Materials Issues Associated with EGR Systems

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PM009

Overview

Timeline

- Start: February 2009
- End: September 2012
- 59% complete

Budget

- Total Project Funding
  - DOE-$1.5 M
- Funding received:
  - FY09: $400K
  - FY10: $360K
  - FY11: $360K

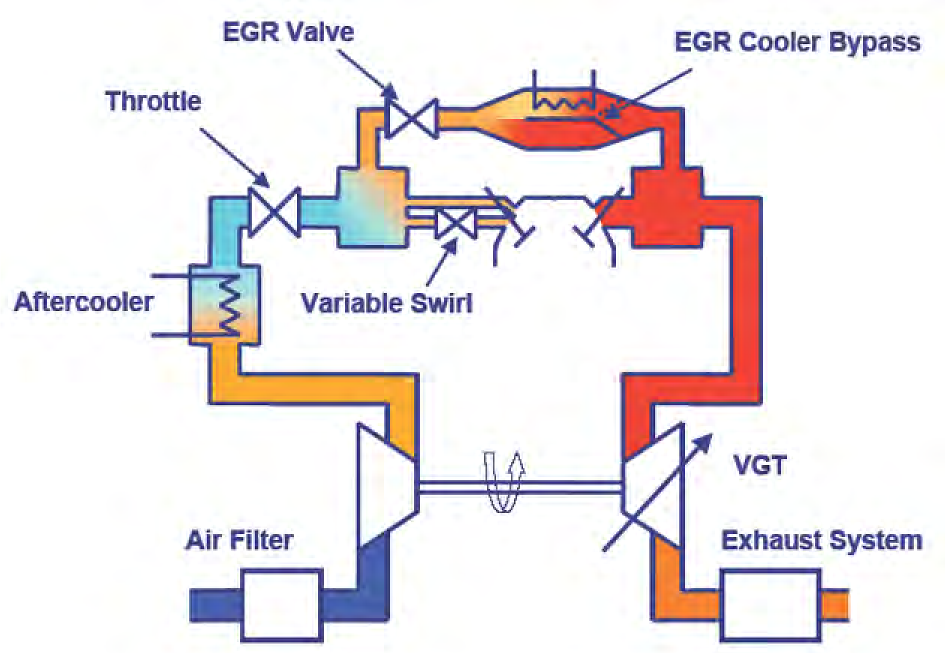
Barrier

- 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.
- 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.
- US Army

Background: Exhaust Gas Recirculation Cooler Fouling



- High-pressure EGR is the dominant NO_X-reduction technology.
- Exhaust gas laden with PM flows through the EGR cooler which causes deposits to form through thermophoresis and condensation.
- The deposit thermal conductivity is very low, which reduces the effectiveness of the EGR system. The deposit growth will also increase the pressure loss leading to a decrease in engine efficiency.
- Increasing demands placed on the technology by more stringent NO_X emissions, advanced combustion, increasing use of non-petroleum-based fuels, and engine/aftertreatment system optimization requirements are leading to expansions of the technology into operational conditions that are relatively unknown or known to be problematic.

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

- Characterize the thermo-physical properties of the deposit under different operating conditions on model EGR cooler tubes.
- Determine the effect of different engine operating conditions on the deposit properties.
- Enable improved models and potential design improvements to reduce fouling and its impact on performance.
- Possibly develop a protocol for regenerating the EGR cooler during use.
- Leverage existing project funded by the DOE Fuels program to allow more in-depth analyses on samples from biodiesel operation.

Milestones

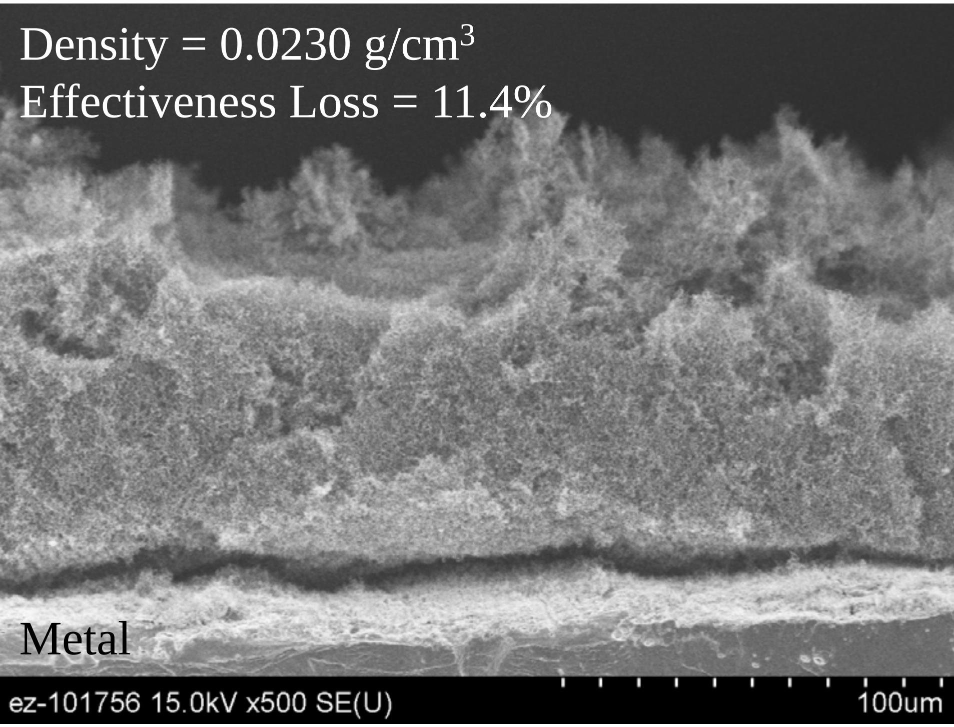
- FY2009
  - Feb-09 Milestone: Assembled EGR Advisory Team from industrial experts at 9 diesel engine manufacturers.
  - Feb-09 Go/No-Go Decision
    - Survey EGR Team Members as to what the greatest materials issues are relating to EGR systems. The survey results clearly indicated EGR cooler fouling as the primary concern.
  - Sep-09 Milestone: Task 2 - Collected EGR coolers from industry representatives for forensic analysis of deposits.
- FY2010
  - May-10 Milestone: Task 2 – Completed preliminary analysis of industry-provided coolers.
  - May-10 Milestone: Task 2 – First Three-Dimensional Neutron Tomographs collected.
- FY2011
  - Feb-11 Milestone: Task 1 – Deposited first EGR cooler deposits on model tubes.

