Materials Issues Associated with EGR Systems

Michael J. Lance, C. Scott Sluder, John M.E. Storey and Hassina Bilheux

Oak Ridge National Laboratory

June 20th, 2014

PM009

Overview

Timeline

- Start: FY09
- End: FY16
- 68% complete

Budget

- Total Project Funding
  - DOE-$1960 K
- Funding received:
  - FY12: $360K
  - FY13: $170K
  - FY14: $160K

Barrier
(Multi-Year Program Plan)

- Meeting EPA standards for NOx 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.

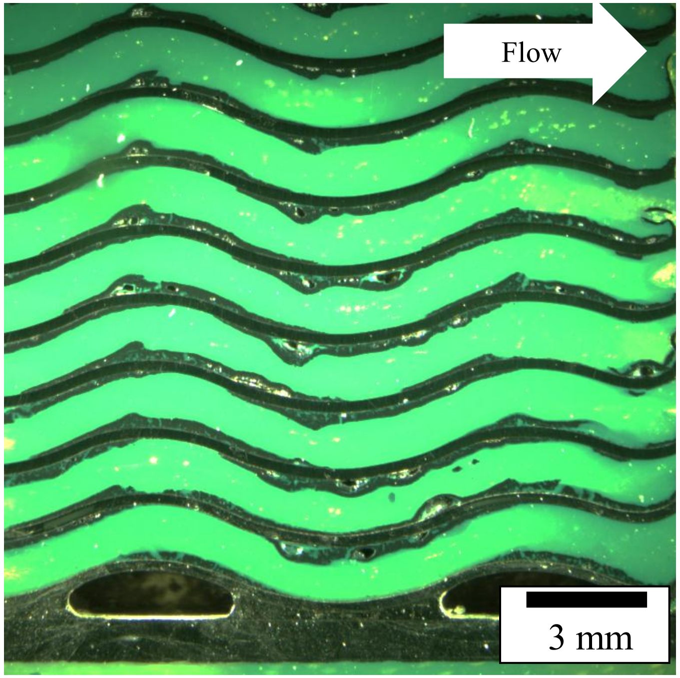
Partners

All U.S. Diesel Engine Manufacturers:

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

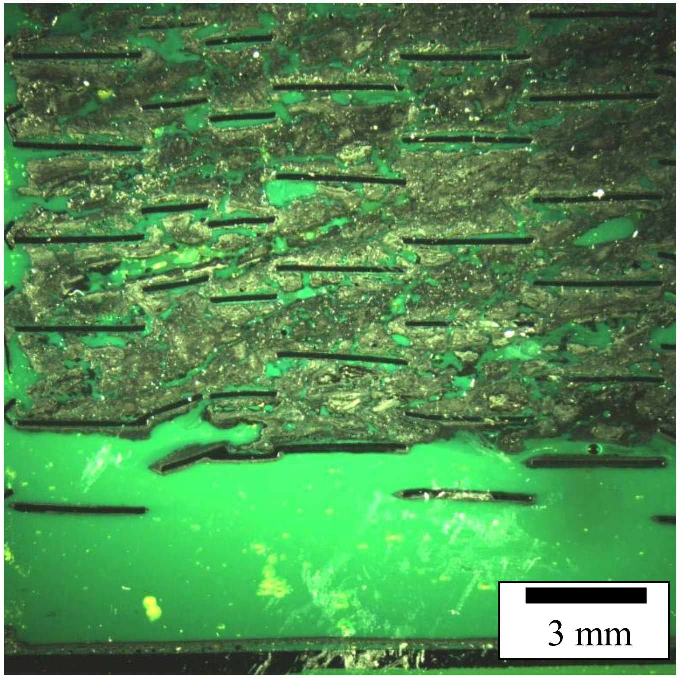
Exhaust Gas Recirculation Cooler Fouling Causes at least 1% Loss of Brake Thermal Efficiency

<u>Stabilized Effectiveness Loss</u>



- 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.

<u>Loss of Flow (Plugging)</u>



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

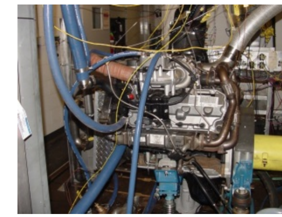
Relevance: Soot/HC deposits are a perennial, industry-wide problem

- This precompetitive research comes at the problem from a materials perspective seeking to measure the properties of real-world deposits as well as changes in laboratory-generated deposits under different operating conditions.
- Future low temperature combustion strategies will result in more PM, exacerbating the problem and causing it to spread to components that haven't had an issue so far (turbocharger).
- Waste-heat recovery approaches will be hindered by fouling.

