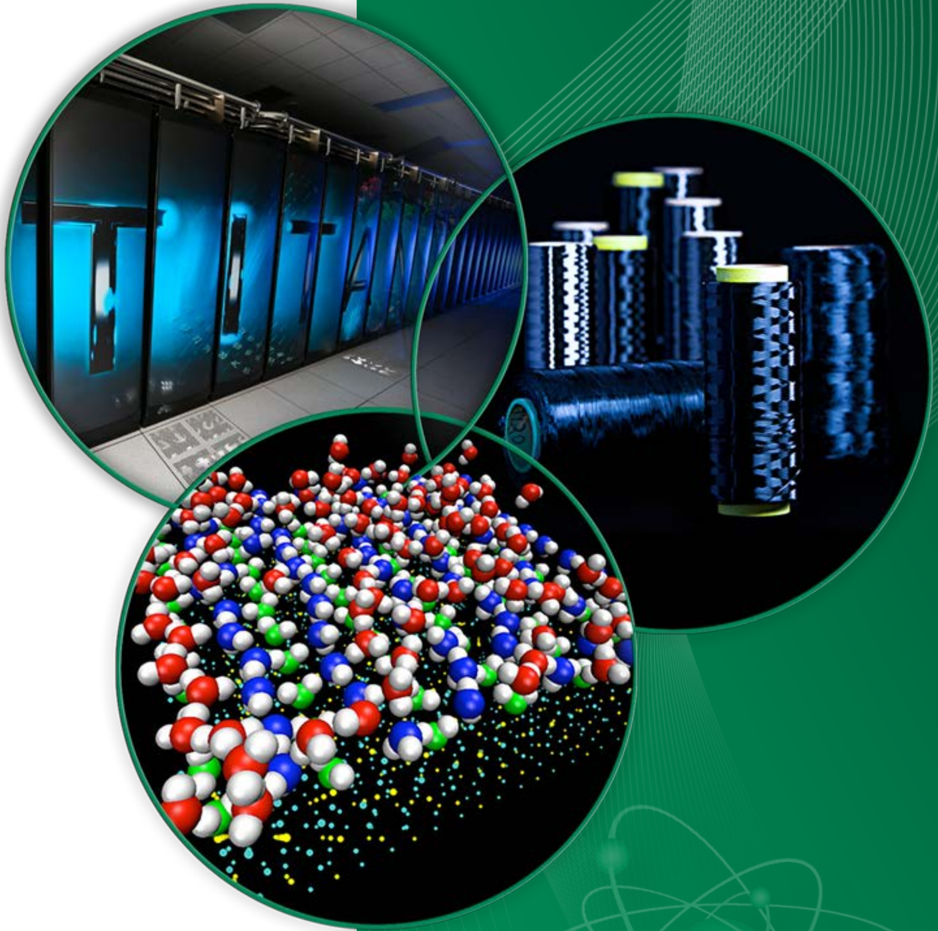
# Durability of Diesel Engine Particulate Filters

Project ID: PM010



2013 DOE Vehicle Technologies Annual Merit Review and Peer Evaluation Meeting

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Randall Stafford; *Cummins Inc.*

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

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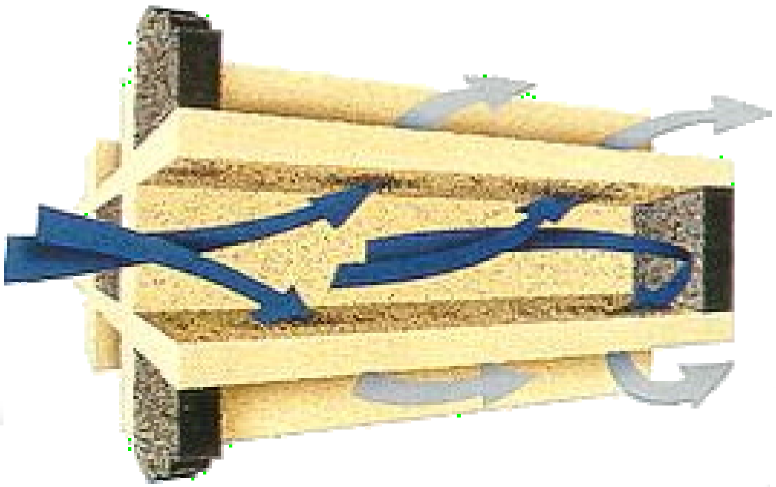
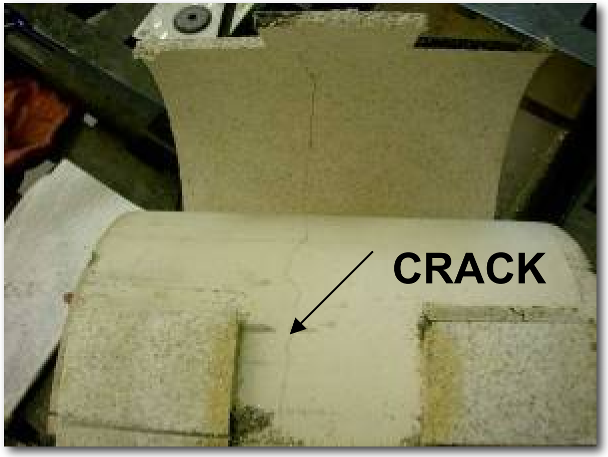
# Background to CRADA

- 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 incurred during regeneration.
- 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 delivered key materials properties information, which enabled application and optimization of the prime path DPF technology, and contributed to down-selecting some alternative materials**
- The elastic moduli are considered here





# Overview

## Timeline

- Start: June 2004
- End: Sept. 2013
- 96% complete

## Budget

- Total Project funding
  - DOE-$2.77M
  - Cummins-$2.77M
- Funding received:
  - FY12 $300k
  - FY13 $170k approved

## Barriers* - Propulsion Materials Technology:

- Changing internal combustion engine 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

- "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* "
- "By 2015, improve the fuel economy of light-duty diesel vehicles by 40%, compared to the baseline 2009 vehicle* "
  - Understanding the relationship of the porosity to the material properties of the filter (and catalyst) substrates leads to optimized regeneration strategies, thermal management and filter efficiency.
  - Increases acceptance of clean diesel resulting reduction in petroleum consumption

* Vehicle Technologies Program, Multi-Year Program Plan 2011-2015, Dec 2010, pp. 2.5-7, 2.3-2.

# Milestones FY12 & FY13

- 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.

- FY13: (1) Determine the origins of the load dependent Young's moduli and quantify the impact of the microstructure on same. (2) Complete characterization of the dynamic and static fatigue response of SiC DPFs.

# Technical Approach/strategy:

- Characterize the materials properties and microstructure of the ceramic DPF substrates.  Properties to be measured include: Young's modulus, fracture toughness, dynamic fatigue, density, thermal expansion and phase content of current and candidate DPF materials supplied by Cummins.
- A new miniature tensile rig with digital image correlation to record load and displacement, respectively, will measure the tensile Young's modulus.
- Refinement of DPF service lifetime prediction models based on measured properties (Cummins).

# ...addresses barriers:

- The above provides materials behavior and property data to models which optimize regeneration. This *changes internal combustion engine regimes*, minimizing the fuel penalty and the reducing the thermal stresses. This also improves *durability* and thereby reduces *cost*, resulting in more *cost-effective emission control*.

