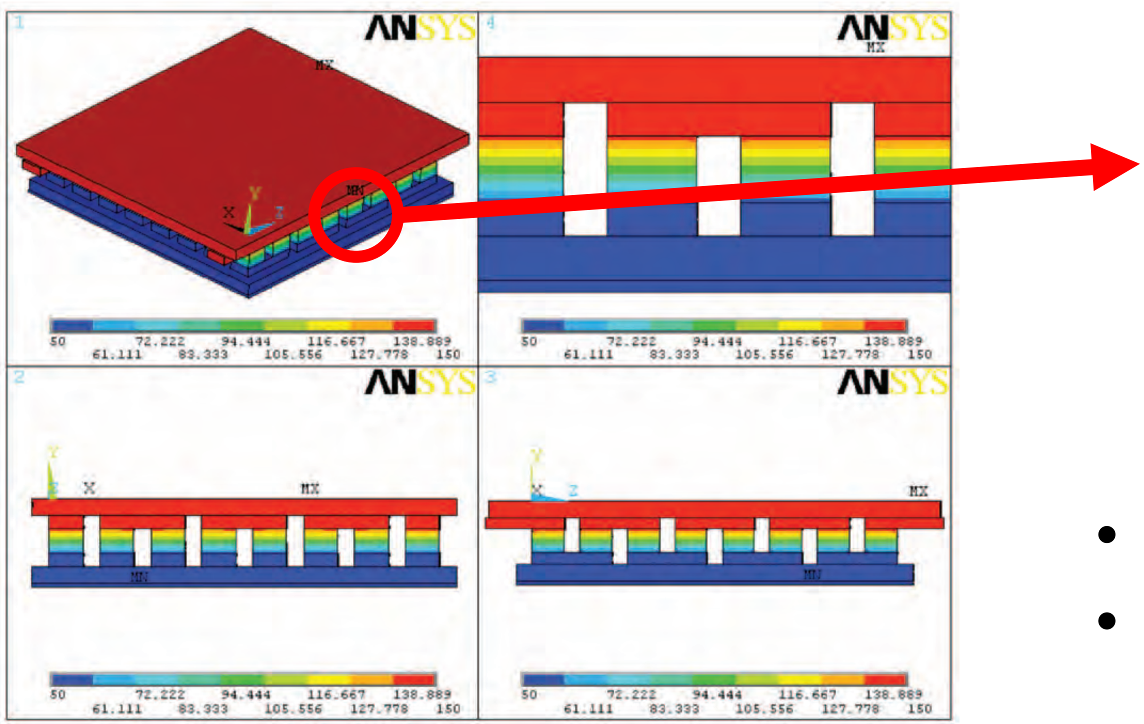
$$S_{Tens} = \frac{K_{Ic}}{Y\sqrt{c}}$$

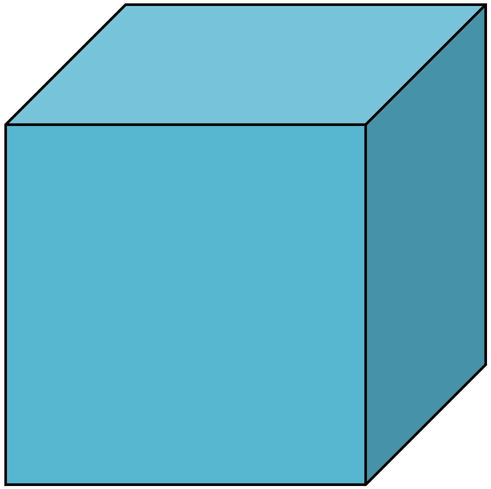
KIc = Fracture toughness
Y = Crack shape factor
c = Griffith flaw size

Tensile Strength << Compressive Strength
Manage tensile stress for conservative design

Must seek to minimize c!

