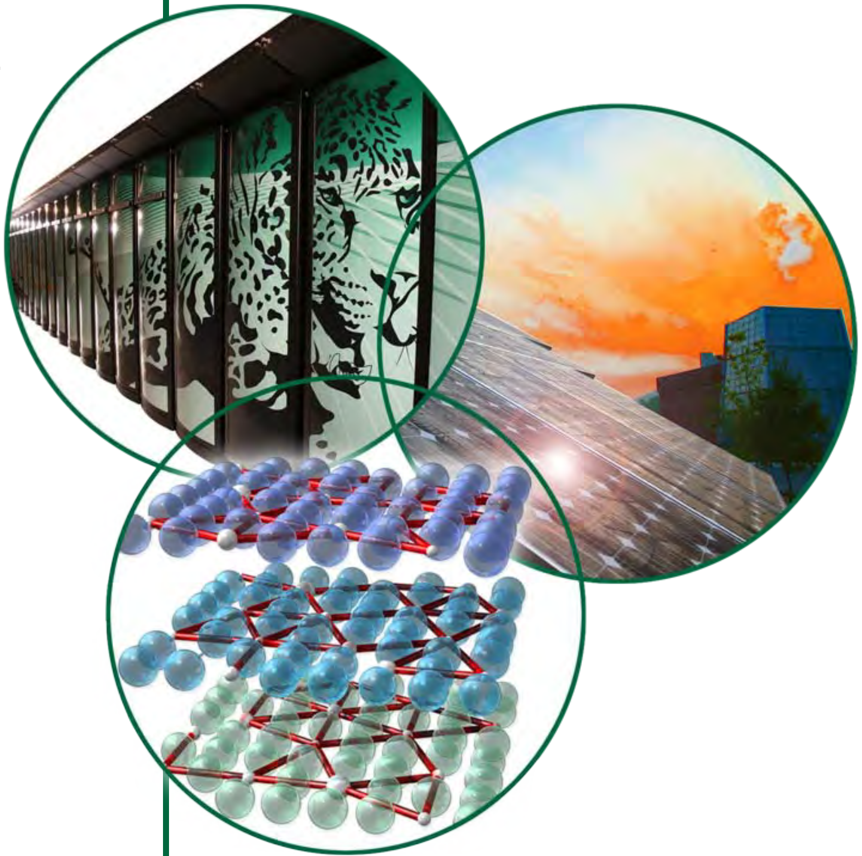
Project ID: PM010

Durability of Diesel Engine Particulate Filters

2011 DOE Vehicle Technologies Annual Merit Review and Peer Evaluation Meeting

May 11, 2011



Thomas Watkins, Amit Shyam, H.T. Lin and Edgar Lara-Curzio; *ORNL*

Randy Stafford and Tom Yonushonis; *Cummins Inc.*

Sponsored by
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U.S. DEPARTMENT OF ENERGY

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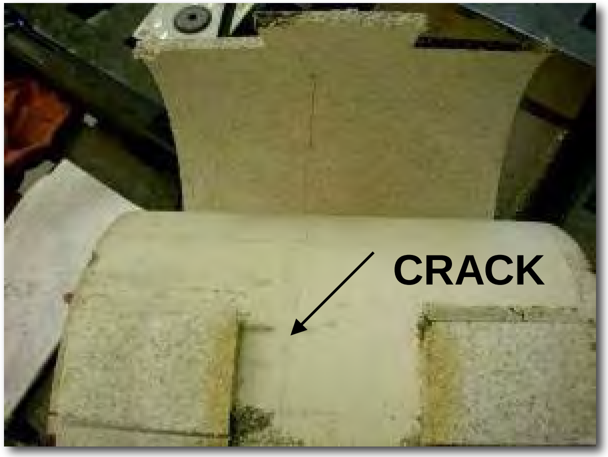
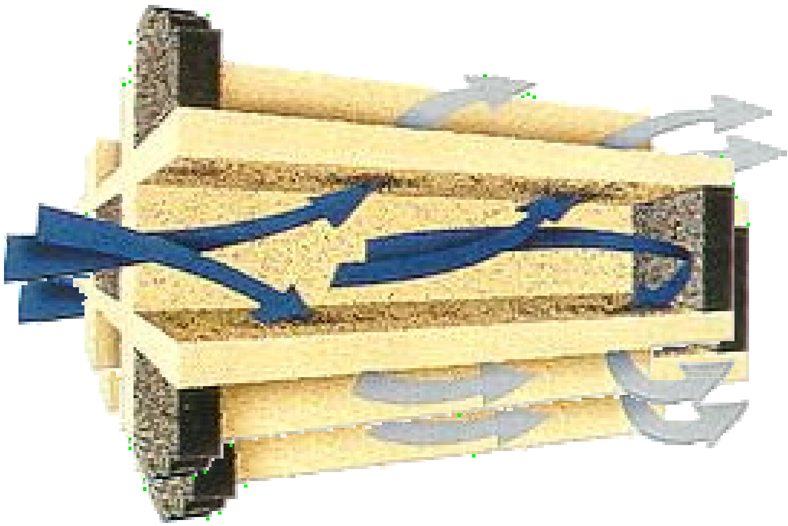
Background

- 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, particularly for DPF regeneration.
- Characterization of material properties is needed for model input





Overview

Timeline

- Start: June 2004
- End: Sept. 2013
- 75% complete

Budget

- Total Project funding
  - DOE-$2.6M
  - Cummins-$2.6M
- Funding received:
  - FY10 $300k
  - FY11 $300k approved

Barriers* - Propulsion Materials Technology:

- Changing internal combustion engine combustion regimes ➔ Optimize to minimize thermal stresses during regen.
- Cost ➔ Precious metal content

Barriers* - Combustion and Emission Control R&D:

- Cost-eff. emission control ➔ reliable regen.
- Poor durability ➔ Thermal stresses and porosity
- Market perception ➔ Understanding improves public's acceptance

Partners

- Cummins Inc.
- Corning Inc.

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

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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.**

Relevance to barriers

- **Impact on barriers: Property Data…**
  - **Input for models to predict behavior accurately. In turn, strategies to mitigate thermal stresses can be formulated for optimized regeneration which *changes engine combustion regimes***
  - **Predictable behavior allow for better DPFs designed which improves *durability***
  - **Improved strategies minimize loss, save precious metals improving *cost-effective emission control***
  - **Net result of above is longer lasting DPFs reducing the amount of precious metals needed or *cost***

Relevance to Vehicle Technologies Goals

- **Advanced Combustion Engine R&D: By 2015, develop materials that reduce the fuel economy penalty of particle filter regeneration by at least 25% relative to the 2008 baseline***
  - **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 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**

- **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.**

* Vehicle Technologies Program, Multi-Year Program Plan 2011-2015, Dec 2010, pp. 2.3-1, 2.5-7.

