Electrically-Assisted Diesel Particulate Filter Regeneration

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PM041

Overview

Timeline

- Start: May 2010
- End: September 2012
- 95% complete

Budget

- Total Project Funding
  - DOE: $640K
  - GM: $640K
- Funding received:
  - FY10: $140K
  - FY11: $250K
  - FY12: $250K

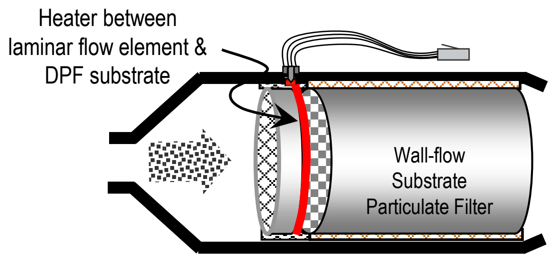
Barrier

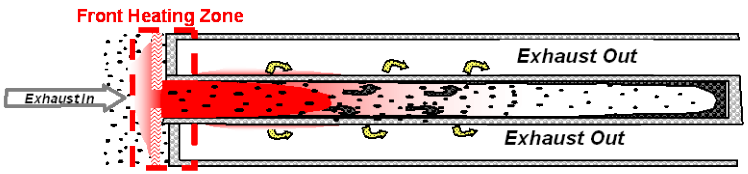
- Improve the technologies and strategies for PM filters to achieve reliable regeneration at low exhaust temperatures.
- By 2015, develop materials, materials processing, and filter regeneration techniques that reduce the fuel economy penalty of particle filter regeneration by at least 25 percent relative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

- 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.
  - Characterized the fuel penalty reduction from the EADPF approach as compared with traditional fuel-based regeneration.
    - **Up to 50% reduction in fuel penalty demonstrated**
- FY12
  - In progress: measurement of DPF substrate temperatures during DPF regeneration via optical fiber technique.