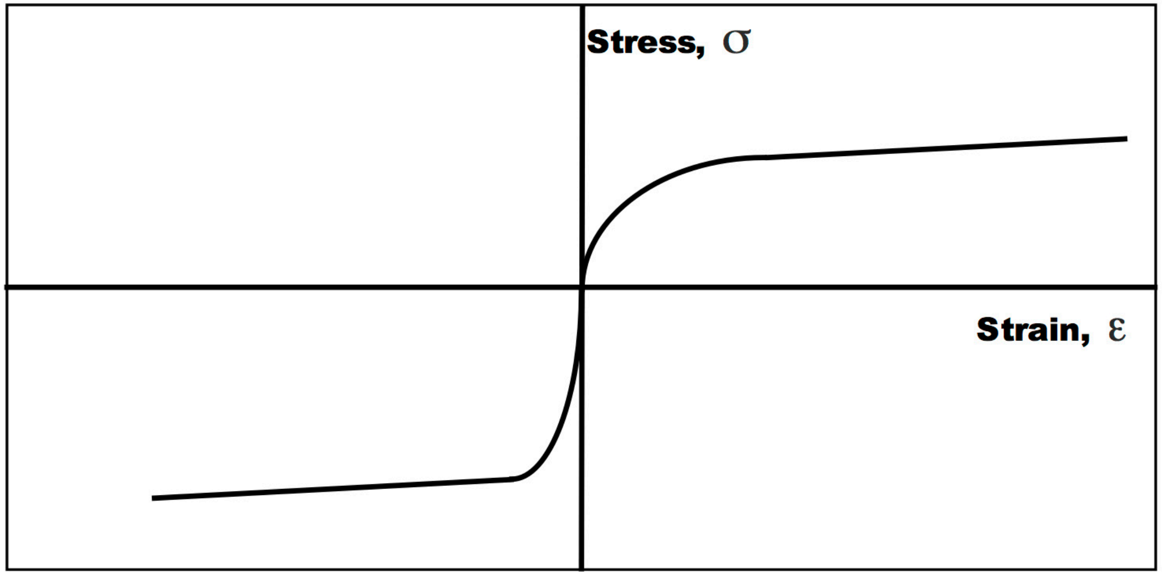
# Approach/strategy: Integration within Vehicle Technologies program

- Utilizes characterization tools acquired and formerly maintained by the High Temperature Materials Laboratory (HTML) Program
- DPF substrate materials used in both DPFs and catalyst systems
- Discussing and utilizing ideas from pm041-Electrically-Assisted Diesel Particulate Filter Regeneration (ORNL)

# Objective

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

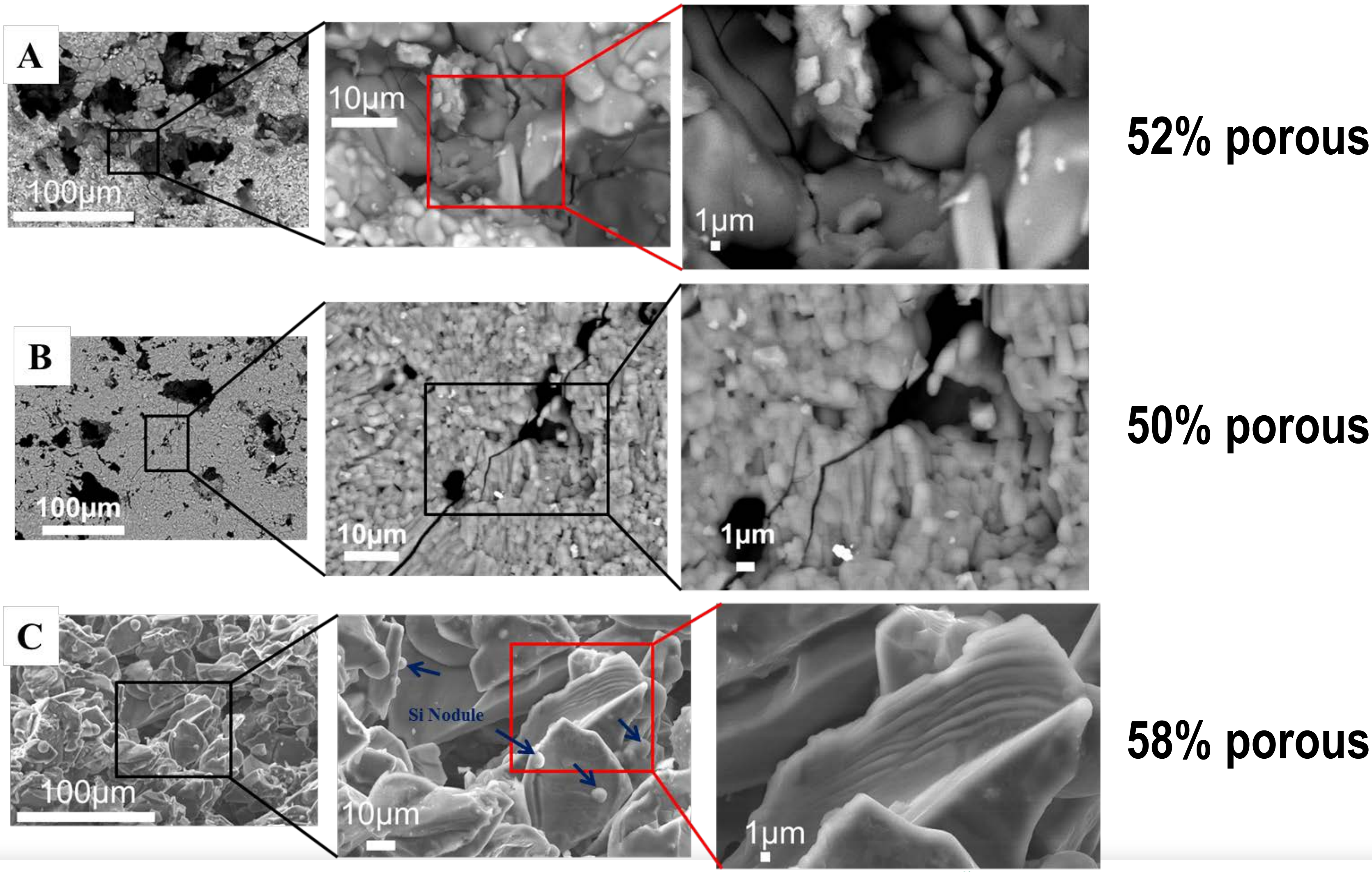
# Background: Elastic modulus is a *critical* property for models but difficult to quantify because it is non-linear in DPF materials*



