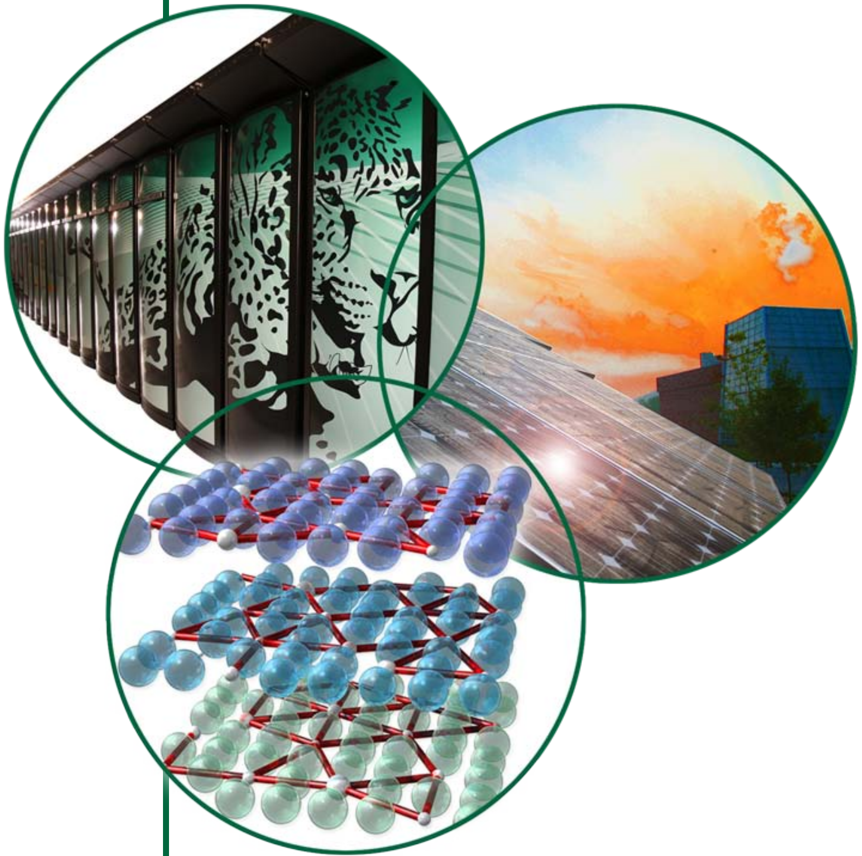
Project ID: PM010

Durability of Diesel Engine Particulate Filters

2010 DOE Vehicle Technologies Annual Merit Review and Peer Evaluation Meeting

June 10, 2010



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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

OAK RIDGE NATIONAL LABORATORY
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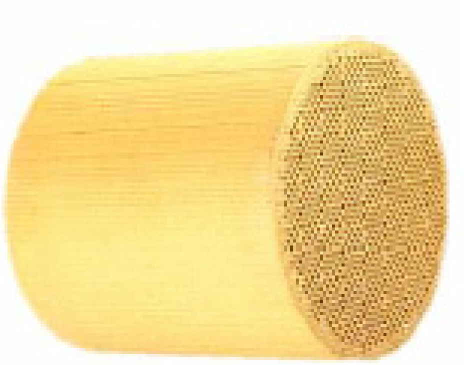
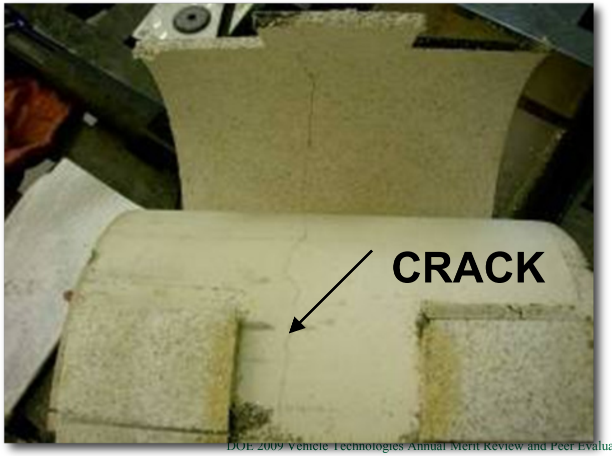
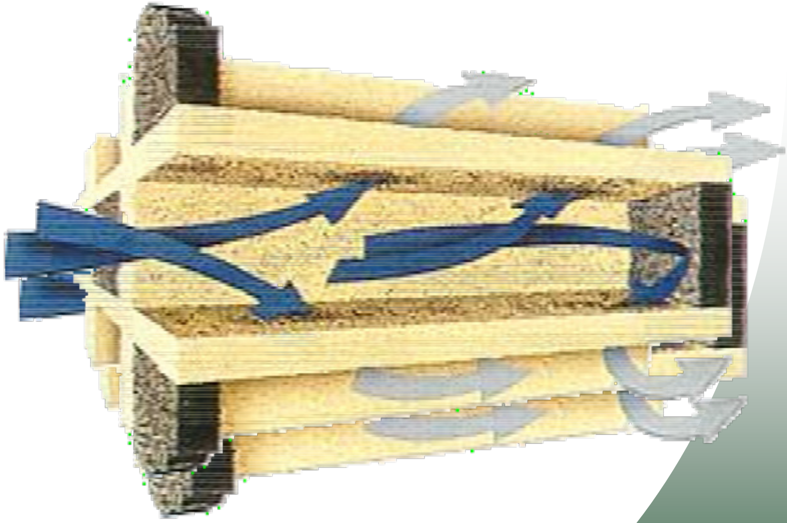
Background