Approach

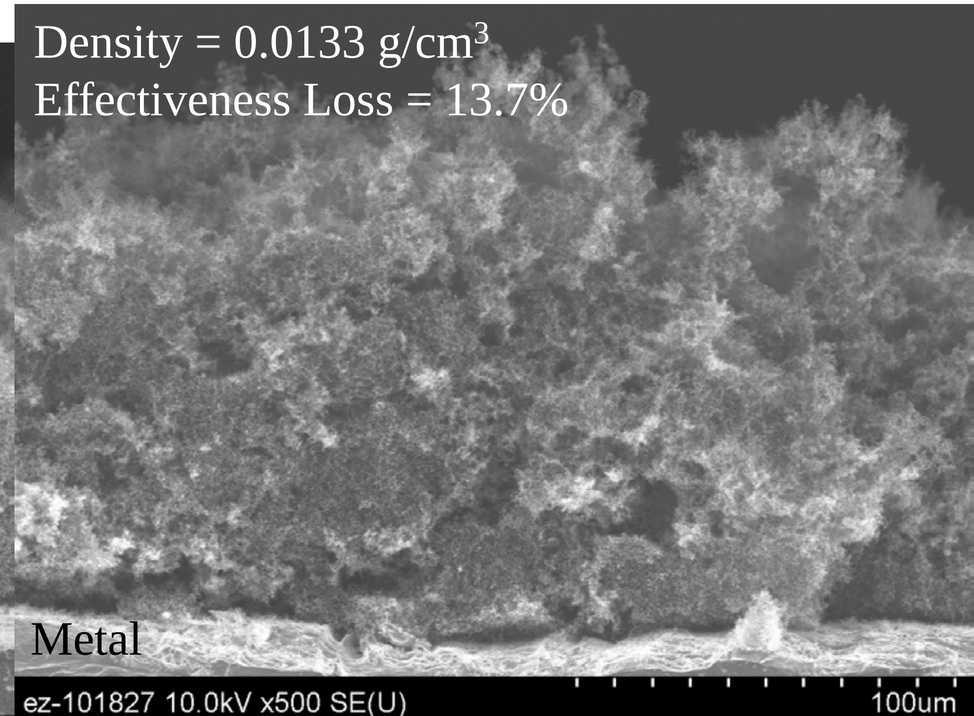
- **Task 1: Tube Sampler for Deposit Formation**
  - A GM 1.9 L engine on a Drivven controller is operational in standard and PCCI modes.
  - Deposits are formed on model cooler tubes with the coolant flow and temperature controllable using an external loop.
- **Task 2: Obtain and Evaluate Representative (Half-Useful-Life) EGR Coolers from Industry Members**
  - Eight companies provided twelve coolers for analysis.
  - This provided us with a reference point that will guide our future research
  - It also provided an opportunity to refine effective characterization tools:
    - Microstructural Analysis: SEM, Electron Microprobe, Optical Microscopy
    - Chemical Analysis: EDS, FTIR, XPS, Raman, GC-MS, XRD
    - Thermal Analysis: Thermal Conductivity, TGA/DTA
    - Neutron Tomography

Task 1: Baseline Deposits formed using Tube Sampler

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



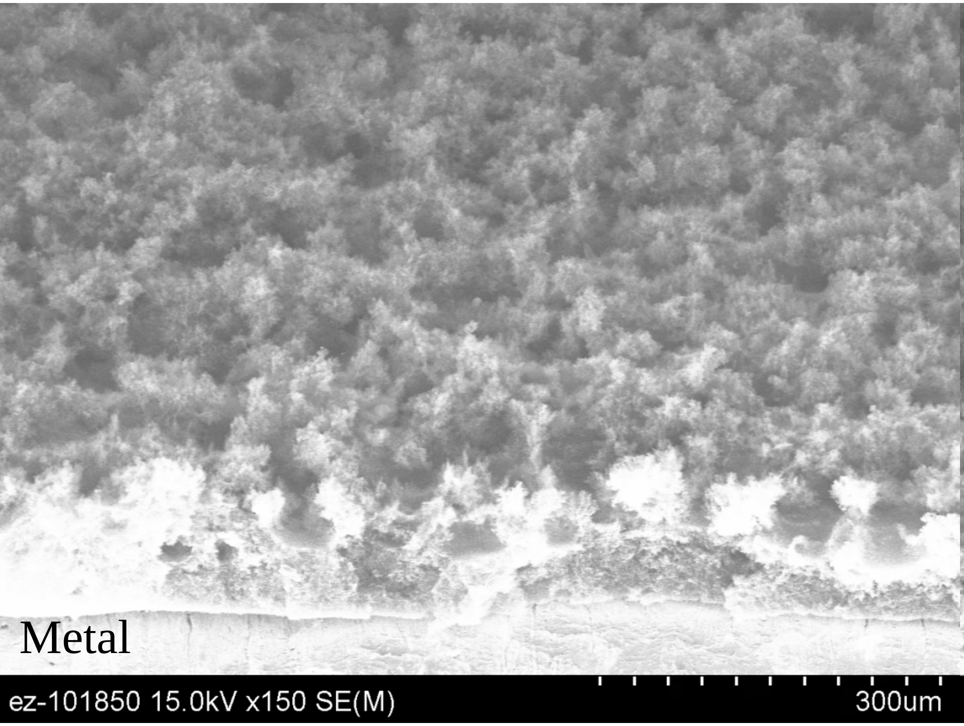
Heavy-Duty Condition:
7-8 Bar BMEP, ~325 C inlet, 28 ppm HC
310 ppm NO_x, 0.97 FSN