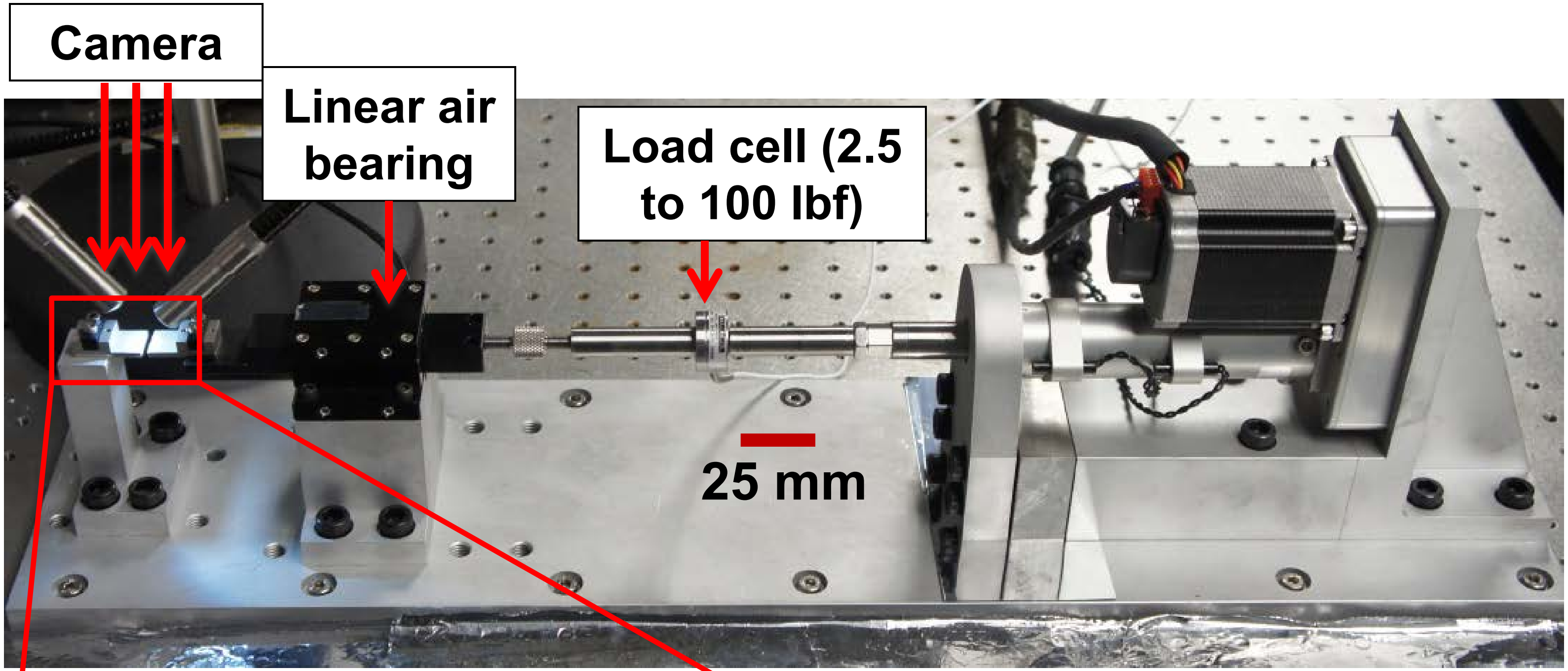

- Dynamic techniques: low loads, high moduli: 10-14 GPa cordierite**
- Static techniques: higher loads, lower moduli: 1-3 GPa cordierite**
- Microstructure: porosity and microcracks and "Honeycomb" structure play a role

*Wereszczak et al., "Failure Stress and Apparent Elastic Modulus of Diesel Particulate Filter Ceramics," SAE Int. J. Mater. Manuf., **5**(2) 517- 27 (2012).
**Stafford et al., 2012, 37th International Conference and Exposition on Advanced Ceramics and Composites (ICACC 2013).

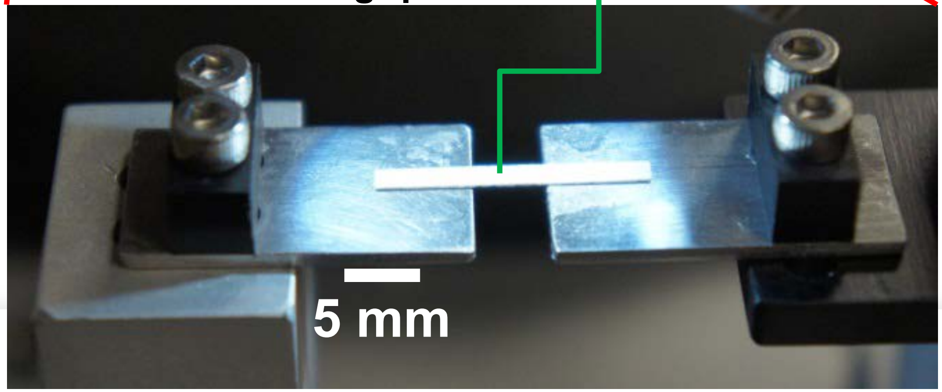
# Tech.Acc.: Microcracks vary with material
# Aluminum titanate(AT) based material→high μcrack ρ
# Cordierite (Duratrap CO)→medium μcrack ρ
# Silicon carbide (SiC) based material→no μcracks



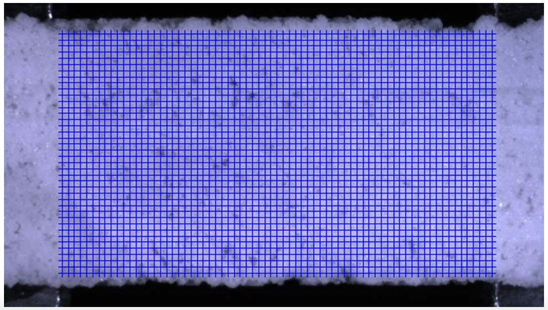
# Tech.Acc.: New microtesting rig determines pulls DPF plate in simple tension and measure strain using digital image correlation (DIC)




DPF wall specimen glued at both ends on grips

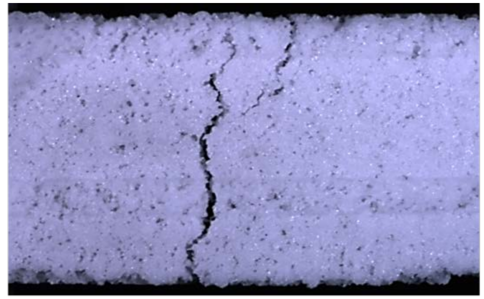



Camera Image + DIC



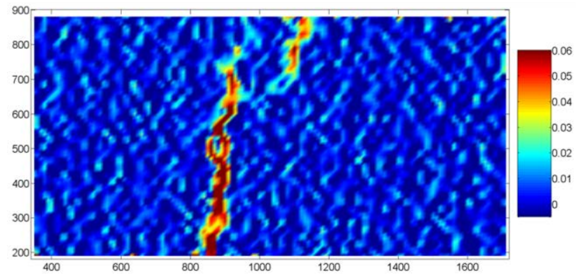
# Tech.Acc.: 2D strain maps: DIC displays localized strains near failure

