Materials Issues Associated with EGR Systems

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PM009

Overview

Timeline

- Start: February 2009
- End: September 2013
- 67% complete

Budget

- Total Project Funding
  - DOE-$1860 K
- Funding received:
  - FY10: $400K
  - FY11: $360K
  - FY12: $360K

Barrier

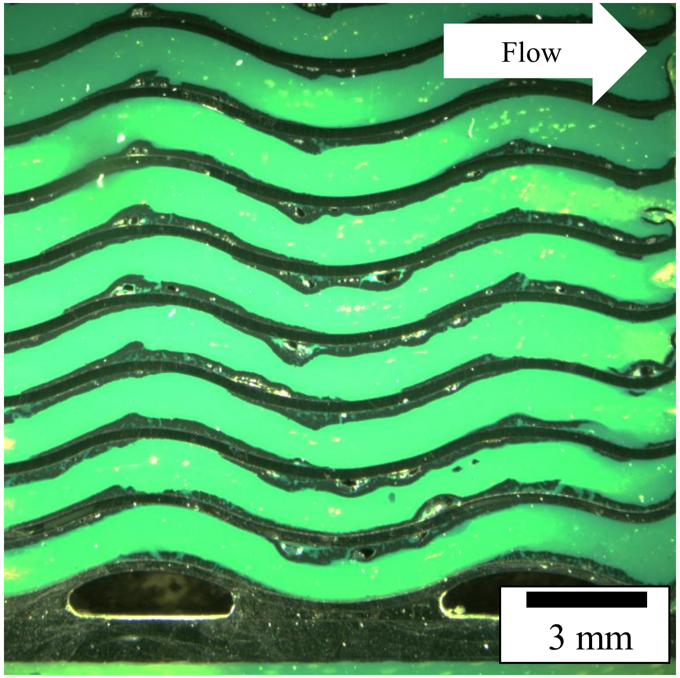
- Page 2.3-4: Meeting EPA standards for oxides of nitrogen and particulate matter emissions with little or no fuel economy penalty will be a key factor for market entry of advanced combustion engines.
- Page 2.3-6: Engine control systems R&D will focus on developing engine controls that are precise and flexible for enabling improved efficiency and emission reduction in advanced combustion engines. These control system technologies will facilitate adjustments to parameters such as … exhaust gas recirculation (EGR) to allow advanced combustion regimes to operate over a wider range of engine speed/load conditions.

Partners

- Caterpillar, Cummins, DAF Trucks, Detroit Diesel, Ford, GM, John Deere, Modine, Navistar, PACCAR and Volvo/Mack.

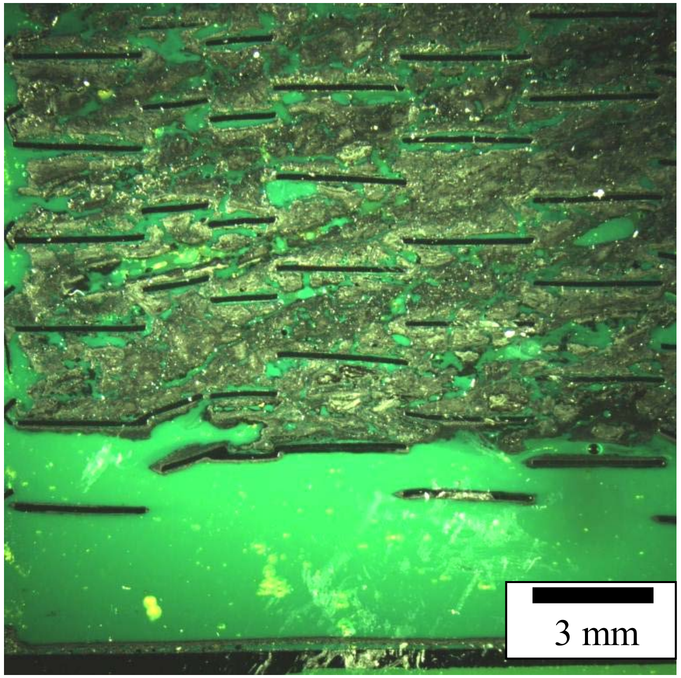
Exhaust Gas Recirculation Cooler Fouling Causes 1 to 2% Loss of Efficiency

Stabilized Effectiveness Loss



- Deposits reduce cooling effectiveness, but do not typically restrict gas flow.
- Low-density, low-K, powdery deposit.
- May be mitigated by changes in cooler geometry or engine operation.

Loss of Flow (Plugging)



- Deposits form plugs strong enough to occlude gas passages.
- Usually evidence of large hydrocarbon influence.
- Lacquer-like or tar-like consistency.

Project Objective: Provide information to industry EGR engineers about fouling deposit properties

- Characterize the thermo-physical properties of the deposit under different operating conditions
  - Laboratory-generated early-stage deposits.
  - Industry-provided late-stage deposits.
- Understand the role of cooler geometry on deposition.
- Develop a protocol for refreshing the EGR cooler during use.
- Enable improved models and potential design improvements to reduce fouling and its impact on efficiency and emissions.

