Durability of Diesel Engine Particulate Filters CRADA No. ORNL-04-0692 with Cummins Inc.

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This presentation does not contain any proprietary or confidential information

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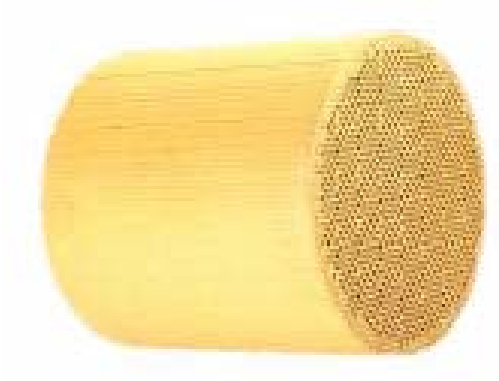
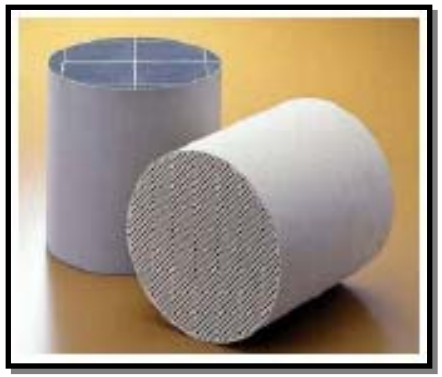
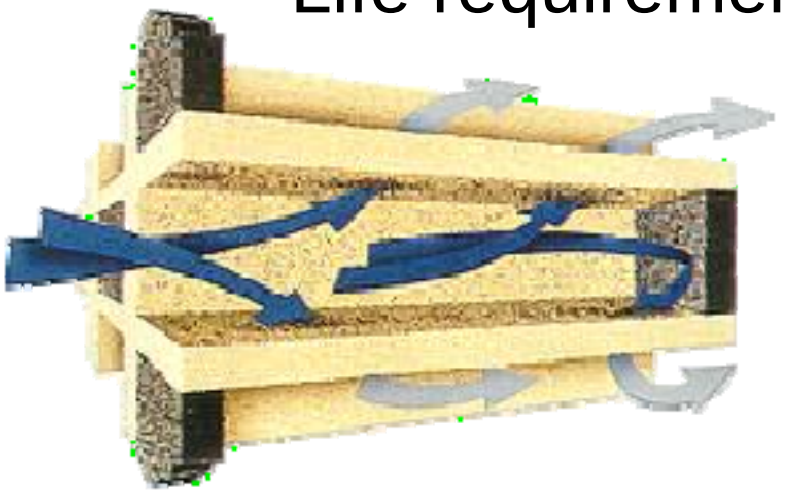
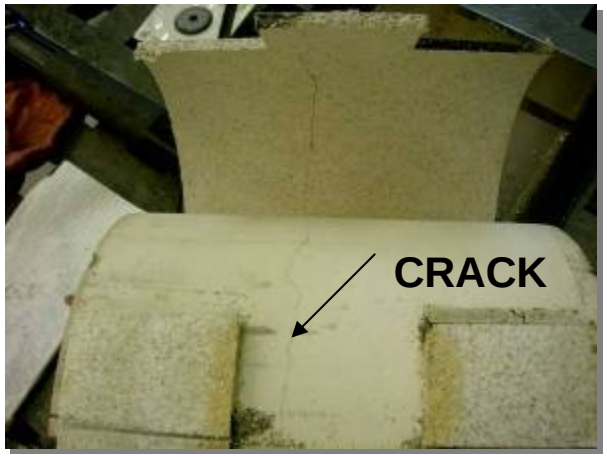
Background





– 2007 EPA Emission Regulations resulted in implementation of diesel particulate filters (DPFs).
  - Honeycomb cordierite filter material selected for use widely throughout the diesel industry
  - Life requirements, i.e. >500,000 miles for heavy duty.





Purpose of Work

- Durable DPF materials with ultra low PM emissions and minimal fuel penalty due to regeneration
- Characterization of DPF Durability and Life

  - Characterize the microstructure and properties that limit the lifetime of *new* filters
  - Develop computational methodology to predict the useful lifetime of a particulate filter
  - Develop test methods and standardized specimen geometries for defining material properties that go into lifetime model
  - Develop nondestructive evaluation techniques to allow the examination of DPFs at normal truck service intervals