Camera Image

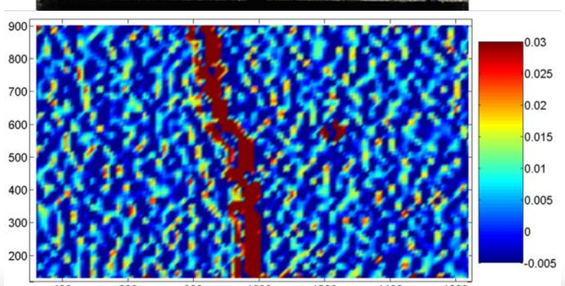


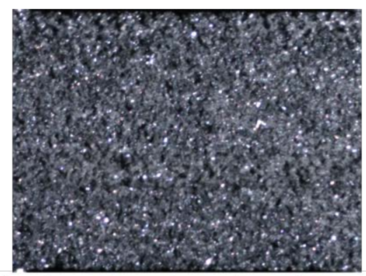
AT

DIC

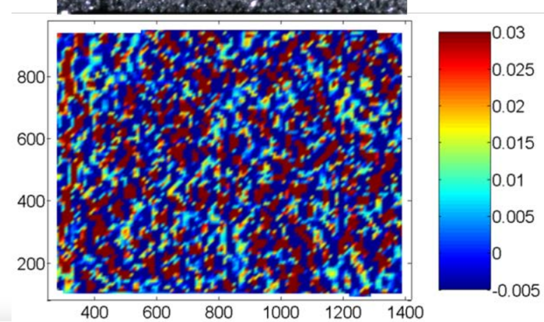



Cordierite



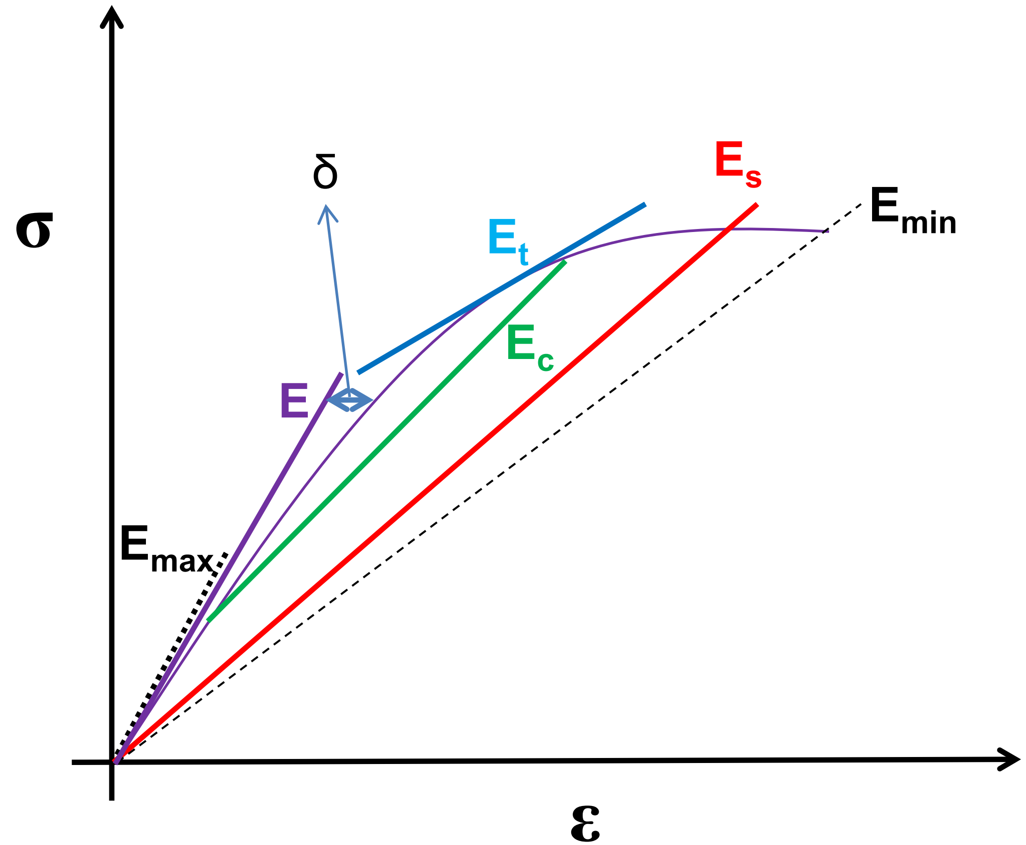



SiC



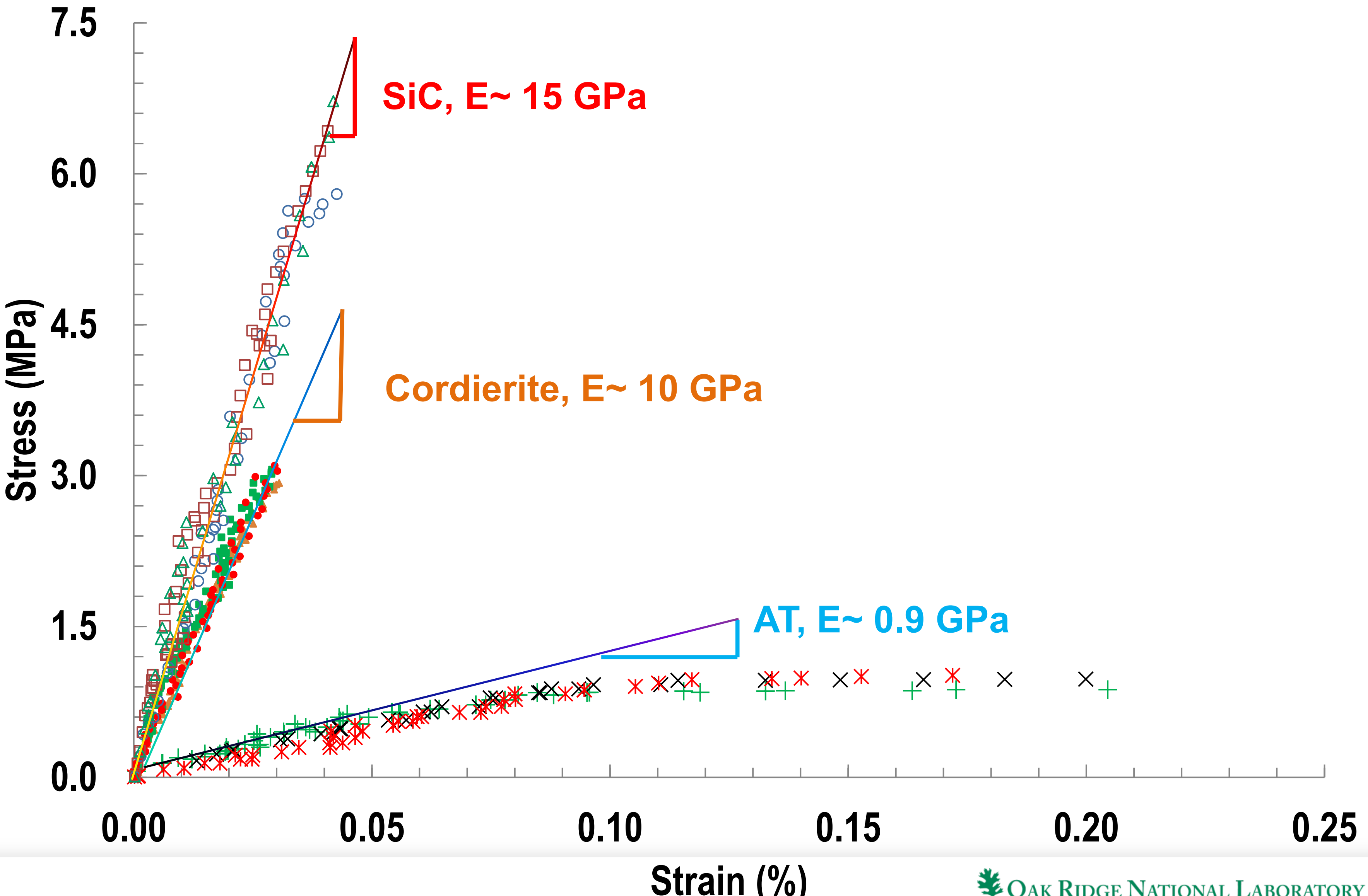
# Tech.Acc.: Various definitions of Modulus exist for materials with a stress-strain relationship that is non-linear

1. **Modulus of Elasticity/ Young's modulus (E)***: the linear portion of the engineering stress –strain curve below the proportional limit.
2. **Secant modulus ($E_s$)****
3. Tangent modulus ($E_t$)
4. Chord modulus ($E_c$)

