Plugging of Exhaust Gas Recirculation Coolers

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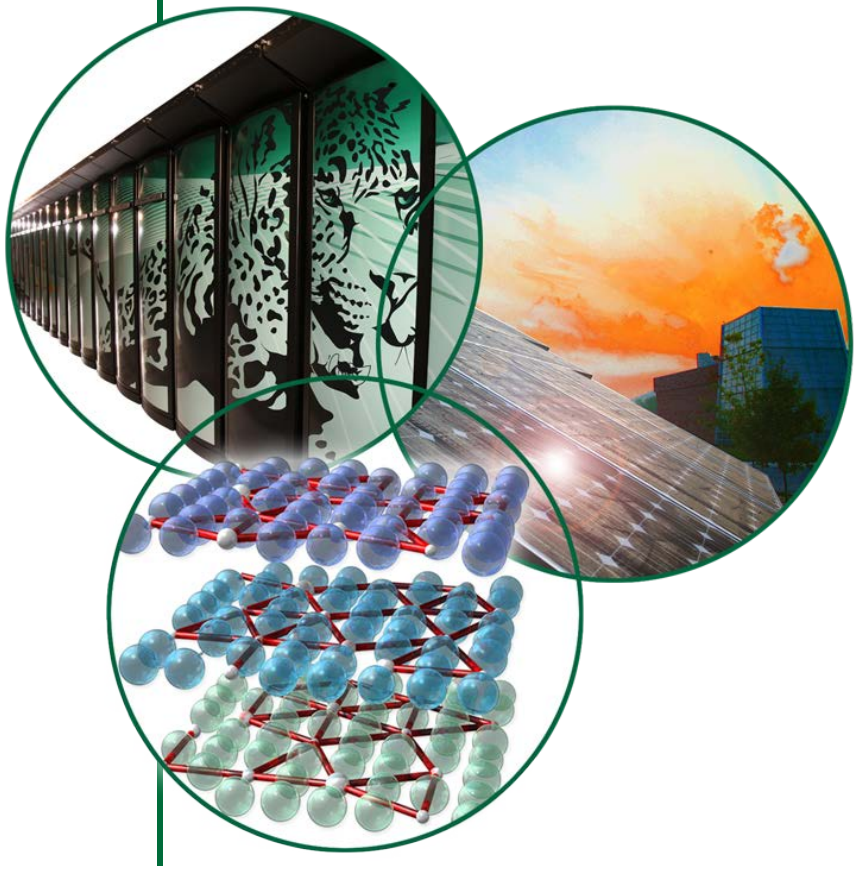

Acknowledgements

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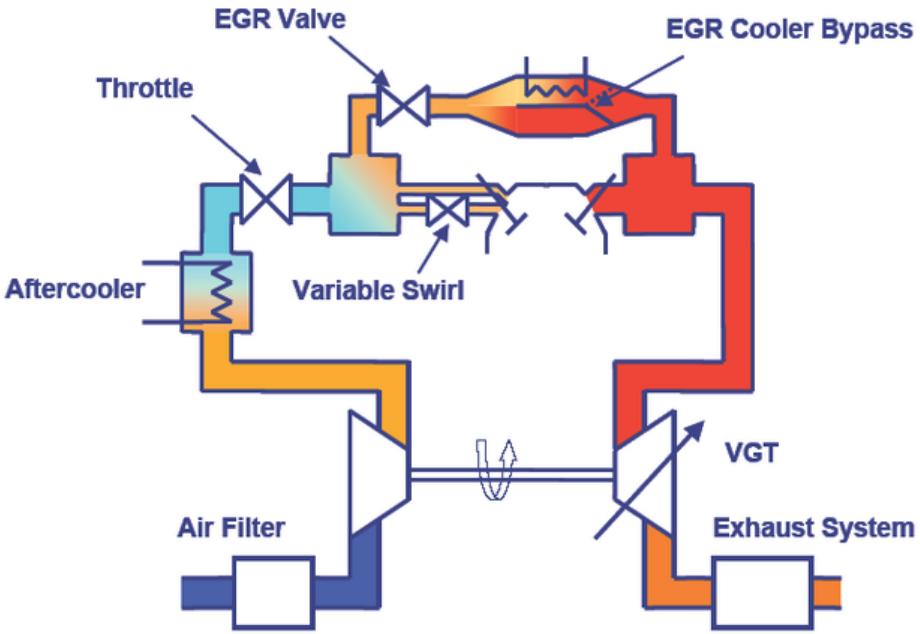
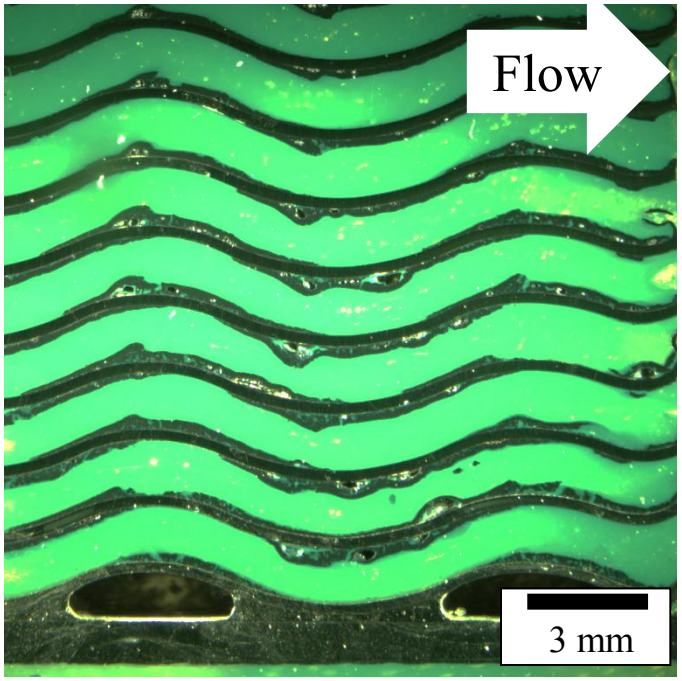
Background: Exhaust Gas Recirculation Cooler Fouling