Milestones

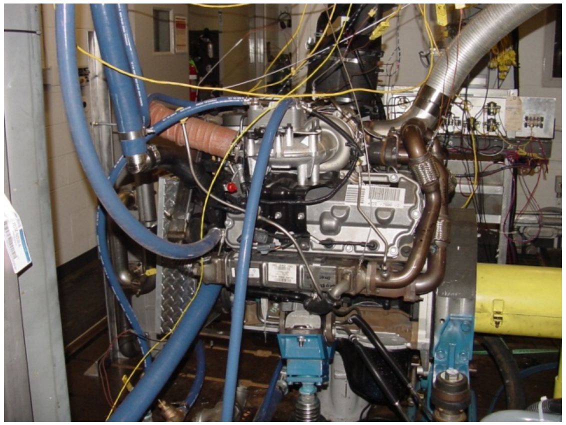
- FY2009
  - Feb-09 Milestone: Assembled EGR Advisory Team from industrial experts at 9 diesel engine manufacturers.
  - Feb-09 Go/No-Go Decision: EGR Fouling chosen as project focus.
- FY2010
  - May-10 Milestone: Task 2 – Completed analysis of 1st round of industry-provided coolers.
- FY2011
  - Feb-11 Milestone: Task 1 – Deposited first EGR cooler deposits on model tubes.
- FY2012
  - Oct-11 Milestone: Task 4 – Received seven more coolers from industry.
  - Nov-11 Milestone: Task 3 – Aged model deposits using bench tube reactor.

Approach

- **Task 1: Tube Sampler for Deposit Formation**
  – A GM 1.9 L engine is used to form deposits on model cooler tubes.
- **Task 2: Obtain and Evaluate Representative (Half-Useful-Life) EGR Coolers from Industry Members**
  – Eight companies provided twelve coolers for analysis.
  – Provided an opportunity to refine effective characterization tools.
- **Task 3: Bench-top tube reactor for Deposit Aging**
  – Simulate diesel exhaust and expose engine-generated deposits to various conditions that mimic different duty cycles.
  – Measure microstructural and physical property changes in deposit.
- **Task 4: 2nd Round of Industry-Provided Coolers representing specific applications**

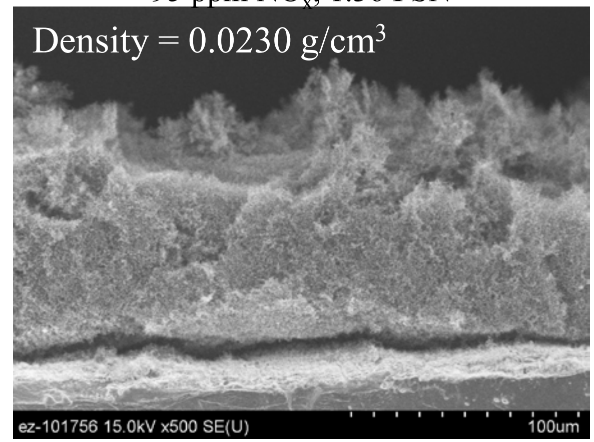
Two Baseline Deposits formed using Tube Sampler

Ford 6.4-L V-8 used as exhaust generator. 1500 rpm and a EGR flow rate of ~30 SLPM for 4 hours.

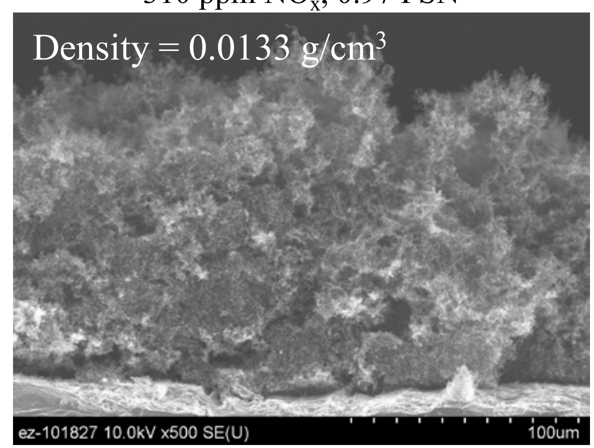


- Exhaust passed through surrogate EGR cooler tubes. Thermal effectiveness of tubes is assessed during exposure.
- Microstructure and properties of deposit can be characterized.

