Electrically-Assisted Diesel Particulate Filter Regeneration

Michael J. Lance, James E. Parks II,
Vitaly Prikhodko, Andrew A. Wereszczak
and William P. Partridge Jr.
Oak Ridge National Laboratory
Eugene V. Gonze and Julian Tan
General Motors

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PM041

Overview

Timeline

- Start: May 2010
- End: September 2012
- 36% complete

Budget

- Total Project Funding
  - DOE: $640K
  - GM: $640K
- Funding received:
  - FY09: $34K
  - FY10: $467K
  - FY11: $250K

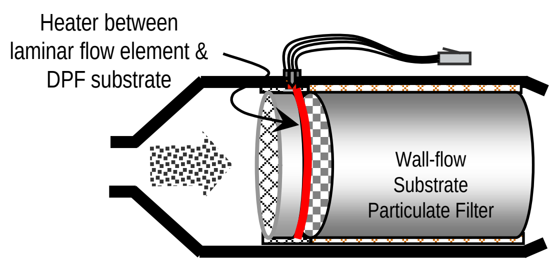
Barrier

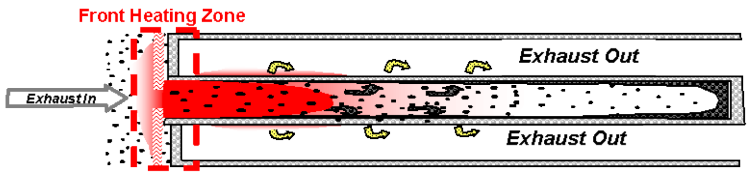
- Improve the technologies and strategies for PM filters to achieve reliable regeneration at low exhaust temperatures.
- By 2015, develop materials, materials processing, and filter regeneration techniques that reduce the fuel economy penalty of particle filter regeneration by at least 25 percent relative to the 2008 baseline.

Partners

- General Motors

Background: Electrically Assisted Diesel Particulate Filter (EADPF) Regeneration





- Diesel particulate filters (DPFs) are used to filter particulate matter from exhaust gas.
- Periodically, the DPF is cleaned or "regenerated" to oxidize or "burn" the accumulated PM in the filter. The regeneration procedure occurs by raising the temperature of the DPF to approximately 600ºC or higher where the carbon-rich PM readily oxidizes.
- The current technique for DPF regeneration consumes extra fuel which is oxidized over a diesel oxidation catalyst in the diesel exhaust to heat the DPF to regeneration temperatures. This extra fuel or "fuel penalty" reduces the fuel economy advantage of the diesel engine.
- General Motors (GM), the CRADA partner for this project, has developed a DPF technology that utilizes electrical power to heat the DPF for regeneration, thereby greatly reducing the "fuel penalty".

Project Objective

To study the efficiency benefits and materials issues associated with the electrically-assisted diesel particulate filter (EADPF) device developed by General Motors (GM).

Milestones

- FY10
  - Milestone: Installed DPF system and electrical power unit including LabView-based control algorithms to control DPF temperatures during engine operation.
  - Milestone: Developed fiber optic probes with angled tip to enable side view of substrate wall during engine experiments.
  - Milestone: Designed and harvested test coupons from DPFs and developed finite element stress model, using µ-FEA (finite element analysis), to relate experimental loading of various test geometries to associated failure stress.
- FY11
  - Jan-11 Milestone: **Measured an order-of-magnitude lower elastic modulus for cordierite DPFs compared to literature values.**
  - Feb-11 Milestone: The effect of the heater on the DPF temperature was measured.

