

# Materials Issues Associated with EGR Systems

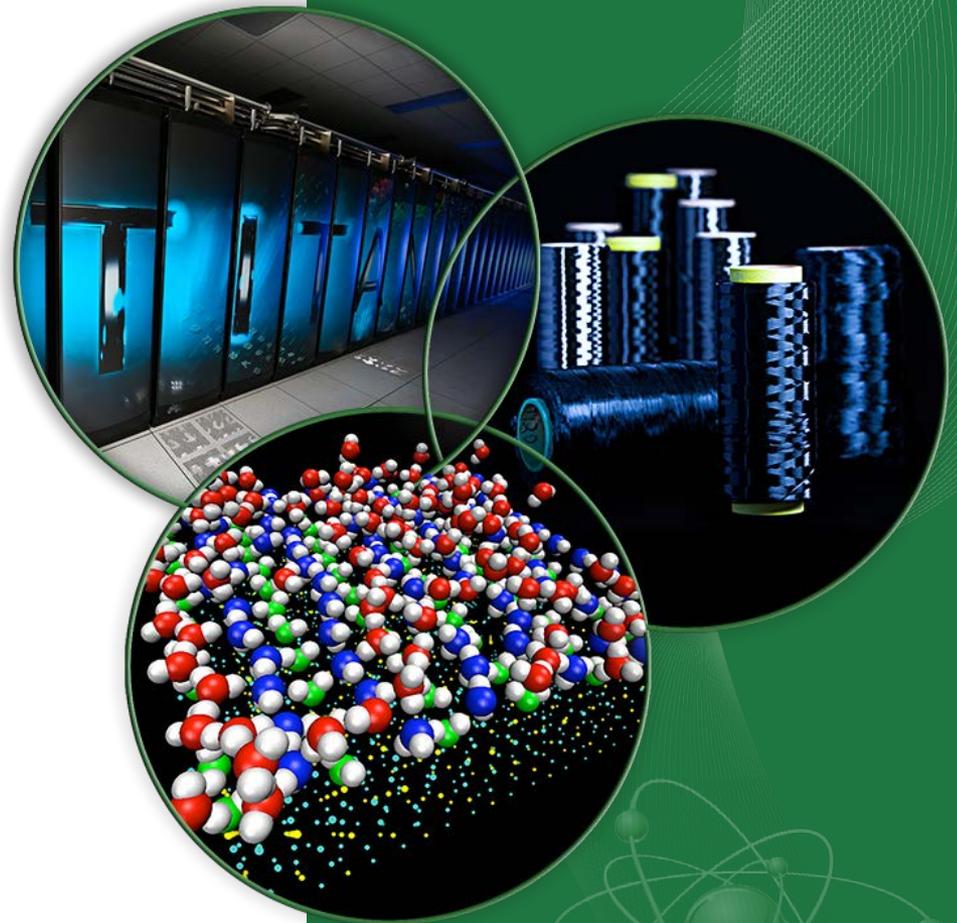
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June 9<sup>th</sup>, 2016

Project ID# PM009

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# Overview

## Timeline

- Start: FY09
- End: FY18
- 75% complete

## Budget

- Total Project Funding
  - DOE-\$2160 K
- Funding received:
  - FY14: \$184K
  - FY15: \$130K
  - FY16: \$165K

## Barrier

(Multi-Year Program Plan)

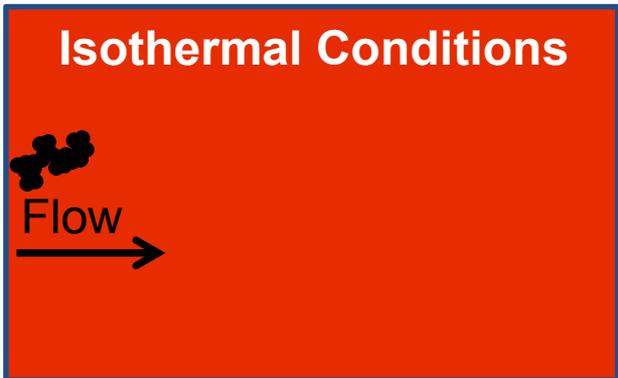
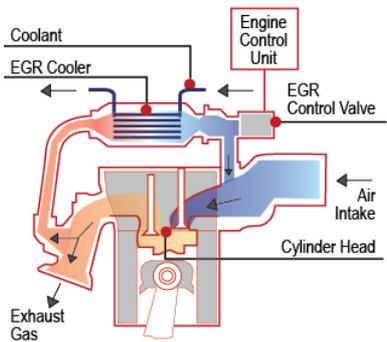
- Meeting EPA standards for NO<sub>x</sub> with little or no fuel economy penalty will be a key factor for market entry of advanced combustion engines.
- Improved efficiency and emission reduction in advanced combustion engines will require exhaust gas recirculation (EGR) to operate over a wider range of engine speed/load conditions.

## Partners

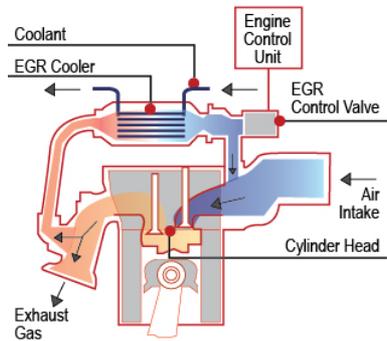
### All U.S. Diesel Engine Manufacturers:

- Caterpillar, Cummins, Detroit Diesel, Ford, GM, John Deere, Navistar, PACCAR and Volvo/Mack
- Modine Manufacturing
- Georgia Institute of Technology

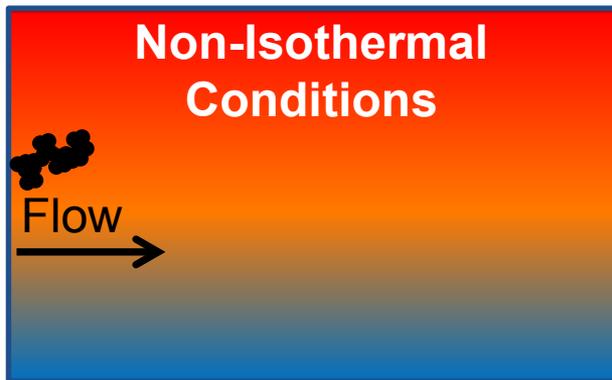
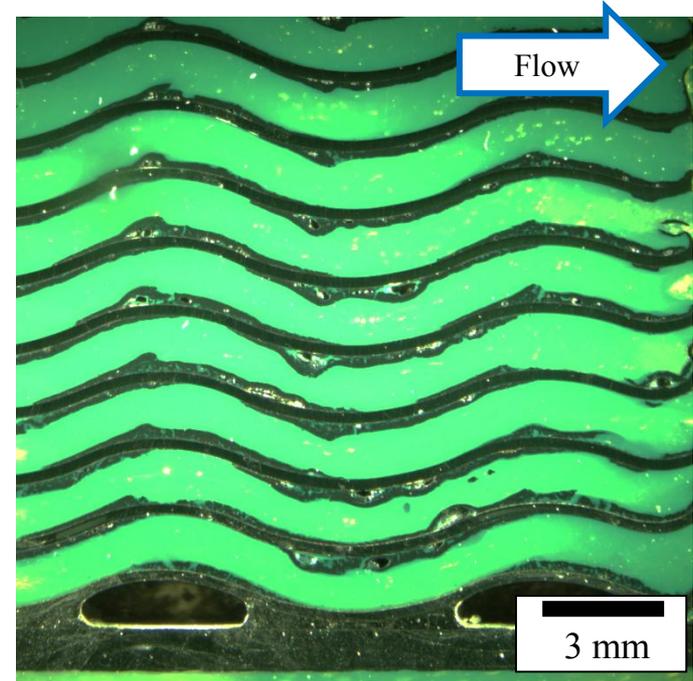
# Background: Exhaust Gas Recirculation Cooler Fouling Causes greater than 1% Loss of Brake Thermal Efficiency



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Industry-Provided Fouled EGR Cooler



- EGR cooler fouling occurs when the particulate matter (PM) and hydrocarbon (HC) in the exhaust gas deposits onto the walls of the EGR cooler through thermophoresis and condensation.
- The resulting deposit has a very low thermal conductivity which reduces the effectiveness of the EGR system.
- The deposit also narrows the channels which increases the back pressure.

