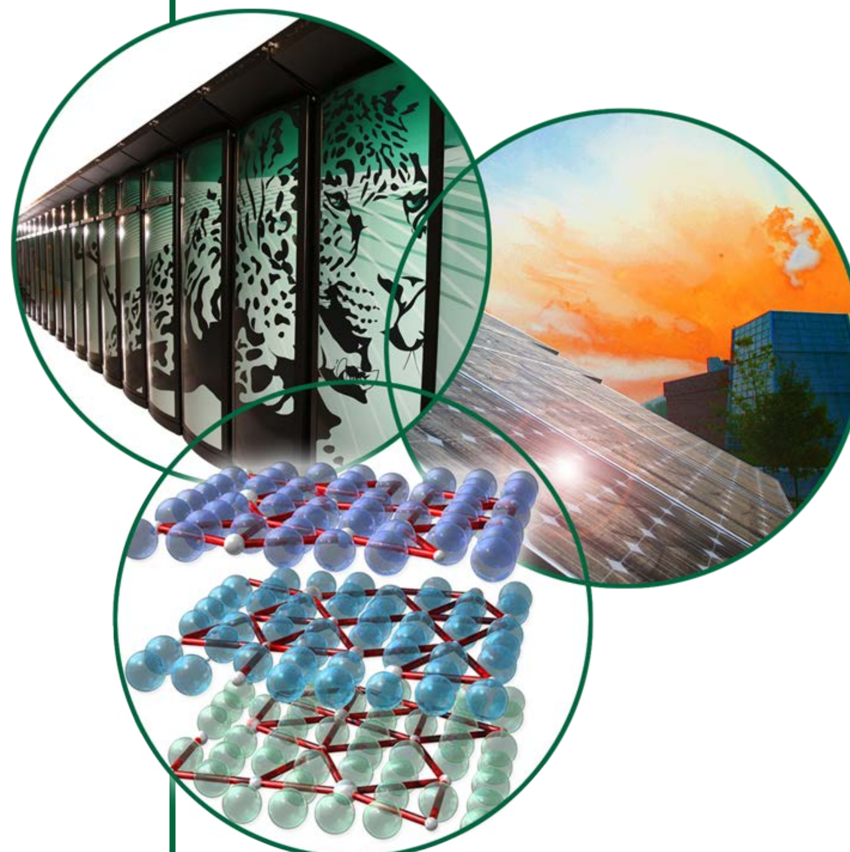
Project ID: PM010

Durability of Diesel Engine Particulate Filters

2012 DOE Vehicle Technologies Annual Merit Review and Peer Evaluation Meeting

May 15, 2012



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Sponsored by
U.S. Department of Energy, Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Vehicle Technologies Program

U.S. DEPARTMENT OF ENERGY

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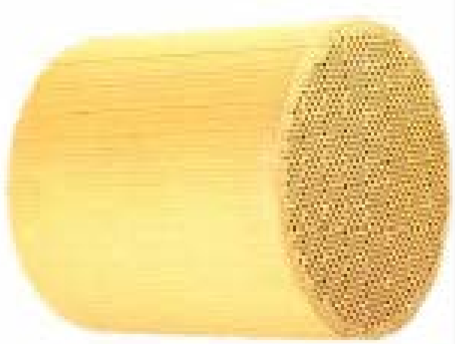
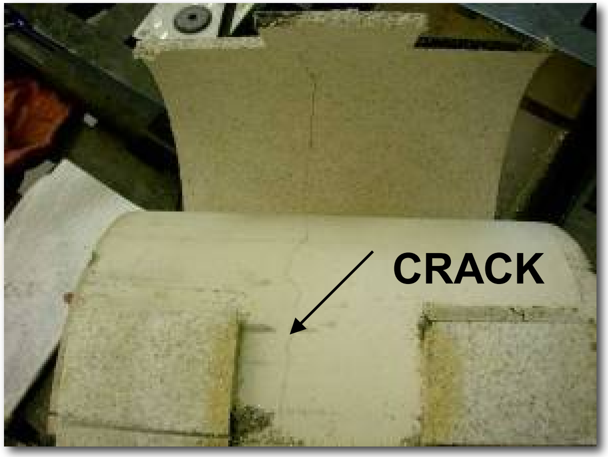
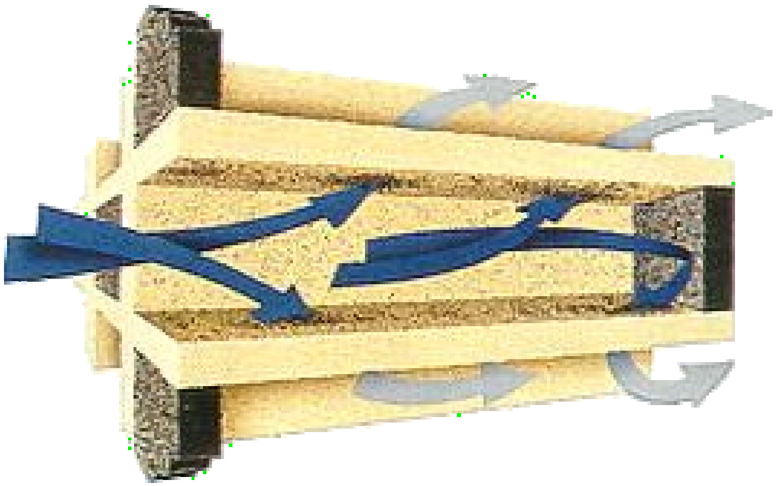
Background to CRADA

- Diesel Particulate Filters (DPFs) play a key role and will continue to be a key technology to meet the prevailing stringent regulations.
- Reliable operation for ~425,000 miles required. Reliability could be reduced due to damage induced by thermal stresses.
- Need for improved materials and designs along with life prediction models to optimize reliability and durability, particularly for DPF regeneration.
- Characterization of material properties is needed for model input
- **The CRADA has previously delivered key materials properties information, which enabled application and optimization of the prime path DPF technology, and contributed to down-selecting some alternative materials**
- SiC is considered here







Overview

Timeline

- Start: June 2004
- End: Sept. 2013
- 86% complete

Budget

- Total Project funding
  - DOE-$2.6M
  - Cummins-$2.6M
- Funding received:
  - FY11 $300k
  - FY12 $300k approved

Barriers* - Propulsion Materials Technology:

- Changing internal combustion engine combustion regimes ➔ Optimize to minimize fuel penalty & thermal stresses during regeneration
- Cost ➔ reduce DPF failures & liability

Barriers* - Combustion and Emission Control R&D:

- Cost-eff. emission control ➔ reliable regeneration w/ minimized fuel penalty
- Durability ➔ Minimize thermal stresses and porosity, reduce failures & liability
- Market perception ➔ Clean diesel improves public's acceptance

Partners

- Cummins Inc.

* Vehicle Technologies Program, Multi-Year Program Plan 2011-2015, Dec 2010, pp. 2.3-4, 5, 8; 2.5-7, 8, 9, 10.

Relevance to barriers

- **Impact on barriers: Property data generated by this CRADA…**
  - **Is input into models to predict behavior accurately. In turn, strategies to mitigate thermal stresses can be formulated for optimized regeneration which *changes engine combustion regimes* and which minimizes failures, improving *cost-effective emission control***
  - **Allows for better DPF design which improves *durability***
  - **Results in longer lasting DPFs reducing the liability and failures which reduce *cost***

Relevance to Vehicle Technologies Goals

- **Propulsion Materials: By 2015, develop materials, materials processing and filter regeneration techniques that reduce the fuel economy penalty of particle filter regeneration by at least 25% relative to the 2008 baseline***
  - **Understanding the relationship of the porosity to the material properties of the filter (and catalyst) substrates enables optimization of porosity, strength, elastic modulus, thermal conductivity, thermal expansion … leading to improved regeneration strategies and thermal management and filter efficiency.**
  - **Increases acceptance of clean diesel by the public. Larger acceptance results in larger percentages of conversion to diesel, with the resulting reduction in petroleum consumption**

- **Improve the modeling and simulation capabilities for exhaust aftertreatment devices to accelerate the design of the most effective emission control systems***
  - **Characterization of DPF materials provides needed material properties for accurate simulation**

* Vehicle Technologies Program, Multi-Year Program Plan 2011-2015, Dec 2010, pp. 2.5-7, 2.3-8.