Milestones

- **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.**

- **Milestones11:**

- **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.**

- **Initiate characterization of the dynamic and static fatigue response of SiC DPFs (latter part FY11).**

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 regen. This improves durability 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**

Measured DPF properties reflect high porosity

Property/Material	Cordierite†	Al_2TiO_5††	SiC
Porosity (%)	50.4	51.9	58.3
Young's Modulus (GPa)*	16.2(0.2)	6.19(1.17)	20(2.5)
CTE parallel¢ ($x10^{-6}$ 1/°C)	0.48	1.07(0.15)	5.00(0.04)
CTE perpendicular¢¢ ($x10^{-6}$ 1/°C)	0.99	2.17(0.15)	5.10(0.08)
Strength (MPa) @ RT¥	7.33(0.45)	2.98	19.5(0.63)

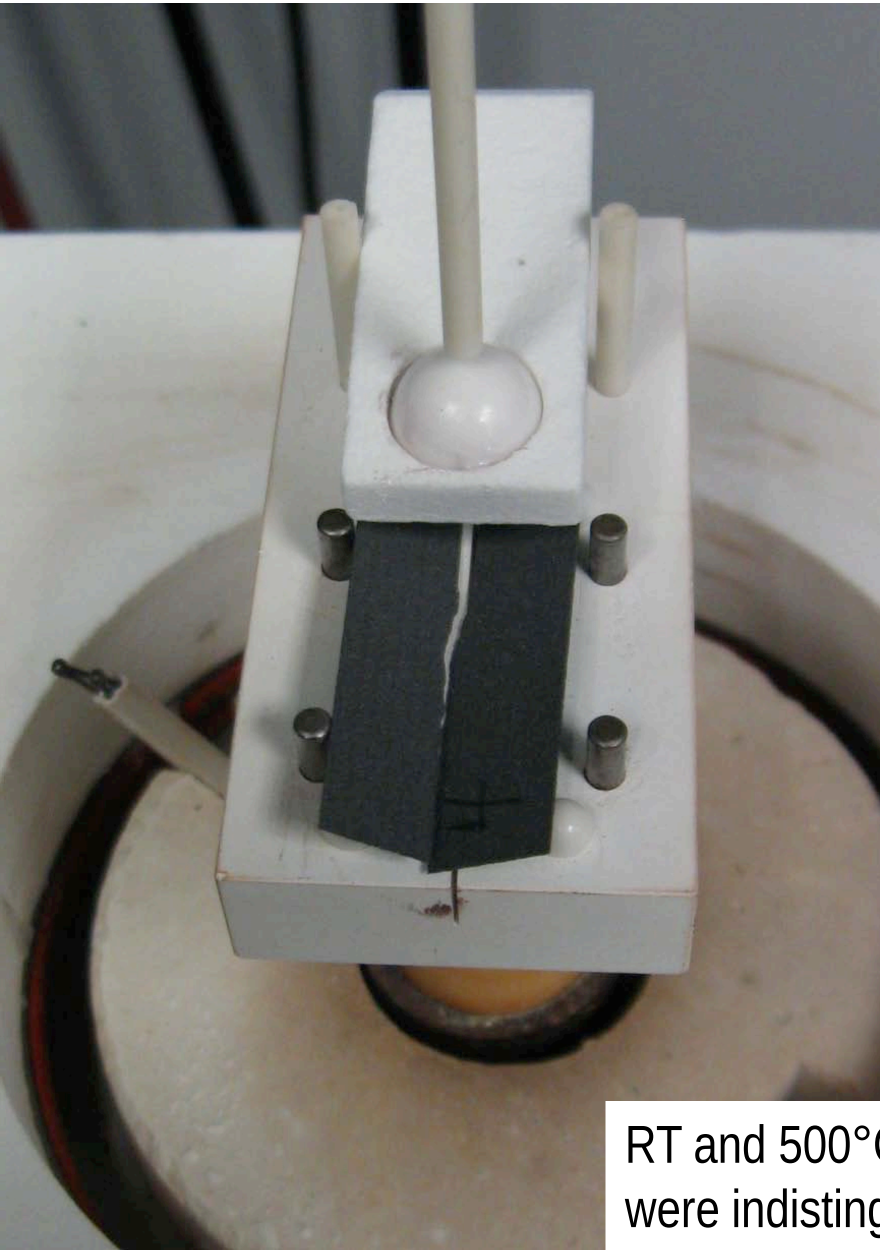
***DMA (Dynamic Mechanical Analysis); MOI corrected; 2-5 samples, Each remounted ≥5 X**

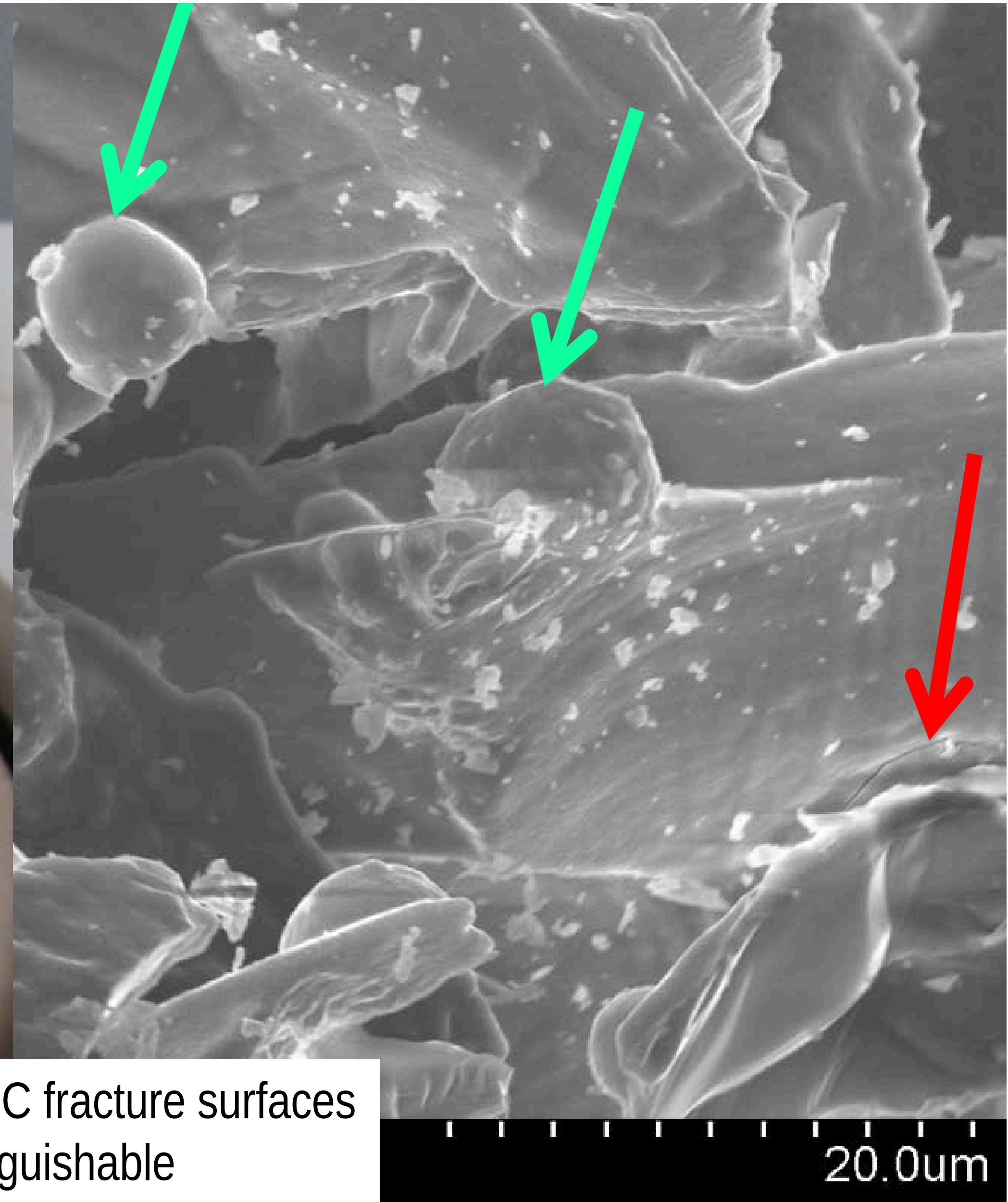
Linear coefficient of thermal expansion, RT -1000°C ¢parallel and ¢¢perpendicular to the extrusion direction