Barriers

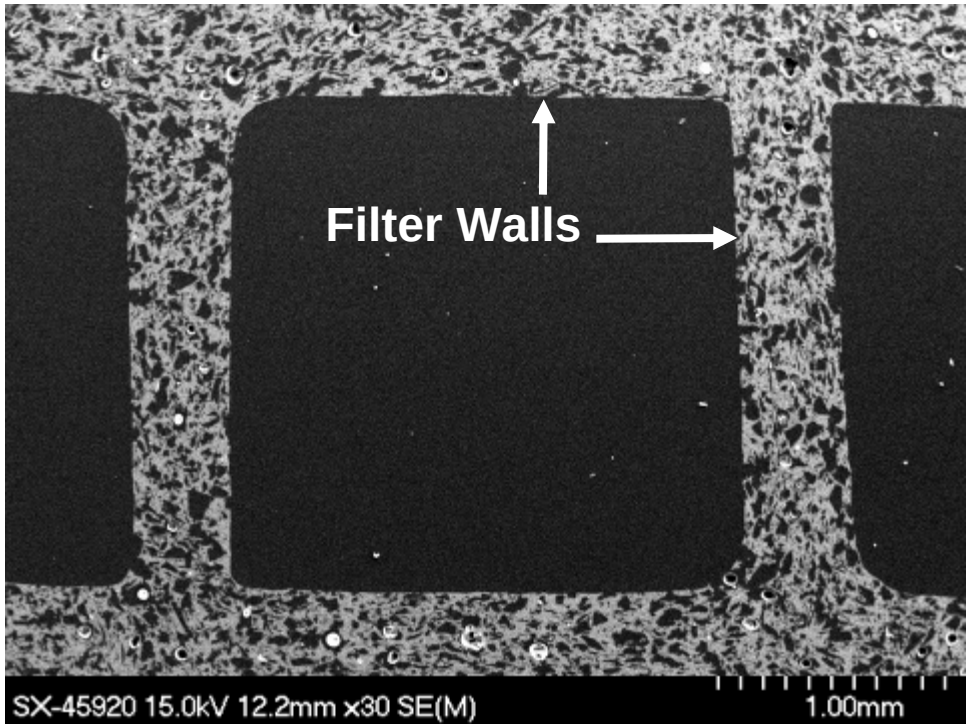
- Increased thermal stresses due to active filter regeneration forced by lower NO_x standard.
- Lack of test methods and life prediction data to evaluate the properties that determine the lifetime of DPFs
  - Standard test methods for ceramics not applicable for fragile porous DPF substrates
- The properties of the substrate change during service conditions
- Complex problem due to interactions between catalyst coatings, soot particles and material microstructure
- Lack of non-destructive evaluation techniques to verify model predictions

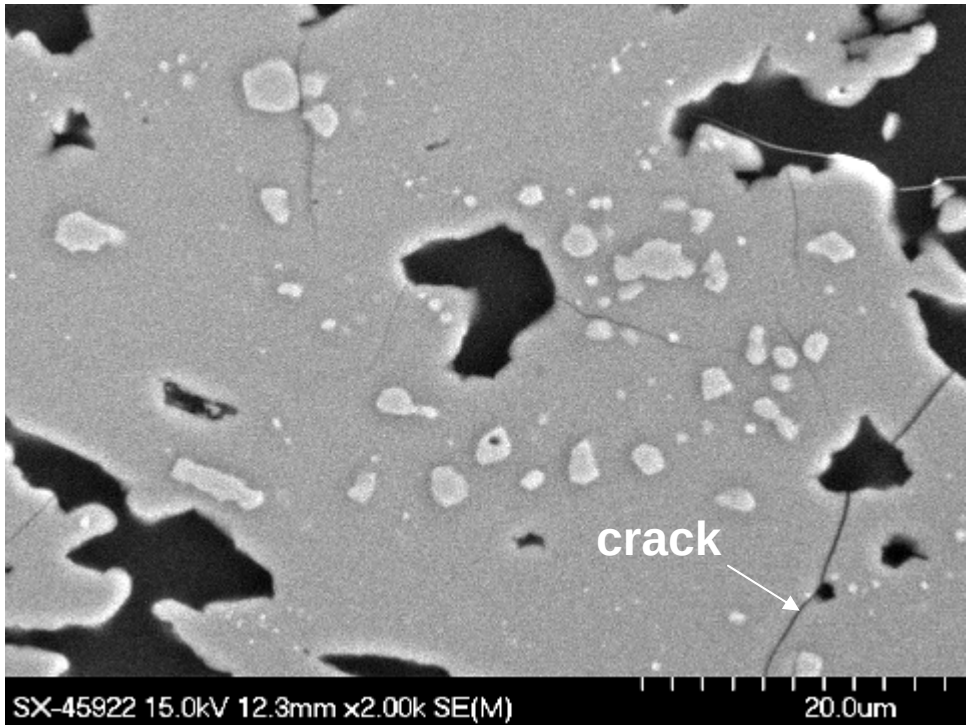
Approach

- Candidate DPF Substrates: Porous Cordierite and Mullite
- Development of test methods for evaluation of elastic, mechanical and thermal properties of porous DPF substrates
- Properties of interest – elastic modulus, strength, fracture toughness, subcritical crack growth, thermal expansion
- Evaluate properties of interest as a function of porosity of substrate, temperature and relevant service environment
- Develop computational lifetime models (FEM based) with material and thermal property database as input to estimate mechanical reliability and durability
- Evaluate the validity of lifetime models
  - Burner rig tests
  - Non-destructive evaluation techniques