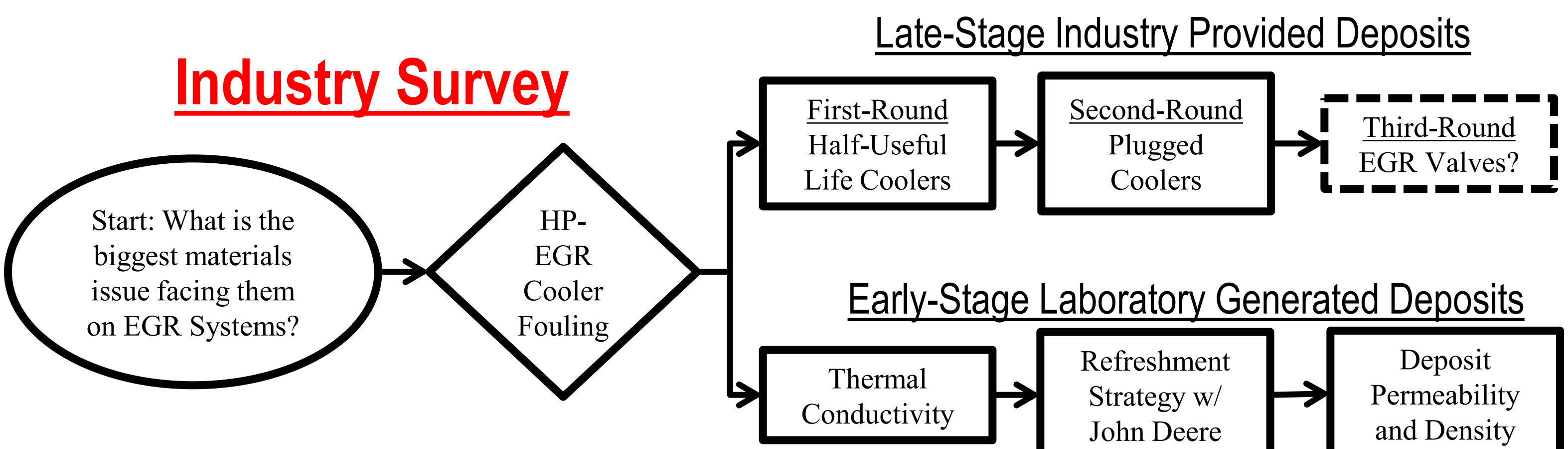
Objective: To mitigate EGR cooler fouling and reduce its impact on efficiency and emissions

- Characterize the thermo-physical properties of the deposit under different operating conditions
  - Early-stage deposits produced at ORNL.
  - Industry-provided late-stage deposits (3rd round requested).

Ford 6.4L



- Develop a protocol for refreshing the EGR cooler during use.
- Determine cooler geometries that will promote deposit removal.



FY14 Milestones

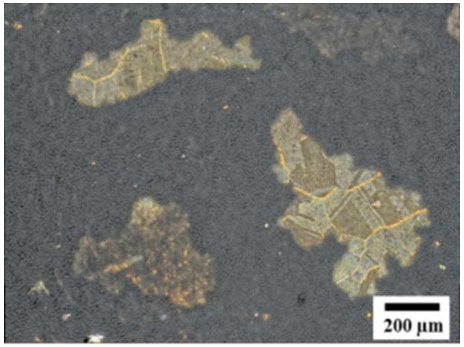
Task Title
Q1: Establish digital image correlation (DIC) methodology for *in situ* tracking changes in deposit morphology (COMPLETED)
Q2: Submit and present two SAE Papers (COMPLETED)
Q3: Manufacture porous aluminum tubes and foul them using our tube sampling system and Ford 6.4L engine at NTRC. (ON TRACK)
Q4: Measure permeability of the deposit using at least two different gases (air and cetane). Measure deposit density changes caused by temperature and water condensation under controlled conditions

Approach

- **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 have been completed.
- **Active Control: Explore Potential Refreshment Strategies**
  - Low-temperature water condensation.
  - High-temperature spallation.
- **Passive Control: Investigate the role of cooler geometry on deposit removal.**

Published Work from 2013 on Stabilized Effectiveness Loss

EGR Cooler Refreshment with John Deere



Deposit spallation occurred with high inlet gas temperatures and high flow rates

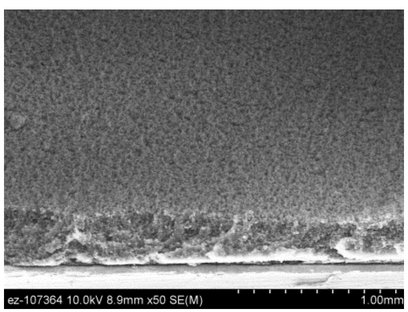
Lance, M.J., Watkins, B.R., Kaiser, M., Ponnaiyan, A., Storey, J.M.E., Sluder, C.S., "Microstructural Analysis of Deposits on Heavy-Duty EGR Coolers," SAE Technical Paper 2013-01-1288.

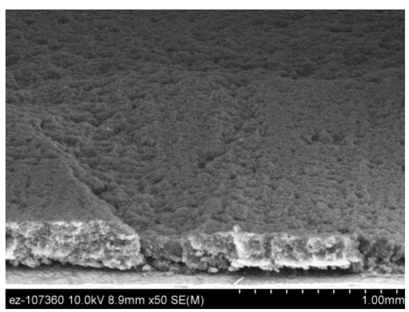
Surface Treatments did not Reduce Fouling

Tube type	Mass gain, mg/cm^2	Effectiveness loss, %
Plain 316 SS	0.598	16.7
Polished SS	0.598	17.9
Al_2O_3-BN	0.601	19.5
Ni-Teflon®	0.600	19.4
SiO_2-Si-O	0.303	16.9

Storey, J.M.E., Sluder, C.S., Lance, M.J., Styles, D.J., Simko, S.J., "Exhaust Gas Recirculation Cooler Fouling in Diesel Applications: Fundamental Studies of Deposit Properties and Microstructure," *Heat Transfer Engineering* **34** [8-9] 655-664 (2013).

