Fuel-Neutral Studies of Particulate Matter Transport Emissions

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Pacific Northwest National Laboratory

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PNNL

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Overview

Timeline

- Start - June 2008
- End - September 2012
- 60% percent complete

Budget

- Total project funding
  - DOE - $800K
- Funding received to date
  - FY08 - $100K
  - FY09 - $100K
  - FY10 - $200K
- Funding for FY11 - $200K

Barriers

- Barriers addressed
  - B. Lack of cost-effective emission control
  - C. Lack of modeling capability for combustion and emission control
  - F. Lack of actual emissions data on pre-commercial and future combustion engines

Partners

- General Motors Company - provide project guidance, provide hardware to ERC
- Engine Research Center at University of Wisconsin, Madison - host and operate test engine

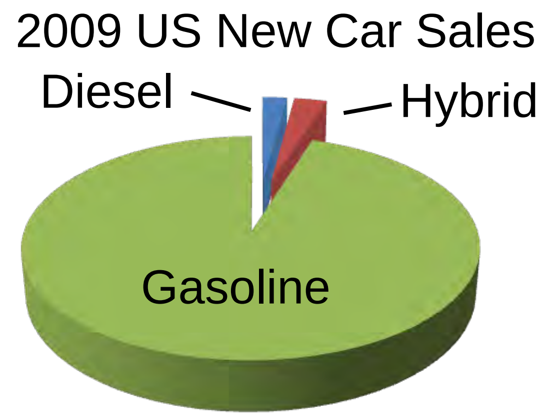
Project relevance

Background

- Gasoline Direct Injection (or Spark Ignition Direct Injection) has the potential to significantly increase the fuel efficiency of light duty vehicles
- Lean combustion more like Diesel cycle implies more particulate generation than current gasoline engines
- Particulates are likely to be smaller than those generated by diesel engines, possibly making it difficult to meet proposed number-based standards
- Optimum systems will probably not simply copy DPF implementations on diesel vehicles
  - Lower overall particulate mass production
  - Higher exhaust temps may make passive regeneration practical with close-coupled filters

Objectives

- Characterize exhaust particulates from advanced combustion engines using readily available fuel blends
- Use insight gained and prior experience with Diesel aftertreatment to jump-start development of optimum aftertreatment technologies *in case they are needed*



Data from edmunds.com

Chevy Traverse with 3.6L VVT DI High Feature V6

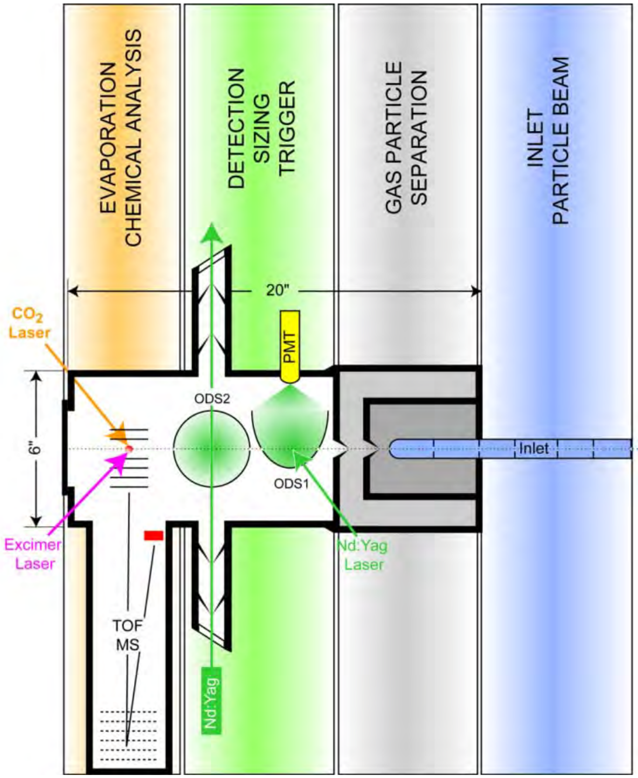
Upcoming milestones

Month/Year	Milestone or Go/No-Go Decision
April - 2011	Go/No-Go decision: Evaluate repeatability of post-rebuild single cylinder test engine with a range of fuels including ethanol blends
April - 2011	A paper based on the results from the FY09 experiments will be presented at the SAE 2011 World Congress & Exhibition (SAE 2011-01-1220)
June - 2011	Submit 2 papers to peer-reviewed journals
June - 2011	Perform second round of cooperative experiments with SPLAT at University of Wisconsin Engine Research Center
December - 2011	Complete analysis of data from cooperative experiments

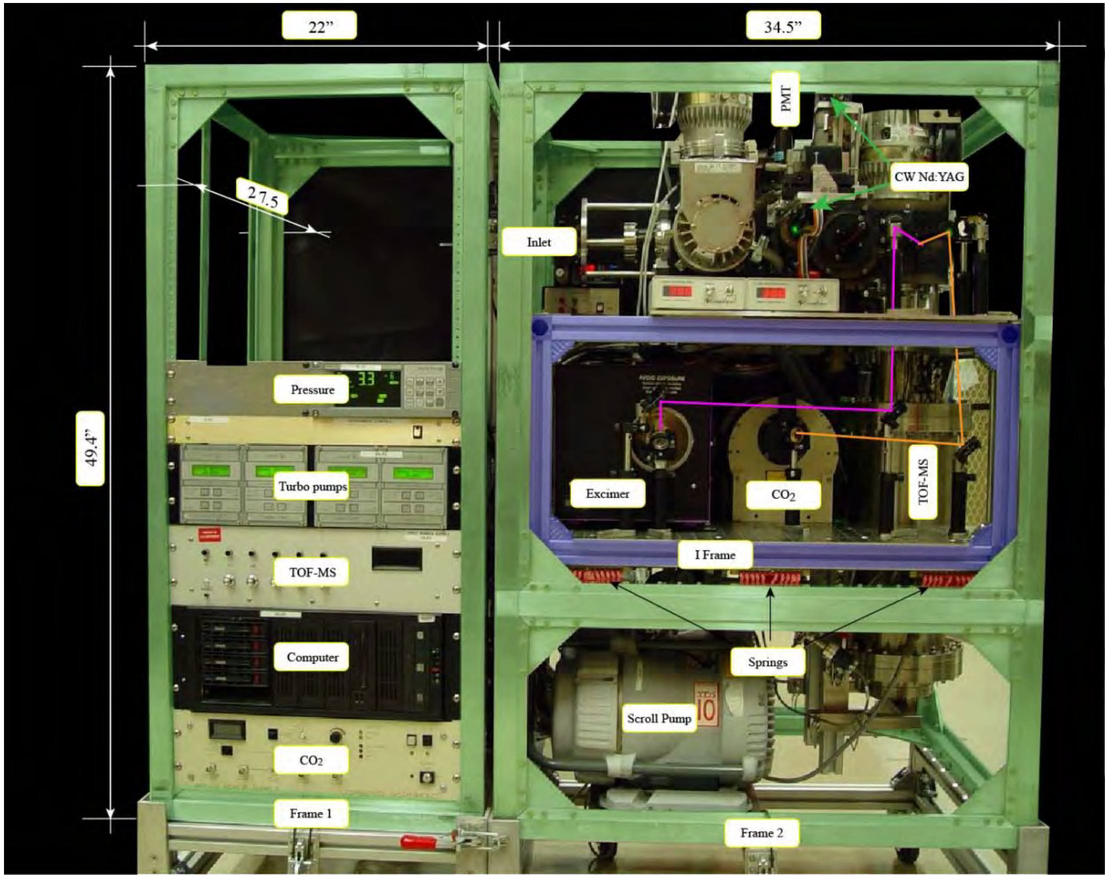
Approach

- Single cylinder SIDI test engine at University of Wisconsin Engine Research Center - Guidance and hardware from GM
- SIDI exhaust particulate characterization
  - Standard instruments (e.g. smoke meter, SMPS)
  - Advanced analyses including SPLAT II
  - Effect of thermo-denuder and evaporative chamber - relevant to proposed number certification tests
  - Advanced TEM analysis with Randy Vander Wal of Penn State
- Parallel efforts
  - Lab filtration studies
  - Effect of filter coatings on filtration performance
  - Unit collector modeling
  - Pore-scale simulation