Accomplishments

Characterization of Materials - Cordierite

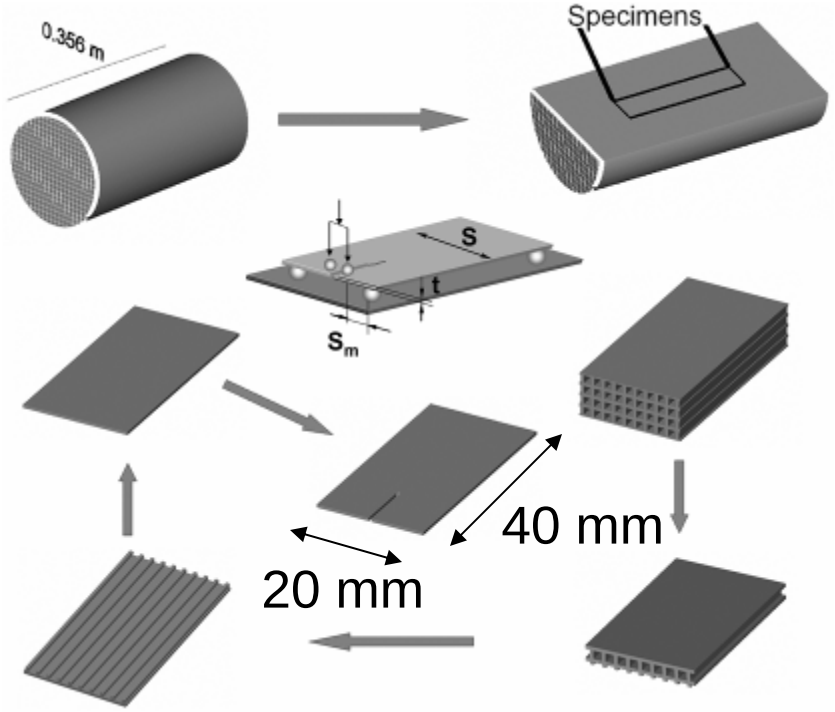


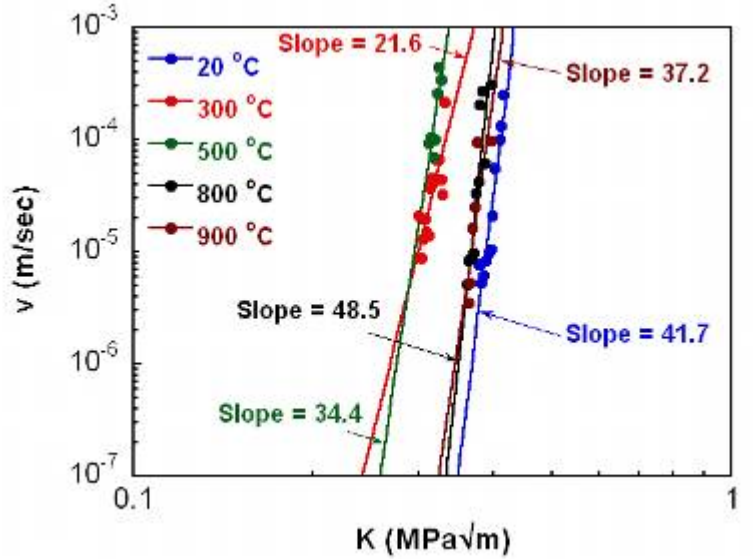


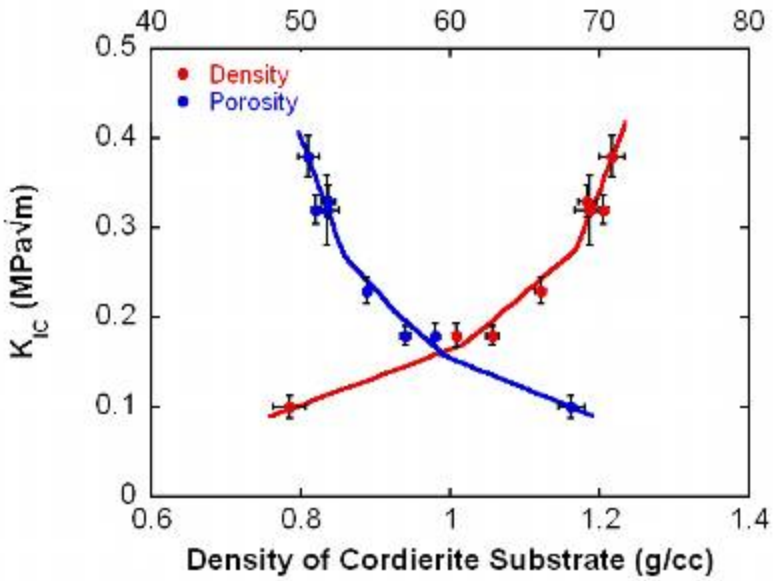
- Metallographic prepared cross section
- Cordierite ($Mg_2Al_4Si_5O_{18}$) - identified as orthorhombic phase by Synchrotron diffraction
- Porosity ~ 50 % for this substrate from image analysis and pycnometer
- Microstructure with porosity, heterogeneity & microcracks