# Relevance: Carbonaceous deposits are a perennial, industry-wide problem

- Deposits may be more problematic in the future because:
  - Low temperature combustion strategies will result in more hydrocarbon, exacerbating the problem of fouling and causing it to spread to other components, i.e., turbocharger, EGR valve.
  - Waste-heat recovery approaches will be hindered by fouling.
- This precompetitive research comes at the problem from a materials perspective in order to mitigate EGR cooler fouling and reduce its impact on efficiency and emissions by:
  - Characterizing the thermo-physical properties of the deposit under different operating conditions
    - Industry-provided late-stage deposits.
    - Early-stage deposits produced at ORNL.
  - Determining novel cooler geometries that will promote deposit removal.

# Milestones

## **Task Title (Agreement 9105)**

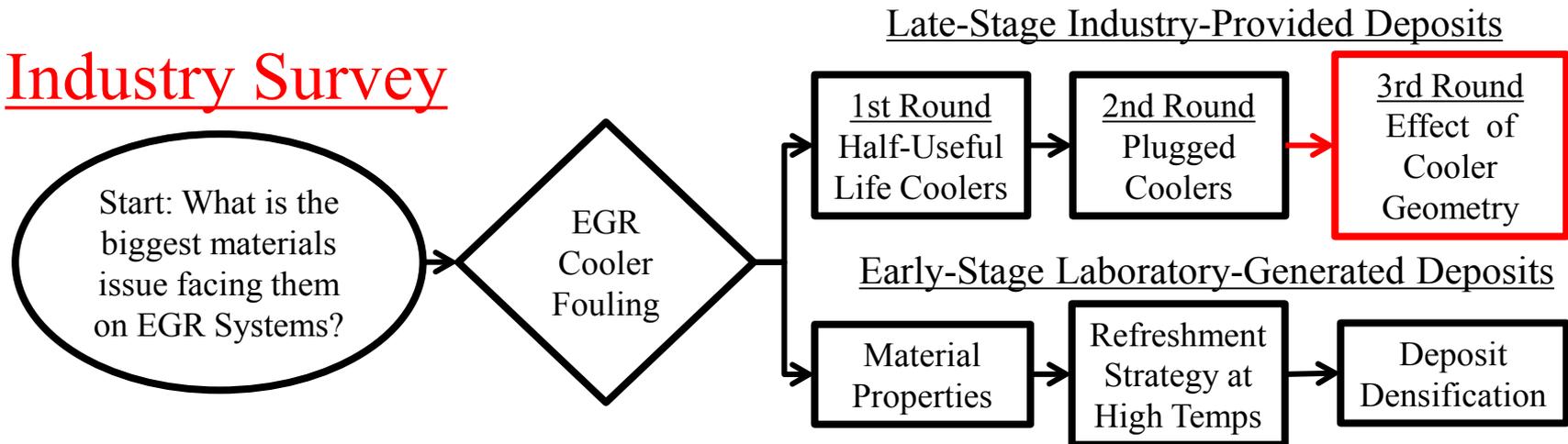
FY15Q3: Deposit thickness will be measured on cross-sectioned samples generated by John Deere at various engine set-points. (Completed)

FY15Q4: Submit annual report. (Completed)

FY16Q4: Measure deposit thickness variations on various EGR cooler designs provided by industry. (On track)

# Approach/Strategy

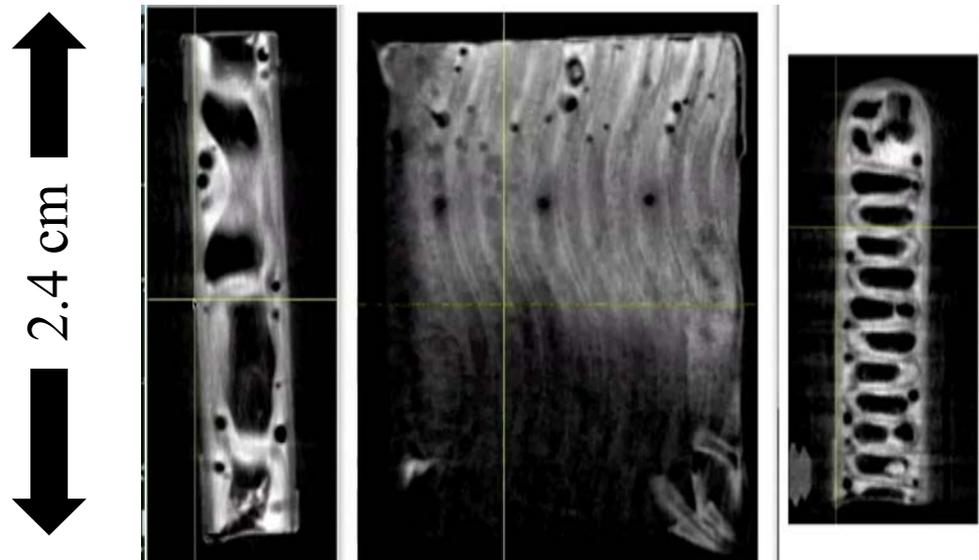
## Industry Survey



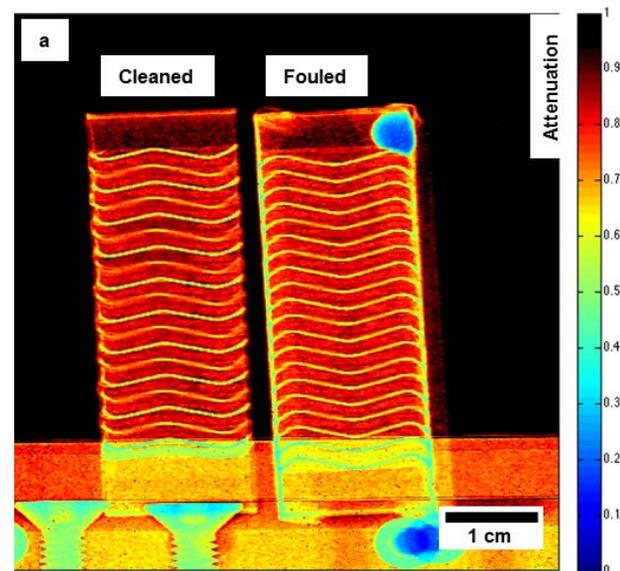
- Experimental Equipment for Deposit Formation and Aging
  - Ford 6.4-L engine to form deposits on model cooler tubes.
  - Portable gas-manifold with high temperature stage for in situ visualization of deposit morphological changes.
- Obtain Industry-Provided Coolers representing specific applications
  - Two rounds of forensic analyses of 22 fouled EGR coolers have been completed.
- Active Control: Explore Potential Refreshment Strategies
  - High-temperature spallation.
  - Low-temperature water condensation.
- **Passive Control: Investigate the role of cooler geometry on deposit removal.**