TE legs and potentially active flaws:





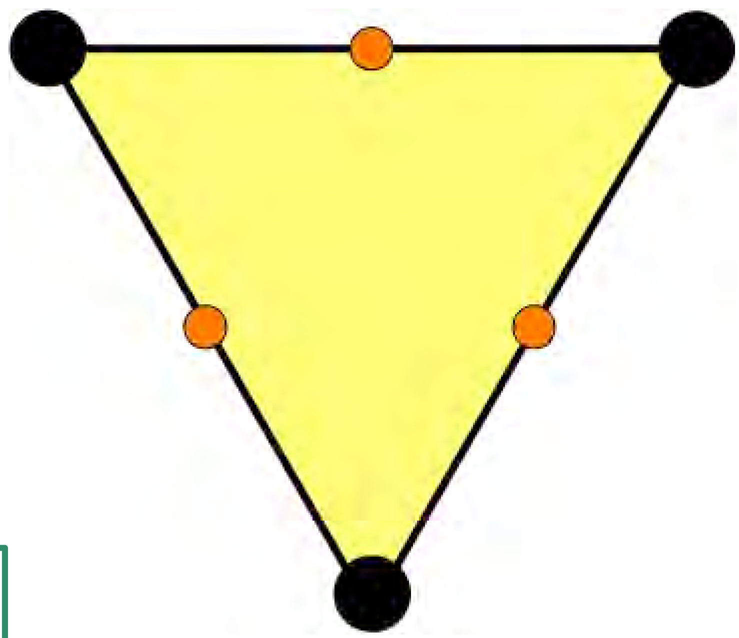
- **Legs ➔ prisms**
- **Volume-, surface-, and edge-located strength-limiting flaws all possibly active**
- **e.g., 3 x 3 x 3 mm**

Technical Accomplishments – 4 of 11

Strength-limiting flaw classification for brittle materials; the potential existence of all are in unchamfered TE Legs

Volume Type
(3-Dimensional)

Pores
Porous Regions
Large Grains
Agglomerates
Inclusions



Surface Type
(2-Dimensional)

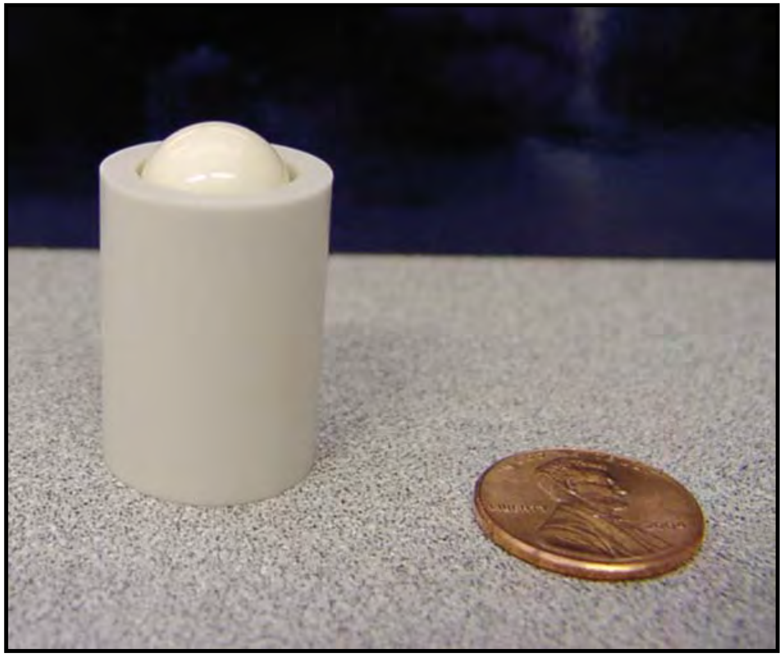
Machining Damage
Pitting
Handling Damage
Chemical RXN Product
Oxidation

Bi-Dimensional Hybrid Flaw

Edge Type
(1-Dimensional)