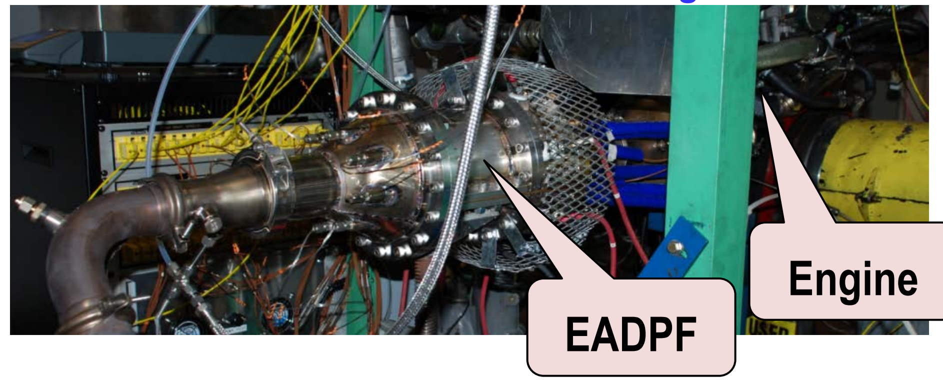
Approach

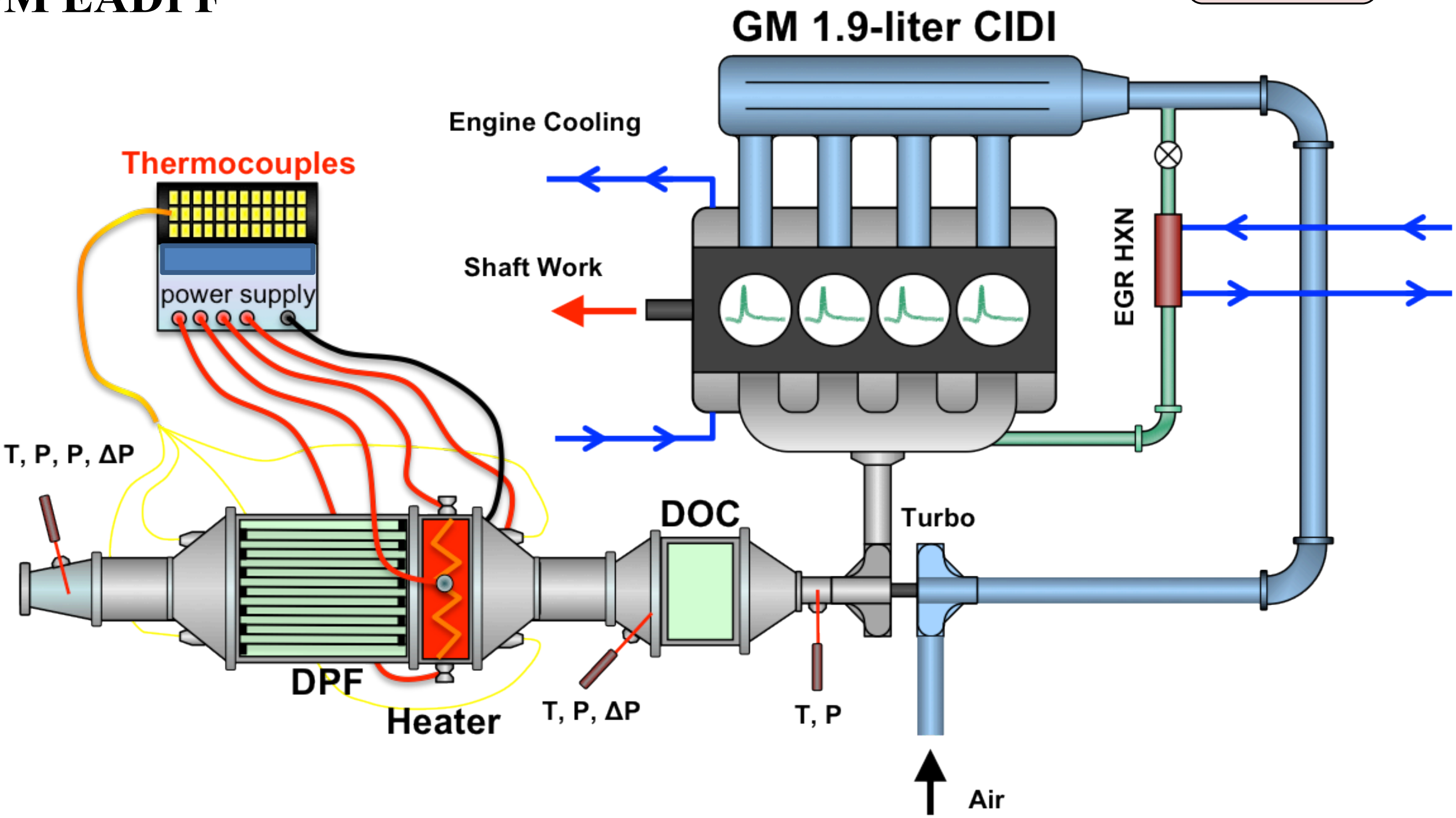
- Task 1: Efficiency and Temperature Measurement
  - **Characterize potential fuel savings of the approach and related benefits to other emission control devices.**
  - **Measure gas and substrate temperatures to obtain accurate picture of conditions experienced during regeneration.**
- Task 2: DPF Mechanical 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 Diesel**
- **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





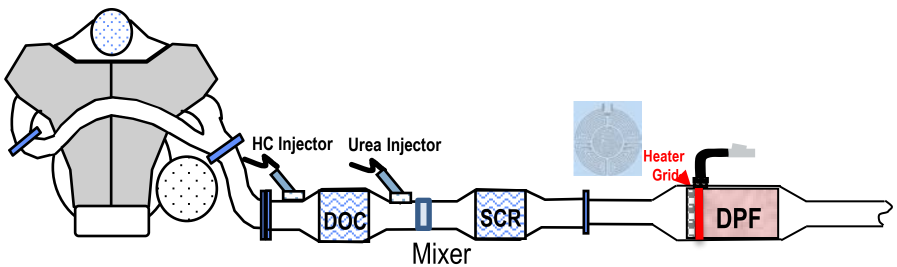
EADPF Achieves High Temperatures for Soot Oxidation in Engine Exhaust