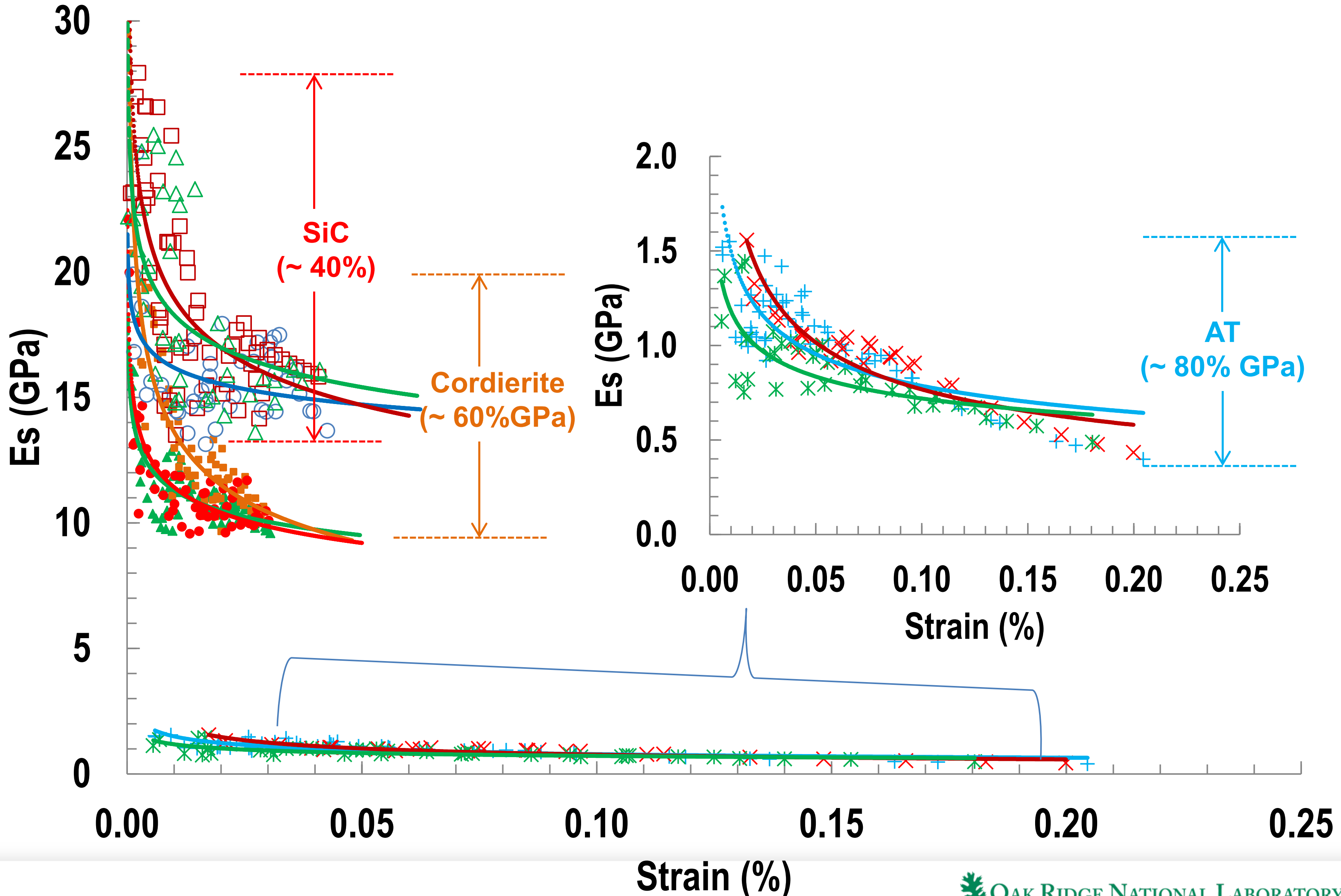



*Here, the proportional limit is defined as the stress corresponding to a *50 με deviation from linearity (δ)* in the stress-strain curve.
***Wereszczak et al., "Failure Stress and Apparent Elastic Modulus of Diesel Particulate Filter Ceramics," SAE Int. J. Mater. Manuf., 5(2) 517- 27 (2012).

# Tech.Acc.: Non-linearity increases with μcrack ρ

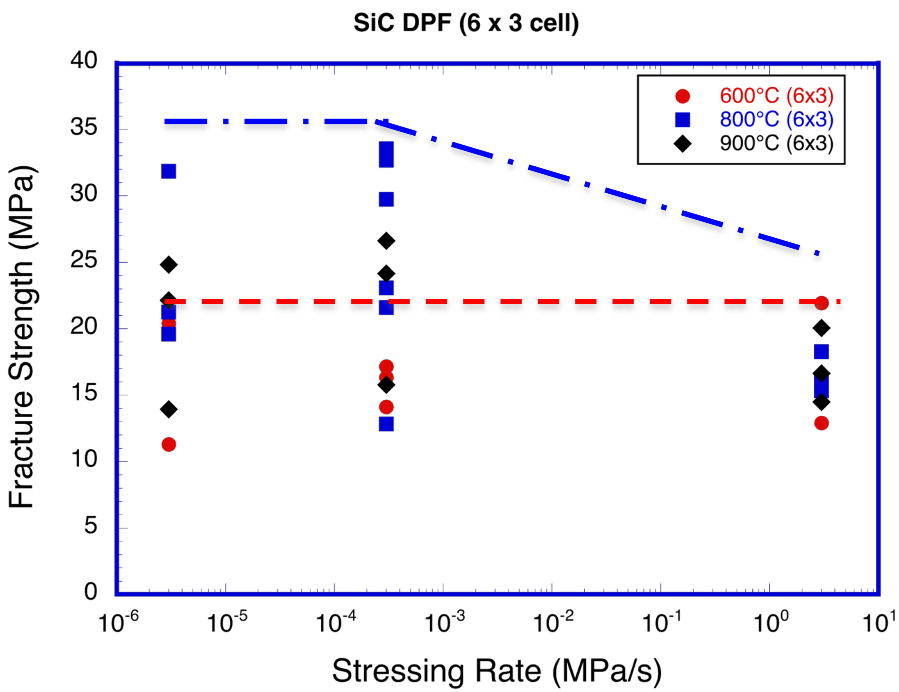


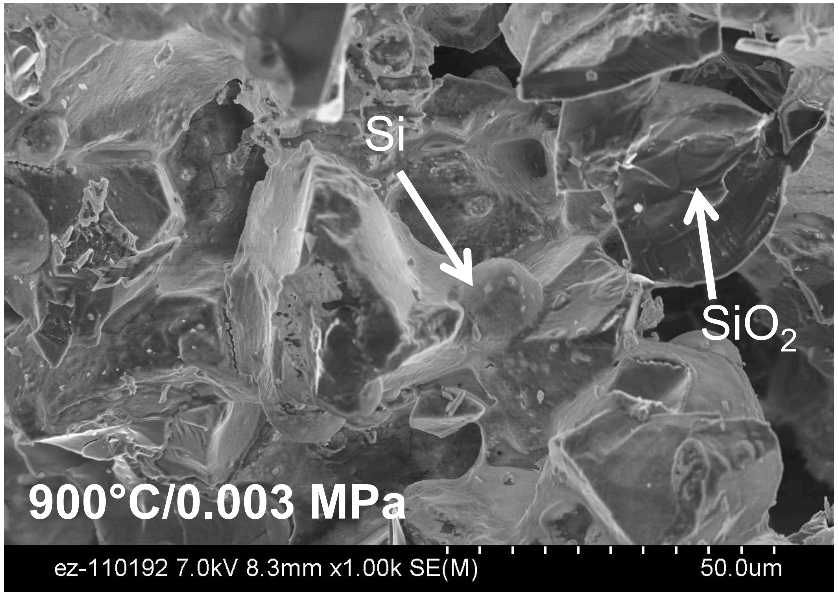
# Tech.Acc.: Secant Modulus (Es) decreases with increasing strain, ε



