Materials Issues Associated with EGR Systems

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PM009

Overview

Timeline

- Start: February 2009
- End: September 2011
- 45% complete

Budget

- Total Project Funding
  - DOE-$1.05 M
- Funding received:
  - FY09: $300K
  - FY10: $270K

Barrier

- After-treatment systems have energy penalties that reduce the overall engine/after-treatment system efficiency.
- The need to use exhaust gas recirculation (EGR) in heavy-duty engines to meet EPA emissions requirements will impose severe operating conditions on conventional cooling systems. Radically new approaches to heat rejection will be needed to prevent decreased energy efficiencies in the system.

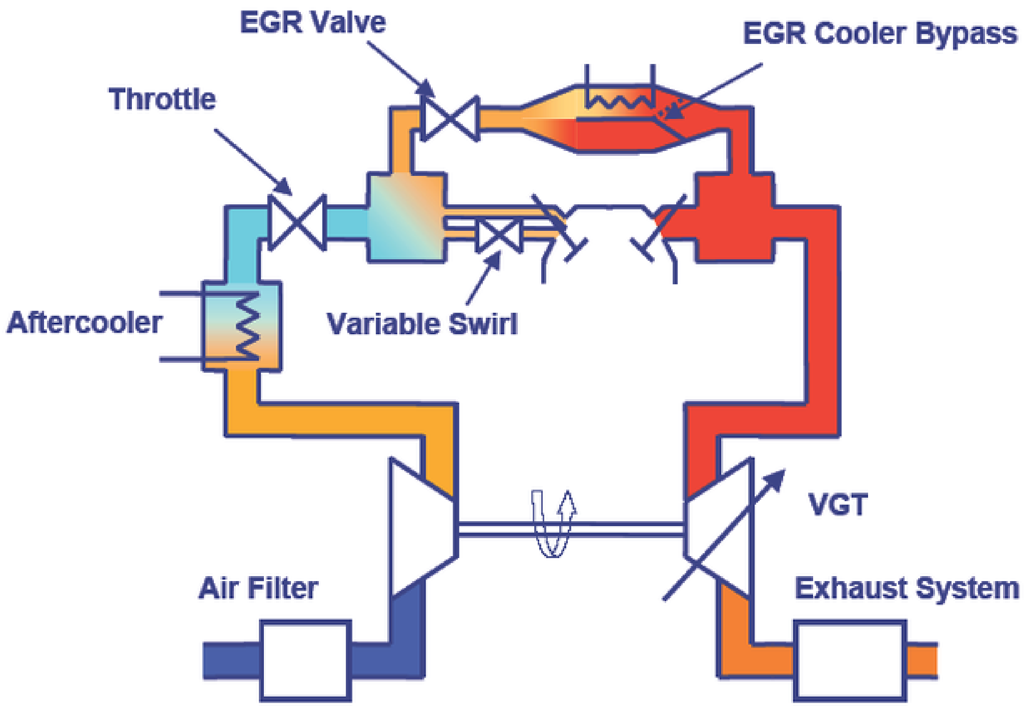
Targets

- Optimize cooled exhaust gas recirculation (EGR) for maximum NO_X reduction and minimum PM emission, mitigating durability concerns with EGR through materials engineering and operational controls.

Partners

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

Background: High-Pressure Exhaust Gas Recirculation (HP-EGR)



- 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.
- 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 specialists about fouling deposit properties

Aim is to enable improved models and potential design improvements to reduce fouling and its impact on performance

- Characterize the thermo-physical properties of the deposit under different operating conditions on model EGR cooler tubes.
- Determine the long-term changes in deposit properties due to thermal cycling and water/HC condensation.
- Leverage existing project funded by the DOE Fuels program to allow more in-depth analyses on samples from biodiesel operation.
- Determine deposit adhesion mechanisms and methods to minimize them.