- 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.
- Characterization of material properties is needed for model input







Overview

Timeline

- Start: June 2004
- End: Sept. 2010
- 96% complete (36 mo. renewal in process)

Budget

- Total Project funding
  - DOE-$1.7M
  - Contractor-$1.7M
- Funding received:
  - FY09 $318k
  - FY10 $238k

Barriers* - Advanced Combustion Engine Research: Emission Control System:

- Poor durability ➔ thermal stresses and porosity
- Numerous components
- Costly precious metal content

Partners

- Cummins Inc.
- Corning Inc.

* FreedomCar and Vehicle Technologies Program, Multi-Year Program Plan 2006-2011, Sept 2006, pp. 3.4-9, 10, 21.

Objective

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

Milestones

- **Milestone09: Determine the change in thermal shock resistance of field tested DPFs and the thermal shock resistance of one alternate substrate DPF material.**

- **Milestone10: Continue to determine the change in thermal shock resistance of field tested DPFs and the thermal shock resistance of a second alternate substrate DPF material (Aluminum Titanate (AT), focus here).**

1 Approach: Technical

- Application of probabilistic design tools, non-destructive evaluation (NDE) techniques and thermo-mechanical characterization methods to AT 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).

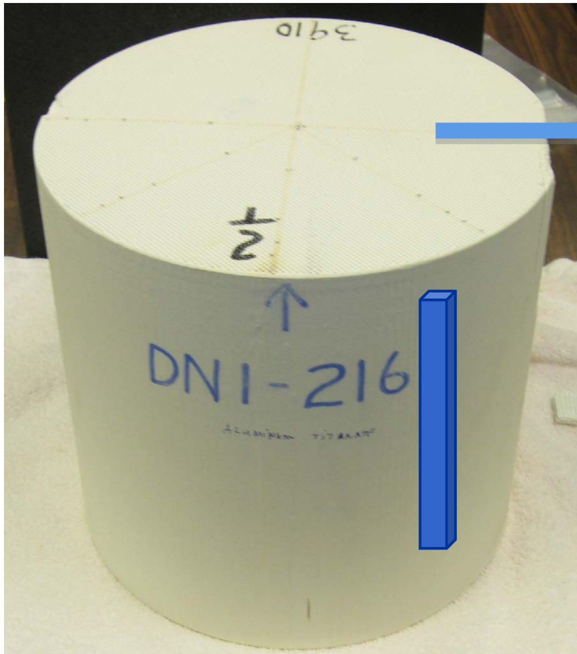
2 Approach: Relevance to barriers & Integration

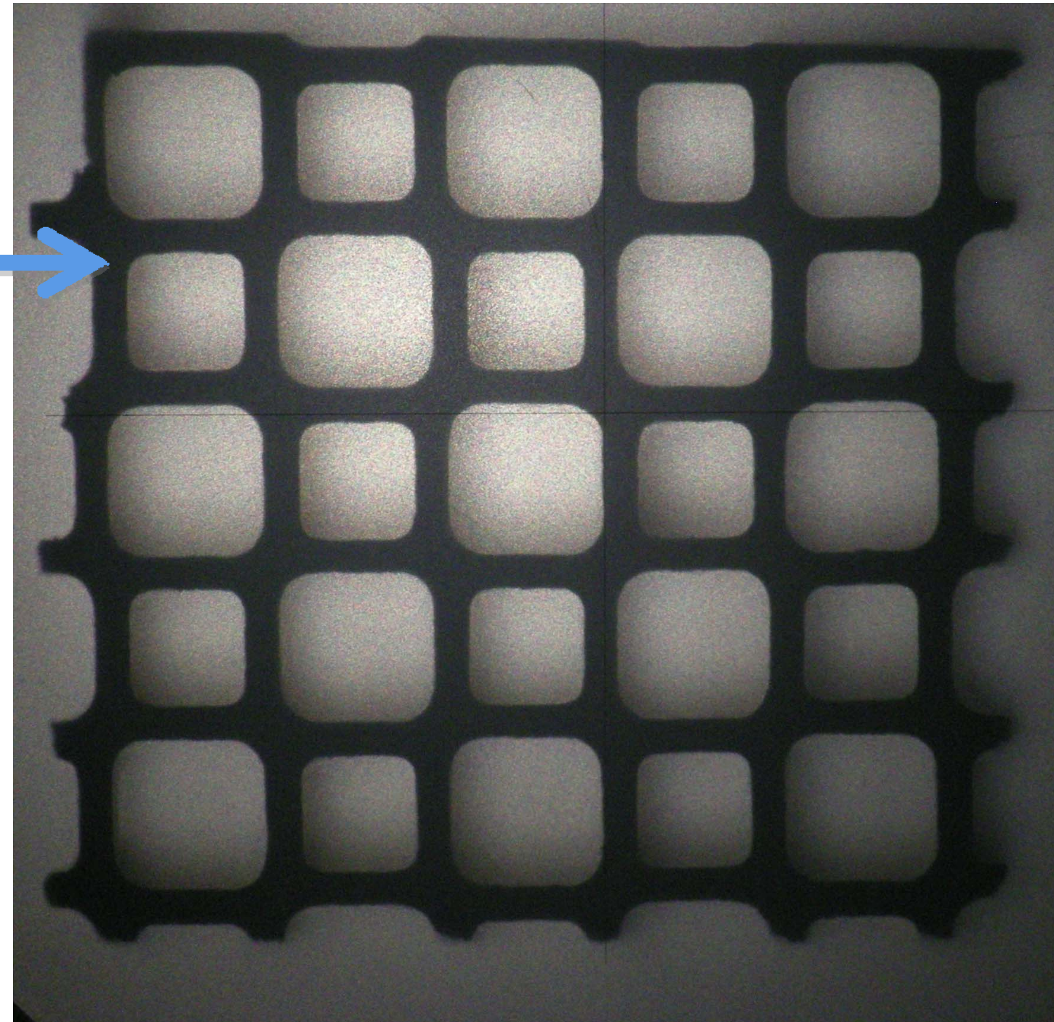
- **Impact on barriers: Property Data…**
  - Input for models to predict behavior accurately. In turn, strategies to mitigate thermal stresses can be formulated and better DPFs designed.
  - Input for design for fewer, multi-functional components
  - Improved strategies minimize loss, save precious metals
- **Integration within Vehicle Technolgies 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