- High-pressure exhaust gas recirculation (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 HC condensation.
- During rich combustion, the high concentration of HCs in the exhaust gas may accelerate the rate of deposition causing plugging of the EGR cooler channels.
- More stringent regulations require the expansion of EGR into engine operating realms known to be problematic.

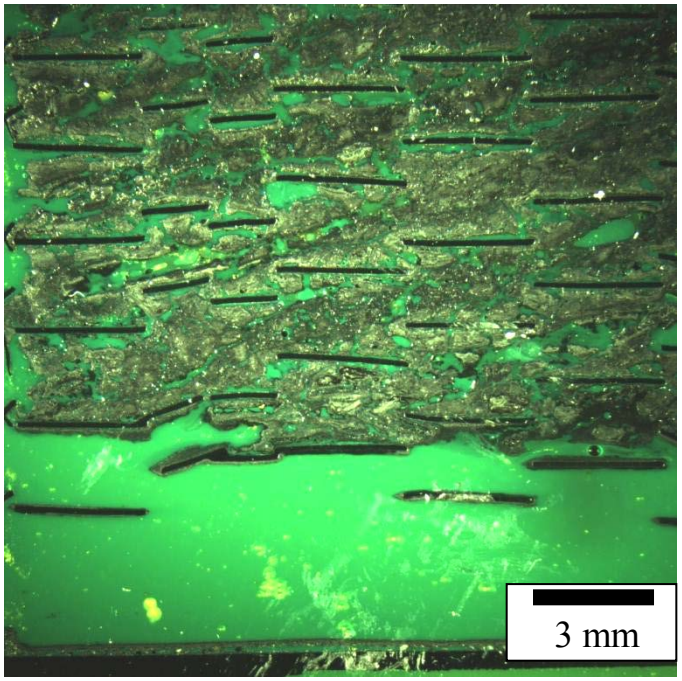
Exhaust Gas Recirculation Cooler Fouling Causes 1 to 2% Loss of Efficiency

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.

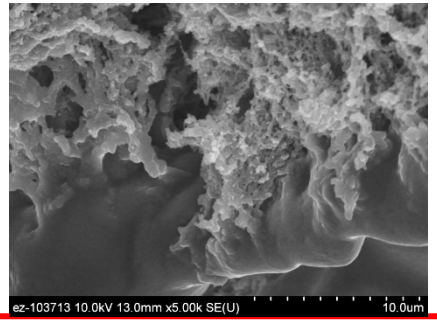
Recent Work on Stabilized Effectiveness Loss at ORNL

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

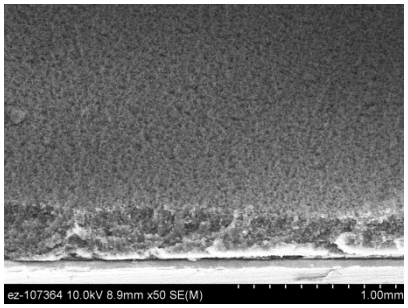
J.M.E. Storey, C.S. Sluder, M.J. Lance, D. Styles, and S. Simko, "Exhaust Gas Recirculation Cooler Fouling in Diesel Applications: Fundamental Studies, Deposit Properties and Microstructure," in press Heat Transfer Engineering.

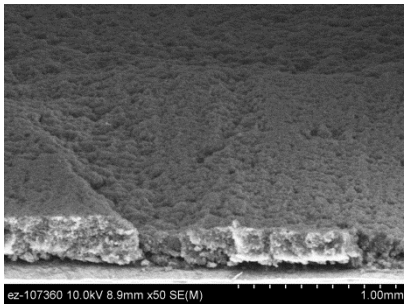
5-factor, 3-level Design-of-Experiments with 9-liter John Deere Engine



M.J. Lance, B.R. Watkins, M. Kaiser, A. Ponnaiyan, J.M.E. Storey, C.S. Sluder, "Analysis of Exhaust Gas Recirculation Cooler Deposits," to be presented at SAE 2013 World Congress & Exhibition.