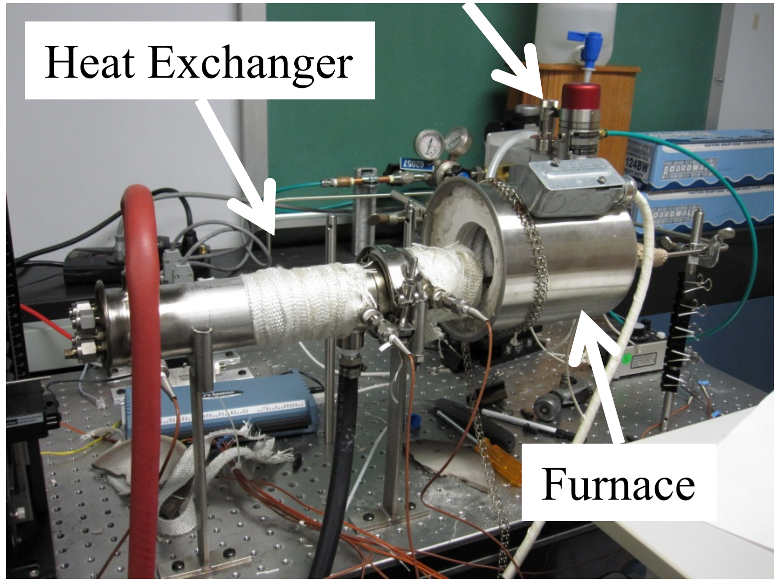
Light-Duty Condition:
2.6 Bar BMEP, ~225 C inlet, 144 ppm HC, 95 ppm NO_x, 1.36 FSN



Heavy-Duty Condition:
7-8 Bar BMEP, ~325 C inlet, 28 ppm HC 310 ppm NO_x, 0.97 FSN

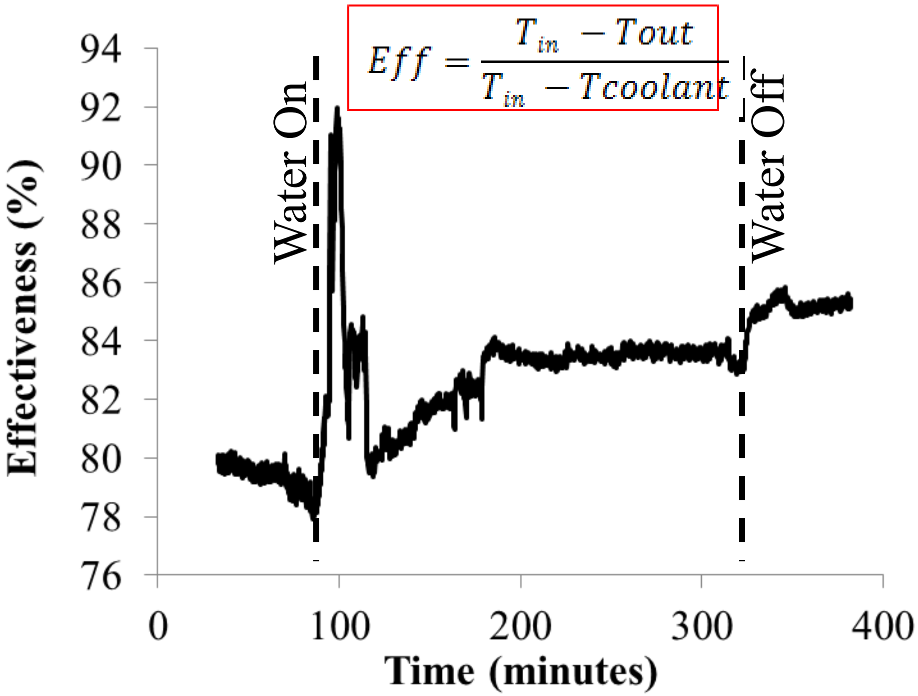


Bench-top Tube Reactor for Deposit Aging

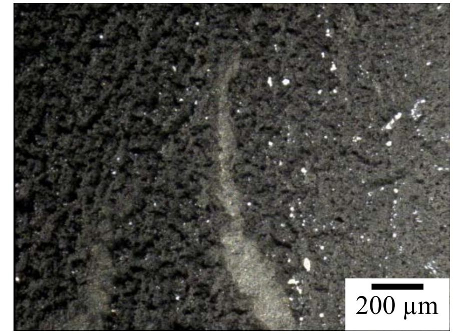


- Samples generated with our engine are then aged in a tube reactor that simulates diesel exhaust.
- Inlet and coolant temperature, gas flow rate and water content are controlled. Temperatures at the inlet and outlet of the tube and the coolant temperature are monitored and used to calculate effectiveness.
- What exhaust conditions will alter the deposit so as to improve the effectiveness of the heat exchanger?

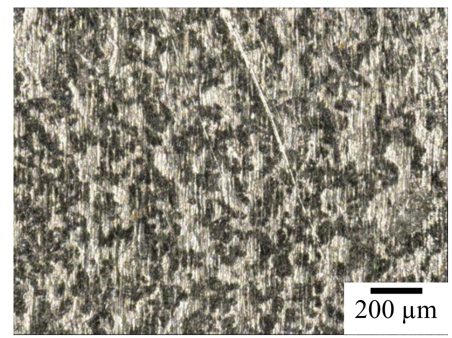
Water Condensation Improved Effectiveness



