Substrate Studies of an Electrically-Assisted Diesel Particulate Filter

James Parks, Maggie Connatser, Vitaly Prikhodko, Bill Partridge, Ethan Fox, Matt Ferber, Andy Wereszczak, Michael Lance
Oak Ridge National Laboratory

Gene Gonze and Michael Paratore
General Motors, Inc.

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OAK RIDGE NATIONAL LABORATORY
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GM Technology for Lower Fuel Penalty During DPF Regeneration

- **Electrically-Assisted Diesel Particulate Filter (EADPF) utilizes electrical heat to control soot burn during DPF regeneration**
- **ORNL, in CRADA with GM, studied EADPF technology to address two main questions:**
  - **(1) what is substrate temperature during regeneration?**
  - **(2) what are the critical material properties of DPF (as related to durability)?**
- **We acknowledge Jerry Gibbs and the Propulsion Materials Program of the DOE Vehicle Technologies Program for their support**

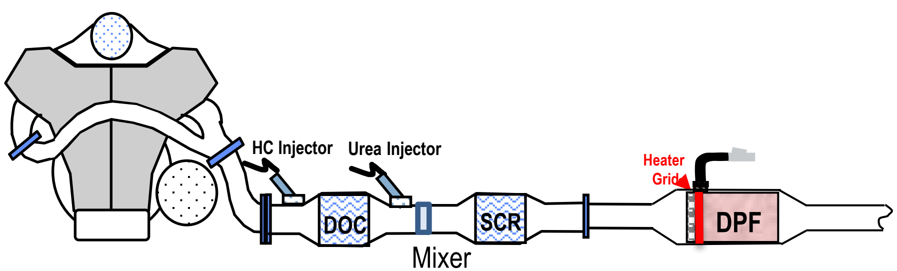
EADPF Achieves High Temperatures for Soot Oxidation in Engine Exhaust

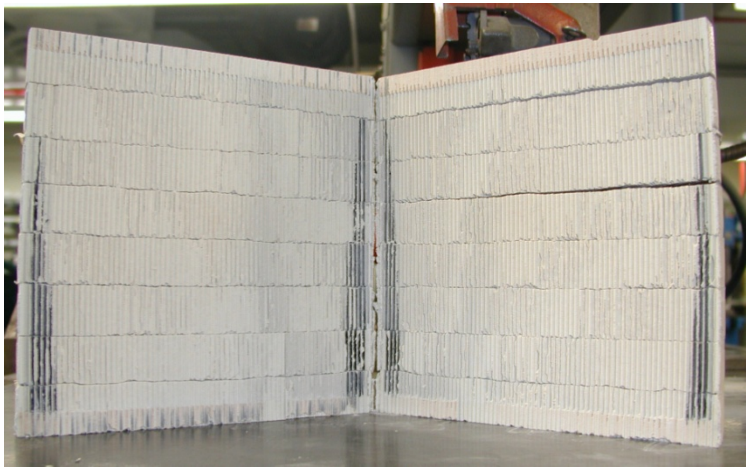
Regeneration Efficiency

95% Soot Removal !!!