3 Approach: Relevance to Vehicle Technologies Goals

- Improve commercial vehicle engine efficiency at least 20%
  - Understanding the relationships of the material properties for the filter (and catalyst) substrates enables optimization of porosity, strength, elastic modulus, thermal conductivity, thermal expansion … leading to thermal management and improved 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
- Achieve engine system cost, durability and emissions targets
  - Thrust is to characterize and improve the durability, resulting in the lowest overall cost and preventing emission release in service.

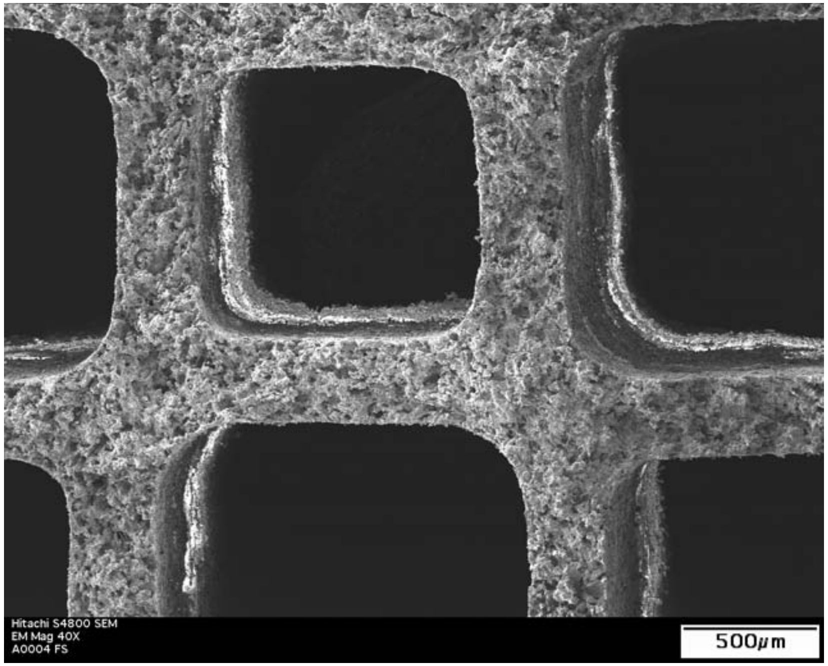
Al_2TiO_5-based DPF Component from Corning; Specimens extracted

