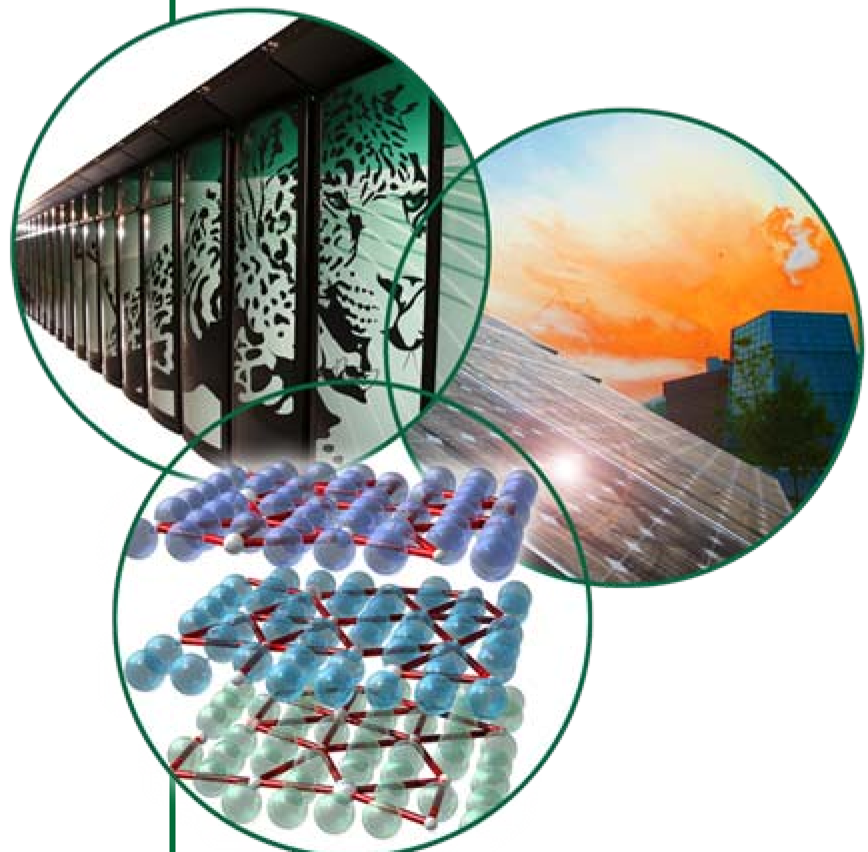
Microstructural Evolution of EGR Cooler Deposits



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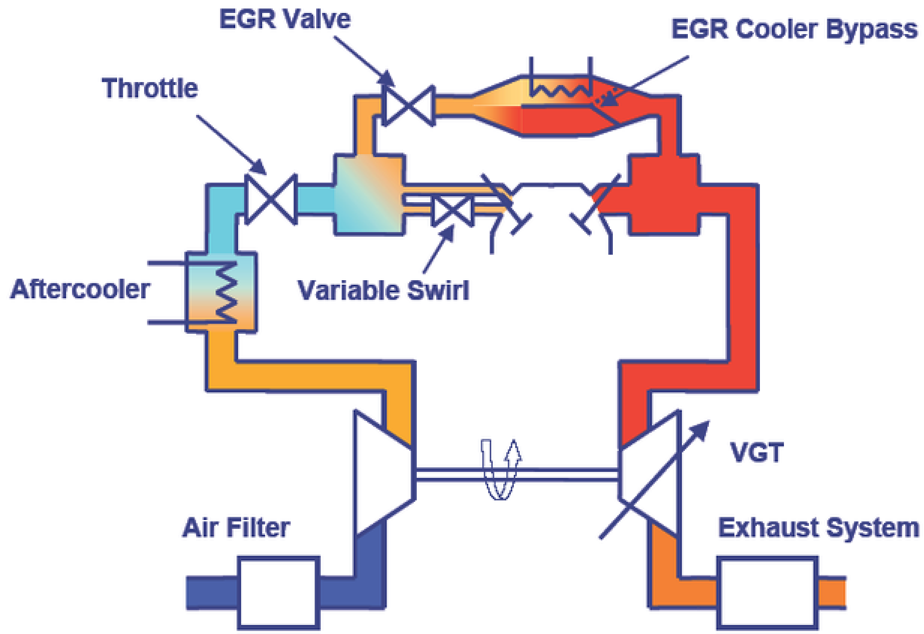
Outline

- Exhaust Gas Recirculation as a Method for Reducing NO_x Emissions
- Review new DOE-funded project: Materials Issues Associated with EGR Systems
- Experimental Methodology for Depositing Particulate Matter (PM) on Model Cooler Tubes
- Microstructural Evolution of EGR Deposits
  - Deposits from Steady-State Laboratory Cooler Tubes
  - Deposits from Half-Useful-Life Industry-Provided Coolers

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.

Background: Fouling of (HP) EGR Coolers

- Information about deposit formation and removal is needed:
  - Thermo-physical and chemical properties of the deposit are needed for modeling.
  - Effectiveness of EGR systems often decline but then reach a plateau. Why?
  - The deposit changes with time due to temperature and HC/water condensation.
  - What is the adhesion mechanism and how can we stop it?
  - How does the deposit affect the EGR valve.
- Bio-based fuels produce different exhaust gas chemistry and PM.

New DOE-Funded Project: Materials Issues Associated with EGR Systems

- Feb-09 Milestone: An advisory team consisting of chief engineers responsible for EGR systems from nine Diesel Crosscut Team members was assembled:
  - Caterpillar, Cummins, Detroit Diesel, Ford, GM, John Deere, Navistar, PACCAR, Volvo/Mack.
- 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

	Problem	
Component	***Fouling***	***Corrosion***
(HP) EGR Cooler	#1	
(HP) EGR Valve	#2	
(HP) Flow Meter		
(LP) EGR Cooler		
(LP) EGR Valve		
(LP) Flow Meter		
(LP) Charge-air Cooler		

Project Objective: Provide information to industry EGR 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.

Approach FY2009

- Task 1: Experimental Setup
  - We are pursuing a traditional engine-on-dynamometer to generate fouling deposits on model tubes.
  - 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
  - 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: XRF, FTIR, XPS, Raman, GC-MS
    - Thermal Analysis: Heat Capacity, Thermal Conductivity, TGA/DTA
    - Neutron Tomography
  - Seven companies have provided eleven coolers for analysis.