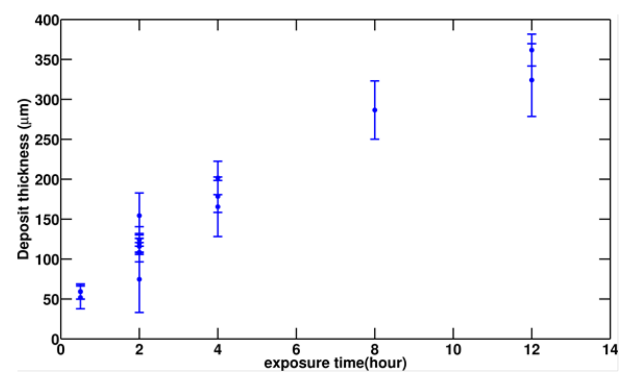
Deposits were Removed on Flat Tubes only at Unacceptably High Flow Rates





Sluder, C.S., Storey, J.M.E., Lance, M.J. and Barone, T.L., "Removal of EGR Cooler Deposit Material by Flow-Induced Shear," *SAE Int. J. Engines* **6** [2] (2013).

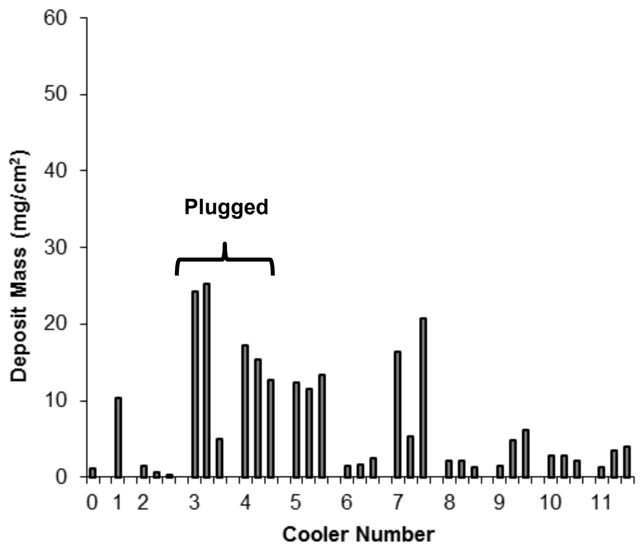
CFD Analysis of Deposition with Ford



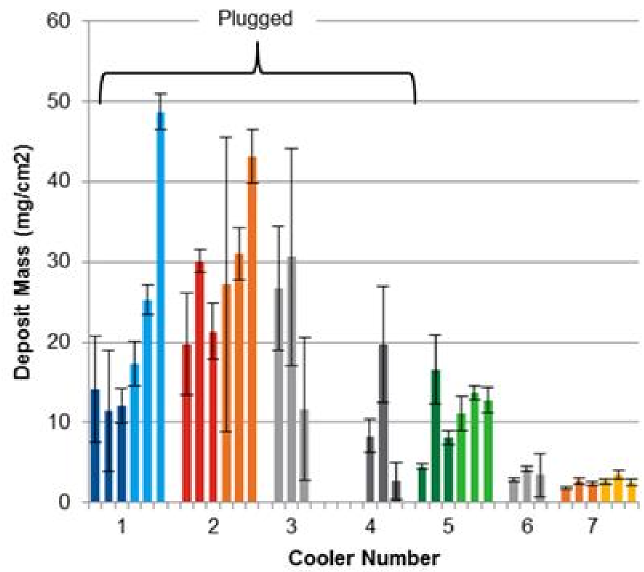
Abarham, M., Zamankhan, P., Hoard, J.W., Styles, D., Sluder, C.S, Storey, J.M.E., Lance, M.J., Assanis, D., "CFD Analysis Of Particle Transport In Axi-Symmetric Tubes Under the Influence of Thermophoretic Force," *Int. J. Heat & Mass Trans.* 61 (2013) 94–105.

Technical Accomplishment: The deposit mass/area was higher in the second round of coolers provided by industry

First Round of Coolers
SAE Paper 2010-01-2091



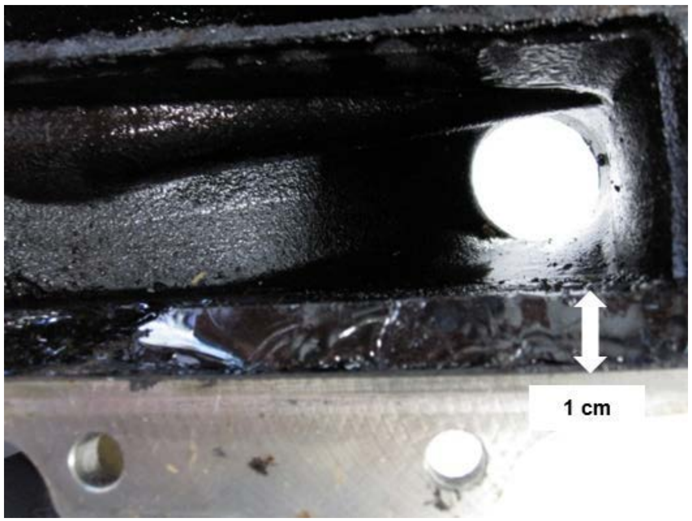
Second Round of Coolers
SAE Paper 2014-01-0629