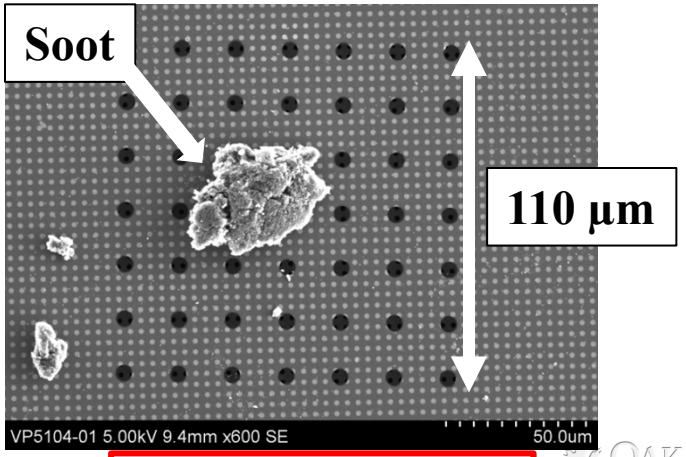
EGR Cooler Deposits were Removed Through Flow-Induced Shear





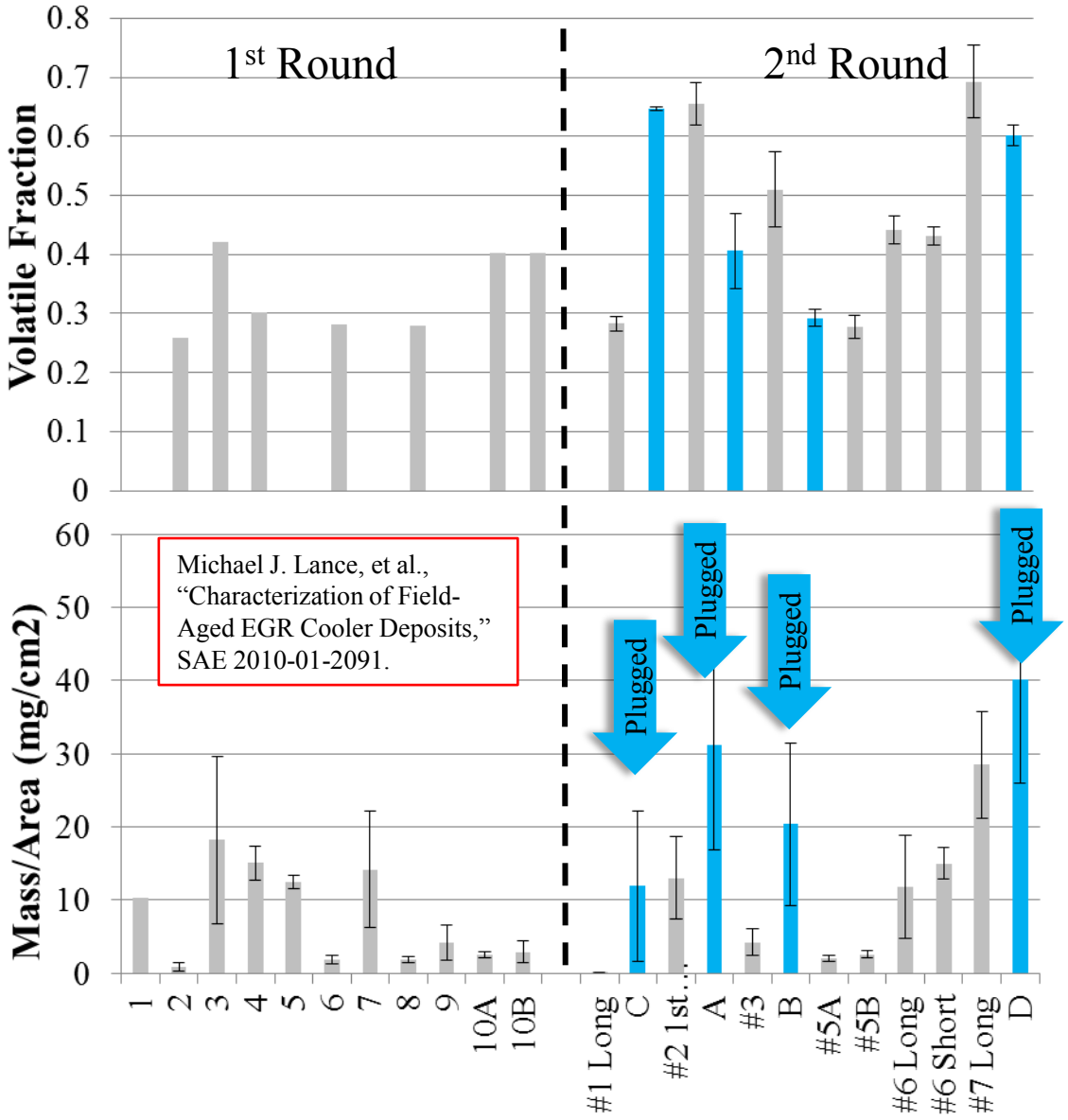
C.S. Sluder, J.M.E. Storey, and M.J. Lance, "Removal of EGR Cooler Deposits Through Flow-Induced Shear" to be presented at SAE 2013 World Congress & Exhibition.