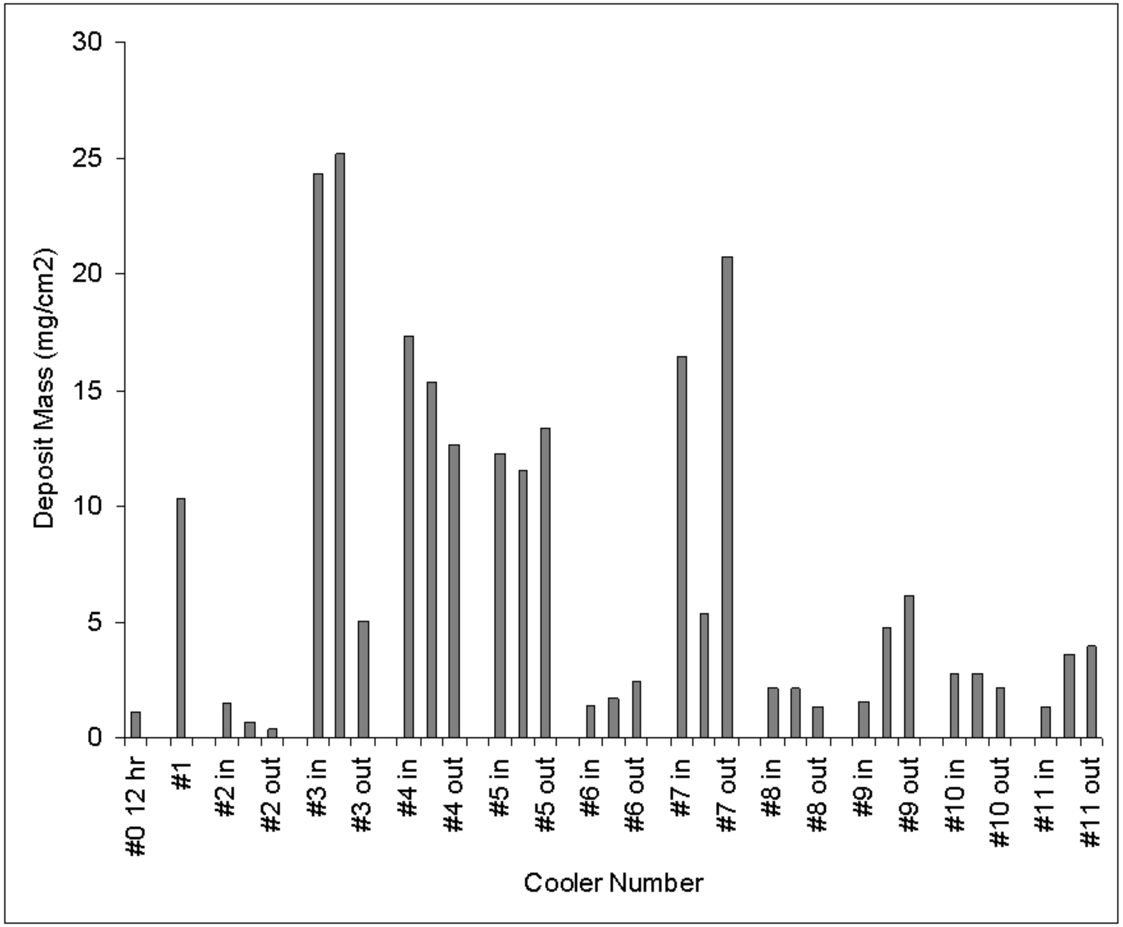
Milestones

- FY2009
  - Feb-09 Milestone: Assembled EGR Advisory Team from industrial experts at 9 diesel engine OEMs.
  - 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 - Collect EGR coolers from industry representatives for forensic analysis of deposits.
- FY2010
  - Mar-10 Milestone: Task 2 – Complete analysis of industry-provided coolers.
  - Apr-10 Milestone: Task 1 – Establish experimental set-up.

Approach

- Task 1: Experimental Setup
  - **A GM 1.9 L engine on a Drivven controller is operational in standard and PCCI modes.**
  - **Most of the sampler system parts have arrived and are ready to be assembled.**
  - **Bench flow reactor is being built for accelerated aging of deposits.**
- Task 2: Obtain and Evaluate Representative (Half-Useful-Life) EGR Coolers from Industry Members
  - **Eight companies have provided twelve coolers for analysis.**
  - **This will provide a reference point that will guide our future research**
  - **It will also provide an opportunity to refine effective characterization tools:**
    - **Microstructural Analysis: SEM, TEM, Electron Microprobe, Optical Microscopy**
    - **Chemical Analysis: EDS, FTIR, XPS, Raman, GC-MS**
    - **Thermal Analysis: Thermal Conductivity, TGA/DTA**
    - **Neutron Tomography**

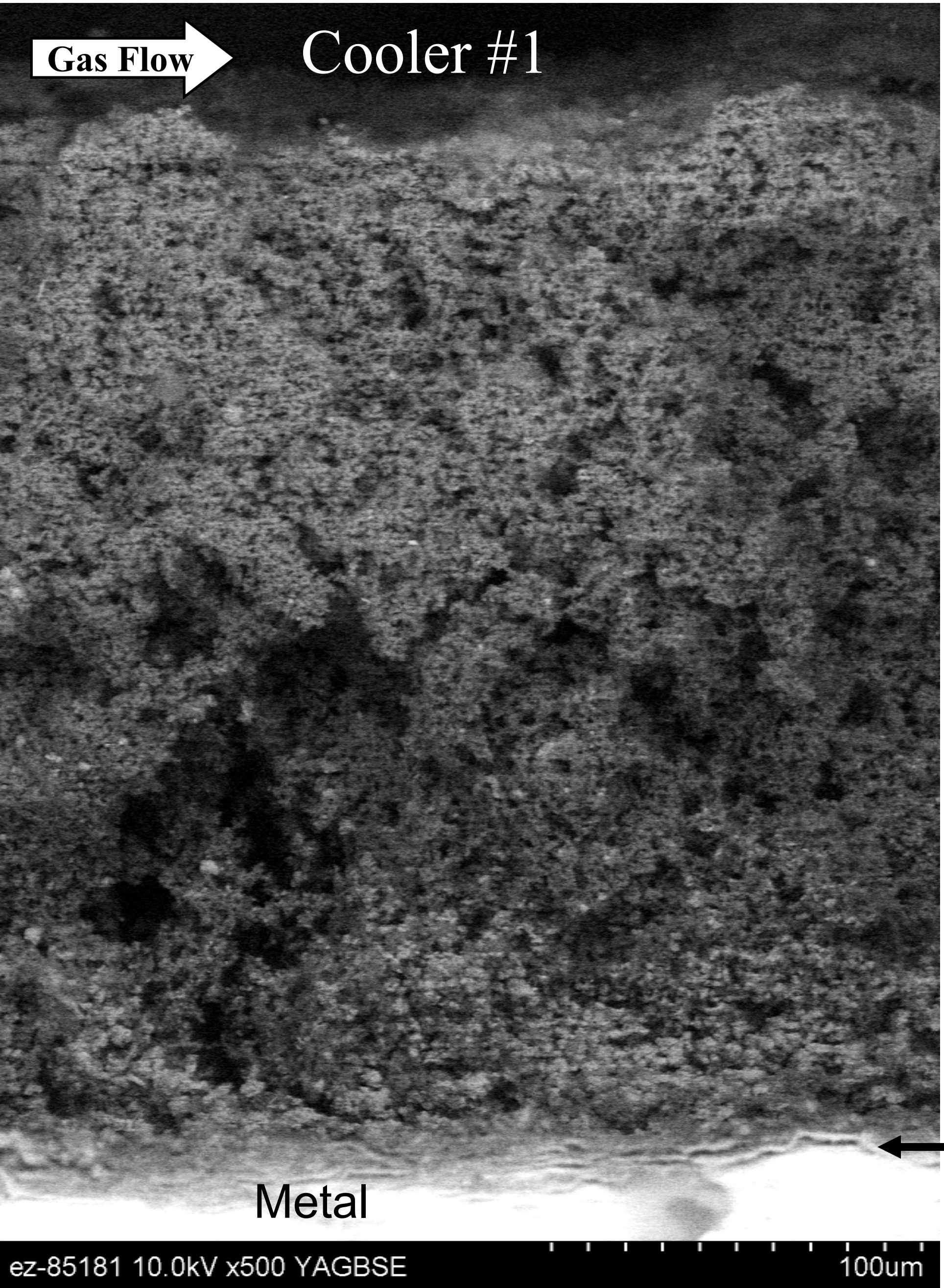
Deposit Mass per Unit Area (mg/cm^2)