Regeneration time

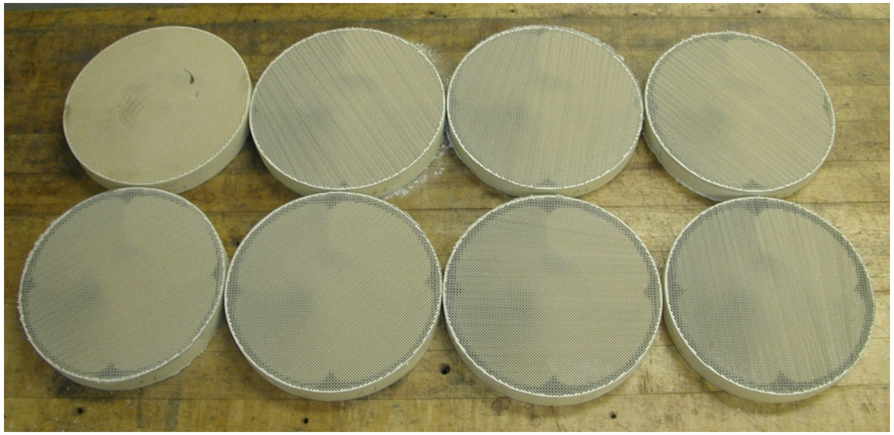
Reduced by 75%





95% Soot Removal

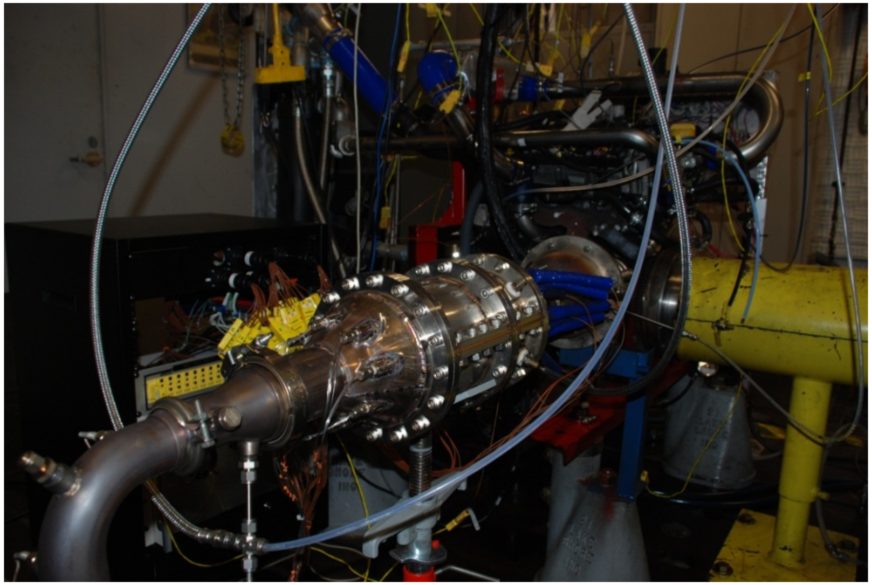
Front   1" In   2" In   3" In

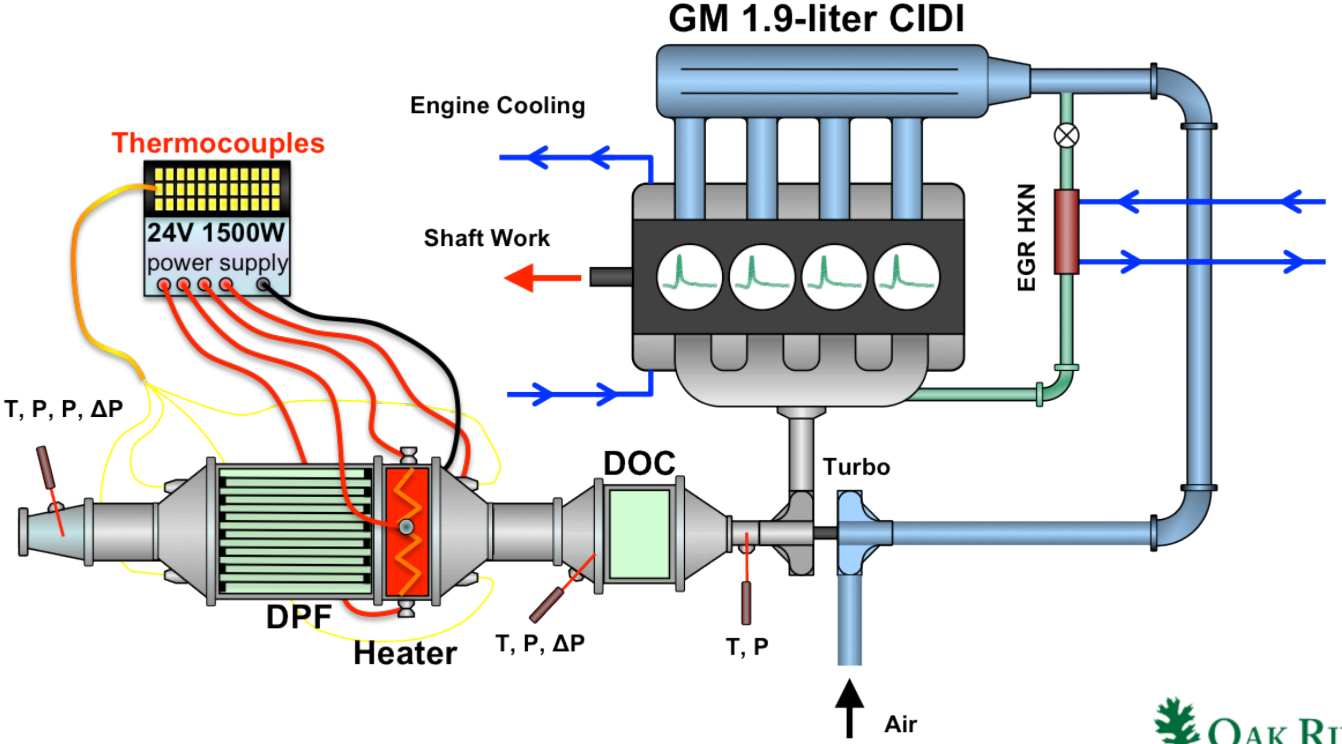


4" In   5" In   6" In   7" In

ORNL Engine Setup

- 1.9-liter 4-cylinder GM CIDI
  - Full-pass Drivven control system
- Model DOC 100 g/ft^3 Pt, 1.25-liter
- GM EADPF
  - Heater w/ 24V 1512W Power supply
  - 2.47-liter DPF (5.66” dia., 6” length)





EADPF Achieves 50% Reduction in Fuel Penalty on 1.9-liter Engine

- EADPF Regen: (1) fuel added via in-cylinder post-injection event to heat exhaust (DOC exotherm) followed by (2) electrical heating to generate controlled temperature for soot oxidation
- Fuel-Based Regen: (1) fuel added via in-cylinder post-injection event to heat exhaust (DOC exotherm) and held until soot oxidation complete

	EADPF Regen	Fuel-Based Regen
Soot Loaded, g/l	4.0	4.9
Soot Regenerated, %	**85 (+/-10%)**	**112 (+/- 10%)**
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**