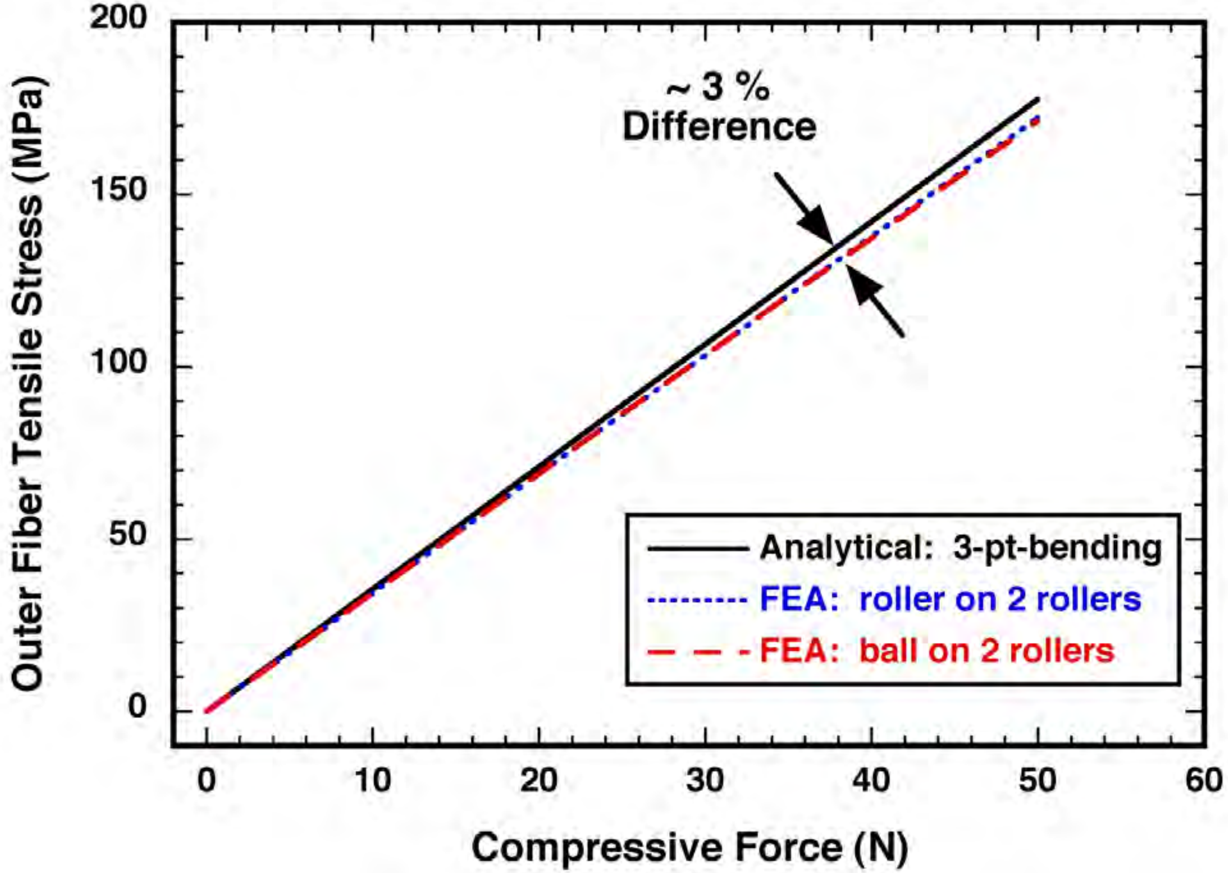
Edge chipping

An All-Alumina High-Temperature "3-Point" Bend Fixture



This is a "Ball on Two Rollers" 3-Point Bend Fixture

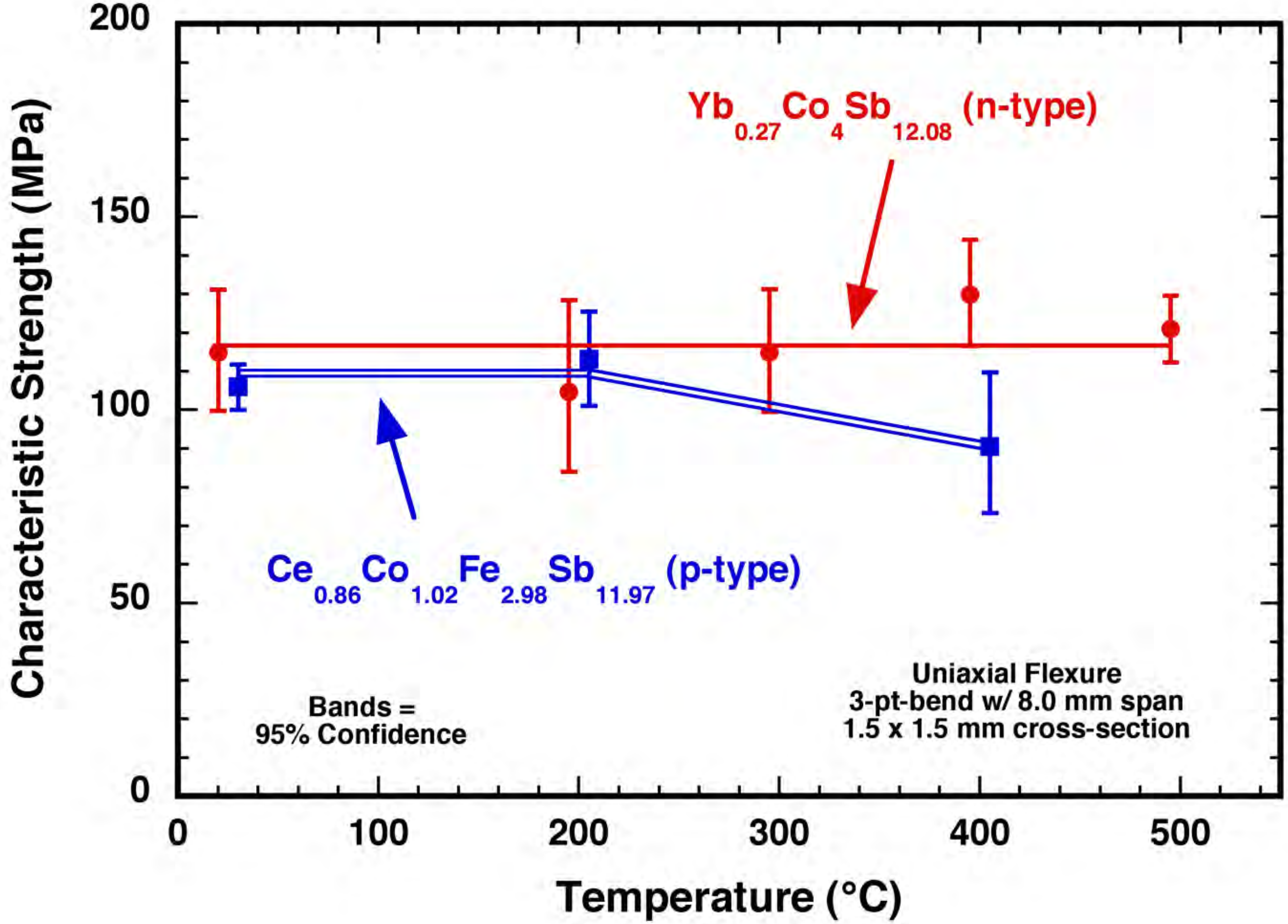
Classical Beam Bending Equation Works