Accomplishments

Test methods for Fracture Property Evaluation



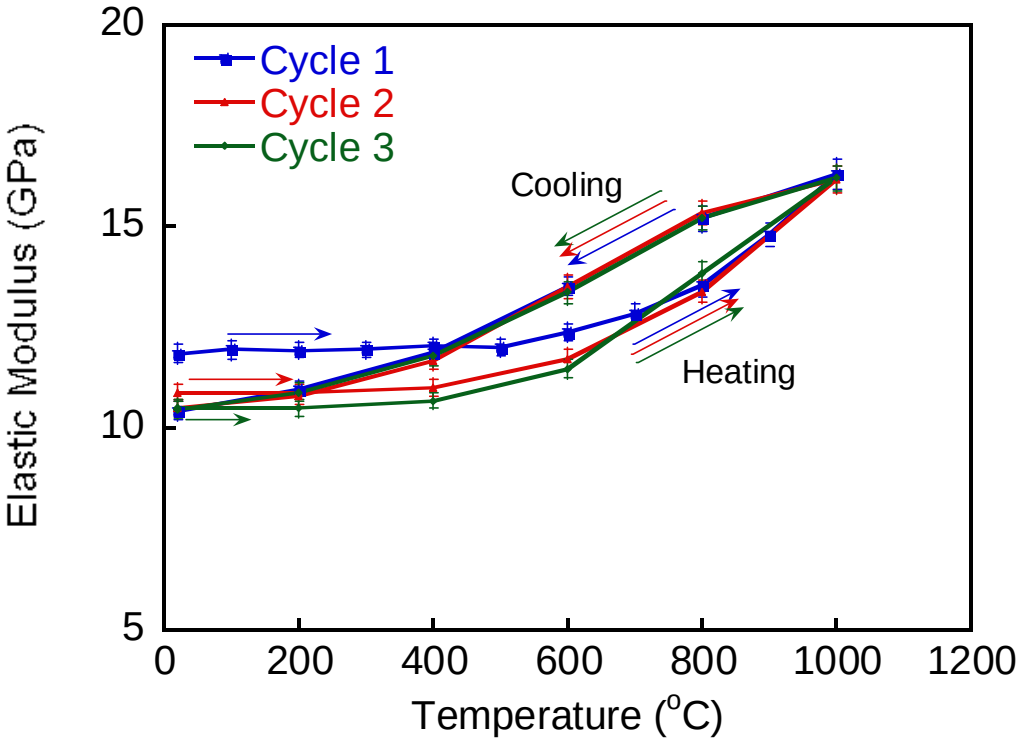




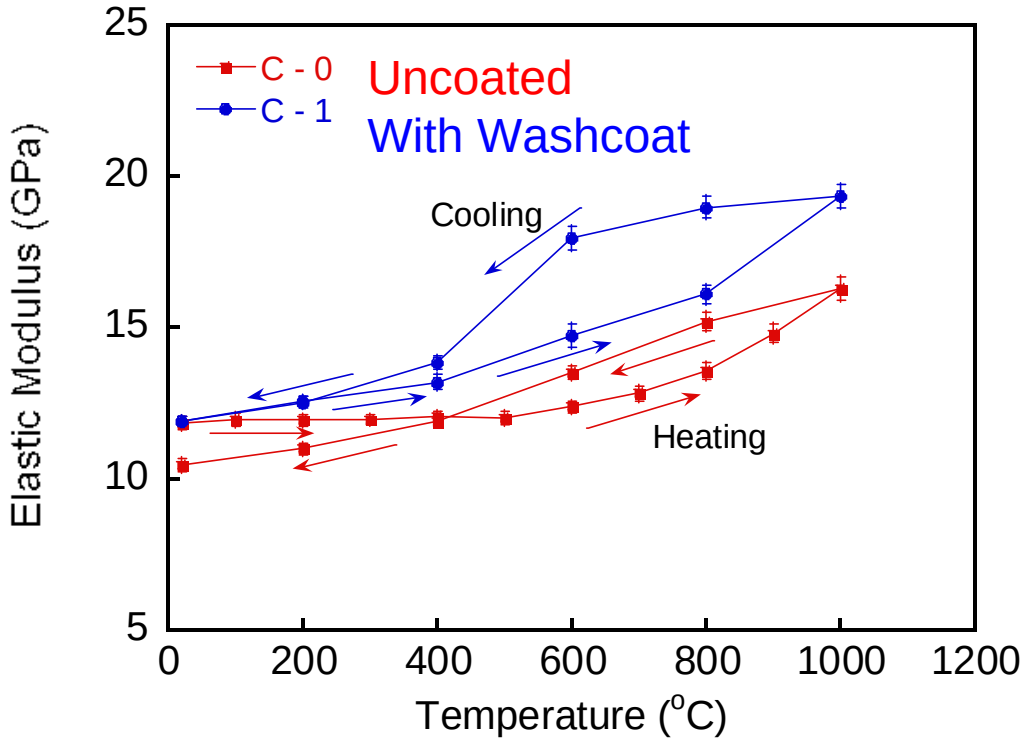
- Double torsion specimens prepared from filter walls for fracture toughness and slow crack growth (SCG) evaluation
- SCG evaluated at temperature
- Fracture toughness a strong function of porosity