Approach - Joint experiments with SPLAT II



- ✓ Size
- ✓ Composition
- ✓ Density
- ✓ Number concentration
- ✓ Morphology
- ✓ Shape (dynamic shape factor, asphericity, asymmetry)
- ✓ Hygroscopicity
- ✓ Fractal dimension



- High detection efficiency – 50% @ *d*=85nm, 100% @ *d*≥125 nm
- High temporal resolution – up to 100 particles/second.

Approach - Test engine

- Single cylinder research engine
- Spark Ignited Direct Injection (SIDI)
- Spray-guided (flat top cylinder)

Geometry	English	SI
CR	11.97	
Bore [in, mm]	3.3842	85.96
Stroke [in, mm]	3.72"	94.6
Disp [in^3, cm^3]	32.89	549.0
Clearance Vol [in3, cm3]	3.05	50.0
Conn. Rod [in, mm]	6.00	152.4

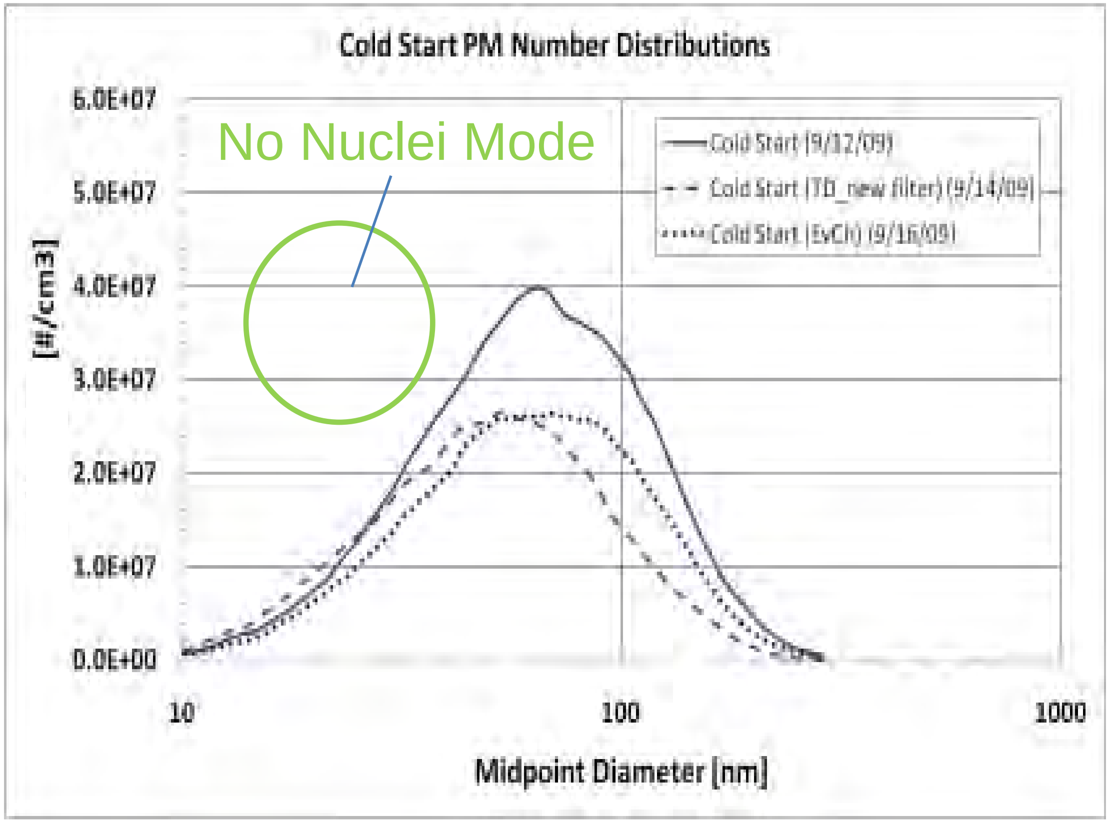
Accomplishments - Experimental matrix for first round of cooperative experiments

- A large dataset (~70 runs) was acquired at ERC in Sept. 2009
- Particulate emitted during each of the engine operating conditions were characterized by sampling
  - Directly after the dilution tunnel
  - After thermal denuder (TD)
  - After evaporative chamber (EvCh)

Condition	Speed	Injection Timing	Fuel Quantity	AF	Spark Advance	Injection Pressure	Intake Temp.	Oil Temp.	Coolant Temp.
	[RPM]	[°bTDC]	[mg/cyc]	[-]	[°bTDC]	[MPa]	[°C]	[°C]	[°C]
Baseline	2000	280	11	15	25	11	45	90	90
Early EOI	2000	**330**	11	15	25	11	45	90	90
Late EOI	2000	**100**	11	15	25	11	45	90	90
Medium Load	2000	280	**16**	15	**23 (knock limit)**	11	45	90	90
Heavy Load	2000	280	**21**	15	**18 (knock limit)**	11	45	90	90
Lean	2000	280	11	**18**	25	11	45	90	90
Rich	2000	280	11	**13**	25	11	45	90	90
MBT-15	2000	280	11	15	**10**	11	45	90	90
Medium Rail Press.	2000	**100**	11	15	25	**8**	45	90	90
Low Rail Press.	2000	**100**	11	15	25	**4**	45	90	90
Cold Start	2000	80	11	15	25	11	**30**	**30**	**30**
Hot Firing	2000	280	11	15	25	11	**95**	**95**	**95**

Joint experiments at U of Wisc ERC - Results (1)

- Untreated diluted diesel exhaust often exhibits a large peak around the primary particle size
- No peaks indicating a significant nucleation mode were observed from the SIDI engine under any conditions studied



