Particle Emissions from 2007 Heavy-Duty Highway Diesel Engines During Active Regeneration of Catalyzed DPF

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Overview

- This work was part of Phase 1 of the Advanced Collaborative Emissions Study (ACES)
- In ACES Phase 1
  - Regulated and unregulated emissions were measured from four exhaust filter-equipped 2007 heavy-duty on-highway diesel engines
  - PM Mass emissions were measured from a full flow constant volume sampler (CVS) in accordance with the code of federal regulations (CFR) Part 1065
  - Particle number and size, and soot mass emissions were measured from an unoccupied animal exposure chamber that was linked to engine exhaust via a dilution system
    - The chamber is the same as the chambers that will be used in ACES Phase 3 health study
  - The ACES Phase 1 report was recently released and available at http://www.crcao.org

2007 Heavy-Duty Highway Diesel Engines

- 2007 diesel engines have gone through major modifications to reduce regulated emissions:
  - Water-cooled exhaust gas recirculation (EGR) to reduce NO_x emissions
  - Filtered crankcase ventilation to reduce blow-by particulate matter (PM) emissions
  - Catalyzed diesel particulate “matter” filter (DPF) in the exhaust to reduce PM,

    total hydrocarbon (THC) and carbon monoxide (CO)
    - Active regeneration and/or cleaning of the catalyzed DPF accomplished by:
      - Diesel fuel injection into exhaust upstream of diesel oxidation catalyst (DOC) located before the catalyzed DPF
      - Hot gas from a fuel burner located before the catalyzed DPF
      - Active regeneration is handled and controlled by the engine control module (ECM) with no influence or control by the engine operator
  - Additional changes such as:
    - High Injection Pressure
    - Variable geometry turbocharging
    - High boost pressure
    - Improved combustion chamber design
    - Reduced oil consumption
    - Etc…

Engines

- Four 2007 production heavy heavy-duty diesel engines were used:

CAT C13, by Caterpillar

Cummins ISX, by Cummins

DDC Series 60,
by Detroit Diesel

Mack MP7, by Volvo

Test Cycles

Test Cycles	Time, min	Average Exhaust Temperature, °C	% of FTP Average Power
FTP[a]	20	243	100
CARBx-ICT[b]	39	131	20
CARBz-CH[c]	49	297	137
16-Hour [d]	960	277	110

[a] This cycle is typically used for emissions certification and ran with and without blow-by (FTP-w and FTP-wo) during ACES