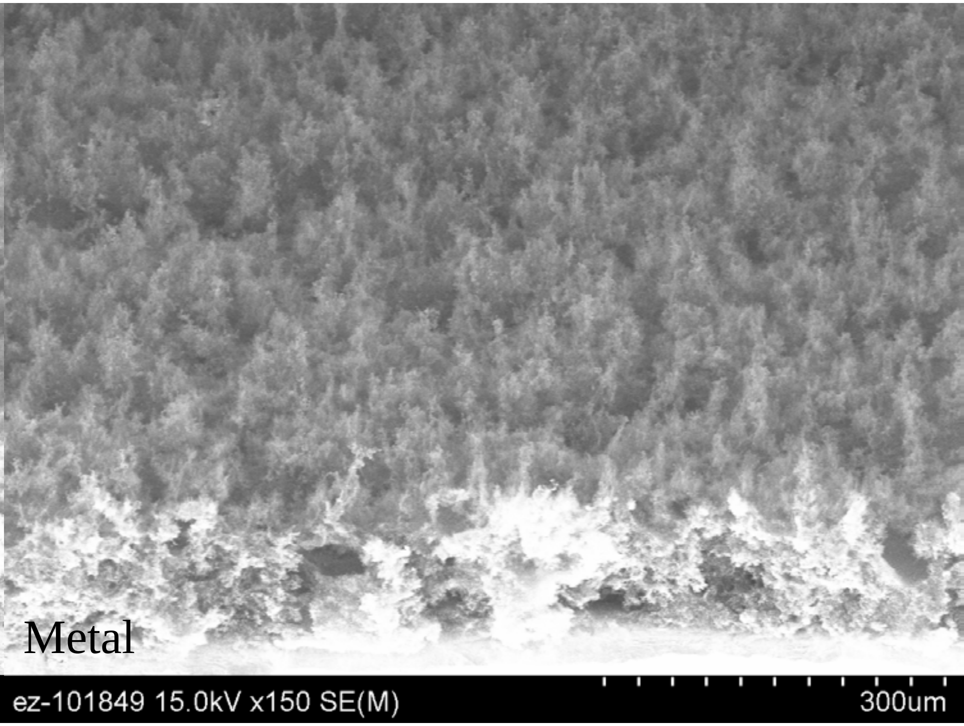
- Both deposits were generated at 1500 rpm and a EGR flow rate of ~30 SLPM for 4 hours. Coolant temperature was 90 C.
- The heavy-duty deposit was thicker and had a lower density than the light-duty condition which increased the effectiveness loss.

Surface Morphology Differences

Light-Duty Condition



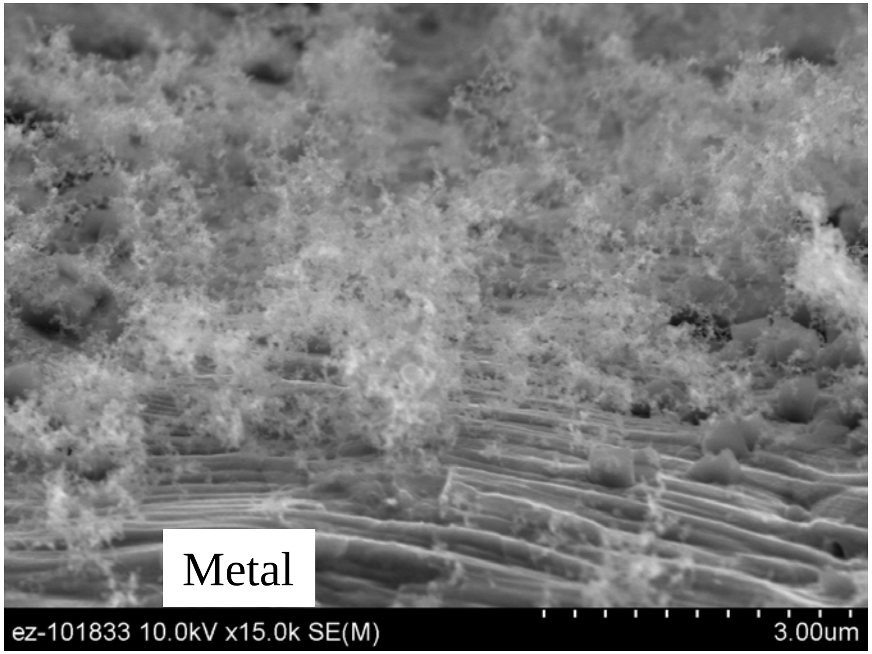
Heavy-Duty Condition



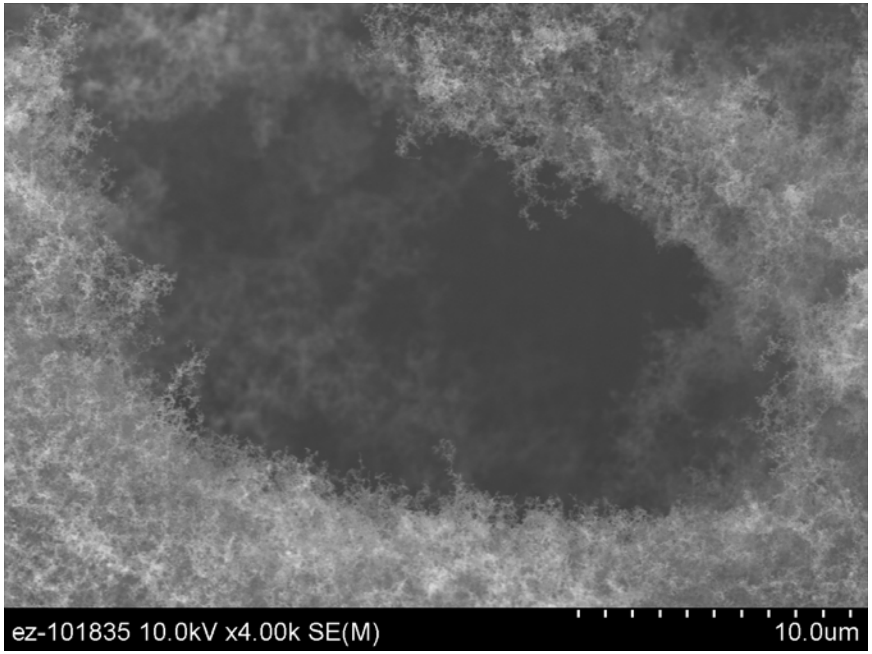
- Images of the surface collected at a 20° tilt.
- The light-duty sample has a clumpier surface whereas the heavy-duty sample appears more dendritic. These longer dendrites of the HD sample apparently allow more large-scale pores to form during deposition.
- This project will proceed by addressing both the light-duty and heavy-duty diesel communities.