¥ Strength MOI corrected

† Cordierite data is FY09 work; †† AT data is FY10 work

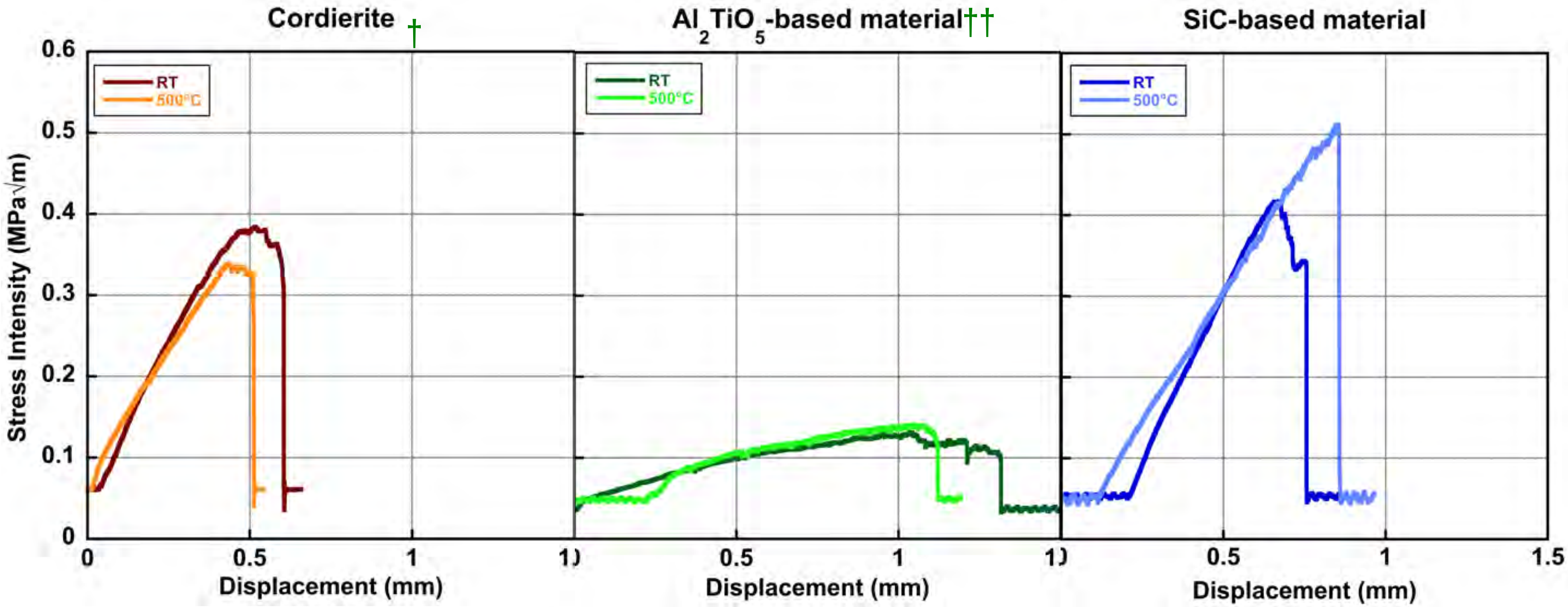
K_{IC} fracture surface displays nodules in SiC-based material that are silicon rich





RT and 500°C fracture surfaces were indistinguishable

Double torsion method used to measure apparent fracture toughness as crack length not needed for determination¥¥



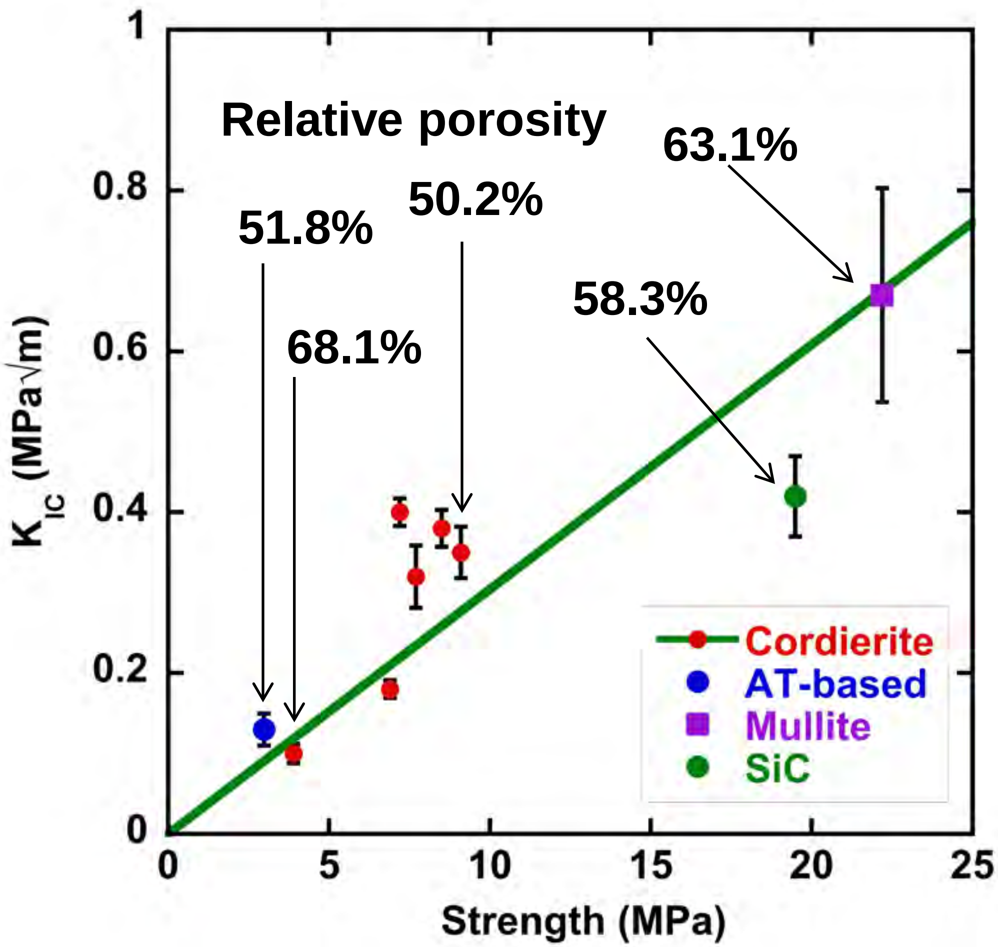
	Cordierite	Al_2TiO_5-based material	SiC-based material
Ave K_{IC}@RT	0.31(0.02)	0.13(0.02)	0.42(0.05)
Ave K_{IC}@500°C	0.25(0.04)	0.16(0.02)	0.55(0.03)