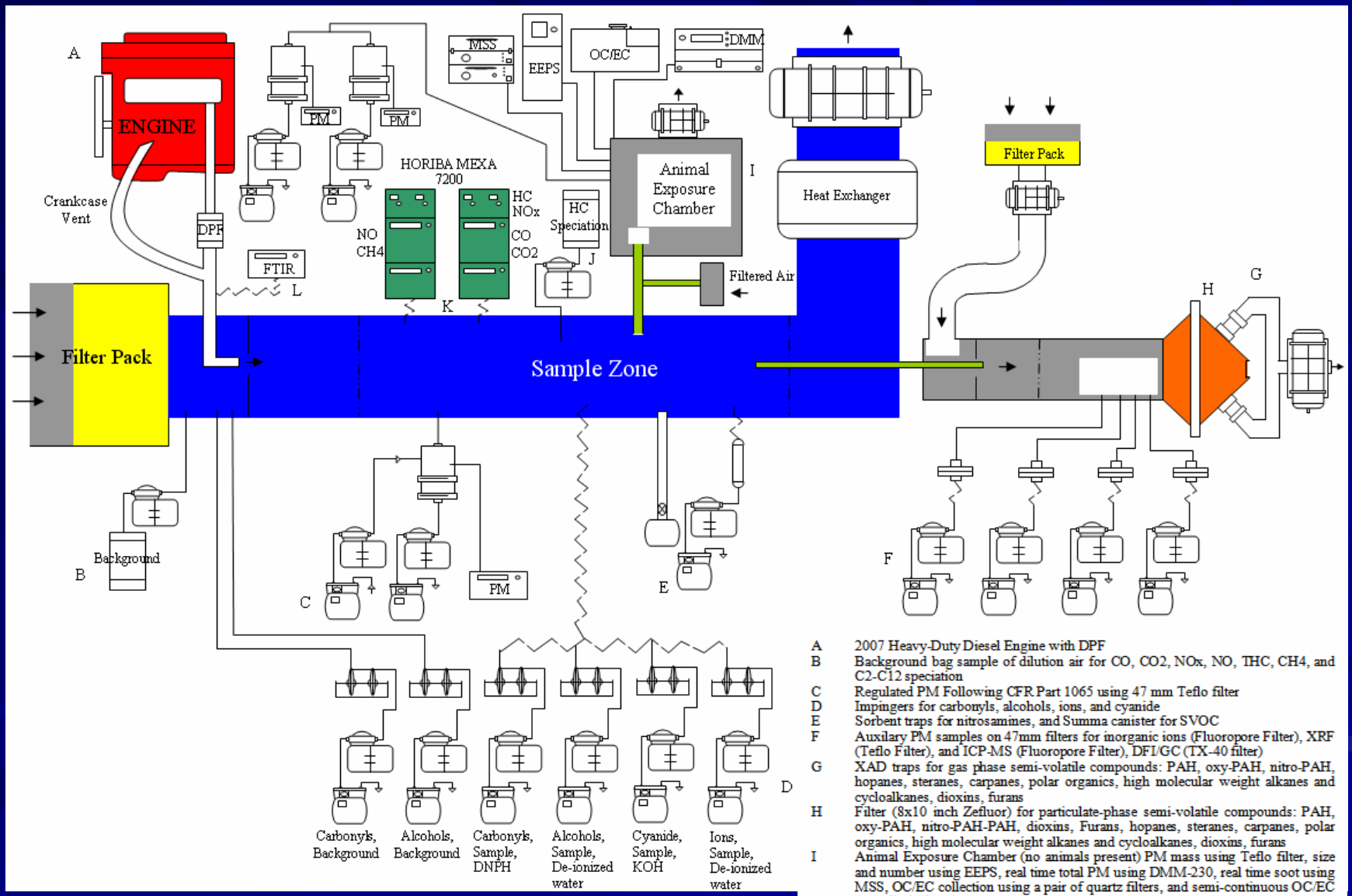
[b] Idle, creep, and transient portions of the CARB-5 Modes

[c] Cruise and high-speed cruise portions of the CARB-5 Modes

[d] Four 4-hour segments that consist of repeats of the FTP and CARB-5 Modes.

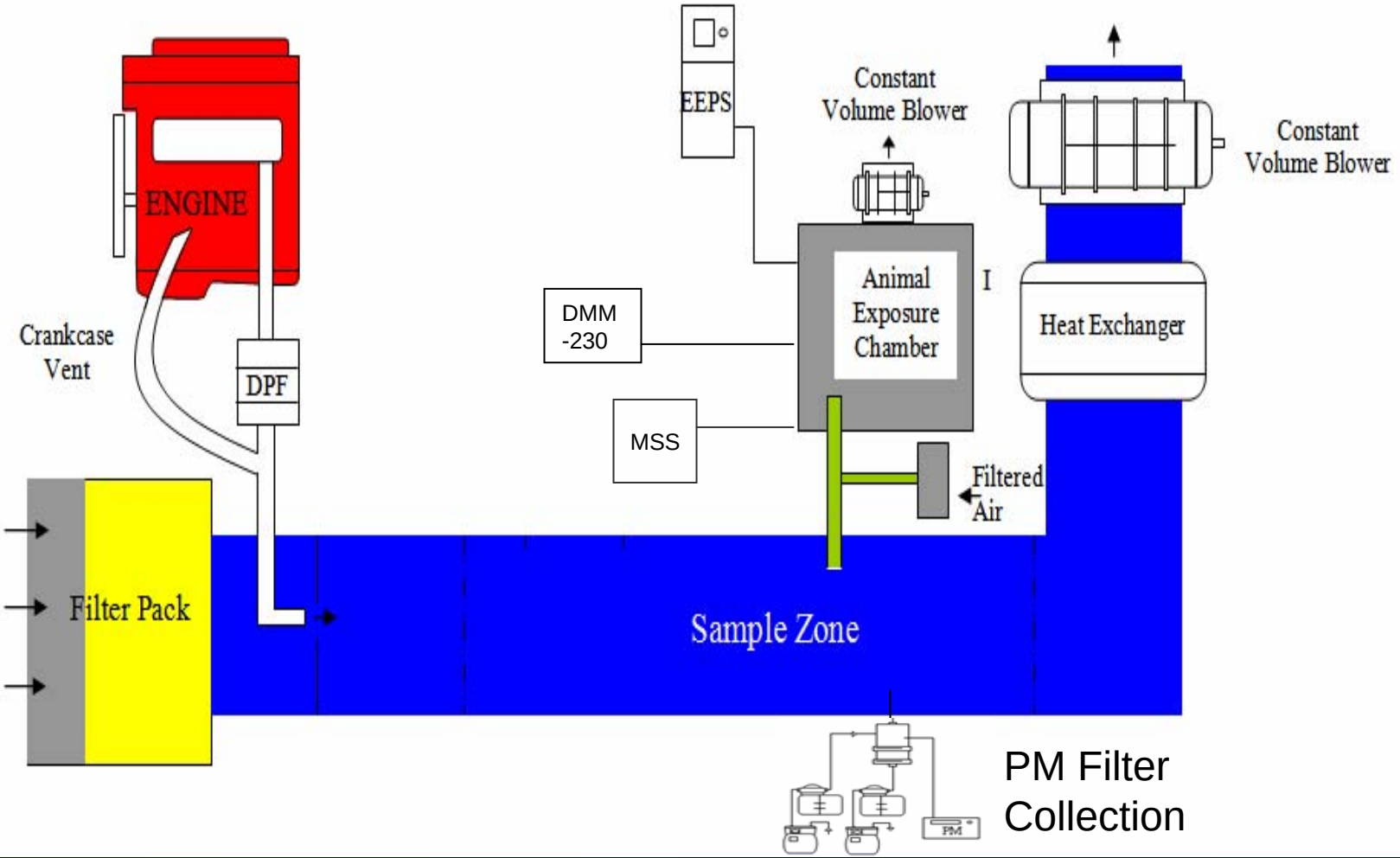
Active DPF regeneration took place during the 16-Hour cycle only.