Microstructural Features of Laboratory-Generated Deposits

Metal-Deposit Interface

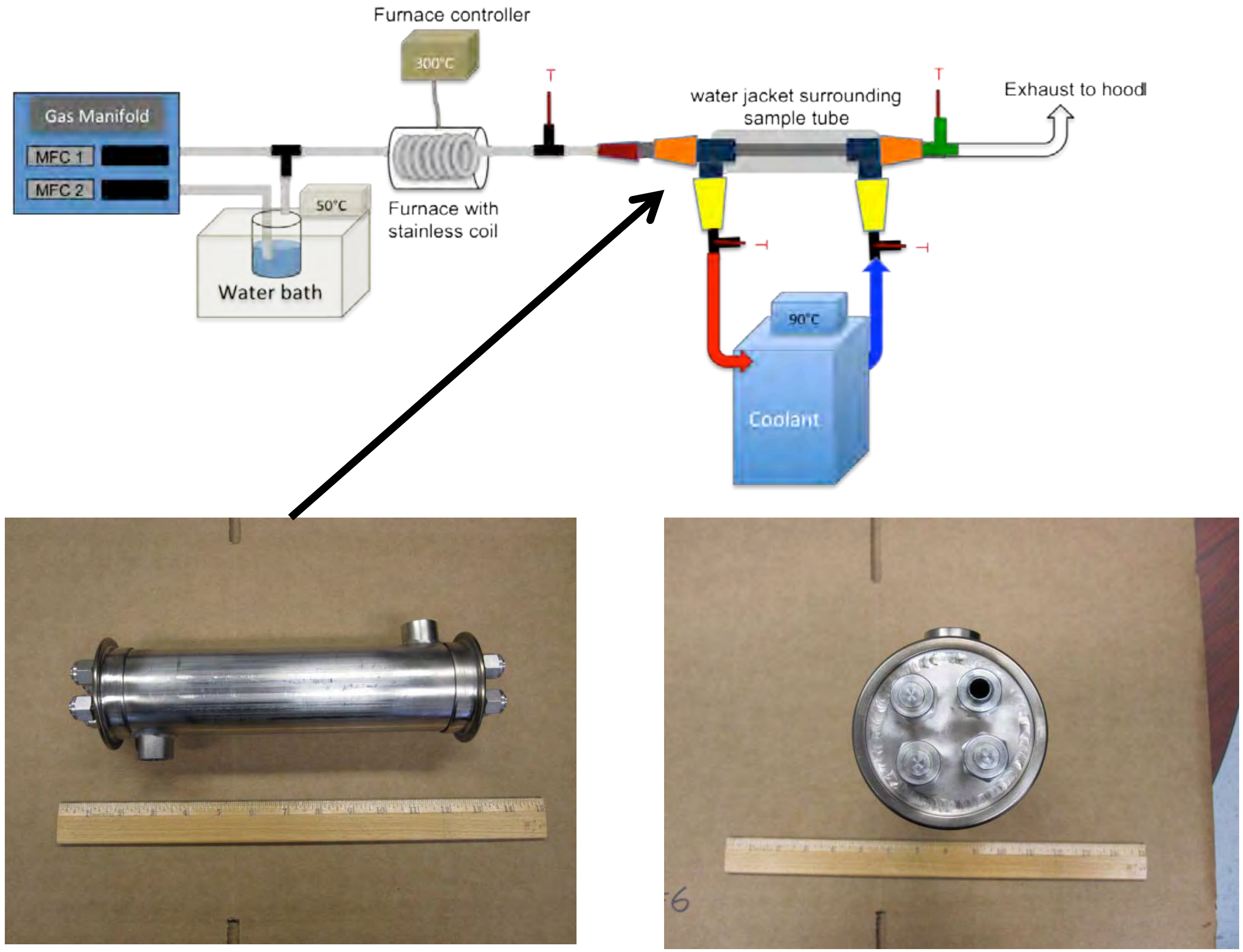


Large-scale Pore (HD Deposit)



- After delamination, PM remains on the metal, indicating that the fracture plane is within the deposit, not at the deposit/metal interface.
- Large-scale pores (1000 times larger than the primary PM size) form during deposition.

