Thermoelectric Mechanical Reliability

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Overview

Timeline

- Project start: October 2006
- Project end date: March 2012
- Percent complete: 70%

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 of the chemical energy in automotive fuel is rejected to the 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
- General Motors

* "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 TE materials 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 TE devices for heat recovery and cooling.**

Milestones

- **FY09: Generate thermoelastic and mechanical property database as a function of temperature on at least one candidate high-temperature-capable p- and n-type material.**

- **FY10:**

  – **Generate thermoelastic and mechanical property database as a function of temperature on candidate p- and n-type TEMats fabricated by Marlow Industries as part of CRADA.**

  – **Develop in-situ thermal-gradient-strength test method for TEMats.**

Technical Approach

- Measure Young's Modulus, Poisson's ratio, CTE, thermal conductivity, heat capacity, and strength as a function of temperature of candidate Marlow TEMats.
- Perform fractography on strength specimens and identify failure initiation sites and strength-limiting flaw types.
- Critically assess machining strategies of TEMats to ultimately maximize their mechanical performance.
- Use probabilistic design and reliability methods with candidate and prototype TE modules.
- Measure strength of TEMats while a thermal gradient is concurrently superimposed.

Technical Accomplishments – 1 of 11

Overview of FY09 results

- **Established a strength database for a reference TEMat (Bi_2Te_3) usable for comparisons to higher-temperature-capable TEMats**
- **High temperature strength test fixturing developed**
- **Preliminary strength-testing of a developmental and high-temperature-capable TEMats (skutterudites) was initiated.**
- **Transport properties of those skutterudites were also evaluated.**

Technical Accomplishments – 2 of 11

Why is mechanical strength important to TE materials?

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

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

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

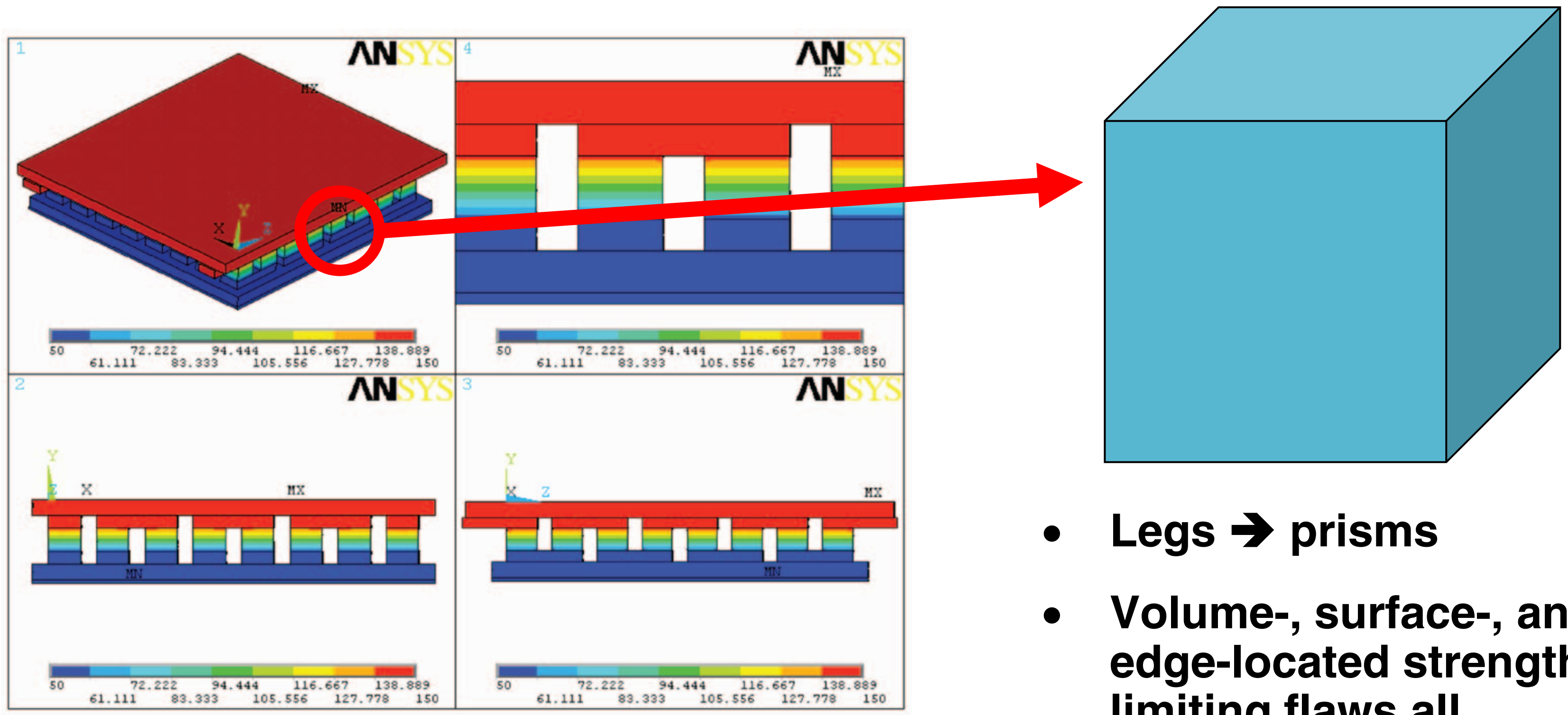
KIc = Fracture toughness
Y = Crack shape factor
c = Griffith flaw size