# Previous Accomplishment: Mixed results were achieved with neutron tomography for imaging the deposit non-destructively

Lacquer-like Deposit



“Dry” Deposit



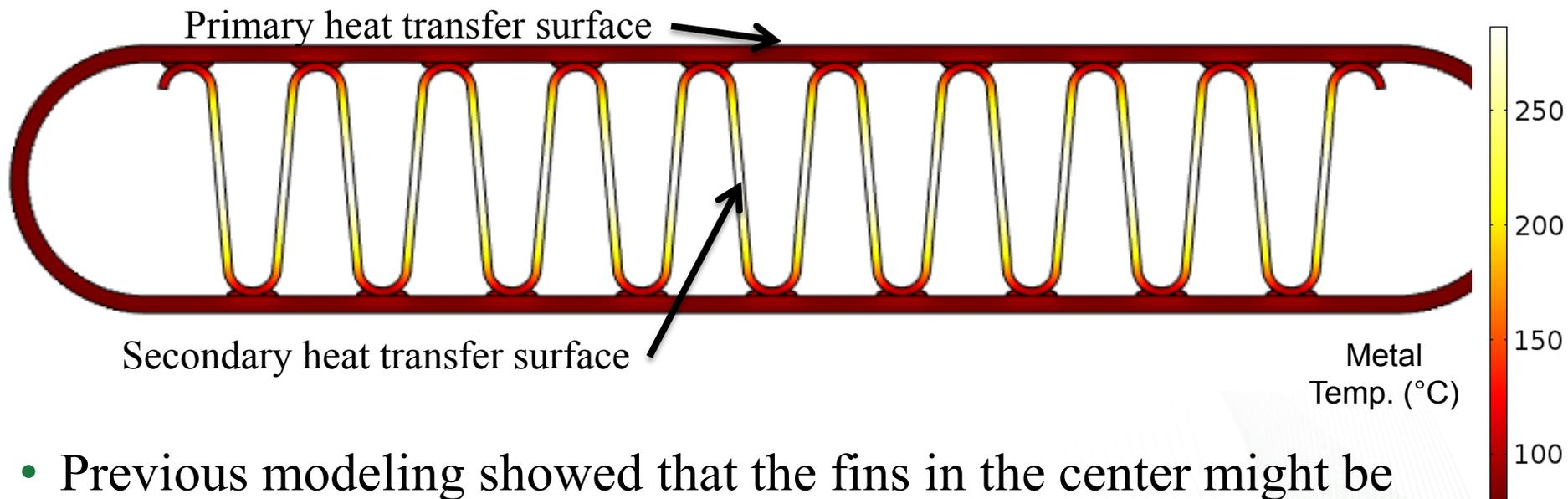
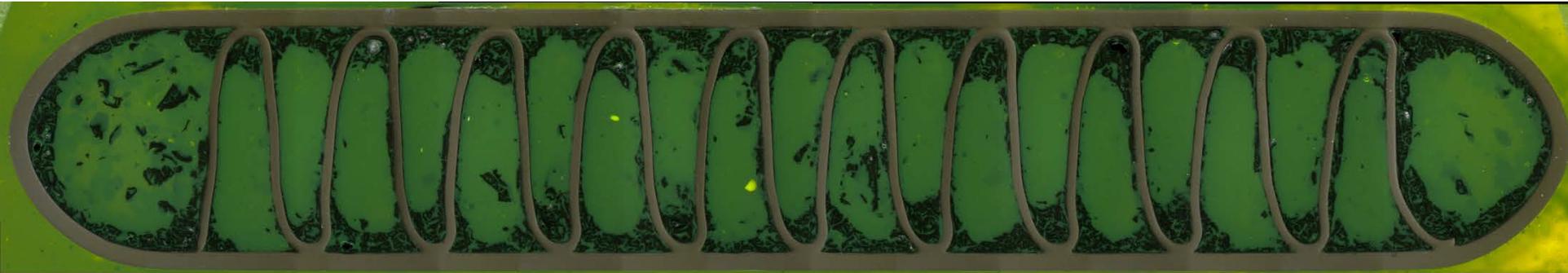
- Deposits that contained a lot of hydrocarbon could be imaged using neutron tomography but these deposits aren't affected much by the cooler geometry and are relatively rare.
- More common are deposits with low (<10 wt%) hydrocarbon which are greatly influenced by the cooler geometry but don't attenuate the neutron beam enough to be detected.
- Two new approaches for measuring deposit thickness have been developed in order to probe the interaction between deposition and cooler geometry.

# EGR coolers fouled by John Deere were used to determine how the cooler geometry influences deposition and removal.

Row #	EGR Rate (kg/h)	EGR Temp (°C)	Smoke (FSN)	Coolant Temp (°C)	HC (ppm)
1	300	350	0.5	85	75
2	300	350	0.5	100	25
3	300	350	2	85	25
4	300	350	2	100	75
5	300	550	0.5	85	25
6	300	550	0.5	100	75
7	300	550	2	85	75
8	300	550	2	100	25
9	550	350	0.5	85	25
10	550	350	0.5	100	75
11	550	350	2	85	75
12	550	350	2	100	25
13	550	550	0.5	85	75
14	550	550	0.5	100	25
15	550	550	2	85	25
16	550	550	2	100	75
17	425	450	1.25	92.5	50
18	425	450	1.25	92.5	50

- 18 coolers with a sinusoidal wave geometry were fouled using a 5-factor, 3-level design-of-experiments (DoE) with the following variables:
  1. EGR flow rate
  2. EGR inlet gas temperature
  3. Soot (PM) level (Smoke)
  4. Hydrocarbon (HC) concentration.
  5. Coolant temperature

# Technical Accomplishment: Variations in the deposit thickness were observed across the tube width.



- Previous modeling showed that the fins in the center might be hotter than the outer surface which is in contact with the coolant.

# Technical Accomplishment: Epoxy-mounted cross-sections were imaged and the deposit thickness was measured.

Samples were cut and mounted in epoxy to show the cross-section of the EGR tube. A fluorescent dye was added to the epoxy to enhance the contrast with the deposit.

The image was thresholded to measure the areas of empty space and deposit for each sample.

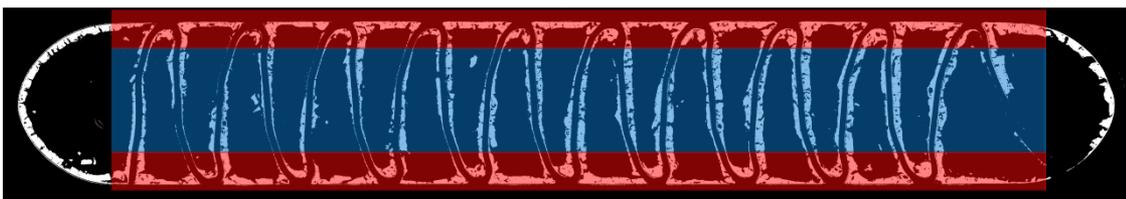
The deposit area on the primary surface (**outer tube**) was then separated from the deposit area on the secondary surface (**inner fins**).



Original image.