Cooler #	*Miles*	*Hours*	*Condition*
1	280000		
2			Dyno-cell
3			
4			
5	89478		Field Aged
6	113764		Field Aged
7	249128		
8		315	Dyno-cell
9		1389	Field Aged
10a	140000		Dyno-cell
10b	140000		Dyno-cell

- **There was no consistent trend between all of the coolers in the change in deposit mass along the length.**

Imaging Method: Fracture Surface



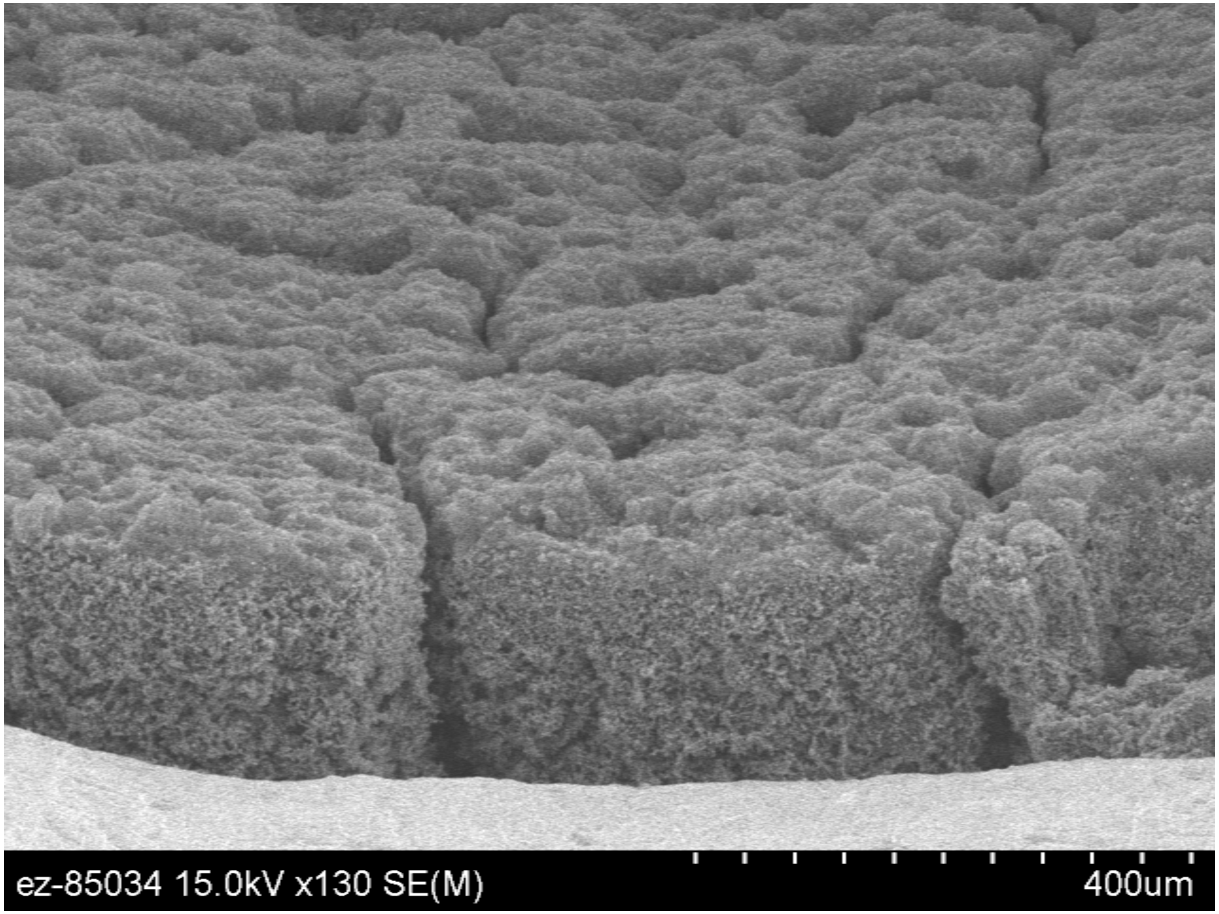
Carbonaceous Deposit

$FeSO_4$ Particles within the deposit

$FeSO_4$ layer on the metal

- **Metal is milled to the thickness of Al-foil and then broken open revealing the deposit fracture surface.**
- **Here, Cooler #1 has $FeSO_4$ particles embedded within carbonaceous material near the metal.**
- **There is also a corrosion layer on the metal itself.**

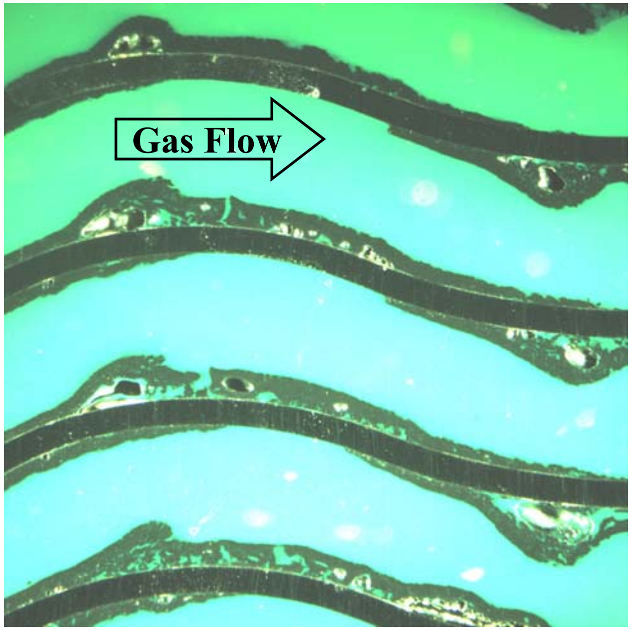
Mud-cracking is Observed in Many Coolers