Based on mass of soot

~50% Fuel Penalty Reduction

~60% Time Reduction

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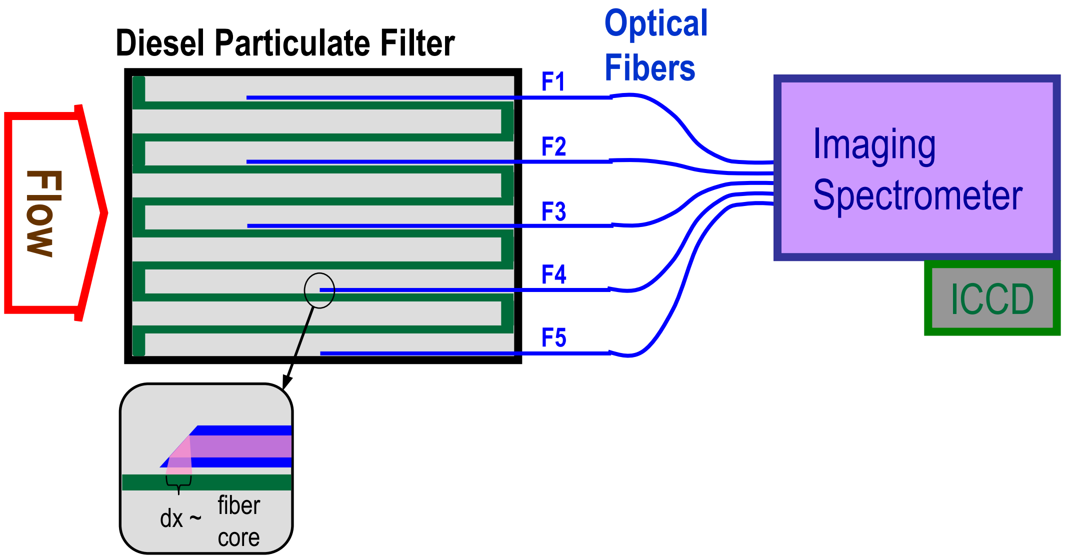
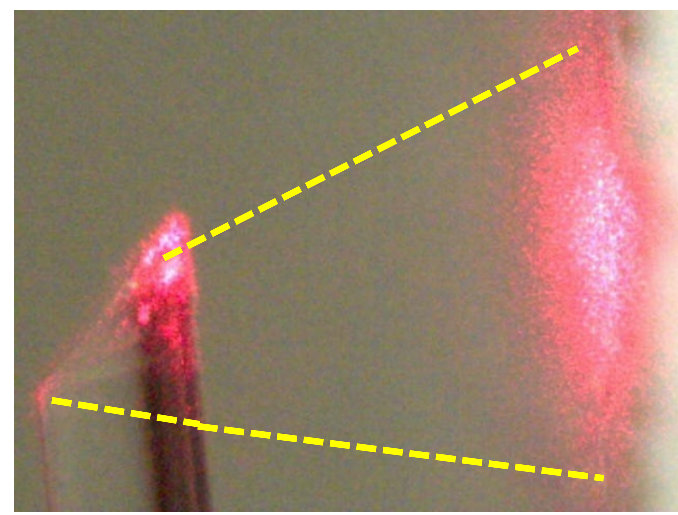
Side Viewing Fiber Optic Probes Allow Temperature Measurement of DPF Channel Wall



- 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)



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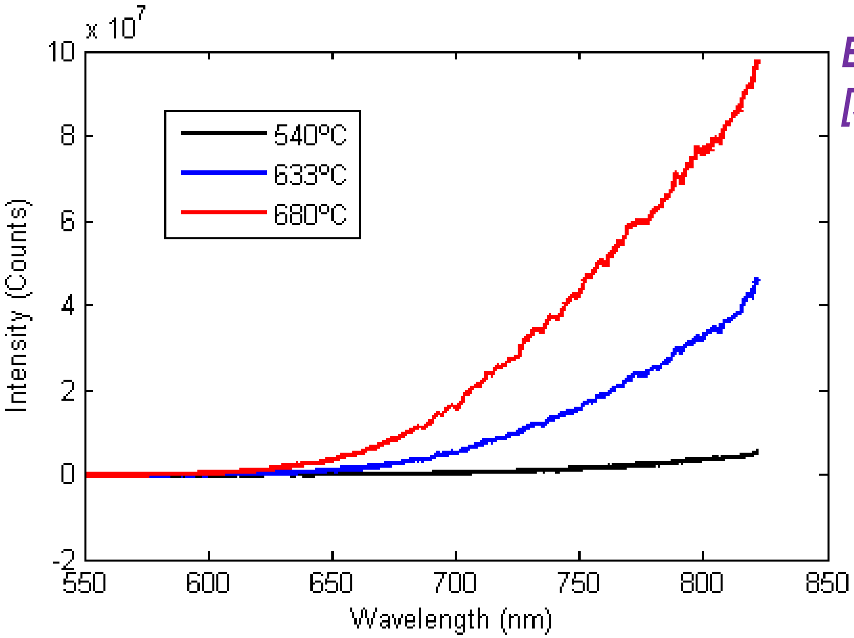
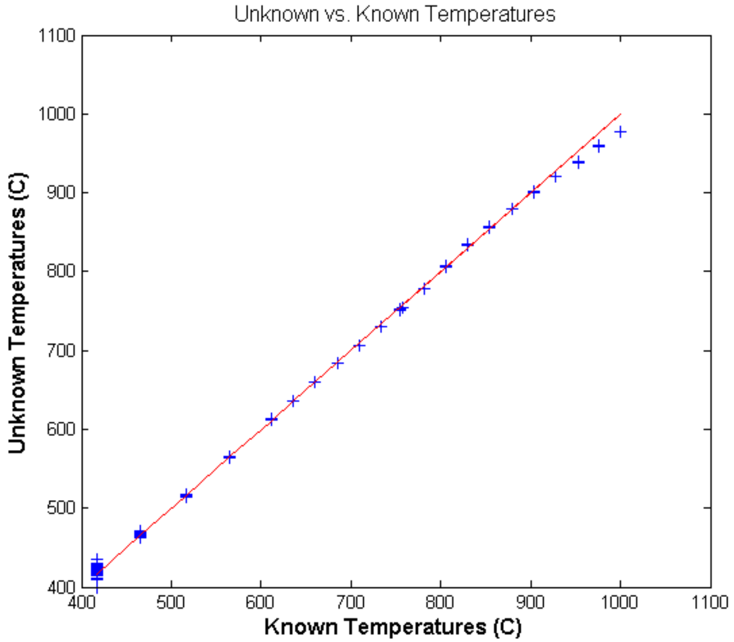
Blackbody Radiation Spectra and Calibration