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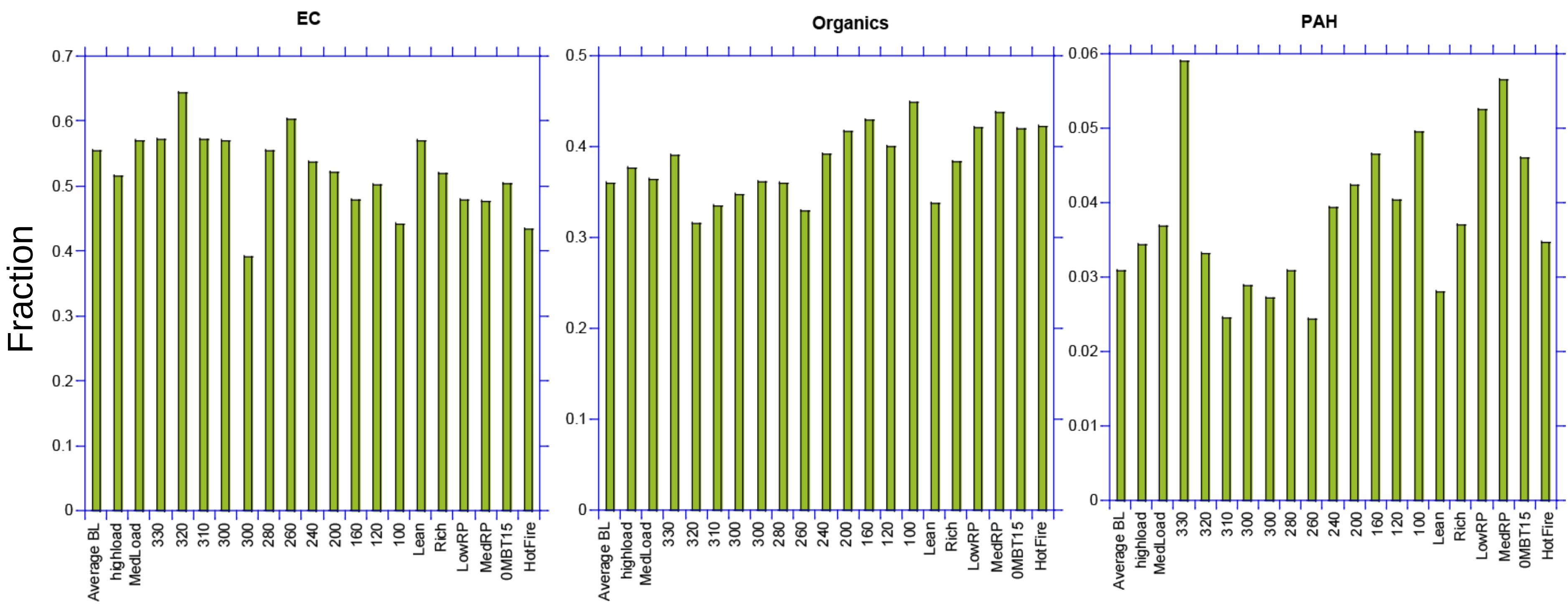
Joint experiments at U of Wisc ERC - Results (2)



- Particles contained elemental carbon, organics, PAHs, and inorganics
- All components seemed to be internally mixed and tightly bound toegher within the same fractal structures
- New engine oil temporarily increased organic content

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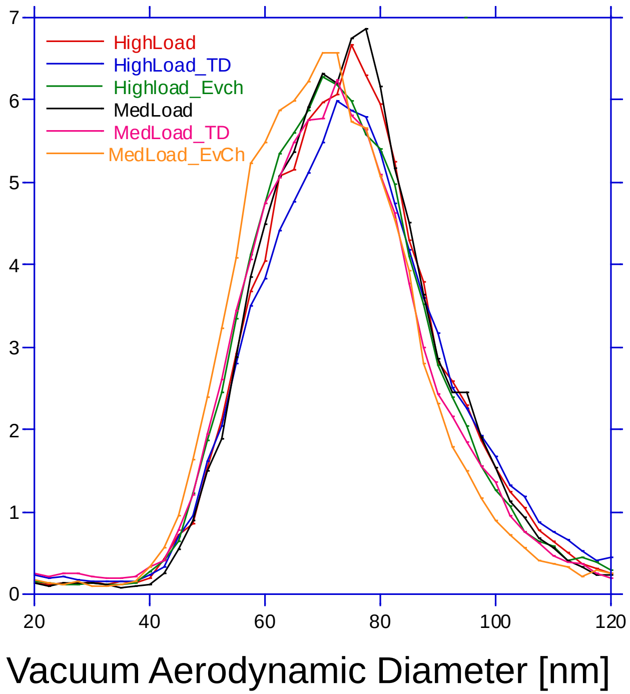
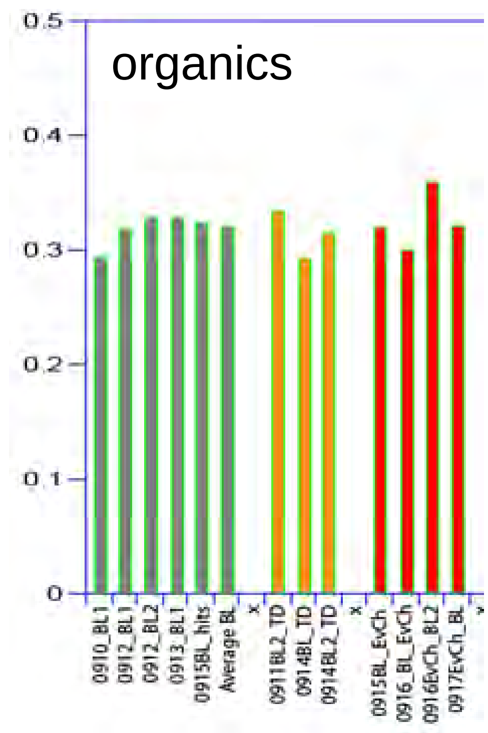
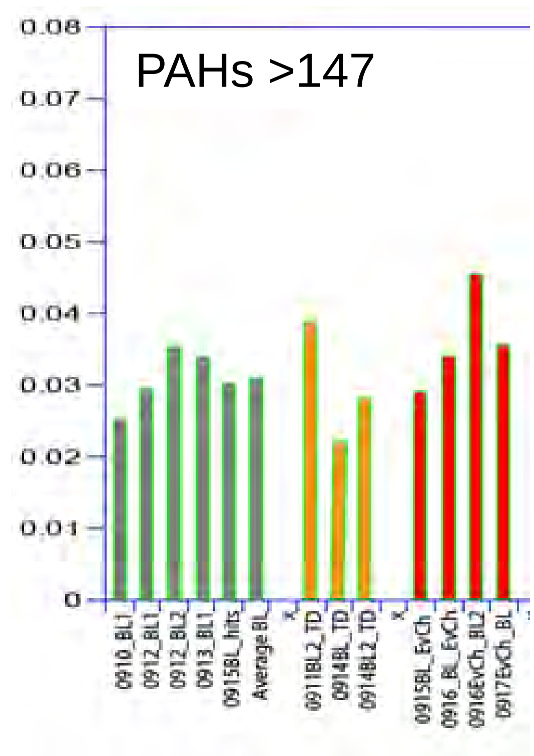
Joint experiments at U of Wisc ERC - Results (3)