- Temperature has negligible effect on toughness of cordierite and AT-based materials; highly microcracked
- Mechanism for increase in toughness for SiC-based material attributed to behavior of free Si (similar to RBSC between RT and 800°C[£])
- Slopes suggest moduli the same or slightly lower at HT

[†] Cordierite data is FY09 work; [††] AT data is FY10 work

¥¥Shyam & Lara-Curzio, (2006); [£] Huang & Zhu (2005)

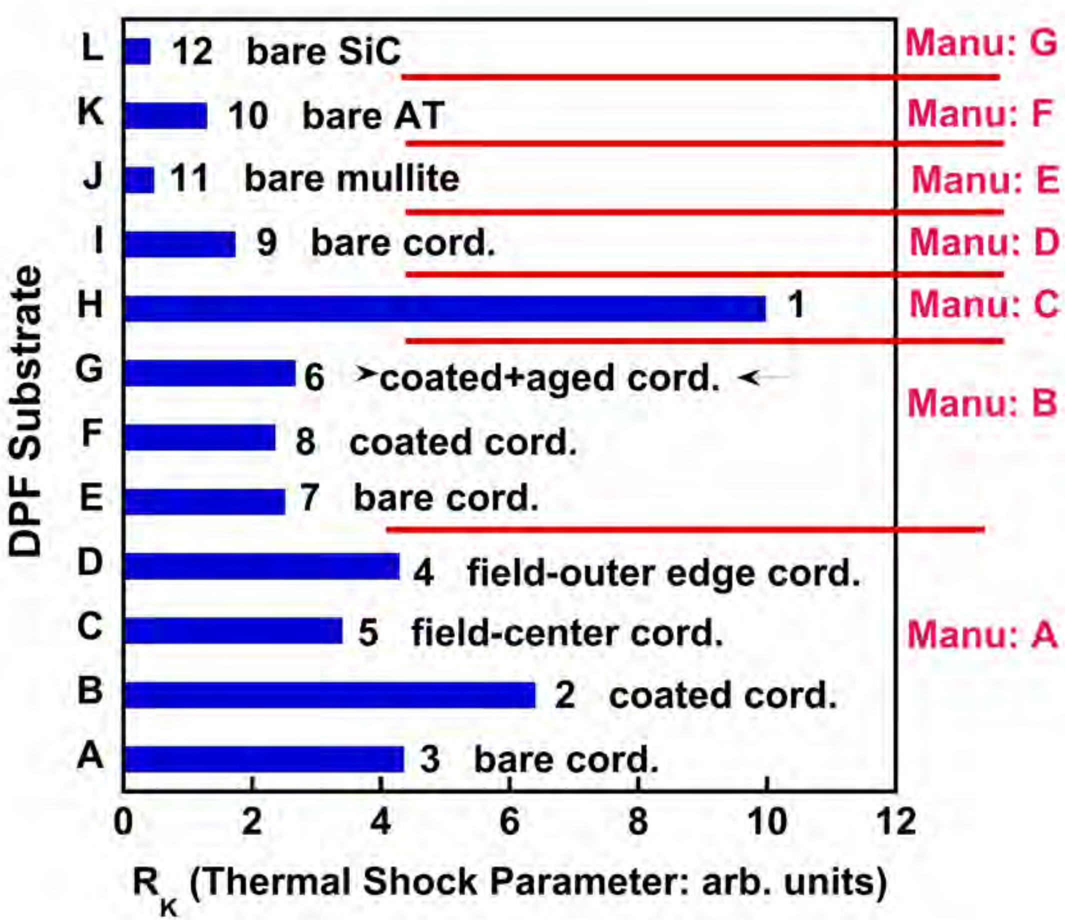
Porosity dominates Properties: e.g. K_{IC} – Strength Correlation