High-Temperature SEM Heating Stage Used to Visualize Devolatilization



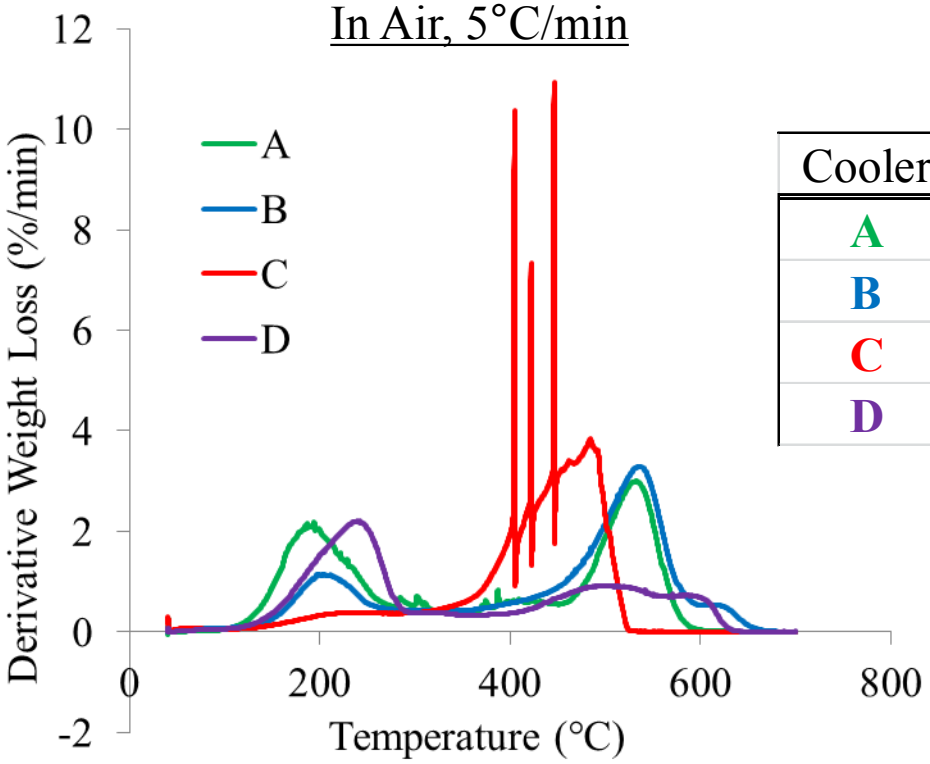
With Carl Justin Kamp (MIT)

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.