# 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)
- More extensive oxidation leading to defect healing and crack blunting could in part lead to the observed increase in fracture strength



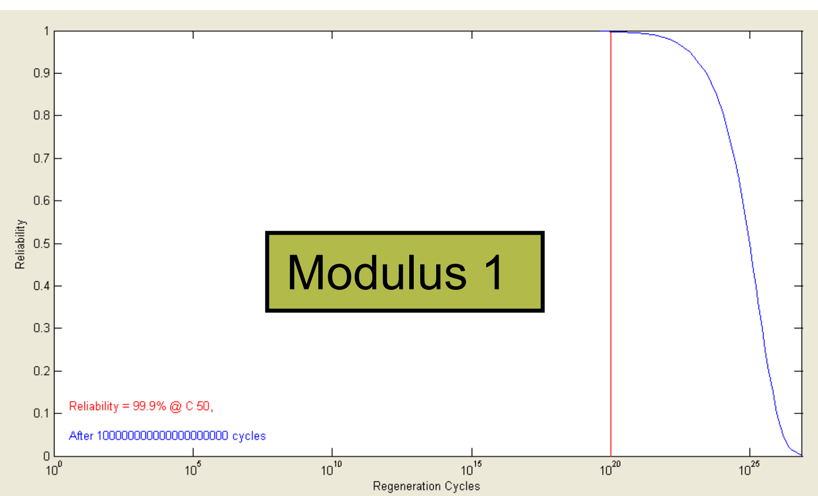

- Temperature: 800 & 900°C strengths larger than 600°C at slowest $\dot{\sigma}$
- Size: No dependence with fracture strength was observed

# Collaborations and coordinations with other institutions: CRADA Partner

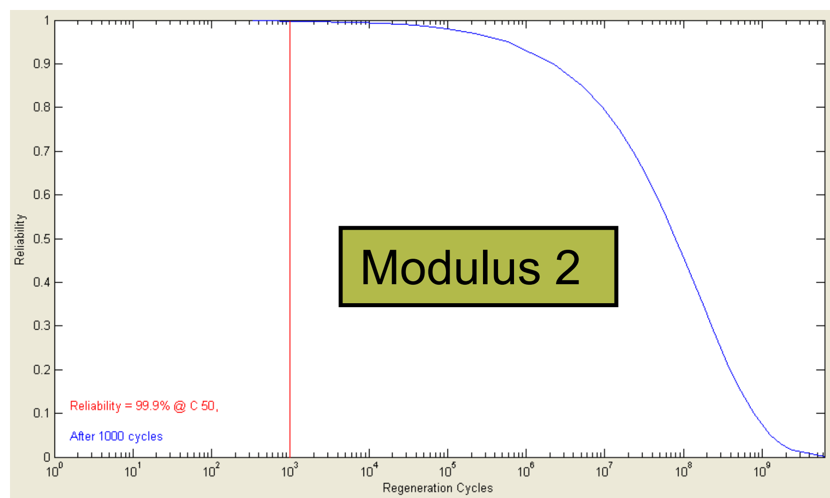
- Cummins (Industry):
  - Cummins' role is to collaborate and guide the work along the most useful path to achieve durability, cost and emissions targets
  - Supplies samples
  - Share experimental results
  - Exchange of technical information to assist with each others analyses
  - Face to face meetings
- Technical discussion with ORNL staff on pm041

# 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.

# Proposed Future Work

- Planning for CRADA to renew
- Characterization of compressive and bending moduli.
- Characterization of the dynamic and static fatigue response under the temperature ranges relevant to the engine operating conditions of a 3rd alternate substrate material.
- Determination of strength, fracture toughness, density/porosity/microstructure, and thermal expansion as a function of time at elevated temperatures of a 3rd alternate substrate material.
- Initiate new testing methodologies for measuring fracture toughness/fracture energy of these highly porous materials.
- Model development to complement the new testing methodologies for fracture toughness/fracture energy of the highly porous materials.

# Summary

- **Relevance:** Property data generated by this CRADA is input into models accurately to predict DPF behavior during regenereation. 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*.

- **Approach/Strategy:**
  - Characterize the materials properties and microstructure of the ceramic DPF substrates supplied by Cummins.
  - Refinement of DPF service lifetime prediction models (Cummins).

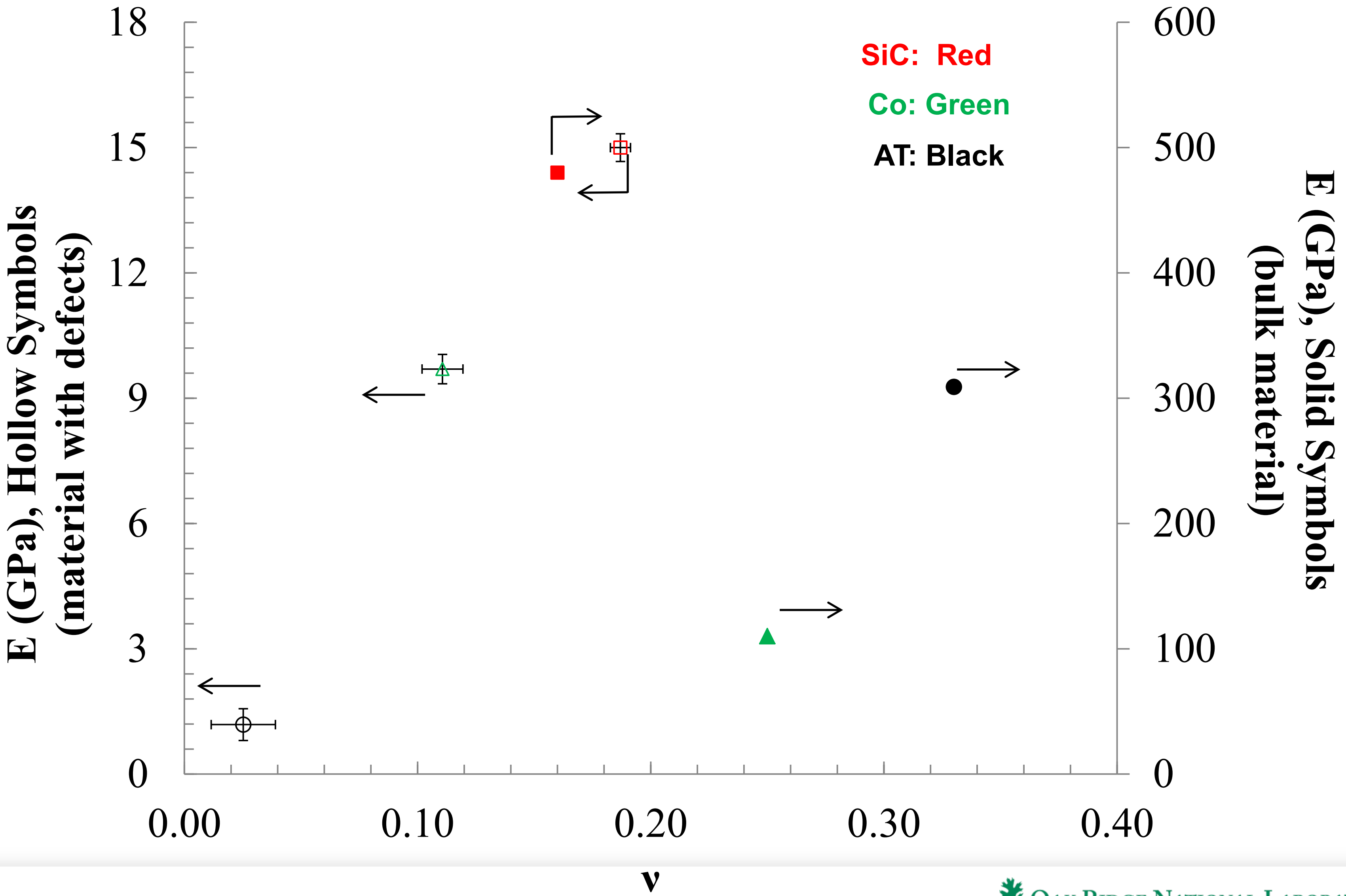
- **Technical Accomplishments:**
  - Built new mini tensile rig with DIC and measured the tensile Young's modulus.
  - Non-linearity of stress strain behavior increases with microcrack density
  - Secant Modulus decreases with increasing strain
  - Strength increases with stressing rate likely due to crack blunting from glass and silicon