Overall Experimental Setup



A	2007 Heavy-Duty Diesel Engine with DPF
B	Background bag sample of dilution air for CO, CO2, NOx, NO, THC, CH4, and C2-C12 speciation
C	Regulated PM Following CFR Part 1065 using 47 mm Teflo filter
D	Impingers for carbonyls, alcohols, ions, and cyanide
E	Sorbent traps for nitrosamines, and Summa canister for SVOC
F	Auxilary PM samples on 47mm filters for inorganic ions (Fluoropore Filter), XRF (Teflo Filter), and ICP-MS (Fluoropore Filter), DFI/GC (TX-40 filter)
G	XAD traps for gas phase semi-volatile compounds: PAH, oxy-PAH, nitro-PAH, hopanes, steranes, carpanes, polar organics, high molecular weight alkanes and cycloalkanes, dioxins, furans
H	Filter (8x10 inch Zefluor) for particulate-phase semi-volatile compounds: PAH, oxy-PAH, nitro-PAH-PAH, dioxins, Furans, hopanes, steranes, carpanes, polar organics, high molecular weight alkanes and cycloalkanes, dioxins, furans
I	Animal Exposure Chamber (no animals present) PM mass using Teflo filter, size and number using EEPS, real time total PM using DMM-230, real time soot using MSS, OC/EC collection using a pair of quartz filters, and semi-continuous OC/EC (very limited use)
J	proportional bag sample for hydrocarbon speciation of C2 through C12 compounds
K	Horiba MEXA 7200 for THC, CO, CO2, NOx, NO analyzer, and CH_4 analyzer
L	FTIR for nitrogen compounds

Experimental Setup Focusing on Particle Number and Size and Soot Mass, and Filter Collection