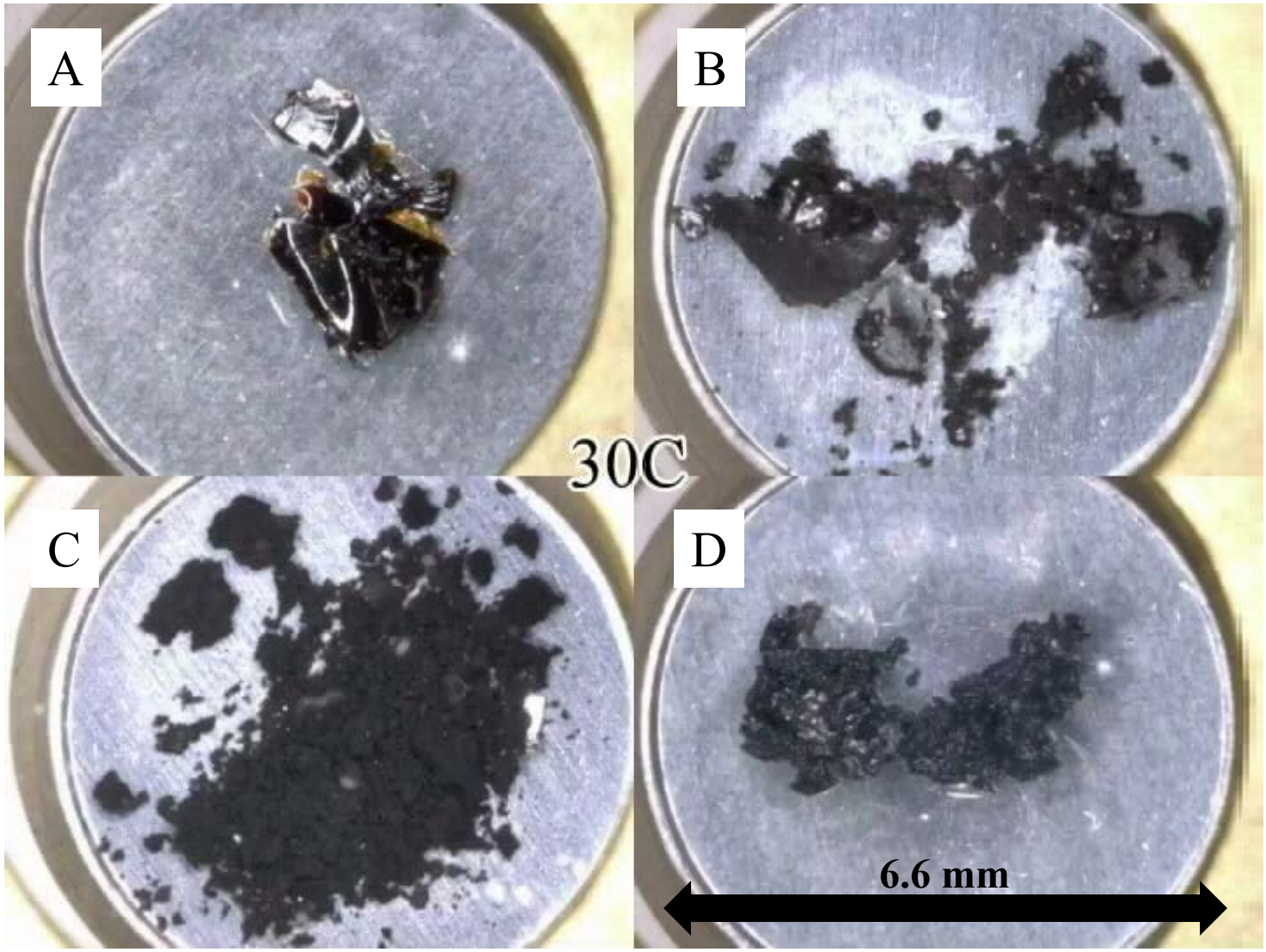
Thermogravimetric Measurements



Cooler	Volatile	Ash	Description
A	78%	0%	Shiny Brittle Lacquer
B	55%	1%	Lacquer and soot
C	26%	8%	Dry, Crumbly
D	59%	13%	Oily, wet

- Coolers A & B were both lacquer-like and had the lowest ash content.
- Cooler C burned at a low temperature and showed exothermic spikes during oxidation.
- Cooler D was very wet and oily and contained the most ash.

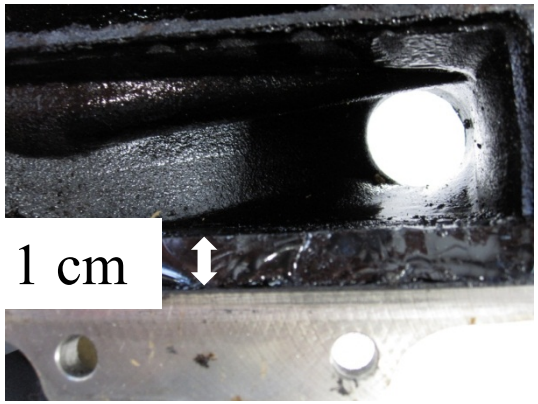
Videos Taken While Heating in Air are Useful for Visualizing Deposit Behavior at High Temperatures



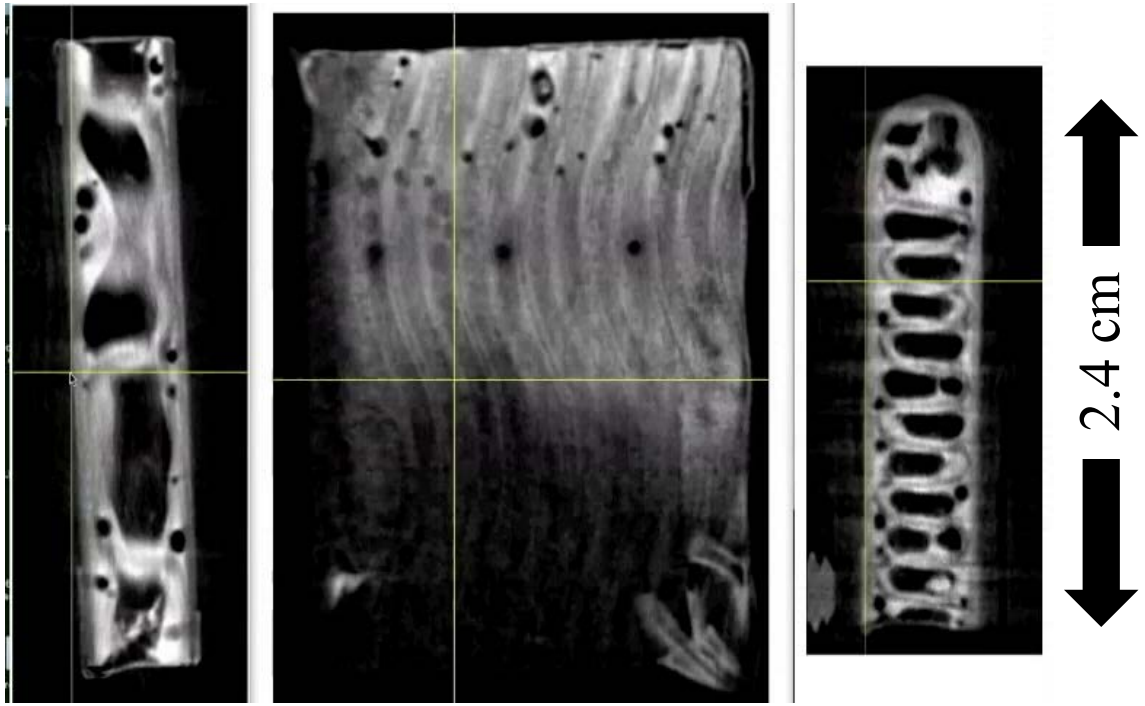
- Cooler D was soot mixed with oil.