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

Must seek to minimize c!

Technical Accomplishments – 3 of 11

TE legs and potentially active flaws:



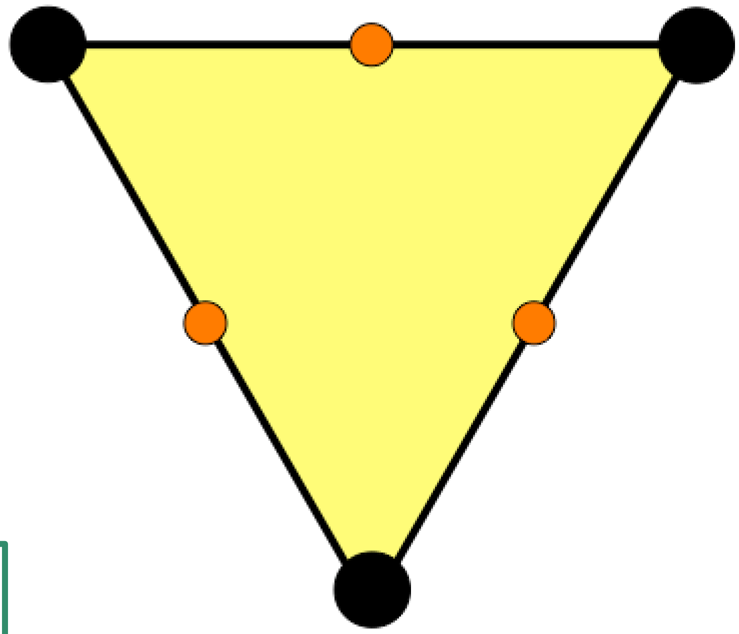
- **Legs ➔ prisms**
- **Volume-, surface-, and edge-located strength-limiting flaws all possibly active**
- **e.g., 3 x 3 x 3 mm**