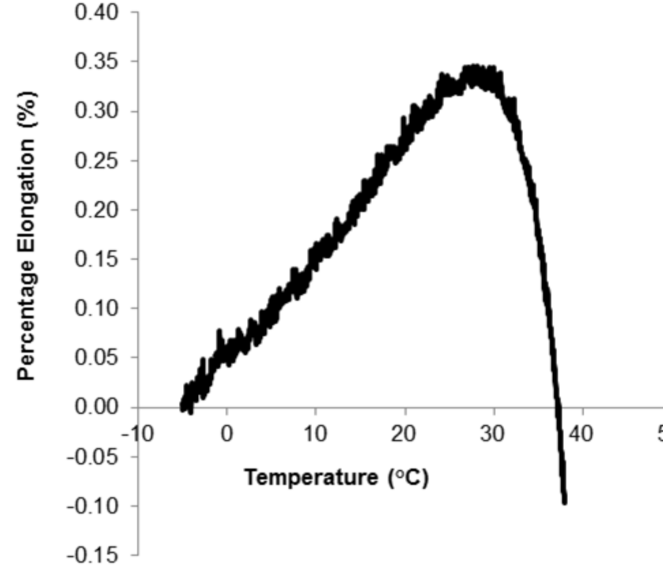
- Coolers representing specific applications known to be problematic for EGR coolers were requested for the second round.
- Coolers run on duty cycles similar to school buses/delivery trucks arrived. These tended to produce the plugging failure mode.

Large amounts of lacquer deposit from cooler #1 permitted a deeper dive into its material properties

Outlet Diffuser



Thermo-Mechanical Analysis (TMA)



- Deposit resulted from a 65 hour test of EGR valve sticking where the EGR valve and throttle were forced open and the engine run at low idle with retarded injection timing.
- Disks with a diameter of 1 cm and 2 mm thick were machined from the deposit.
- Lacquer deposit starts to soften around room temperature.

Technical Accomplishment: Thermal Properties of Two EGR Deposits

$$k = \alpha \rho C_p$$

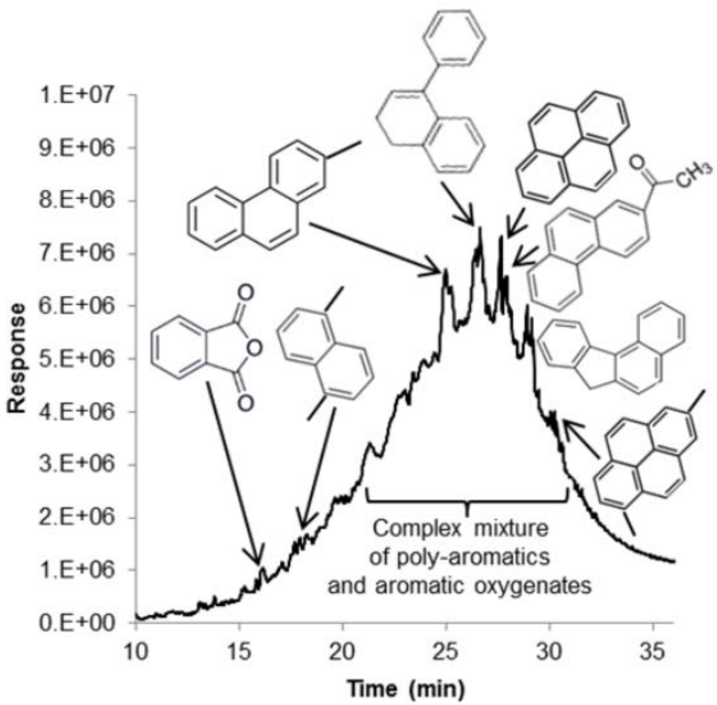
	Thermal Diffusivity	Density	Specific Heat Capacity	Thermal Conductivity
Deposit	α (cm^2/s)	ρ (g/cm^3)	C_p (J/gK)	k (W/mK)
Lacquer	0.0011	1.176±0.004	1.589	0.202
PM	0.014±0.006	0.035±0.003	0.851±0.030	0.041±0.014

Lance, M.J., Sluder, C.S., Wang, H., and Storey, J.M.E., "Direct Measurement of EGR Cooler Deposit Thermal Properties for Improved Understanding of Cooler Fouling," SAE Technical Paper 2009-01-1461

- Lacquer deposit was 34 times denser than a “stabilized” PM deposit.
- This caused the thermal conductivity to be 5 times higher which keeps the surface cooler allowing more HC condensation and PM deposition which eventually leads to plugging.

Technical Accomplishment: Unique ORNL characterization tools determined the chemistry of lacquer deposits

<u>Pyrolysis GC-MS at ORNL</u>

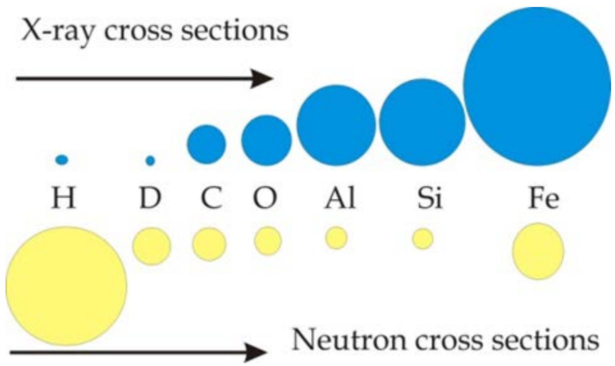


- Peaks are variants of 2 to 4-ring PAHs and oxygenated PAHs.
- Resinification of phenols through contact with formaldehyde.
- High amounts of NOx will produce nitric acid which acts as a catalyst.
- Recommendation: Dew point of HC is critical. EGR walls must be held at temperatures above dew points.