Accomplishments

Test methods for Elastic Property Evaluation



Effect of Thermal Cycling

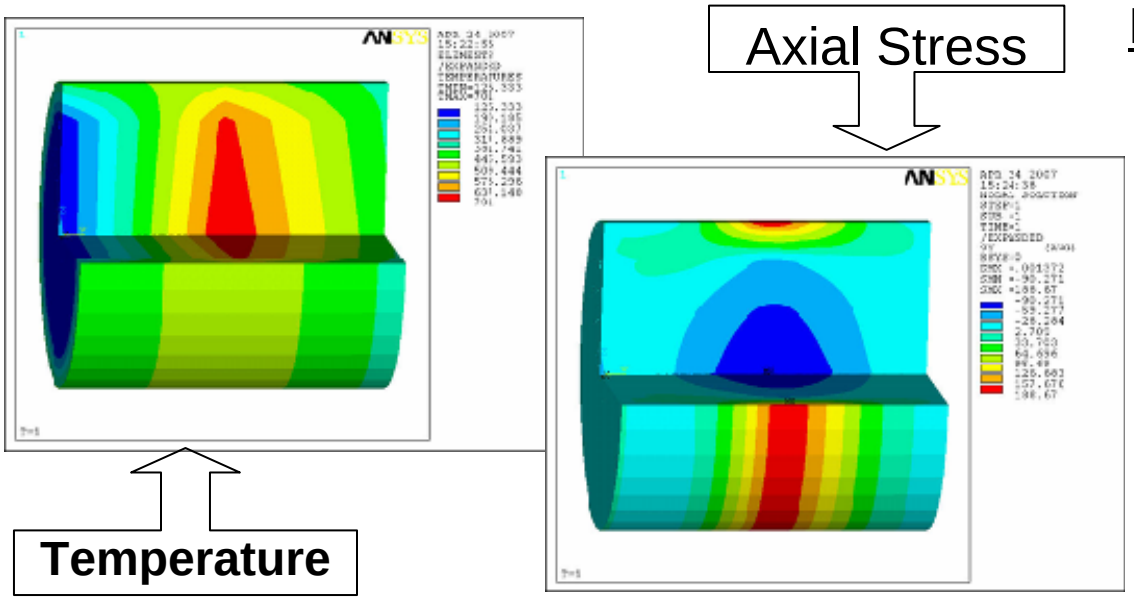


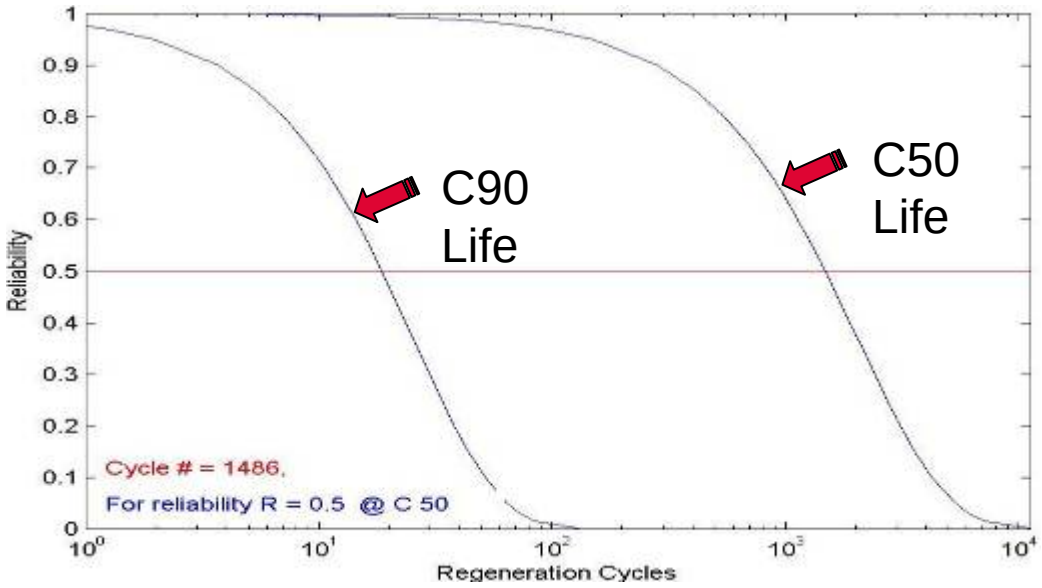
Effect of Catalytic Washcoating

- Elastic modulus evaluated by resonant ultrasound spectroscopy (RUS)
- Material properties are expected to change during service!
- Washcoating and soot loading influence the material properties