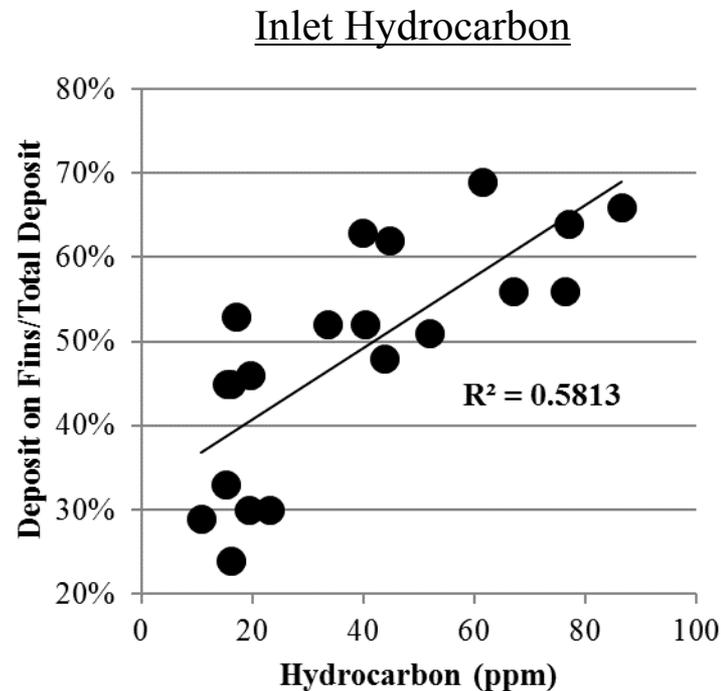
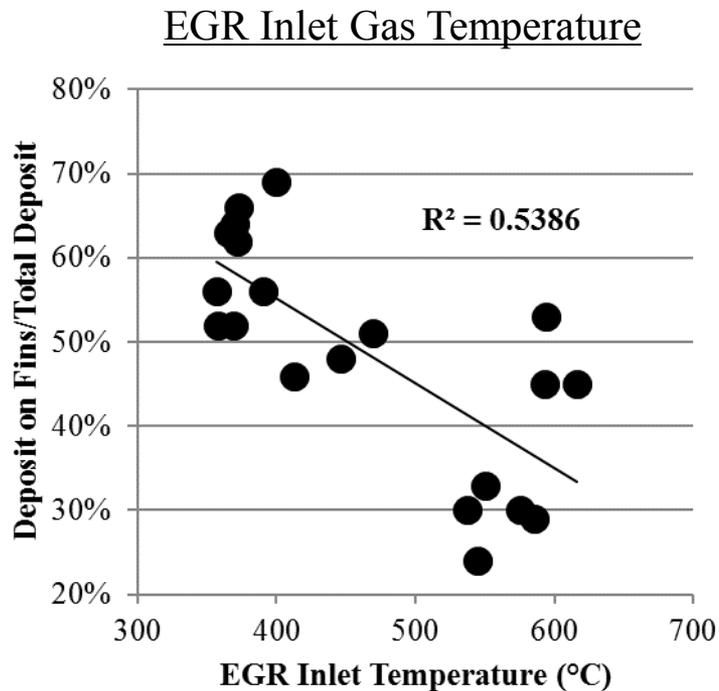


Total empty space thresholded.



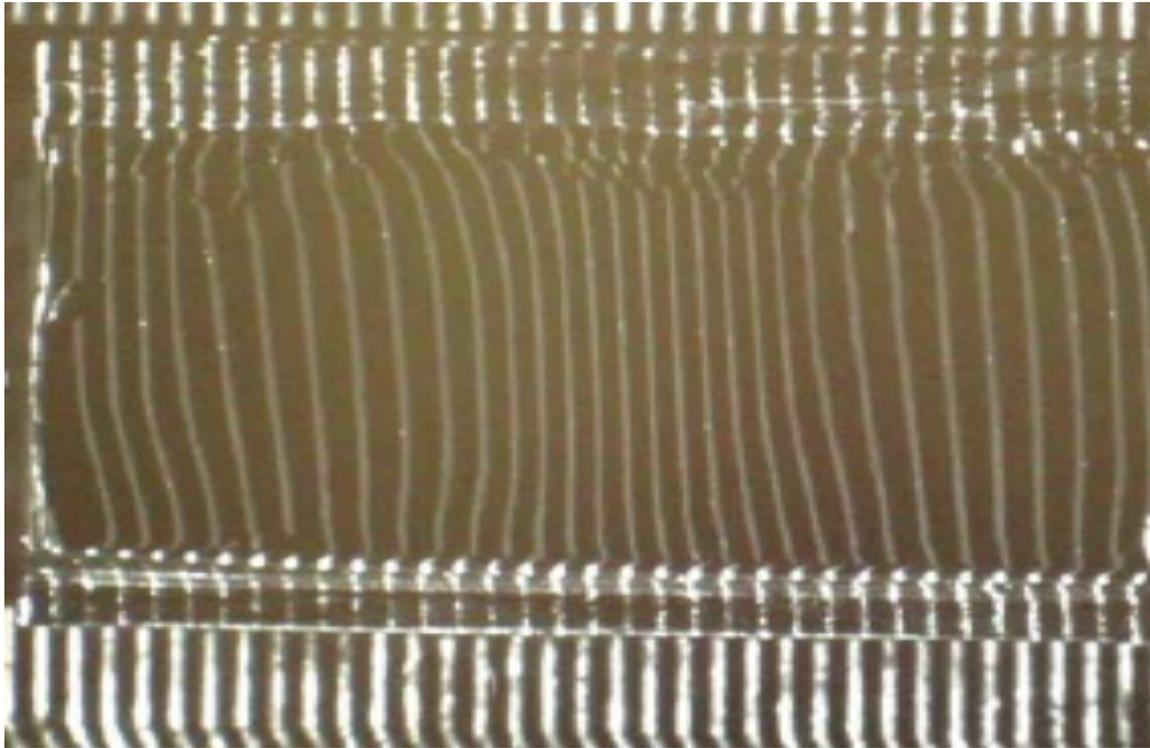
Deposit thresholded.

# Technical Accomplishment: Two engine operating conditions strongly influenced how much deposit formed on the fins.

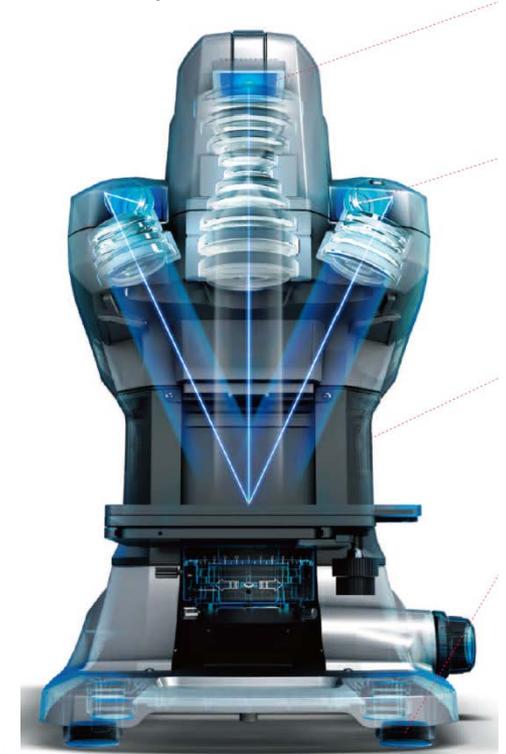


- At low inlet gas temperatures, the deposit thickness was uniform throughout. At high inlet gas temperatures the deposit is thinner on the fins due to higher metal wall temperatures which reduces thermophoresis.
- Increasing the inlet hydrocarbon content may enhance the stickiness of the metal fin causing an increase in the deposit thickness.

Technical Accomplishment: A new optical profilometer was used to collect 3D images of the undisturbed deposit surface.