St. Venant's Principle

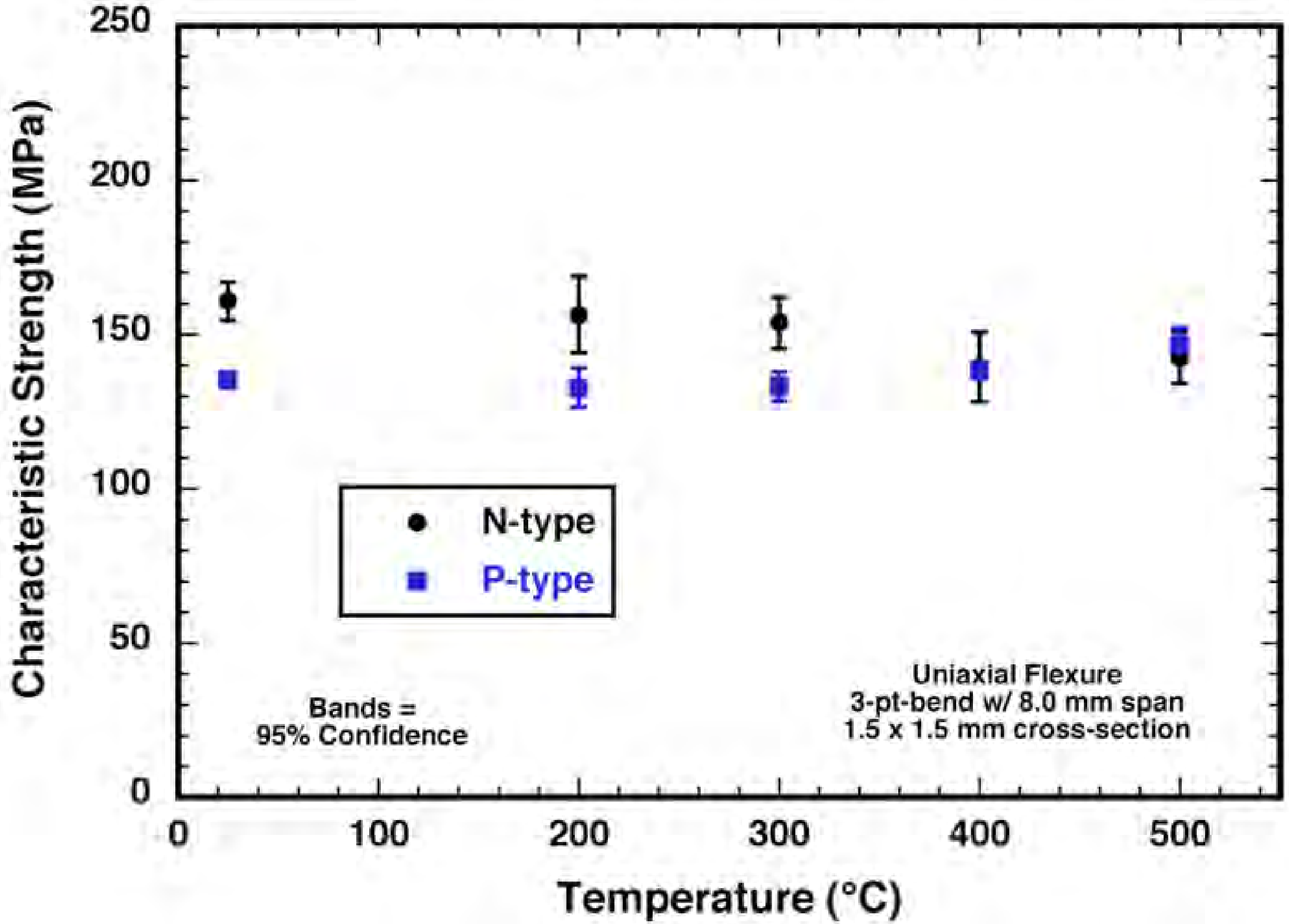
Technical Accomplishments – 7 of 11

Failure Stress as a Function of Temperature – Vintage 1



Technical Accomplishments – 8 of 11

Failure Stress as a Function of Temperature – Vintage 2