- **Reference DPF substrate in furnace at controlled temperature served as calibration standard**

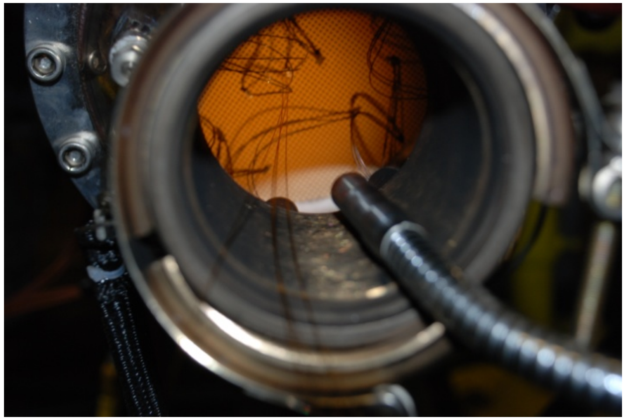


Blackbody radiation data from fiber probe [spectra corrected for quantum efficiency of detector]



"Unknown" (Blackbody)"vs. "Known" (Thermocouple) calibration standards

Pictures from installation of fiber optic probes (in the downstream channels of the DPF)



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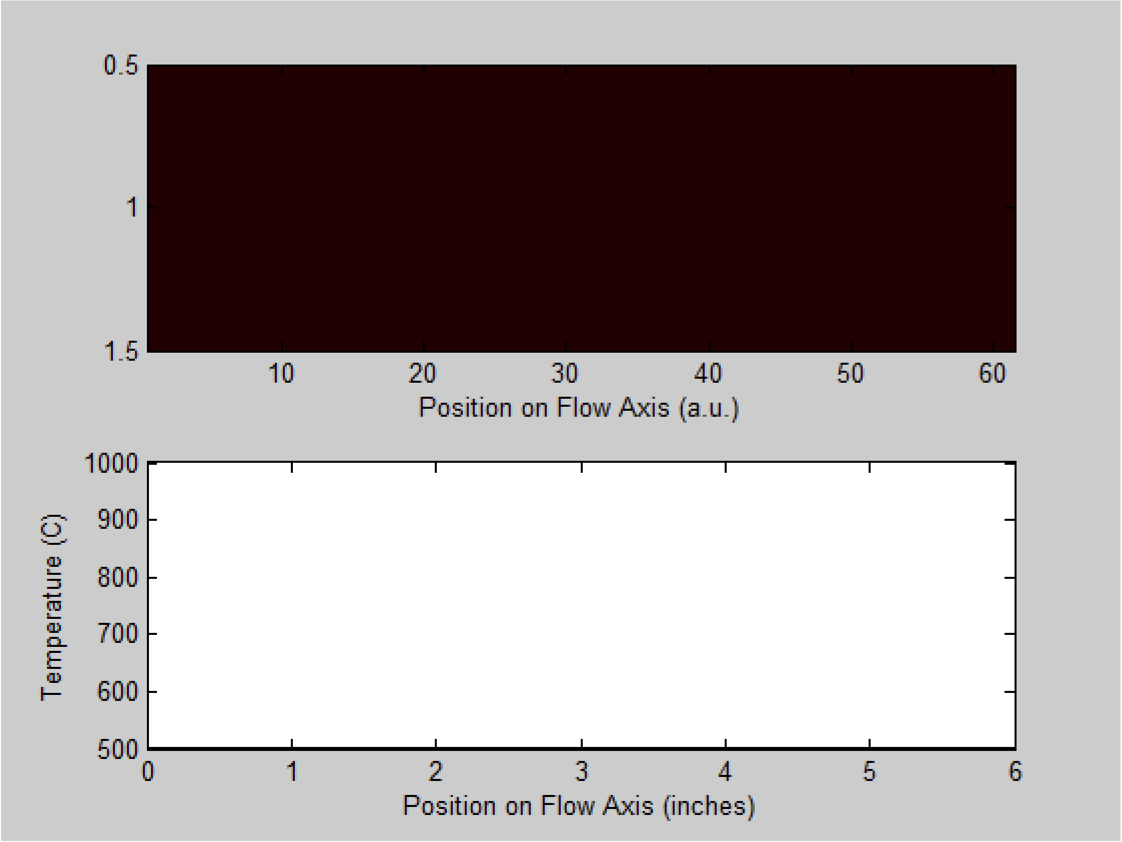
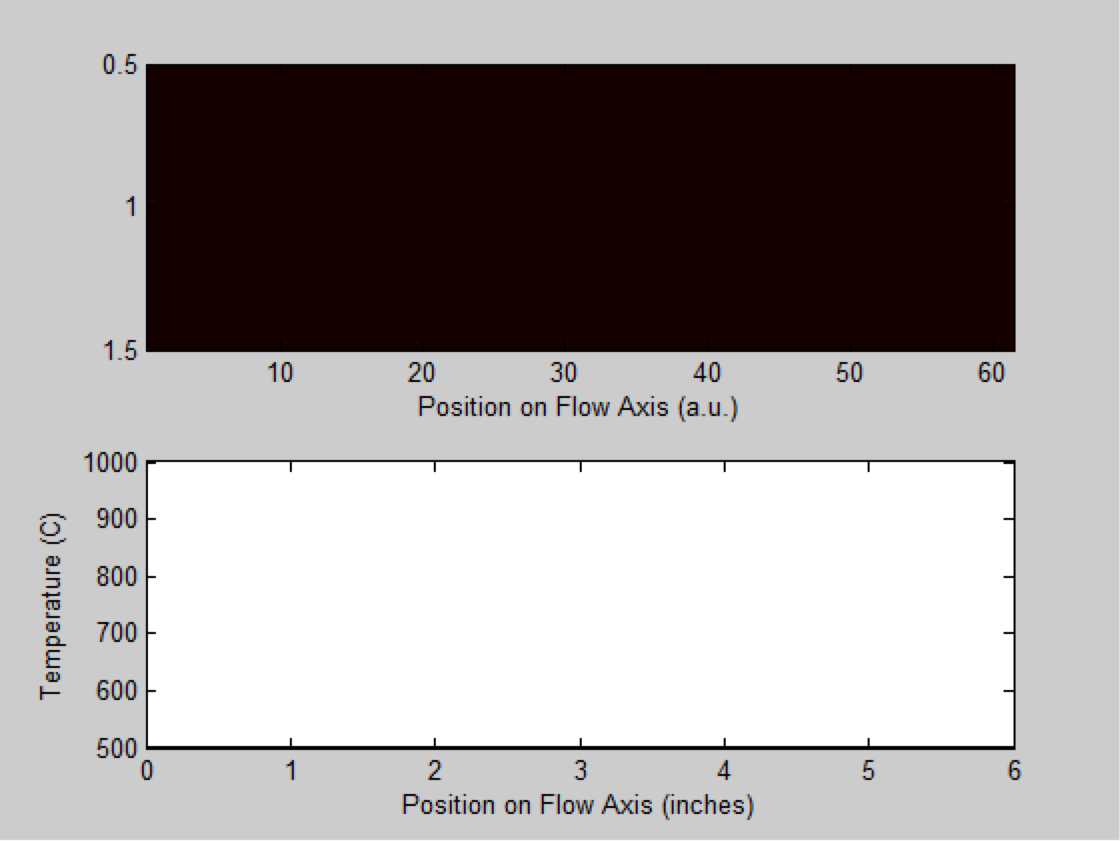
Regeneration Data in Movie Form