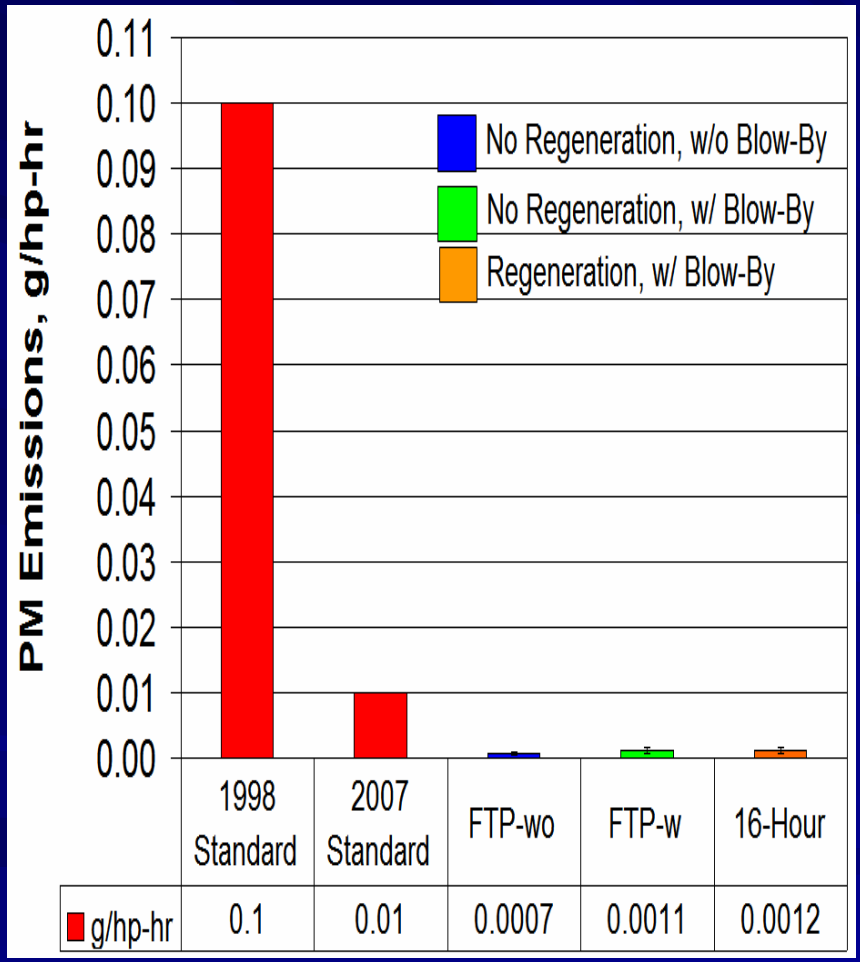


EEPS: Engine Exhaust Particle Sizer, TSI (Total Size and Number Measurement)

DMM-230 : Dekati Mass Monitor, Dekati (Total Particle Mass)

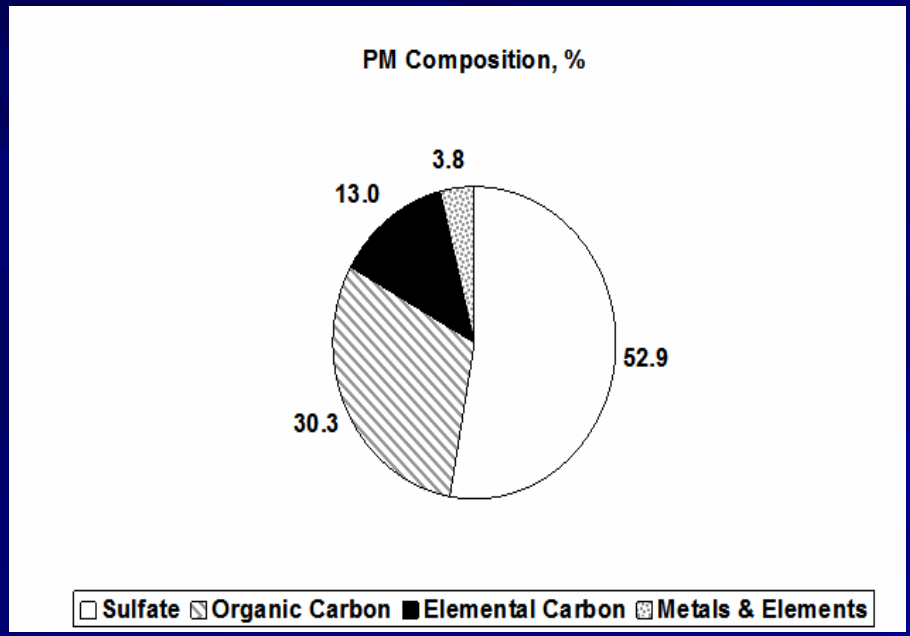
MSS: Micro-Soot Sensor, AVL (Carbon Particle Mass)