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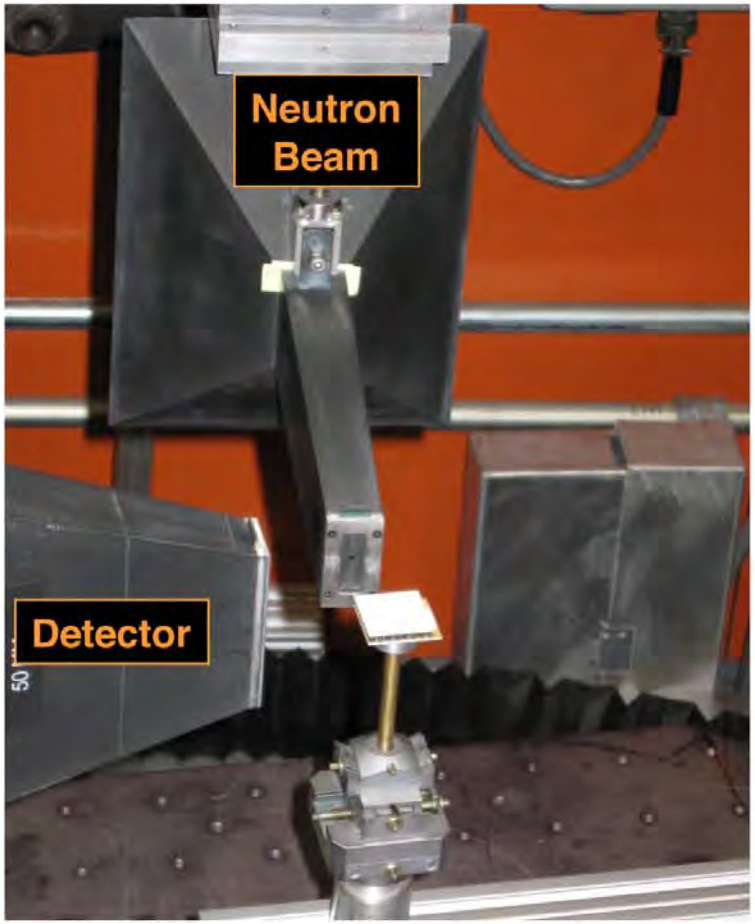
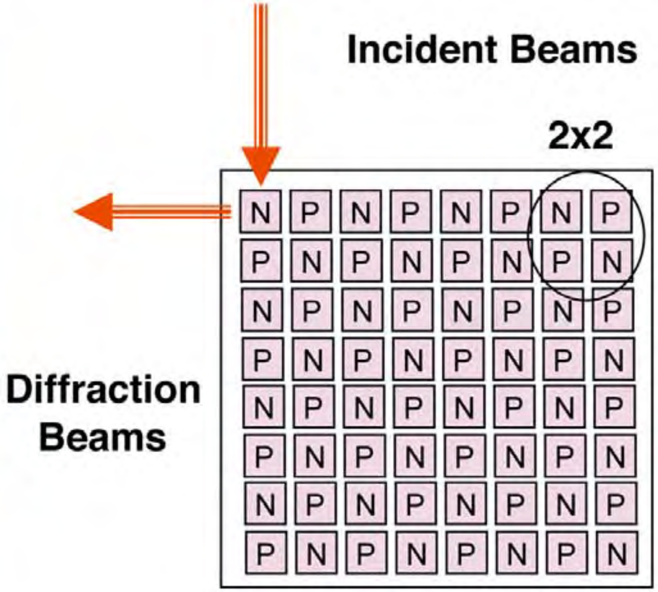
Neutron diffraction being used to measure residual stresses in thermoelectric devices