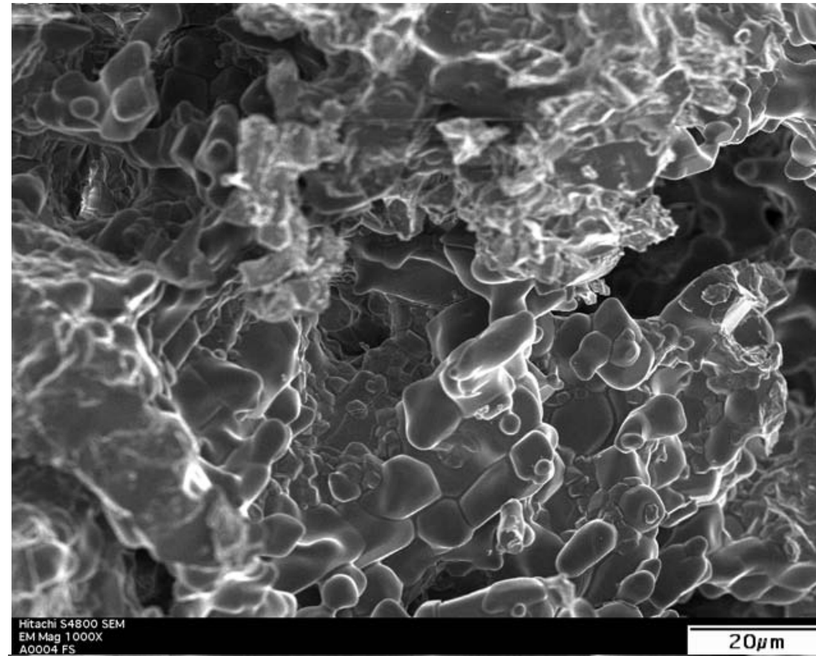


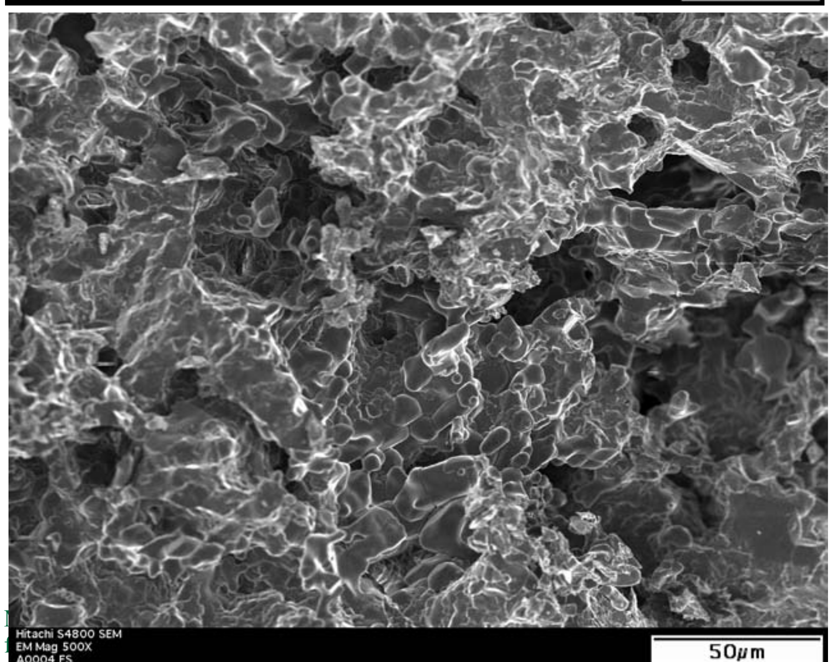


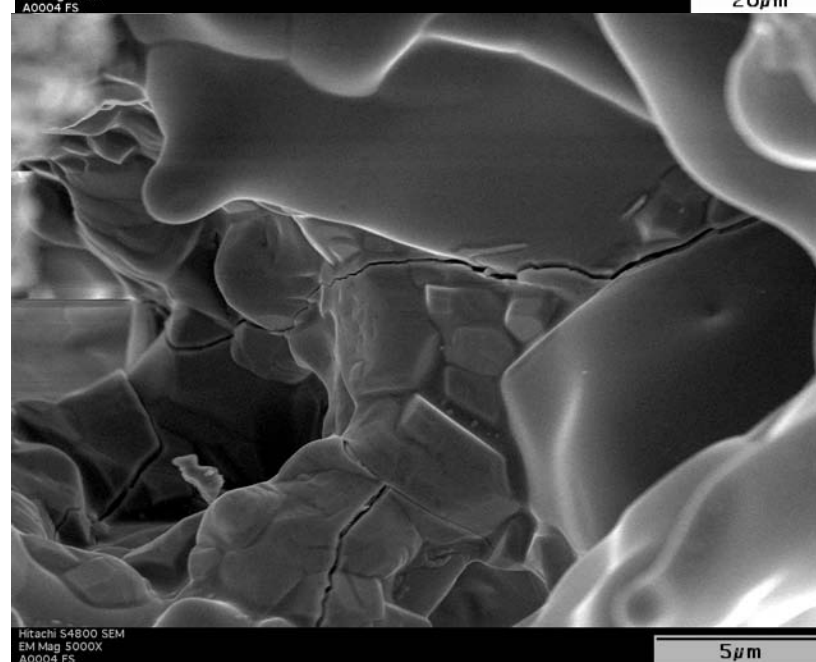
- Al_2TiO_5-based DPF
- 26.5 X 25.5 cm (D X H)
- Sample machining not trivial