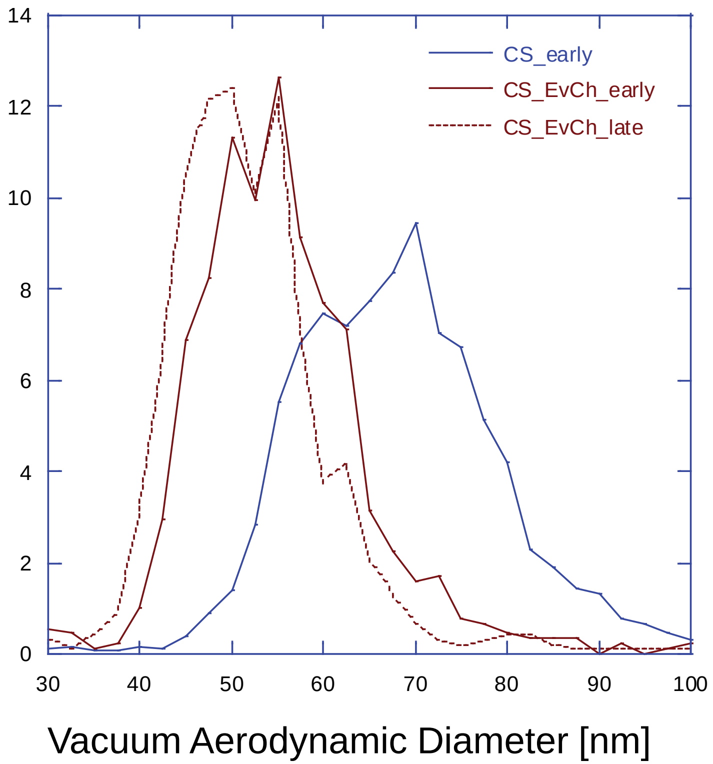


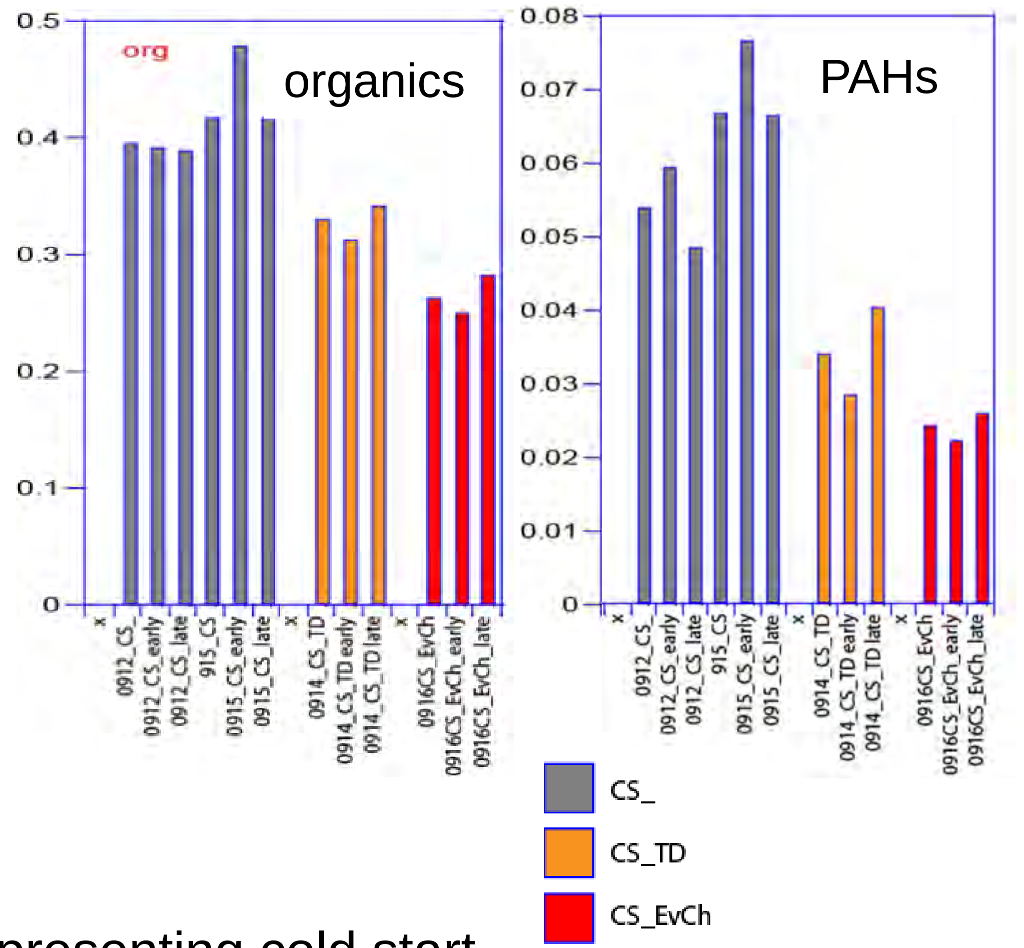




- Proposed particle number regs for diesel include volatile particle removal (VPR) methods in testing protocols
- Neither thermodenuder (TD) or evaporative chamber (EvCh) significantly altered SIDI particle size distribution or composition under *most* conditions

Joint experiments at U of Wisc ERC - Results (4)





- Only exception was condition representing cold start
- Both VPR methods altered size distribution and composition
- 6.6% reduction in organics with TD, 13.1% with EvCh

