

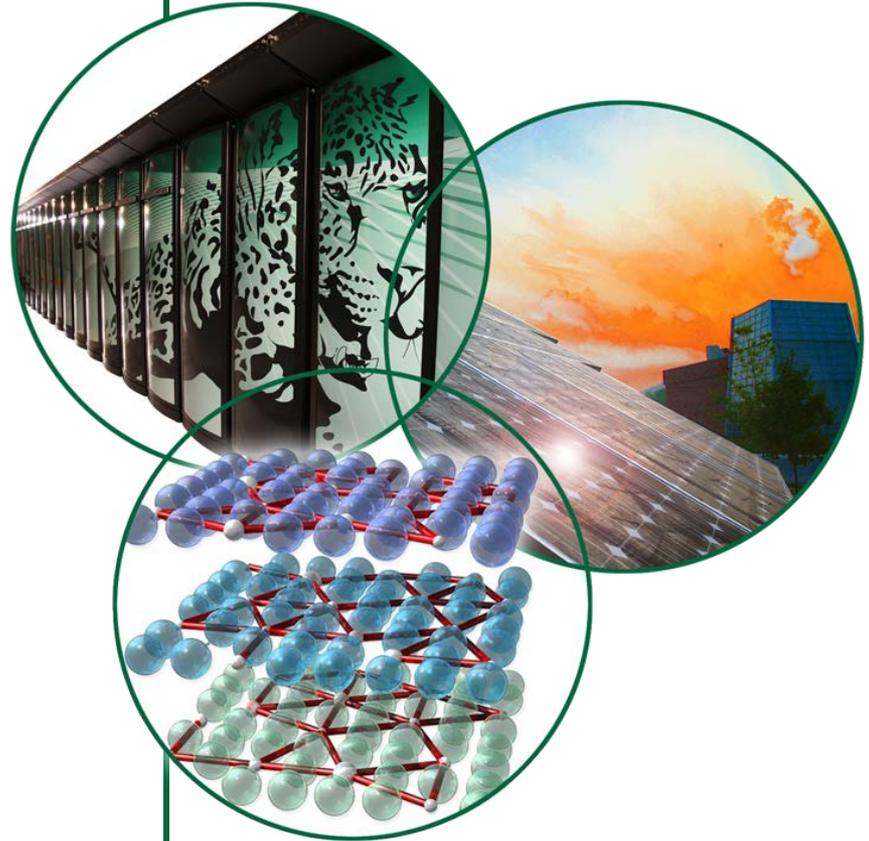
Hydrocarbon and Deposit Morphology Effects on EGR Cooler Deposit Stability and Removal

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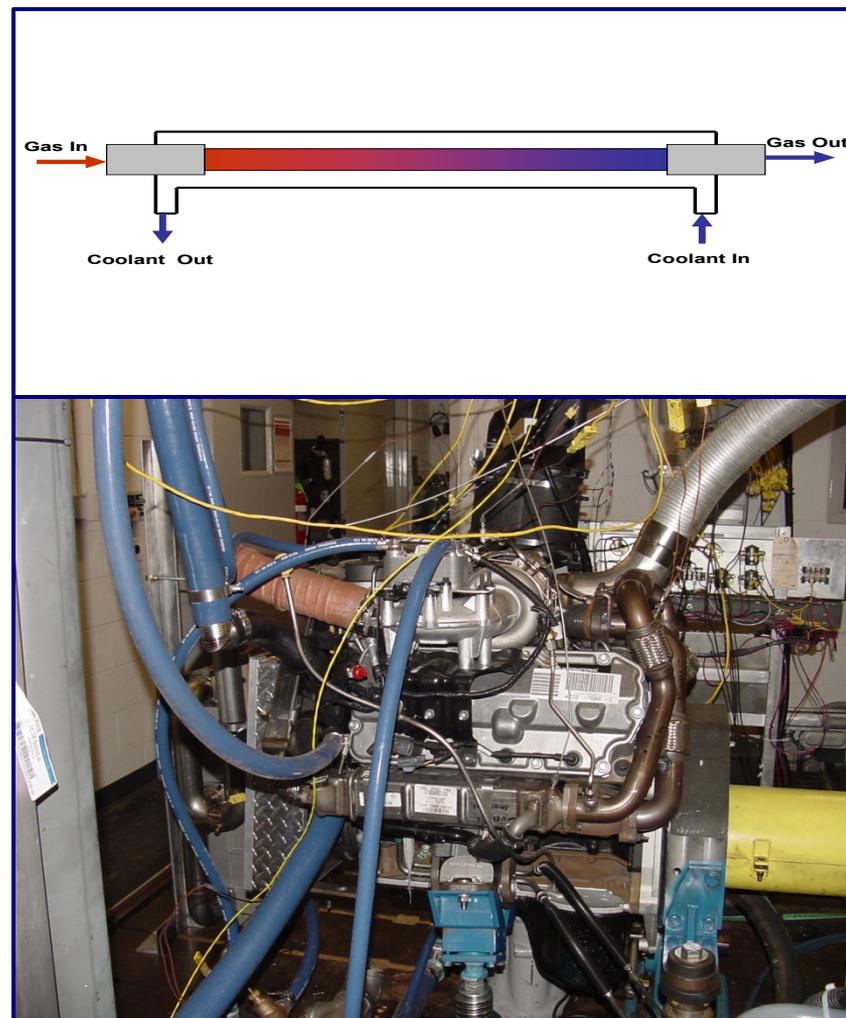
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Surrogate EGR cooler tubes are employed to enable multiple analyses of deposits.