Cooler A: Deposit Flowed and Boiled During Use

Outlet Diffuser

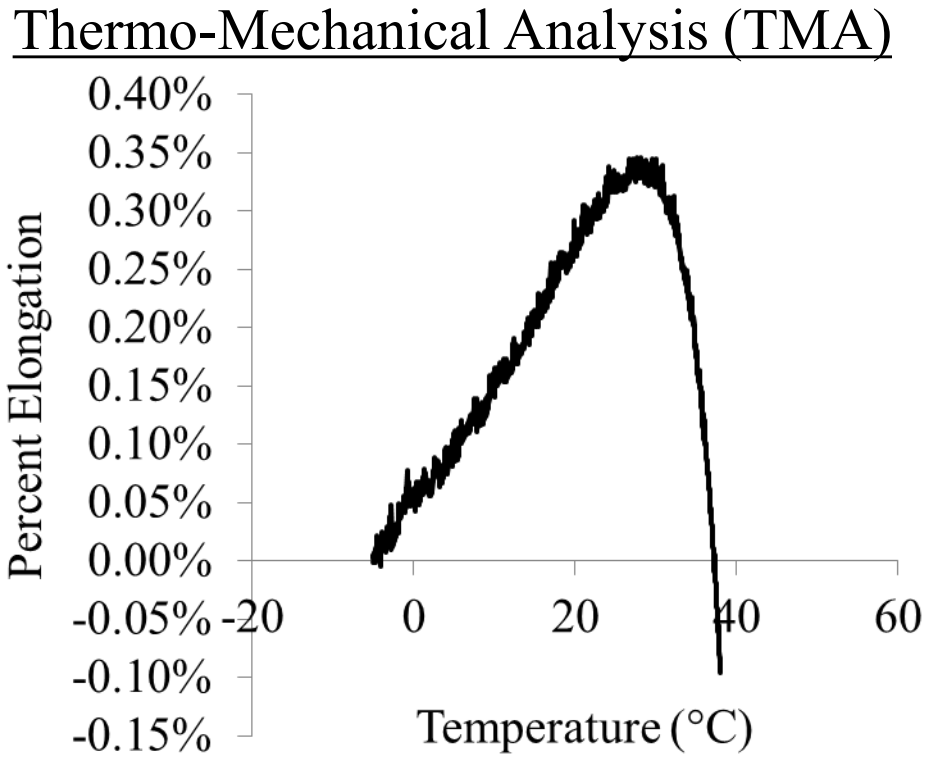


Neutron Tomography



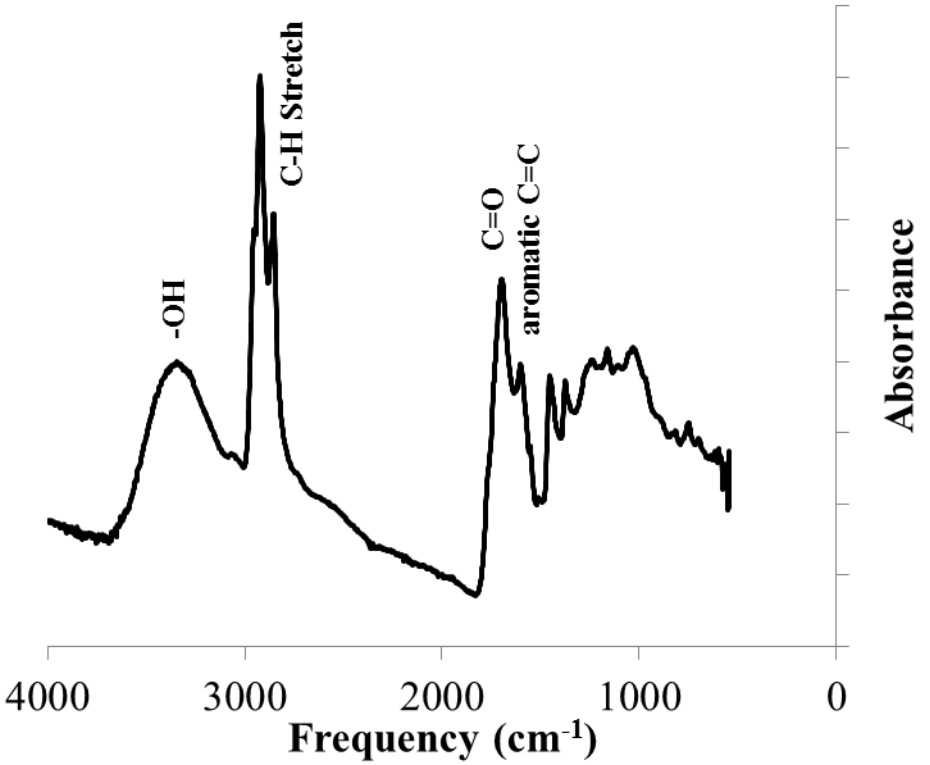
- Industry Representative:
  - "This particular test was an extremely severe EGR valve sticking test. The EGR valve and throttle were forced open, the engine ran at low idle, and timing was retarded by 7 degrees."
- Bubbles in the deposit were observed using neutron tomography.