Average Total PM Mass Emissions



- 90 percent reduction in PM emissions was mandated by US EPA for 2007 heavy-duty diesel engines and beyond
- High efficiency wall-flow DPF technology selected by the engine manufacturers achieved more than 99 percent reduction in PM mass emissions relative to 1998 engine technology

PM Composition Emitted from DPF-Equipped On-Highway Heavy-Duty diesel engines



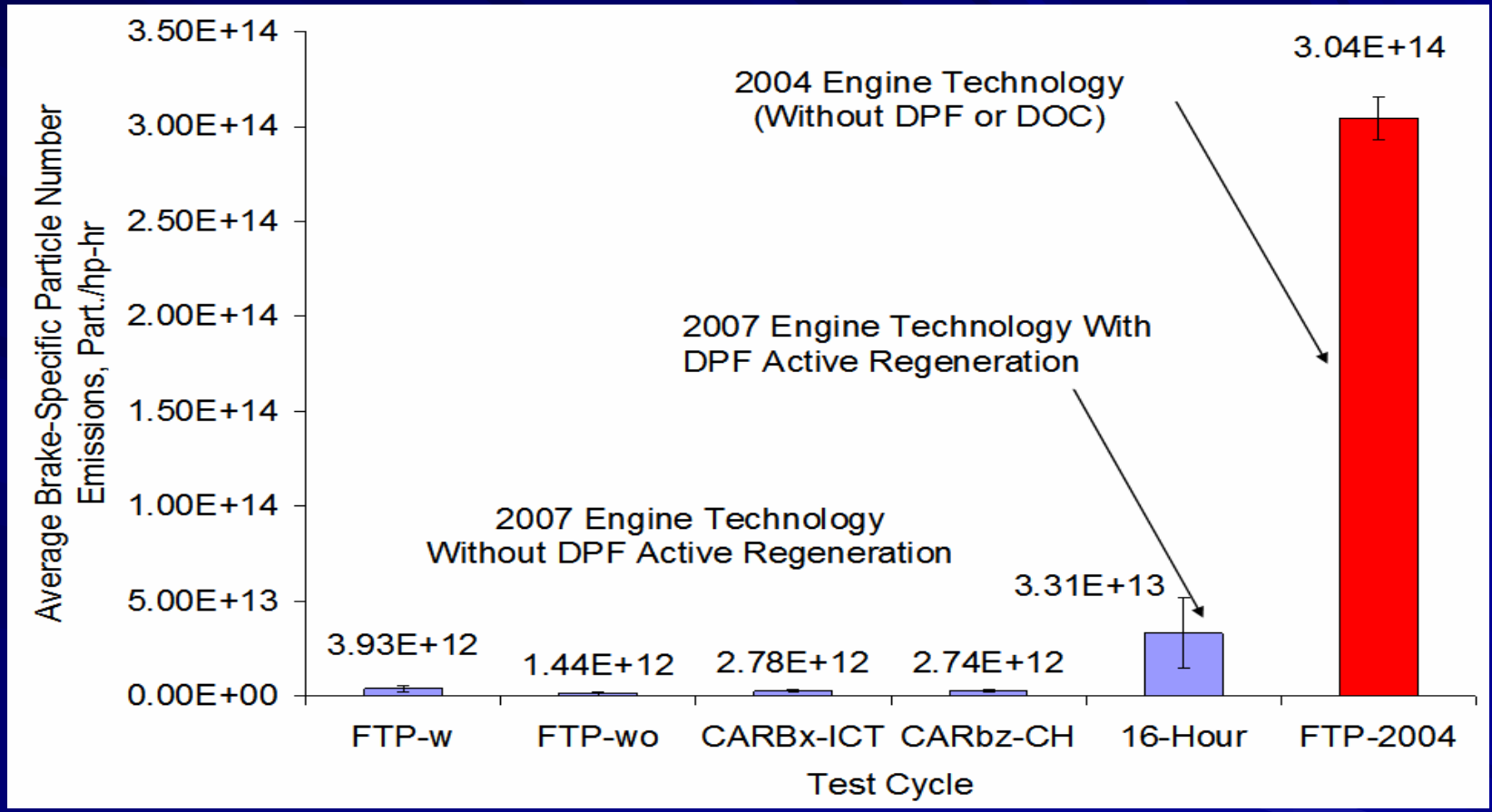
- The remaining small PM mass emitted from wall-flow DPF-equipped engines is composed mainly of volatile sulfate and organic carbon species
- Much of the volatile matter collected may be due to filter artifacts
- Solid PM of metallic ash and elemental carbon comprised less than 17 percent of total PM mass