- Ford 6.4-L V-8 used as exhaust generator.
- Surrogate tubes provide more accessible samples for study than full-size coolers.
- Exhaust passed through surrogate EGR cooler tubes at constant flow rate and coolant temperature.
 - Tubes were $\frac{1}{4}$ inch square cross-section stainless tubes.
 - 12.5 inch length.
 - Thermal effectiveness of tubes is assessed during exposure.
- Subsequent analyses of tube deposits:
 - Total mass of deposits
 - Volatile / non-volatile deposit mass
 - GC/MS characterization of the deposit HCs
 - Deposit layer thermal and physical properties



Previous studies have shown fouling to rapidly compromise the thermal effectiveness of EGR coolers.

Effectiveness loss significant within hours.

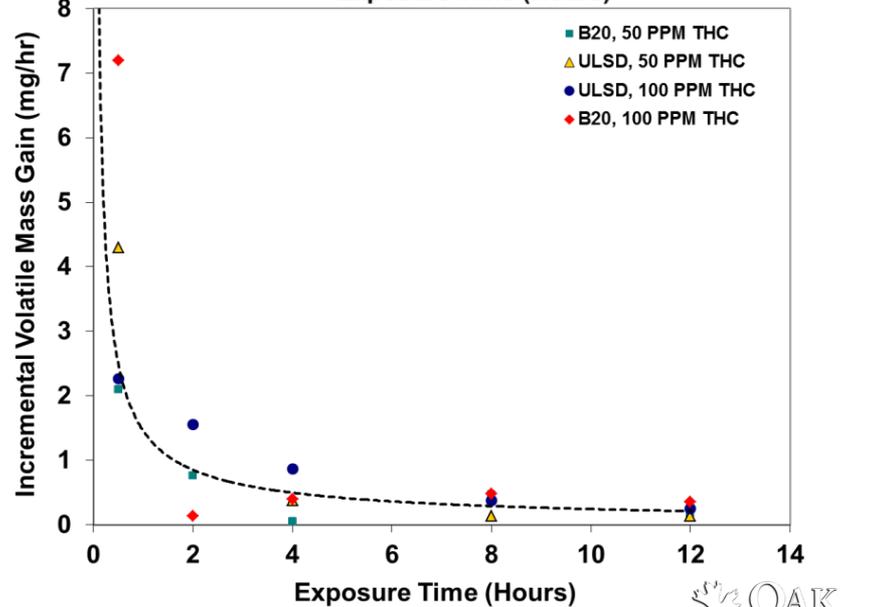
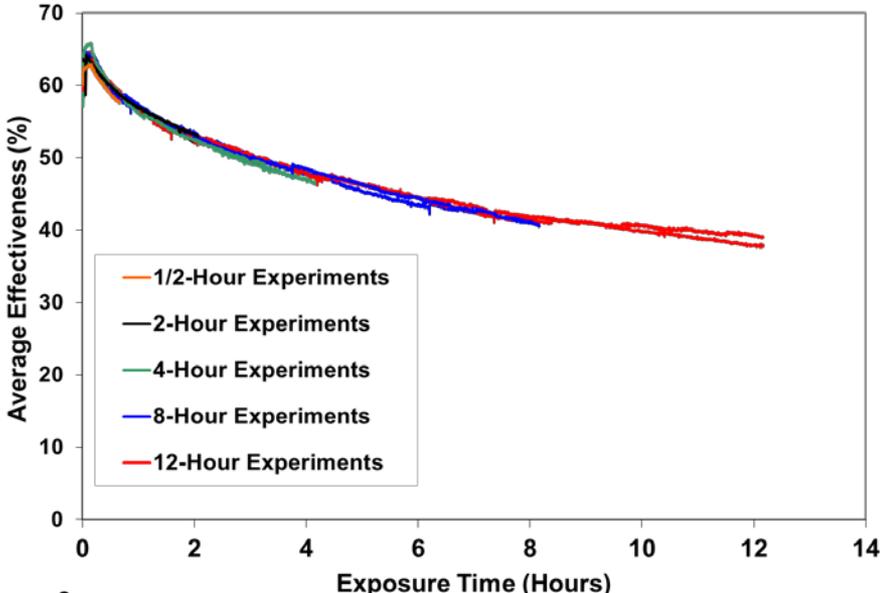
- Curvature of effectiveness-time profile means deposit properties are changing.
- Thermal conductivity similar to engineered insulation.