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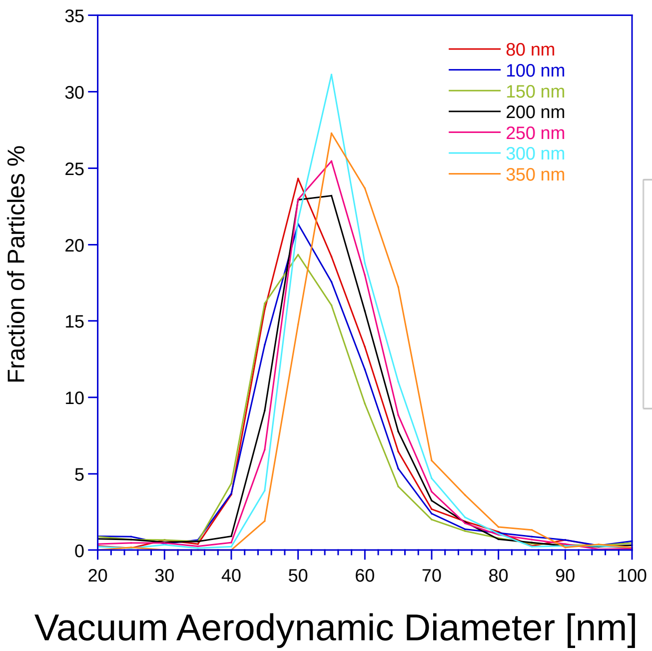
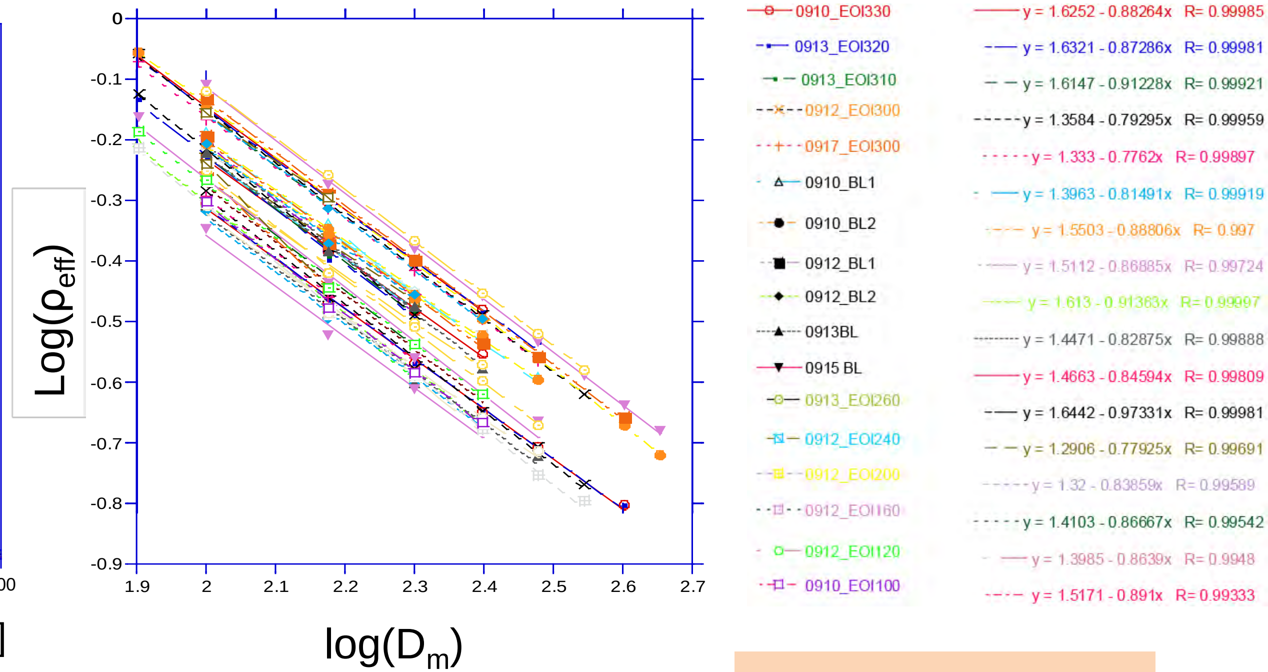
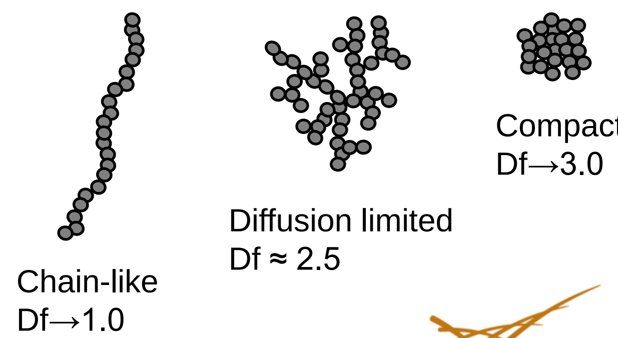
Joint experiments at U of Wisc ERC - Results (5)





- Distribution of aerodynamic diameters for particles classified by mobility diameter indicates range of particle shapes
- Fractal dimension can be estimated by comparing particle effective density to mobility diameter
- Fractal dimension for all conditions (w and w/o VPR) fall within the range 2.03-2.22

Fractal dimension



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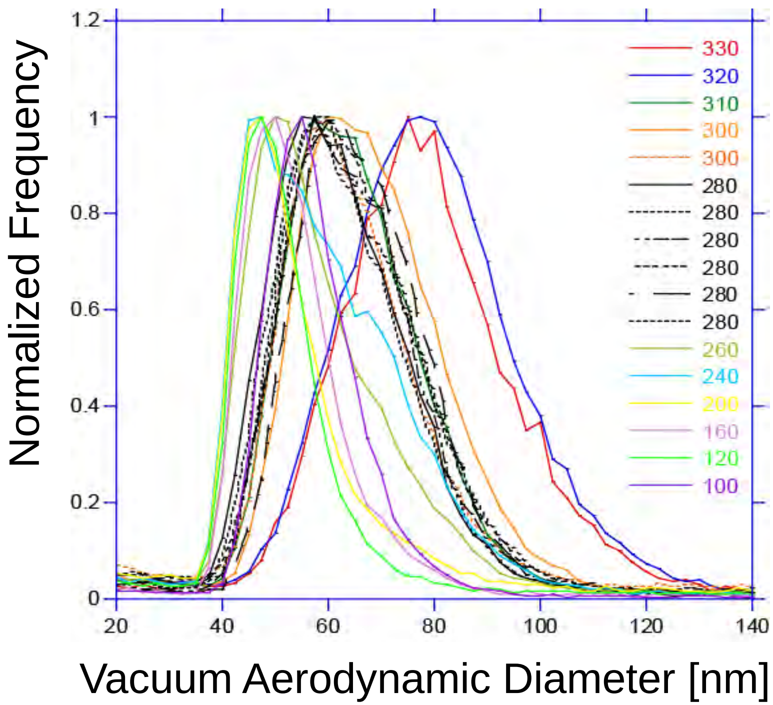
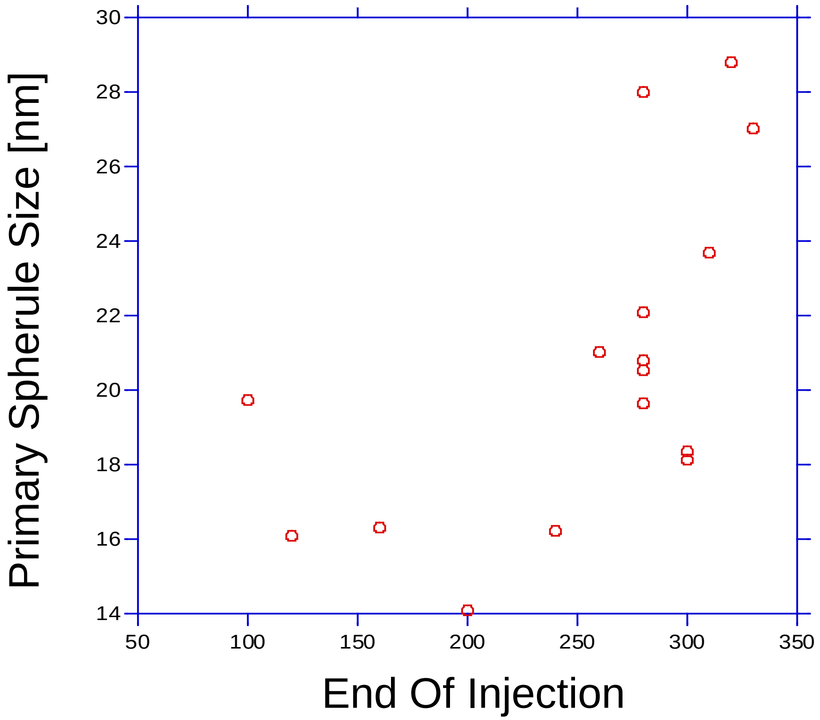
Joint experiments at U of Wisc ERC - Results (6)