- Total (Solid Plus Volatile) Particle Number and Size Measurement

Exposure Chamber Characteristics

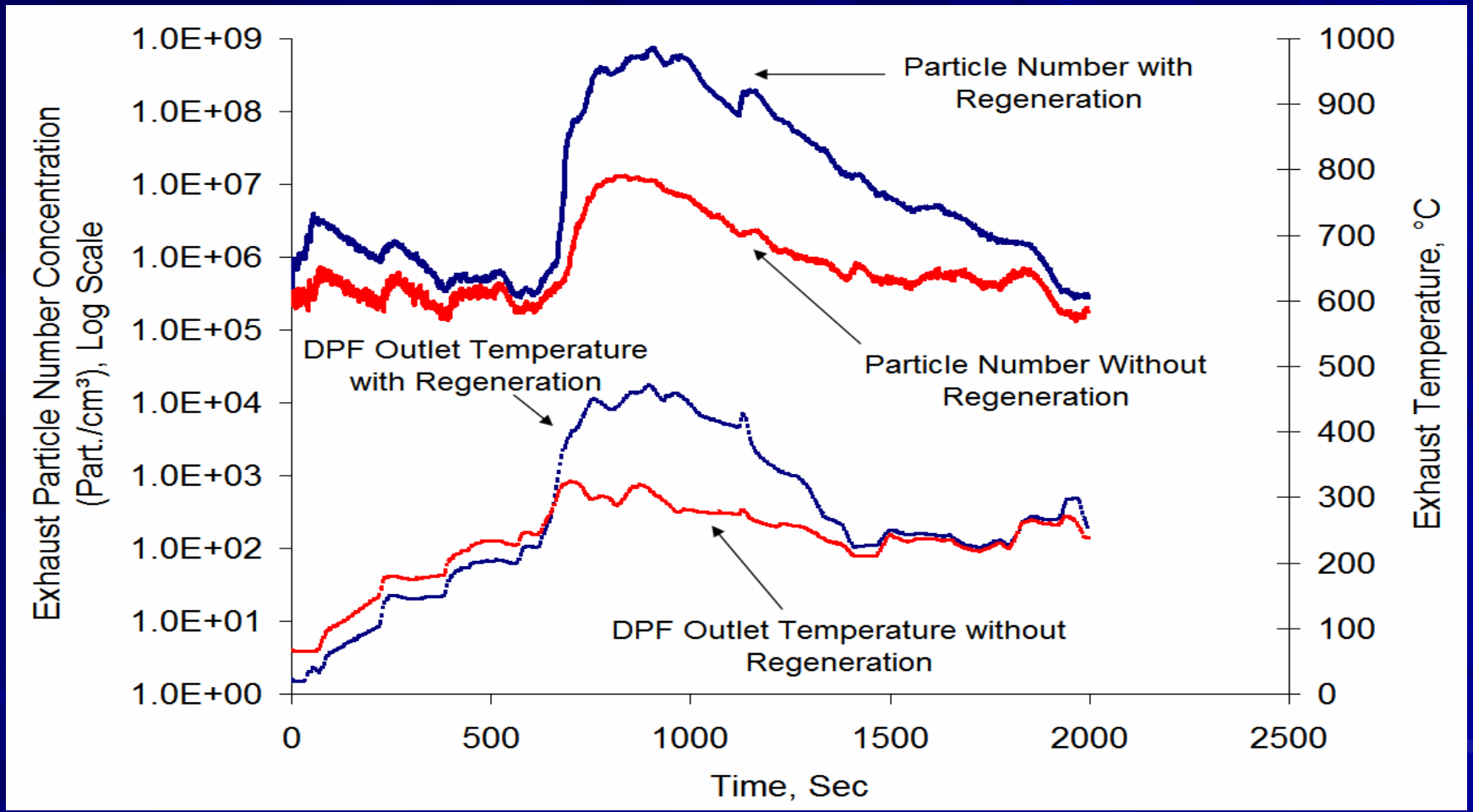
- The exposure chamber emission measurements were used to provide useful emissions information for the ACES Phase 3 health study.
  - Chamber residence time
    - 5 minutes for 90 percent purge
    - 20 minutes for 100 percent purge
  - Chamber temperature
    - ~27°C
  - Chamber average dilution ratio for different cycles:
    - FTP: 34
    - CARBx-ICT: 40
    - CARBz-CH: 16
    - 16-Hour: 25