Hydrocarbon Deposition

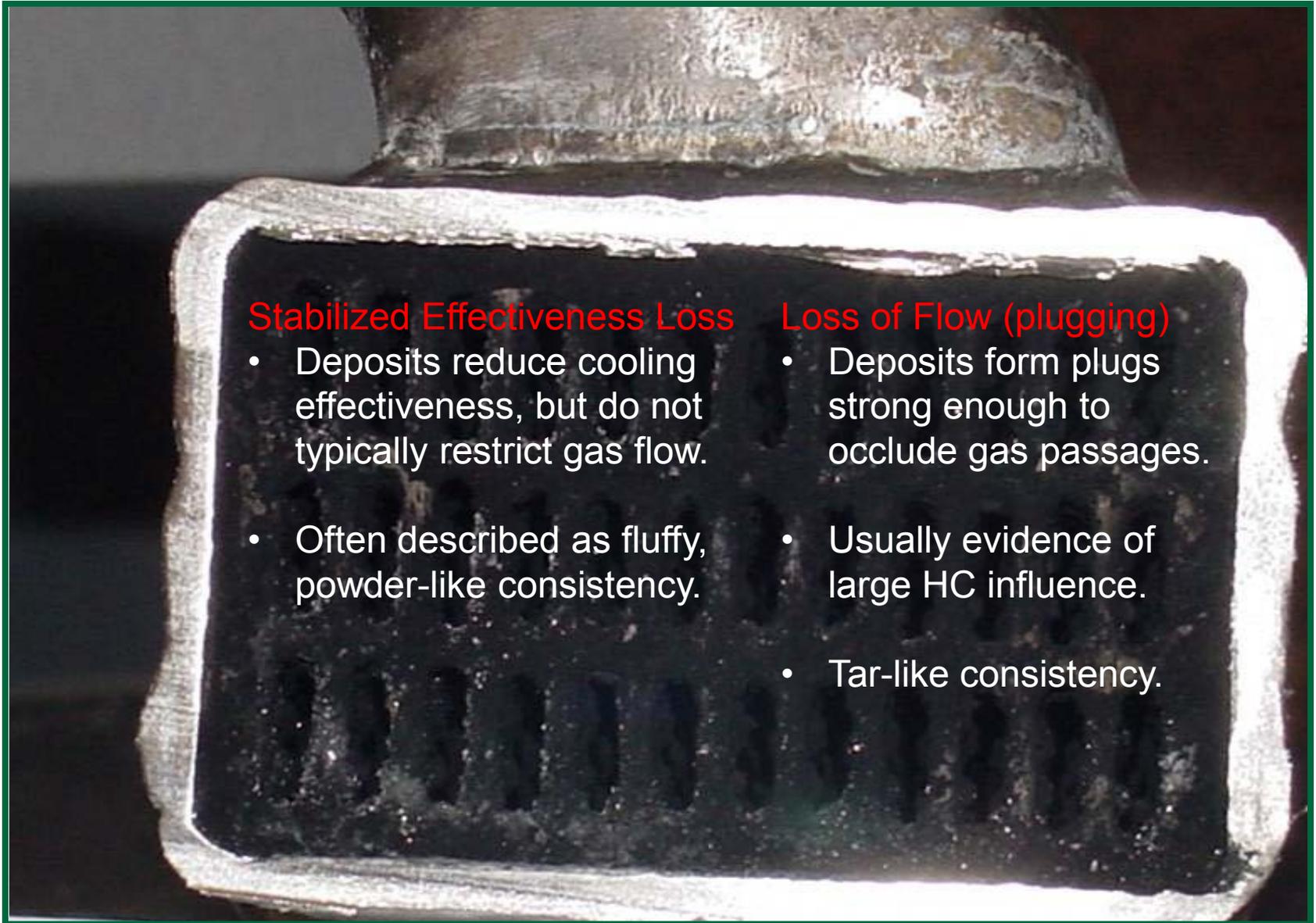
- Initially high, decreases rapidly.
- Formation of high-temperature gradient fouling layer.
- HCs most located near the cold wall; lessens their ability to be significant in terms of deposit properties.

Takes ~6.8g of liquid HCs (SG 0.75) to fill the voids formed by 1g soot.

- Most deposits have more soot than HCs.



Fouling usually leads to one of two potential failure modes:



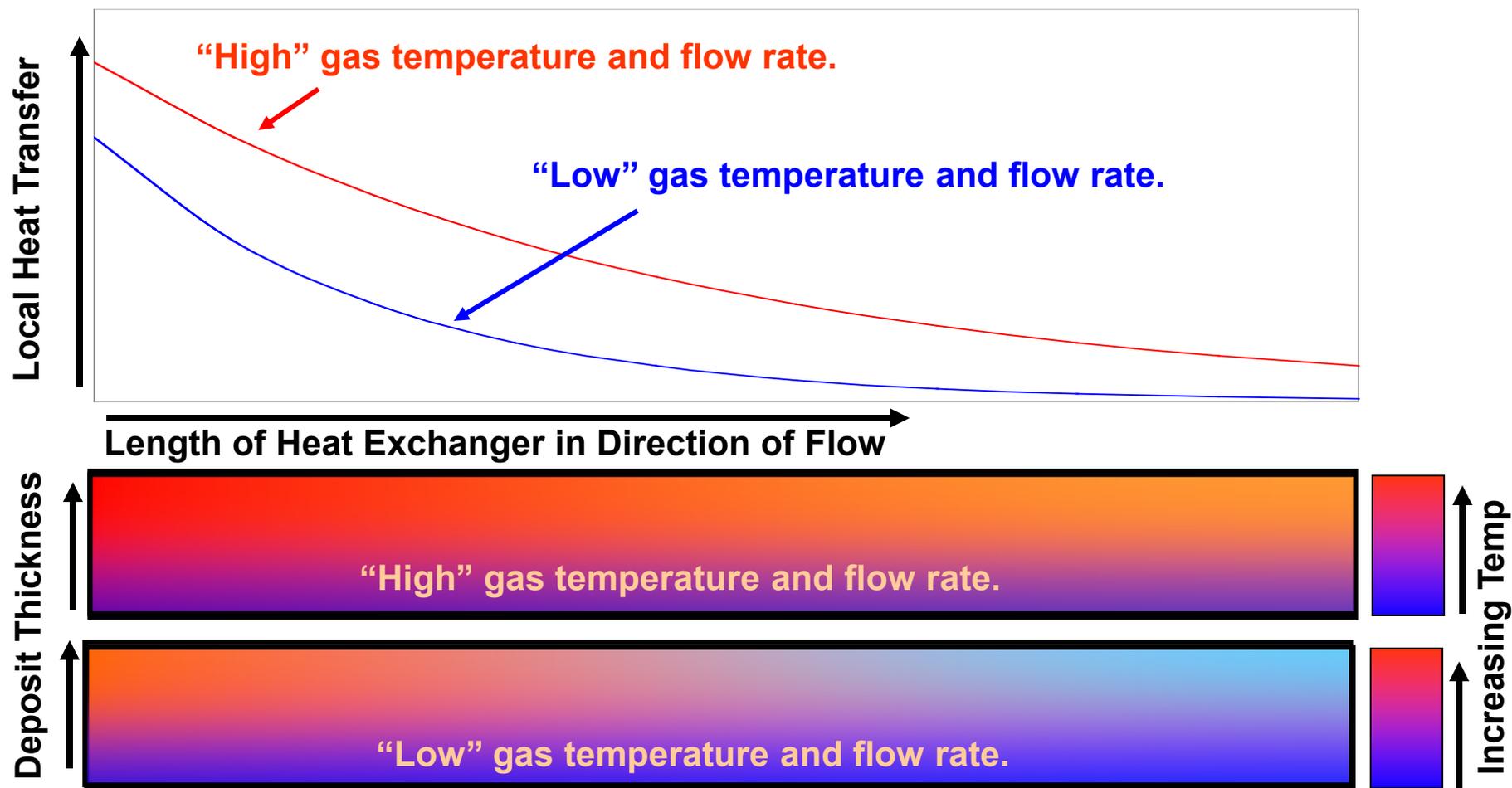
Stabilized Effectiveness Loss

- Deposits reduce cooling effectiveness, but do not typically restrict gas flow.
- Often described as fluffy, powder-like consistency.

Loss of Flow (plugging)

- Deposits form plugs strong enough to occlude gas passages.
- Usually evidence of large HC influence.
- Tar-like consistency.

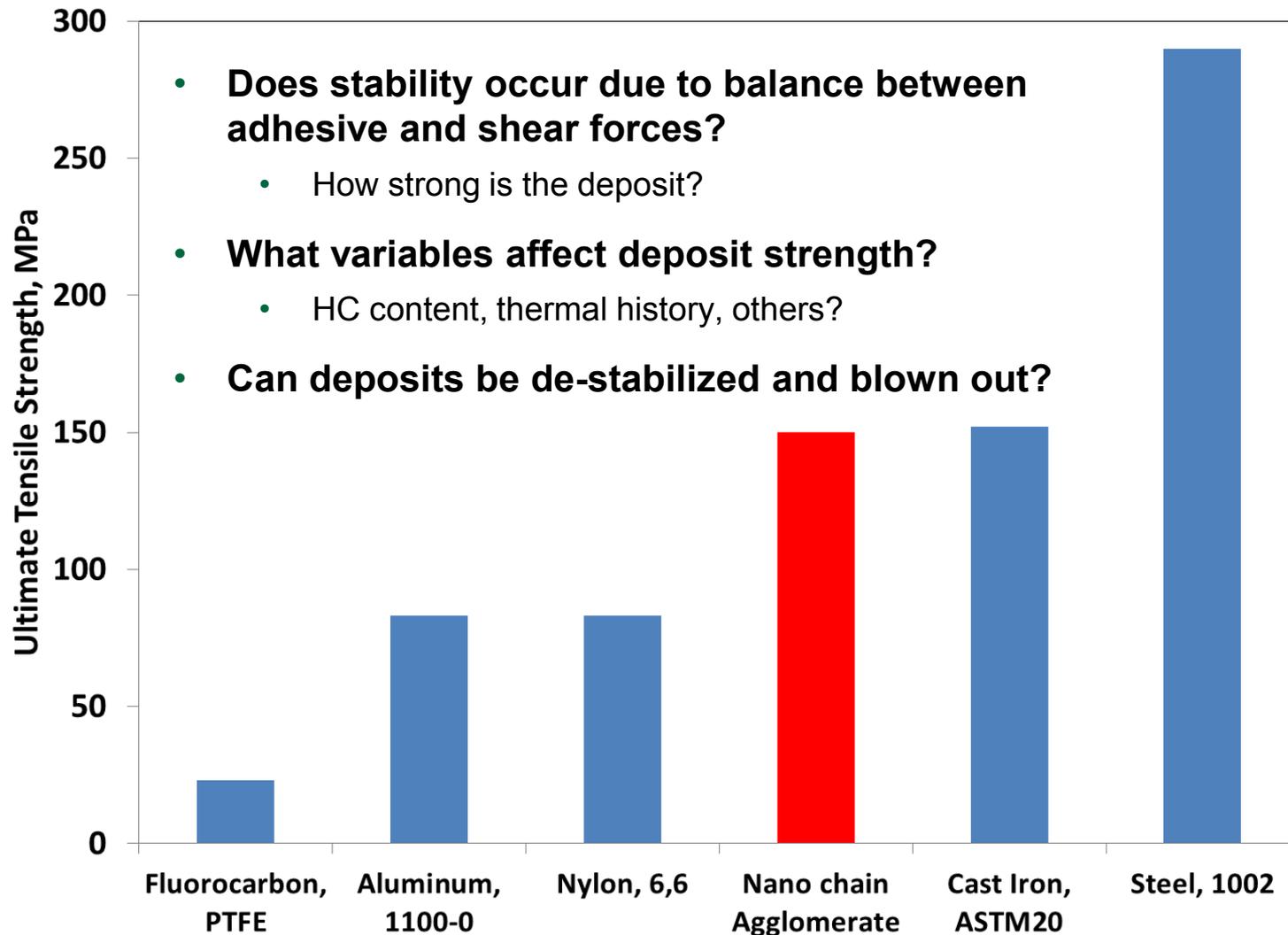
How can deposits high in HC content form?



Use of a “large” heat exchanger at “low” heat transfer conditions may result in deposit layer temperatures conducive to HC deposition.

Conditions such as drop-to-idle or cold start may result in thermally and physically significant deposit HC levels and may be impacted by fuel chemistry.