Bench-top Tube Reactor for Deposit Aging

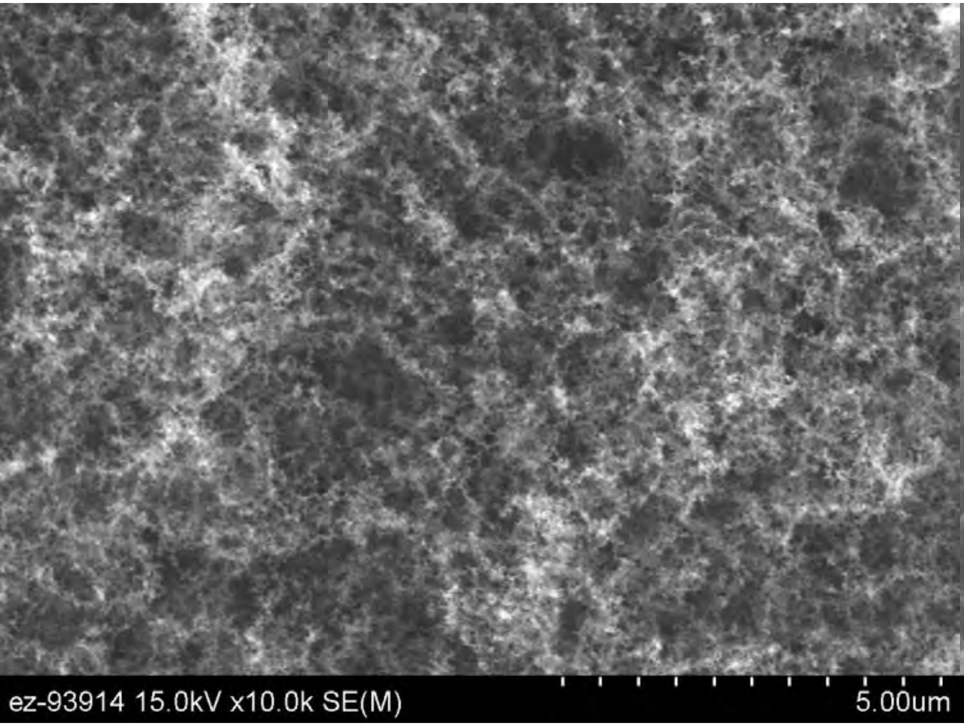


- Samples generated with our engine are aged in a tube reactor and the changes in the deposit properties and microstructure are monitored.

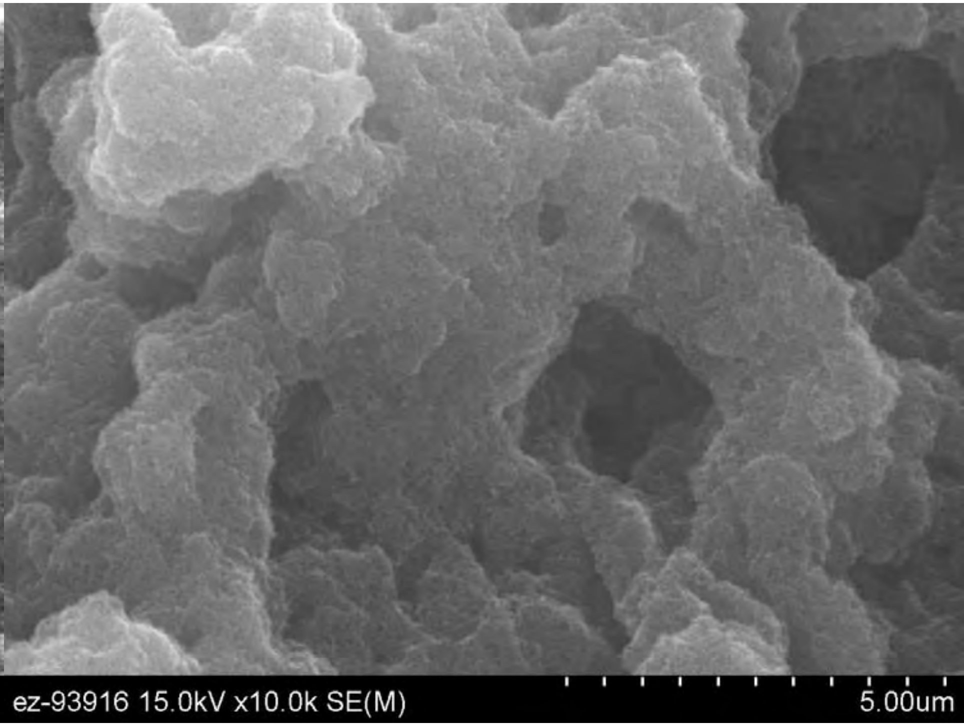
- Inlet and coolant temperature, gas flow rate, water and HC content are controlled.

Effect of Water Condensation and Drying on Microstructure: A Route to EGR Cooler Regeneration

Light-Duty Deposit



After Water Immersion and Drying



- Thermal conductivity is controlled mainly by deposit density. Since the deposit starts off with such a low density, there is the potential to dramatically improve its properties by collapsing the PM microstructure.
- Deposit microstructure shows a dramatic shrinkage following water immersion.
- Changing the engine operating conditions so as to condense water or HC on the deposit may regenerate the fouled cooler.