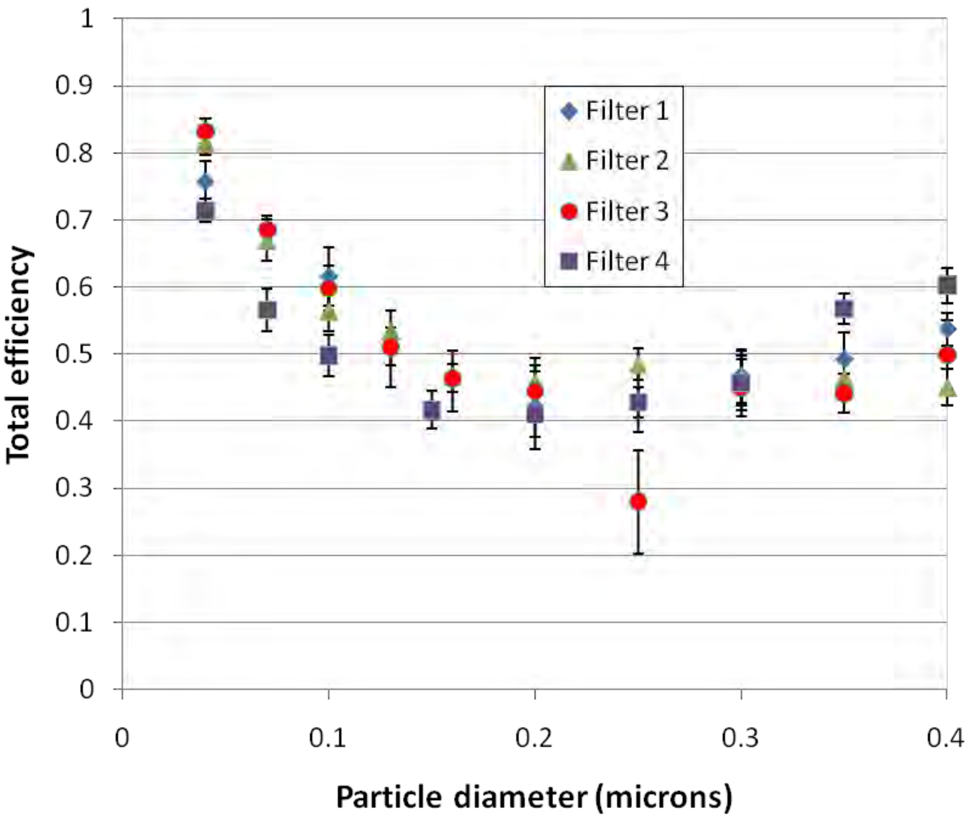




- Shift of aerodynamic diameter peaks indicates changing primary particle size at various operating conditions
- Primary particle sizes were estimated assuming a density of 2.27 and a linear relationship between log of mobility diameter and log of effective density

Fundamental clean filtration efficiency experiments - Preliminary results

Current production cordierite:
200/12 ~1.8 cm/s wall-flow velocity



- Single-cell filter samples
- Aerosolized ammonium sulfate salt particles
- Narrow size distributions selected using Differential Mobility Analyzer upstream of filter sample
- Highest penetration at ~200nm mobility diameter
- Cake required for high number efficiency

Collaborations

- Partners
  - General Motors Company (Industry): Provide hardware, expertise, and operational guidance for engine experiments at the ERC. Advise on project direction and priorities.
  - Engine Research Center at University of Wisconsin, Madison (Academic): Operate test engine - including shakedown tests, independent experiments, and cooperative experiments. Assist in analysis and publication of data.
  - Pennsylvania State University (Academic): Perform advanced TEM and image analysis to characterize GDI soot nanostructure and compare to diesel soot.

Proposed Future Work

FY 2011

- Complete publication of results from first round of cooperative experiments
- Conduct second round of cooperative experiments with SPLAT II
  - Build on first round results
  - Expand to ethanol fuel blends
- Fundamental filtration studies w/ lab-generated particles
  - Focus on number efficiency of clean filters
  - Examine effect of coatings
- TEM analysis of SIDI particulates
  - Corroborate particulate features such as primary particle size estimated by SPLAT data
  - Compare SIDI soot nano-structure (relevant to formation mechanisms and oxidation behavior) to those from a wide variety of other combustion sources

FY 2012

- Complete analysis of second round data and publish findings
- Evaluation of unit collector filtration models (commonly used for DPF modeling)
  - Current models may not be geared to accurate filter efficiency prediction, especially for small particles that dominate number counts
- Consider experiments to characterize SIDI soot oxidation kinetics
- Consider additional experiments with engine and operating parameter enhancements for higher fuel efficiency