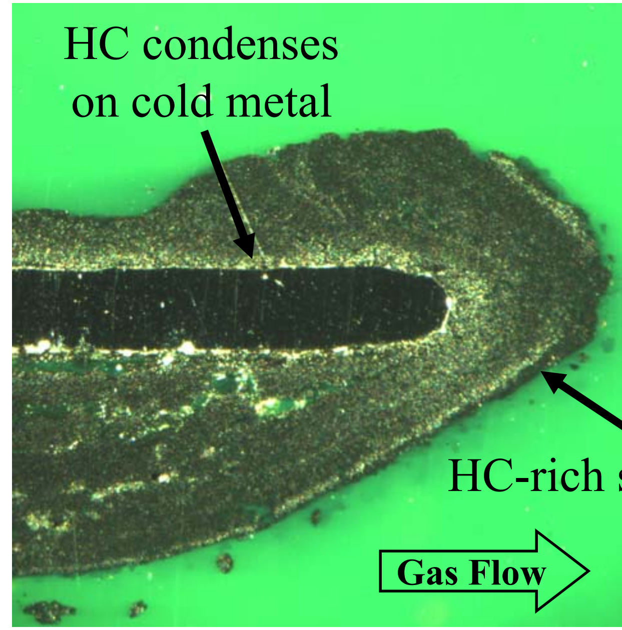
- **Mud-cracking and subsequent spallation of the deposit may be a significant regeneration mechanism.**
- **Spallation has been observed near turbulators on many of the coolers.**
- **Spontaneous regeneration of the EGR cooler has been reported.**

Imaging Method: Epoxy Mounting

Cooler #2

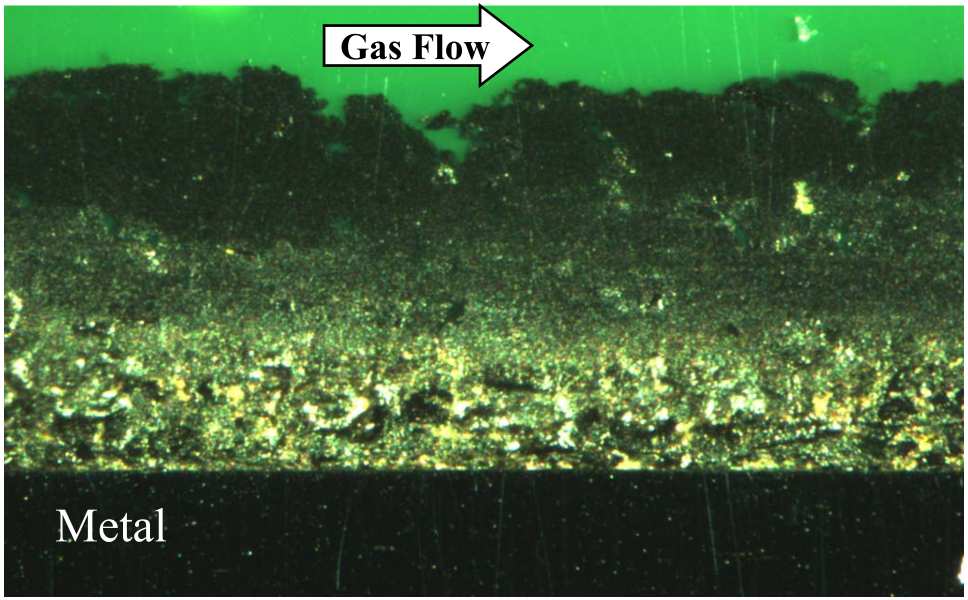


Cooler #3



- **Epoxy mixed with a fluorescent dye is poured over a ¾” section of tube without a vacuum. Mount is then ground on one side until the outer tube is gone. A second epoxy infiltration, this time with vacuum, is then done. The sample is then ground and polished.**
- **The technique is useful for seeing the interaction between the tube geometry and the deposit (above left) and seeing where the HC is distributed throughout the deposit cross-section (above right).**
- **As the black soot is covered in HC, its reflectivity increases, providing contrast when using optical microscopy.**
- **This technique is NOT useful for determining deposit thickness since the epoxy tends to collapse the soot microstructure.**