Al_2TiO_5-Porous, microcracked, rectangular

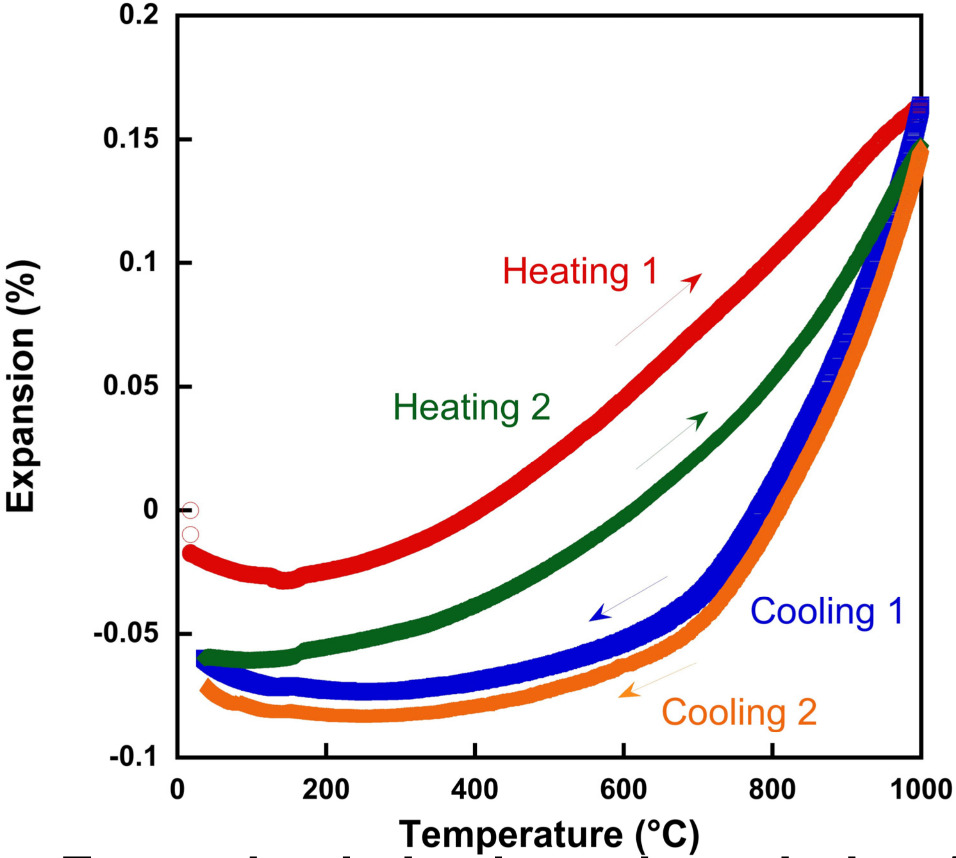


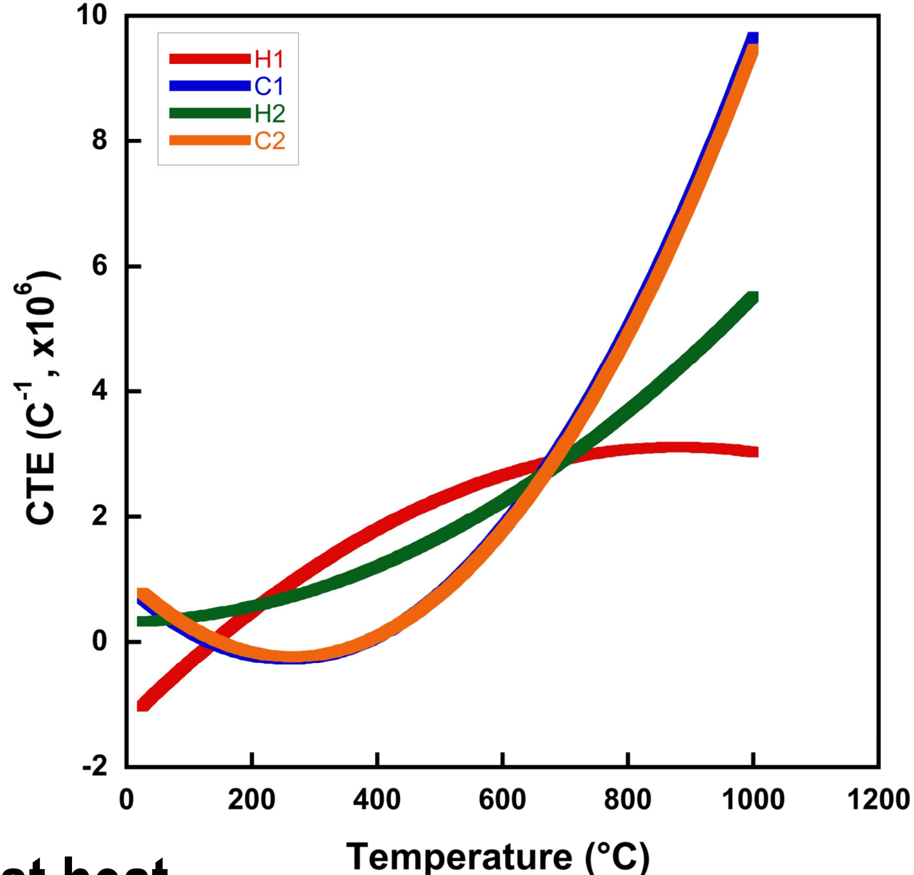






Expansion behavior typical of a ceramic with large CTE anisotropy



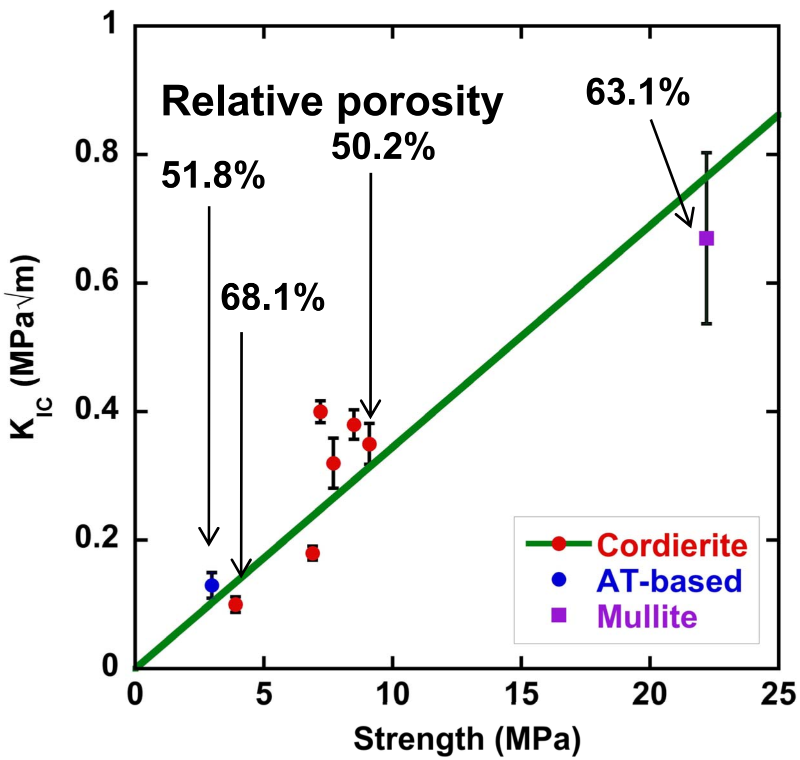


- Expansion behavior unique during 1st heat
- Hysteresis from opening, closing, healing, (re)fracturing of microcracks †