Near Inlet



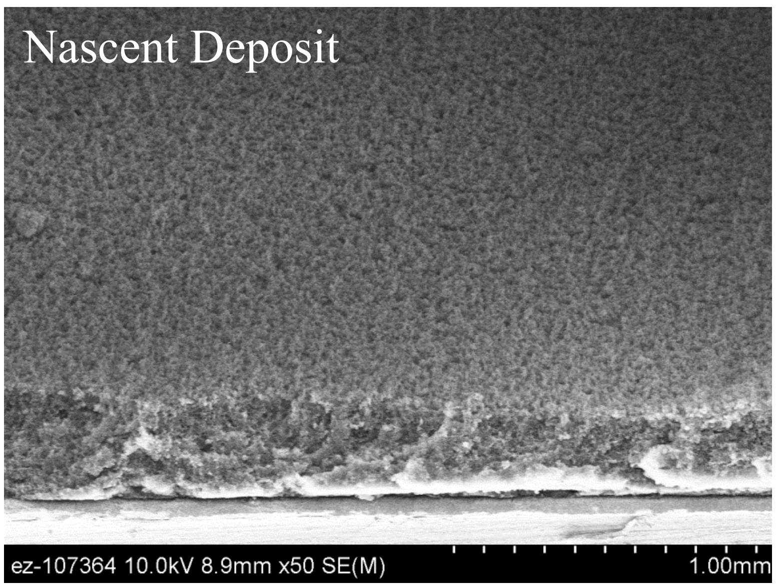
Near Outlet

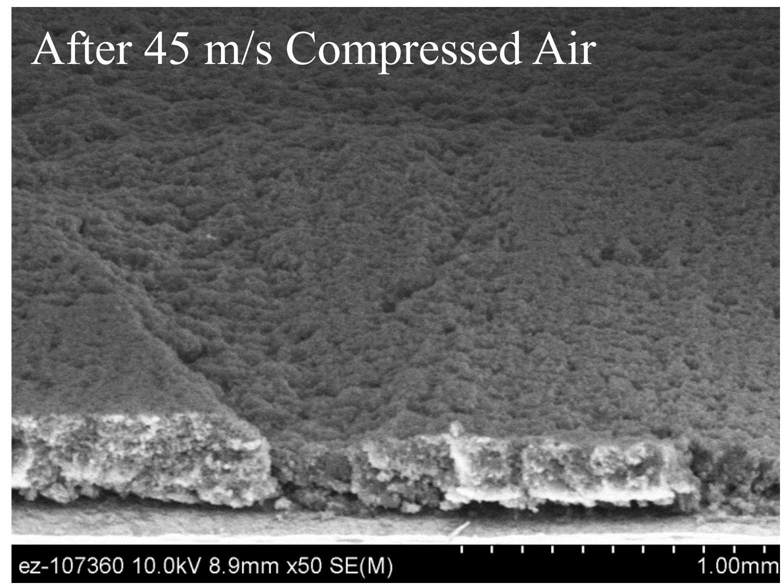


- Simulating idle: Flow rate was 5 SLPM at 10% water. Inlet temperature was 200°C and coolant temperature was 10°C.
- Effectiveness improved ~5%. Deposit appeared denser near the outlet.
- Thermal conductivity is controlled mainly by deposit density. Since the deposit is >95% porous, there is the potential to greatly improve its thermal properties by collapsing the PM microstructure.
- Changing the engine operating conditions so as to condense water or HC on the deposit may refresh the fouled cooler.

Another path for improvement: Cooler Geometry

- Internal cooler geometry is designed to produce turbulent flow of the gas in order to increase residence time and hence heat transfer.
- Trade-off: turbulation also increases mass transfer (PM) and pressure loss.
- Can we change geometry to promote deposit removal?