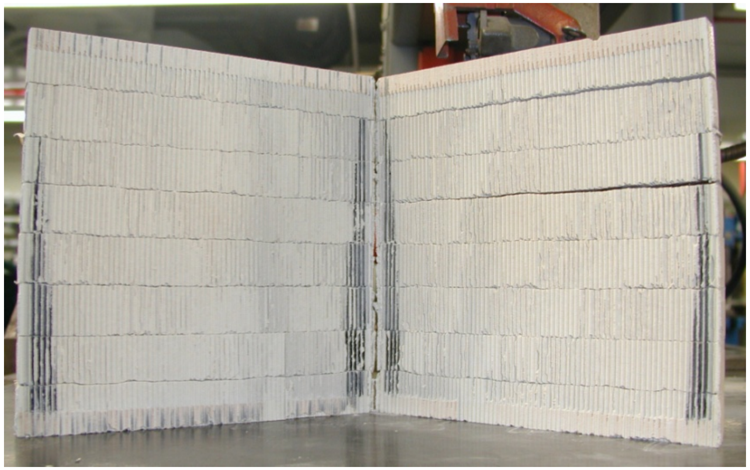
Regeneration Efficiency

95% Soot Removal !!!

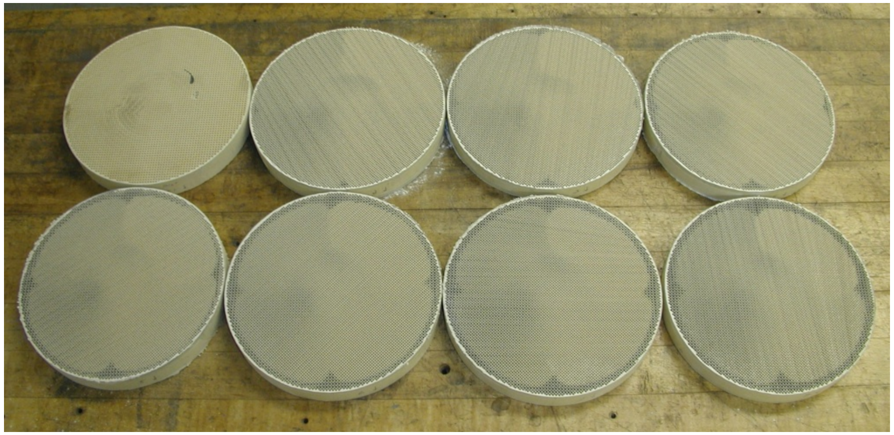
Regeneration time

Reduced by 75%





95% Soot Removal

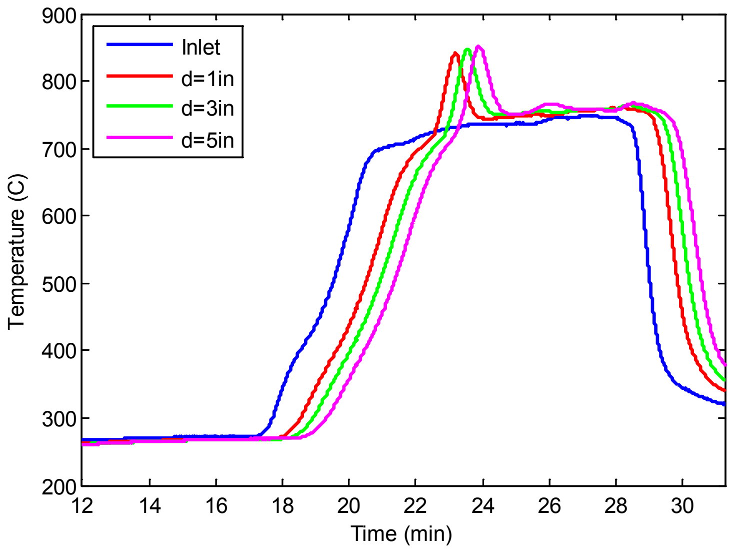


Section cut out

Temperature Profile of EADPF Regeneration Shows Peak Migration Through DPF

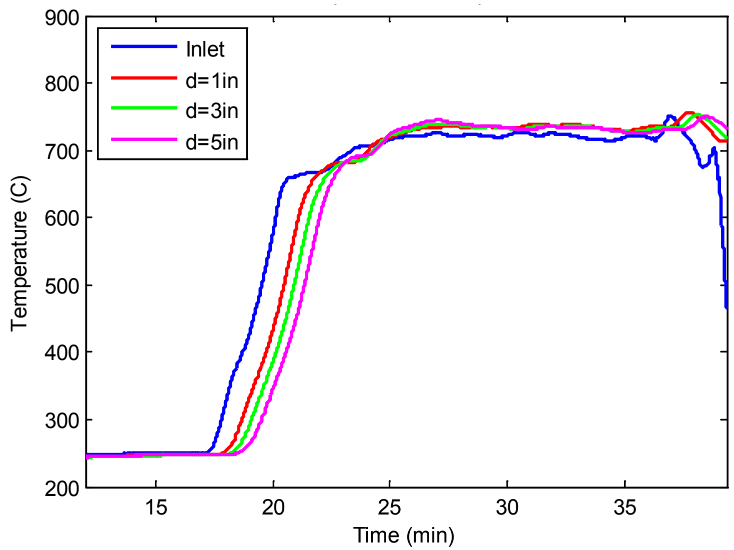
EADPF Regen

Heater temperature spike transmits along flow axis during regen enabling faster PM oxidation



Traditional Fuel-based Regen

Uniform heating of DPF achieved, but slower PM oxidation results as peak temperatures are limited



EADPF Demonstrates 50% Reduction in Fuel Penalty

	EADPF Regen	Fuel-Based Regen
Soot Loaded, g/l	4.0	4.9
Soot Regenerated, %	**85**	**112**
Extra Fuel, g	195.5	426.8
Extra Fuel Energy, kJ	8389.0	18317.3