Technical Accomplishments – 4 of 11

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

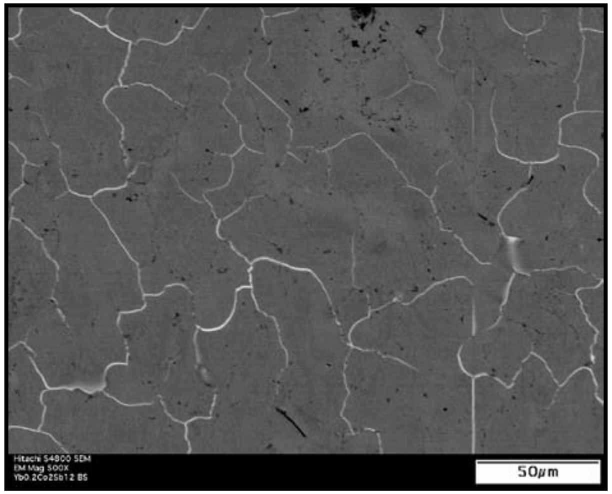
Edge Type
(1-Dimensional)

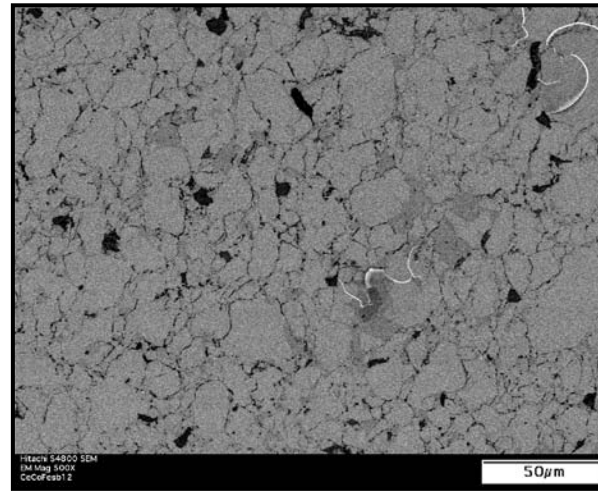
Edge chipping

Technical Accomplishments – 5 of 11

$Yb_{0.27}Co_4Sb_{12.08}$ (N-Type) | **$Ce_{0.86}Co_{1.02}Fe_{2.98}Sb_{11.97}$ (P-Type)**