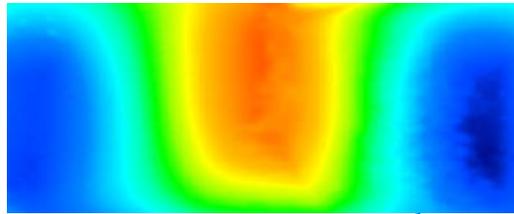
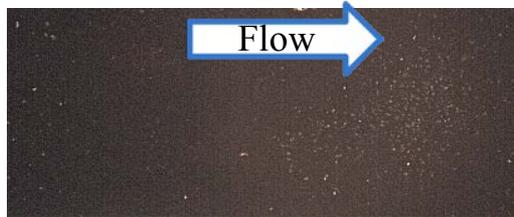
Keyence VR-3000



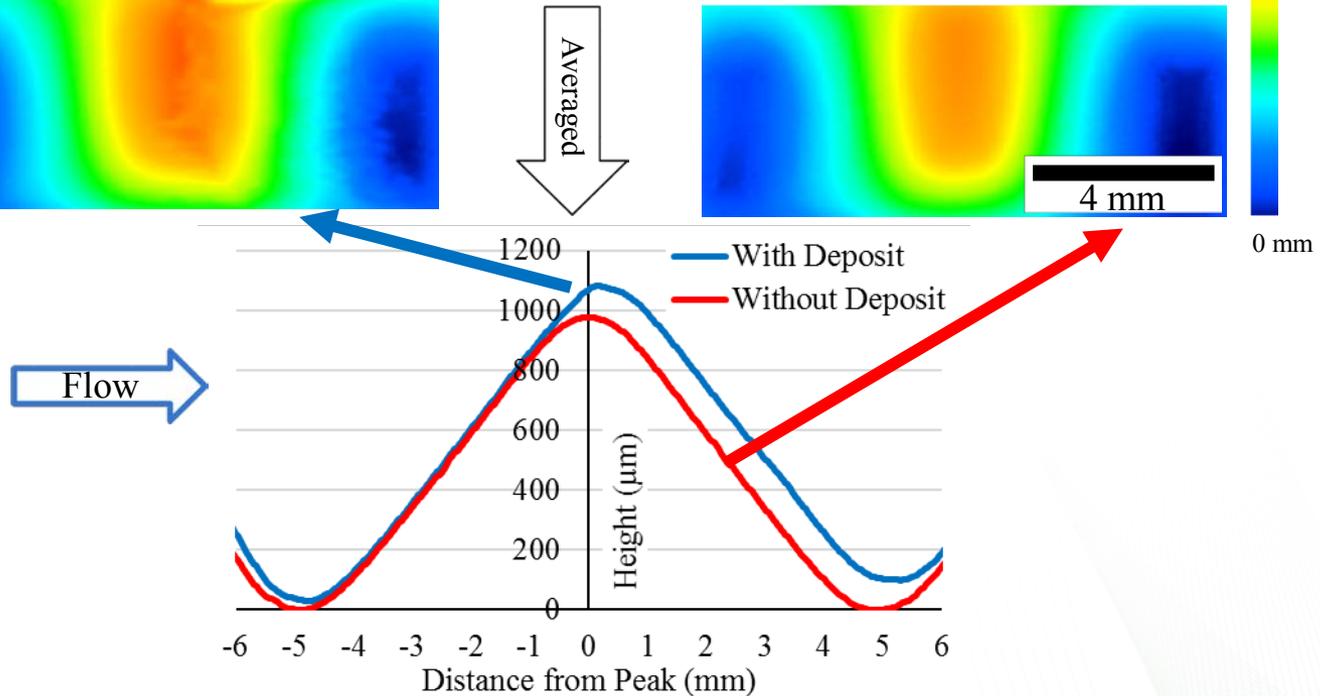
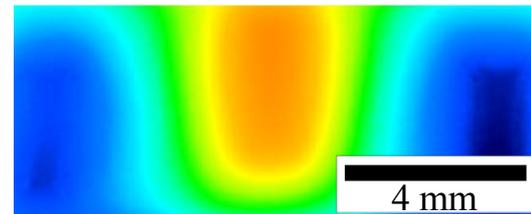
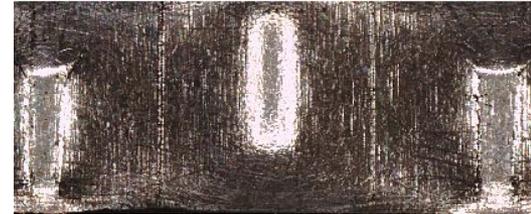
- “Structured” light is illuminated on the surface and the microscope uses trigonometry to calculate surface height to a  $\sim 1 \mu\text{m}$  resolution.

# Technical Accomplishment: Collecting 3-D images before and after the deposit is removed allowed for the measurement of thickness with respect to the fin geometry.

Before deposit removal



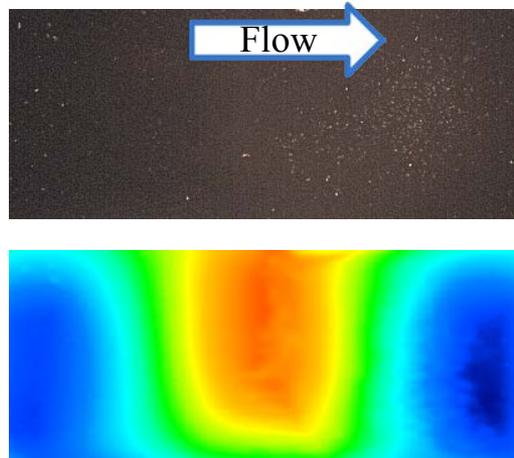
After deposit removal



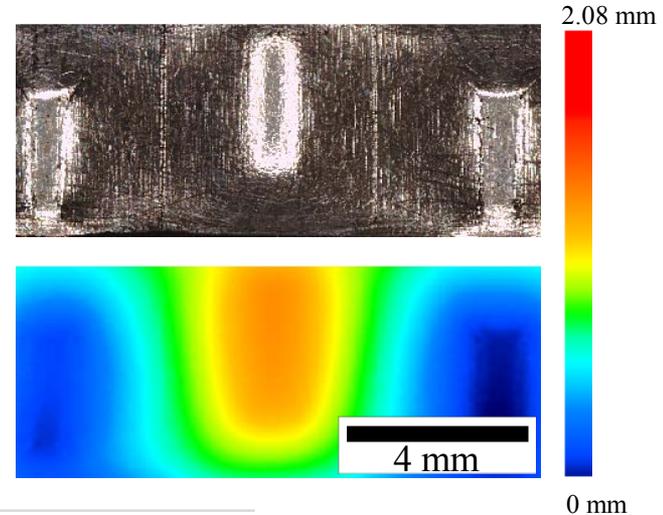
- The true deposit thickness is determined across one entire wavelength of the fin.

# Technical Accomplishment: Collecting 3-D images before and after the deposit is removed allowed for the measurement of thickness with respect to the fin geometry.