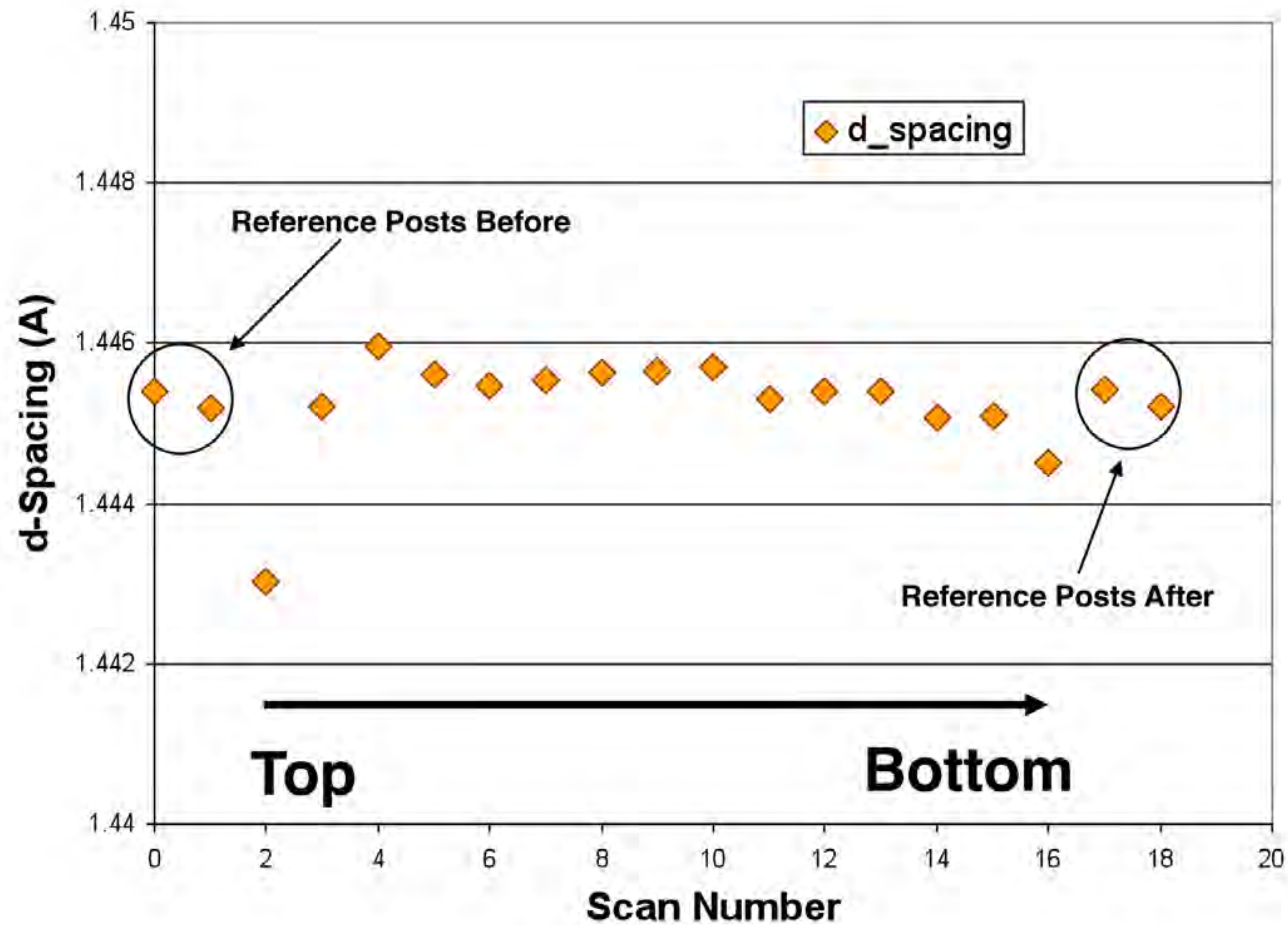




The penetration ability of neutrons allows scanning of the 8 x 8 array

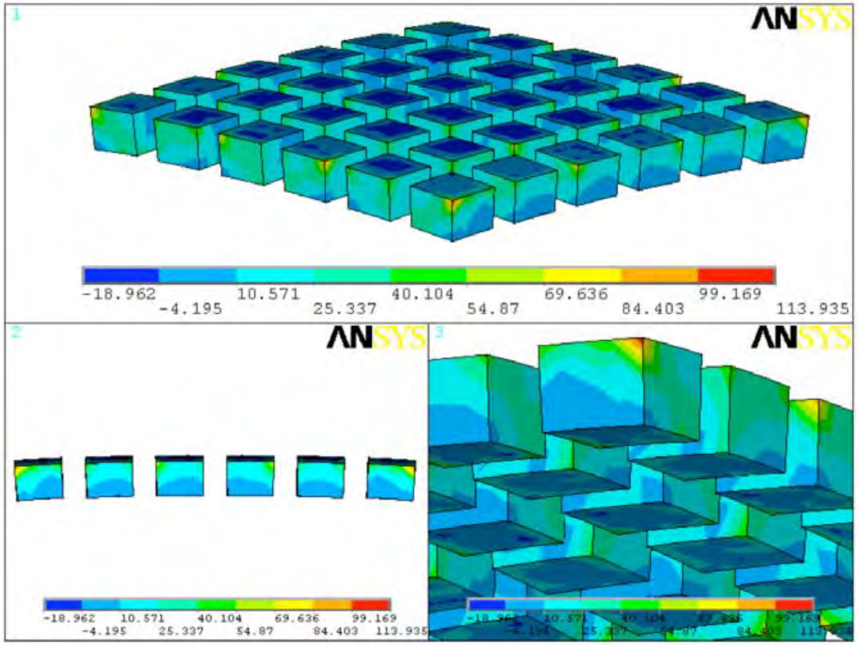
Technical Accomplishments – 10 of 11

Analysis enables correlation of predicted and measured residual stresses



How is this information being used?

- **High 1st principal tensile stresses exist in the bulk and on surfaces and edges**
- **Apply strength data to estimate and reduce risk of fracture**
- **Improve reliability by:**
  - **Improving strength of TEMat**
  - **Lessening tensile stresses in the legs (via geometrical changes)**
  - **Both**



Must manage the competition and concurrent activities of Edge- vs. Surface- vs. Volume-based strength limitation

Future Work

- **Continue to collaborate with Marlow Industries, a manufacturer of high-temperature-capable TEMats and TEDs, to contribute to the reliability improvement of their candidate TEMats (FY11 & FY12).**

- **Identify and quantify the size of strength-limiting flaw populations (FY11 & FY12).**

- **Support other mechanical reliability issues associated with the TEDs, for example, combating potential residual stresses associated with metallization (FY11 & FY12).**

Summary

- **Strength of high-temperature-capable TEMats**
  - The strength of new vintages of N- and P-type skutterudites were evaluated.
  - Both candidates for use in TE devices for high-temperature energy harvesting.
  - The strength of the new vintage of skutterudite increased by ~ 25%.

- **General strength testing of bulk TEMats**
  - As long as prismatic TE legs continue to be considered for TE devices, the competing roles of edge-, surface-, and volume-strength-limiting flaws should be considered for meaningful reliability analysis.
  - Representative testing (i.e., stressing) is produced by evaluating actual TE leg geometries (or as close to them as possible).

- **Testing in FY11**
  - Mechanical property evaluation of next Marlow TEMats.
  - Mechanical characterization of other material constituents in TEDs.