Milestones FY11 & FY12

- FY11: Continue to investigate the interaction and properties of washcoat, soot and substrate (focus here: SiC substrate properties) on properties of new and field tested DPFs.
- FY11: Initiate characterization of the dynamic and static fatigue response of SiC DPFs.
- FY12: Complete the determination of strength, fracture toughness, density/porosity/microstructure, and thermal expansion of uncoated DPFs as a function of time at elevated temperatures of 300, 500, 800 and 900°C for a second alternate substrate DPF material.

Technical Approach/strategy:

- Application of probabilistic design tools, non-destructive evaluation (NDE) techniques and thermo-mechanical characterization methods to DPF ceramic substrates.
- Rank the thermal shock resistance of candidate DPF substrates.
- Refinement of DPF service lifetime prediction models based on characterization of field returned filters (Cummins).

…addresses barriers:

- The above provides materials behavior and property data to models which optimize regeneration. This improves durability and reduces liability and fuel penalty making emission control more cost effective.

Approach/strategy: Integration within Vehicle Technologies program

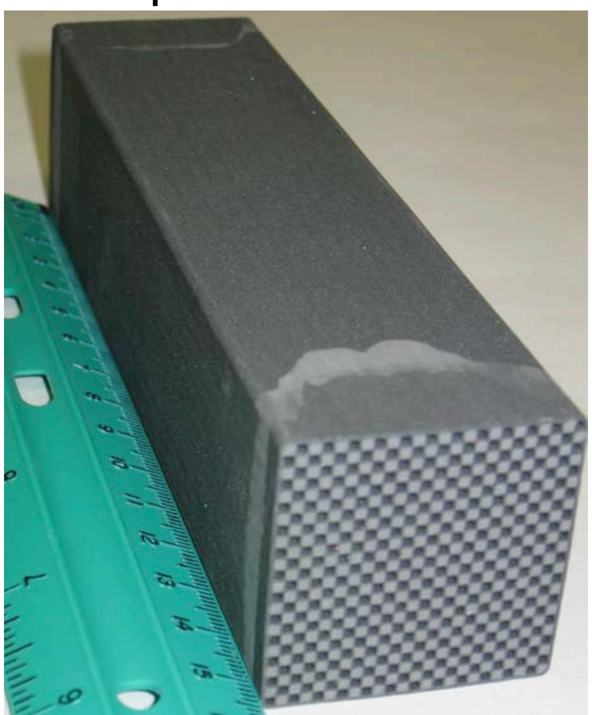
- Utilizes characterization tools acquired and maintained by the High Temperature Materials Laboratory (HTML) Program
- DPF substrate materials used in both DPFs and catalyst systems

Objective

- Implement test techniques to characterize the physical and mechanical properties of ceramic diesel particulate filters (DPFs) and develop analyses and inspection tools for assessing their reliability and durability.

Background: Why investigate SiC-based DPF

- SiC has not been used in HD industry
- Many differences exist between the LD and HD applications (e.g., much tougher durability requirements)
- Inherent underlying material difference: cordierite and AT are micro-cracked; SiC is not, which was expected to translate into different responses to stress