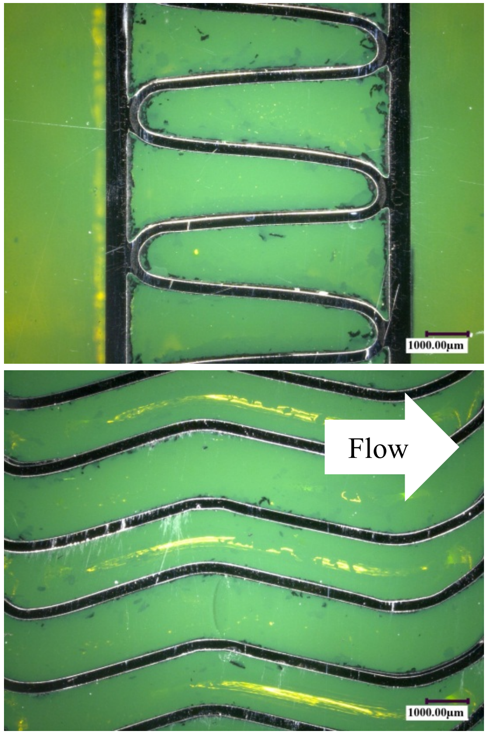


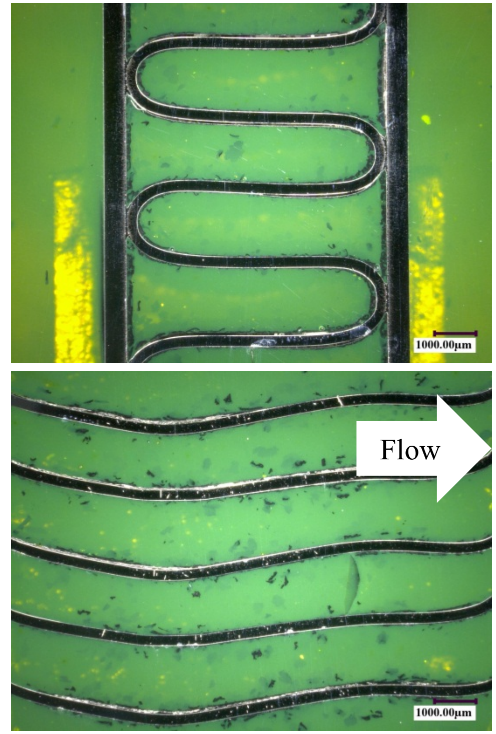


- Spallation can be induced on flat tubes at unacceptably high velocities that would produce significant pressure loss.

Two Modine Samples with Different Geometries were Fouled and Analyzed

<u>Production Geometry</u>
sinusoidal fin is enhanced with a series of alternating offset "bumps".

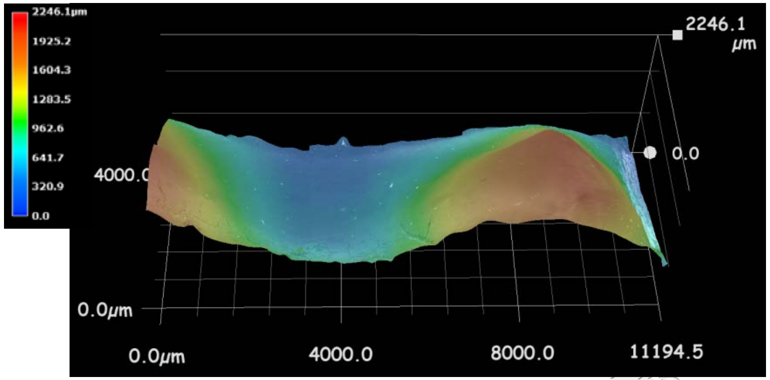




<u>Test Geometry</u>
pure sinusoidal fin that has lower thermal performance but less pressure drop.

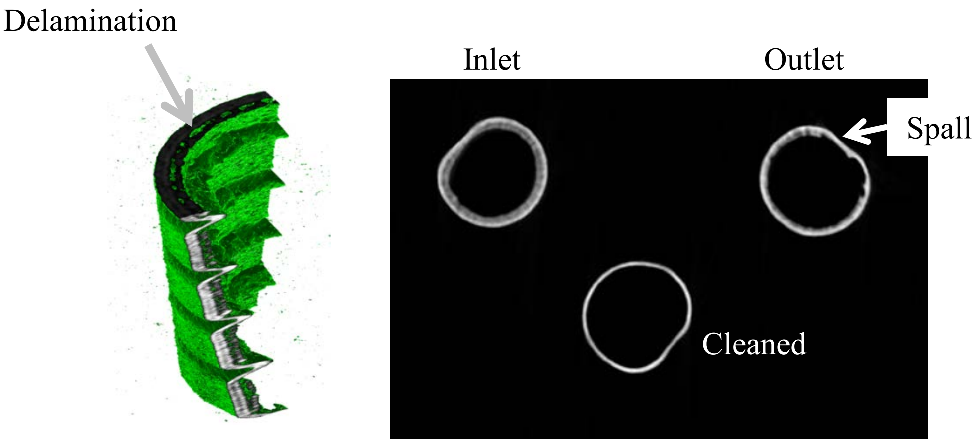
- Both geometries were fouled using the same engine conditions by John Deere.
- No obvious differences in the deposit thickness or surface features have been observed so far.

<u>Keyence Digital Microscope and Optical Profiler</u>



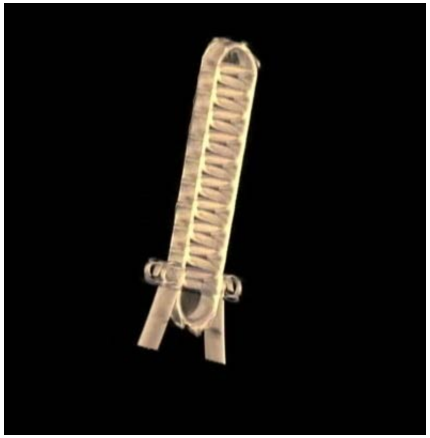
Visualizing the Effect of Geometry on Fouling: Neutron Tomography