Electric Energy, kJ	654.6	NA
Total Regen Energy, kJ	**9044**	**18317**
E-Energy fuel equivalent, g	15.3	NA
Extra Fuel Total, g	210.8	426.8
Time Required, min	**8**	**20**

~50% Fuel Penalty Reduction

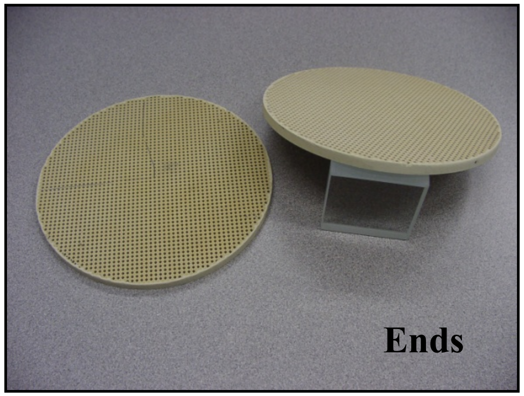
Technical Accomplishments Summary (Task 1): Engine-based DPF substrate temperature task

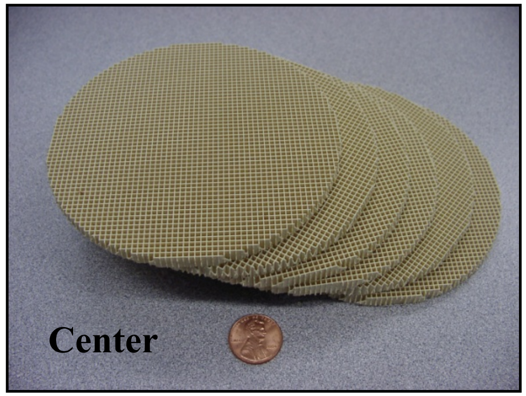
- **EADPF demonstrated on GM 1.9-liter engine at ORNL**
  - Demonstrated up to 50% reduction in fuel penalty with EADPF approach (vs. traditional fuel-based regeneration)
  - Demonstrated >85% regeneration efficiency measured on mass basis
- **Fiber optic-based temperature measurement demonstrated on bench scale in preparation for engine-based experiments**
  - 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
  - Engine-based studies ongoing in FY12