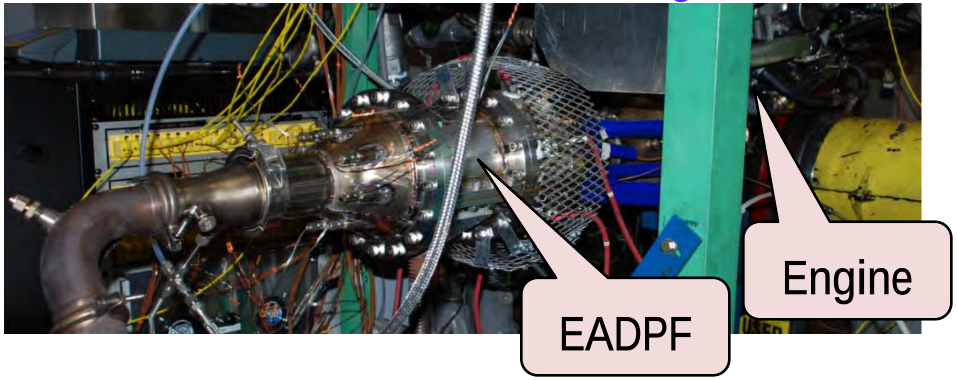
Approach

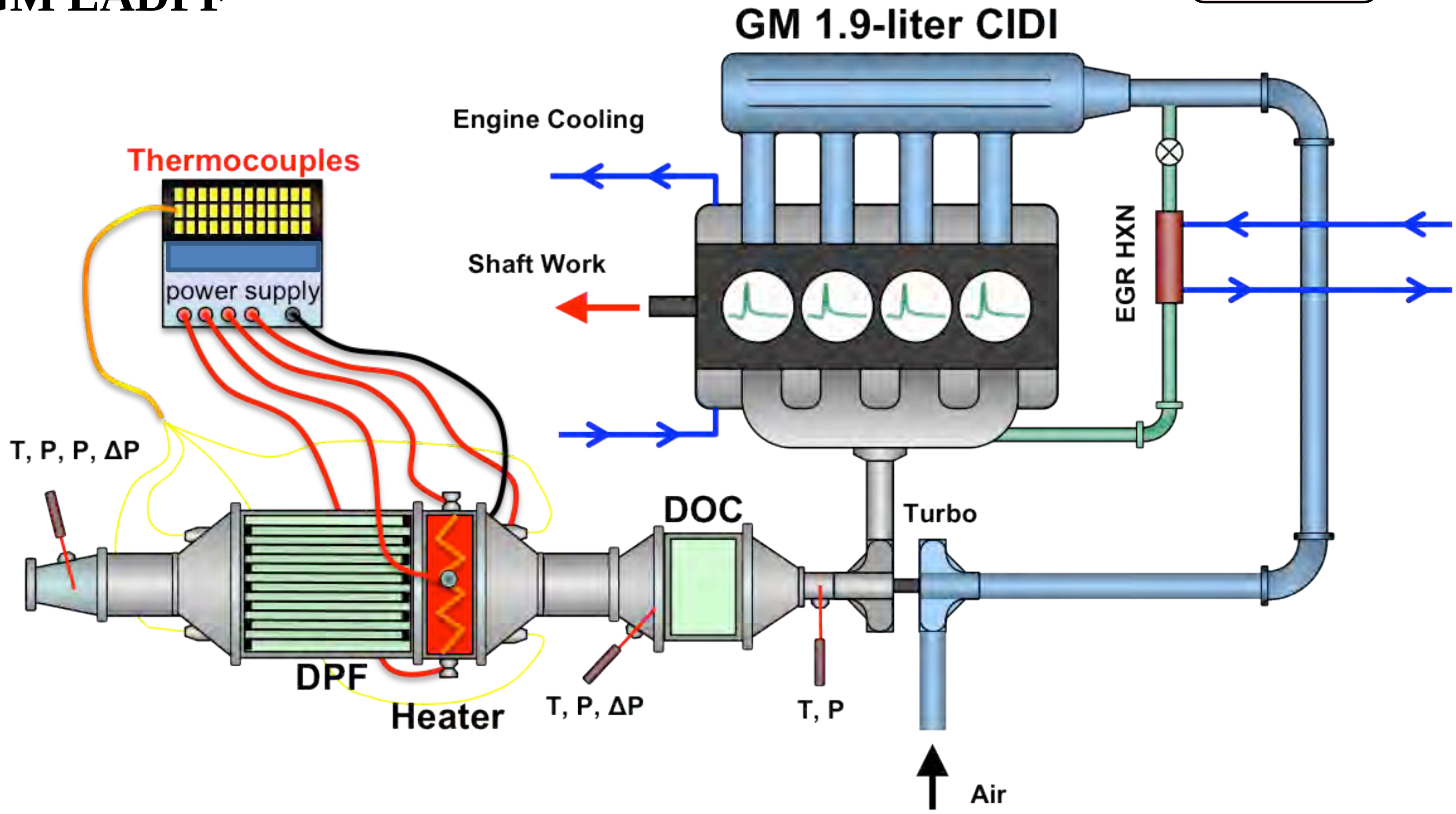
- Task 1: Efficiency and Temperature Measurement
  - **Characterize potential fuel savings of the approach and related benefits to other emission control devices.**
  - **Measure gas and substrate temperatures to obtain accurate picture of conditions experienced during regeneration.**
- Task 2: DPF Mechanical Properties Measurement
  - **Resolve current disconnect between cordierite substrate model predictions and actual substrate durability.**
  - **Use data and results to develop general design rules on heater geometries to optimize substrate durability.**
- Task 3: Heater Alloy Selection
  - **Conduct a high-level discussion on the durability of the heater alloy.**

Task 1-Experimental Setup: GM Engine at ORNL

- **1.9-liter 4-cylinder GM CIDI**
- **Full-pass Drivven control system (enables post fuel injection)**
- **Model DOC 100 g/ft^3 Pt, 1.25-liter**
- **GM EADPF**