- 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

New thermal shock ranking methodology utilized

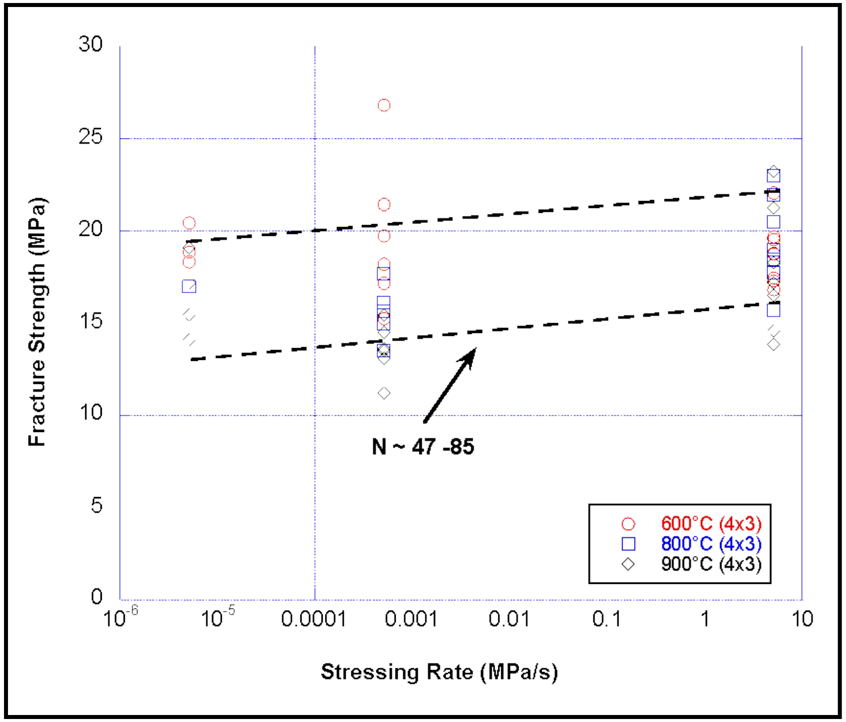


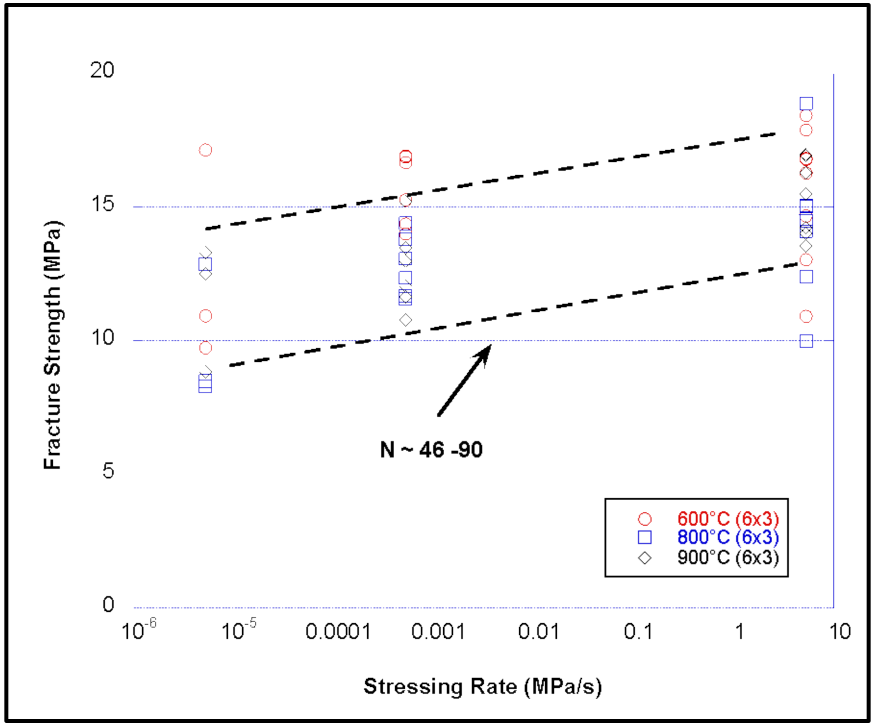
- $R_K = K_{IC}/\alpha E$
  - Easier to perform fracture toughness tests than strength (less material and fewer samples)
- Properties measured
  - K_{IC}, Fracture Toughness (at room temperature) – Double Torsion
  - α, Coef. of Thermal Exp. RT to 1000ºC – TMA analyzed parallel and perpendicular to extrusion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

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

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

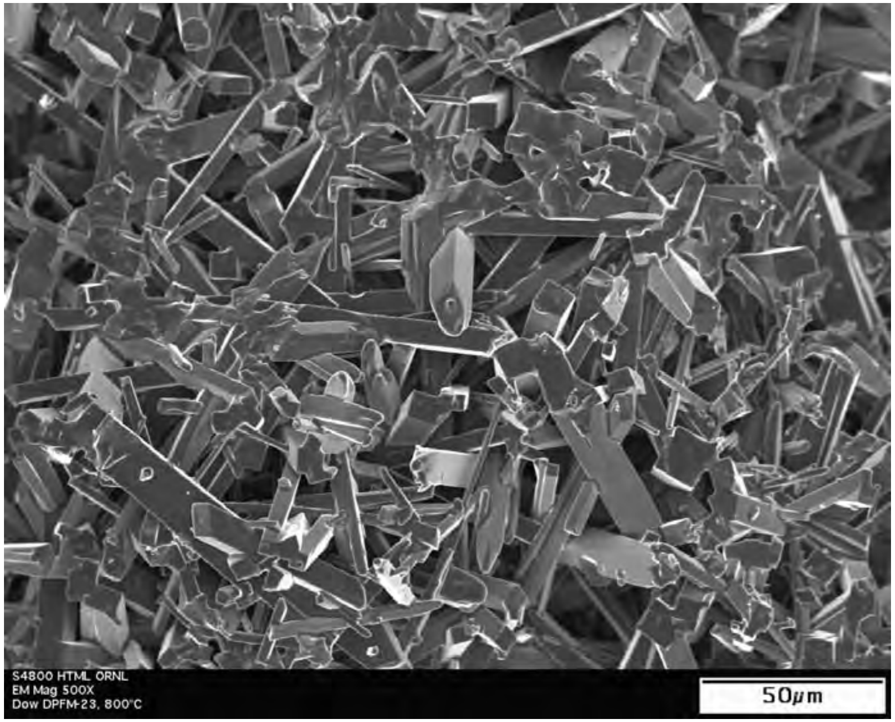
There is a Minor Effect of Specimen Size on the Dynamic Fatigue Response of Mullite (Al_2O_3•$2SiO_2$) DPF Specimens

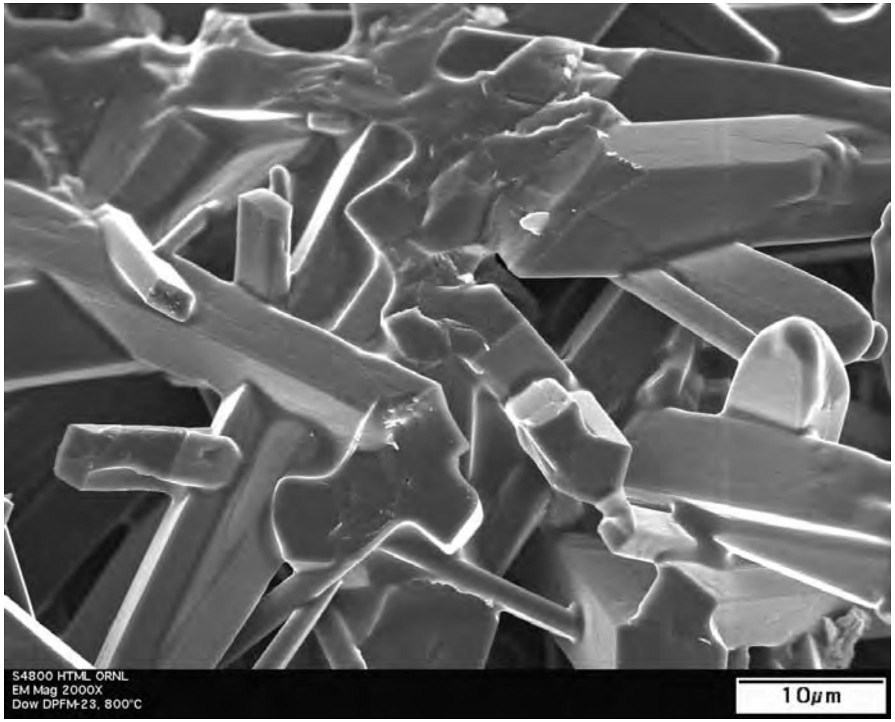




- **The dynamic fatigue exponents obtained from the slopes of strength vs. stress rate curves suggest good resistance to slow crack growth processes at elevated temperatures**
- **The fatigue fracture strength of mullite DPF is 2-3 times higher than cordierite DPF**