Cooler A: Lacquer Deposit Starts to Soften around Room Temperature



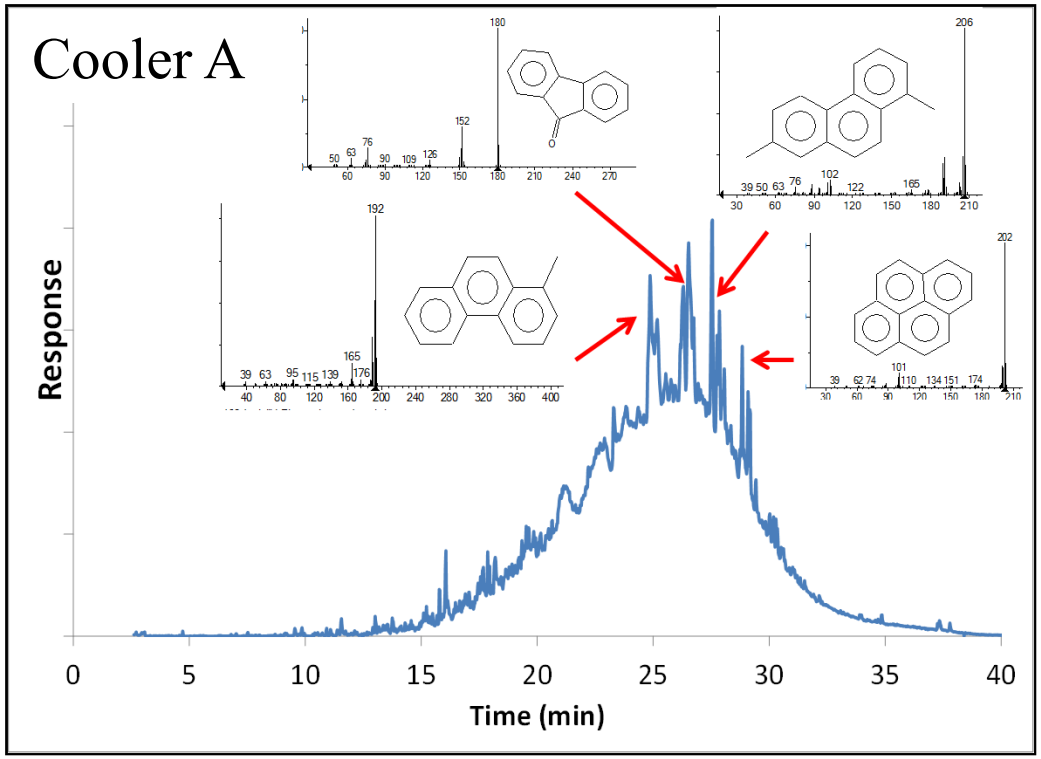
- Density = 1.2 g/cm^3
  - More similar to a polymer than fuel or oil.
- Thermal Conductivity = 0.11 W/mK

Fourier Transform Infrared (FT-IR) Spectroscopy of Cooler A Showed the Presence of Oxygen-containing Hydroxyl and Carboxyl Groups



- X-ray Photoelectron Spectroscopy (XPS) showed 15 at% oxygen and 0.5 at% nitrogen.

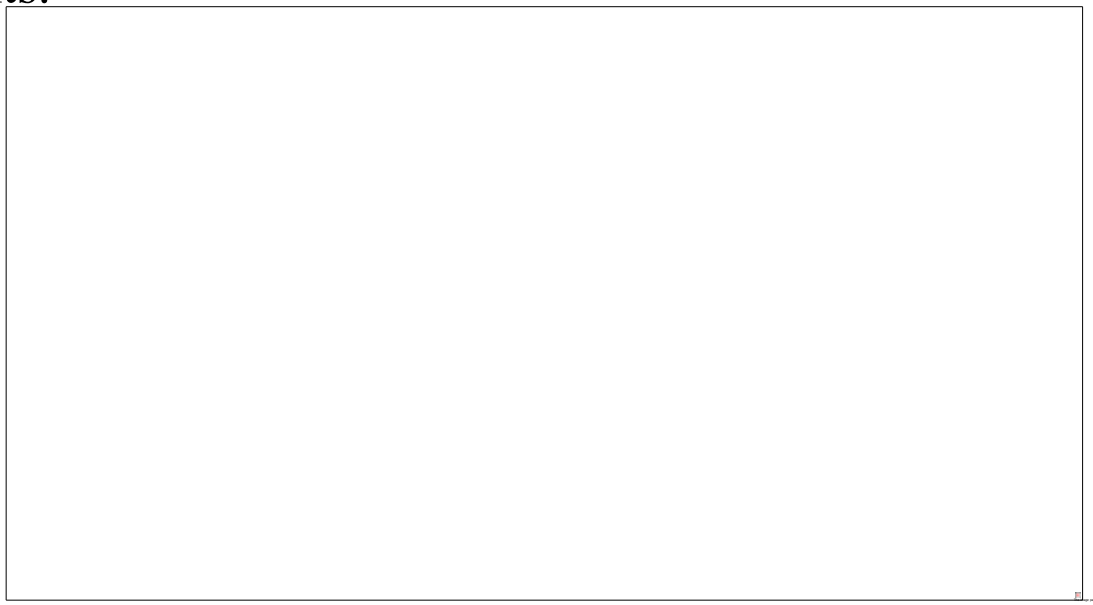
Pyrolysis GC-MS was used to Determine Lacquer Chemistry