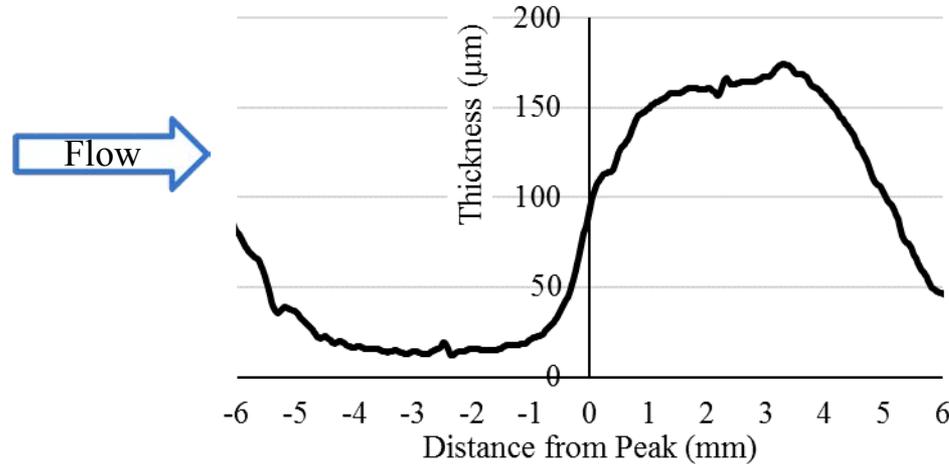
Before deposit removal



After deposit removal

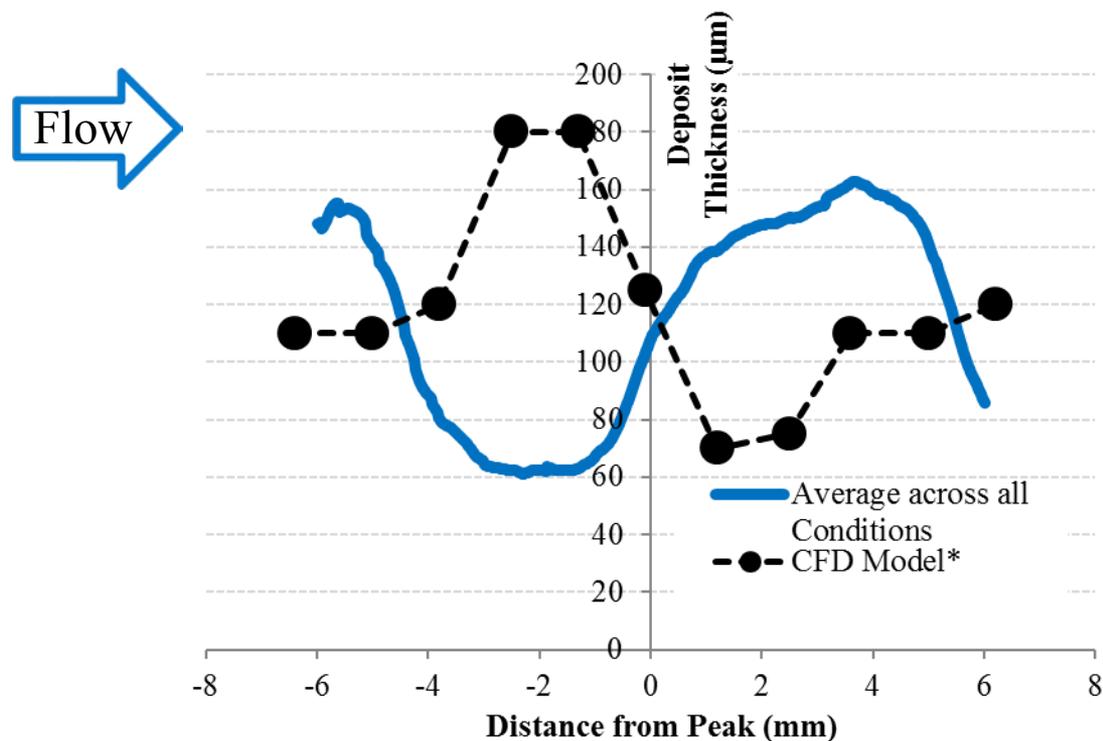


Averaged



- The true deposit thickness is determined across one entire wavelength of the fin.

## Technical Accomplishment: Thickness measurements contradicted the predicted location of deposits based on CFD modeling.

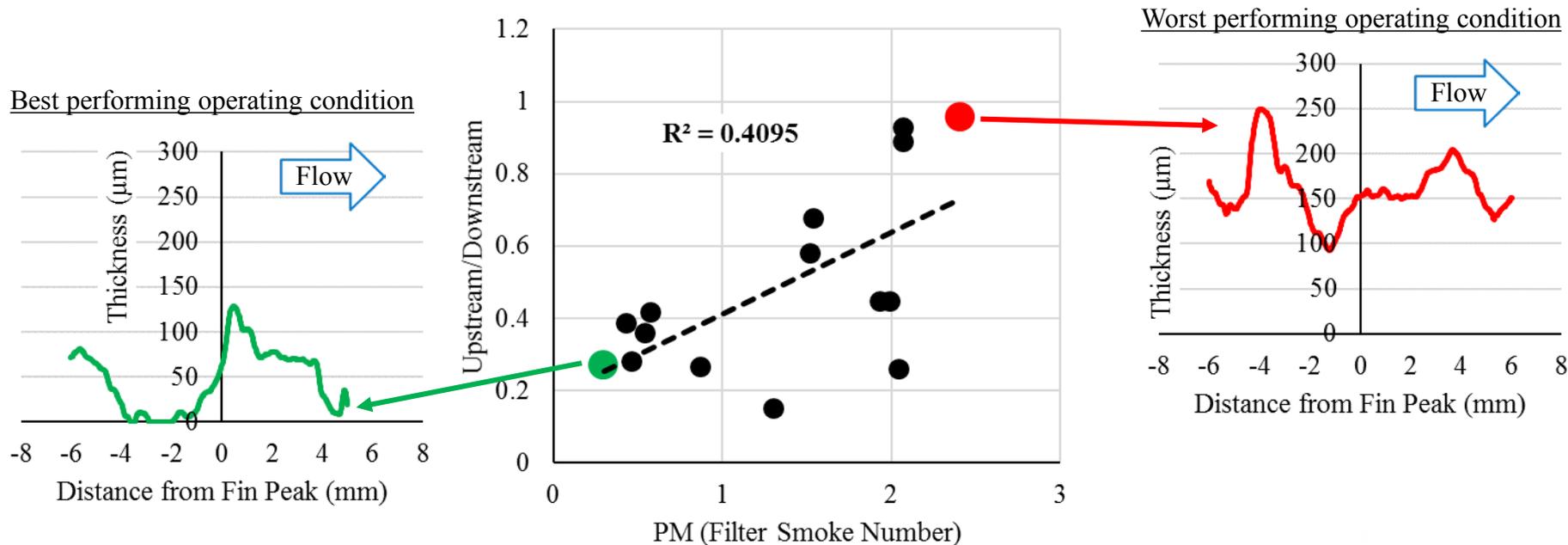


\*Nagendra, K., et al., "Modeling of soot deposition in wavy-fin exhaust gas recirculator coolers," *Int. J. Heat and Mass Transfer* **54**(7-8):1671-81 (2011).

- Modeling shows that the exhaust gas impacts the upstream side of the fin leading to a thin boundary layer which increases the temperature gradient and hence thermophoretic deposition of PM.
- However, the exhaust gas also creates shear forces on the upstream side of the fin which may lead to lower deposition rates and deposit removal. This was not considered in the CFD model.
- These first ever measurements of deposit thickness on real-world coolers show the importance of considering shear forces and their interaction with cooler geometry in EGR cooler fouling.

# Technical Accomplishment: The PM level was the only engine operating condition that significantly affected the deposit location along the flow direction

## Thickness on upstream side/thickness on downstream side



- The downstream migration of the deposit was determined by taking the ratio of the deposit thickness on the upstream side by the downstream side.
- The lowest PM condition had almost no deposit on the upstream side of the fin showing that fouling had hardly occurred there. This cooler also had the lowest pressure drop and highest heat transfer (best performing).
- The deposit that formed under the highest PM condition was uninfluenced by the sinusoidal wave of the fin which shows that with enough soot in the exhaust, the deposition rate exceeds the removal rate and fouling will proceed in an uncontrolled manner. This cooler had the highest pressure drop and lowest heat transfer (worst performing).

# Responses to Previous Year Reviewers' Comments

Comment: “the CFD model will have to be improved to properly model and correlate deposit location and thickness. The reviewer further noted that cooler geometry is not one of the listed variables.”

Response: We have started a collaboration with Georgia Tech and GM that will utilize our results to guide their CFD modelling efforts. Also, industry-provided coolers with different geometries will be studied in the future.

Comment: “the reviewer suggested examining other geometric parameters, turbulence behavior and temperature gradient/dynamic change with time and along the structure.”

Response: Work presented above studied the effect of temperature gradient on fouling using epoxy-mounted samples. Future work will look at different cooler geometries provided by the EGR materials advisory team.

Comment: “The reviewer speculated that the project's dependence on field samples with limited exploration of the impacts of engine operating factors may be a limitation on understanding all aspects of this phenomenon.”

Responses: The samples from John Deere provided a full design-of-experiments to study the effects of varying engine operating factors on EGR fouling.