- **Collaborations and Coordination with Other Institutions:** Cummins inputs these materials properties into their in-house models

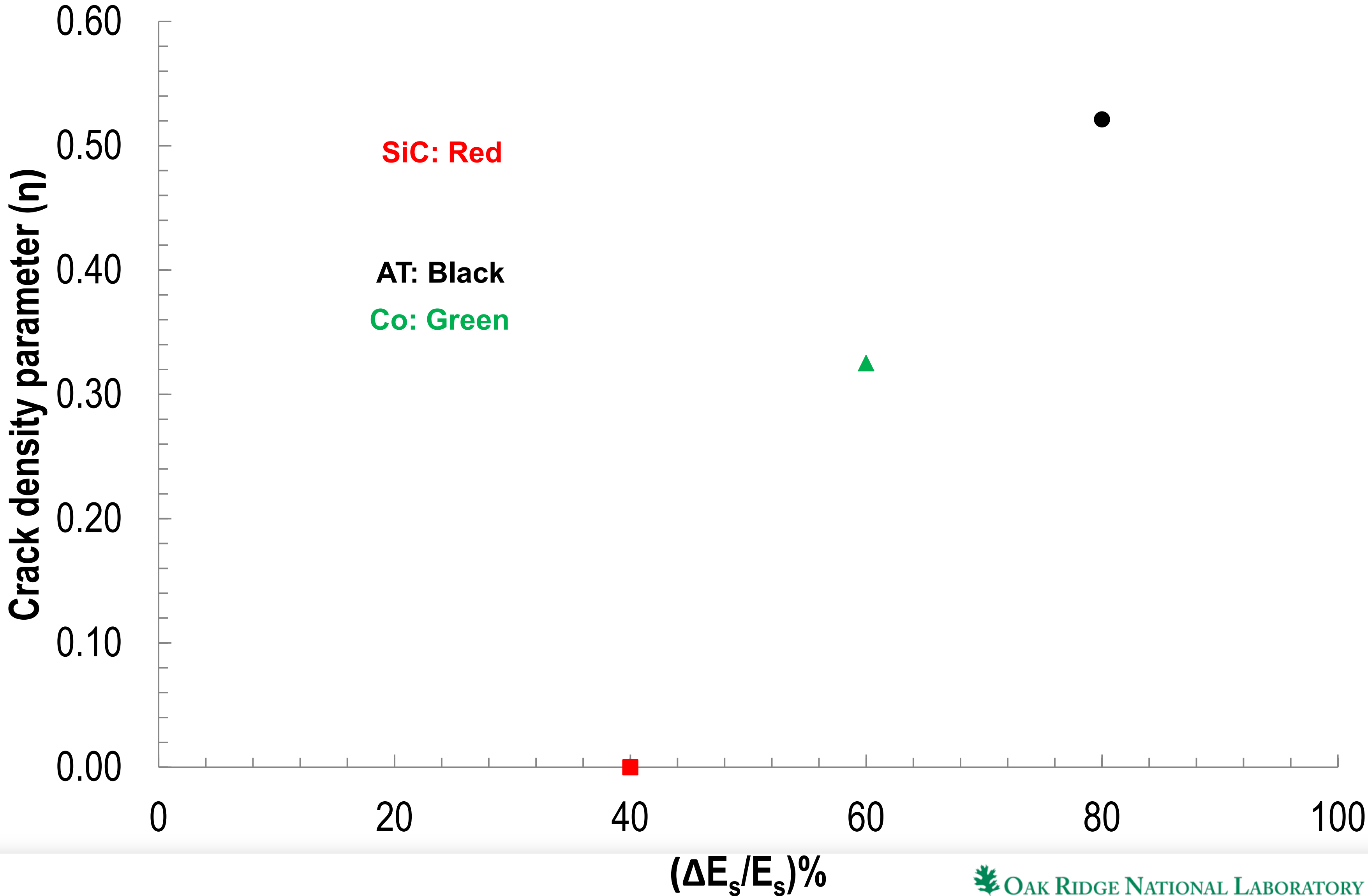
- **Proposed Future Work:** Investigate compressive and bending moduli; examine a 3rd alternate DPF material