Successful Imaging of Deposit that contained Hydrated Iron Sulfate



Resolution: ~70 µm

Modine Production Cooler

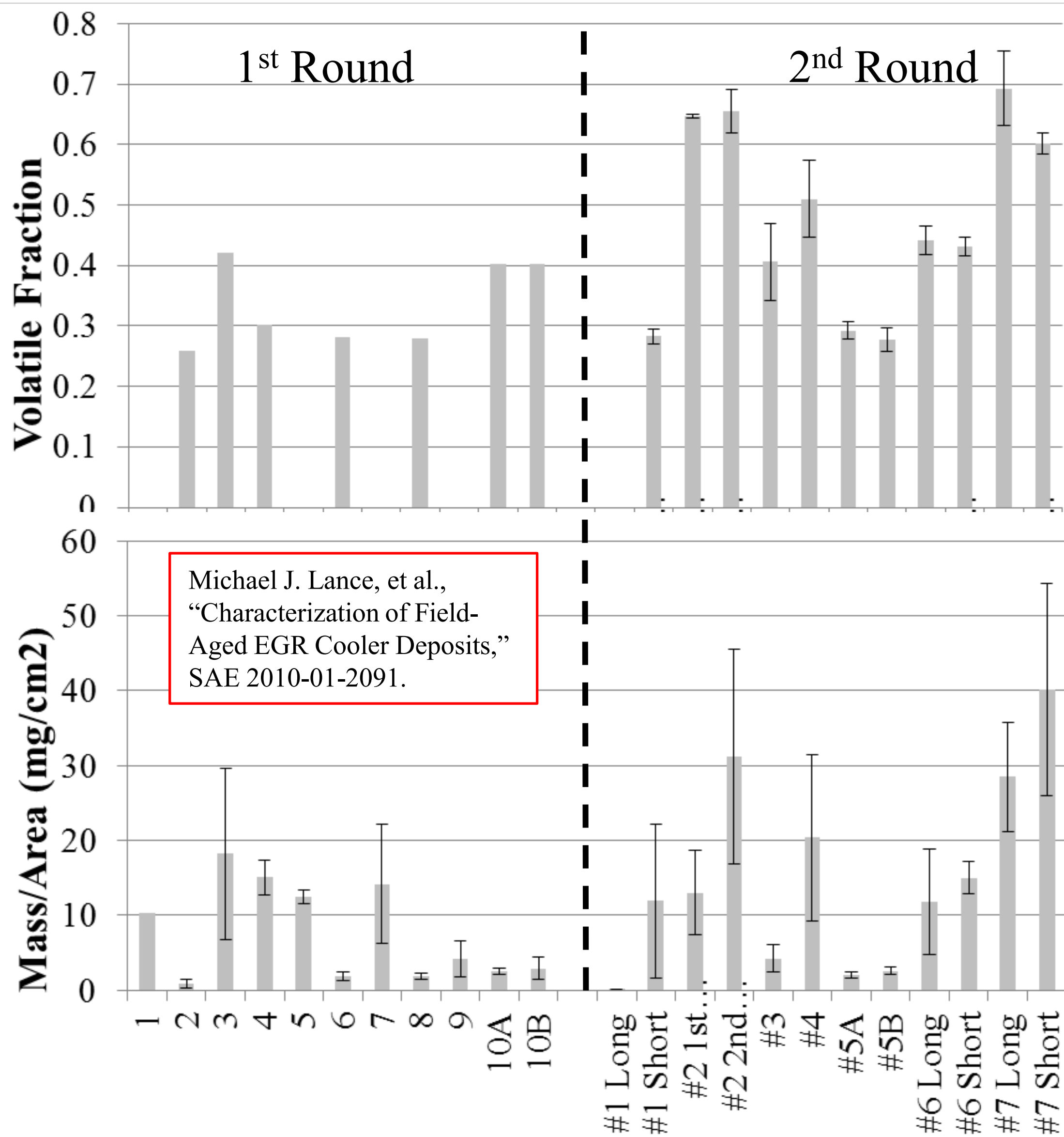


- Dr. Jens Gregor (Associate Professor of Radiology, UT Graduate School of Medicine) was contracted to develop software to aid in the reconstruction and image processing.
- Modine deposit did not contain enough hydrogen needed to attenuate neutrons.
- Future plan: We will use a wavy tubes made by additive manufacturing to investigate geometry effects on fouling using our own engine and tube sampler.