- AT: $\alpha_{||} = 1$, $\alpha_{\perp} = 2$; cordierite††: $\alpha_{||} = 0.5$, $\alpha_{\perp} = 1$ ($\times 10^{-6}$/°C)

†† FY09 work

† Buessem et. al., Ceram. Age 1952. Bush&Hummel, J. Am. Ceram. Soc. 1958, 1959. Morosin&Lynch, Acta Cryst. 1972.

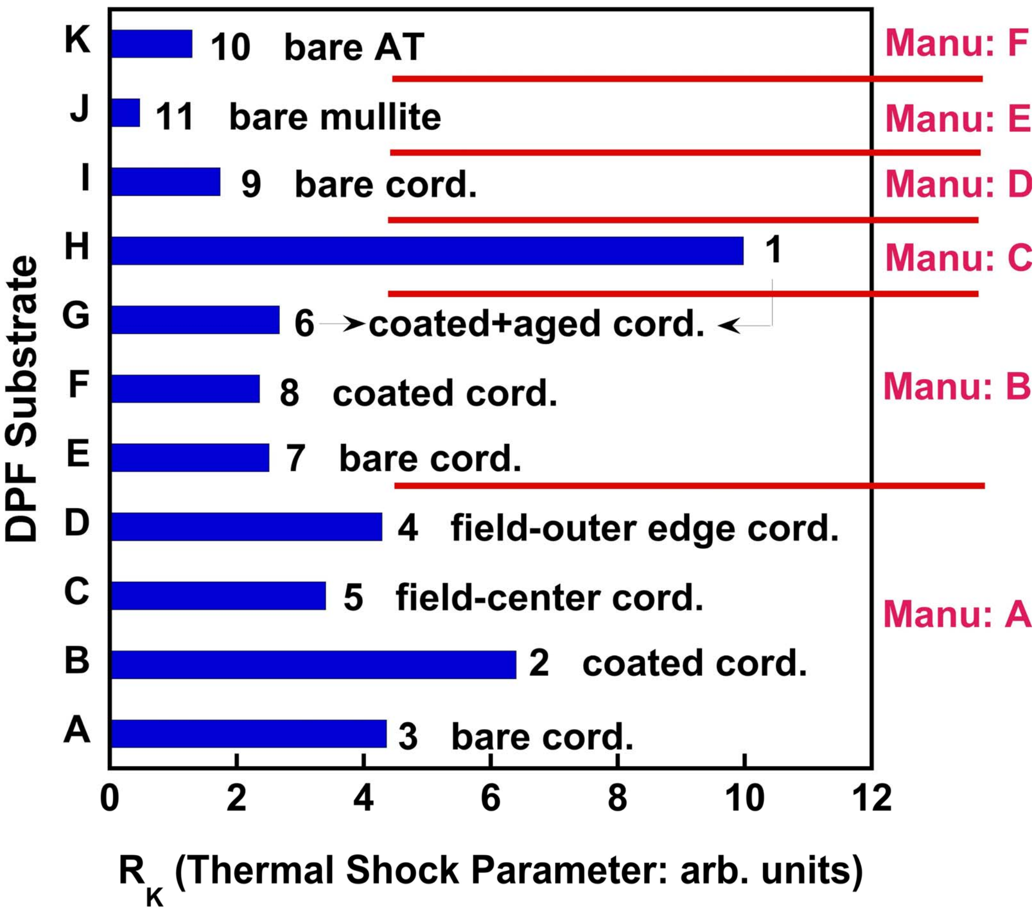
Porosity dominates Properties: e.g. K_{IC} – Strength Correlation