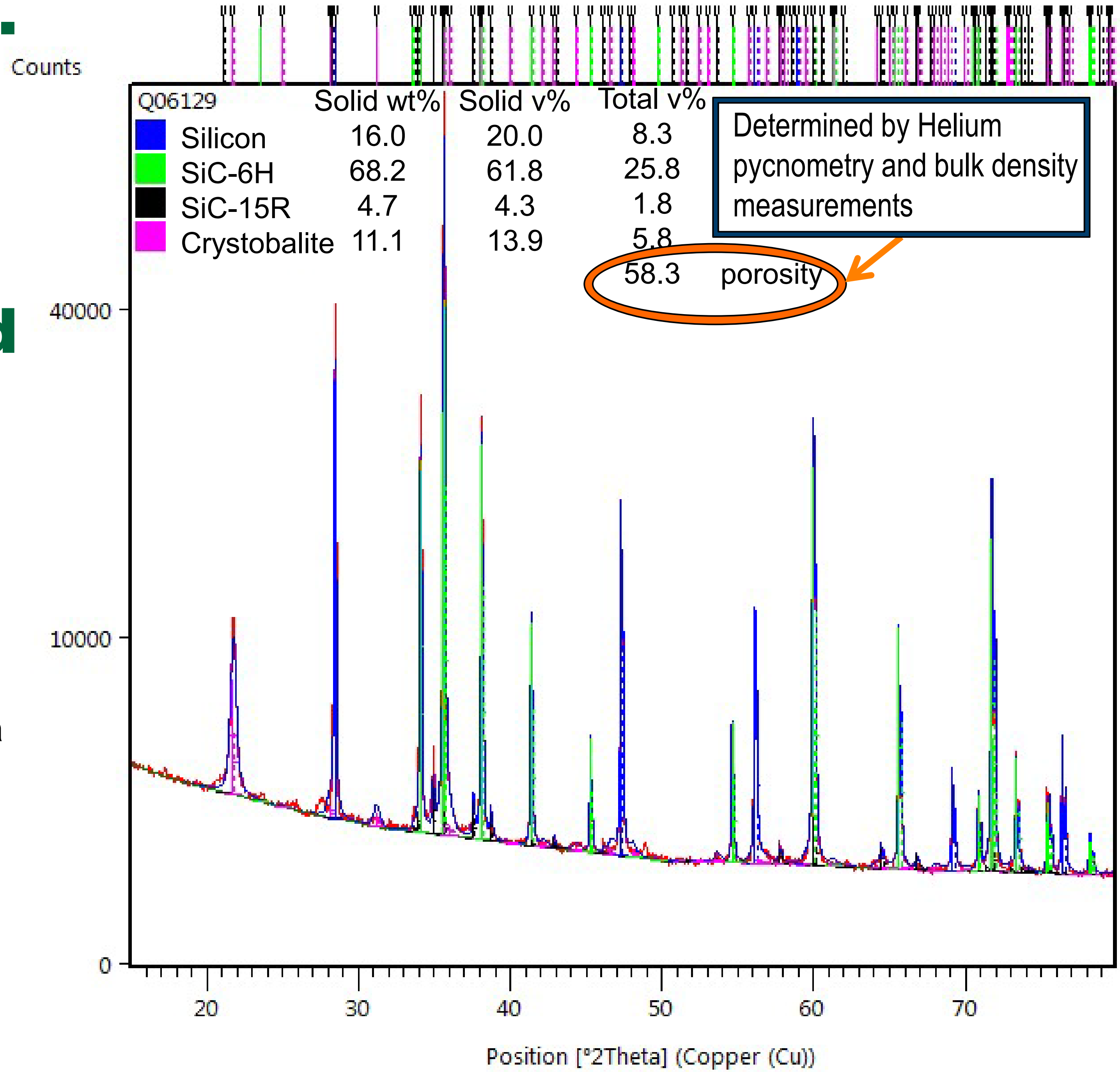


35 mm

Cell size = 1.1x1.1mm

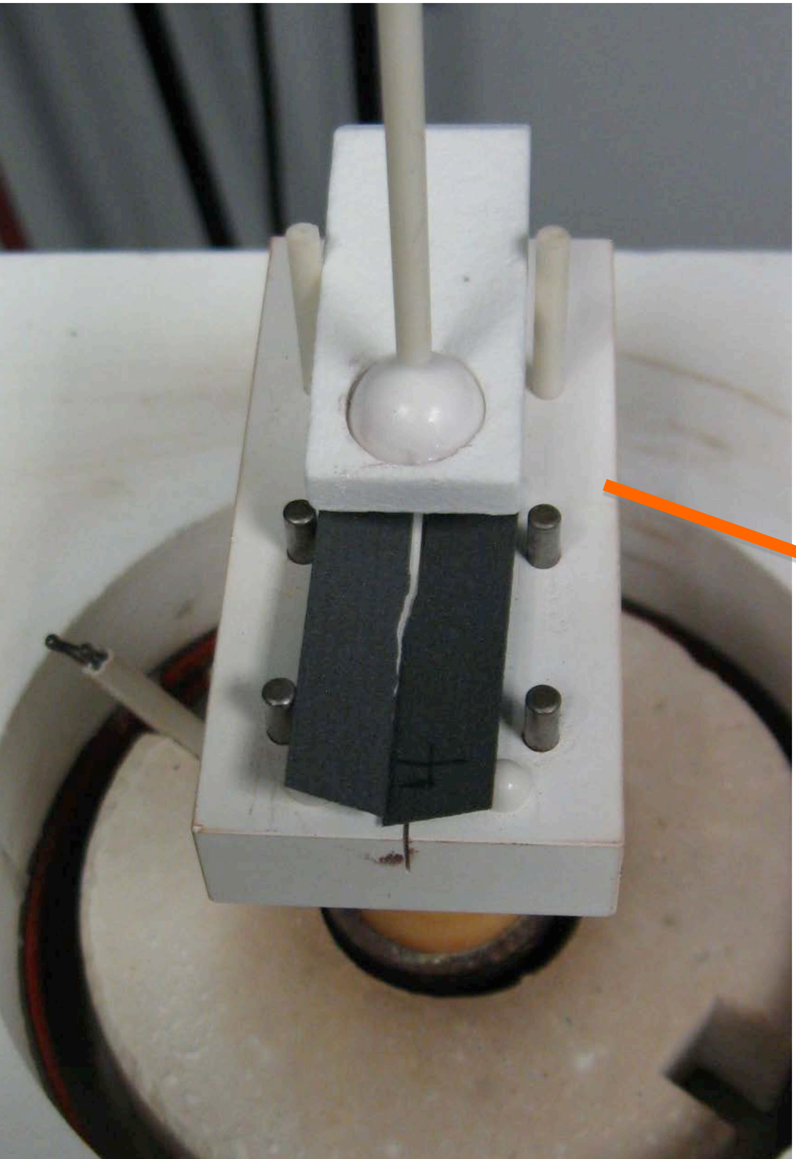
Wall thickness = 0.4 mm

Tech.Acc. : XRD identified four phases; quantified using Reitveld analysis

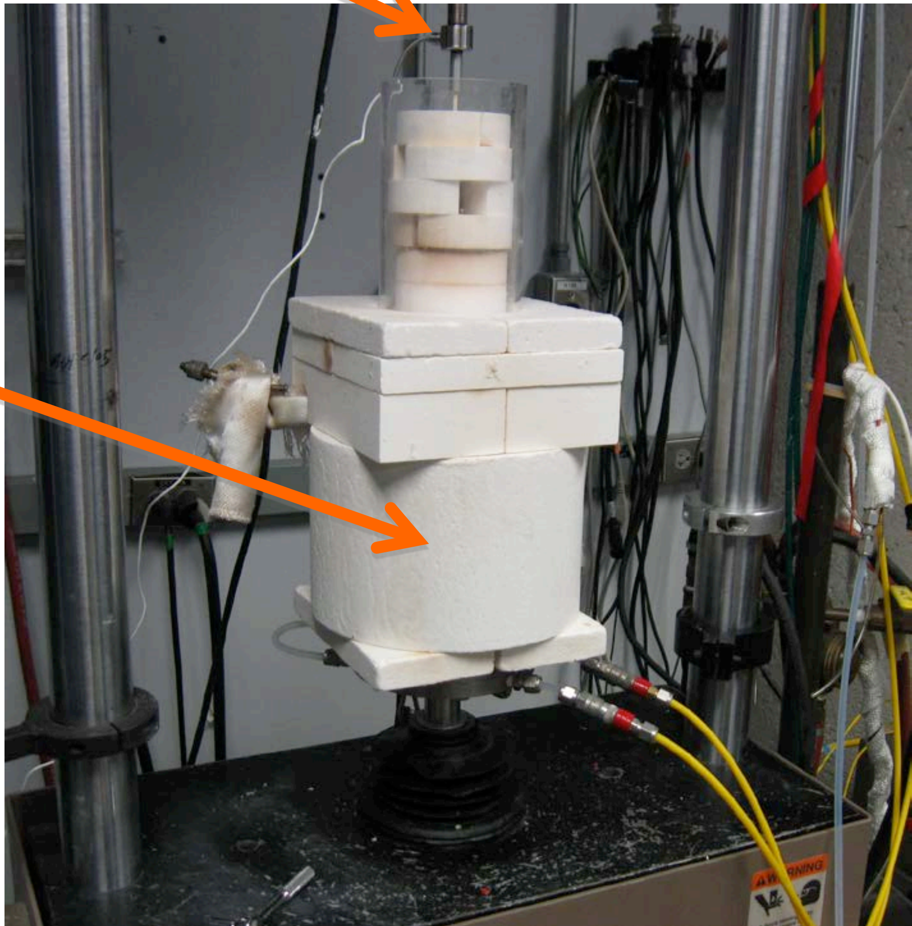


High Si V% of this material qualifies it as a porous siliconized SiC (Si/SiC) or reaction bonded SiC (RBSC)

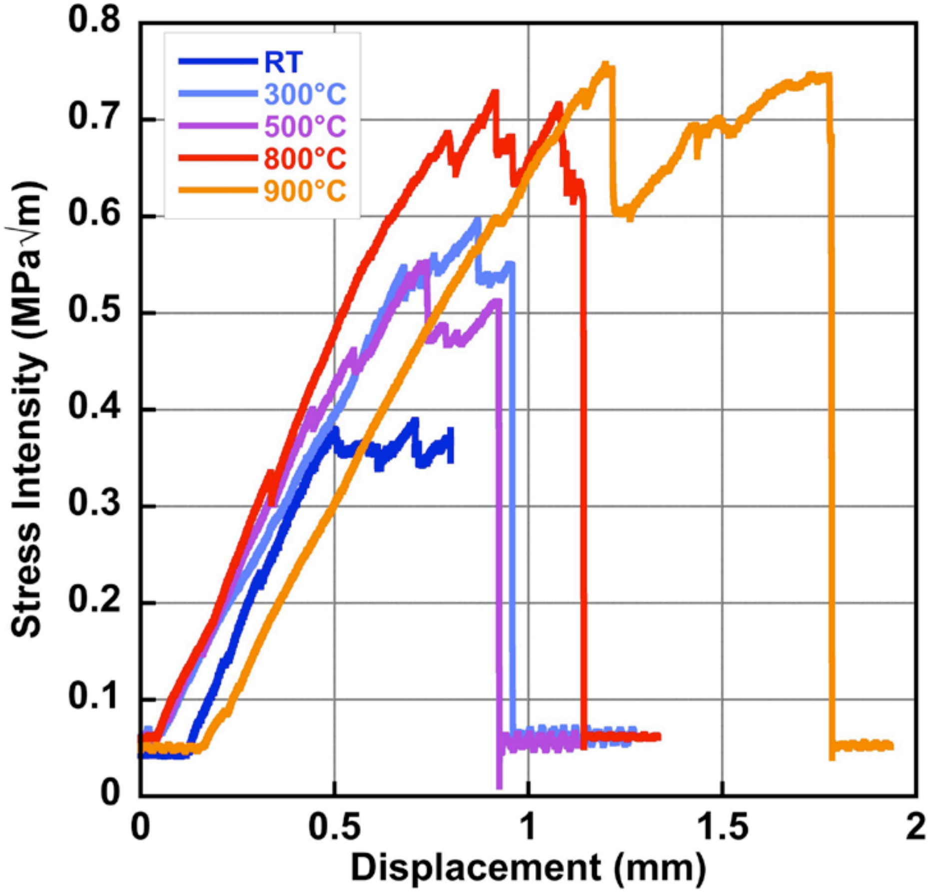
Technical accomplishment: High temp fracture toughness experimental Setup