Task 2-Technical Accomplishments

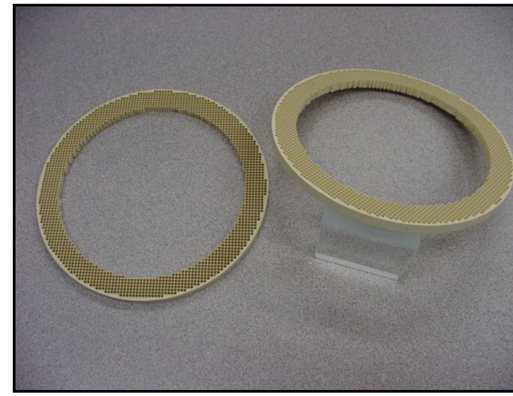
Three Test Specimens for Estimating Failure Stresses and Elastic Moduli in DPFs:

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

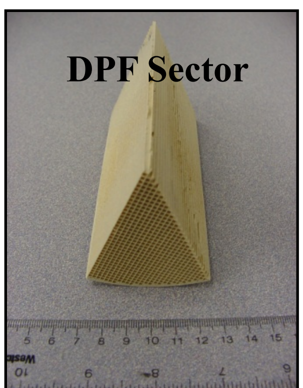




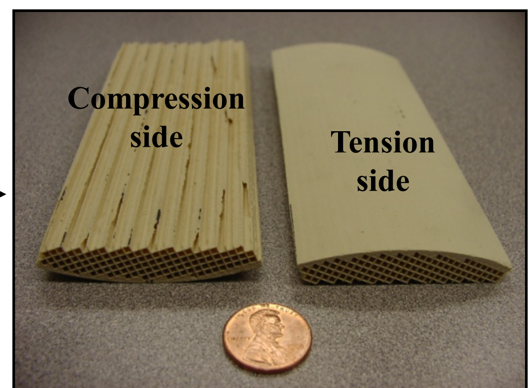
O-Ring Flexure
(Diametral Compression)



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



Apex Cut off



Finite Element Analysis and Mechanical Testing Iteratively Performed:

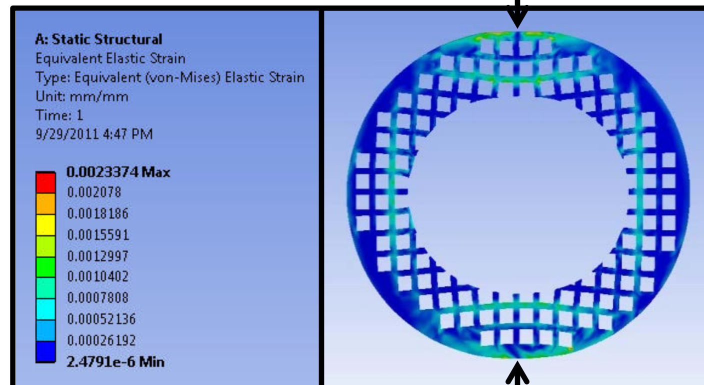
FEA Modeling → Predict Displacement as a Function of Load

Mechanical Testing → Measure Failure Load & Displacement

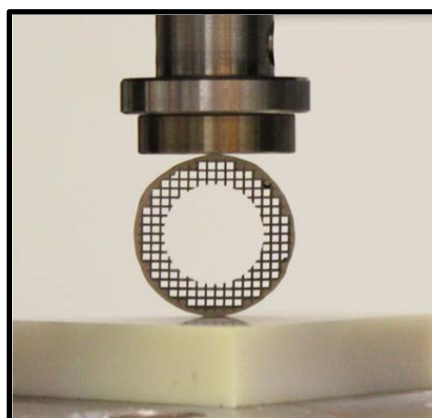
→ Match in FEA or MOI by Varying Secant Modulus