CAD Drawing

Manufactured Tube

2nd Round of Coolers Representing Specific Applications

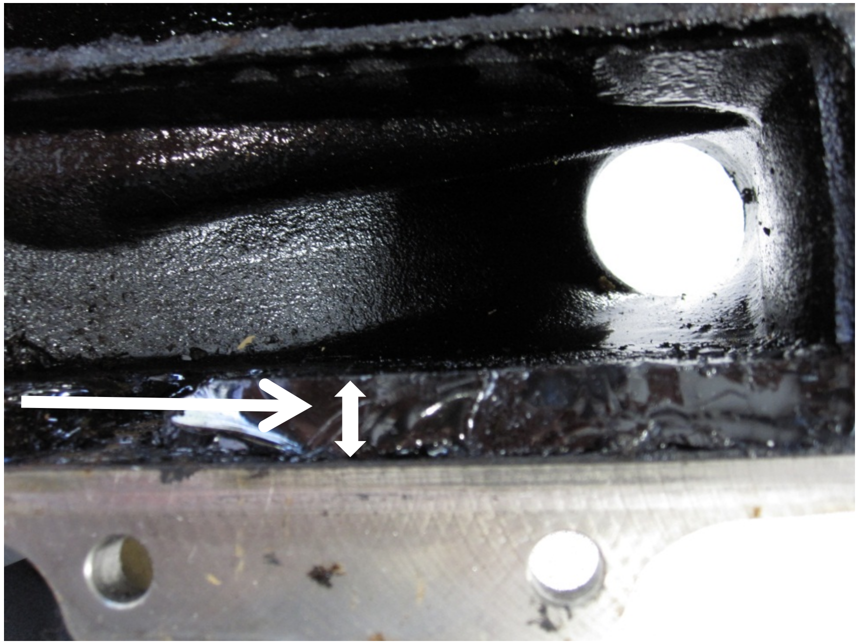


- First round of industry-provided "half-useful-life" coolers came with little information.
- A second round was requested with more information about cooler origins.
- Coolers tended to show the plugging failure mode from applications requiring long idling times; school buses, delivery trucks, etc.