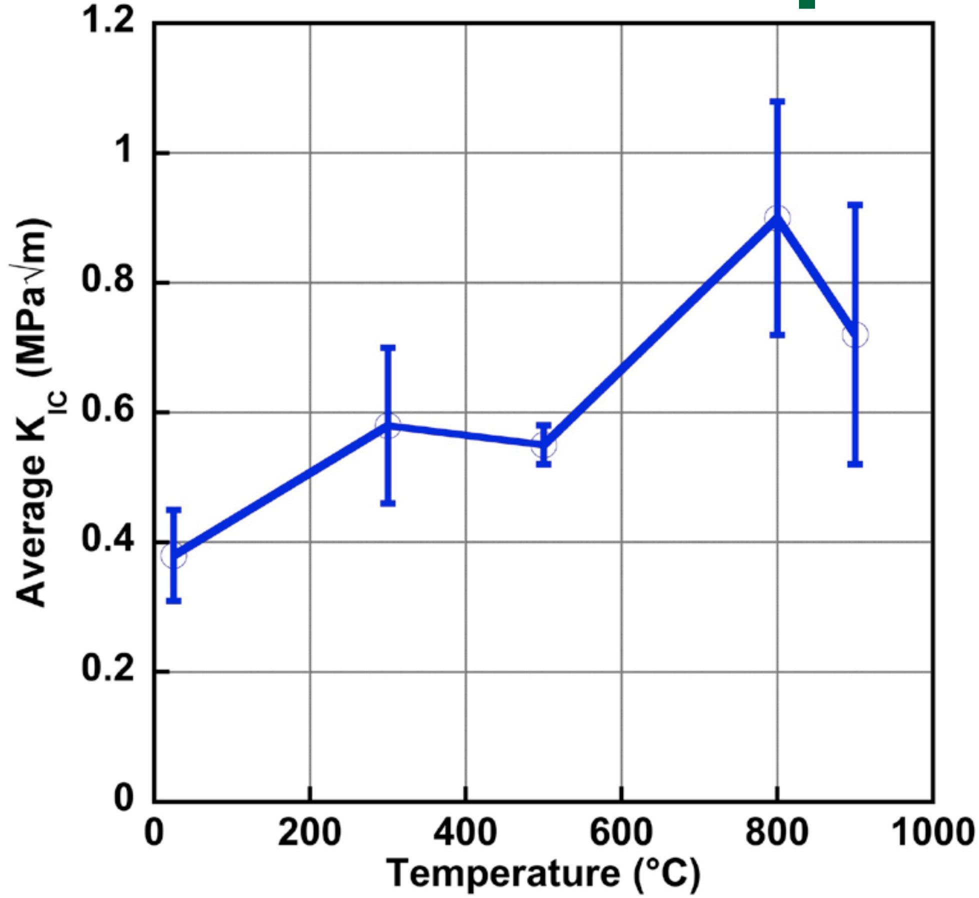


Load cell and Al_2O_3 push rod



Technical accomplishment: Toughness of SiC-based material increases with temp

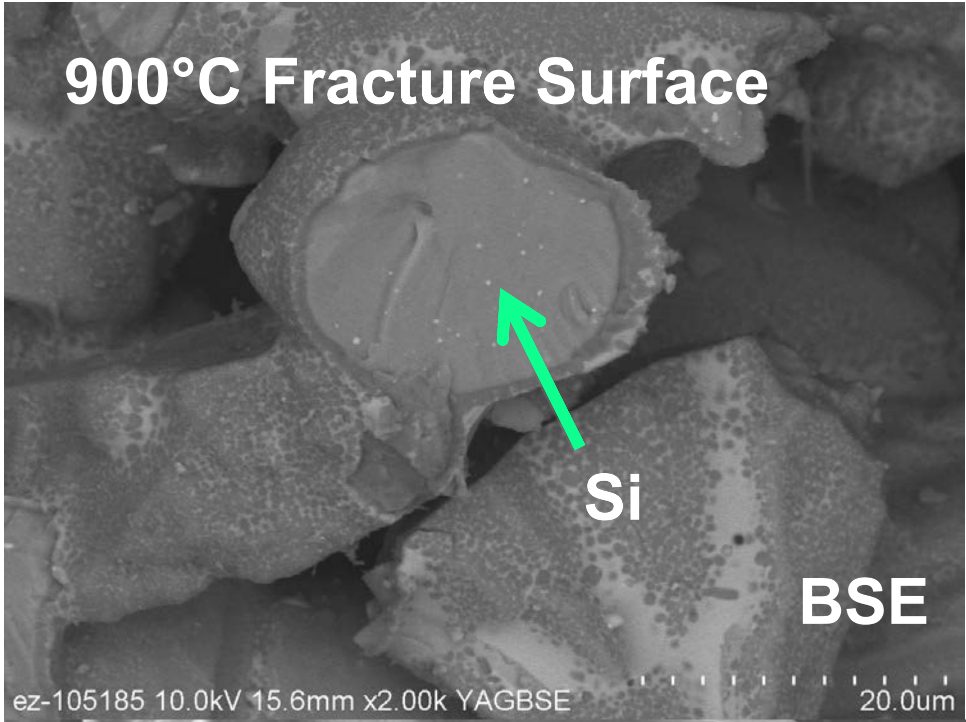


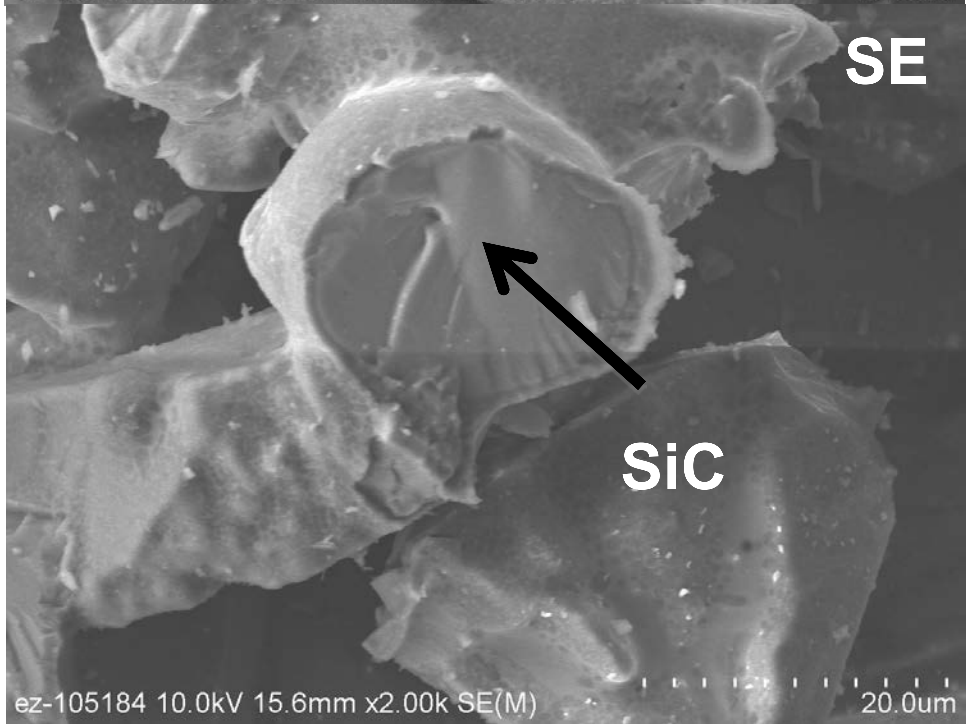


- Maximum load used to calculate K_{IC}
- Non-zero start-finish K_I due to double torsion jig top load/weight
- Slopes suggest moduli are slightly lower at HT
- Toughening mechanism likely related to free Si.