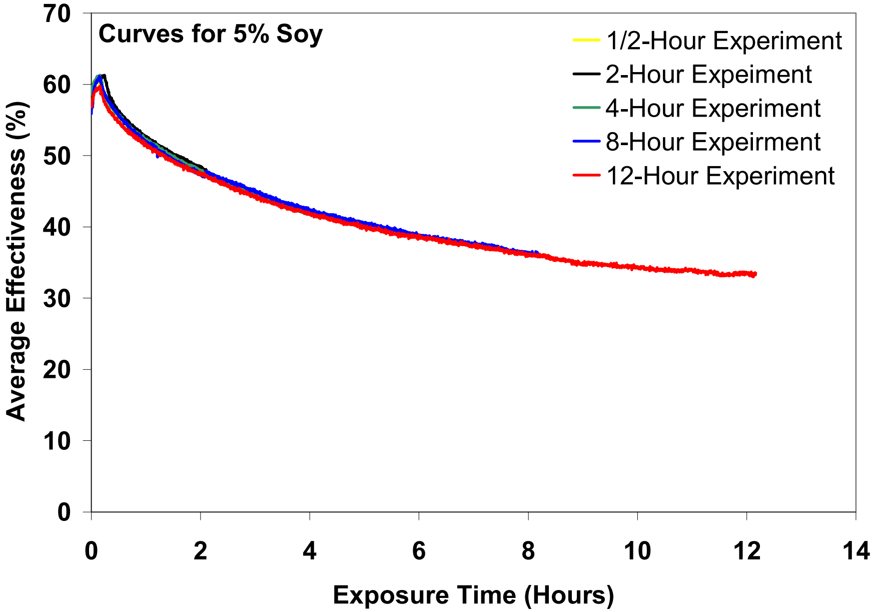
Approach to investigating NPBF effects on EGR cooler fouling is based on studying surrogate EGR cooler tubes

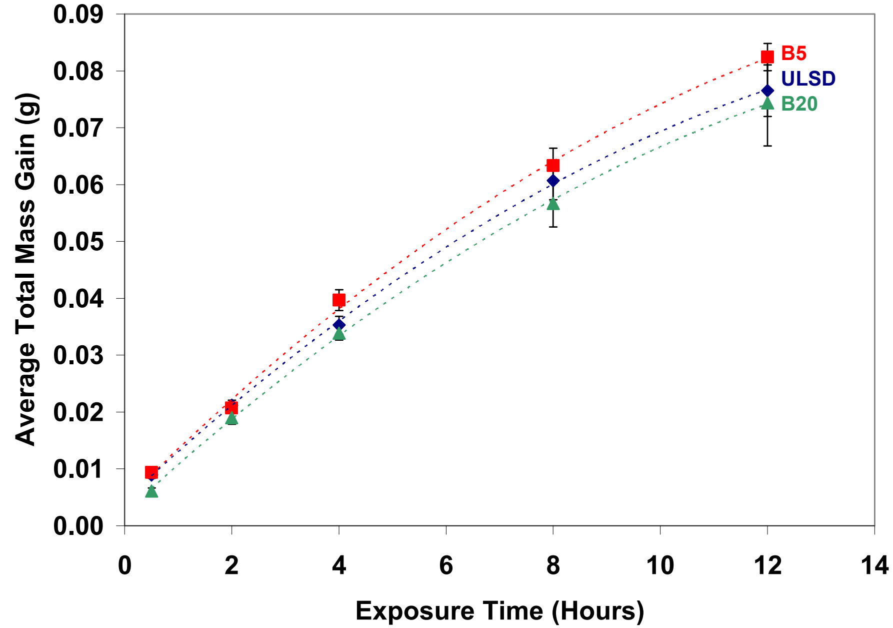
- Ford 6.4-L V-8 used as exhaust generator.
- Engine was operated at 2,150 RPM with a brake power output of 49 kW.
- Exhaust passed through surrogate EGR cooler tubes at constant flow rate and coolant temperature.
  - Tubes were ¼ inch square cross-section stainless tubes.
  - Thermal effectiveness of tubes is assessed during exposure.

Experimental Conditions

- Fuel:
  - Ultra-low sulfur certification diesel (ULSD) sourced from Chevron-Phillips Specialty Chemical Company
  - 5 and 20% volume blend of soy biodiesel in ULSD (B5 & B20)
- Feed gas conditions:
  - 1.5 Smoke Number
  - 50 PPM HC (as C_1)
- Tube Conditions
  - 40, 70 and 90 °C coolant
  - 375 °C inlet gas temperature
  - 30 SLPM per-tube gas flow

Significant thermal effectiveness loss due to deposit formation occurs within a few hours





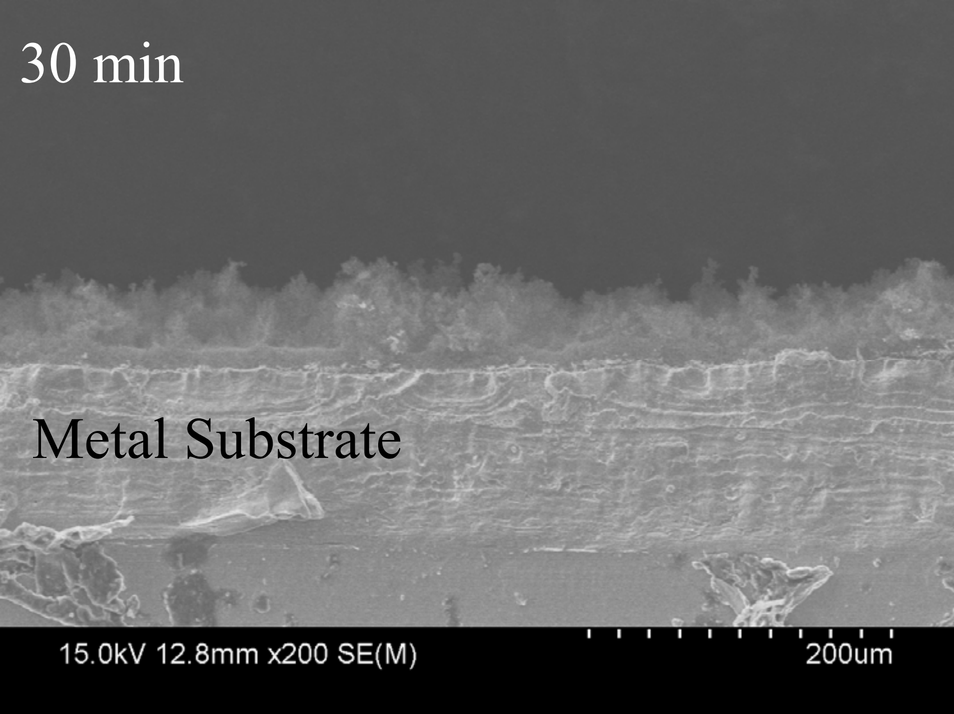
- Steady-flow, time-of-exposure experiments showed very good repeatability.
- Mass accumulation in the tubes showed similar profiles for ULSD, B5, and B20 fuels.