Lance, M.J., Storey, J.M.E., Lewis, S.A., and Sluder, C.S., "Analysis of Lacquer Deposits and Plugging Found in Field-Tested EGR Coolers," SAE Technical Paper 2014-01-0629.

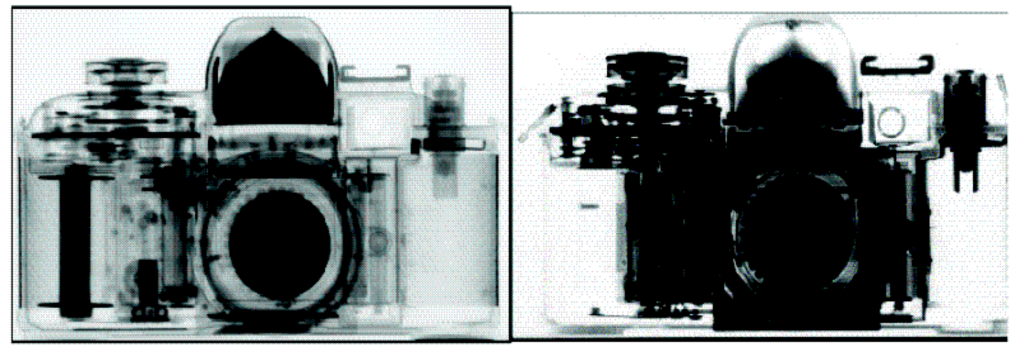
Rationale for using Neutrons to Visualize EGR Deposits

Attenuation of Various Elements



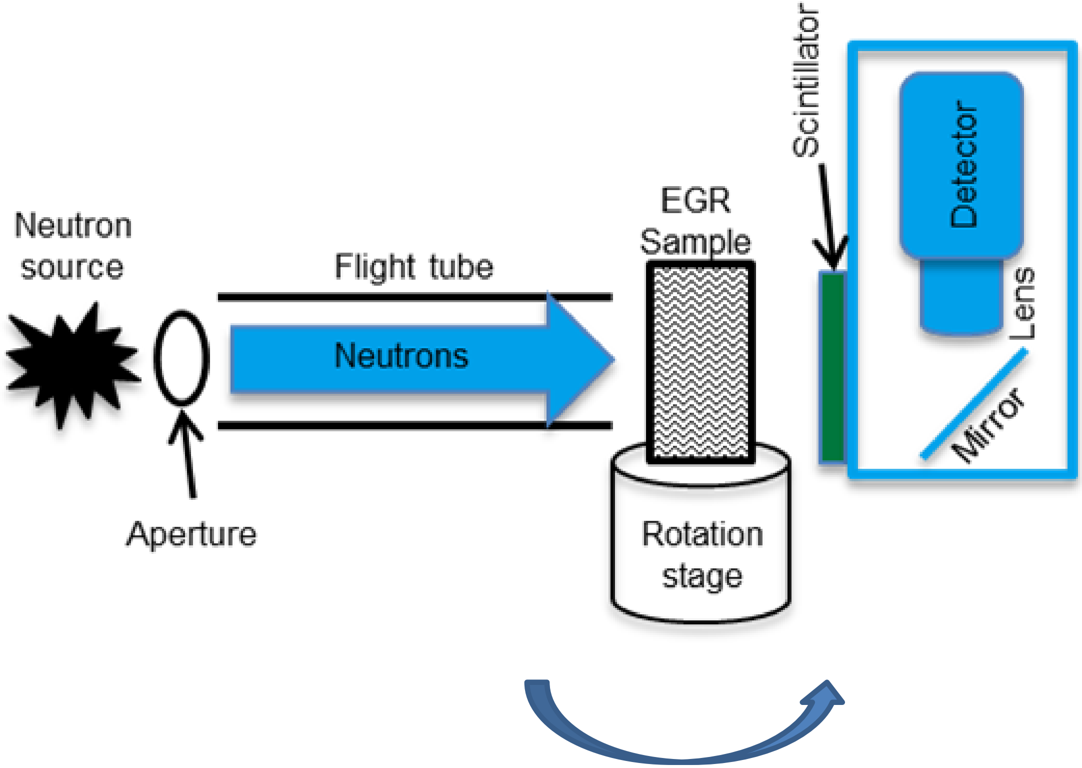
Courtesy of E. Lehmann,PSI

Neutron *Radiograph of camera* **X-ray** *Radiograph of camera*



- Soot deposits are very soft making deposit visualization difficult.
- Neutrons easily pass through metals but are attenuated by hydrogen.
- Deposit thickness and removal is greatly dependent on the complex internal EGR cooler geometry.
- Location of HC in the deposit is of interest.
- Real-times changes could be observed.