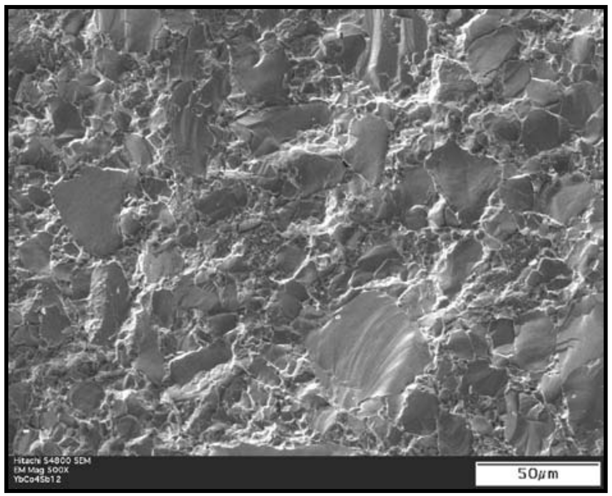
Polished Surfaces

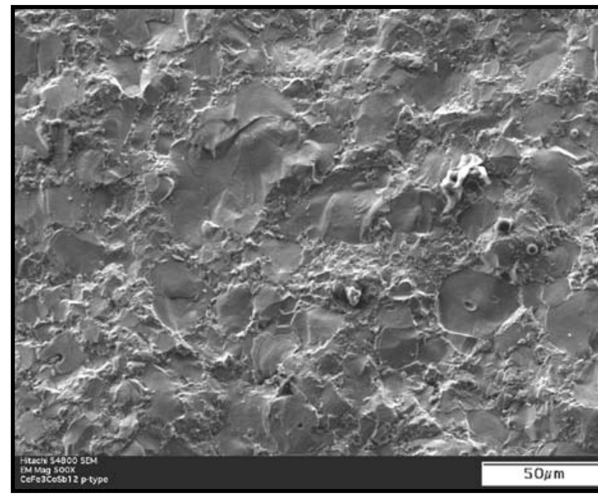




50 μm

Fracture Surfaces





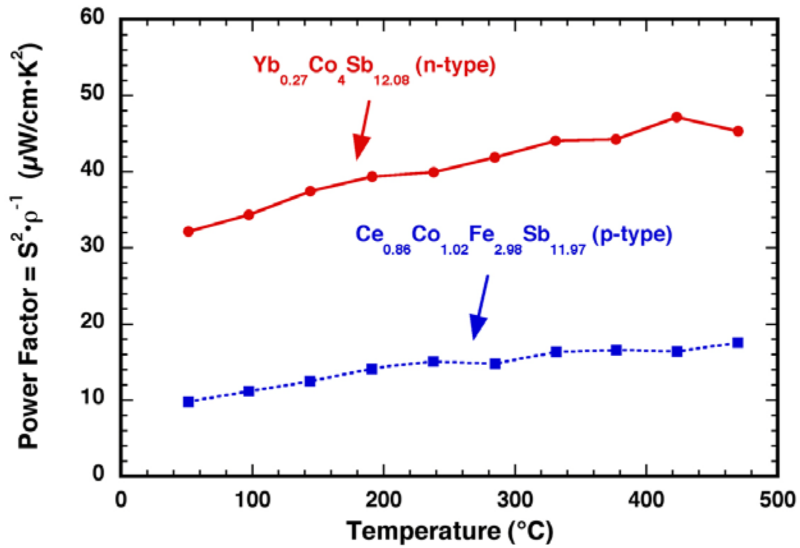
Example: for 2c = 44 μm (i.e., 325 sieve mesh), K_{Ic} = 1 MPa√ m, and Y = 1.5

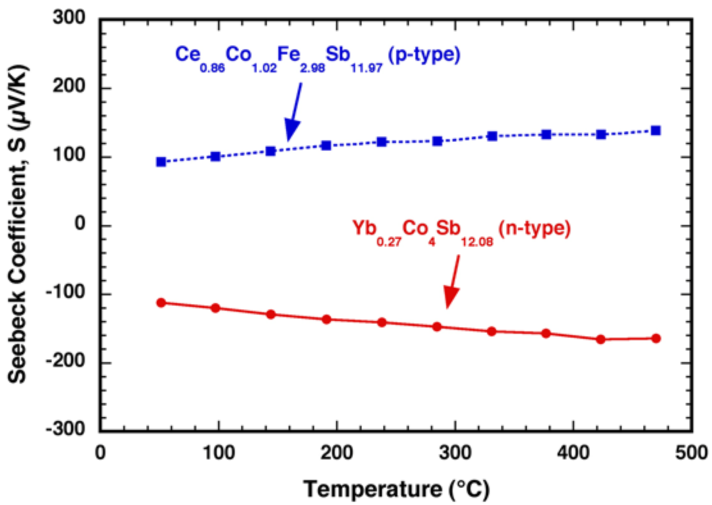
S_{Tens} = 140 MPa

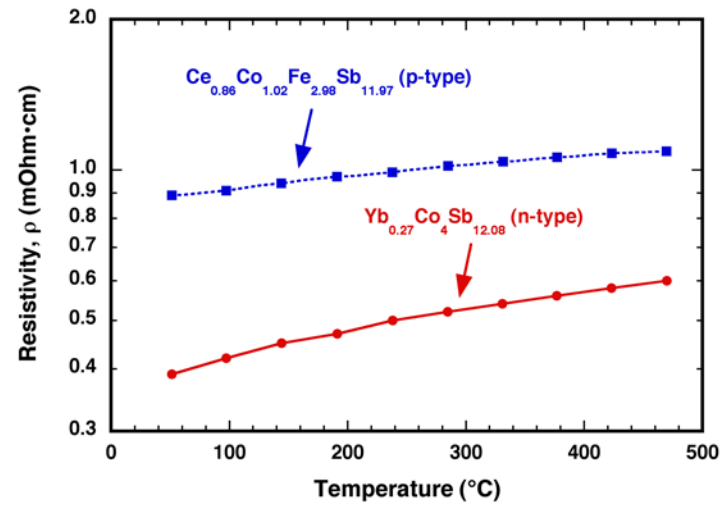
S_{Tens} will never be stronger than that unless "c" is reduced