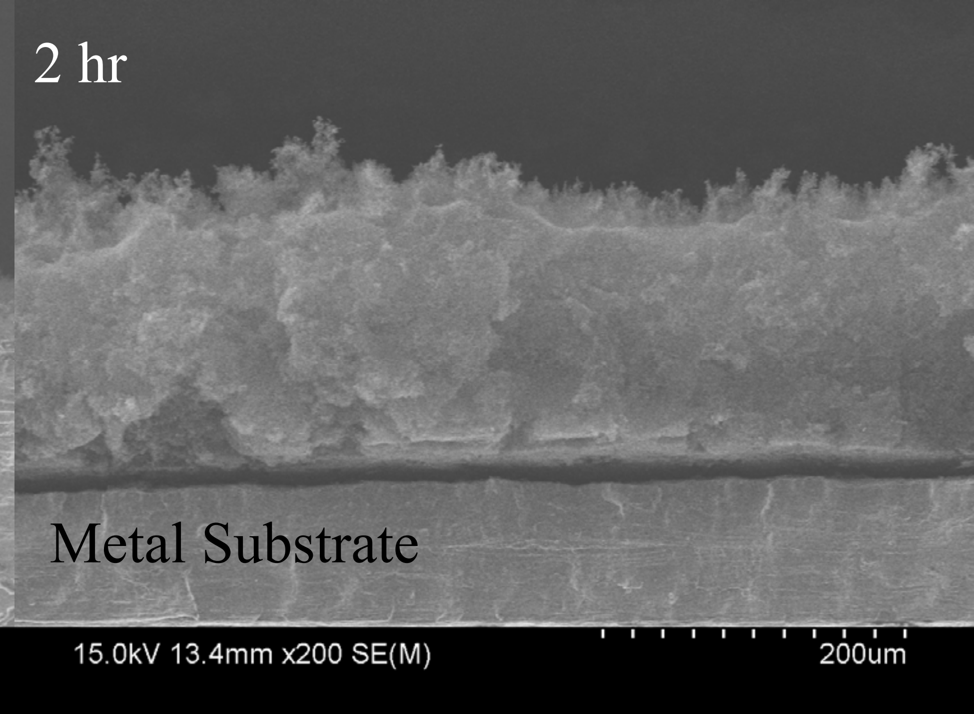
C. Scott Sluder and John M. E. Storey, "EGR Cooler Performance and Degradation: Effects of Biodiesel Blends," SAE Paper 2008-01-2473.

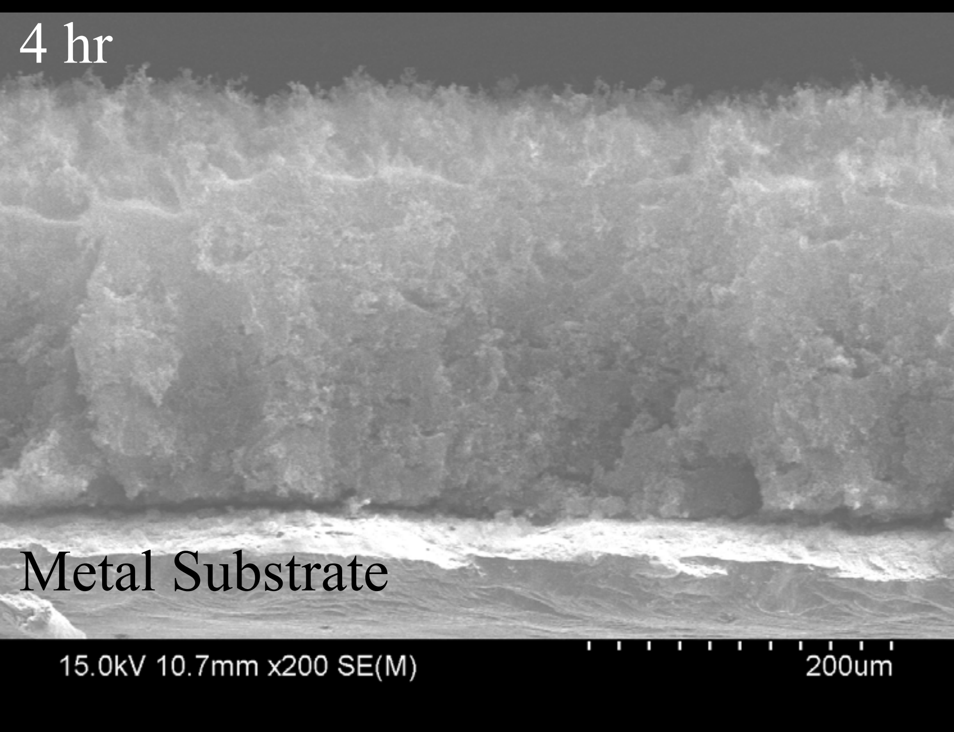
Thermal Conductivity at 25°C

Property	*SS 304*	*ULSD*	*B5*	*B20*
Thickness (mm)	0.5150	0.4140	0.3725	0.3600
Density (g/cm3)	7.9300	0.0316	0.0363	0.0379
Cp (J/gK)	0.4700	0.8668	0.8170	0.8706
Apparent Diffusivity 1,2 (cm2/s)		0.0280	0.0190	0.0172
Diffusivity (cm2/s)	0.0395	0.0209	0.0115	0.0097
Thermal Conductivity (W/mK)	14.7220	0.057	0.034	0.032