Fracture Surface of Mullite DPF Specimen Tested at 800°C in air revealed clean and smooth whisker morphology





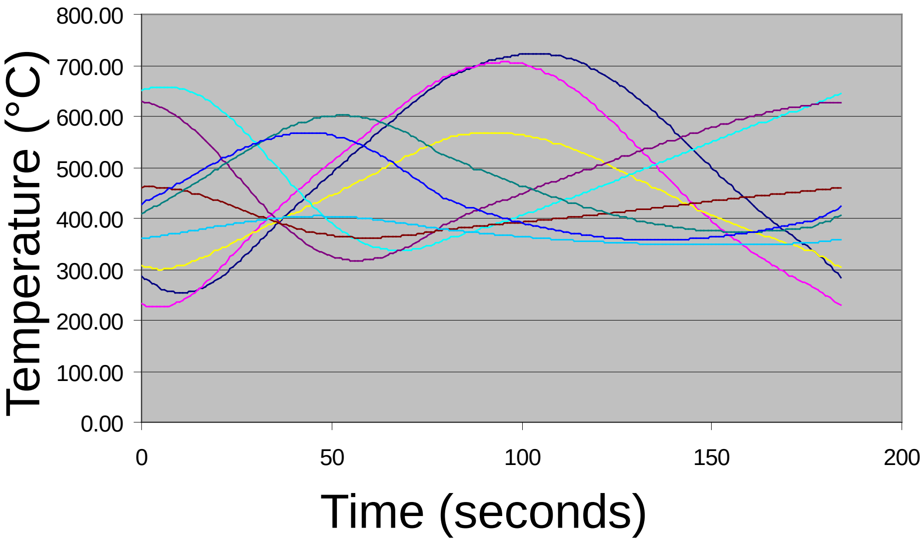
- **No indication of apparent environmental effects on the fracture process, consistent with high fatigue exponent N values**
- **Whisker morphology contributes the highest fracture strength among three DFP materials**

Collaborations and coordinations with other institutions: Partners

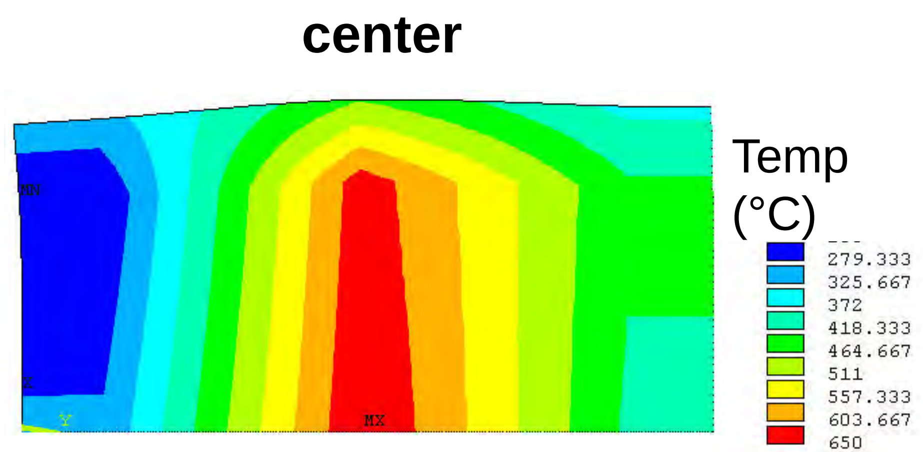
- Cummins (Industry):
  - Cummins' role is to collaborate and guide the work along the most useful path to achieve durability, cost and emissions targets
  - Supplies samples; share experimental results on samples (e.g. strength data shown here); exchange of technical information to assist with each others analyses; face to face meetings at least 2X/year
- CORNING (Industry):
  - Corning's 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

Collaborations and coordinations with other institutions: Tech transfer

- **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)

Future Work

- **Continue to characterize the dynamic and static fatigue response of SiC DPFs (FY11-13).**
- **Continue to study the interaction of washcoat, soot and substrate on properties (FY11).**
- **Characterize the effect of joints between segments on mechanical integrity in multi-element structures (FY11 & 12).**
- **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*

- **Carried out physical and mechanical property measurements on third and fourth alternate substrate DPF materials: SiC and mullite and ranked its relative thermal shock resistance to others (continued from FY2010).**

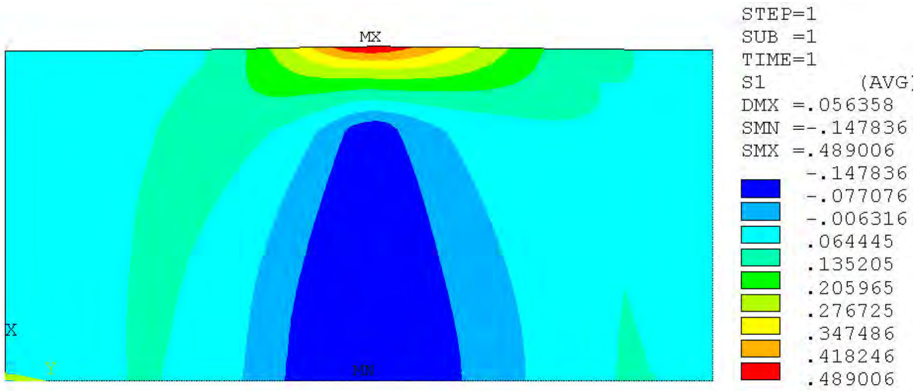
- **Refined the relationship between porosity and the elastic-fracture properties for diesel particulate filter substrates.**

- **Compared properties of cordierite, Al_2TiO_5-based, SiC-based and Al_2O_3•$2SiO_2$ DPF materials**