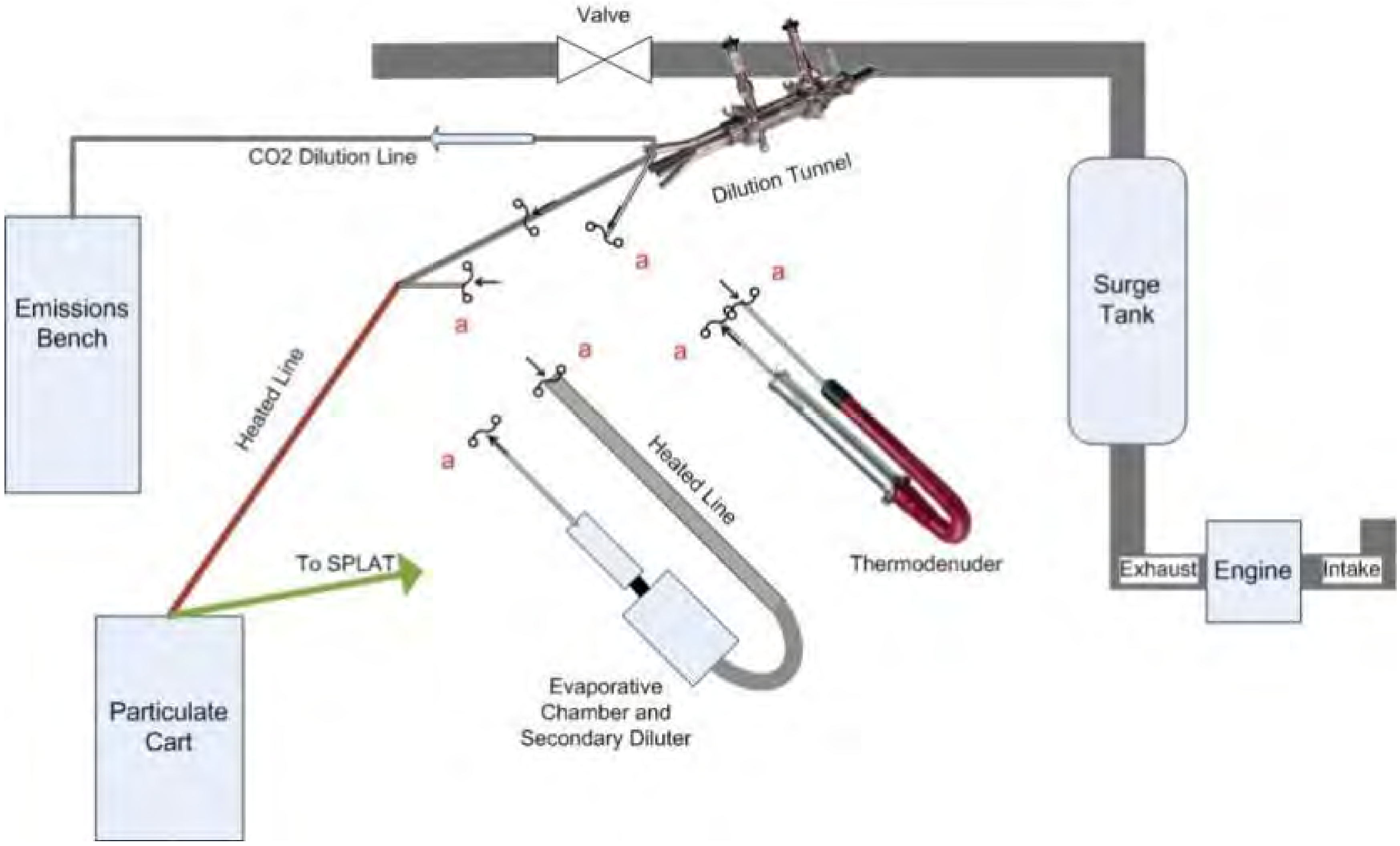
Summary

- The first round of cooperative experiments has yielded a number of important conclusions regarding the particulates from the SIDI test engine
  - No nuclei mode particles were observed
  - Particles contained elemental carbon, PAHs, and inorganics, all tightly bound together within the same fractal structures
  - Neither thermodenuder nor evaporative chamber significantly altered particle size distributions or compositions for most conditions examined
  - Conditions intended to mimic cold start did result in some additional organic content that could be stripped away by volatile particulate removal methods
  - The fractal dimensions of all particles observed fell in the range 2.03-2.22
  - Estimated primary particle sizes changed with end of injection timing and generally fell within the range of 14-29 nm
- Findings have been discussed with the CLEERS focus groups, will be presented at SAE 2011, and are being formally published
- Fundamental filtration experiments confirm that production DPF filters depend upon the presence of a soot cake for high capture efficiency

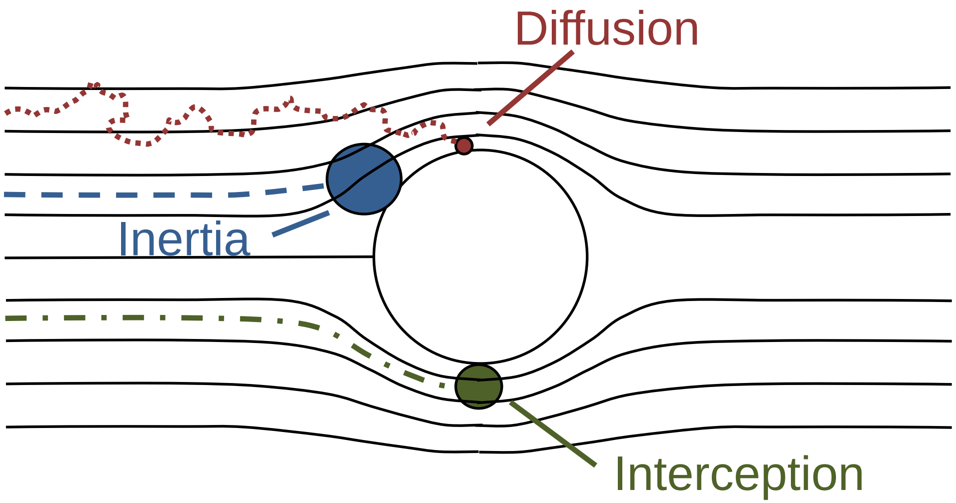
Technical Back-Up Slides

(Note: please include this “separator” slide if you are including back-up technical slides (maximum of five). These back-up technical slides will be available for your presentation and will be included in the DVD and Web PDF files released to the public.)

Engine Research Center laboratory setup



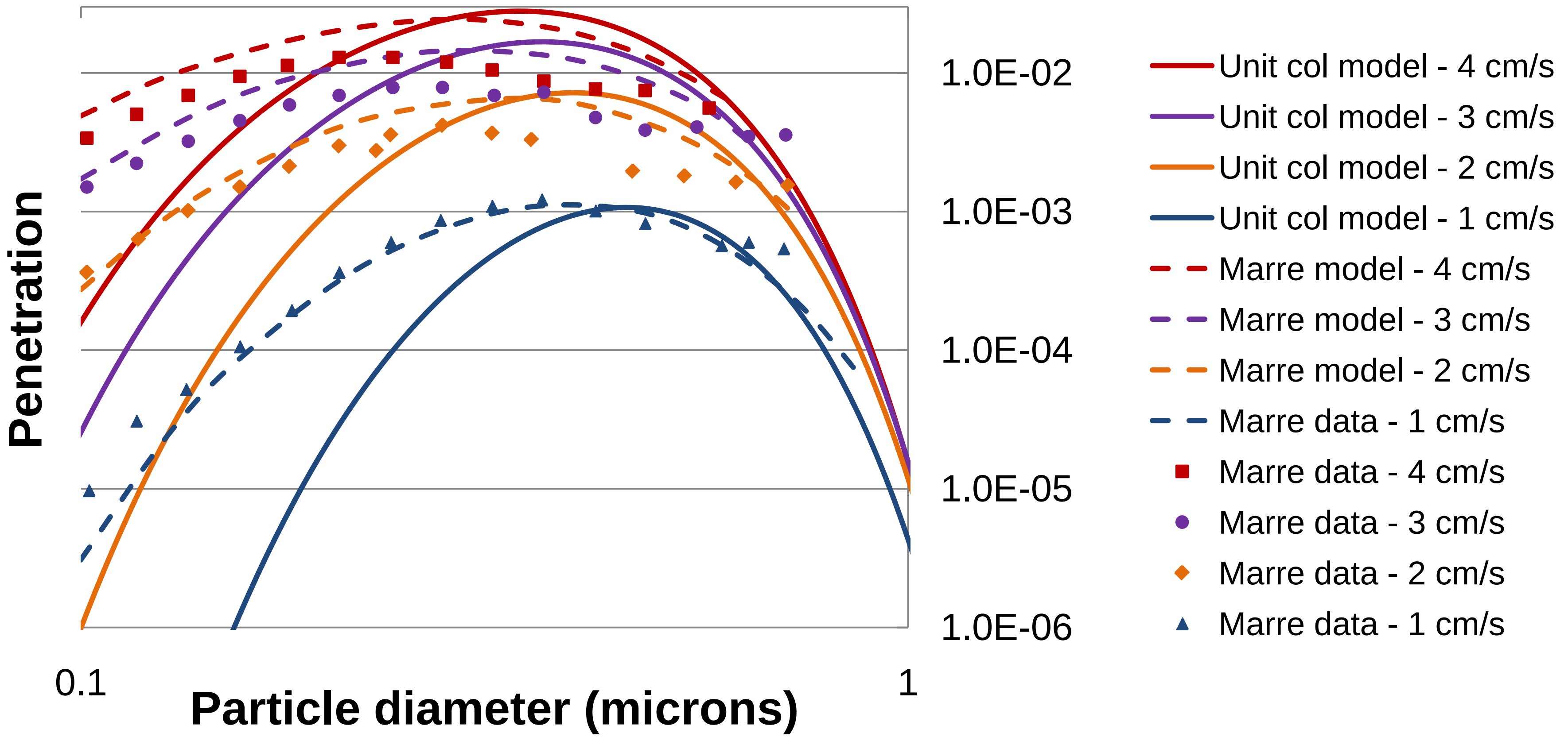
Unit collector models



- Classical model used to model depth filtration and transition to cake filtration
- Basis for most practical device-scale DPF models
  - Konstandopoulos
  - MTU
  - Corning
- Traditionally focused on overall mass capture throughout a full DPF operating cycle - most mass captured by cake
- Accuracy for capture of nano-particles has been questioned in the literature