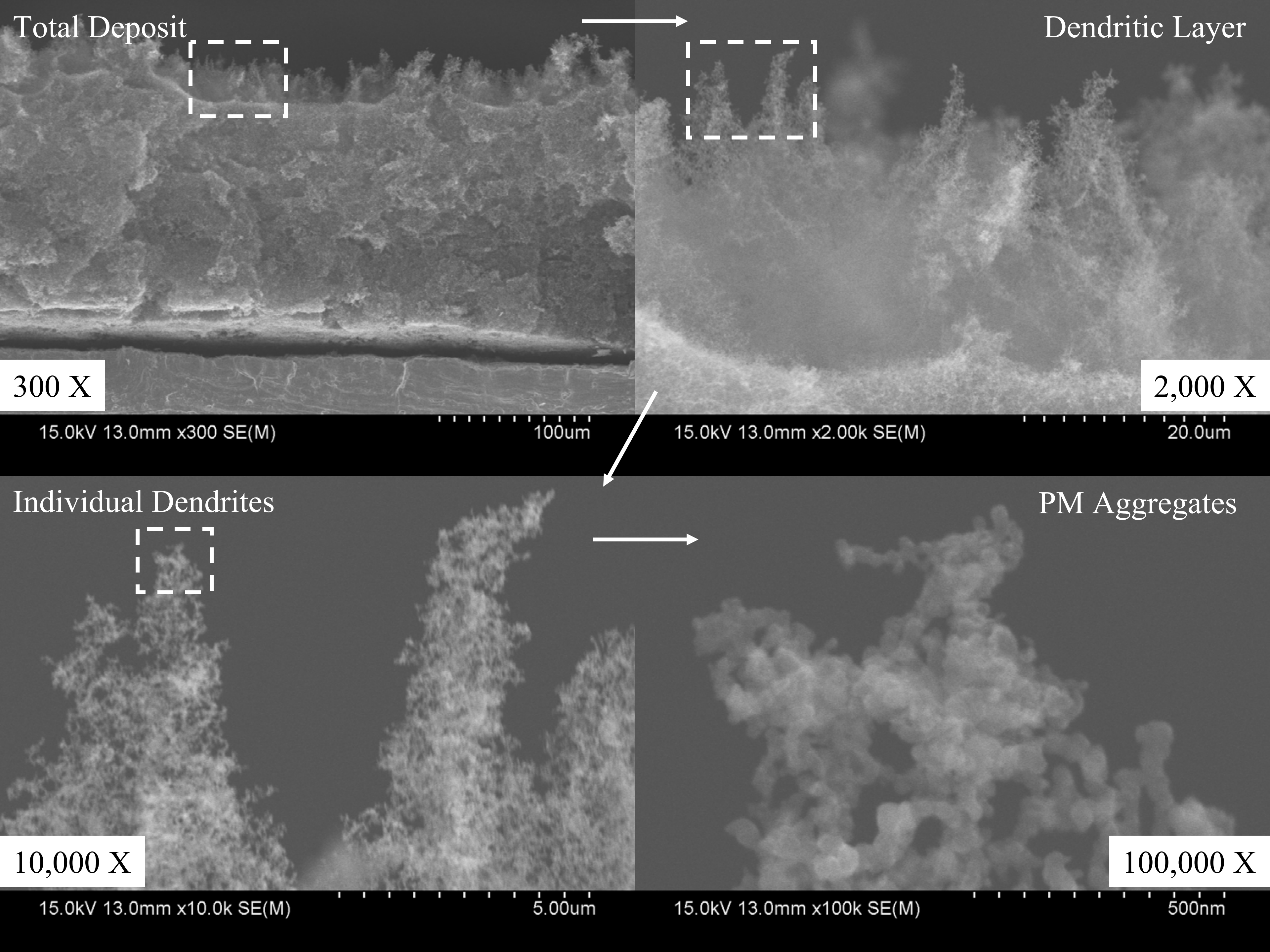
- The average thermal conductivity of the deposit was 0.041 W/mK.
- Since the thermal conductivity of air is 0.025 W/mK, the deposit is only slightly above air and is much lower than stainless steel which is ~15 W/mK.
- The porosity of the deposit was ~98% which is the main determinant of the thermal conductivity.