Cooler #2 : Lacquer-like Deposit

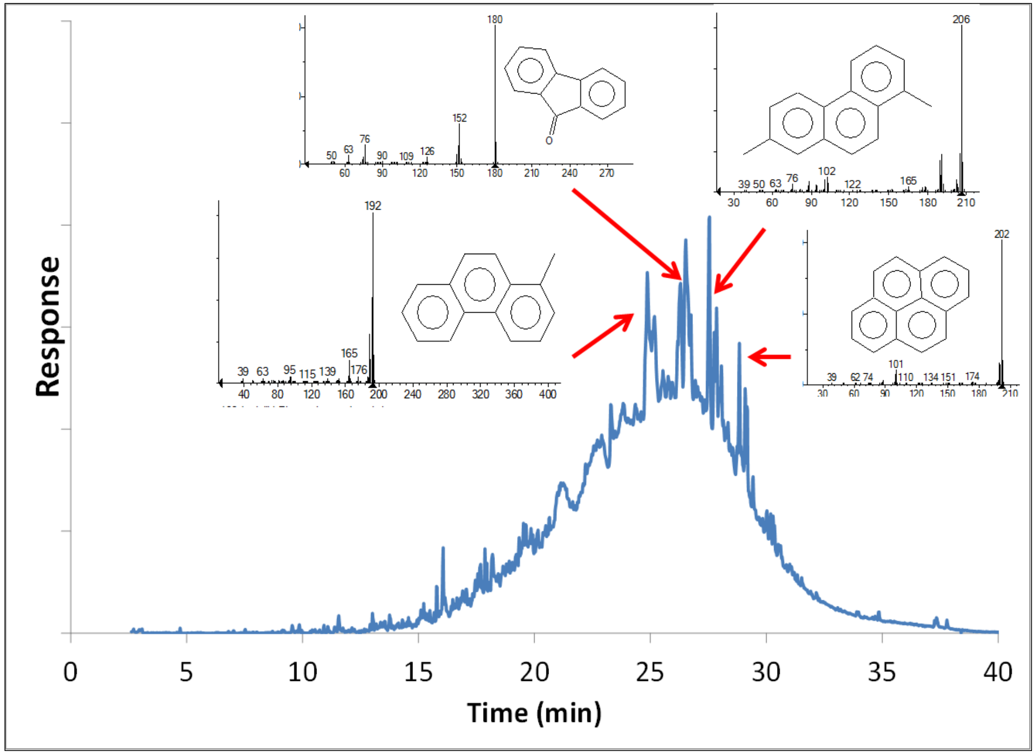
Outlet Diffuser

1 cm
Thick

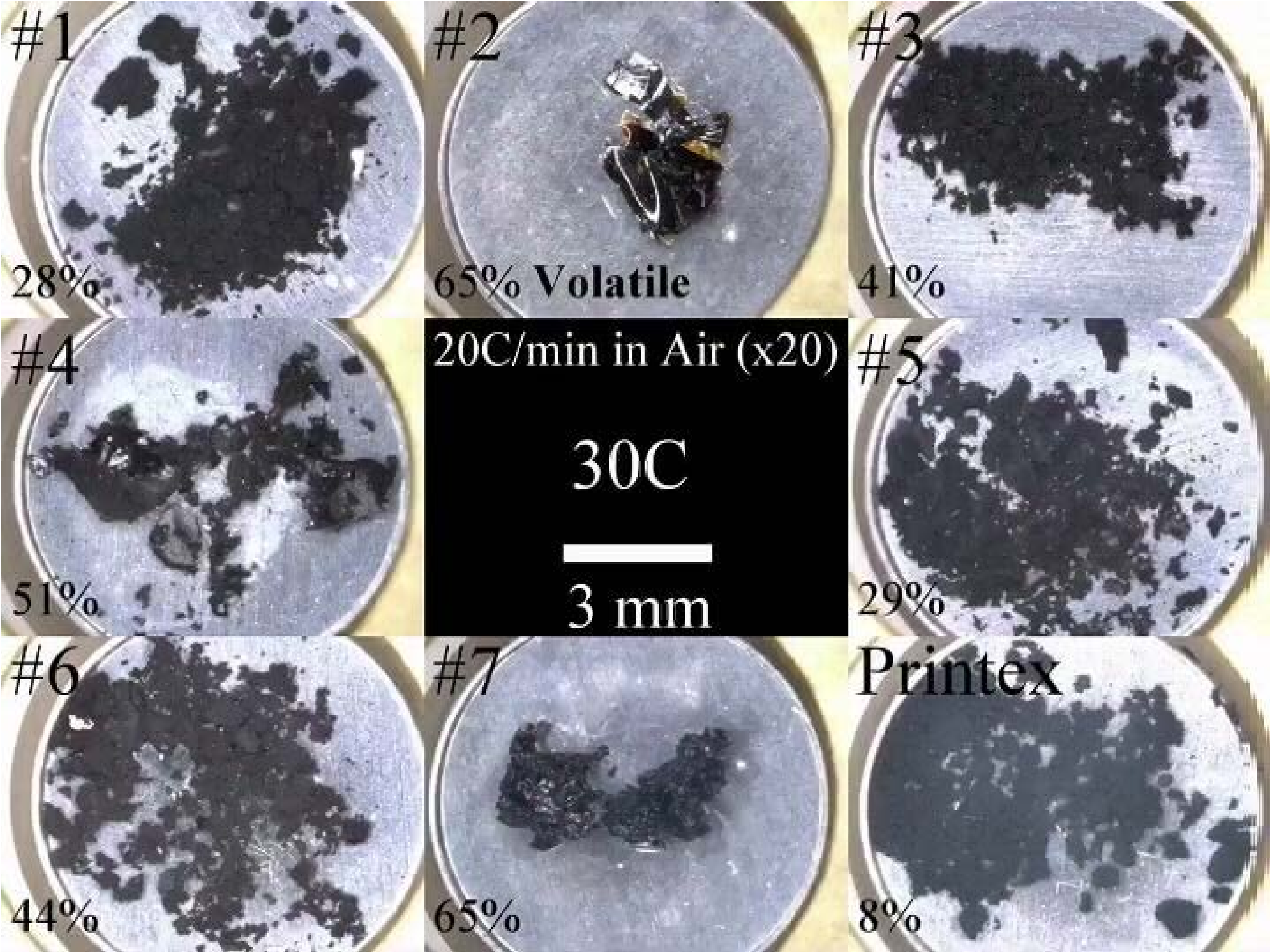


- Industry Representative: "This particular test was an extremely severe EGR valve sticking test. The EGR valve and throttle were forced open, the engine ran at low idle, and timing was retarded by 7 degrees."
- Chemistry
  - TGA showed 65% volatile measured in N_2 up to 700°C. No ash remained after complete oxidation.
  - FTIR showed the presence of hydroxyl (-OH).
  - XPS and EDAX only showed C and O, and only trace amounts of N.

Pyrolysis GC-MS was used to Determine Lacquer Chemistry



- Peaks are variants of 2, 3, 4 ring PAHs and oxygenated PAHs - narrow range of melting points/boiling points.
- Paraffinic fuel peaks are not present.
- Deposit chemistry was representative of PM collected from low temperature combustion regimes – “proto-soot” compounds that have not lost all of the hydrogen necessary to form particulate carbon.


#1
28%
#2
65% Volatile
#3
41%
#4
51%
20C/min in Air (x20)
30C
3 mm
#5
29%
#6
44%
#7
65%
Printex
8%

Collaborations: EGR Materials Advisory Team

- An advisory team consisting of chief engineers responsible for EGR systems from ten members of the diesel crosscut team was assembled.
- EGR team companies included light-duty, heavy-duty and off-road diesel truck manufacturers:

Future Work

1. Fundamental studies of deposit properties using laboratory-generated early-stage deposits
   - Add hydrocarbon and NO_x additions to the bench-top tube reactor.
   - Analyze change in deposit material properties (density, thermal conductivity, microstructure) caused by varying HC and water content, flow rate, air and coolant temperature with the goal being densification and/or removal of the deposit.
   - Study the interaction between geometry and fouling using CAD designed additive manufacturing wavy tubes.
2. Second round of industry-provided coolers for late-stage deposit characterization.
   - Continue chemical and microstructural analyses of plugged cooler deposits.

Summary

Relevance

EGR fouling results in 1-2% loss in efficiency.

Approach

Fundamental Studies: (1) Refreshment Strategy and (2) Geometry Effects.

Real-World: (3) Industry-Provided Samples.

Technical Accomplishments and Progress

- Laboratory-generated deposits were successfully formed on model cooler tubes using two standard operating conditions.
- Proof-of-Principle: Tube effectiveness improved following water condensation.
- Preliminary investigations of the effect of geometry on fouling were conducted.
- Forensic analysis of cooler deposits may allow one to infer deposit formation and removal mechanisms.

Collaboration with entire diesel engine community.

Proposed Future Work

Use tube sampler, reactor and CAD designed wavy tubes to better understand fouling while continuing to characterize late-stage deposits.