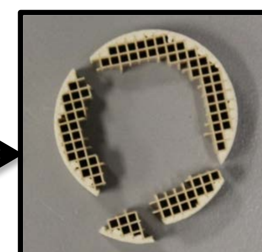
→ **Determine Maximum Failure Stress**

FEA with ANSYS



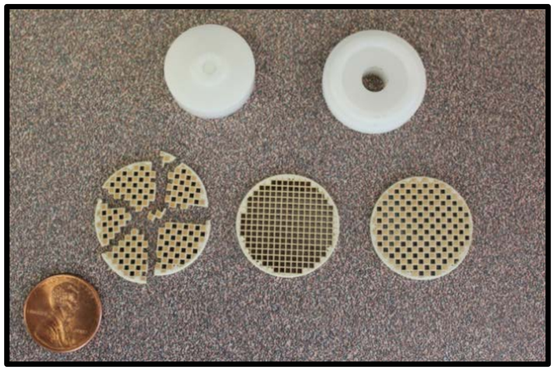
Mechanical Testing

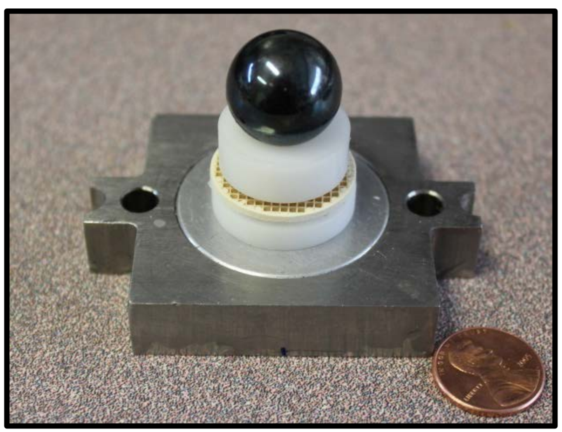




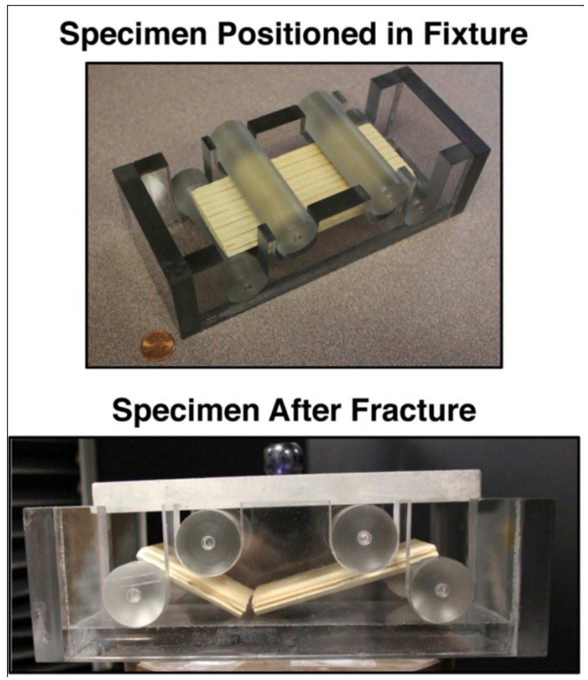
Test Methods

Equibiaxial Flexure

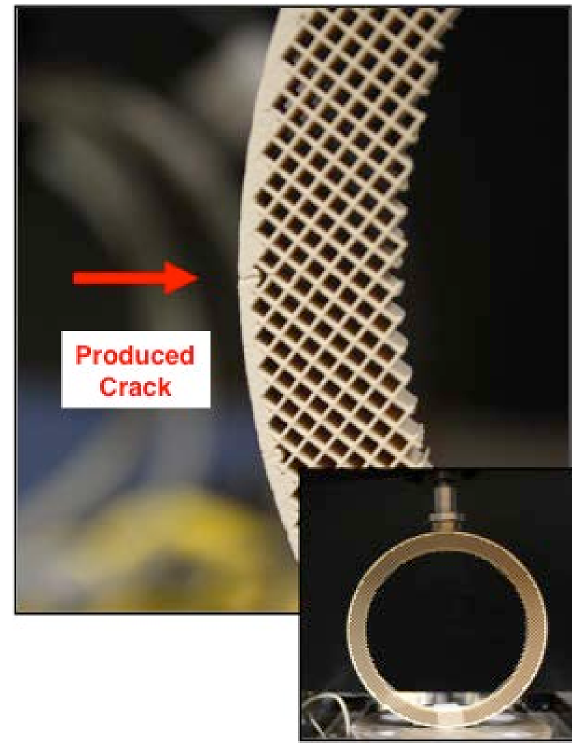




Sectored Flexure



O-Ring Compression



Elastic Modulus and Tensile Failure Strength

Results consistently show elastic modulus of DPF cordierite is lower than reported sonic-based-measured literature values while tensile failure stresses are equivalent