Photo of EADPF installed on GM engine at ORNL





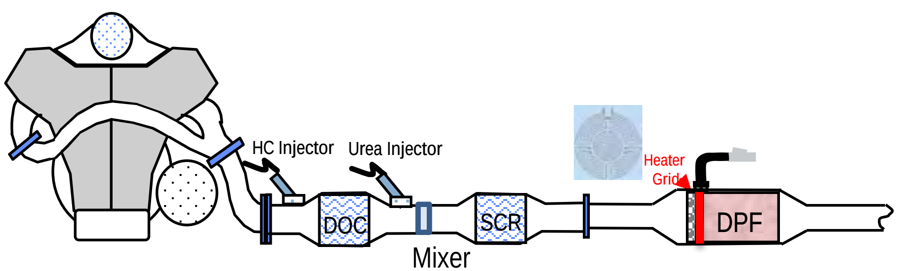
EADPF Achieves High Temperatures for Soot Oxidation in Engine Exhaust

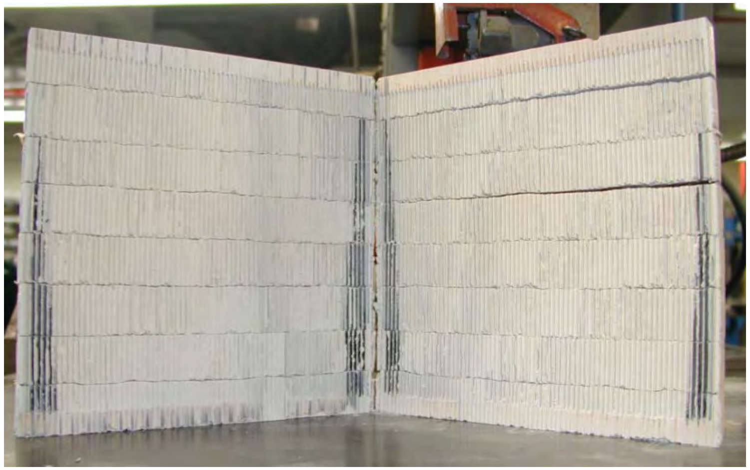
<u>Regeneration Efficiency</u>

95% Soot Removal !!!