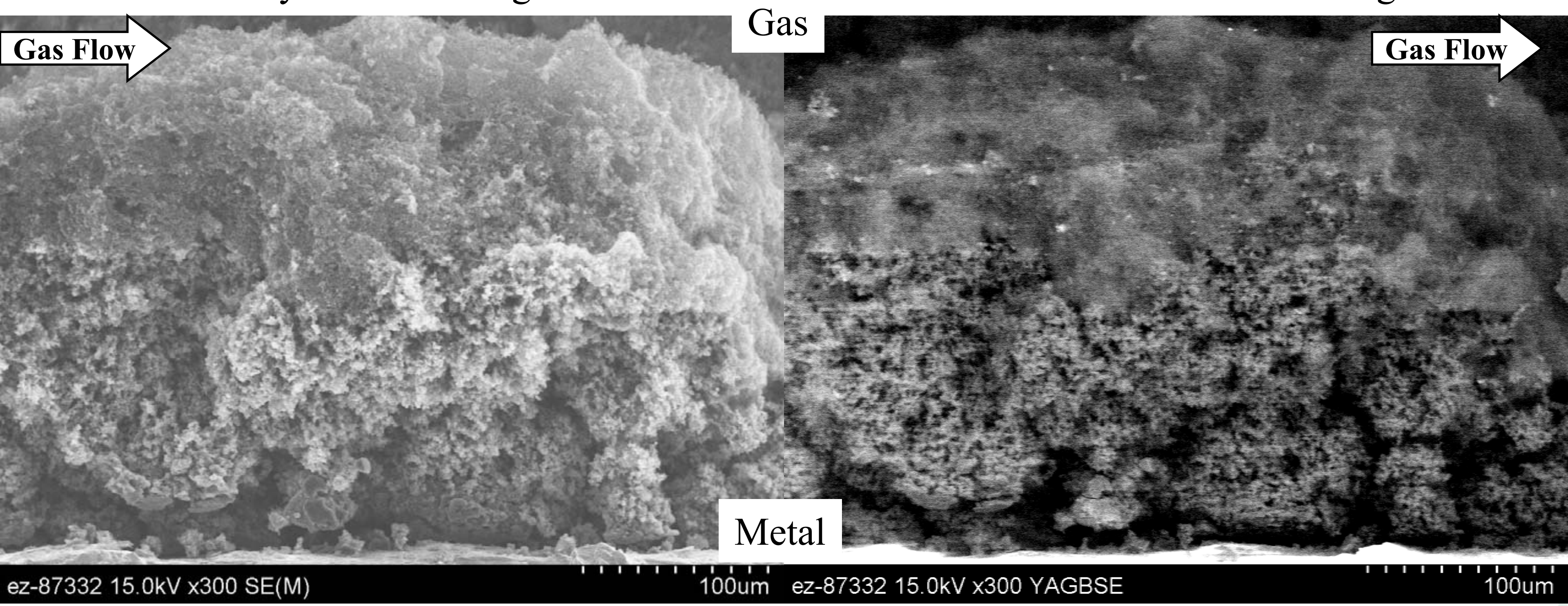
Hydrocarbon Condensation



- A common feature of most of the coolers is the higher HC concentration at the metal. This is seen here by the increasing reflectivity near the metal.
- This is caused by a thermal gradient across the deposit with lower temperatures near the metal which allows heavy HC species to condense.
- More deposit is often seen at the sides of the tube as opposed to the finned center, presumably because it is more effectively cooled there.
- HC may be beneficial in low amounts by causing the deposit to be denser.

Effect of HC on Microstructure

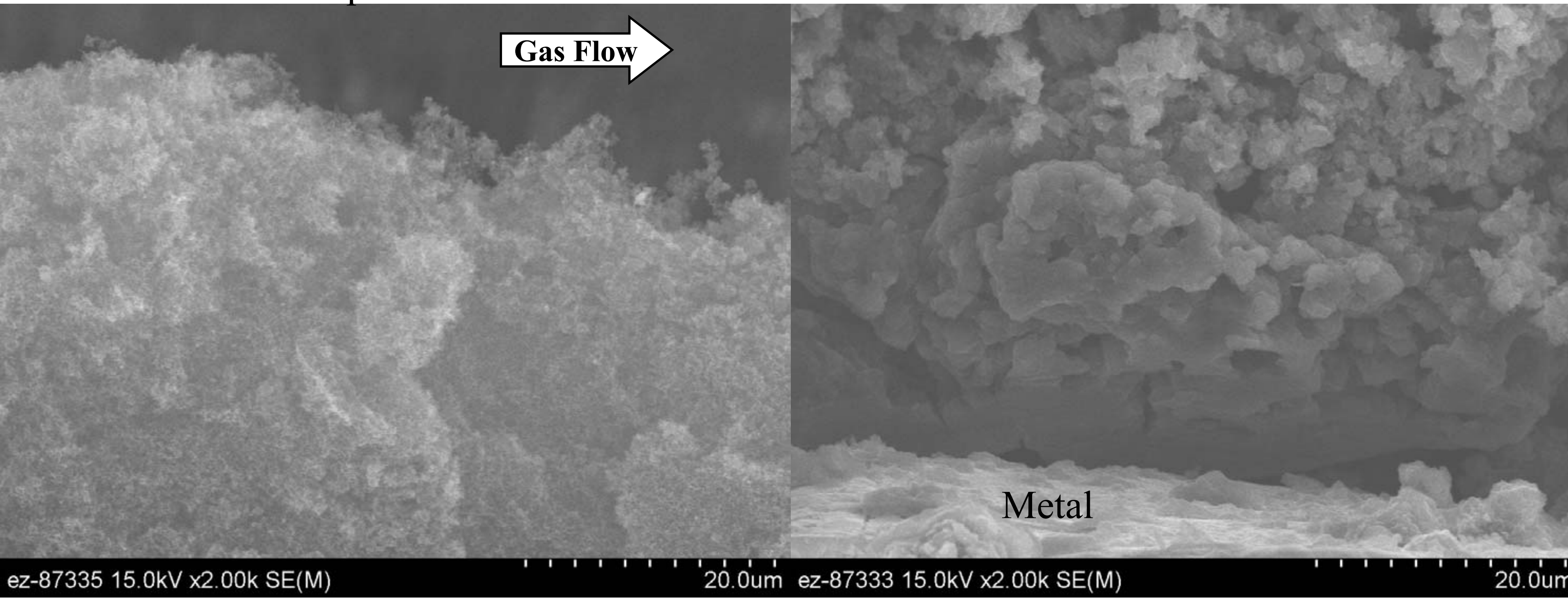
Secondary Electron Image | Back-scattered Electron Image



- **The back-scattered electron image (right) is good for seeing local regions of higher density and for any high-Z elements (Fe, Ca, Zn, etc.)**
- **Here, there appear to be two distinct regions in the deposit cross-section: a dense HC-rich region near the metal and a fluffy dry region near the exhaust gas.**