- 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

New thermal shock ranking methodology utilized (milestone09 and partial milestone10)



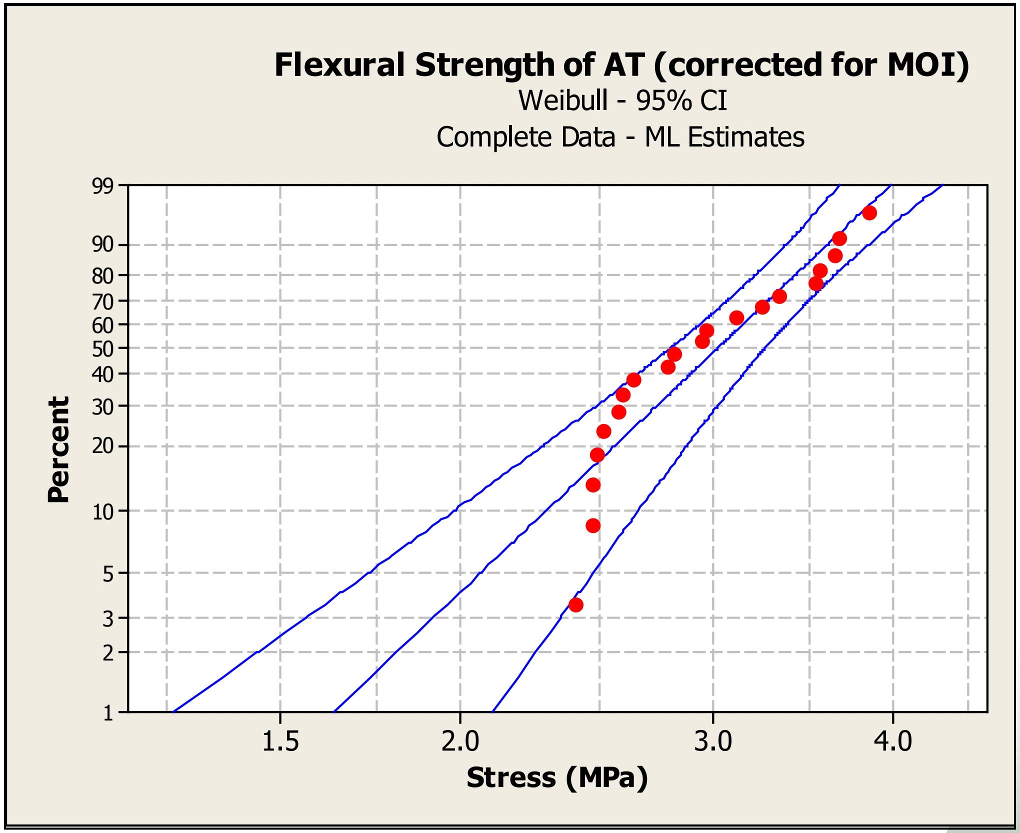
- $R_K = K_{IC}/\alpha E$
  - Easier to perform fracture toughness tests than strength (less material and fewer samples)
- Properties measured
  - K_{IC}, Fracture Toughness (at room temperature) – Double Torsion
  - α, Coef. of Thermal Exp. RT to 1000°C – TMA
  - CTE analyzed parallel and perpendicular to extrusion
  - E, Elastic Modulus – DMA

- Note that the above analysis is highly simplified; assumes:
  - Homogeneity
  - Isotropy

† Cordierite & mullite data is FY09 work

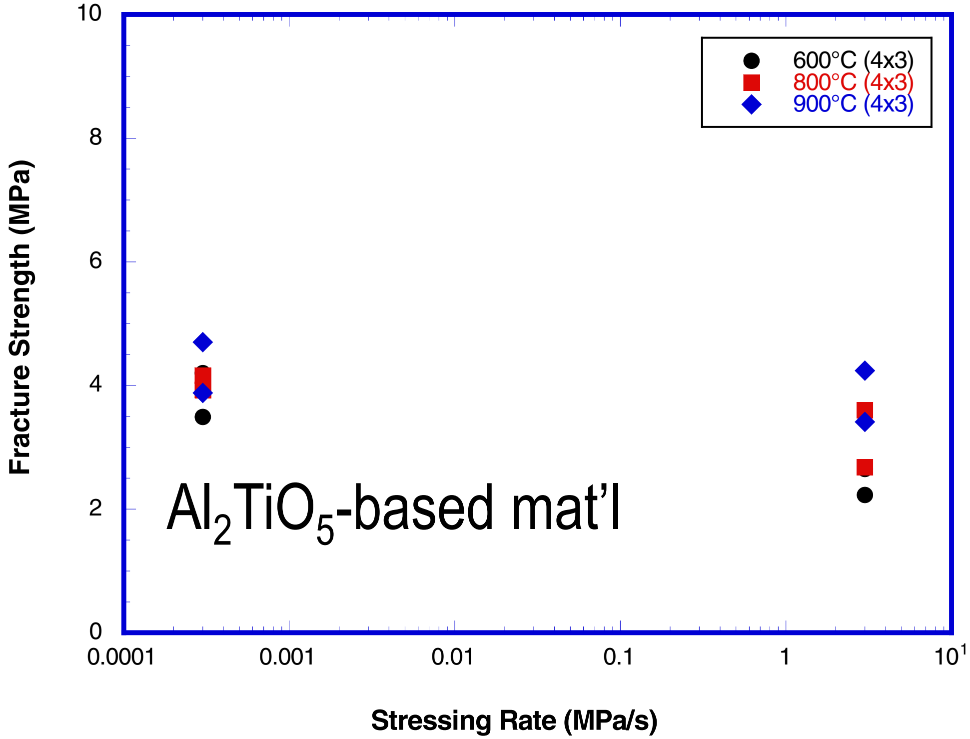
4 point flexural strength testing* at Cummins reveals bimodal distribution