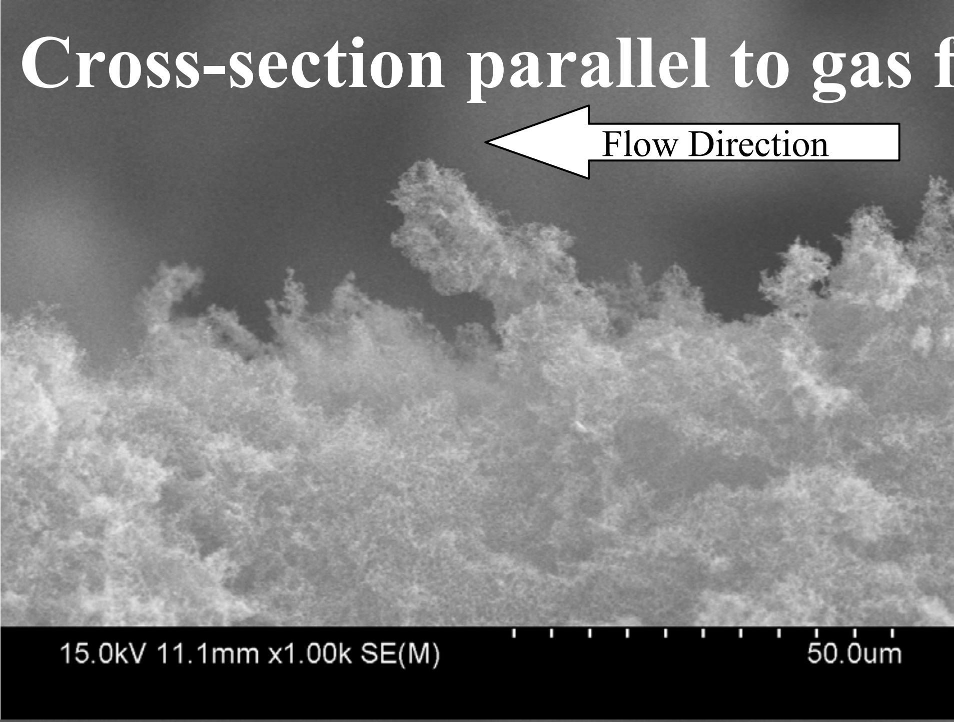


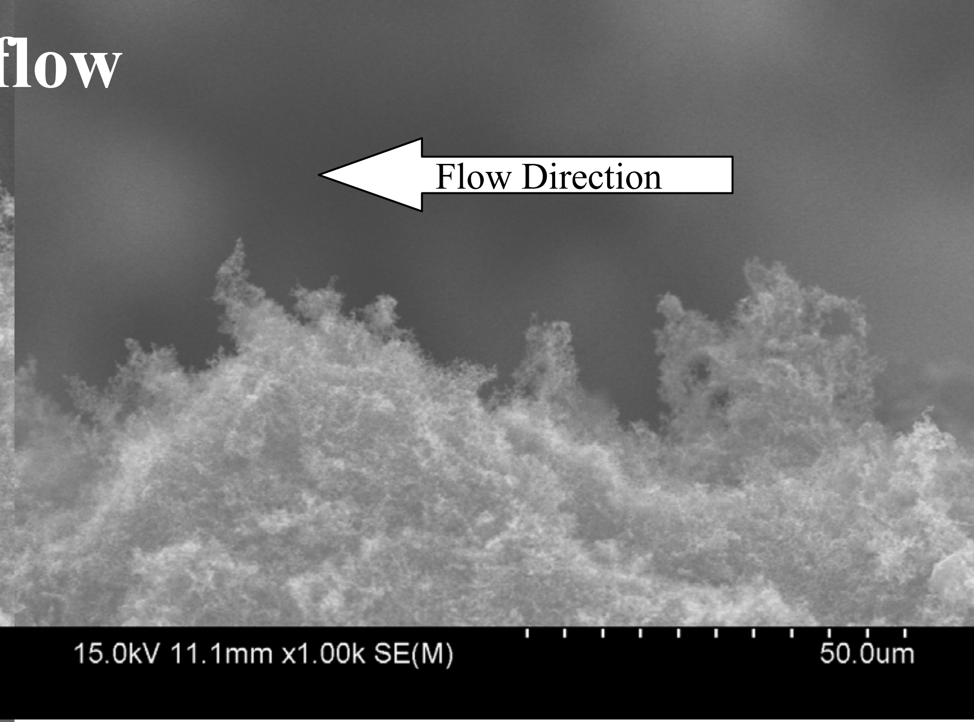


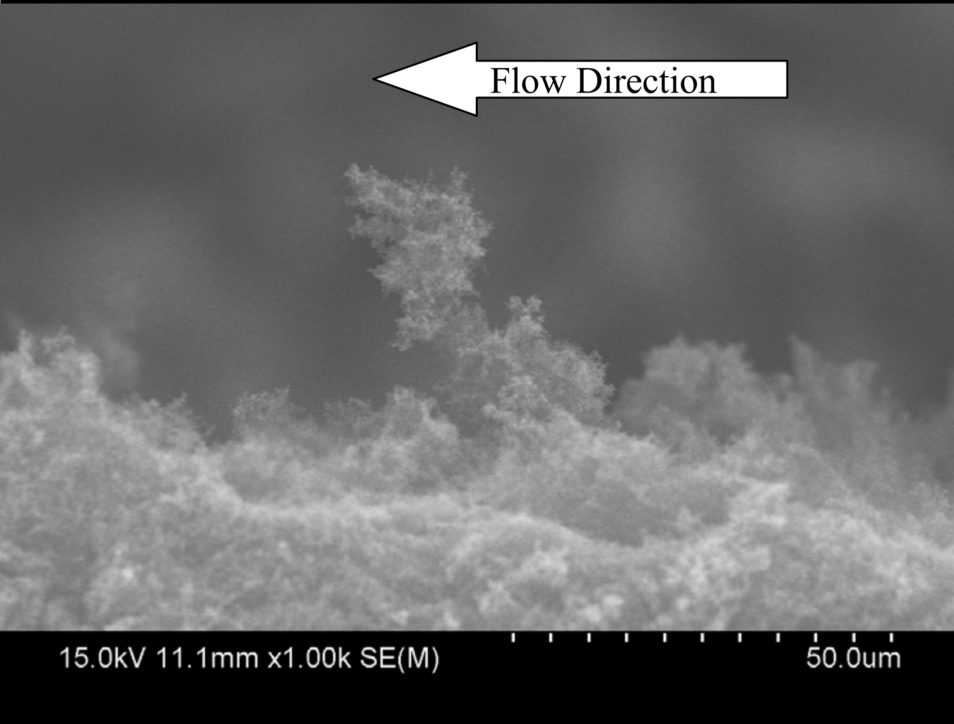
- The deposit cross-sections exhibit two layers:
  - A denser bottom layer
  - A dendritic top layer


Total Deposit
Dendritic Layer
300 X
2,000 X
15.0kV 13.0mm x300 SE(M)
100um
15.0kV 13.0mm x2.00k SE(M)
20.0um
Individual Dendrites
PM Aggregates
10,000 X
100,000 X
15.0kV 13.0mm x10.0k SE(M)
5.00um
15.0kV 13.0mm x100k SE(M)
500nm

Cross-section parallel to gas flow



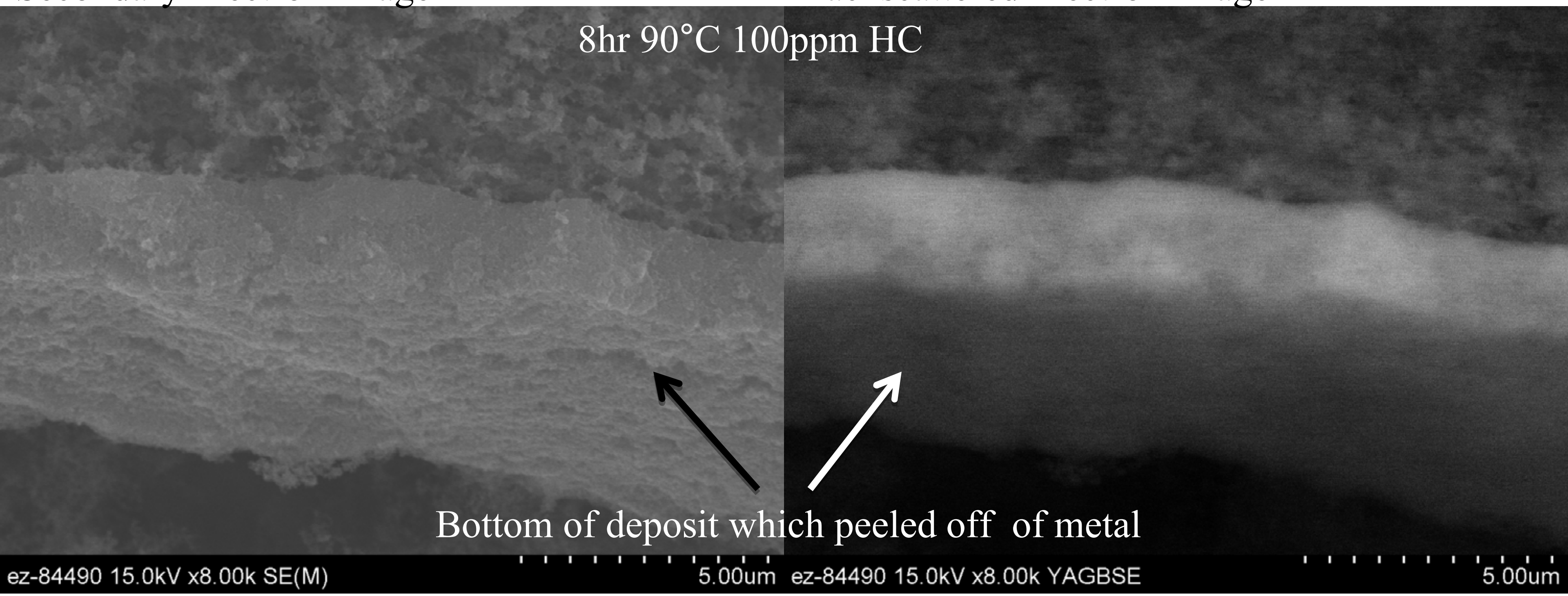




- Many dendrites seem to bend in direction of gas flow.
- No dendrites bent against the gas flow.