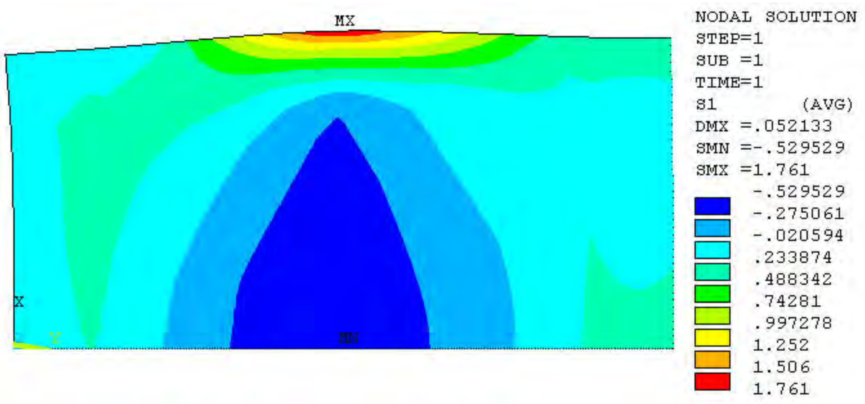
Technical Backup slides

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.**



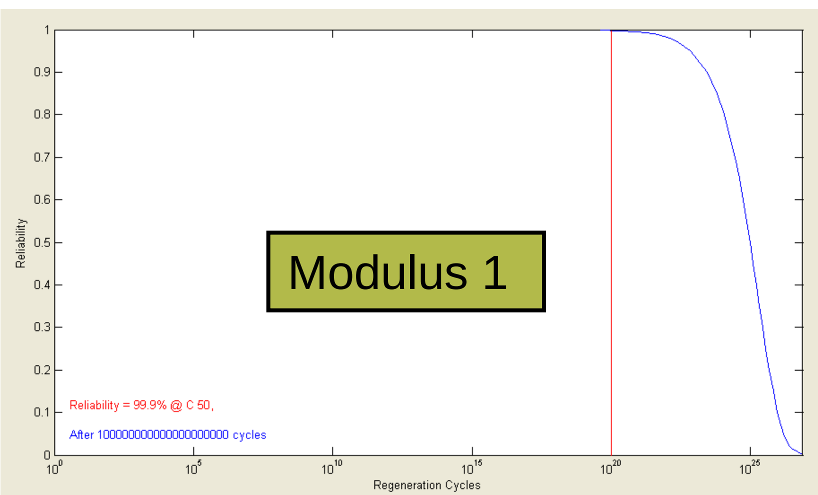
Modulus 1



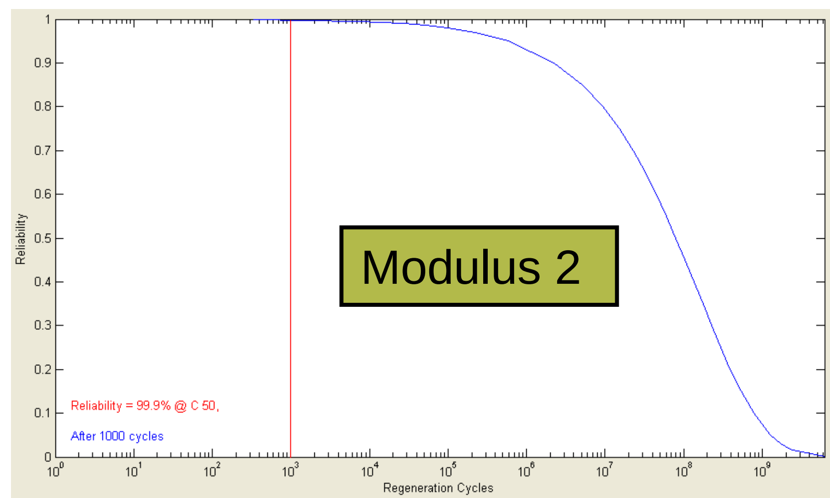
Modulus 2

Collaborations and coordinations with other institutions: Tech transfer3

- **Different stress results (from different modulus inputs) give very different life predictions.**
- **More work to understand effect of modulus measurement is necessary to optimize the stress and life models.**



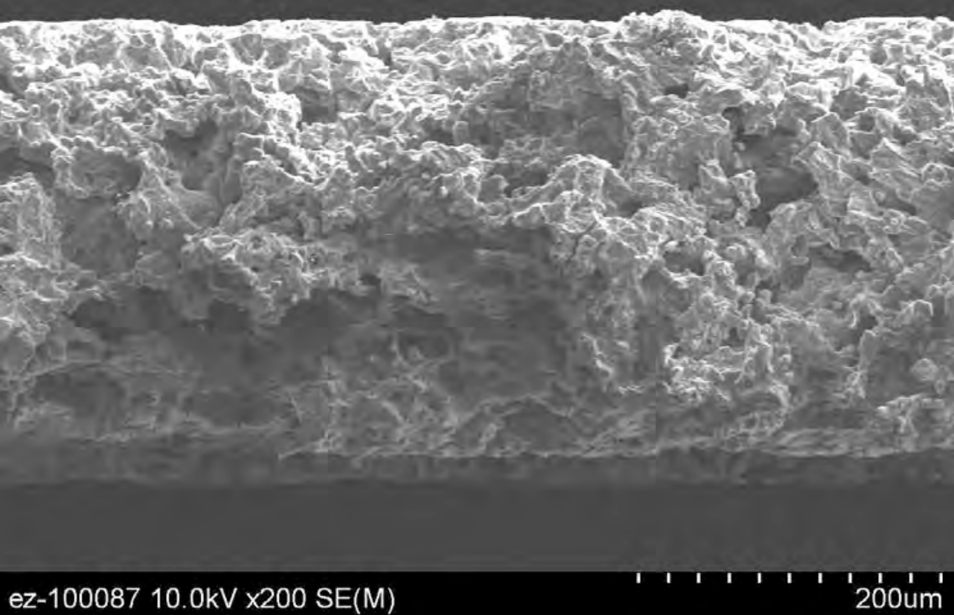
99.9 % component will survive up to **$1x10^{20}$** cycles.