Technical Accomplishments – 6 of 11

Transport Properties of the Skutterudites

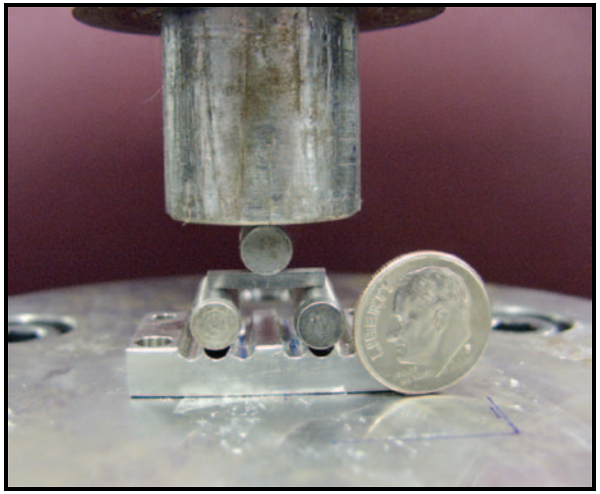






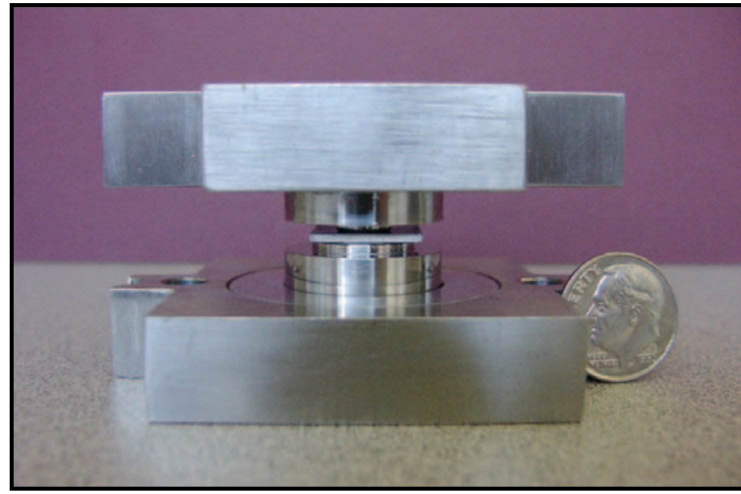
An Alternative to the Testing Convention Was Needed

3-Pt-Bend (Uniaxial Flexure)



- **Metal fixturing; limits test temperature**
- **Need to sustain alignment; seek passive self-alignment**
- **Simpler the better**

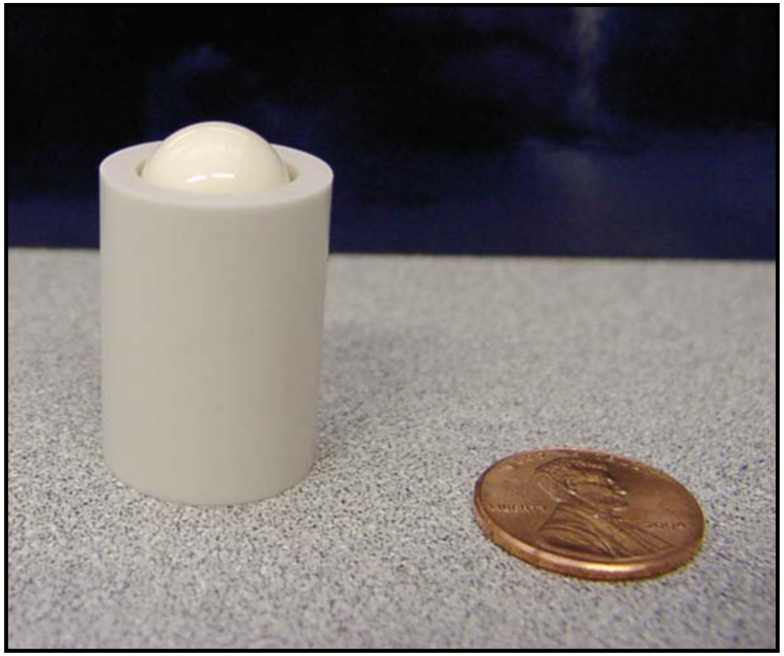
Ring-on-Ring (Biaxial Flexure)