Average Total Particle Number Emissions



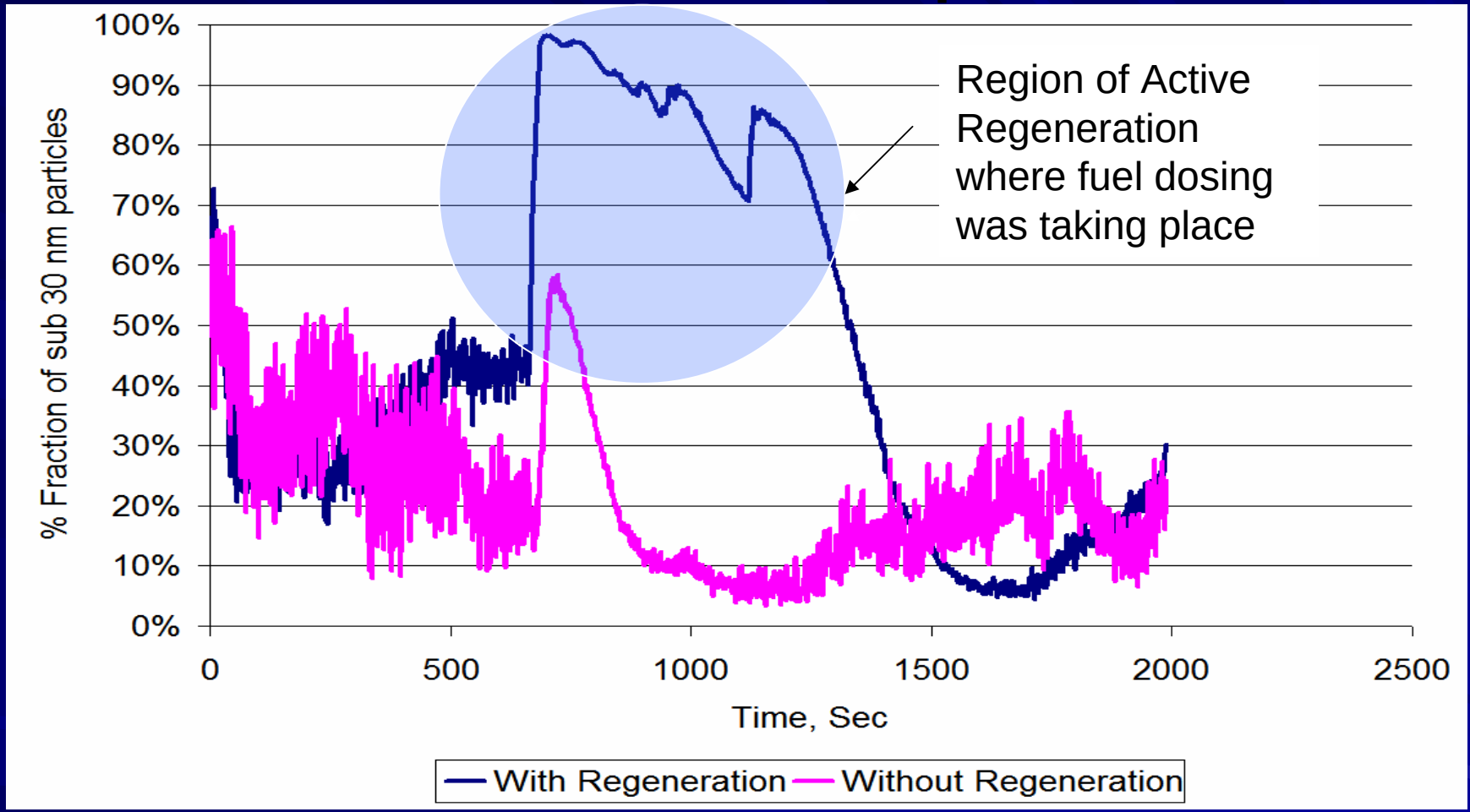
- Without DPF regeneration, the particle number emissions average was 99 percent lower than the level emitted by a 2004 engine technology, and with regeneration it was 90 percent lower
- With Active DPF regeneration, the number emissions average was a factor of 10 higher than events without regeneration