1x Soot Loading

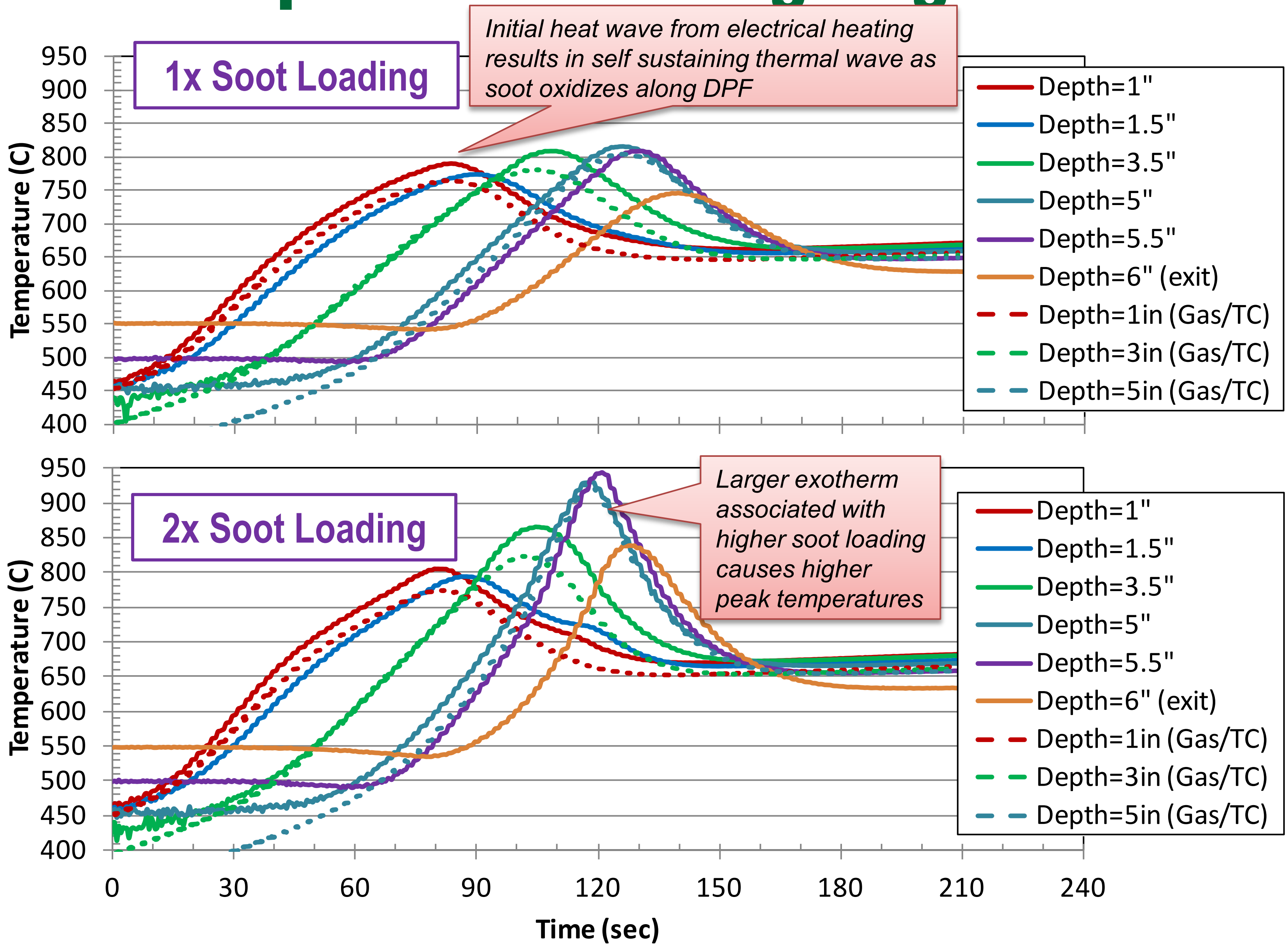


Regeneration Data in Movie Form

2x Soot Loading

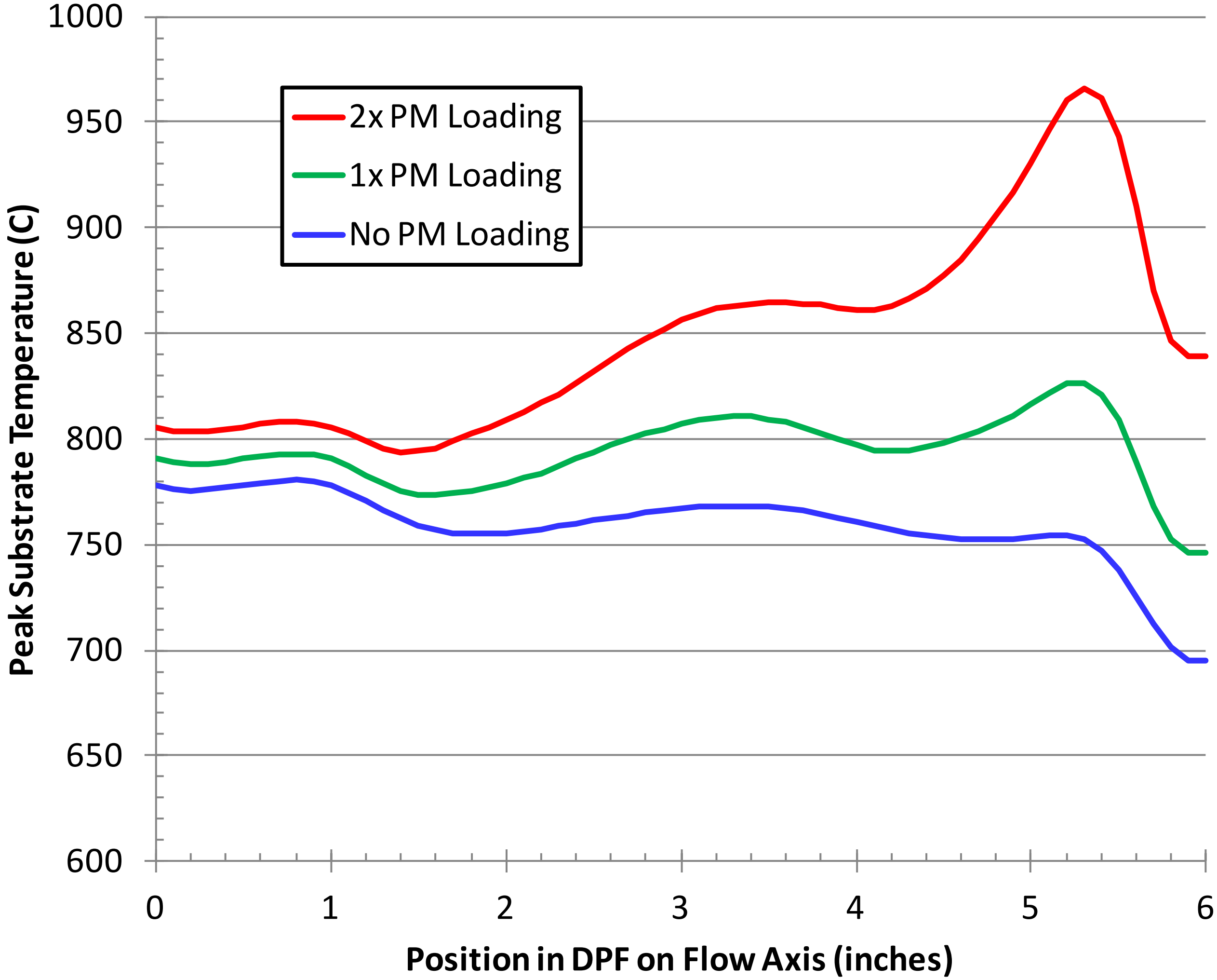