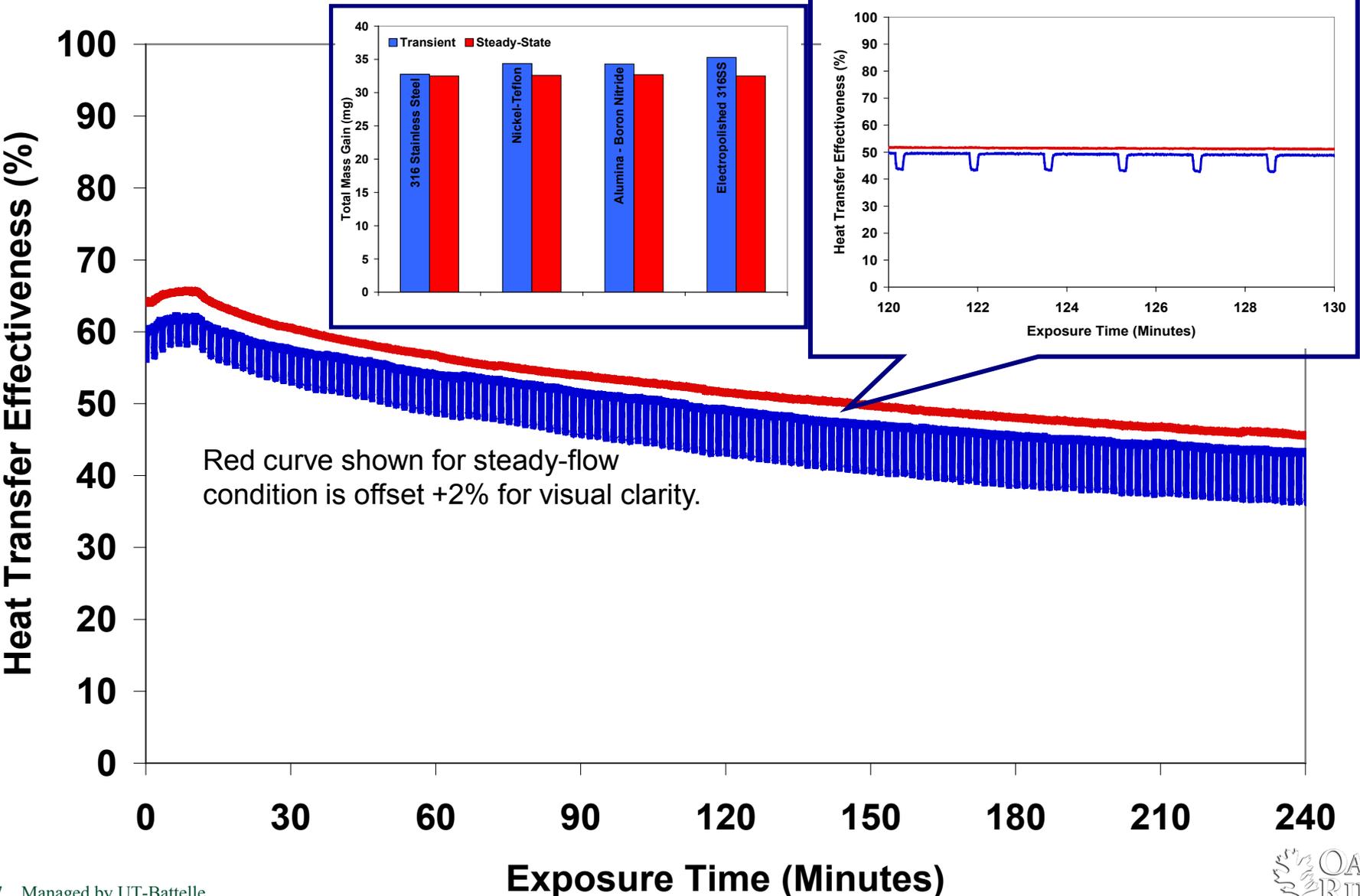
Deposit removal may be a key link in understanding cooler stability and plugging processes.



NCA data from Rong et al, "Mechanical Properties of Nanoparticle Chain Aggregates by Combined AFM and SEM: Isolated Aggregates and Networks," Nano Letters 2006, Vol.6, No. 12, pp 2646-2655.

Comparative materials data from Juvinall and Marshek, Fundamentals of Machine Component Design, 2nd Edition, 1991.

Doubling the gas velocity periodically during fouling to increase shear forces at deposit interface resulted in increased deposition, rather than removal of deposits.