Accomplishments

Modeling and Lifetime Prediction





Modeling

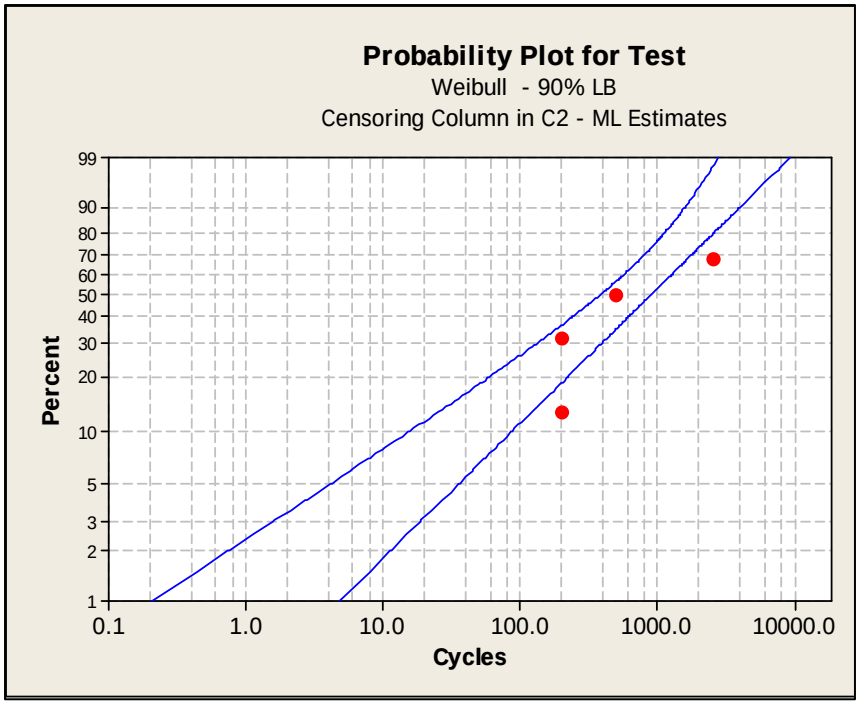
- 2D and 3D including thermal history
  - Uses material properties for specific substrate and catalyst coating as measured in previous material property tests.
  - Predicts locations of maximum stress in component

Life Prediction

- Probability based function
  - Uses R50/C50 and R50/C90 as bounds
- Prediction of component failure
  - Includes thermal history of component
  - Uses material properties from previous testing

Accomplishments

Model Evaluations - Tests and NDE Techniques



- Burner rig temperature cycles between soot combustion temperature and normal operating temperature.
- Run for repeated cycles to simulate life time of filter.