Filtration efficiency as a function of particle size

- Most classical models assume 100% capture of sub-micron particles
- Literature discusses phenomena which may decrease capture efficiency for nanoparticles



Marre, S., J. Palmeri, A. Larbot, and M. Bertrand, "Modeling of submicrometer aerosol penetration through sintered granular membrane filters"*. JOURNAL OF COLLOID AND INTERFACE SCIENCE, 2004. 274(1): p. 167-182.*

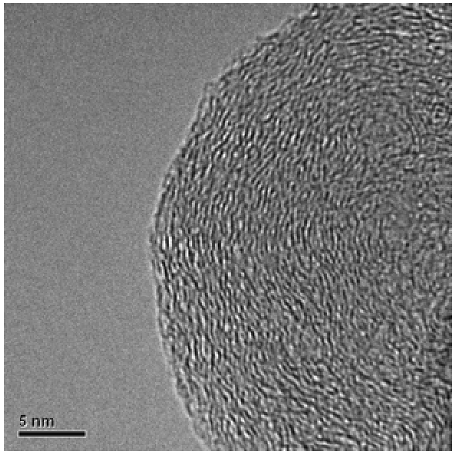
Project history

Summary Timeline

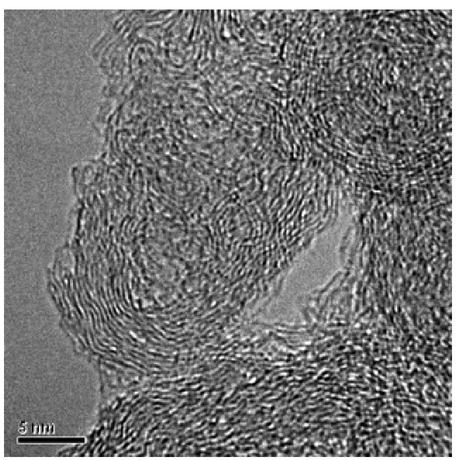
- July 2008: Kickoff teleconference
- July 2008 - May 2009: Construction of SIDI test engine at ERC with equipment and guidance from GM
- January 2009: Planning visit to ERC by PNNL staff
- June - August 2009: Shakedown of test engine
- September 2009: First round joint experiments at ERC
- October 2009 - May 2010: Analysis of resulting data, planning second round of joint experiments
- June - July 2010: New ERC students coming up to speed on prototype engine
- July 2010: Timing belt failure damaged test engine
- July 2010 - present: Rebuild engine w/ new cylinder head and valve train. Shakedown and comparison to original engine performance. Several other improvements have also been made.
- June 2011 - Next window for cooperative experiments with SPLAT II

TEM morphology & nanostructure characterization

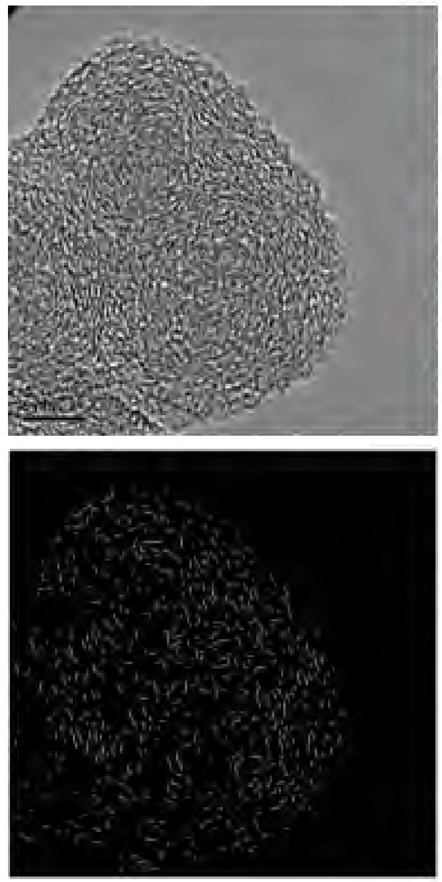
- HR-TEM = high resolution transmission electron microscopy

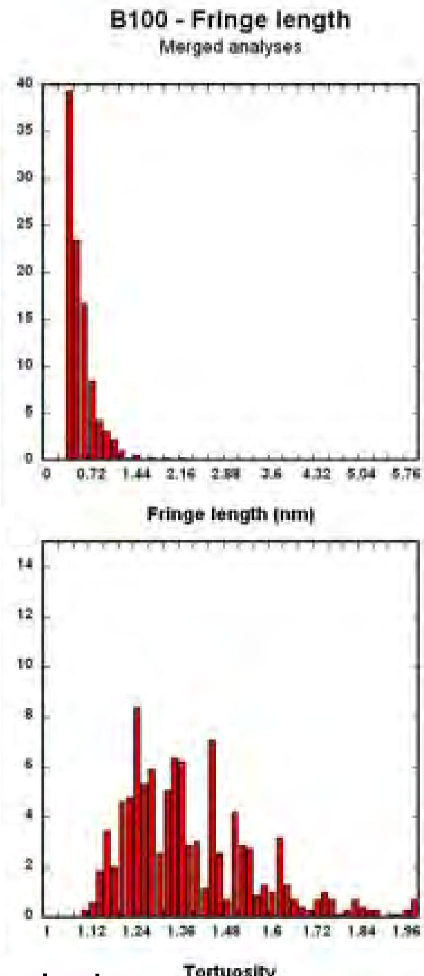


Nascent PM



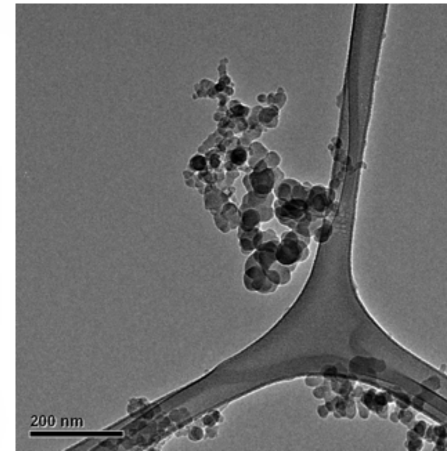
Partially oxidized PM



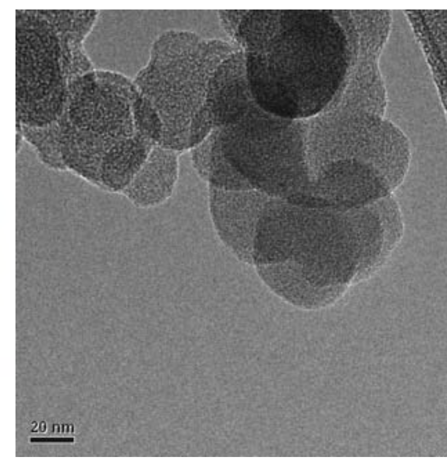


Fringe analysis

Randy Vander Wal -
Penn State University



Aggregate / Fractal



Primary particle size