Tech.accomp.: Examined fracture surfaces to look for evidence of toughening mechanisms

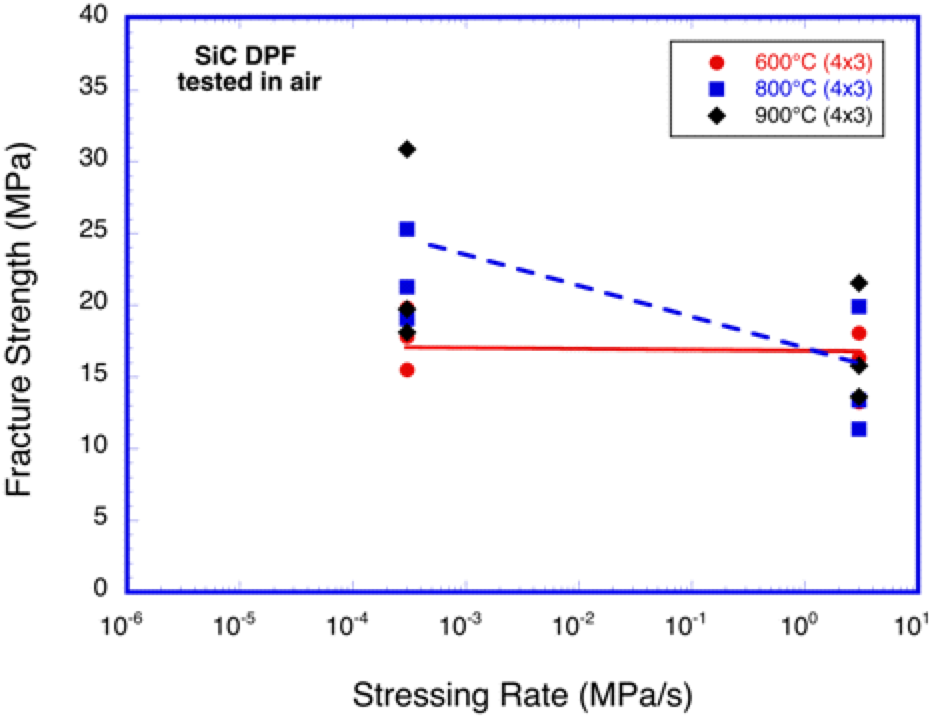
- RT and HT fracture surfaces of double torsion samples were similar, except for distinct oxidation layer in 800 & 900°C samples
- Simple static test showed permanent deformation after 24 hrs at 900°C
- Toughening mechanisms likely include:
  - Crack tip blunting, healing
  - Oxidation layer and/or possibly glass formation to close or fill in cracks/flaws
  - More in Reviewer Only slides

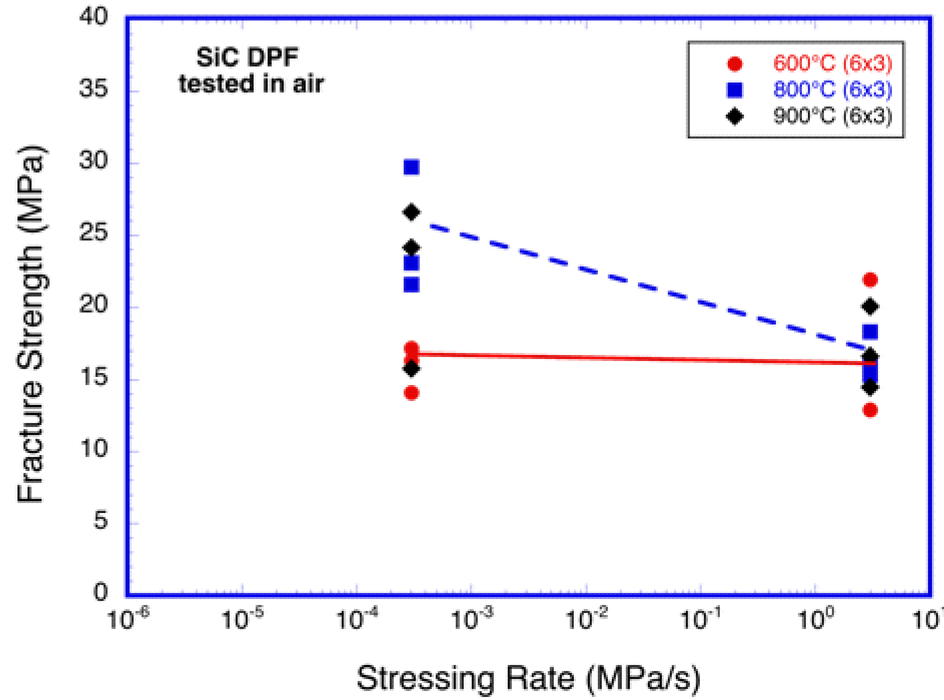




Tech.Acc.: There is an apparent stressing rate effect at temperatures ≥ 800°C

$\dot{\sigma}$: 35-45% increase in fracture strength when tested at 0.003 MPa/s (typically this decreases in most materials)





T: 800 & 900 C strengths larger than 600 C at slowest $\dot{\sigma}$
Size: No dependence with fracture strength was observed

Typical Si/SiC strength behavior with temperature*

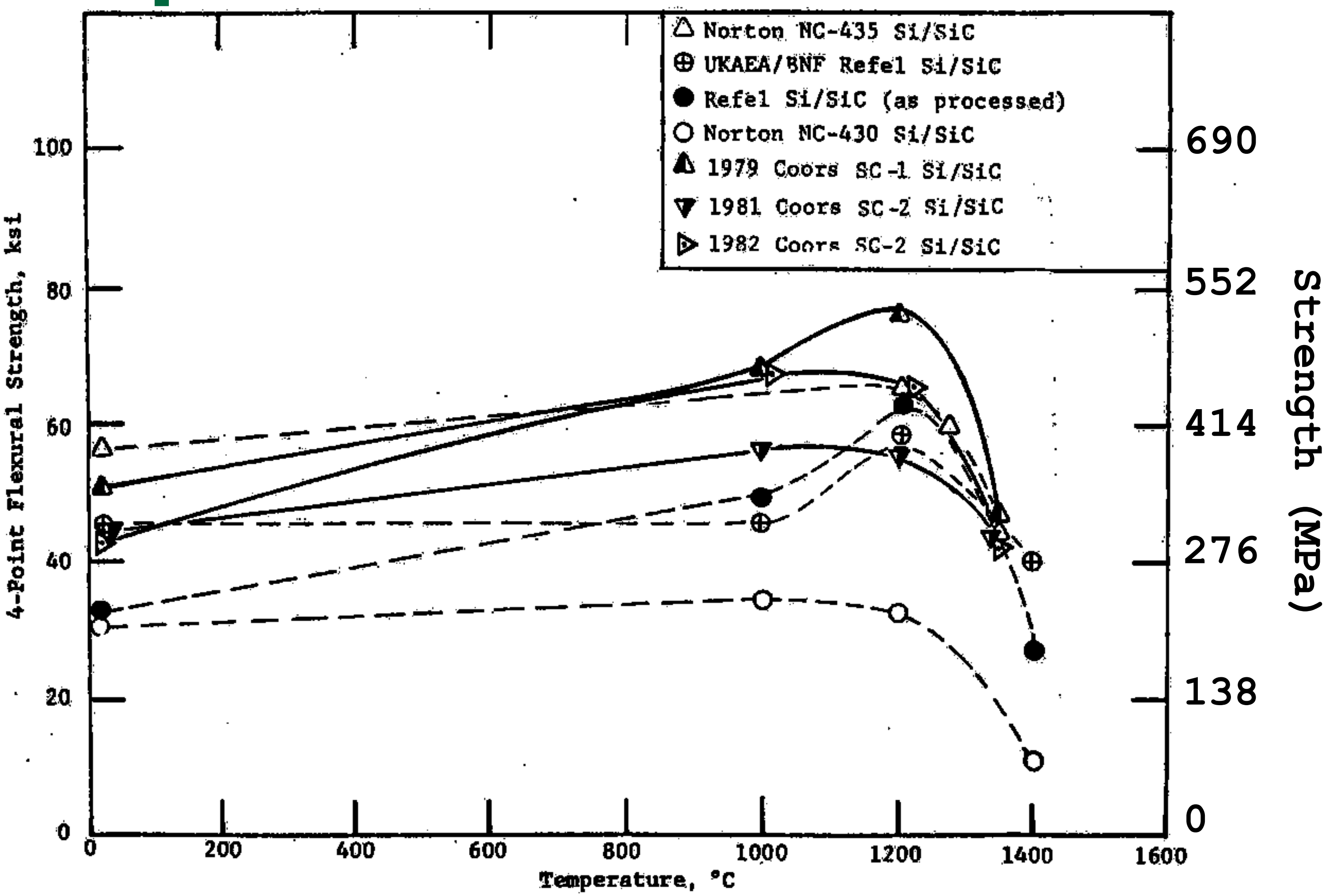
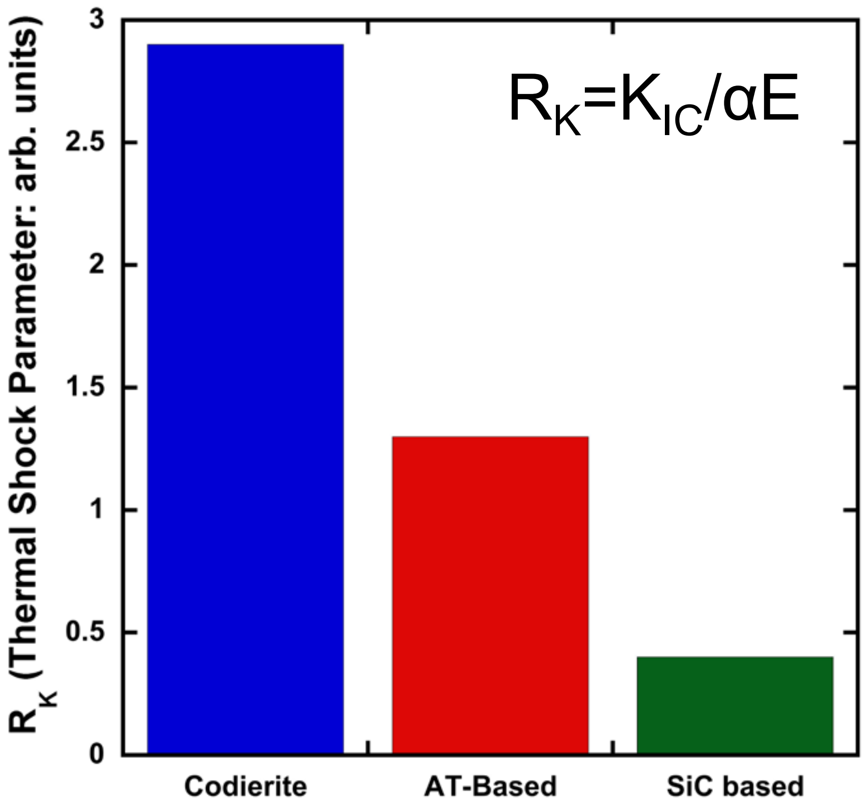