- **RoR; edge effects are never operative**

Technical Accomplishments – 8 of 11

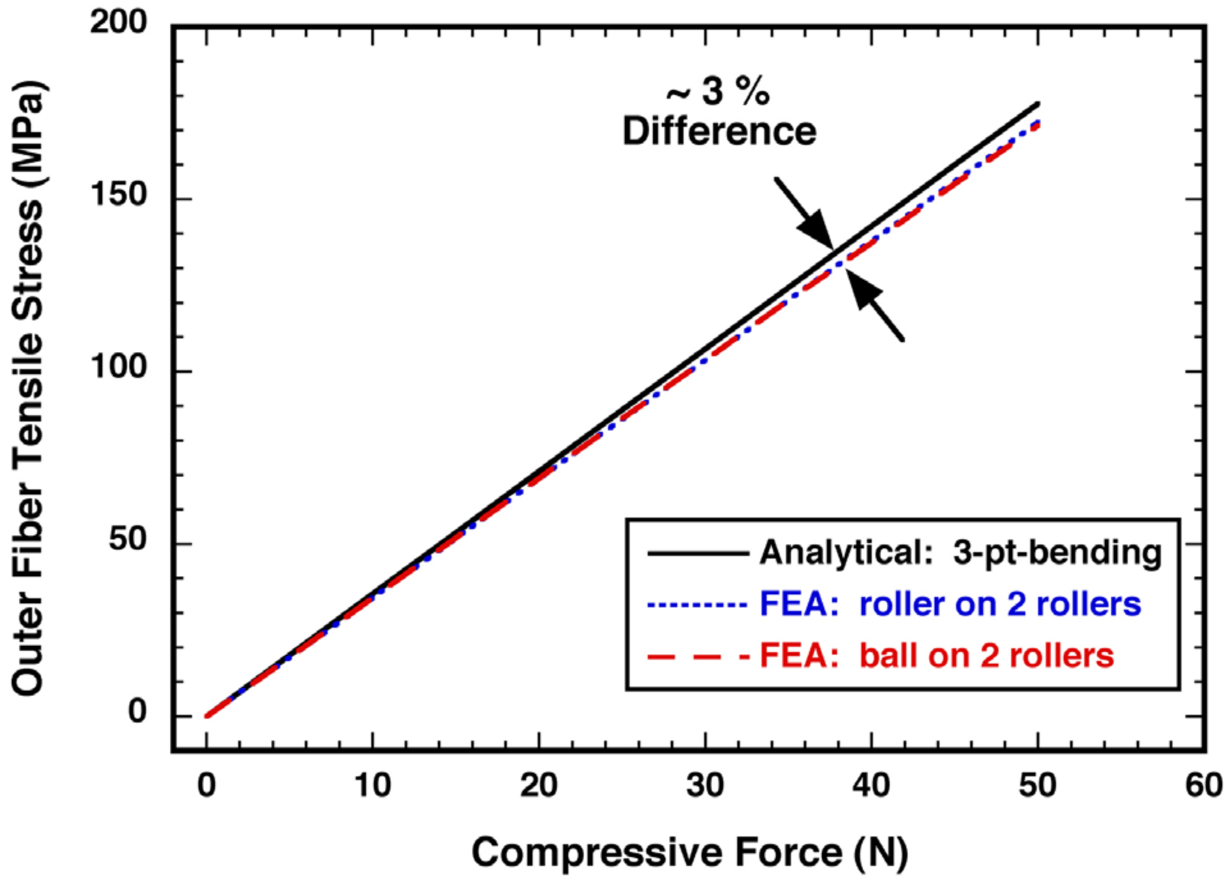
An All-Alumima High-Temperature "3-Point" Bend Fixture