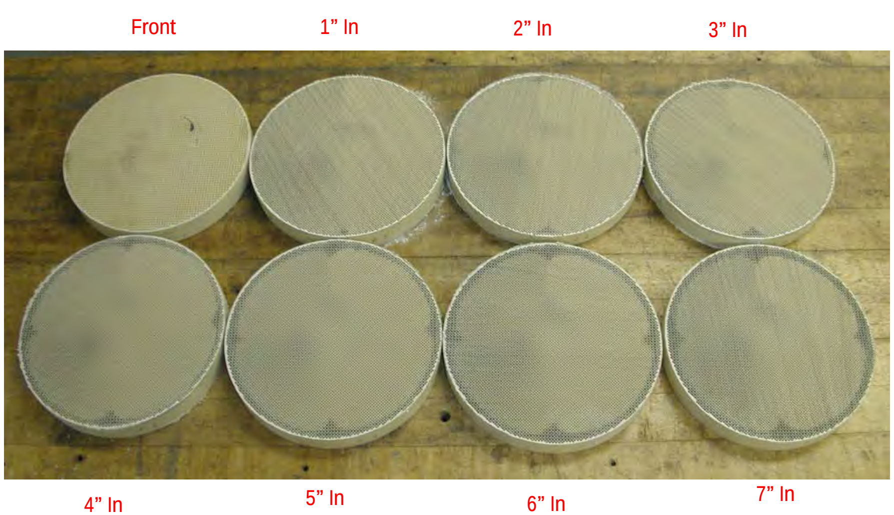
<u>Regeneration time</u>

Reduced by 75%



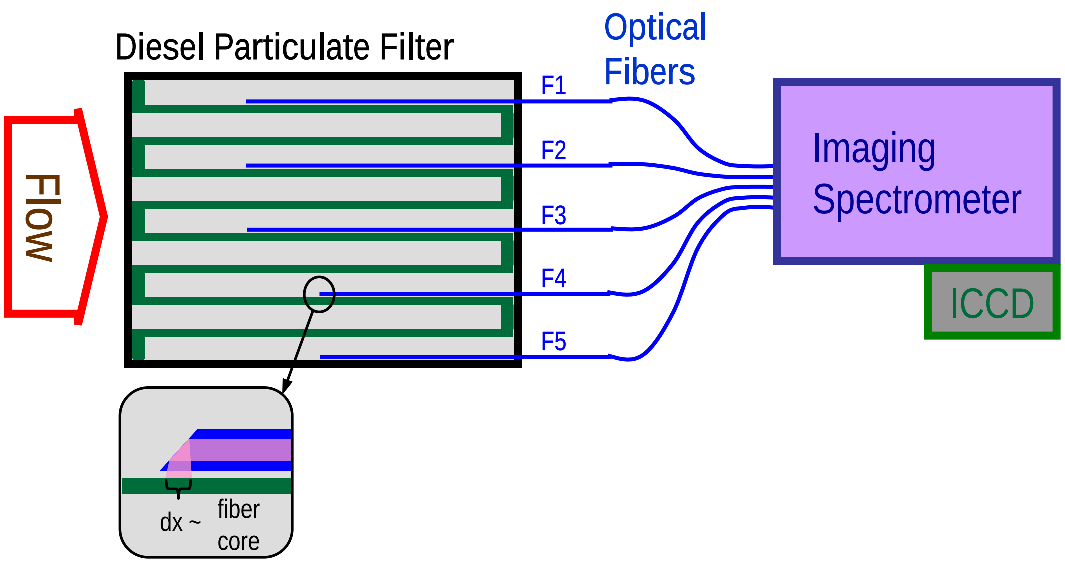


95% Soot Removal



Section cut out

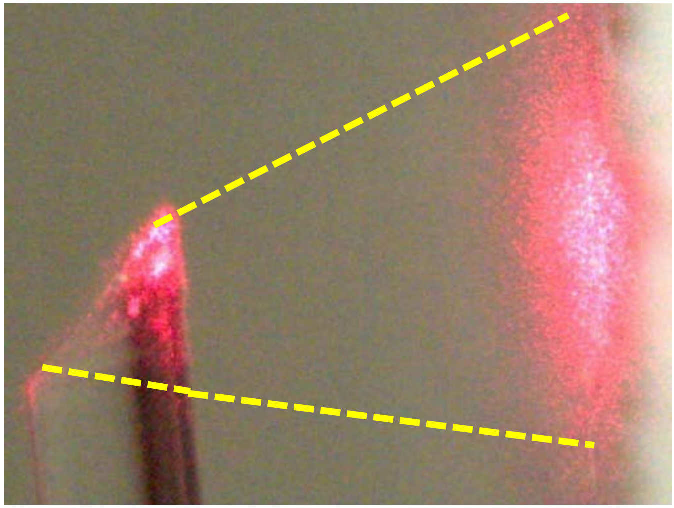
Side Viewing Fiber Optic Probes Allow Temperature Measurement of DPF Channel Wall



- Approach is to utilize fiber optic temperature measurement technique to directly determine cordierite substrate temperature during operation on engine
- Fiber optics have been polished with angled tip to enable side view of channel wall

Optical microscope image of fiber optic with angled tip (fiber diameter is 250 microns)

Red laser light traveling down fiber to tip is internally reflected and travels out of fiber in direction perpendicular to fiber axis (reverse process will be used to collect light from same direction)

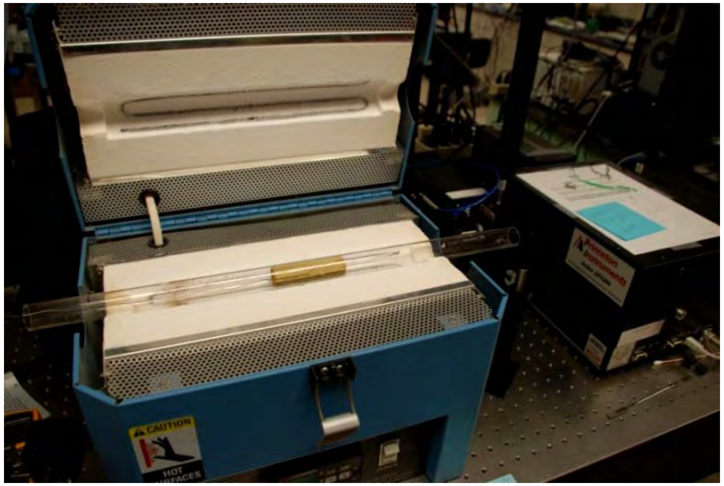


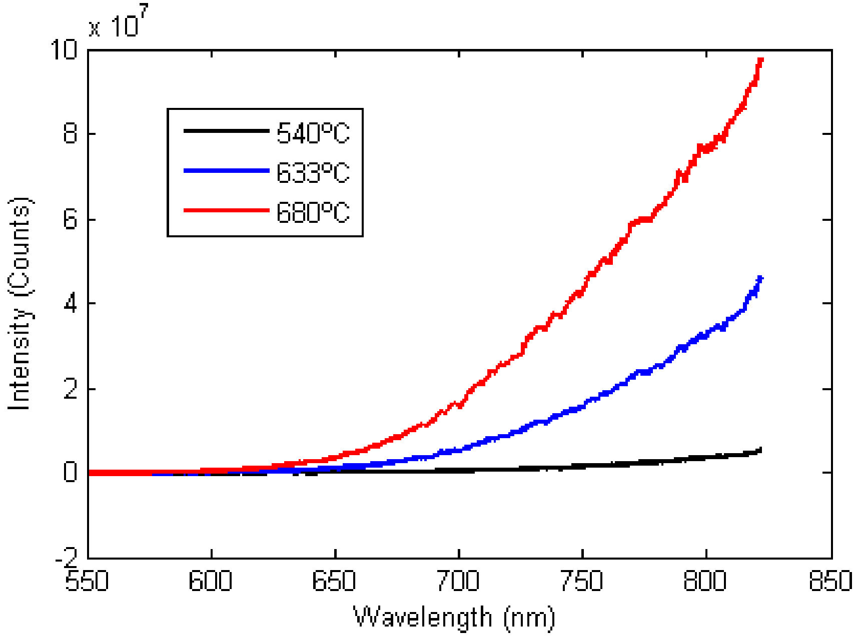
Fiber Optic Temperature Measurement Technique Calibrated on Bench