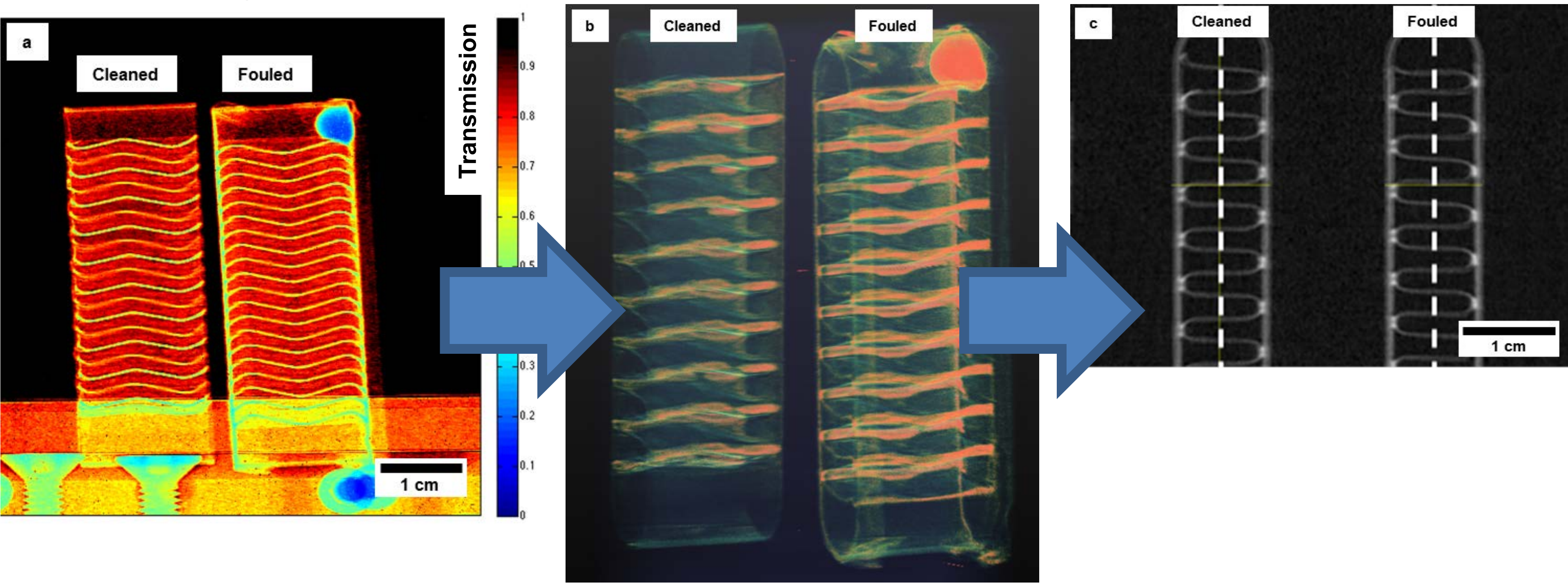
Neutron Tomography Experimental Set-up



- 85 MW High Flux Isotope Reactor (HFIR) CG-1D neutron imaging beamline at the Oak Ridge National Laboratory (ORNL).
- 7 X 7 cm field of view with ~70 μm spatial resolution.
- 360 images were acquired by rotating the sample in either 0.5°or 1°increments.
- Run times were 8 to 14 hours.

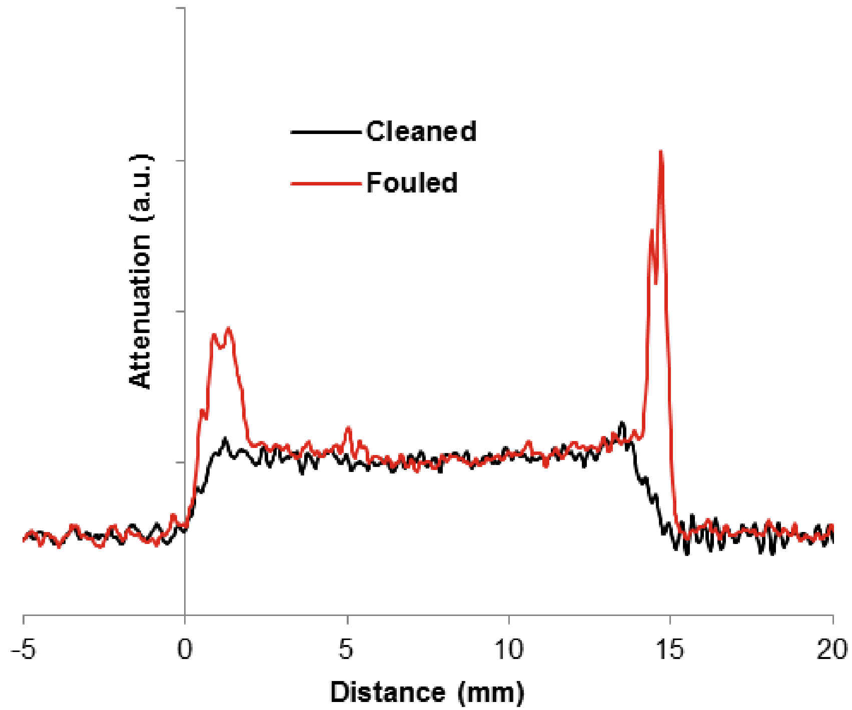
Technical Accomplishment: Modine provided the EGR cooler which was fouled by John Deere

2-D Radiographs   Volume Rendering of 3-D Tomograph   Slices from Tomograph



- Minor differences between the two samples may be due to misalignment of the two samples.

No difference in attenuation was discovered between the cleaned and fouled coolers.

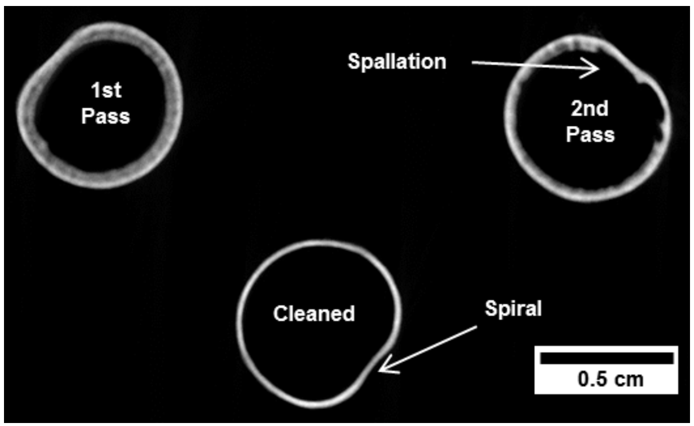


- Neutron tomography failed to image the deposit on this cooler due to:
  - Low HC concentration. (TGA revealed only 1% weight loss up to 400ºC)
  - Low density of the deposit.
  - Poor contrast with the metal.