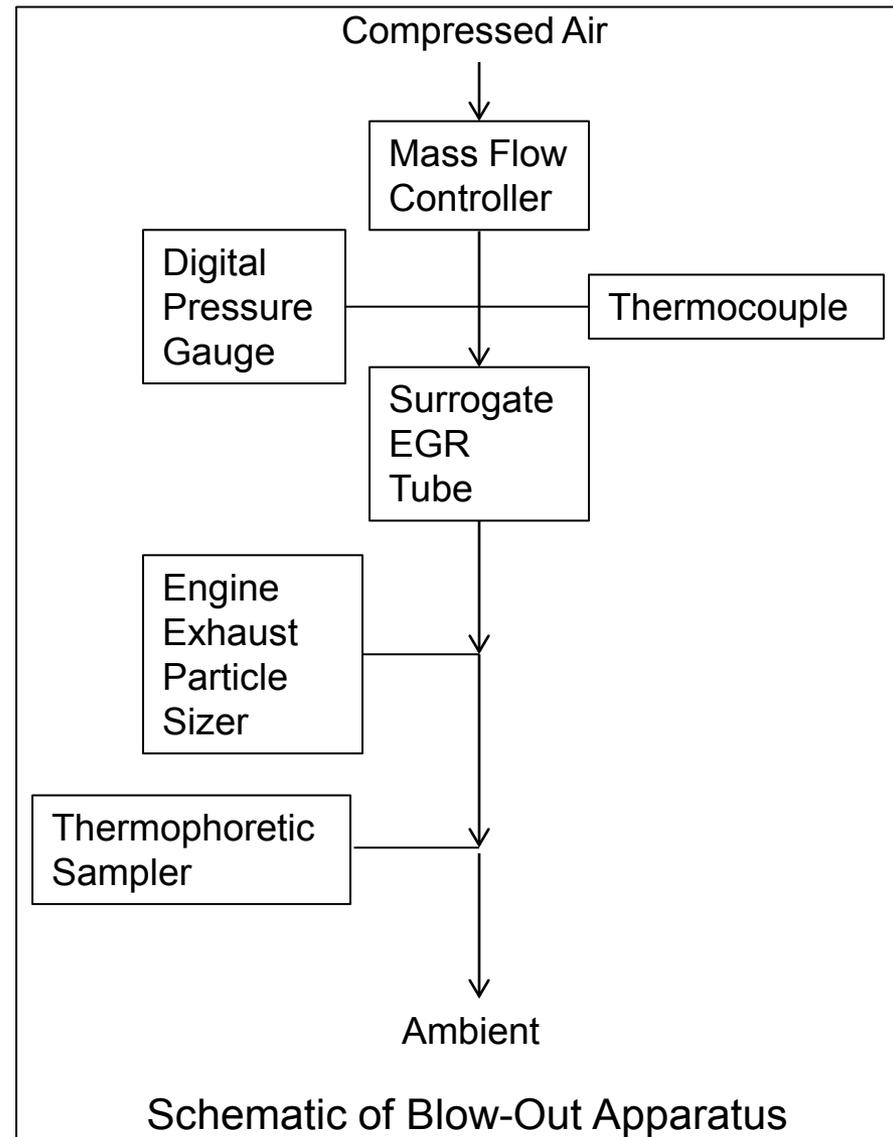
A series of tubes were fouled to produce samples that were used to examine particle spallation at high gas velocities.

Fouling Conditions:

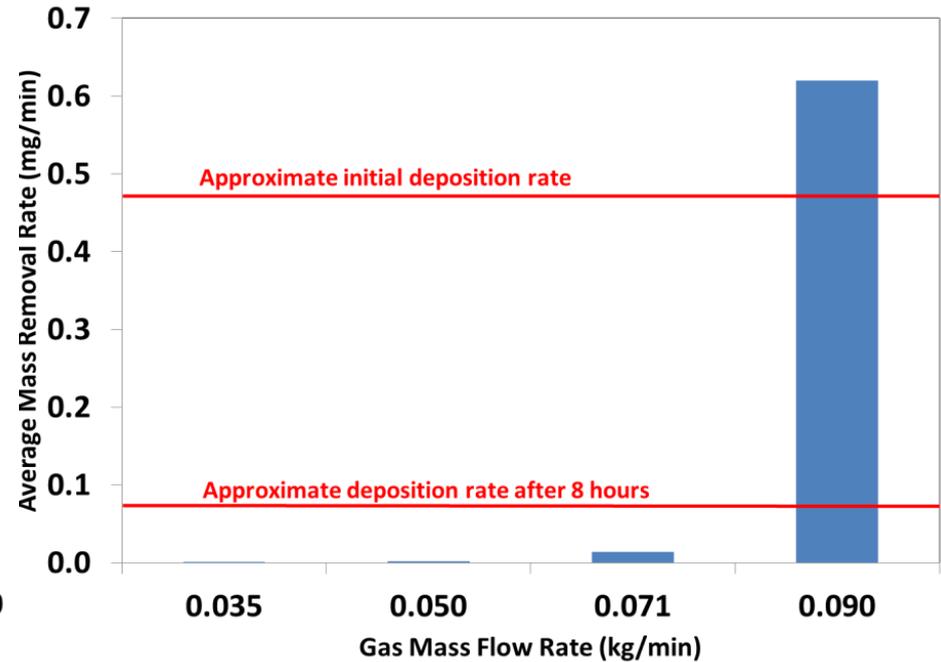
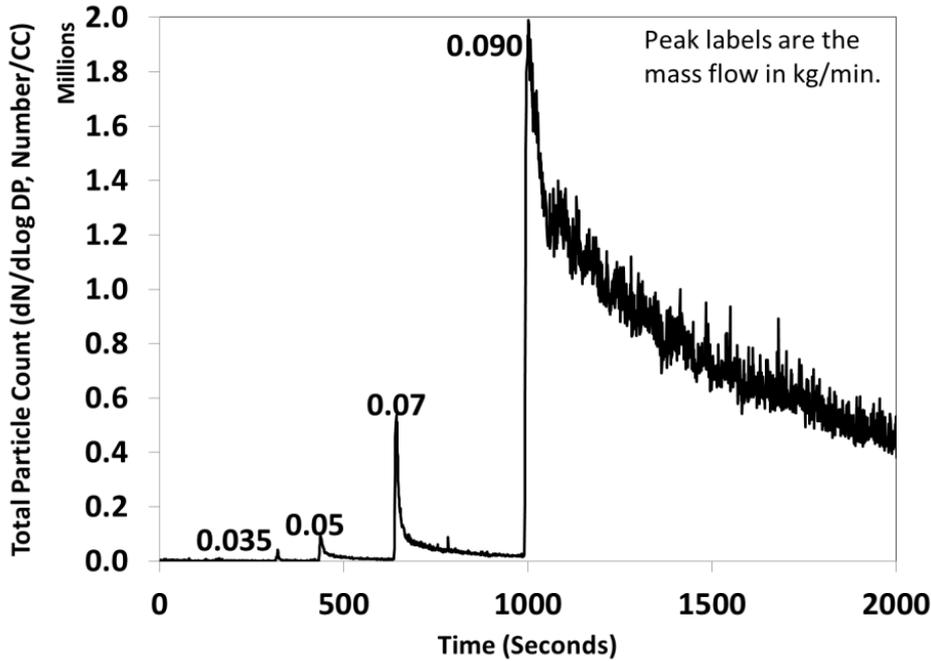
- 375 C Gas Inlet, 90 C coolant
- 0.05 kg/min/tube gas flow
- 1.5 FSN, 40 PPM (C₁) HCs
- 8 Hours Exposure

Average deposit:

- Mass: 60 mg
- Volatile fraction: 6%
- Thickness: 300 microns
- Effectiveness Loss: 24%



Spallation of tube deposits was successfully observed.