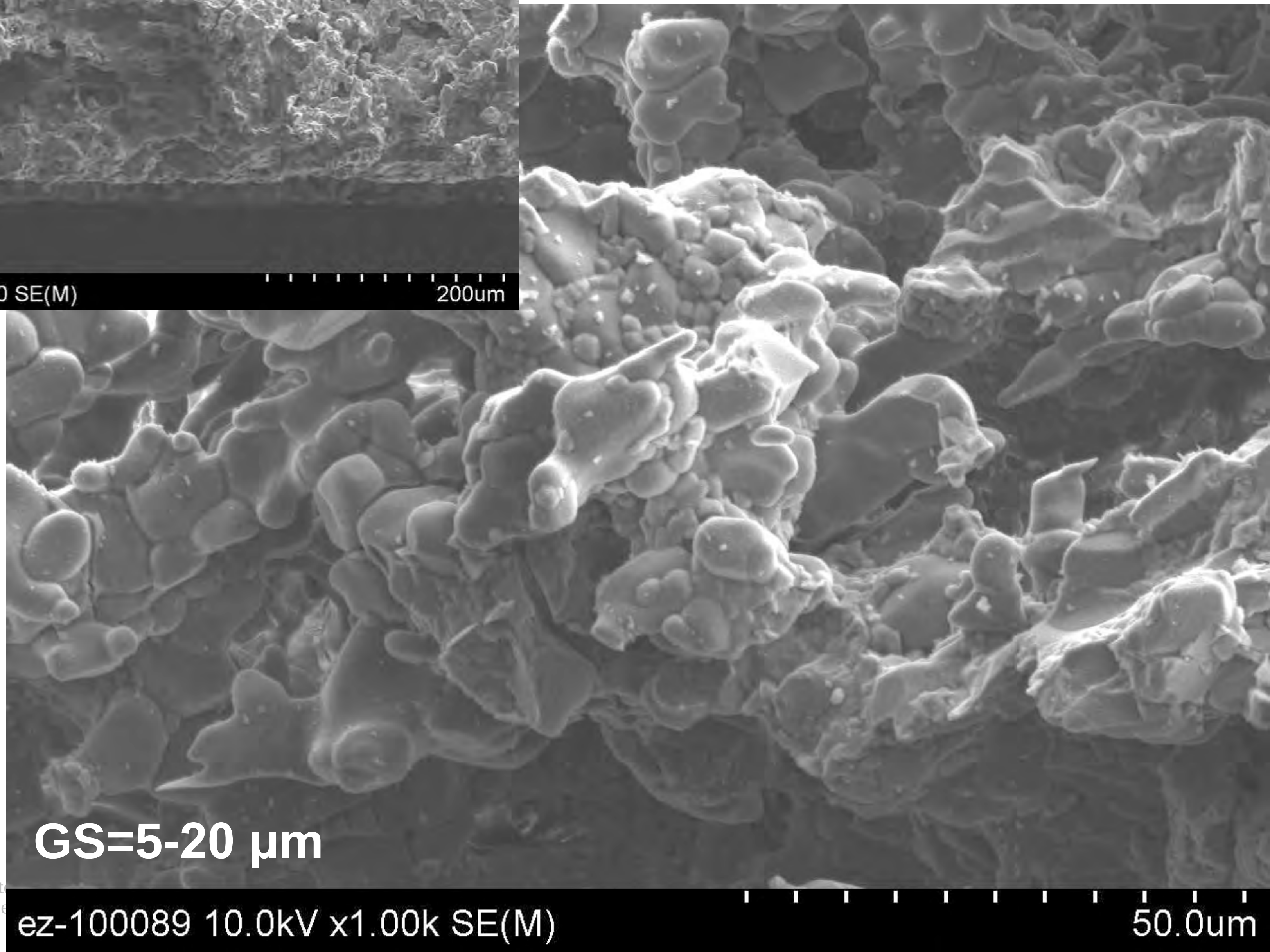


99.9 % component will survive up to **1000** cycles.

AT DT fracture surface

- microcracked





DPF materials are very porous

- **Density:** Definitions given in ASTM D3766, **ASTM International, West Conshohocken, PA.**

Property/Material	Cordierite	Al_2TiO_5	SiC
Bulk (g/cc)*	1.22	1.65(0.03) **	1.18(0.03)
Skeletal (g/cc)¥	2.46	3.43(0.05)	2.83(0.05)
Relative ρ (%)ø	49.6	48.1	41.7
Porosity (%)	50.4	51.9	58.3
Wall thickness (mm)	~0.38	~0.30	~0.28

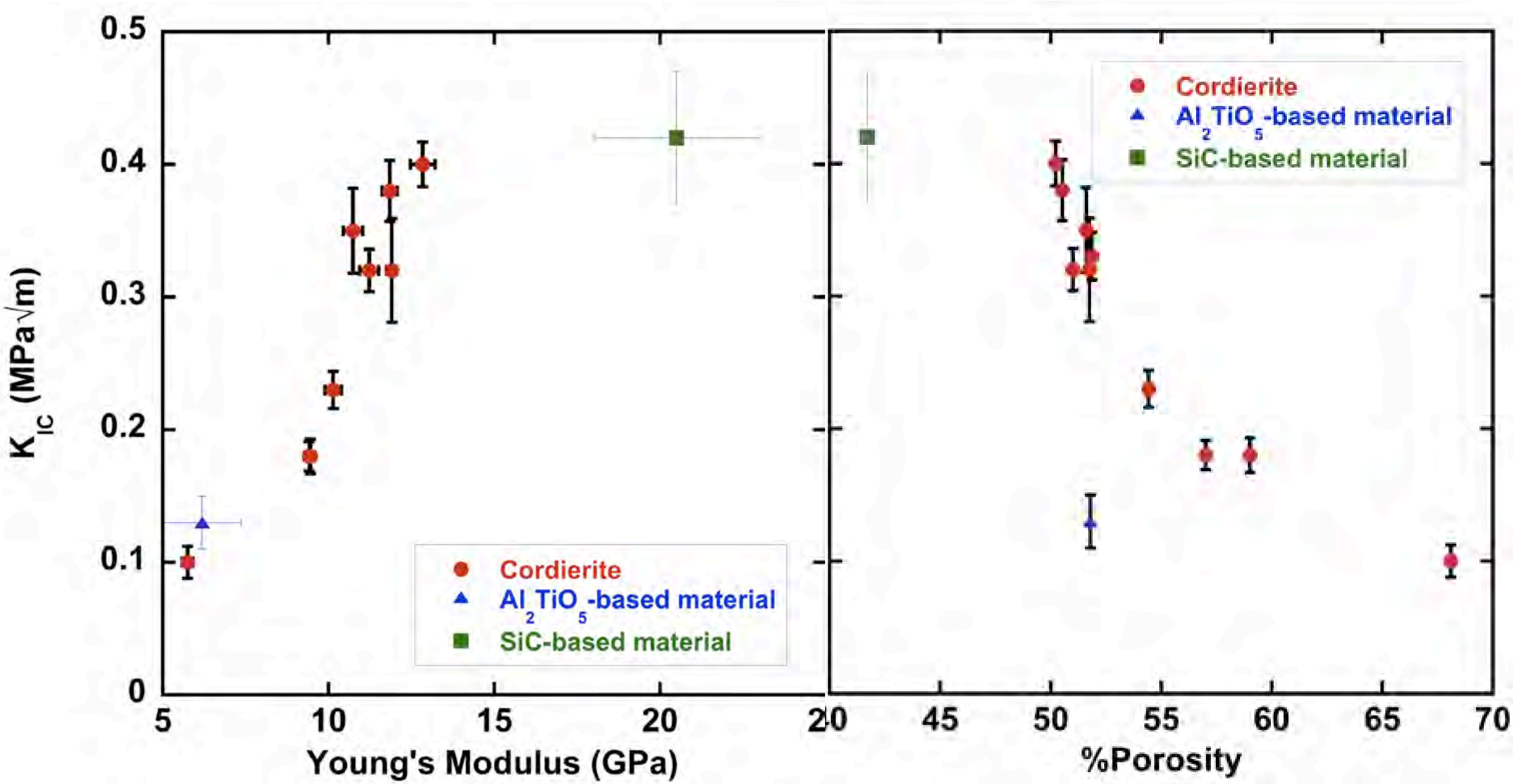
* Geometric volume: includes solids plus all open and closed porosity of plate samples, i.e., no channels

** () values = standard deviation

¥ He pycnometry: volume includes solids plus all closed porosity

Ø Relative density (ρ_{bulk}/ ρ_{skel} *100)

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



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