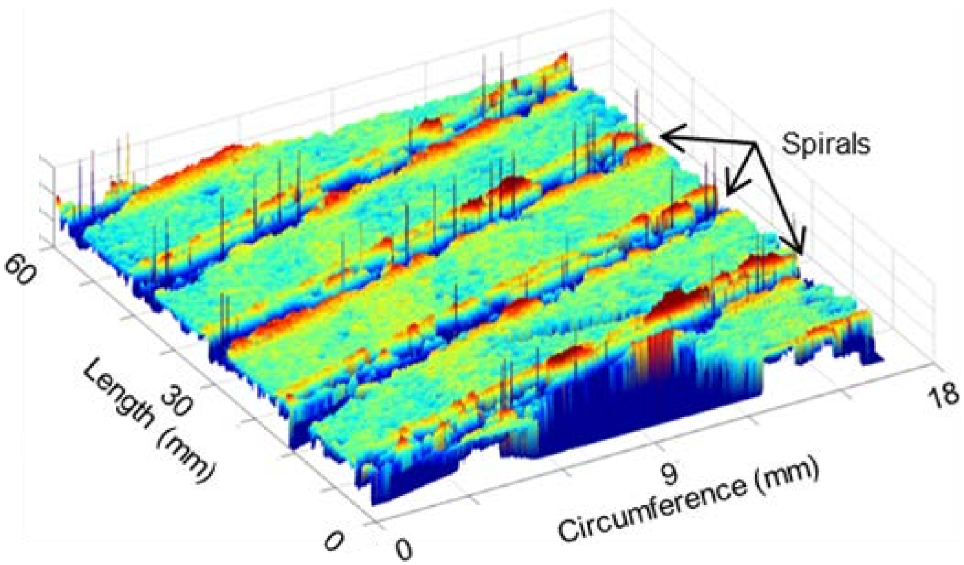
One EGR cooler deposit contained hydrated metal sulfates ($FeSO_4 \cdot 4H_2O$) that greatly improved the neutron imaging

Spiral Geometry

Slices



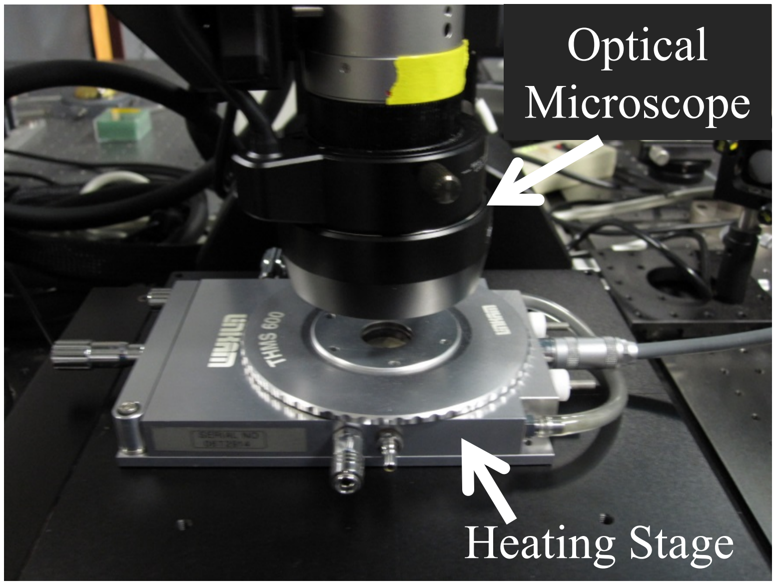
The spiral surface was flattened using Matlab®



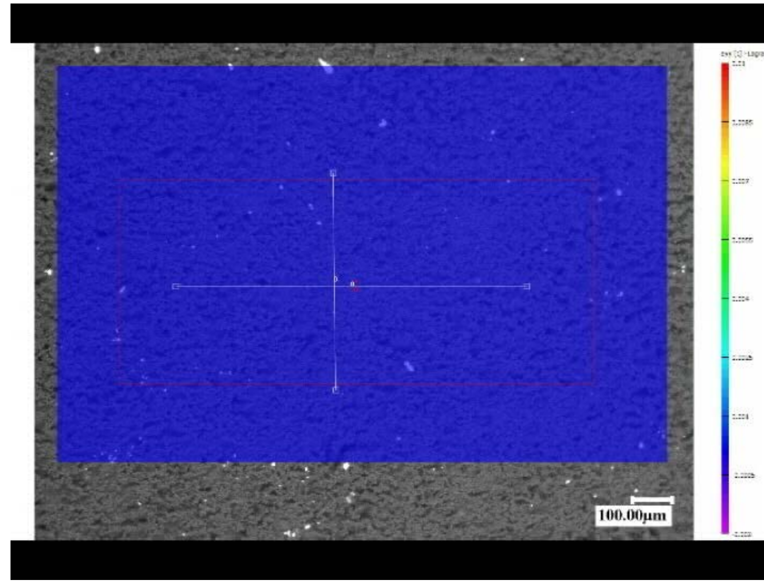
- Deposit removal is occurring on the peak of the spiral turbulator as indicated by the thinner total wall thickness shown in blue (above).
- On either side of the spiral, the deposit is thicker as indicated by the red color.
- Neutron Tomography has also been applied to diesel particulate filters and fuel injectors at ORNL.