- Bench scale fiber optic measurement of catalyst monolith shows blackbody radiation curves consistent with theoretical expectations
- Current focus is on calibration and readying for engine application

ICCD image of fiber optic array input slit shows multiplexing capability

Fiber optic probe inserted into cordierite substrate heated in furnace





Blackbody radiation data from fiber probe [note: spectra corrected for quantum efficiency of detector]

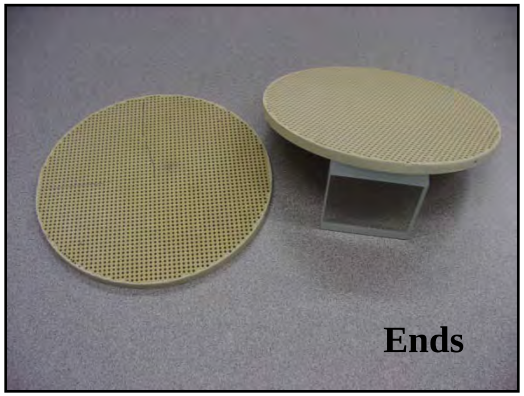
Technical Accomplishments Summary (Task 1): Engine-based DPF substrate temperature task

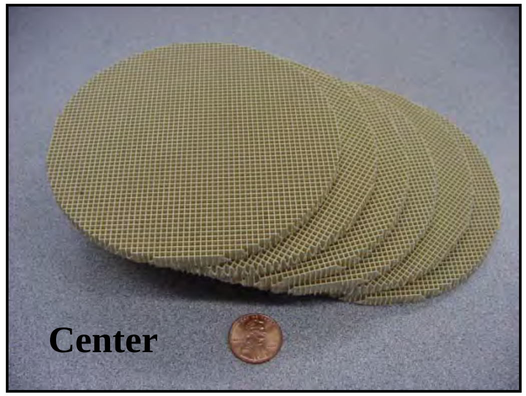
- **EADPF operational on GM 1.9-liter engine at ORNL**
  - **EADPF heating to soot oxidation temperatures demonstrated**
  - **Array of thermocouples integrated into data acquisition system, but…some issues are causing shorting of thermocouples on heater**
  - **Fix for thermocouple issues underway;…will finalize control strategies after fix completed**
- **Fiber optic-based temperature measurement demonstrated on bench scale**
  - **Fibers successfully polished with angled tip to enable side viewing of substrate channel wall**
  - **Spectrometer with multi-fiber input and ICCD camera detector functional for multiplexed data acquisition**
  - **Initial calibrations of blackbody radiation curves conducted**

Task 2-Technical Accomplishments

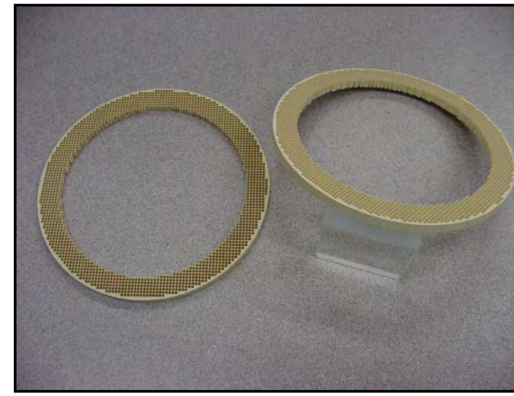
Three Test Specimens for Estimating Failure Stresses in DPFs:

Biaxial Flexure of Disks
(Ring-on-Ring, Adaptation of ASTM C1499)

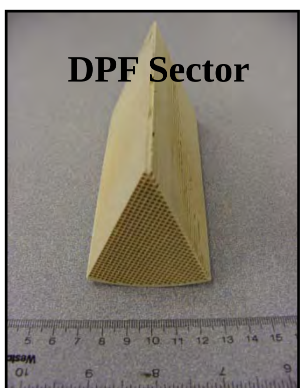




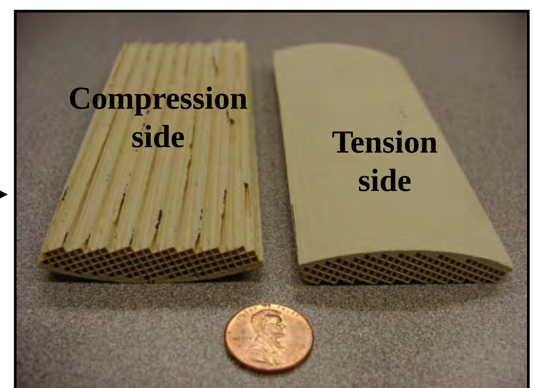
O-Ring Flexure
(Diametral Compression)