← Burner rig test result

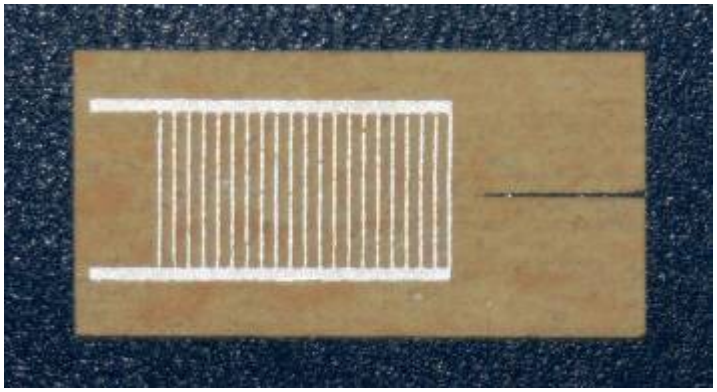
Burner rig test filter →

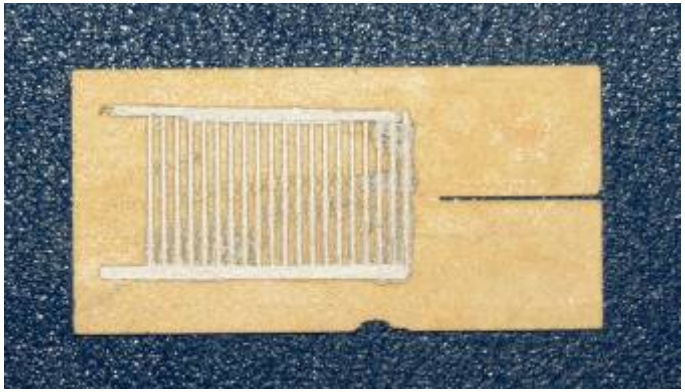
BAKED DECAL PATTERN

PRINTED MASK PATTERN

Crack gages developed for NDE of filters

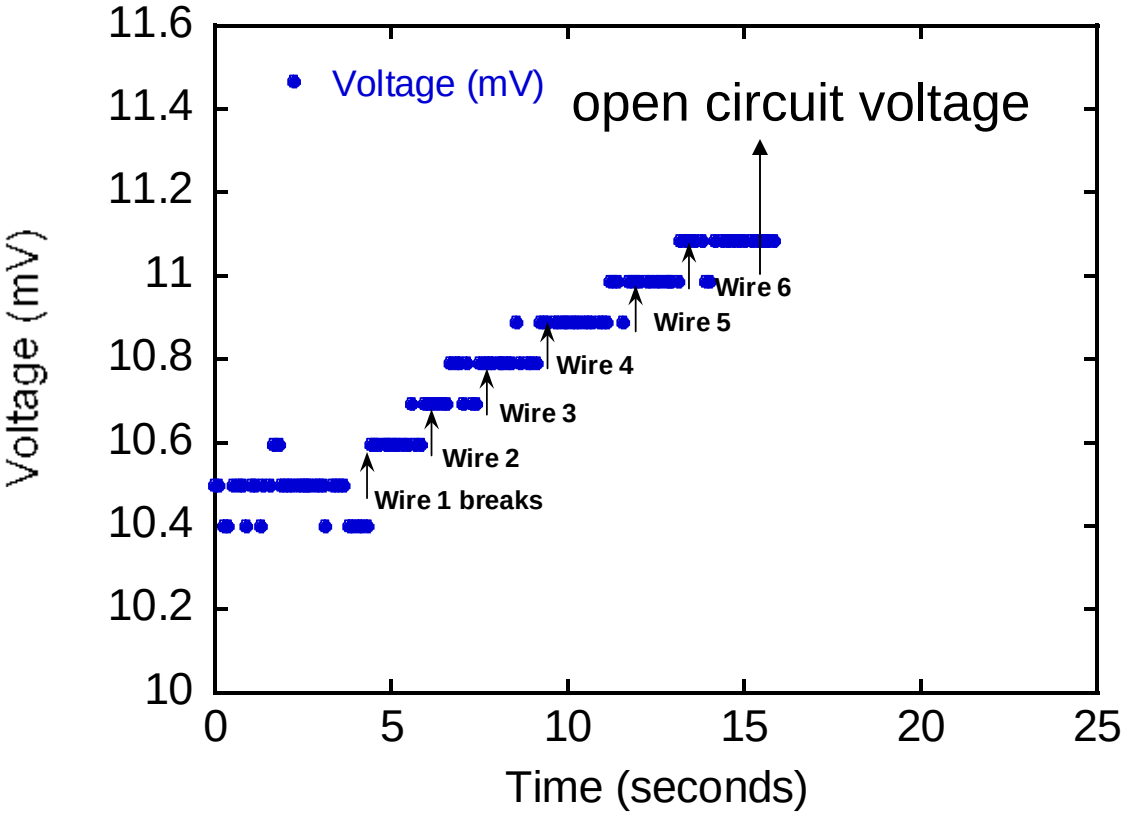
US Patent application filed

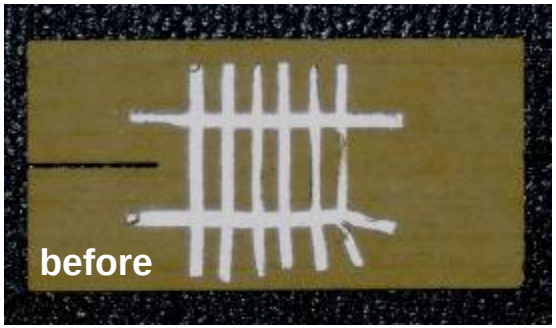


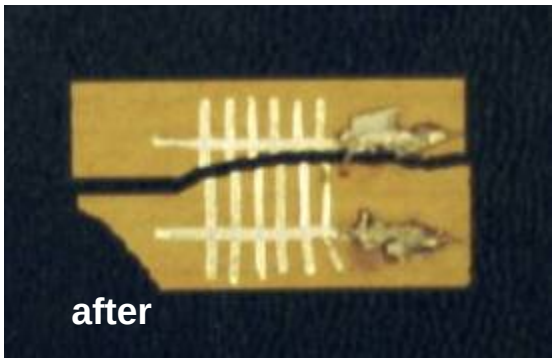


Accomplishments

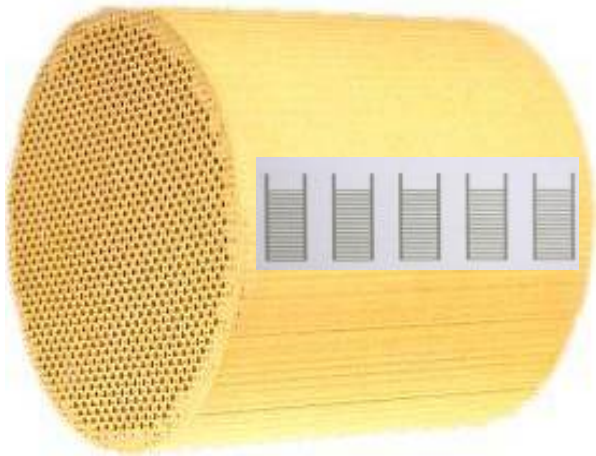
NDE Technique Development & Implementation







- Voltage across crack gage increases as crack grows
- Possible implementation in a filter →
- US Patent application filed



Technology Transfer!!