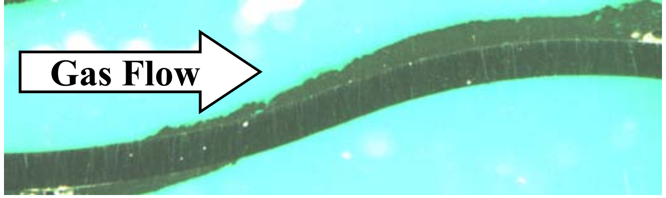
Comparing Top to Bottom of Deposit

Top Bottom

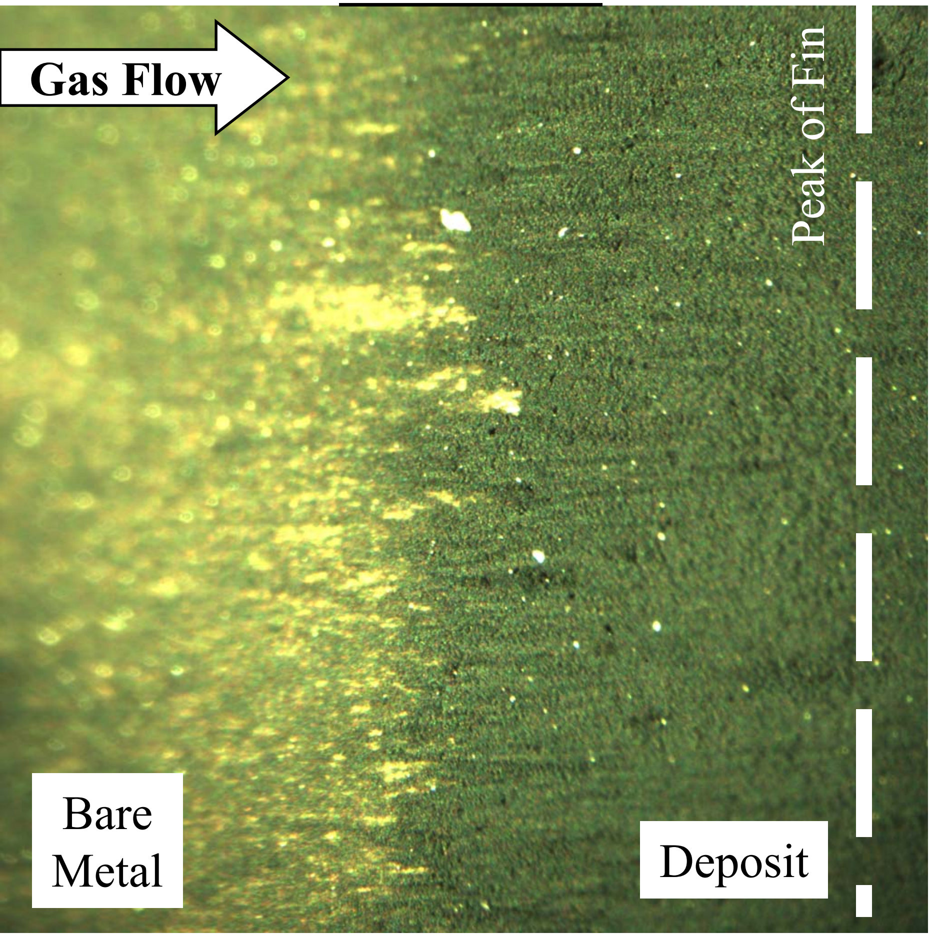


- **Fine particulate matter (PM) can be seen on the top surface of the deposit (left).**
- **The bottom surface near the metal appears much coarser and the fine PM is hard to find.**
- **The density of the dry PM-composed deposit has been measured at ORNL to be ~2%. The condensing of HC on the PM appears to collapse the porous structure of the deposit causing it to be denser and therefore more thermally-conductive.**
- **Since HC will be concentrated at the metal surface, it will greatly influence the adhesion of the deposit.**