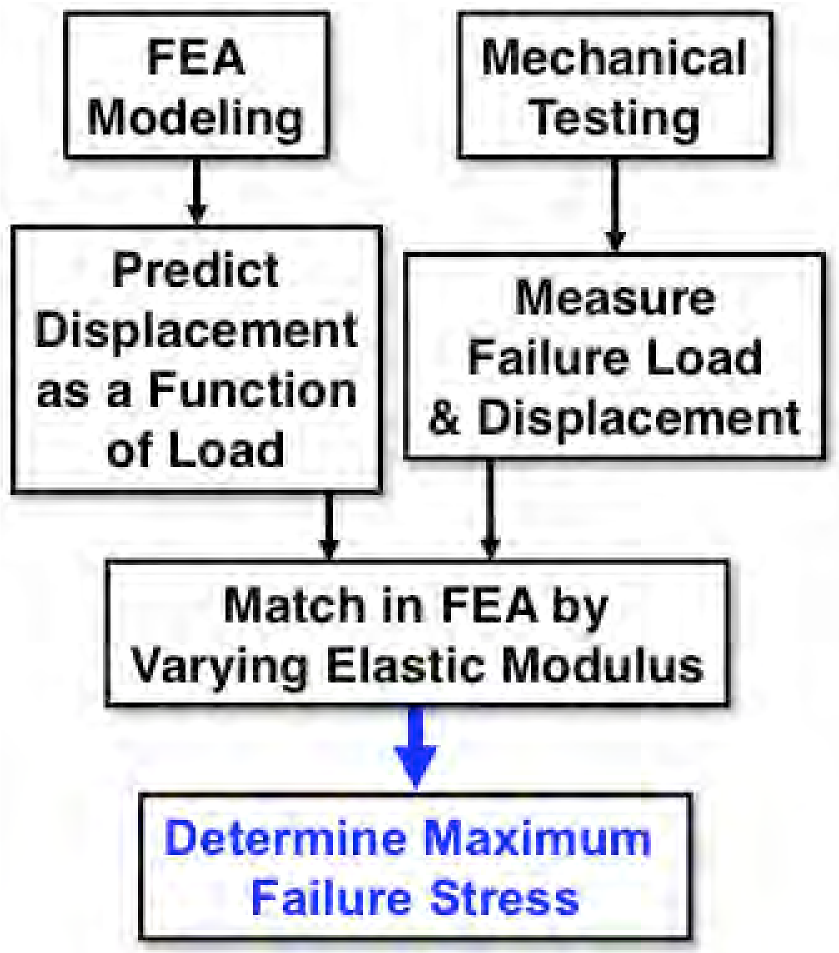
4-Pt Loading of Sectored Flexure Specimen
(Adaptation of Wereszczak ASTM JTE Work)