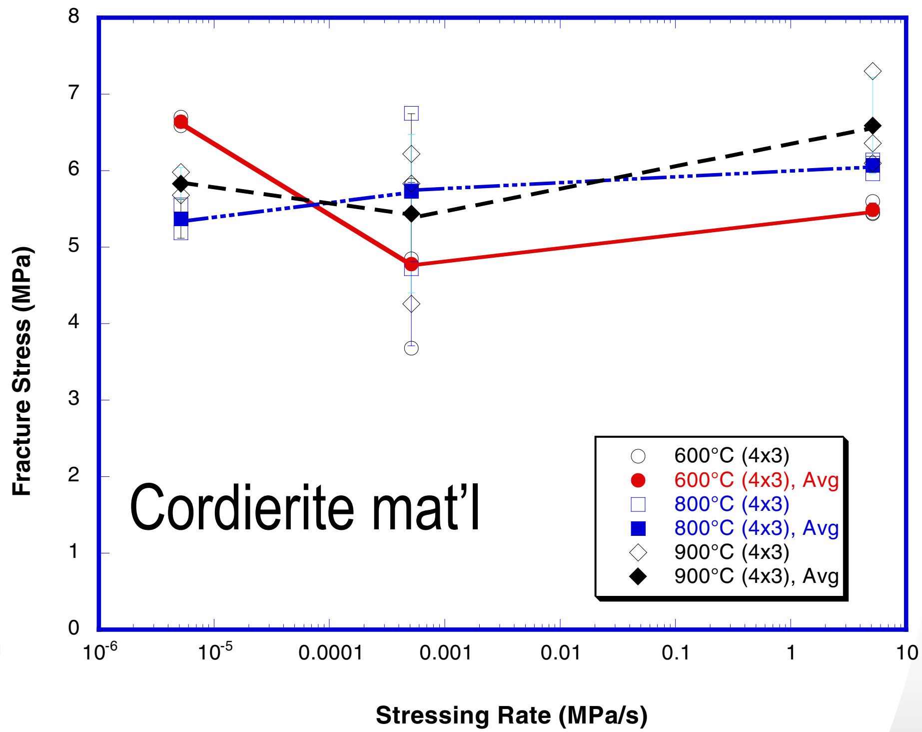
- **20 Sample**
  - Tested parallel to extrusion dir
  - 17 x 9 cell cross section
  - Inner/outer span: 45/90 mm
  - 0.5 mm/min.
- **Flexural Strength**
  - Mean 2.98 MPa
  - σ_c 3.19 MPa
  - m 6.9
- **Plot indicates 2 flaw populations: TBD**



*ASTM C1674-08, Test Method B

Probabilistic design: Dynamic fatigue, Al_2TiO_5-based DPF exhibits lower strength than cordierite DPF





- **Observed trends were insensitive to the specimen geometry (6x3 data; not shown)**

Collaborations and coordinations with other institutions

- **Partners**
  - **Cummins Inc. (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 (e.g. strength data shown here); exchange of technical information to assist with each others analyses; face to face meetings at least 2X/year
  - **Corning Inc. (Industry):**
    - Corning role is to consult on material application and supply material necessary for testing. Corning has been active for some periods of the CRADA.
    - Supplies samples; exchange of technical information

- **Tech transfer**
  - Efforts contributed to refinement of aftertreatment systems Dodge Ram Pickup trucks
  - Data used to translate thermal maps into ANSYS stress models

Future Work

- Characterized field returned diesel particulate filters and compared their properties to virgin filters. This information would be utilized to refine the DPF service lifetime prediction models (FY10, completes milestone10).
- Characterize the dynamic and static fatigue response of SiC DPFs (FY11).
- Continue interaction of washcoat, soot and substrate on properties (FY10 & 11).
- Characterize the effect of joints between segments on mechanical integrity in multi-element structures (FY11 & 12).

Summary

- **Carried out physical and mechanical property measurements on second alternate substrate DPF material: Aluminum Titanate and ranked its relative thermal shock resistance to others (continued from FY2009).**

- **Refined the relationship between porosity and the elastic-fracture properties for diesel particulate filter substrates.**

- **Compared properties of cordierite and Al_2TiO_5-based DPF materials**