Test Method	Elastic Modulus (GPa)*	Source
Dynamic Resonance-Based	4 - 7	[3]
Dynamic RUS	12.3 ± 0.3	[10]
Quasi-static / Mechanical Uniaxial Compression	> 13 GPa at zero MPa; ~ 6 GPa at 9 MPa	[13]
Quasi-static / Mechanical Equibiaxial Flexure	0.5 - 1.5	Present study
Quasi-static / Mechanical Sectored Flexure	1 - 3 Interior strut 4 - 24 Exterior skin	Present study
Quasi-static / Mechanical O-Ring Flexure	1.1 - 2.1	Present study

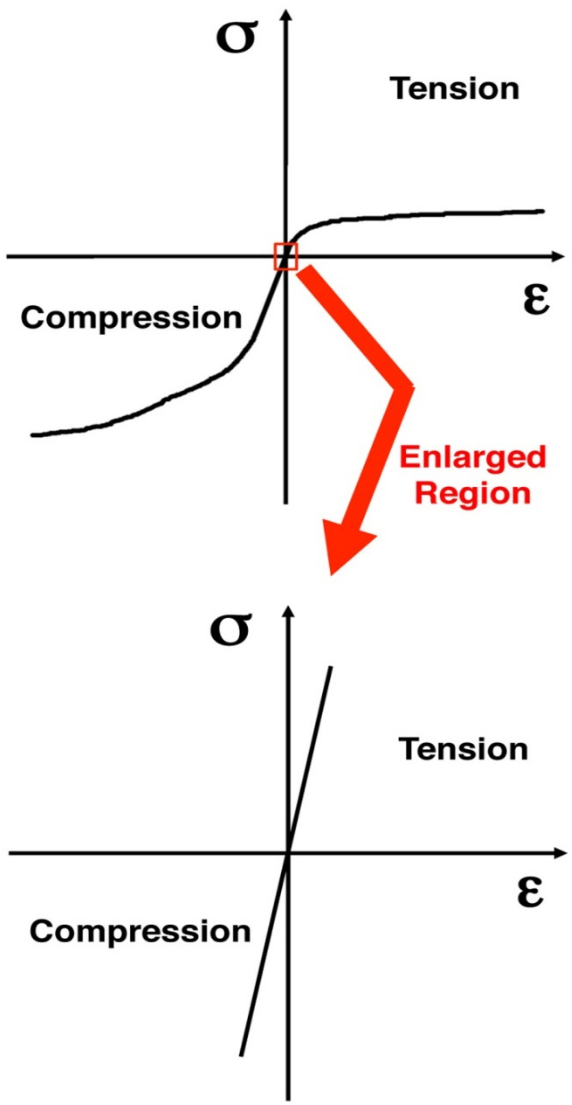
Test Method	Tensile Failure Stress (MPa)*	Source
ASTM C1674 like (4-pt flexure)	2.4 - 3.6 (interior strut) axial	[2]
ASTM C1674 like (4-pt flexure)	4 - 6 (interior strut) axial	[3]
ASTM C1674 (4-pt flexure)	2 - 5 (interior strut) axial	[4]
ASTM C1674 (4-pt flexure)	4 - 7.5 (interior strut) axial	[5]
Equibiaxial Flexure	2 (est) (interior strut) > 4 (est) (50% end fill) radial	Present study
Sectored Flexure	5 - 13 (est) (exterior skin) axial	Present study
O-ring Flexure	2 - 4 (est) (exterior skin) hoop	Present study

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

Key Findings Illustrate Importance of Industry/National Laboratory Partnerships

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

Why the Elastic Modulus Discrepancy?



- Asymmetrical stress strain curve
- RUS assumes linear elasticity for all strains
- Tangent modulus is the most accurate, however a continuous stress strain curve is needed
- Estimation of a secant modulus is a good compromise

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
  - Complete measurements of DPF substrate temperature.
- Task 2
  - Develop rules of design for the heater.
  - Consider herein described test methods for standardization.
- Task 3
  - None.

Summary

- Task 1
  - EADPF system demonstrated 50% fuel penalty reduction on GM 1.9-liter engine at ORNL (vs. traditional fuel-based technique)
  - >85% PM oxidation demonstrated for regeneration times of 8 minutes
  - Fiber optic-based temperature measurement demonstrated on bench scale being utilized on engine setup for 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.