# Collaborations: EGR Materials Advisory Team

- The EGR team continue to advise the project and provide real-world coolers:
  - Caterpillar, Cummins, Detroit Diesel, Ford, GM, John Deere, Navistar, PACCAR, Volvo/Mack.
- John Deere: Ran engine tests that resulted in fouled EGR coolers.
- General Motors and Georgia Institute of Technology: Computational fluid dynamics modeling of deposit formation and removal.

# Remaining Challenges and Barriers

- Designing a better cooler geometry that will promote deposit removal requires a comparison of our measurements to CFD modeling.
- Cooler geometries other than the sinusoidal fin need to be measured in order to better understand the best geometry for enhancing deposit removal.

# Future Work

- A collaboration with General Motors and the Georgia Institute of Technology has started and will lead to recommendations for improved EGR cooler design by incorporating deposit removal into CFD models using our measurements as inputs.
- Coolers donated by industry will be revisited and the deposit thickness measured. These coolers have a variety of designs including segmented fins, spiral tubes, and stamped winglet designs which will provide a broad range of cooler geometries to compare to the sinusoidal fin studied here.

# Summary

## Relevance

EGR fouling results in  $>1\%$  loss in brake thermal efficiency and may hinder high efficiency engine strategies like low temperature combustion and waste heat recovery.

## Approach

Measure deposit thickness relative to the underlying cooler geometry to understand how the geometry may be altered to promote deposit removal.

## Technical Accomplishments and Progress

As inlet gas temperatures increase, the fins become hotter than the coolant resulting in less heat transfer but also less deposit formation. Much of the EGR cooler surface area may be well above the coolant temperature.

Deposit thickness measurements contradicted CFD modeling illustrating the central importance of shear forces and cooler geometry in fouling.

Operating conditions that generate high levels of PM will overwhelm beneficial effects the cooler geometry has on deposit removal.

## Collaboration

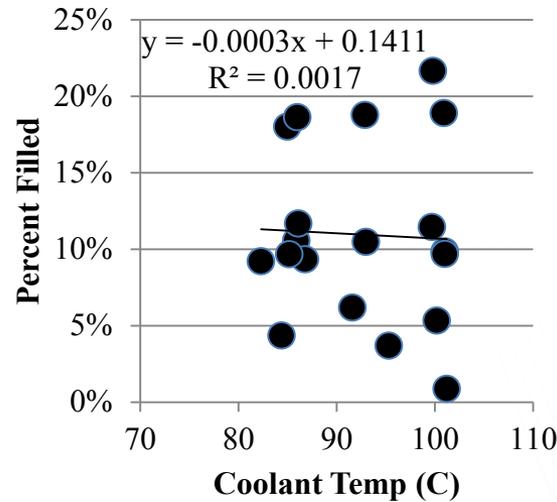
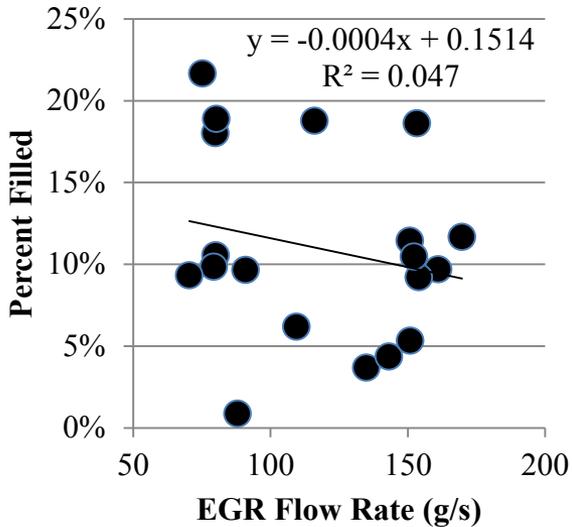
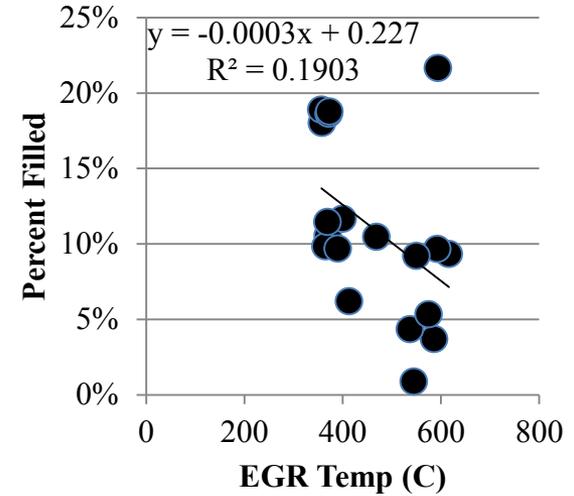
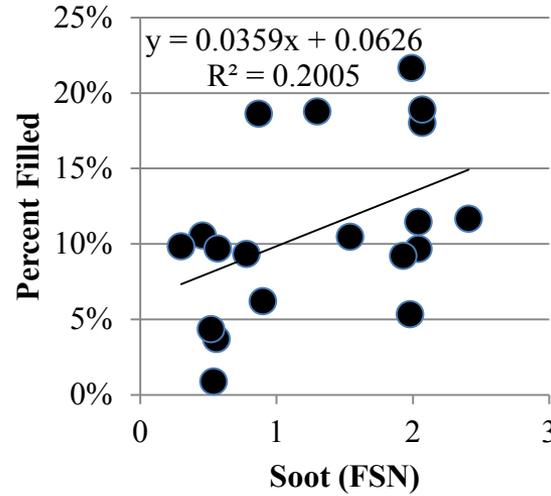
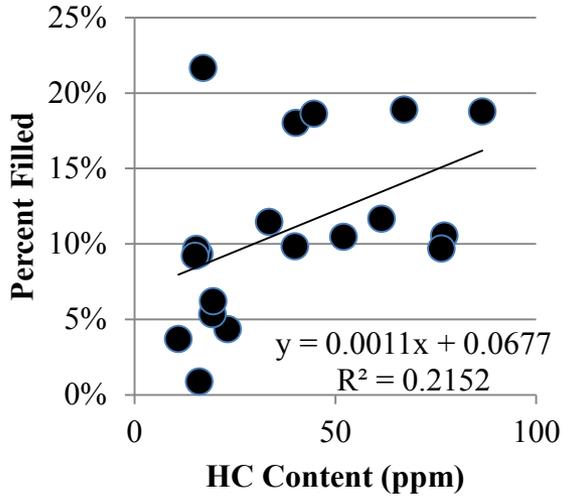
With entire diesel engine community; leveraging their in-kind investments of expertise, testing and materials.