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

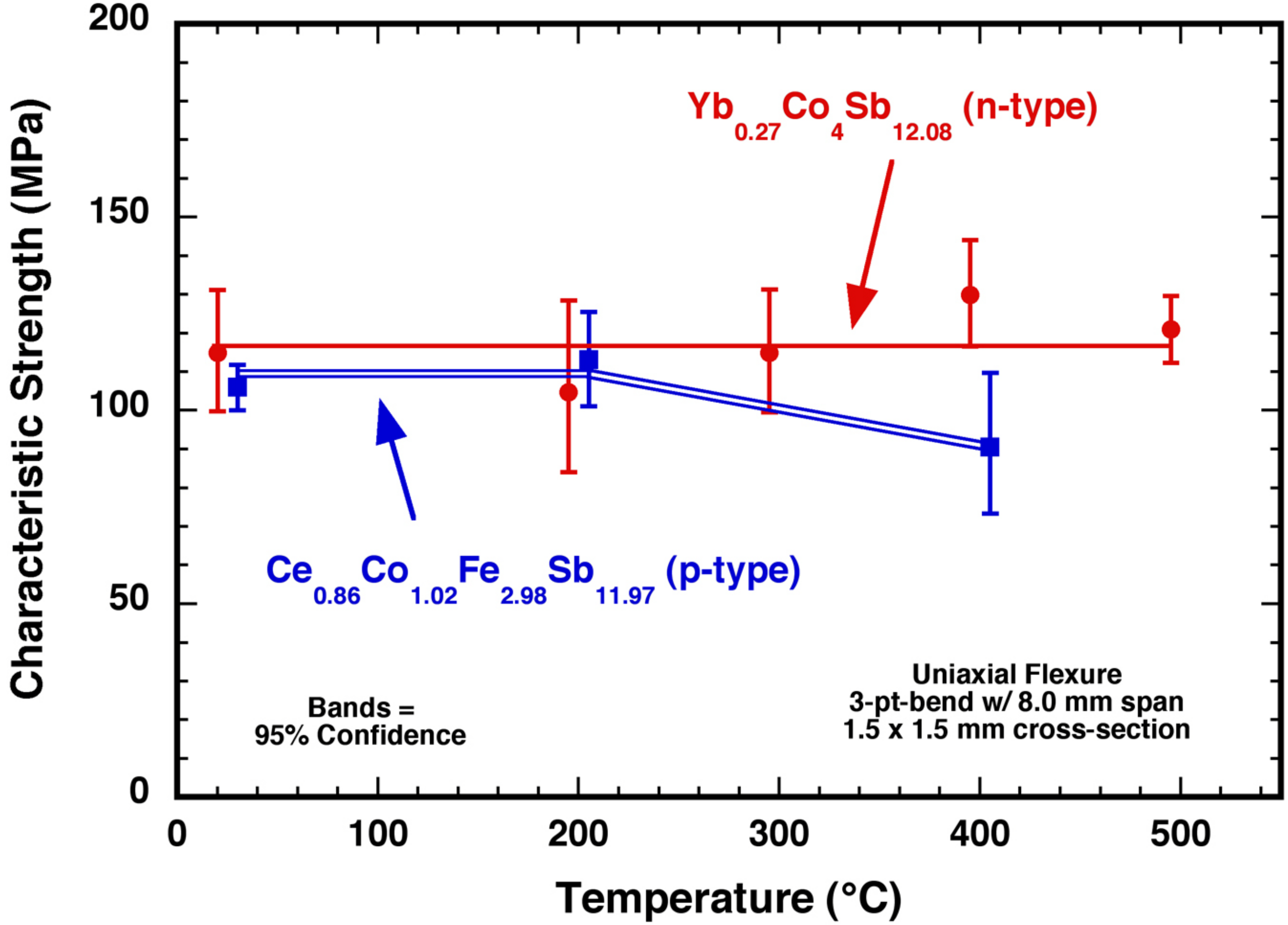
Technical Accomplishments – 9 of 11

Classical Beam Bending Equation Works



St. Venant's Principle

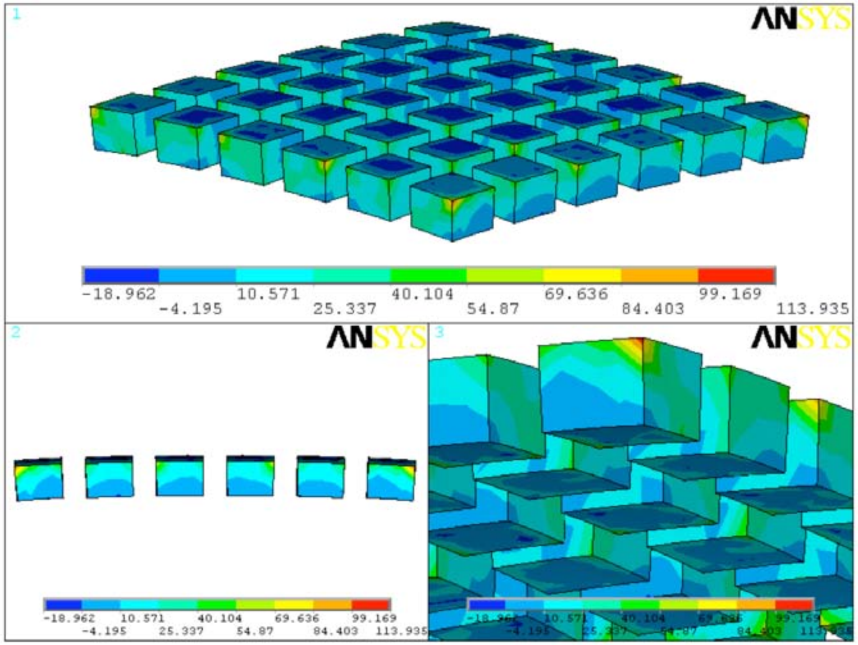
Failure Stress as a Function of Temperature



Technical Accomplishments – 11 of 11

How will this information be used?

- **High 1st principal tensile stresses exist in the bulk and on surfaces and edges**
- **Apply (censored) strength data to estimate and reduce risk of fracture**
- **Improve reliability by:**
    - **Improving strength of TE material**
    - **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 TEMs and TEDs, to contribute to the reliability improvement of their candidate TEMs (FY10 & FY11).**

marlow industries
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- **Develop a thermomechanical test system that will enable strength measurement of TEM specimens while a thermal gradient is concurrently imposed through the specimen thickness (FY10&FY11).**

- **Develop method to identify and quantify the size of strength-limiting flaw populations (FY10 & FY11).**

Summary

- **Strength**
  - The strength of N- and P-type skutterudite compositions were evaluated.
  - Both candidates for use in TE devices for high-temperature energy harvesting.
  - The strength of the N-type TE was sustained through 500°C whereas that for the P-type TE decreased by ~ 15% at 500°C.

- **General strength testing of bulk TEs**
  - 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).

- **New strength test fixture and method**
  - A self-aligning, high-temperature three-point-bend fixture was developed.
  - The classical and closed-form beam-bending strength equation is used with it.