Spalling of Particles

- Significant beginning at
 - 0.071 kg/min
 - 45 m/s gas velocity
- Insignificant at flows comparable to or lower than the deposition flow rate.
 - 25 m/s at end of fouling period.
- Peak number concentration and total spalls released follow an exponential trend with increasing mass flow rate.
- Following the peak concentration, spallation decays as an exponential function of time.

Preliminary data with PM-dominated deposits suggests that deposit thermochemical history effects stability under shear.

Nascent and 200C case have similar mass removal.

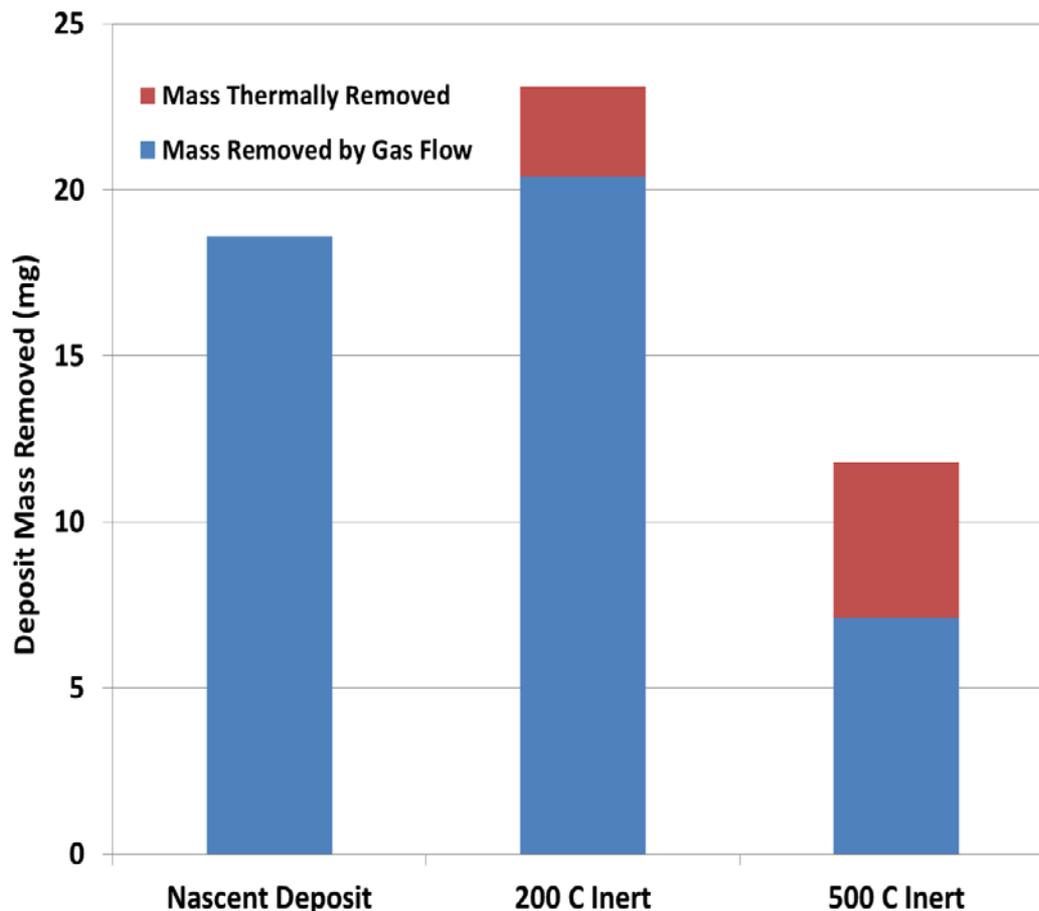
- Consistent with HCs limited to the deposit “near” the tube wall.

500C case showed much less mass removal.

- Unexpected
- Suggests sintering of the deposit.
- Higher resistance to shear.
- May enable other removal processes that require a less frangible deposit.

Experiments with deposits with considerable HC content are underway.

- 50% or more HC content.
- Low temp, low flow, moderate HC and PM.



- Flow removal by compressed air at 90 g/min for 30 min.
- HC removal under argon for 3 hours at either 200C or 500C.
- 500C removal included hold at 200C for one hour prior to increase and hold at 500C.

Spalls from the deposit are not simply re-entrained diesel particulate.