- Peaks are variants of 2 to 4 ring PAHs and oxygenated PAHs with a narrow range of melting/boiling points.
- Cooler B contained 3 to 5 ring PAHs.
- Paraffinic fuel or oil 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.

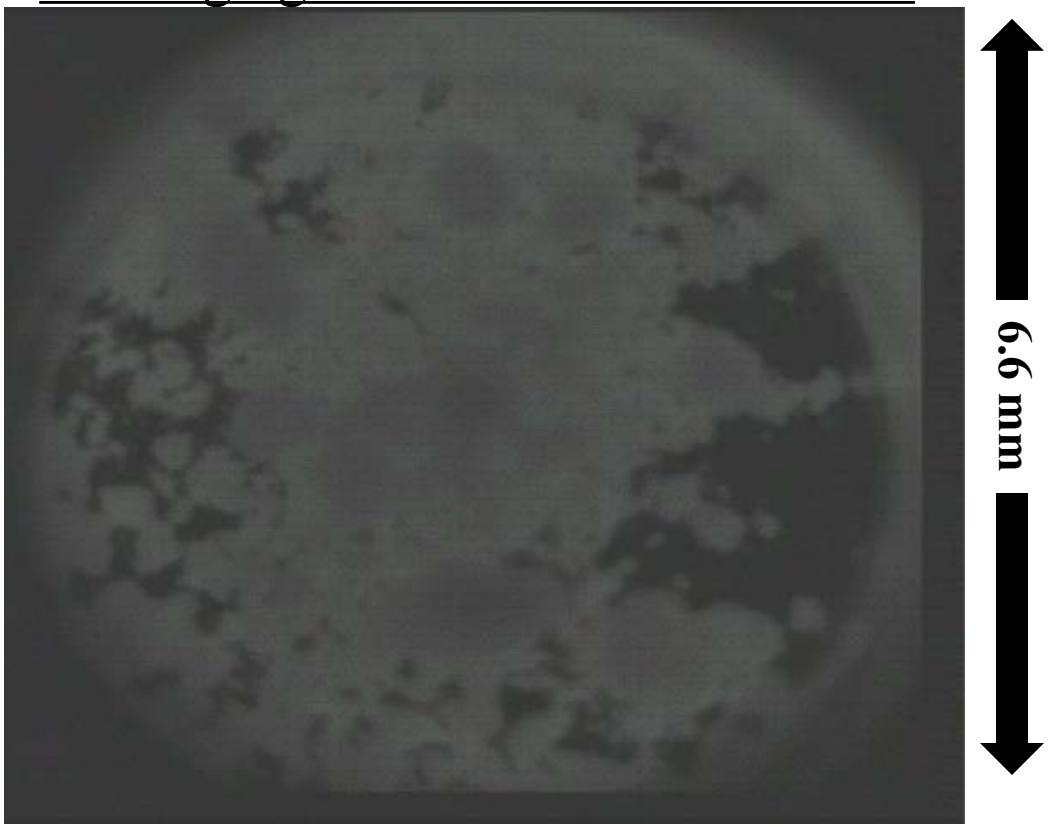
These Observations Compare well to Recent Experimental Work

- N. Furukawa, et al., "On the mechanism of exhaust gas recirculation valve sticking in diesel engines," *International Journal of Engine Research,* September 2012.
  - Resinification of phenols through contact with formaldehyde.
  - High amounts of NO_x will produce nitric acid which acts as a catalyst.
  - Dew point of HC is critical. EGR walls must be held at temperatures above dew points.



Cooler C Deposit Contained Oxygenated Species

IR Imaging from 500 to 700°C in Air



- An infrared camera revealed local heterogeneous oxidation likely caused by oxygenated PAHs feeding the combustion.
- Contained similar HC species to coolers A and B but at far lower concentrations and more dispersed by soot.
- Soot may be hindering the gas-liquid phase reaction that produces lacquer.

Summary

- Coolers exhibiting plugging failure were donated by industry representatives.
- Coolers A and B contained lacquer-like deposits which were composed of polycyclic aromatic hydrocarbons possibly polymerized by aldehyde and catalyzed by nitric acid.
  - This deposit can be prevented by maintaining the cooler above the dew point of the hydrocarbons.
- Cooler C contained the similar species as the lacquer but at lower amounts with more soot.
- Cooler D deposit was probably due to a failure in a lubricant seal.