Dodge Ram is first with cleaner diesel

Pickups with new Cummins engine meet strict 2010 emissions rules

By Ken Thomas, Associated Press,* January 24, 2007

*The Indianapolis Star

Technology Transfer
February 15, 2007, Letter from John Wall, VP & CTO of Cummins Inc. to T.R. Watkins

- “Our two existing [9130 & 10461] Cooperative Research and Development Agreement (CRADA) programs with HTML/ORNL grew from a long-term partnership in the area of materials research, which over the years delivered substantial breakthroughs in understanding and characterization of different metallic and ceramic materials, enabling engines to be lighter, more reliable, and operate with higher efficiency and lower emissions.”
- “The value of such collaborations in a globally competitive environment is that these provide industry with state of the art tools and knowledge critical for maintaining technology leadership in the world.”

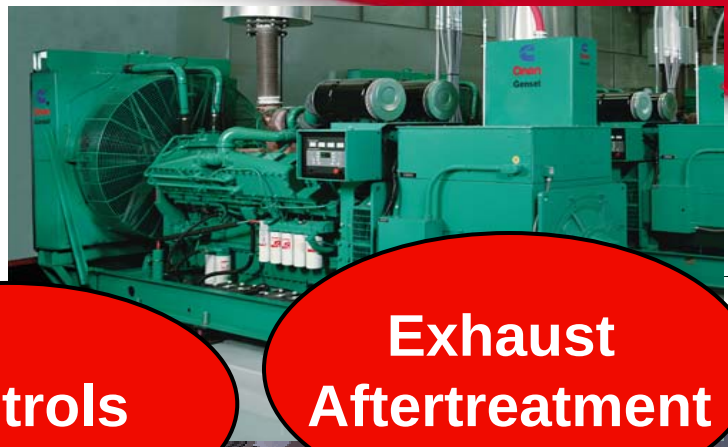
- Joint technology development between ORNL and Cummins Inc.

Publications/Patents

- T. M. Yonushonis, R. J. Stafford, E. Lara-Curzio and A. Shyam, “Apparatus, system, and method for detecting cracking within an aftertreatment device” *US Patent Application* Filed, March 2007.
- A. Shyam, E. Lara-Curzio, T.R. Watkins and R. J. Parten, “Mechanical Characterization of Diesel Particulate Filter (DPF) Substrates", *Journal of the American Ceramic Society* (in press).
- A. Shyam, E. Lara-Curzio, H-T Lin and R. J. Parten, “Fracture Toughness of Porous Cordierite", *Ceramic Engineering and Science Proceedings*, vol. 27, no. 2, pp. 75-81, 2007.
- T.M. Yonushonis, R. J. Stafford, C. Klepser, T. R. Watkins, A. Shyam and E. Lara-Curzio, “Ceramic Particulate Filters”, *Diesel Engine-Efficiency and Emissions Research (DEER) Conference*, Detroit, August 2007.
- A. Shyam, E. Lara-Curzio and T.R. Watkins, “Fracture mechanical characterization of porous cordierite ceramics”, *Materials Science &Technology*, Detroit, September 2007.

Plans for Next Fiscal Year

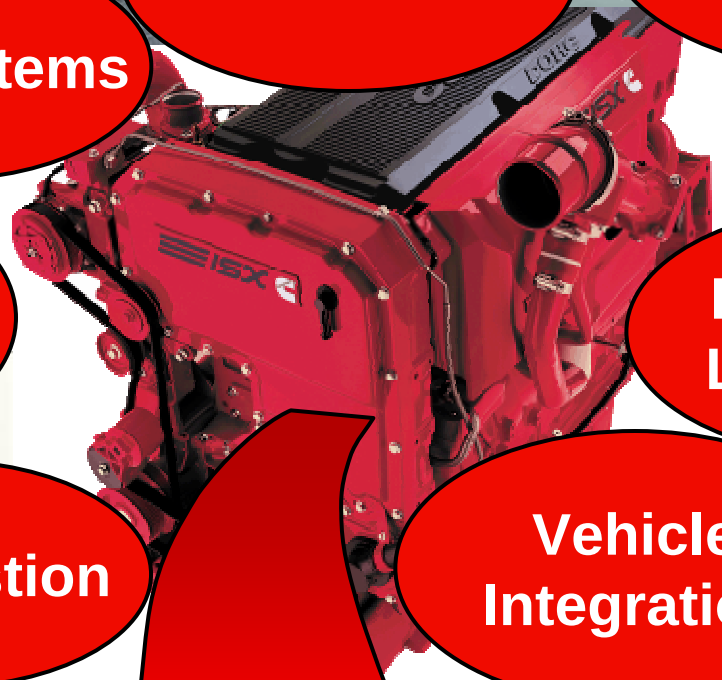
- Evaluation of the material properties of filters returned from field (high mileage filters)
- Evaluation of the interaction between catalytic washcoating, soot and material microstructure on material properties
- Refine lifetime prediction models based on material properties
- Development of NDE techniques that can be implemented with truck service intervals



Controls

Exhaust Aftertreatment

Fuel Systems



Air Handling

Fuels and Lubricants

Combustion

Vehicle Integration

Industry, universities and national laboratories must work together for our customers to deliver <u>The Right Technology</u>