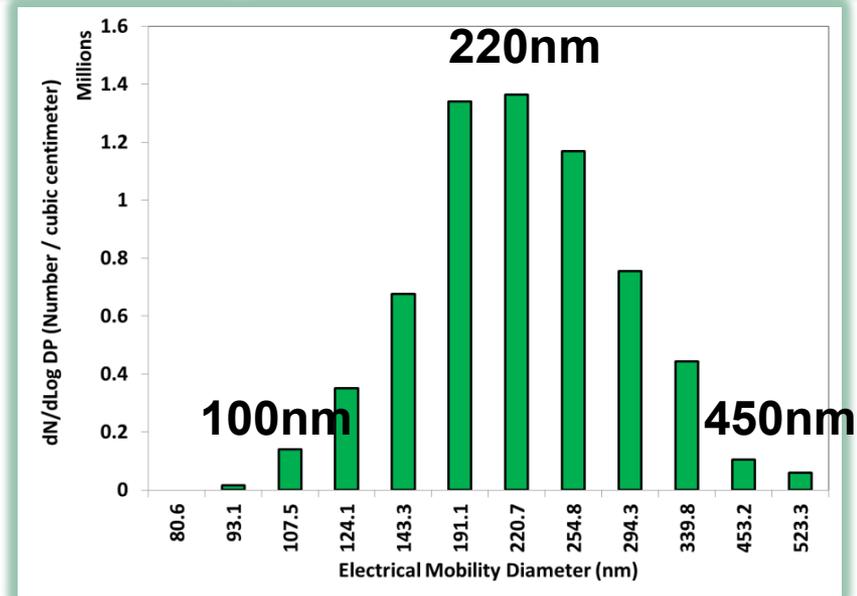
Image of a spall

1 μm

Deposit before spallation

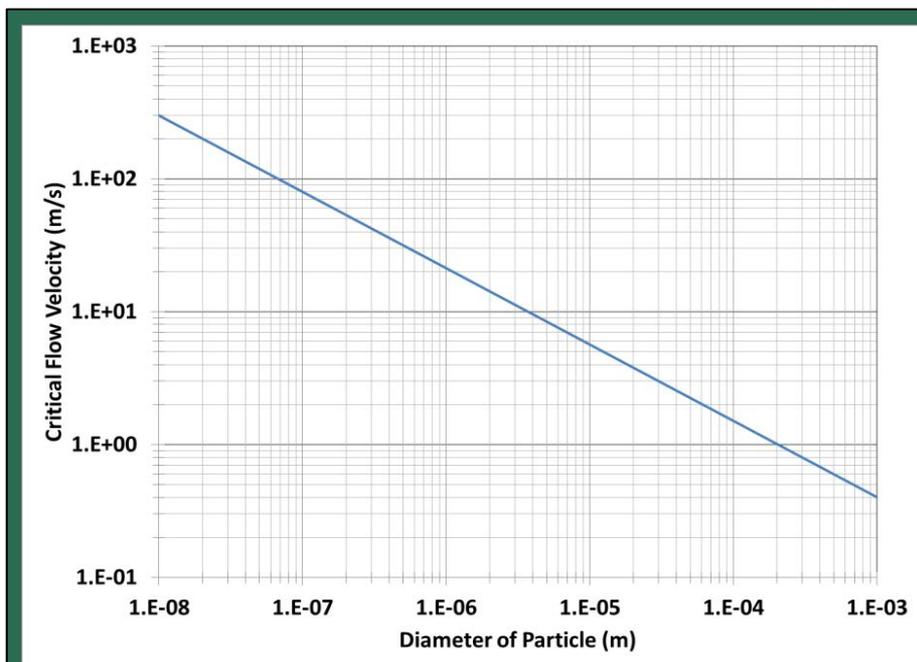
Deposit after spallation

- Spalls are much larger than typical diesel particulates.
- Areas experiencing spallation become rougher than the parent deposit.
 - Less pronounced in the sample treated at 500 C after fouling.
- Observations point to the formation of a cohesive deposit even during short time periods.



Several studies have suggested that particle trapping in the deposit is a balance between deposition and removal during the fouling process.

- Many studies have shown that particle retention or trapping efficiency declines as gas velocity increases.
- Several studies point to a “critical rolling velocity”.
 - Suggest that flow-induced shear can roll particles away and re-entrain them in the flow.
- Studies to date have measured the change in fouling with velocity, but have not measured particle removal from deposit layers.



Redrawn from M.S. Abd-Elhady et al, “Influence of gas velocity on particulate fouling of exhaust gas recirculation coolers,” International Journal of Heat and Mass Transfer 54 (2011) 838-846.

- Glass and metal spheres ($D > 5 \mu\text{m}$), not carbon particulate.
- “Analysis limited to spherical, non-charged particles”.

M.S. Abd-Elhady et al, “Minimum gas speed in heat exchangers to avoid particulate fouling,” International Journal of Heat and Mass Transfer 47 (2004) 3943-3955.

No proven linkage yet that low fouling at high gas velocities results from deposit re-entrainment/removal.

Positive: Velocity shown for spallation is lower than predicted velocity for lack of fouling.

- 55 m/s for spallation
- 80 m/s critical rolling velocity for 100nm spherical particle

Negative: 55 m/s gas velocity hasn't been shown to avoid fouling, and still has significant pressure loss.

- Sensitivity of spallation velocity to deposit thickness?
- Malayeri et al. (2010) observed fouling at 120 m/s with CAST soot

So: Does spallation occur during fouling?

- Not observed to date.
- Likely requires higher flow rates.

Take-away: Need to exercise caution in applying the critical rolling velocity model to carbon particulate.

- Electrostatic charges.
- Potentially chemically reactive.
- Not spheres, but interlocking chains.
- Spalls are not typical particulate and are also not spheres.

Conclusions and Future Plans

- Spallation can occur at velocities > 45 m/s.
- Amount of removal increases exponentially with the velocity.
- Spalls are not typical diesel particulates.
- Mass removal is not simply re-entrainment of incident particles.
- Thermochemical history of the deposit is important.
- Relationship between spallation and observations of lack of fouling are not clear.
- Future plans
 - Low-temperature conditions (plugging)
 - HC content, including different fuels
 - More flow rates
 - More deposit layer thicknesses