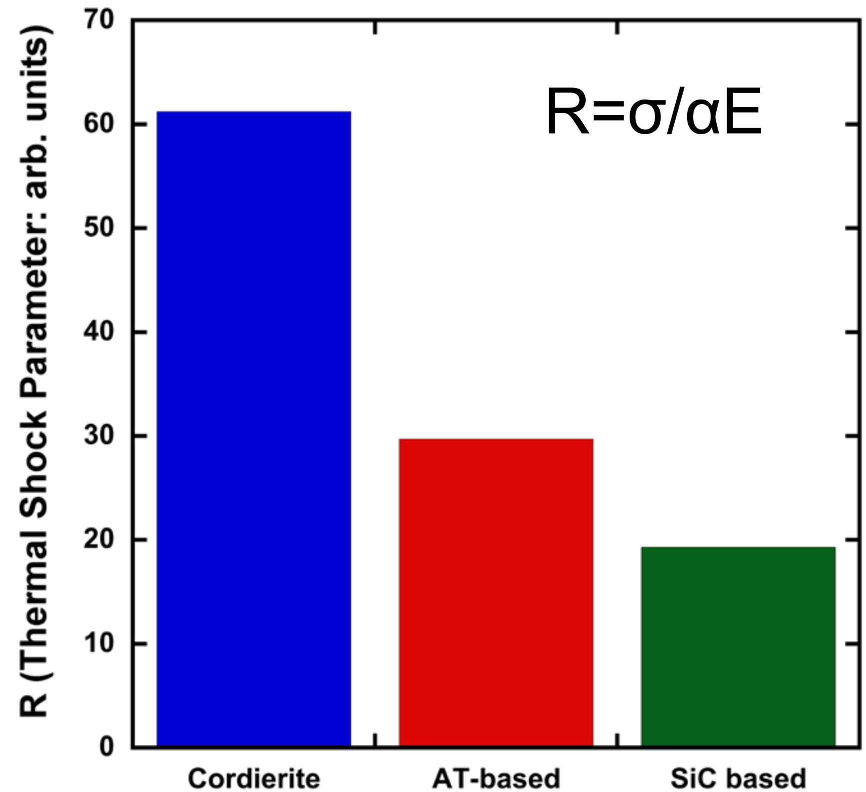
Figure 64. Flexural strength of siliconized silicon carbide materials.

*After: Larson and Adams, AFWAL-TR-83-4141, 1983.

Strength ⇧ with T: Tressler et al. (1985,1993); Larsen et al. (1979,1983); Tomlinson et al. (1992); Breder (1995); Huang&Zhu (2005)

Tech.Acc.: New thermal shock ranking methodology compared to traditional





- Trends are very similar; measured properties used
- R_K -Easier to perform fracture toughness tests than strength (less material and fewer samples)
- Note that the above analysis is highly simplified; assumes:
  - Homogeneity
  - Isotropy

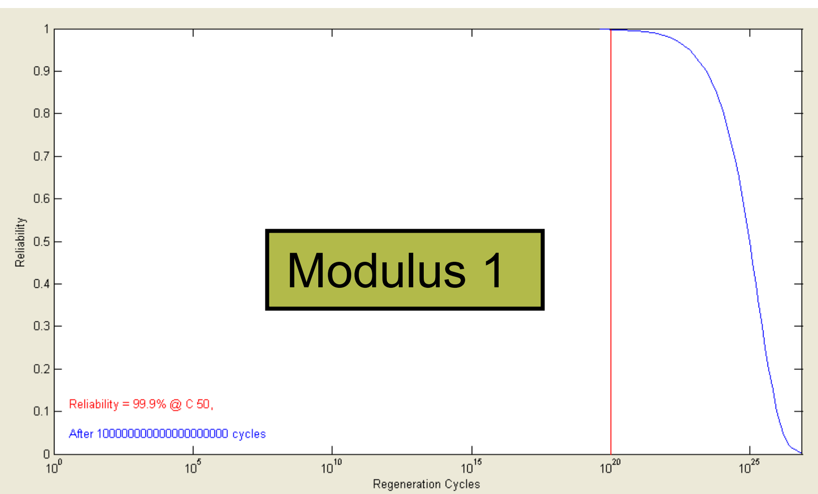
† Data is FY09-FY11 work

Collaborations and coordinations with other institutions: CRADA Partner

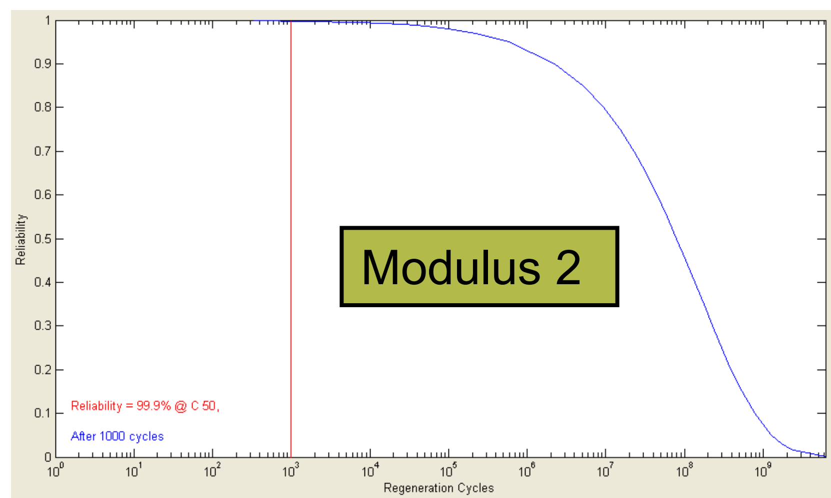
- Cummins (Industry):
  - Cummins' role is to collaborate and guide the work along the most useful path to achieve durability, cost and emissions targets
  - Supplies samples
  - Share experimental results on samples
  - Exchange of technical information to assist with each others analyses
  - Face to face meetings at least 2X/year

Collaborations and coordinations with other institutions: Tech transfer

- **CRADA data used to translate thermal maps into ANSYS stress models and inputs to life prediction code.**
- **Different stress results (from different Young's modulus inputs) give very different life predictions.**
- **More work to understand this effect of modulus measurement is necessary to optimize the stress and life models.**



99.9 % component will survive up to **$1x10^{20}$** cycles.