DPF Temperatures During Regeneration



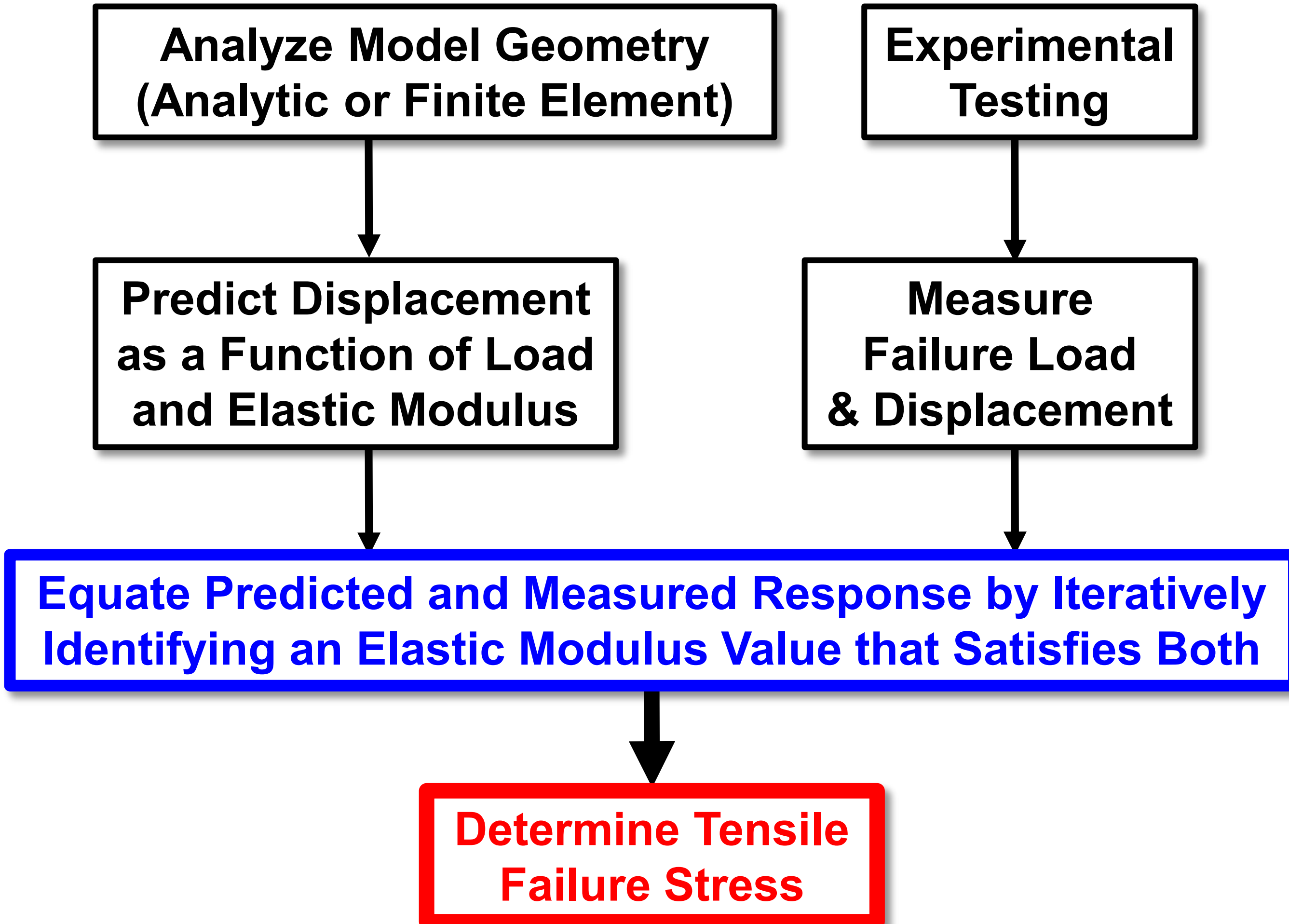
Solid Line=Substrate Temperatures (Blackbody Radiation)
Dashed Line=Gas Temperatures (Thermocouple)