# Technical Backup slides

# Young's modulus is directly proportional to Poisson's ratio reflecting the influence of defects

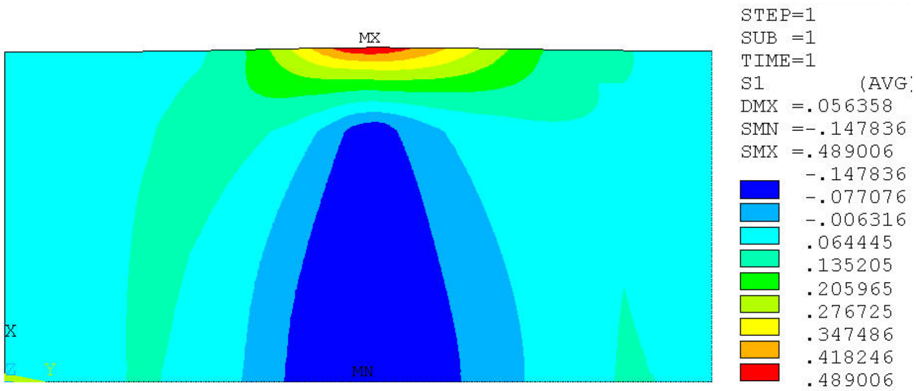


# A higher Crack density parameter is proportional to normalized decrease in secant modulus

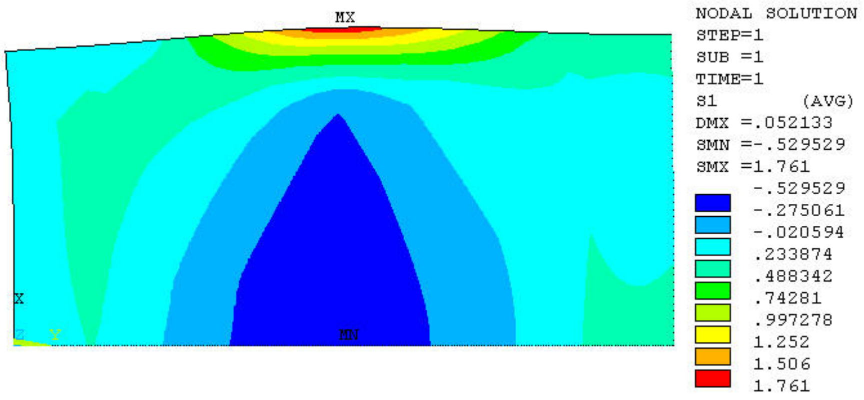


# Collaborations and coordinations with other institutions: Tech transfer2

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



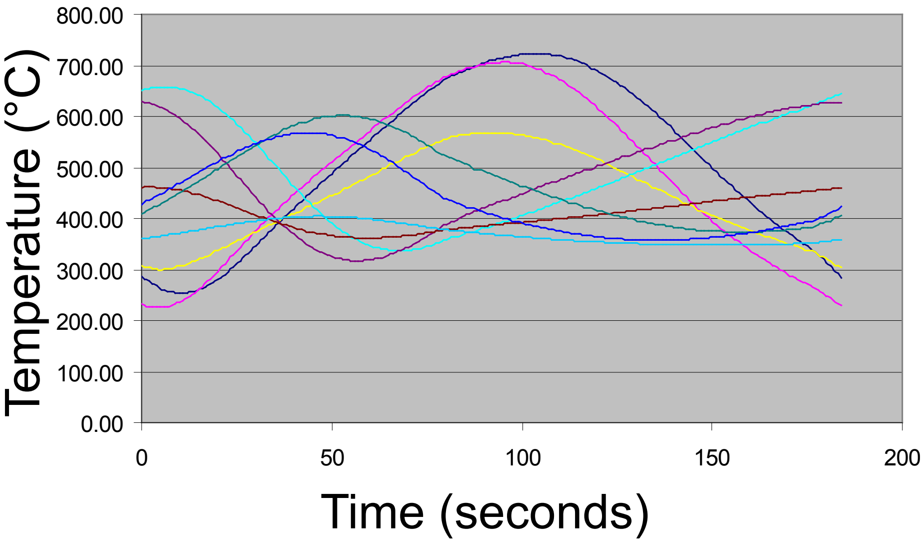

Modulus 1



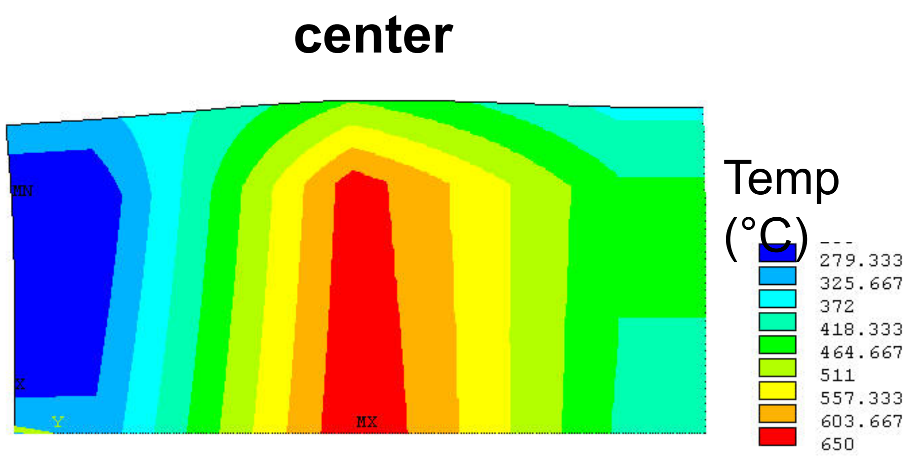

Modulus 2

# 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.

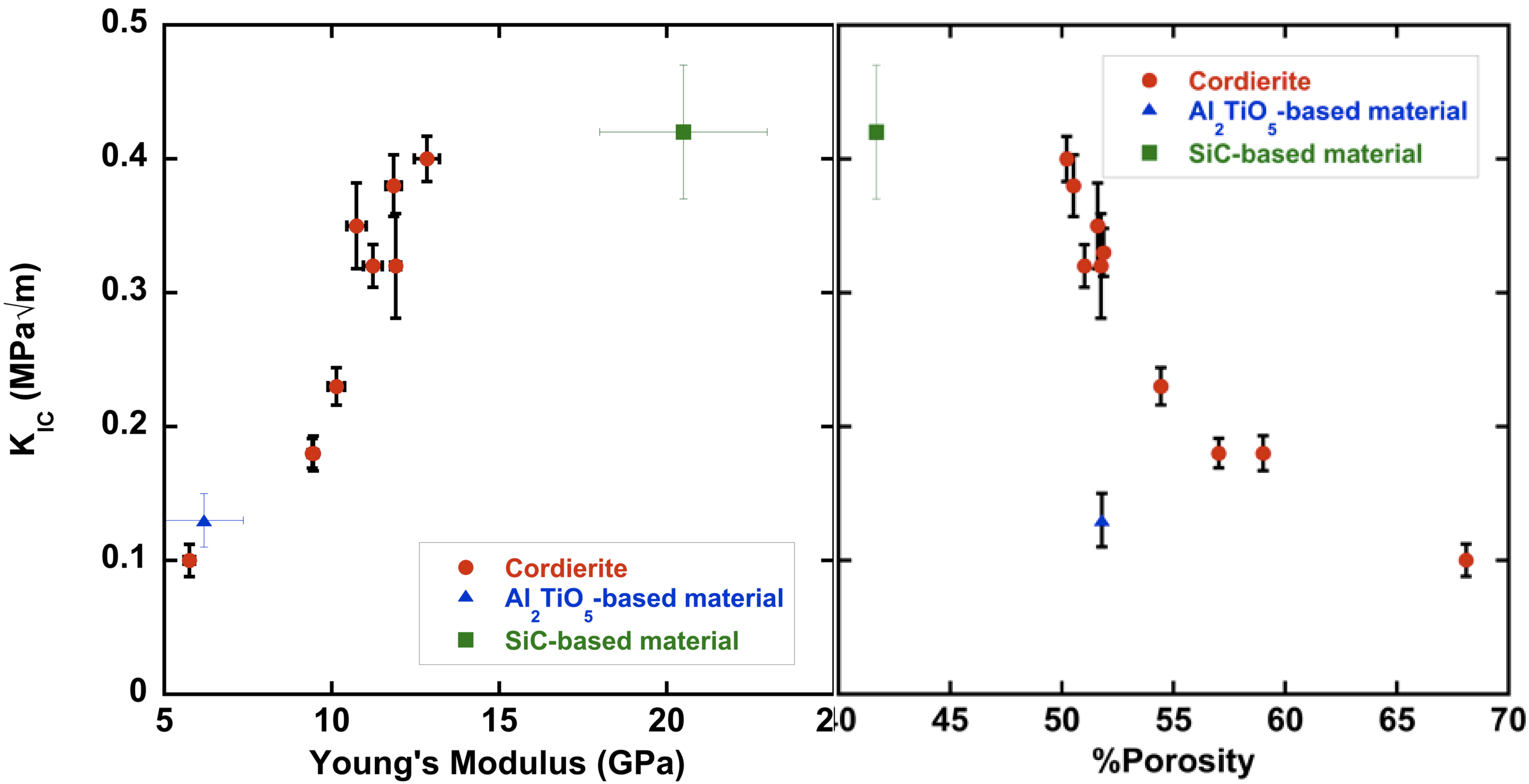



Thermal cycle temperature distribution (°C)




Temperature distribution at t = 0, (°C)

# $K_{IC}$ 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