99.9 % component will survive up to **1000** cycles.

Future Work

- **Continue to characterize and understand the differences in measurement techniques for Young's moduli.**
- **Continue to characterize the dynamic and static fatigue response of SiC DPFs (FY11-13).**
- **Complete the determination of strength, fracture toughness, density/porosity/microstructure, and thermal expansion of coated DPFs as a function of time at elevated temperatures of a second alternate substrate (FY12 & 13).**

Summary: Property data support modeling which optimize regeneration which ***changes engine combustion regimes, improves durability, efficiency; reduces cost…VT goals***

- **Data is input into Cummins models and used to modify regeneration regimes to reduce the fuel penalties and improve filter durability (minimize thermal stresses).**

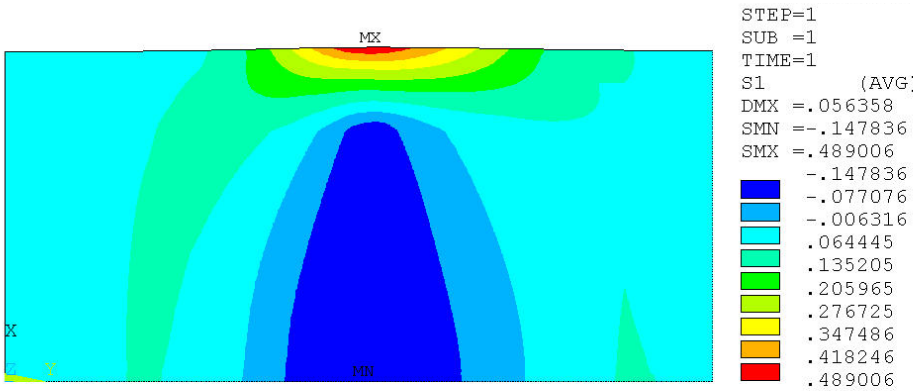
- **Investigated SiC-based materials as an alternate DPF material to cordierite**

- **Completed the determination of fracture toughness and microstructure of uncoated DPFs as a function of time at elevated temperatures of 300, 500, 800 and 900°C for SiC-based DPF materials.**

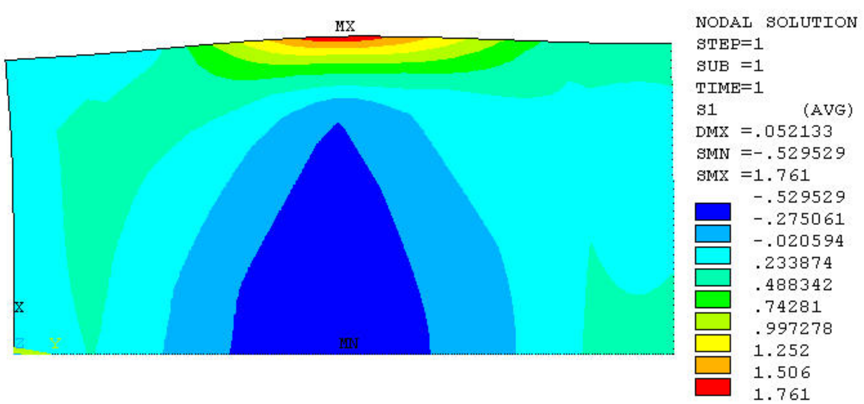
Technical Backup slides

Collaborations and coordinations with other institutions: Tech transfer2

- **The modulus for stress model was measured by RUS and sonic resonance.**
- **Values were corrected for porosity and temperature effects.**



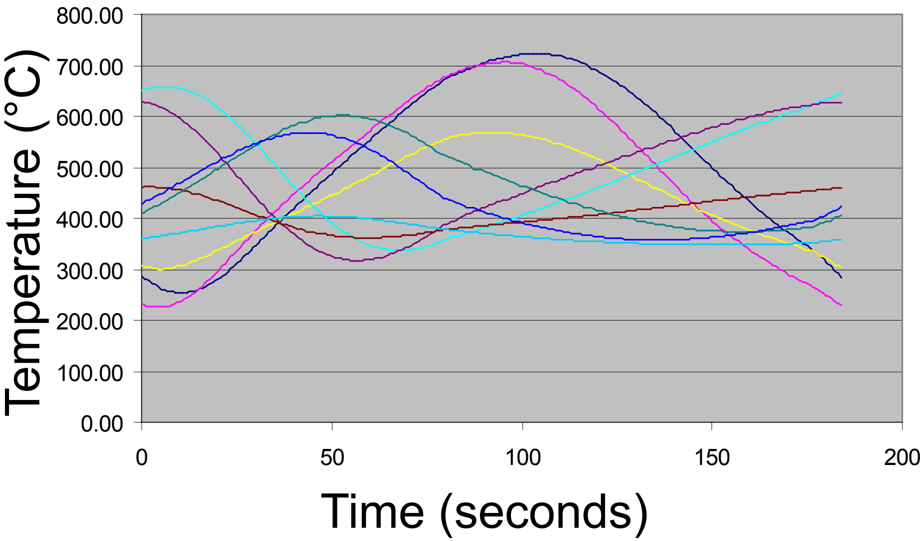
Modulus 1



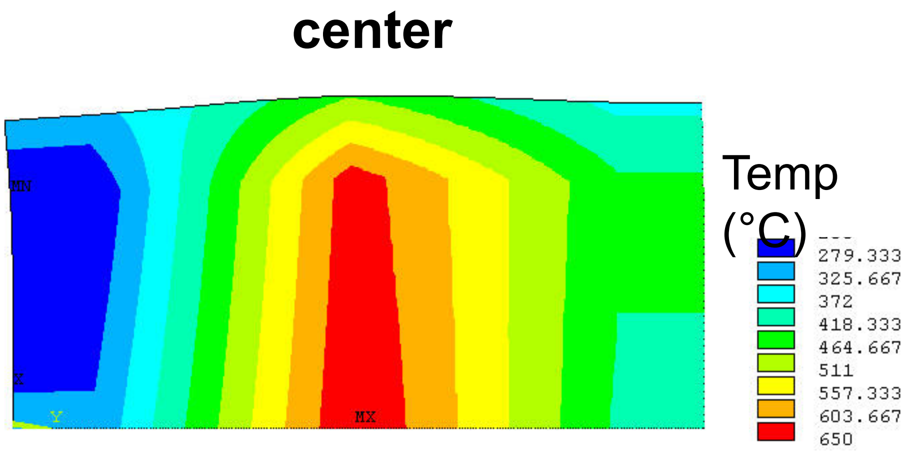
Modulus 2

Collaborations and coordinations with other institutions: Tech transfer3

- Efforts contributed to refinement of aftertreatment systems Dodge Ram Pickup truck
- CRADA data used to translate thermal maps into ANSYS stress models and inputs to life prediction code.