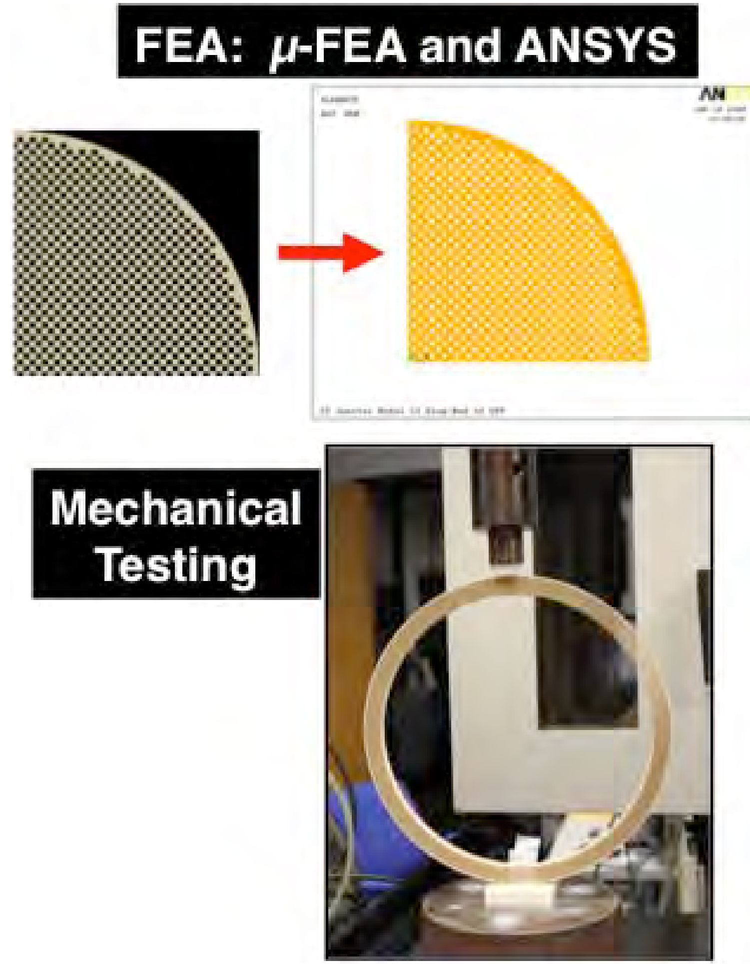


Apex
Cut off

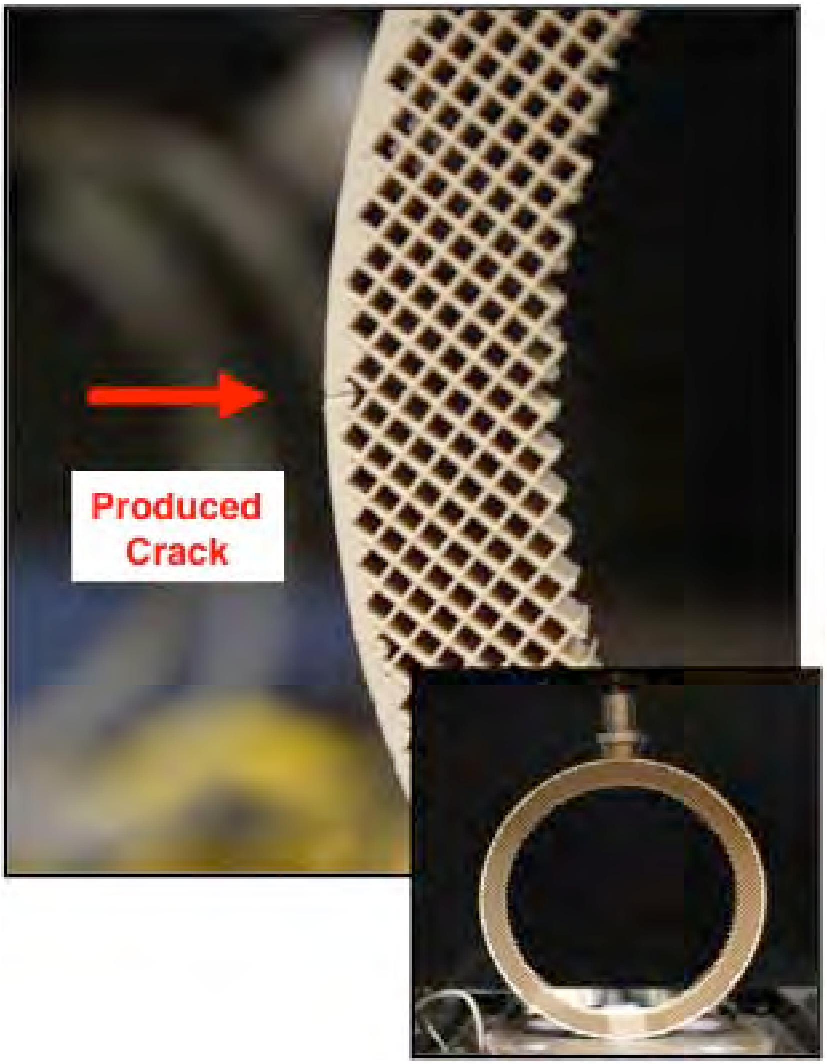


Finite Element Analysis and Mechanical Testing Iteratively Performed:





O-Ring Testing (Samples Uniaxial Hoop Tension in DPF):