Task 2: Forensic Analysis of Industry-Provided Coolers

Industry-Provided Coolers

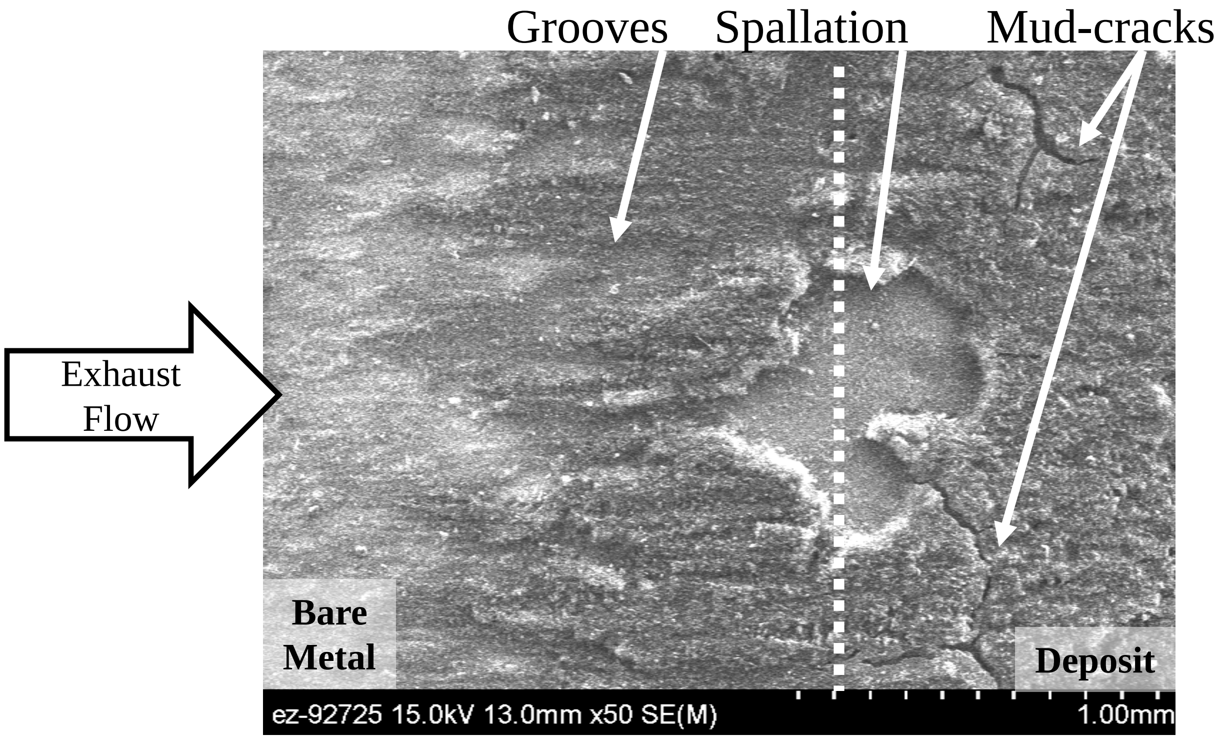
Cooler #	*Miles*	*Hours*	*Condition*	*Heat Transfer Surface Area (m^2)*
1	280000		Field Aged	1.29
2			Dyno-cell	2.84
3			Dyno-cell	0.51
4			Dyno-cell	0.90
5	89478		Field Aged	1.04
6	113764		Field Aged	1.09
7	249128		Field Aged	4.38
8		315	Dyno-cell	1.50
9		1389	Field Aged	1.10
10a	140000		Dyno-cell	0.46
10b	140000		Dyno-cell	0.46

Summary of Observations

Observation	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10a*	*10b*
Plugging			X	X							
Corrosion	X								X		
Density Gradient	X	X	X	X		X	X	X	X	X	X
Mudcracking	X	X	X			X	X	X			
Spallation	X	X						X			
Grooving		X					X	X	X		
Silicates							X				

- Every cooler showed a gradient in the deposit microstructure from coarse to fine moving away from the metal.
- This effect may be caused by the collapsing of the PM nanostructure due to hydrocarbon and/or water condensation during operation.
- Most coolers showed similar deposit removal mechanisms.

Three Common Deposit Removal Mechanisms



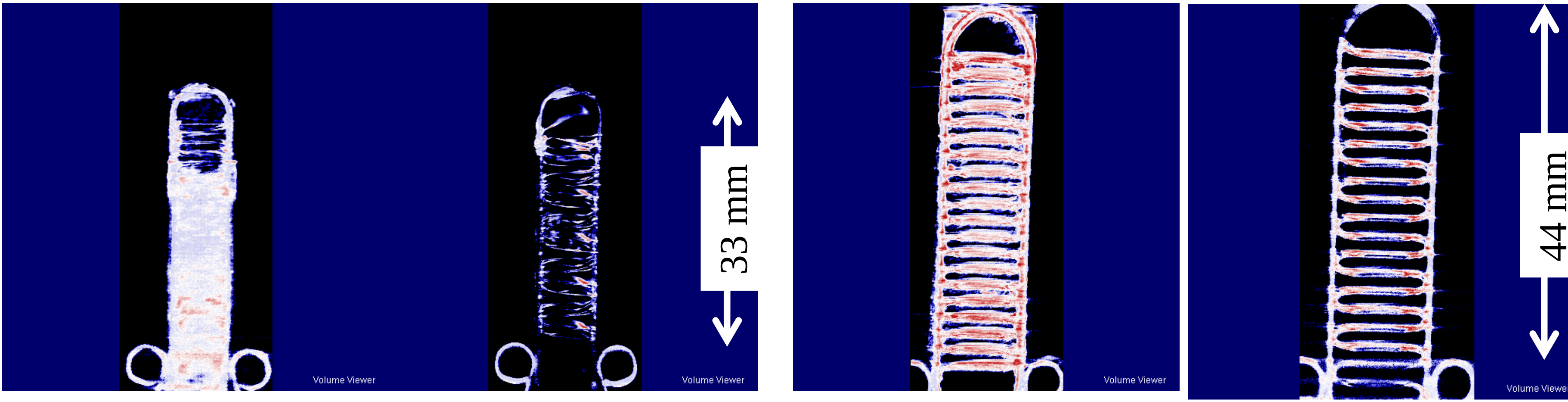
Dashed line indicates the peak of the sinusoidal fin.

- Longitudinal grooves, mud-cracks and spallation have been observed on many coolers, suggesting that the deposit is shrinking by some mechanism. This may be the origin of spontaneous regeneration that has been reported by many EGR consortium members.
- Communication of Results to Broader Community:
  - Two DEER meetings (oral)
  - Nine Diesel Crosscut Team Meetings
  - Two SAE meetings (Excellence in Oral Presentation Award)
  - Two Global Powertrain Conference Meetings
- Work has generated follow-on-funding from two EGR consortium members and the US Army.