Heavy hydrocarbon species condense on the cold metal forming a dense layer

Secondary Electron Image Backscattered Electron Image



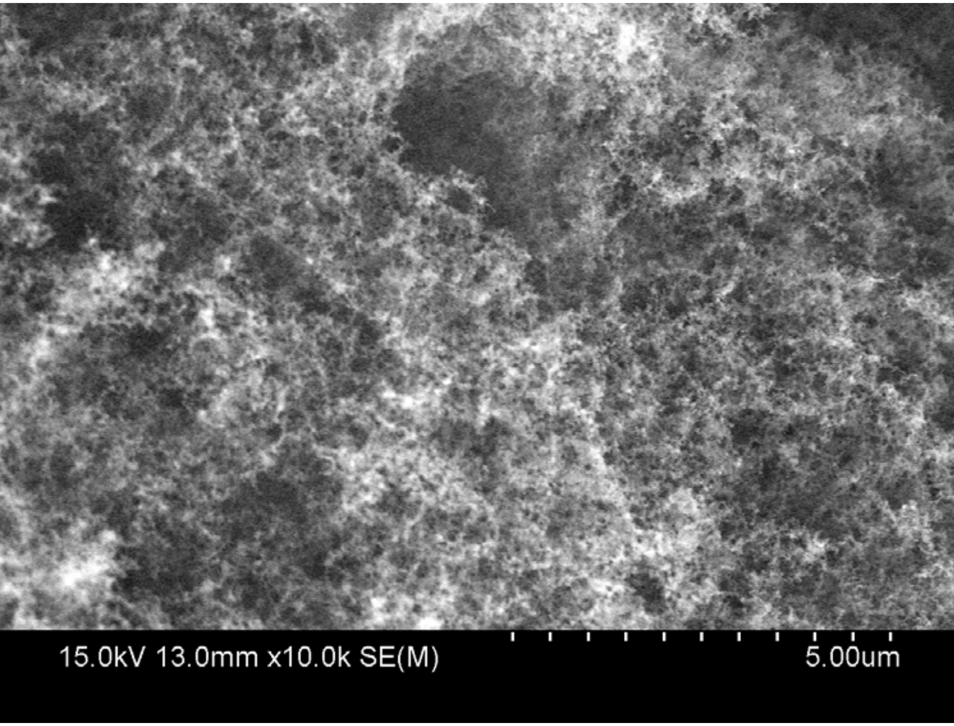
- This layer is very thin compared to the porous soot on top of it and thus won't affect the effectiveness of the cooler tube.
- Due to the thermal gradient, the HC can't condense far into the deposit and will remain near the metal.

Hypothesis for Deposit Formation under Steady-State Conditions

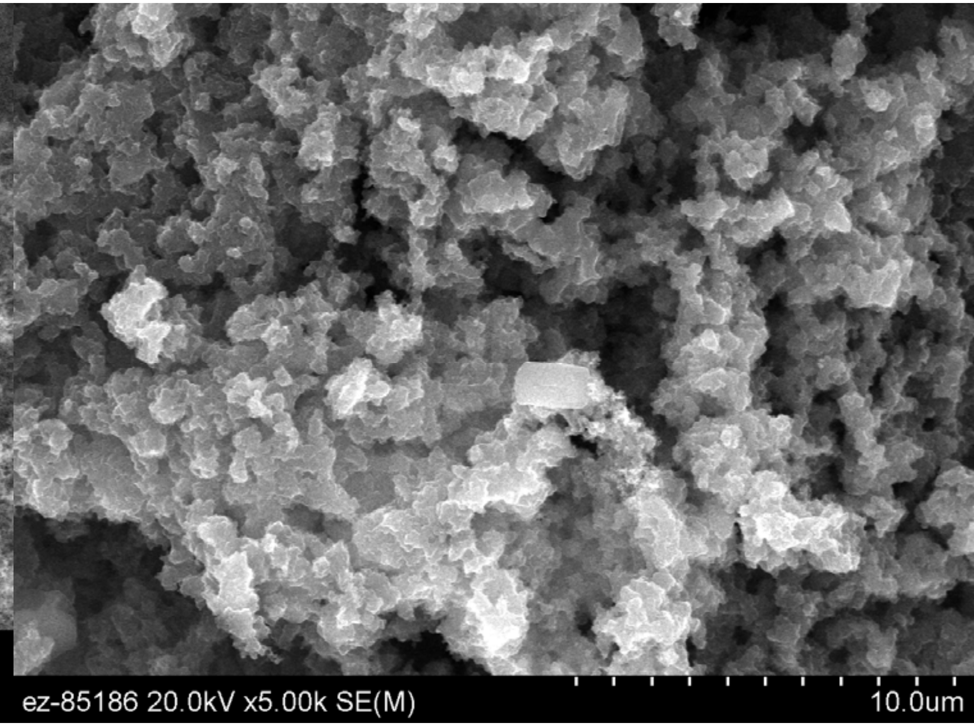
- PM aggregates initially deposit randomly on the surface. Hydrocarbon condenses.
- Subsequent aggregates are caught by the initial aggregates forming dendrites that grow perpendicular to the surface.
- Once a critical mass/height is reached, the gas flow will topple the dendrite, fracturing it at its base.
- The toppled dendrites will lay flat on one another forming the denser bottom layer.
- New PM aggregates from the gas will then randomly deposit in the new ‘open’ area formed following dendrite toppling.
- This process will repeat itself as the deposit thickens.

Comparison of Early-Stage and Late-Stage Microstructures

Steady-State Deposit (~100s of miles)

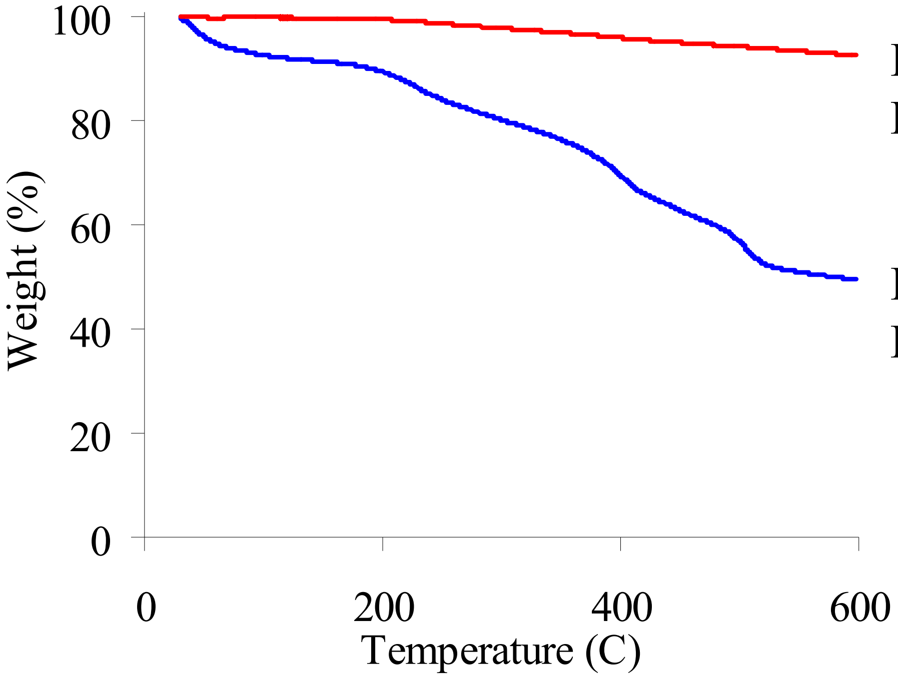


Half-Useful-Life Deposit (280,000 miles)