Peak Temperatures Show Addition of Exotherm Proportional to Particulate Loading



Peak substrate temperature data interpolated with cubic spline fit to visualize results at all DPF positions

Iterative Analysis & Mechanical Testing Enables Estimation of Elastic Modulus & Failure Stress

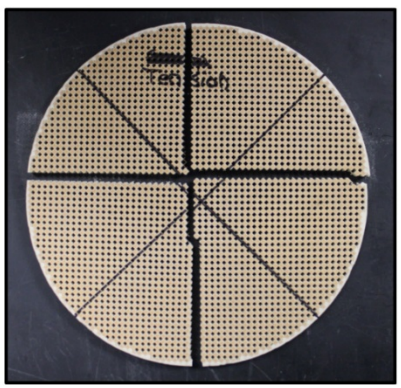


Mechanical Studies Specific to DPF Substrate Geometry

Biaxial Radial Tension

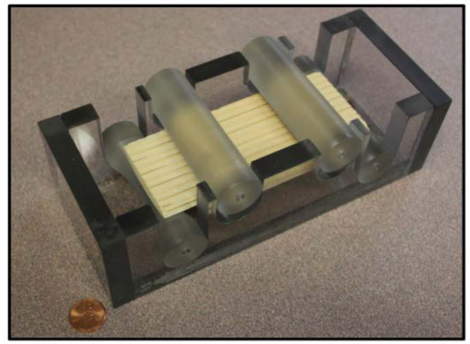
Specimen and Ring Fixtures

Example of Failed Disk

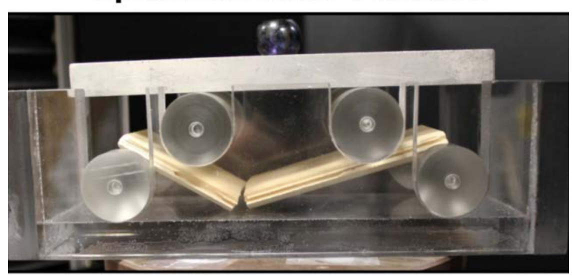


Uniaxial Axial Tension

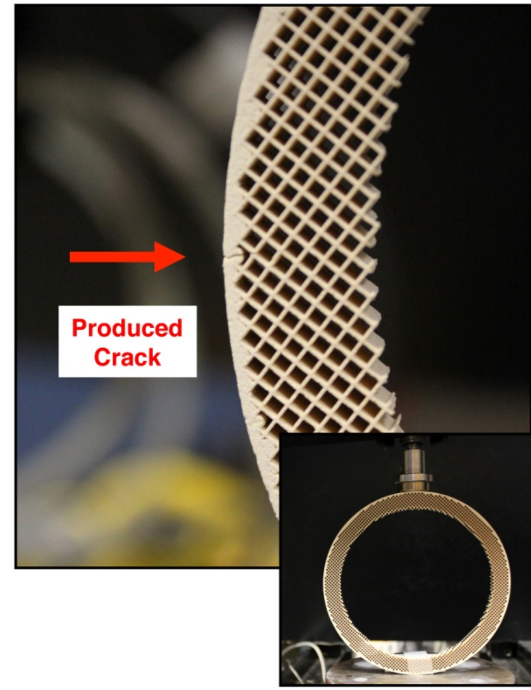
Specimen Positioned in Fixture



Specimen After Fracture



Uniaxial Hoop Tension



Our Results Show DPF Cordierite has a Lower Elastic Modulus than Previously Thought

Test Method	Elastic Modulus (GPa)*	Source
Dynamic Resonance Ultrasound Spectroscopy (RUS)	12.3 ± 0.3	Shyam et al., JACS, 2008
Dynamic Resonance-Based	4 - 7	SAE Paper 2004-01-0959, 2004
Mechanical / Q-Static Uniaxial Compression	> 13 GPa at 0 MPa; ~ 6 GPa at 9 MPa	Bruno, et al., AdvMatForum, 2010
Mechanical / Q-Static Biaxial Flexure (Tension)	0.5 – 1.5	This Project
Mechanical / Q-Static Sectored Flexure (Tension)	1-3 GPa (interior strut) 4-24 GPa (exterior skin)	
Mechanical / Q-Static O-ring Flexure (Tension)	1.1 – 2.1	

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

For more details, see Wereszczak, et.al. SAE 2012-01-1252

Summary

- The Electrically-Assisted Diesel Particulate Filter (EADPF) technology achieves **~50% reduction in fuel penalty** as compared with conventional fuel-based regeneration techniques
- Importantly, the **time required for regeneration is also greatly reduced** (by ~60% or more)
- Some reduction in soot removal efficiency (85-95% based on mass) is observed but the overall efficiency is suitable for repeated operation
- Substrate temperatures based on blackbody radiation measured with a fiber optic probe technique show 10-30ºC higher temperatures than gas temperatures measured with thermocouples, and soot loading has a large impact on the peak temperatures observed
- Measurements of the elastic modulus of the DPF substrate are approximately **an order of magnitude less** than previously reported values, and the measurements support greater durability predictions from simulations of DPFs