Thermal cycle temperature distribution (°C)



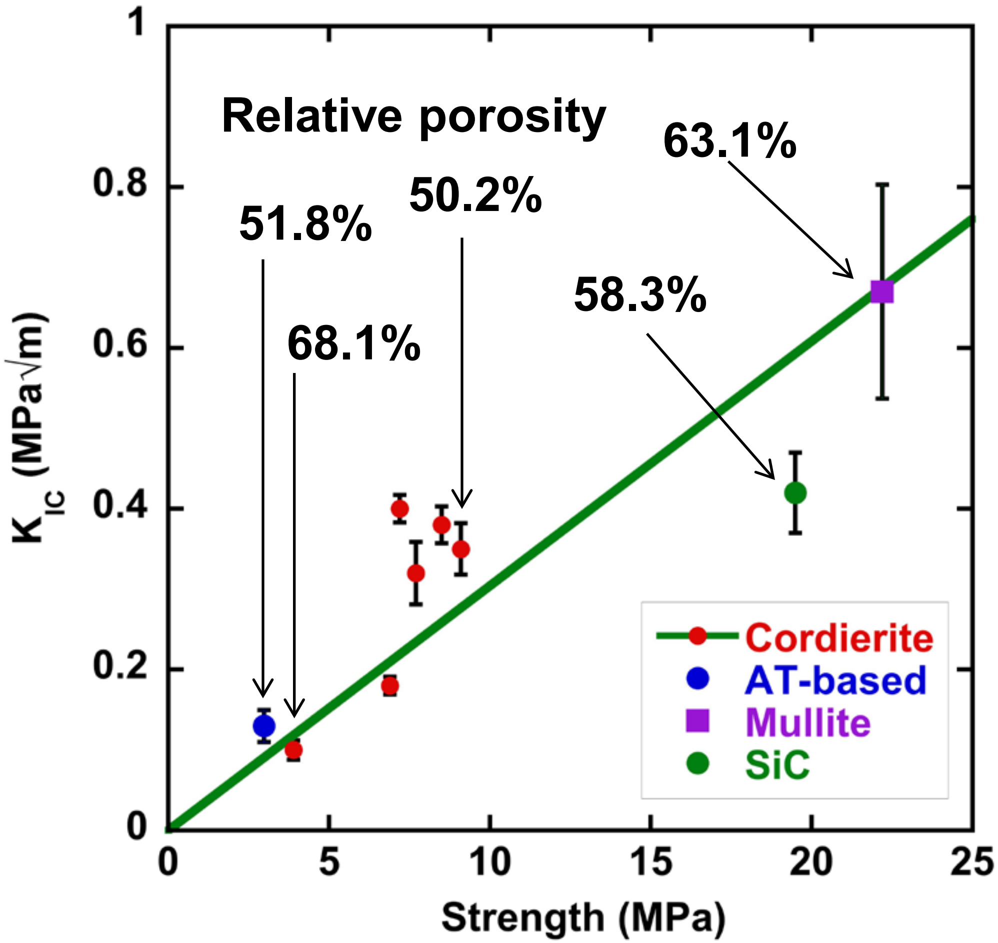
Temperature distribution at t = 0, (°C)

Literature for Si/SiC and RBSC heat exchangers suggest mechanisms for K_{IC} increase with temp

- Toughening mechanism(s) attributed to plastic/softening behavior of free Si at T>1000°C in dense materials
  - Crack tip blunting, healing 1
  - Stress redistribution due to grain cluster movement 1,3,7
  - GB softening, sliding 3,6,2
  - Creep cavitation (hard to see here) 1,3
- Behavior is dependent upon volume fraction of Si, temperature, time at temperature and stress level 1,4
- Oxidation and/or possibly glass formation to close or fill in cracks/flaws 5,6

1. Tressler et al. (1985,1993); 2. Larsen et al. (1979,1983); 3. Wiederhorn et al. (1988,1992,1996); 4. Chakrabarti&Das (2001); 5. Tomlinson et al. (1992); 6. Huang&Zhu (2005); 7. Breder (1995).

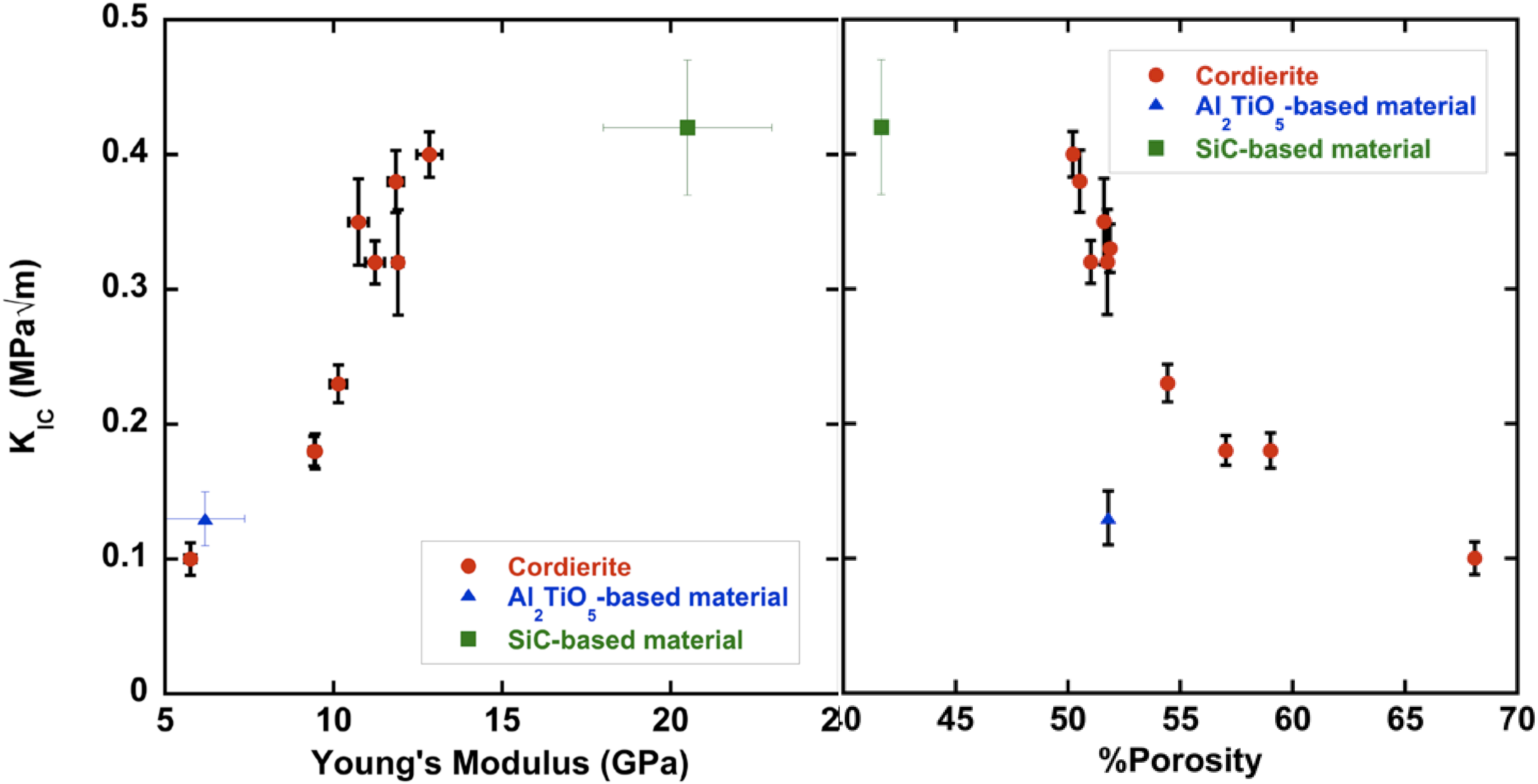
Porosity dominates Properties: e.g. K_{IC} – Strength Correlation



- Strength values for honeycomb bars corrected for Moment of Inertia (MOI)
- Increasing fracture toughness leads to increasing strength
- It is easier to perform fracture toughness tests compared to strength tests (fewer specimens and less material)

† Cordierite & mullite data is FY09 work; AT-based data is FY10 work

K_{IC} of porous DPFs appear to have a semi-linear relationship with Young's modulus and porosity



[†] Cordierite & mullite data is FY09 work; AT-based data is FY10 work