- The late-stage deposit microstructure is far coarser than the early-stage deposit.

Thermo-gravimetric Analysis in Argon (Devolatilization)

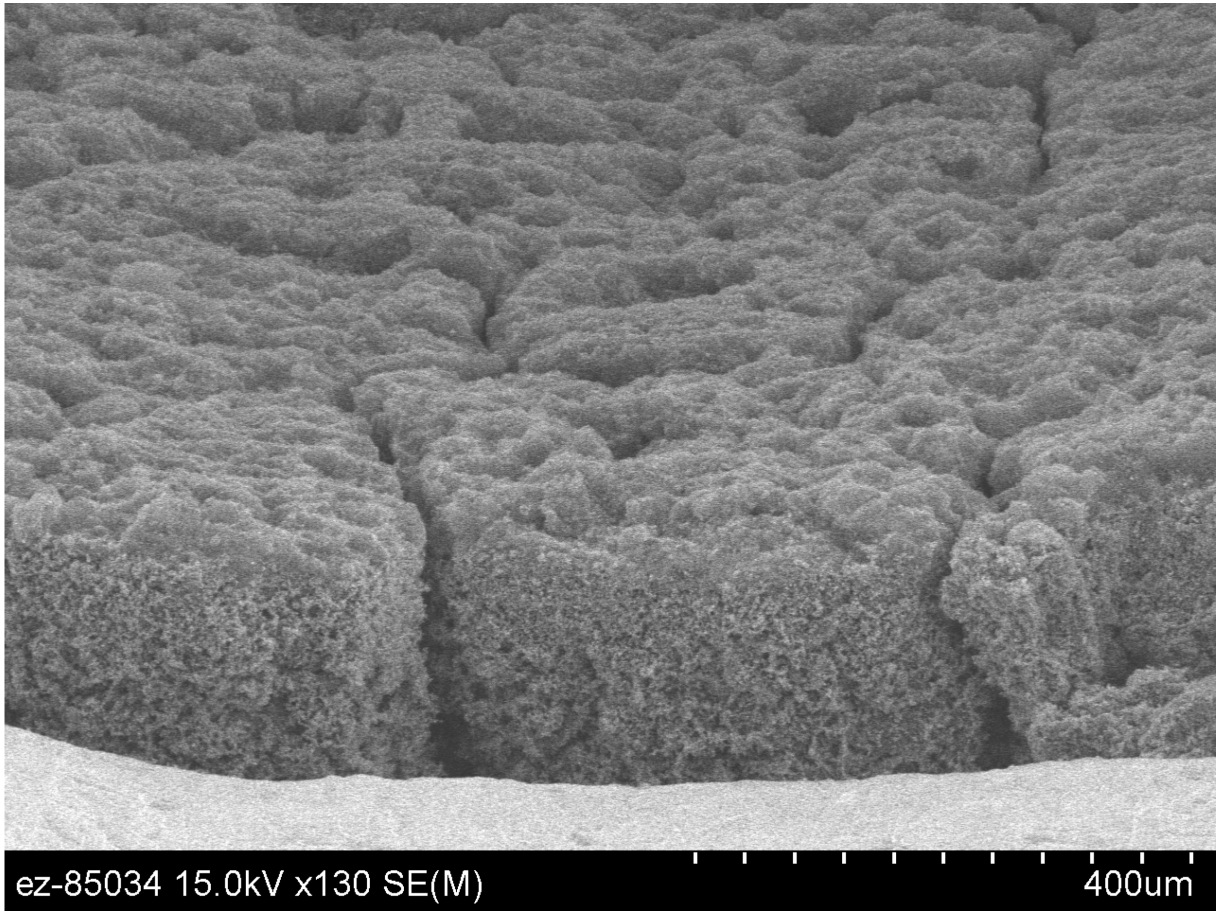


Early-Stage Deposit : ~5% weight loss
Density = 0.032 g/cm^3

Late-Stage Deposit : ~50% weight loss
Density = 0.79 g/cm^3

- The late-stage deposit had 10 times more hydrocarbon and 20 times the density than the early-stage deposit.
- The thermal conductivity of the late-stage deposit is likely to be far higher than the early-stage deposit as well.