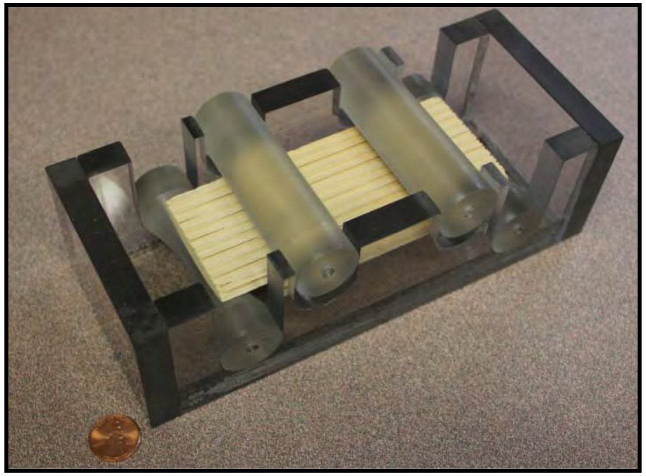


Observations

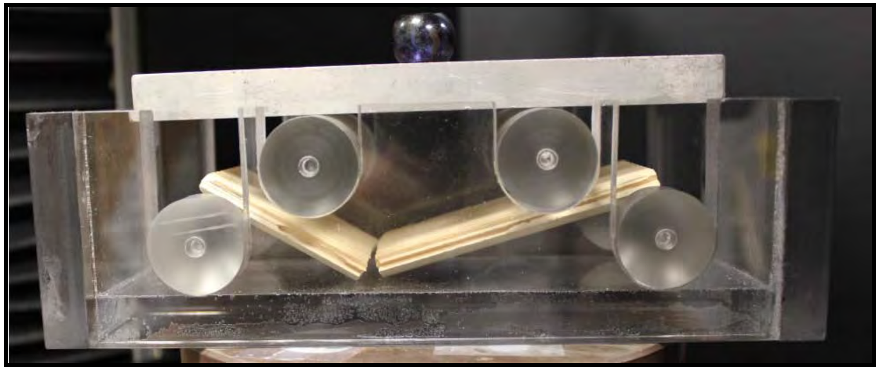
- **Easy to harvest and test**
- **Uniaxial stress inherently applied, and 0° and 45° orientations tested**
- **Crack initiation occurs at:**
  - **6 or 12 o-clock position for 0°**
  - **3 or 9 o-clock position for 45°**
- **Estimated apparent elastic modulus ranges between 1100-2100 MPa for all specimens**
- **Uy-E inverse proportionality jives with Winkler's Curved Beam Theory**

Sectored Bar Flexure Testing (Samples Uniaxial Axial Tension of DPF OD):

Specimen Positioned in Fixture



Specimen After Fracture



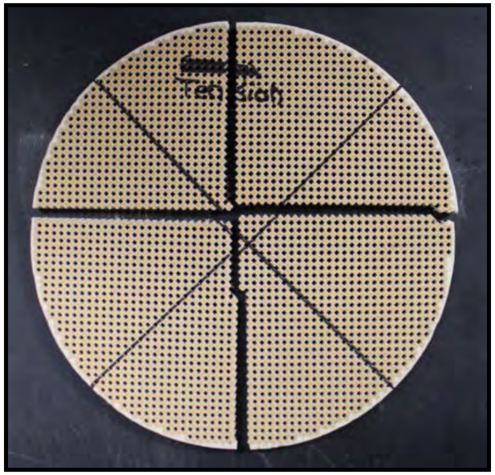
Observations

- Easy specimen to harvest and mechanically test
- Uniaxial stress inherently applied, and ~ 22.5° angle tested here
- Moment of inertia being estimated
- Fixture has a 120mm lower span and 60mm upper span

Biaxial Disk Flexure Testing (Samples Biaxial Radial Tension in DPF):

Specimen and Ring Fixtures

Example of Failed Disk



Observations

- Easy to harvest and test
- Equibiaxial stress inherently applied, and all angles of rotation therefore sampled
- End (50% filled) and interior structure can be analyzed
- Cored disk from o-ring can be tested (efficient use of material)
- 3D FEA model under construction
- Fixture has a 80mm lower span and 40mm upper span

Elastic Modulus

Preliminary results suggest elastic modulus of the DPF cordierite is lower than reported sonic-based-measured literature values:

Test Method	Elastic Modulus (GPa)*	Source
Resonance Ultrasound Spectroscopy (RUS)	12.3 0.3	Shyam *et al.*, JACS, 2008.
Resonance-Based	4 - 7	SAE 2004-01-0959
Mechanical (O-ring)	1.1 – 2.1	This Project
Mechanical (Biaxial Flexure)	TBD	
Mechanical (Sectored Flexure)	TBD	

**** A function of porosity – comparison intended to illustrate coarse comparison.***

<u>Key Findings Illustrate Importance of Industry/National Laboratory Partnerships</u>

- Actual service stresses are lower than previously thought
- Potential to drive industry-test standardization

Collaborations

- This project has a 50/50 cost share with General Motors. GM has provided DPF heater assembly and DPF bricks for analysis.

Future Work

- Task 1
  - Finalize control strategy details for EADPF operation in engine exhaust after fix of thermocouple issue on heater
  - Measure fuel penalties for EADPF and conventional DPF approaches
  - Implement fiber optic temperature measurement of substrate on engine
- Task 2
  - Resolve elastic property discrepancies of mechanical and sonic measurements.
  - Complete measurements of failure stress in DPFs as a function of position and orientation of stress application.
  - Develop rules of design.
  - Consider herein described test methods for standardization.
- Task 3
  - Metallurgy and corrosion experts at ORNL will participate in a discussion with GM and their heater supplier concerning trade-offs between heater alloy cost, performance and reliability.

Summary

- Task 1
  - EADPF system operational on GM 1.9-liter engine at ORNL
  - Initial demonstration of EADPF operation to temperatures suitable for soot oxidation completed
  - Fiber optic-based temperature measurement demonstrated on bench scale will be implement on engine setup to enable substrate wall temperature measurement
- Task 2
  - O-ring, biaxial flexure disks, and sectored flexure specimens being used to measure failure stress of DPF materials as a function of orientation and direction of stress application.
  - Elastic modulus (E) estimated through a combination of mechanical loading and finite element analysis (μ-FEA and ANSYS).
  - An E of 1.1-2.1 GPa results in experimental and FEA correlation. This is about one order-of-magnitude lower than E estimated by sonic or resonance methods.
  - If this lower elastic modulus is representative of the DPF material, then the actual and predicted service stresses in a DPF would be lower than those arising from the use of sonic- or resonance-based measured values of E.