Neutron Tomography of Industry-Provided Cooler Tube Sections

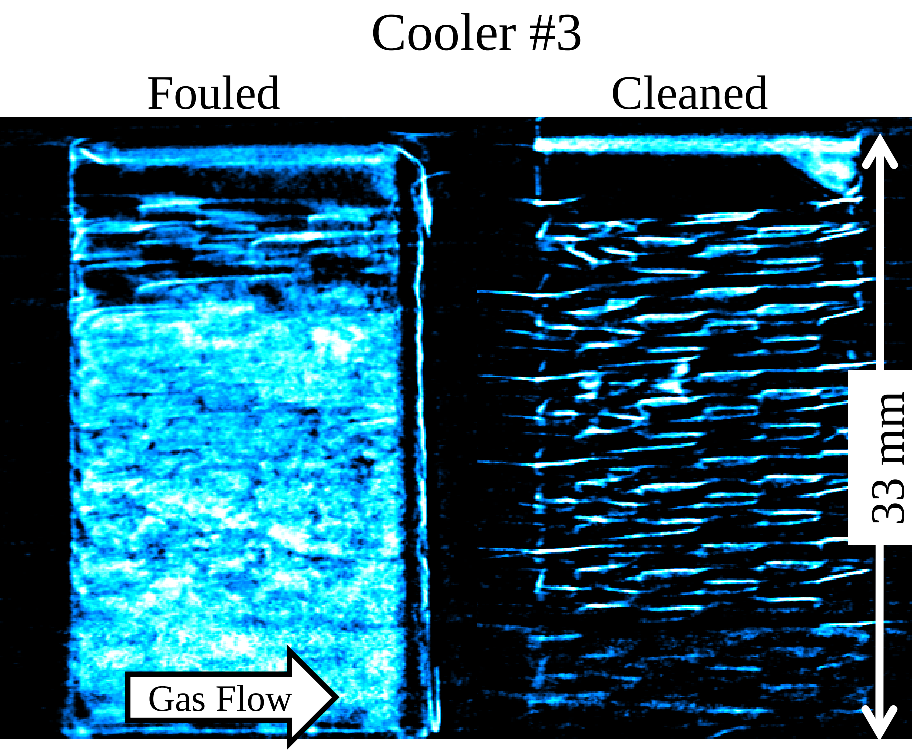
Cooler #3 | Cooler # 5

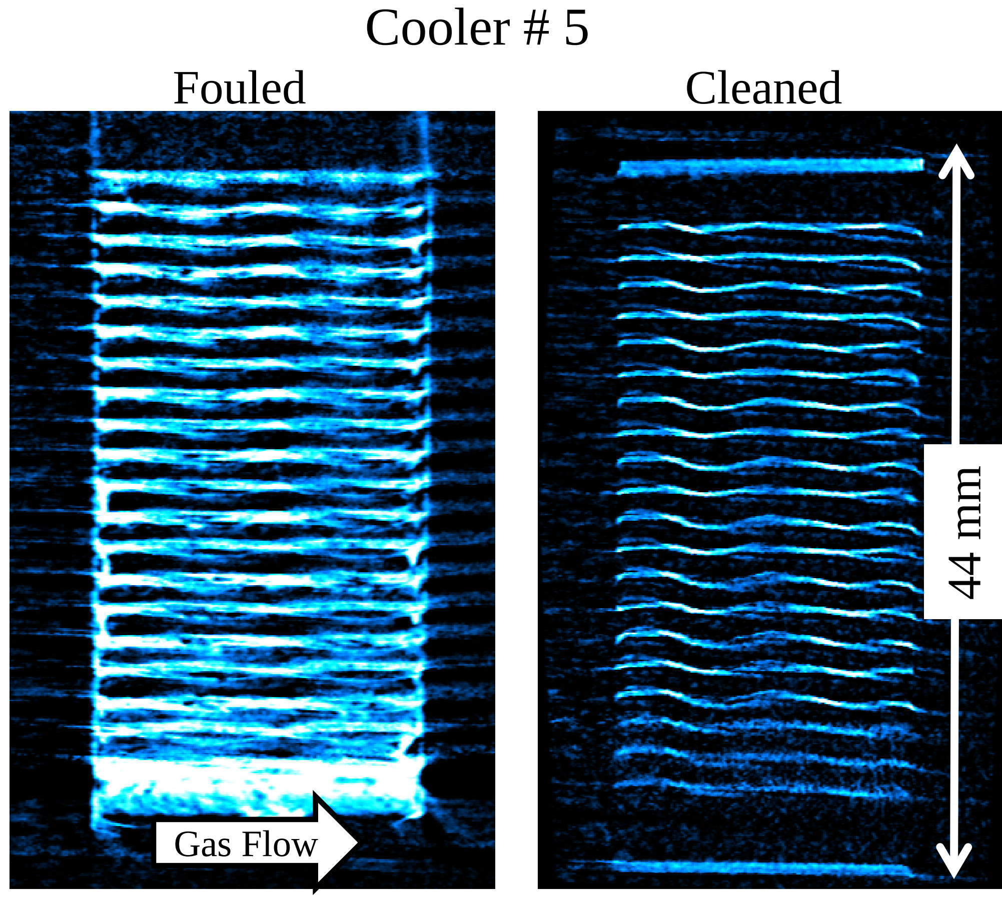
Fouled | Cleaned | Fouled | Cleaned



- Neutrons are strongly attenuated by hydrogen which allows for non-destructive imaging of the deposit through the metal.
- The two coolers with the most HC were selected for neutron tomography.
- 720 2-D projections of the cooler sections were acquired by rotating the sample around its axis of symmetry.
- The spatial resolution was ~70 µm which may soon improve to 35 µm.