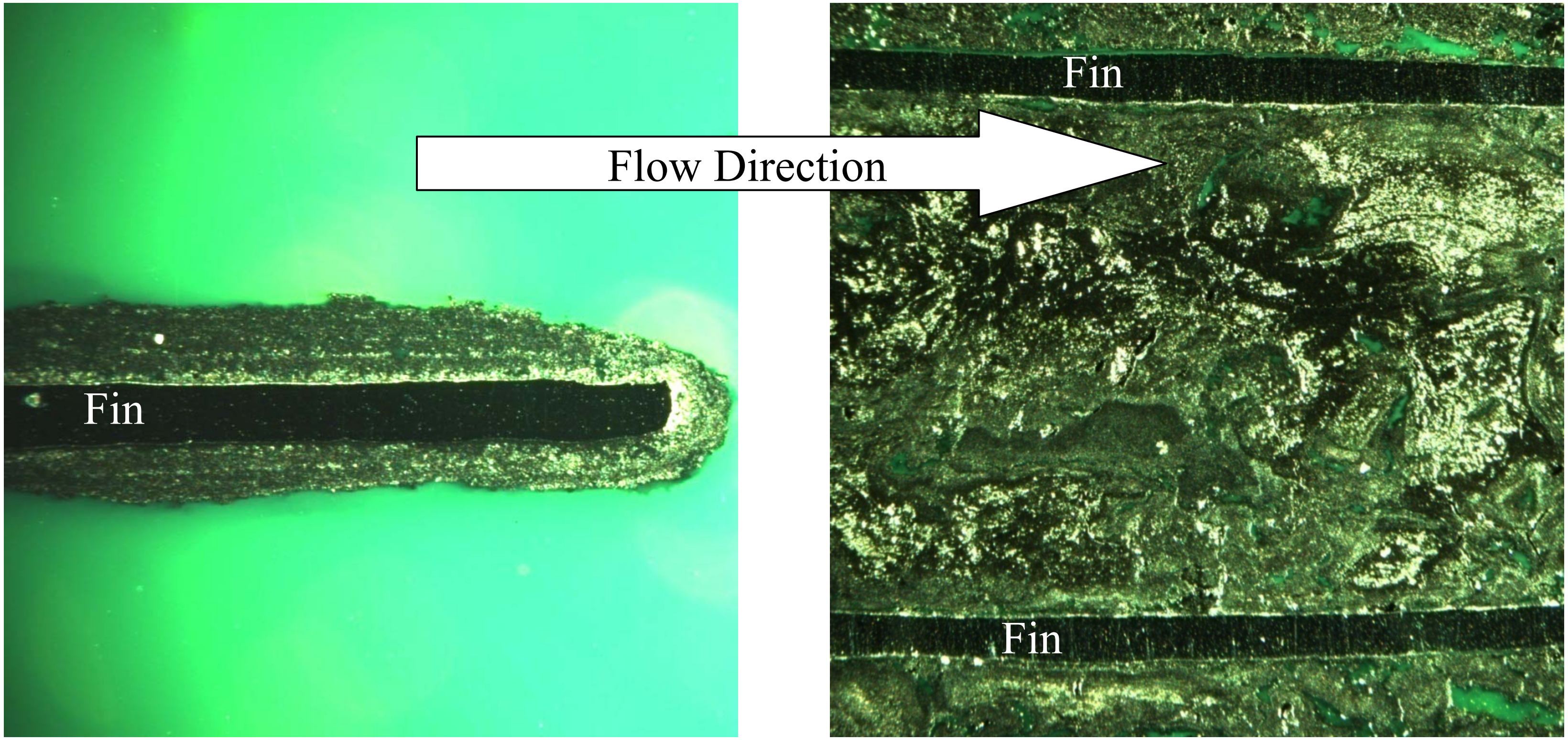
Mud-cracking is observed in many coolers



- Mud-cracking and subsequent spallation of the deposit may be a significant regeneration mechanism.
- Spontaneous regeneration of the EGR cooler has been reported.

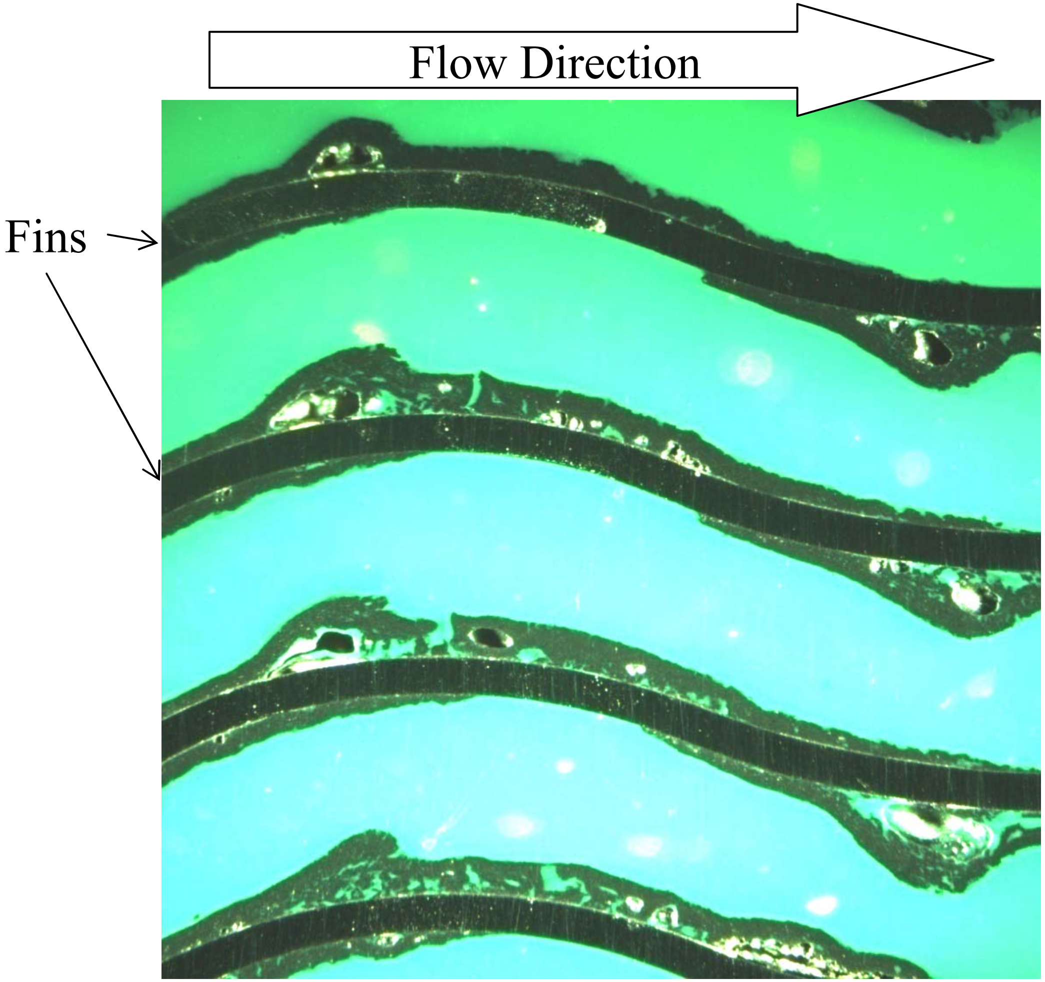
Clogging of Cooler

Near Inlet of Cooler | Near Outlet of Cooler



- Some coolers exhibited significant clogging.
- Here, hydrocarbon-rich strata can be observed in the deposit (left).
- This suggests the importance of HC transients in deposit formation.
- There may be simple changes to the operating conditions that can mitigate problems like this.

Effect of Geometry



- Heat exchanger geometry has an enormous effect on the deposit properties: thickness, porosity, hydrocarbon content.
- Spallation often occurs adjacent to turbulators.

Summary

- A team of industry advisors has been assembled that will help guide future research directions of this pre-competitive research.
- An engine and a sampler tube system for laying down controlled PM deposits is being designed and purchased. A portable gas manifold for controlled post-deposition aging is being built.
- A conceptual model of deposit formation under steady-state conditions has been proposed based on microstructural imaging.
- Comparison between the early-stage and late-stage cooler deposits suggest the importance of aging and transient operation.

Acknowledgements

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Questions?