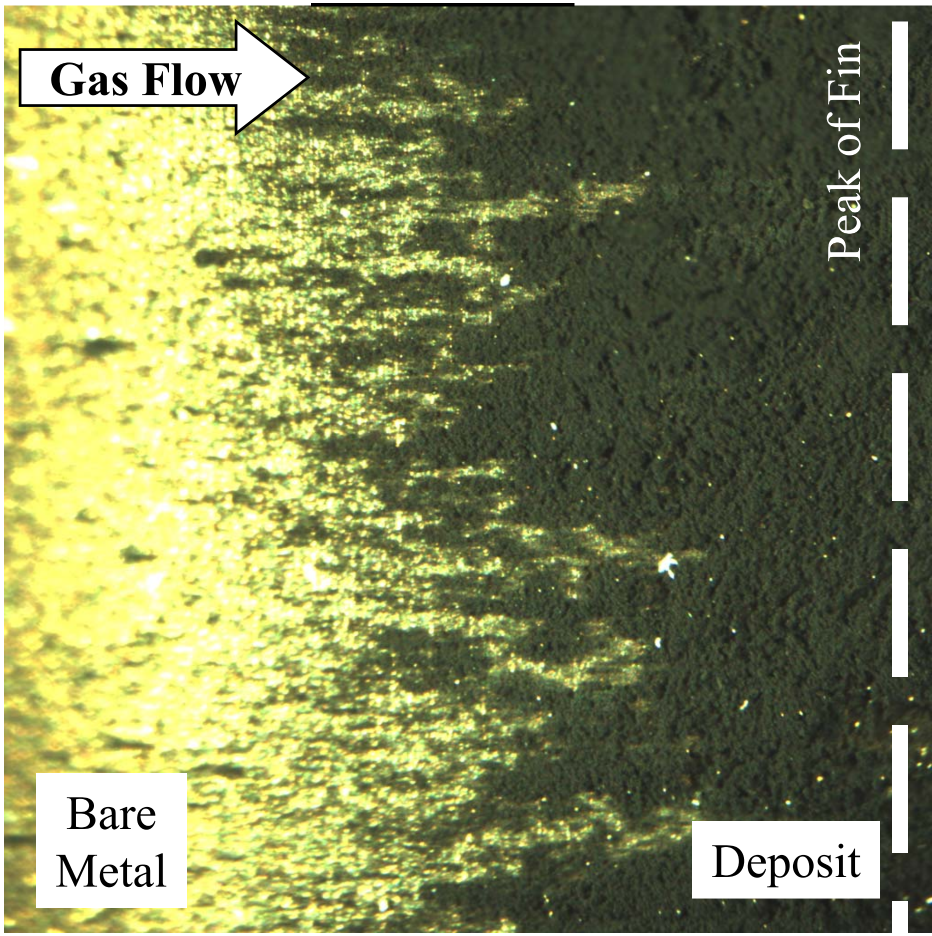
Erosion of Deposit



Cooler #6



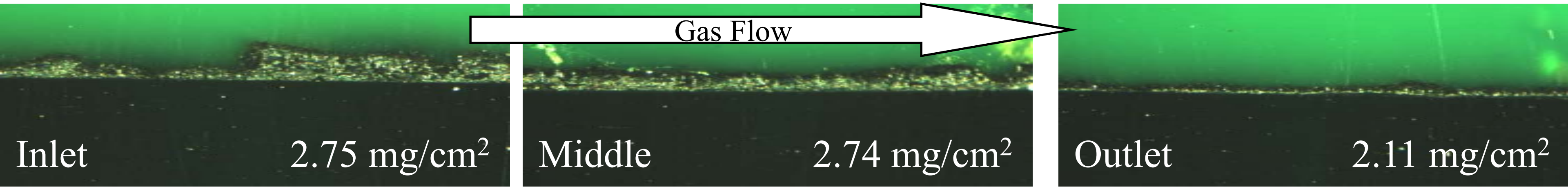
Cooler #2



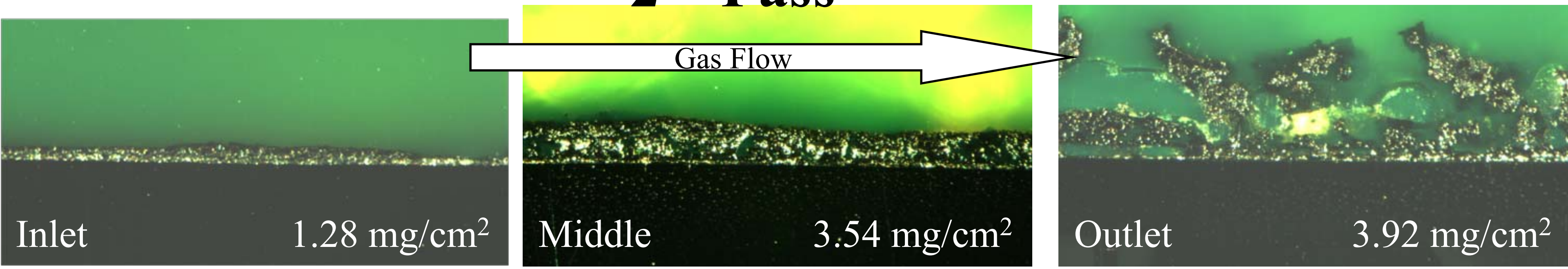
- **The deposit is being eroded on the leading edge of the sinusoidal peak of each fin.**
- **The erosion is uneven and forms channels or grooves in the deposit, presumably from the action of the flowing exhaust gas and/or snowballing.**
- **This microstructure has been observed on most of the coolers.**

Variation in Deposit Thickness (Cooler #10a & b)

1st Pass



2nd Pass

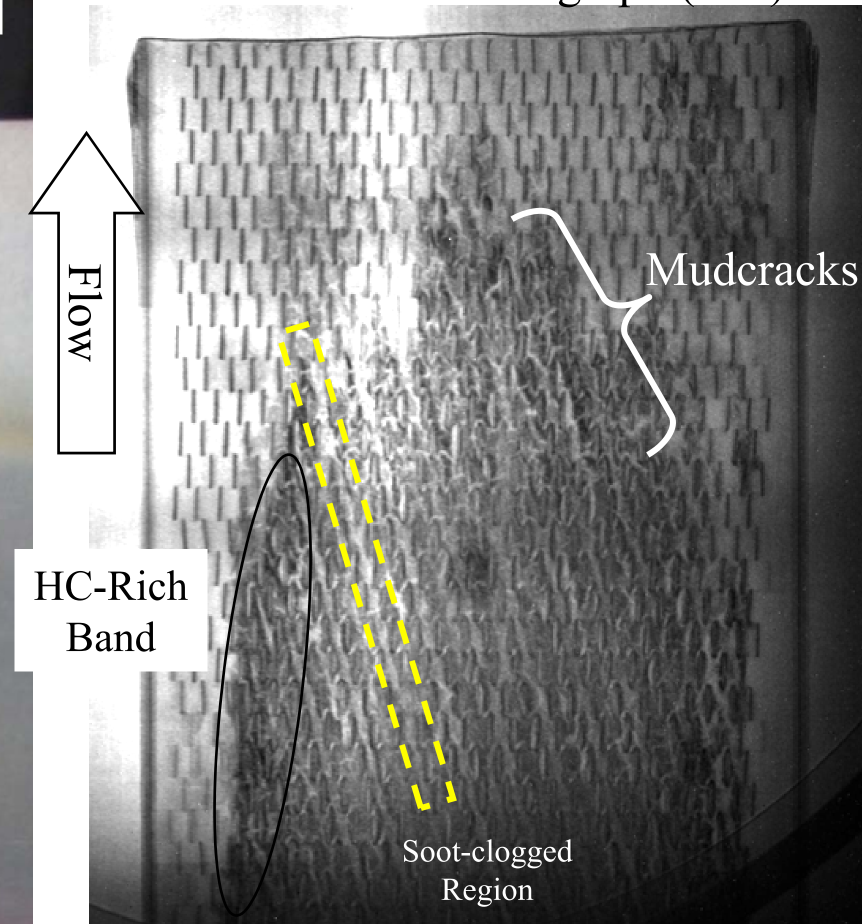


- **Deposit gets thinner and lighter down the length of the 1st pass.**
- **However, it gets thicker and heavier down the length of the 2nd pass.**
- **Fouling will be determined by multiple interacting processes including both deposition and removal phenomena.**

Neutron Imaging of Cooler Clogging

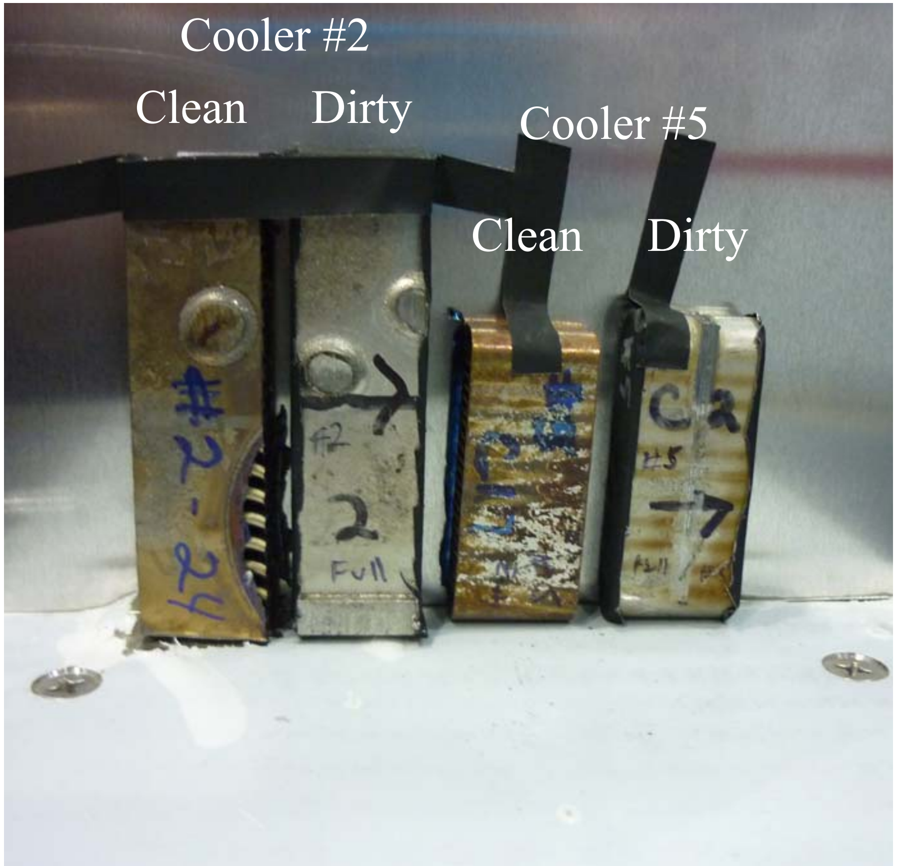
Picture of Tube Exterior on Scintillator Plate