Lance, M.J., Bilheux, H.Z., Bilheux, J.C., Voisin, S., et al., "Neutron Tomography of Exhaust Gas Recirculation Cooler Deposits," SAE Technical Paper 2014-01-0628.

Digital Image Correlation can Track Surface Strains as low as 0.03%

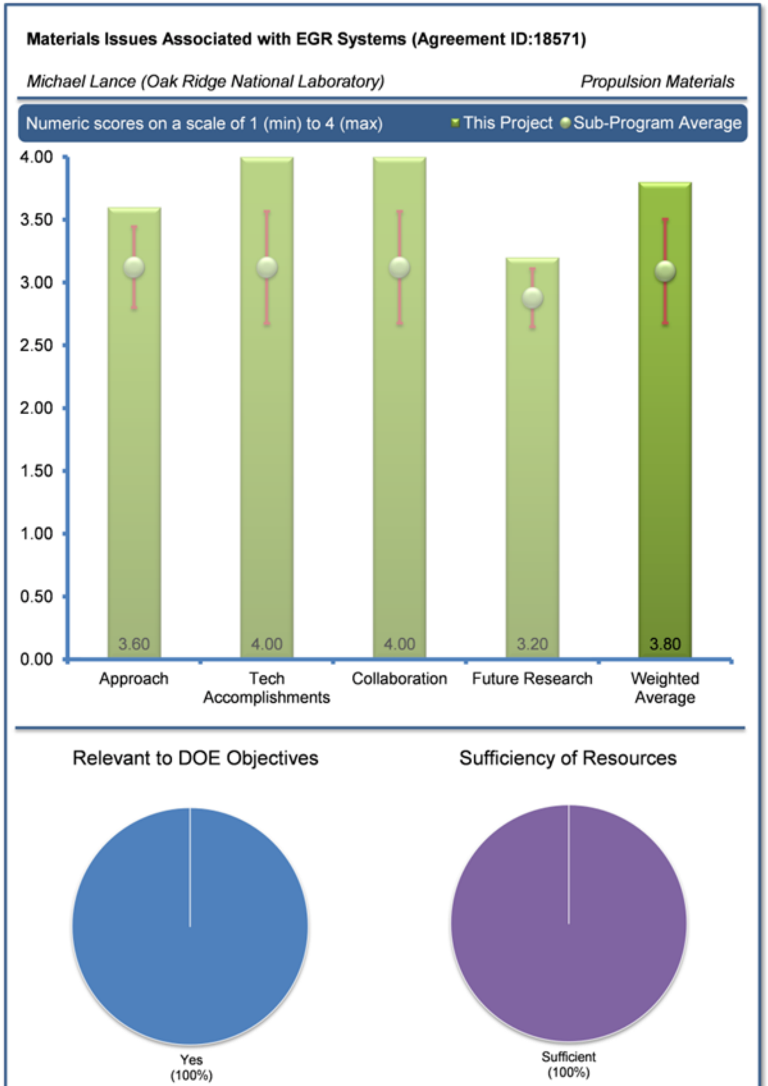


Heating to 320°C in air resulted in a volumetric shrinkage of ~0.4%



- The images are post-processed to form deformation contours based on a pattern-matching algorithm using the commercial software VIC-3D 2007 (Correlated Solutions, Inc.)
- This first test shows that digital image correlation (DIC) is a powerful tool for characterizing density changes of the deposit in different environments.

Response to Previous Year Reviewer Comments



Comment: "The reviewer questioned whether the principal investigators (PIs) had ruled out application of materials that are resistant to fouling."

Response: As discussed above, we have investigated the effect of coatings on the fouling process and have found no benefit.

Comment: "The reviewer would like to see how the information on the composition will be applied in the development of the test protocols."

Response: Our research suggests that the coolant temperature must be held above the dew point of the hydrocarbons that lead to plugging.

Comment: "The reviewer judged that the stated results should be achievable within the remaining time, but also noted that the project suffered from a reduction in funding."

Response: Despite the reduction in funding, progress has been made by increasing collaboration with our industry contacts.

Collaborations: EGR Materials Advisory Team

- An advisory team consisting of chief engineers responsible for EGR systems from nine 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. Active Control: Characterize the changes in PM morphology following aging in controlled environments using digital image correlation.
2. Measure change porosity and permeability of deposit using porous aluminum tubes as the substrate.
3. Passive Control: Investigate the role of geometry on deposit removal.
   - Computational fluid dynamics (CFD) simulation performed at Modine.

Summary

Relevance

EGR fouling results in >1% loss in brake thermal efficiency.

Approach

Real-World: Industry-Provided Samples

Active Control: Low-temperature condensation

Passive Control: Cooler Geometry

Technical Accomplishments and Progress

2nd round of industry-provided coolers was used to determine the origin of plugging and lacquer-like deposits and to demonstrate non-destructive neutron tomography.

Two SAE papers were published in FY14.

Collaboration

with <u>entire diesel engine community</u>; leveraging their in-kind investments of expertise, testing and materials.

Proposed Future Work

Use tube sampler and DIC technique to better understand refreshment strategies while continuing to work with industry characterizing late-stage deposits.