## Proposed Future Work

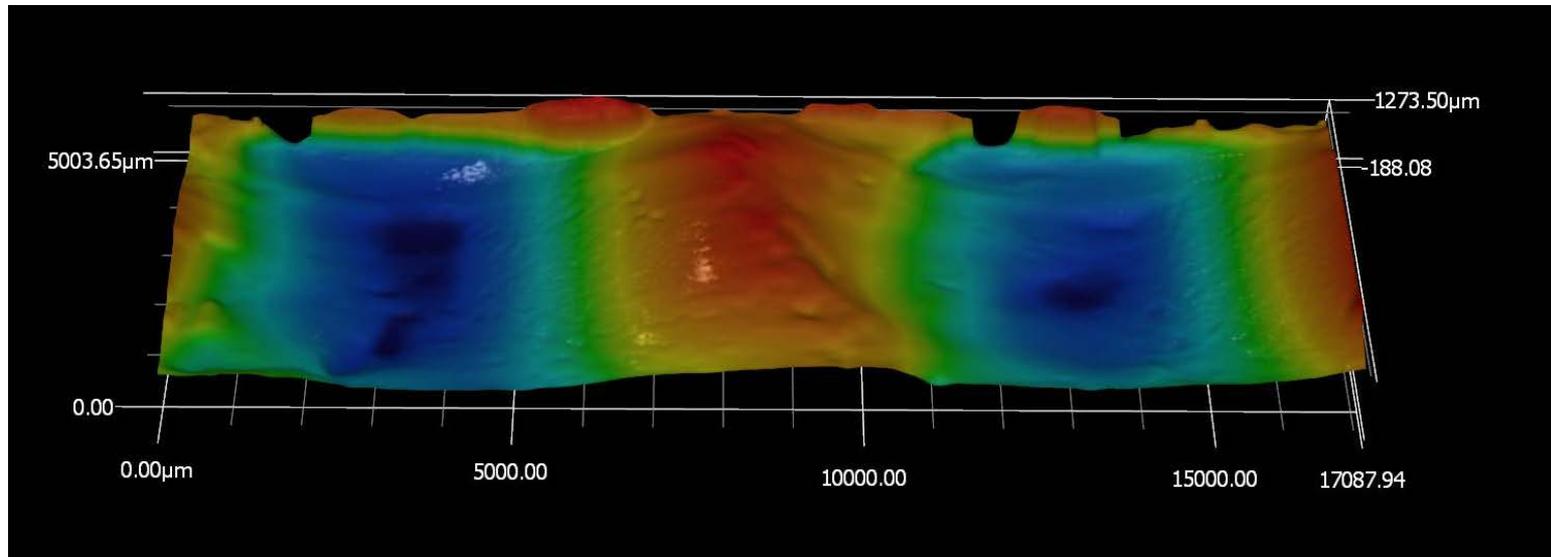
Determine optimal cooler geometry for deposit removal using CFD with GM and Georgia Tech.

# Technical Back-Up Slides

# Technical Accomplishment: Higher HC and Soot increased the total thickness of the deposit.

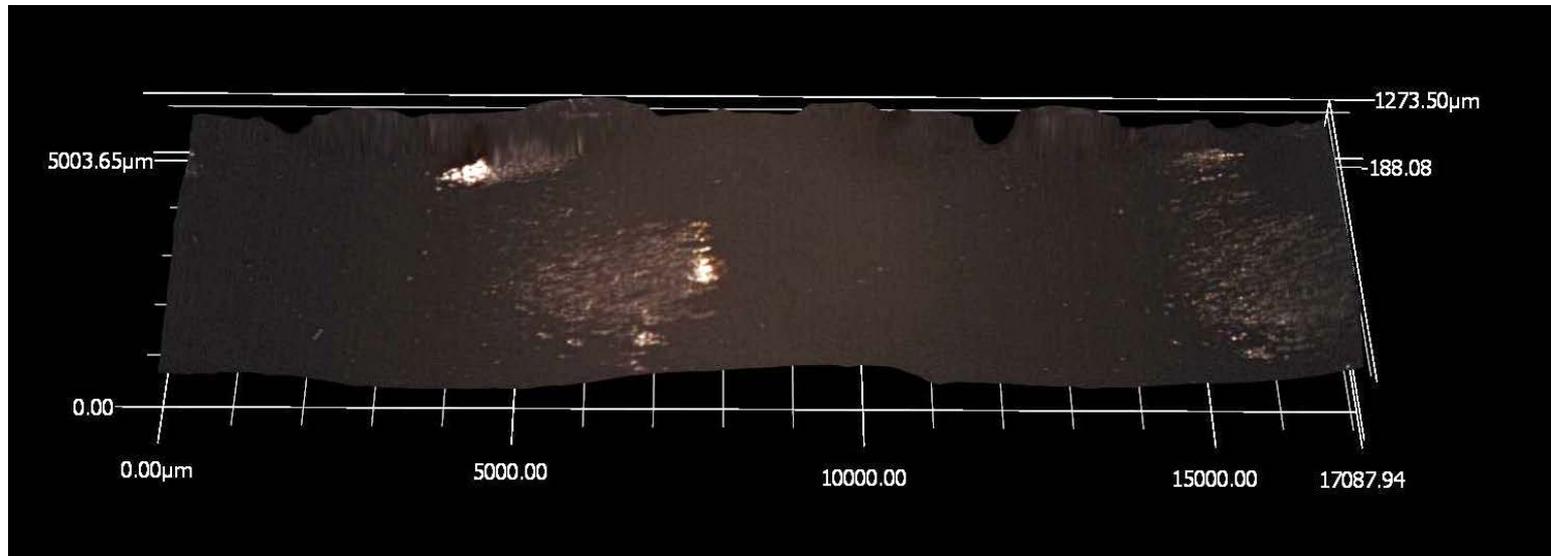


Technical Accomplishment: On the upstream side of the peak there are grooves in the deposit that indicate shear removal has occurred



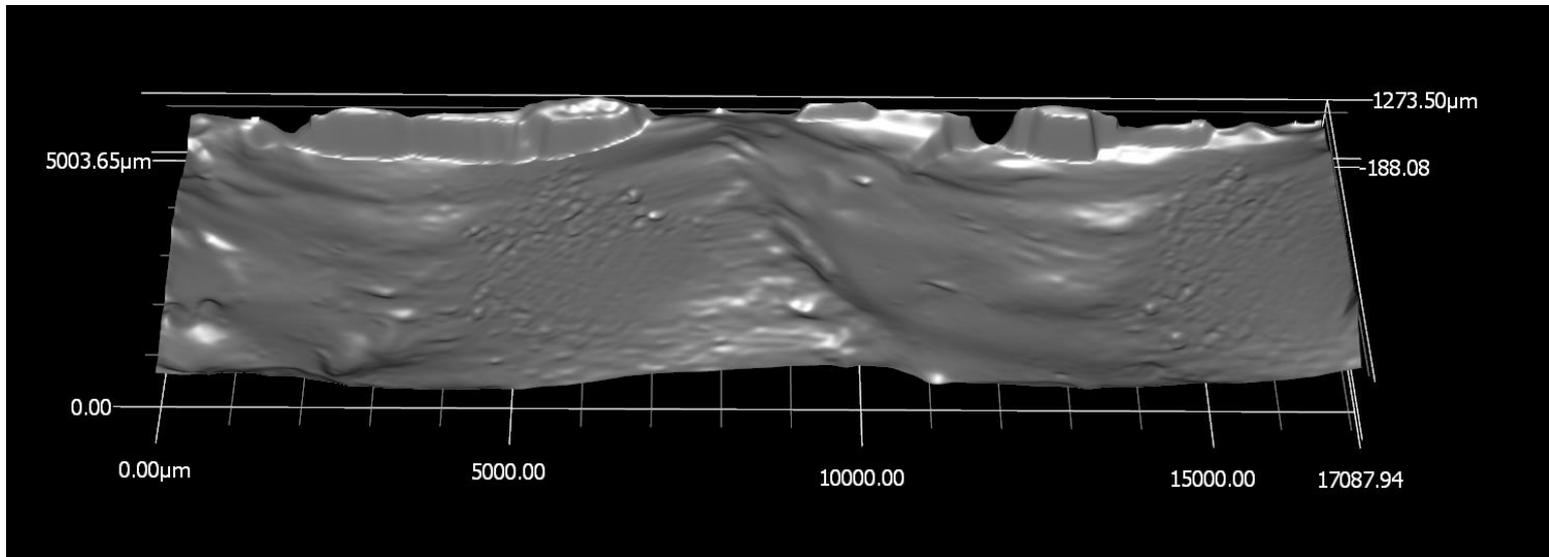
- The highest heat transfer occurs at the upstream side of the peak where the boundary layer is the thinnest. The CFD model also predicted that the thin boundary layer will result in the most deposition.

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