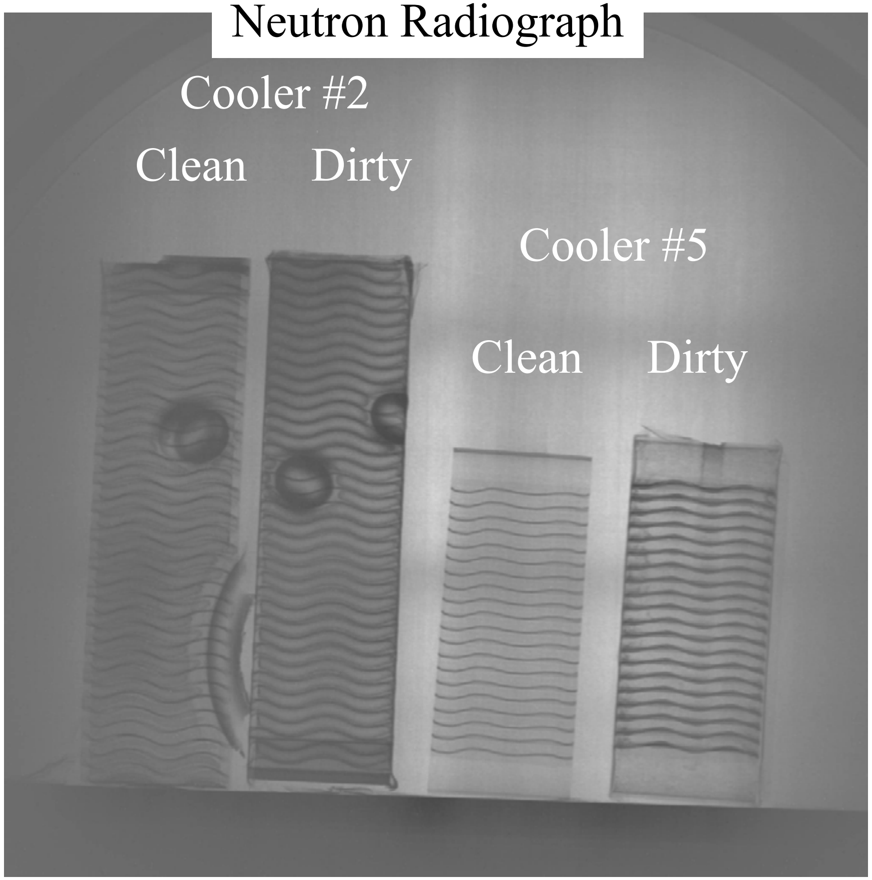
Neutron Radiograph (2-D)



- This is an image of one tube which shows the soot distribution (as the dark areas) in the cooler.
  - The exhaust gas can still pass on the right and left of the tube where there is no deposit.
  - Diagonal channels (e.g., within yellow box) seem to be forming in the clogged regions which apparently allow the exhaust gas to move through these regions.
  - The darker band on the left side of the clogged region may indicate more hydrocarbon loading in this region.
  - There appears to be breaks (mudcracks?) in the deposit that form orthogonal to the gas flow.

Clean and Deposit-Loaded Cooler Sections





- **Cooler #2 and #5 had the lowest and highest percent hydrocarbon, respectively.**
- **The attenuation of neutrons is dependent on the hydrogen density in the deposit and the deposit thickness.**
- **The clean cooler #2 sample appears lighter than the deposit-loaded sample in the neutron radiograph because it was slightly tilted against the scintillator plate.**
- **Cooler #5 shows a clear darkening due to the presence of the deposit.**

Collaborations: EGR Materials Advisory Team

- An advisory team consisting of chief engineers responsible for EGR systems from ten diesel engine OEMs was assembled.

- EGR team companies included light-duty, heavy-duty and off-road diesel truck manufacturers:

Future Work

- Complete sampler system for controlled formation of EGR deposits.
- Test bench flow reactor for deposit aging.
- Evaluate the Role of Hydrocarbon in Cooler Fouling
    - Complete Task 2, focusing on characterizing the HC: GC-MS, TGA/DTA, FTIR, and mechanical properties.
    - Use our sampling system to investigate the effect of start-up/shut-down cycling on HC condensation.
    - Use bench flow reactor to investigate the effect of aging on the deposit properties.
- Coating Evaluation
    - Evaluate commercially-available coatings in our sampling system with the goal of better understanding deposit adherence.

Summary

- EGR will remain a key emissions technology for the foreseeable future as EPA regulations worsen degradation issues associated with PM.
- A team of industry advisors has been assembled that will help guide future research directions of this pre-competitive research.
- Hydrocarbon condensation plays a pivotal role in EGR fouling and will affect clogging, densification, heat transfer, mud-cracking and adhesion.
- Microstructures indicating deposit erosion were observed on most coolers.
- Microstructural analysis of EGR cooler deposits may reveal degradation mechanisms that can be easily prevented.
- Neutron imaging is very useful for non-destructively observing cooler clogging where large amounts of HC-rich deposits are present.
  - Information obtained from these images may provide improved design rules for internal heat exchanger geometries that would reduce clogging.

Acknowledgement

- Instruments that are part of the HTML User Program at ORNL were used in this investigation. The HTML User Program is funded by DOE's Vehicle Technologies Program.