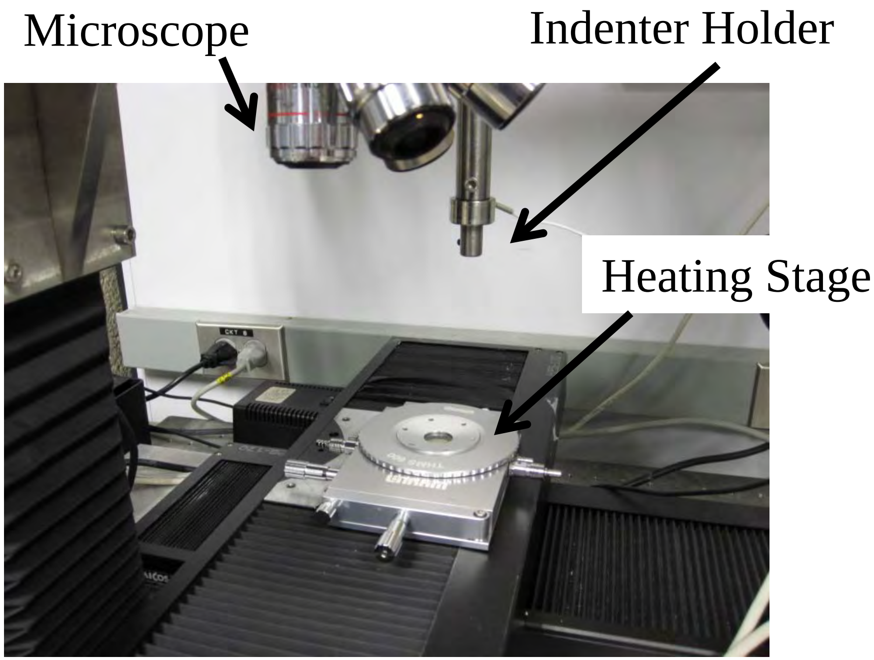
Neutron Tomography of Industry-Provided Cooler Tube Sections

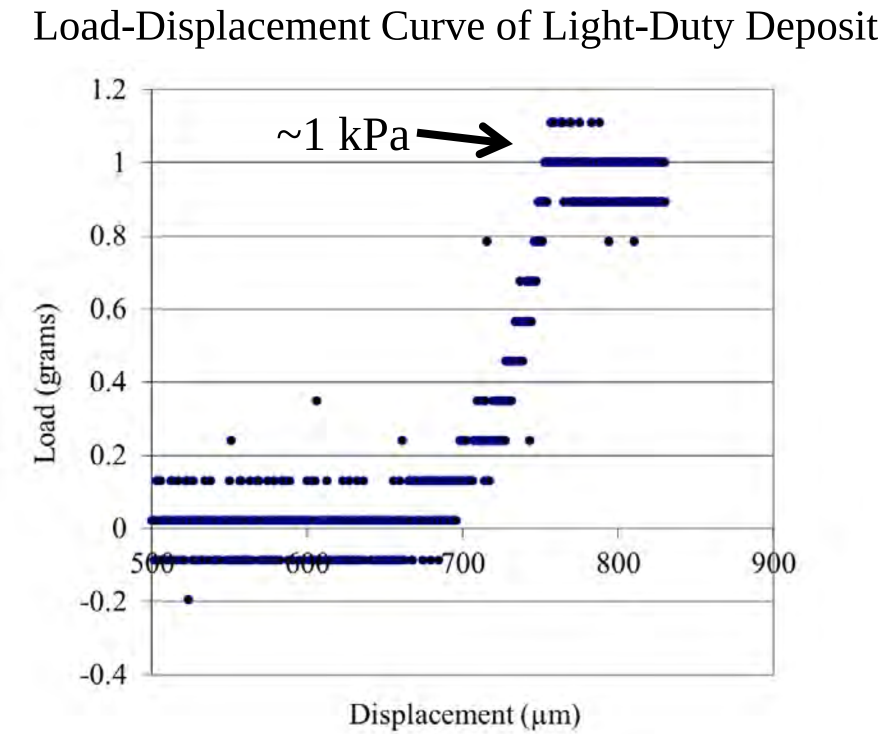




- The resolution was not high enough to measure thickness directly but we can still gather useful information about the deposit location relative to the heat exchanger geometry.
- A new project funded by the US Army (partnering with Modine) is focusing on the effects of internal heat exchanger geometry on fouling.
- Dr. Jens Gregor (Associate Professor of Radiology, UT Graduate School of Medicine) has been contracted to develop software to aid in the reconstruction and image processing.

Mechanical Properties: Instrumented Indentation





- Load-Displacement curve of deposit on a metal substrate can be measured as function of temperature.
- A crushing strength can be measured that will allow us to approximate fracture strength.
- Deposit stiffness can be estimated from the slope of the curve.
- Mechanical properties measurement is critical for understanding removal mechanisms.

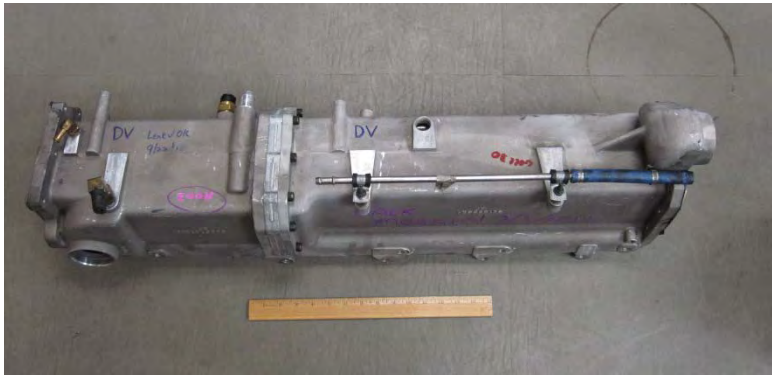
Collaborations: EGR Materials Advisory Team

- 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
   - Two baseline deposits will be studied: light-duty and heavy-duty.
   - Bench-top tube reactor will be used to age the deposit under different conditions.
   - Analyze change in deposit material properties (density, thermal conductivity, microstructure) caused by varying HC and water content, flow rate, air and coolant temperature, etc.
2. Second round of industry-provided coolers for late-stage deposit characterization.
   - All industry EGR Team members have agreed to send coolers that will represent specific applications.

EGR Cooler from a School Bus



Summary

- Laboratory-generated deposits were successfully formed on model cooler tubes using two standard operating conditions.
- A bench-top tube reactor is now completed and being tested.
- Hydrocarbon/water condensation plays a pivotal role in EGR fouling and will affect plugging, densification, thermal conductivity, mud-cracking and adhesion.
- Forensic analysis of cooler deposits may allow one to infer deposit formation and removal mechanisms.
- Neutron tomography was shown to be a valuable tool for imaging EGR cooler fouling and will have broad application to many other emission control technologies.

Acknowledgement

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