Exhaust Particle Number Concentration and Temperature Profiles with and without DPF Regeneration



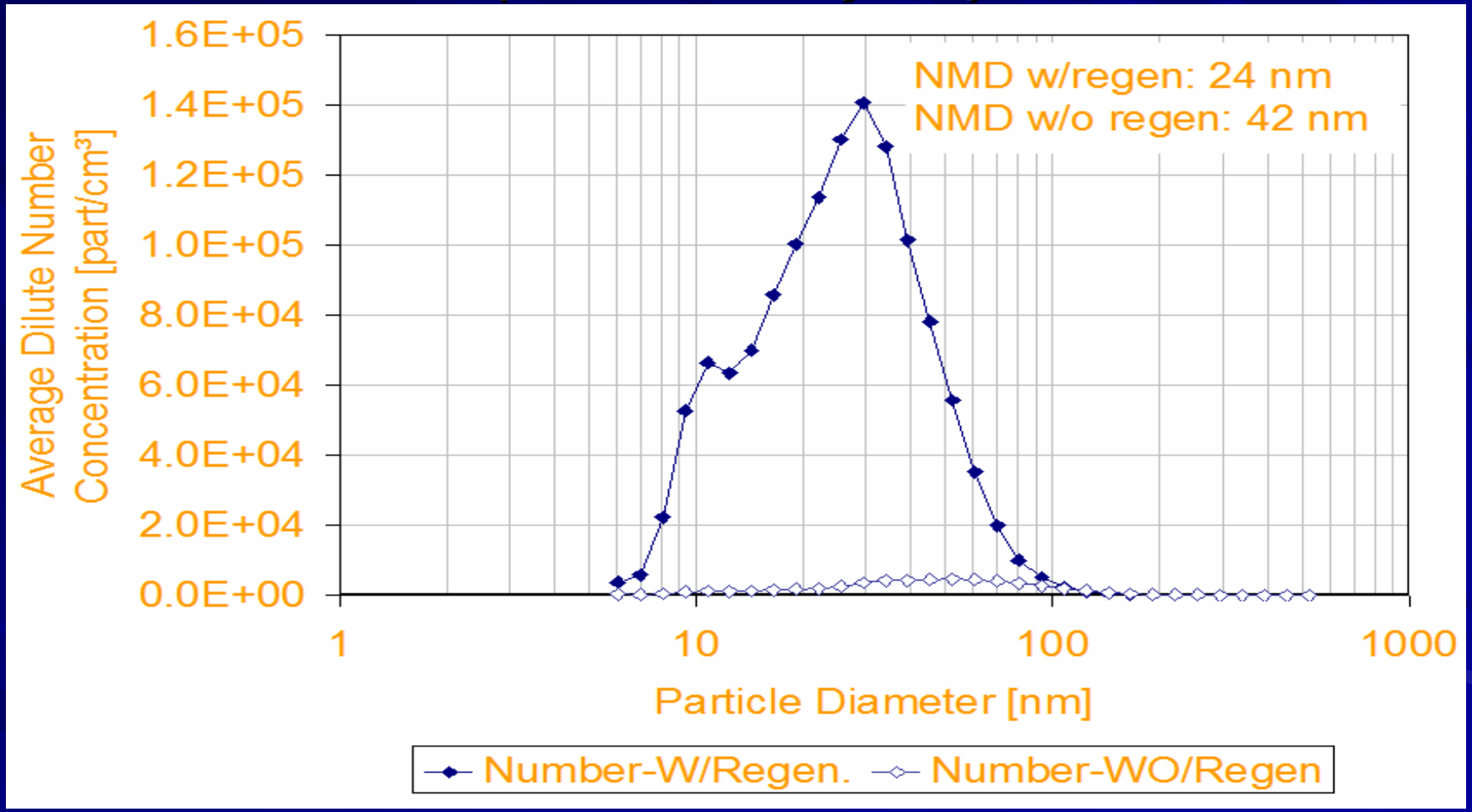
During DPF regeneration, real time particle number in exposure chamber increased by a factor of 10 to 100, compared to the condition without DPF regeneration . Number count w/o regen. increases above 300°C.

Sub-30 nm Nanoparticles



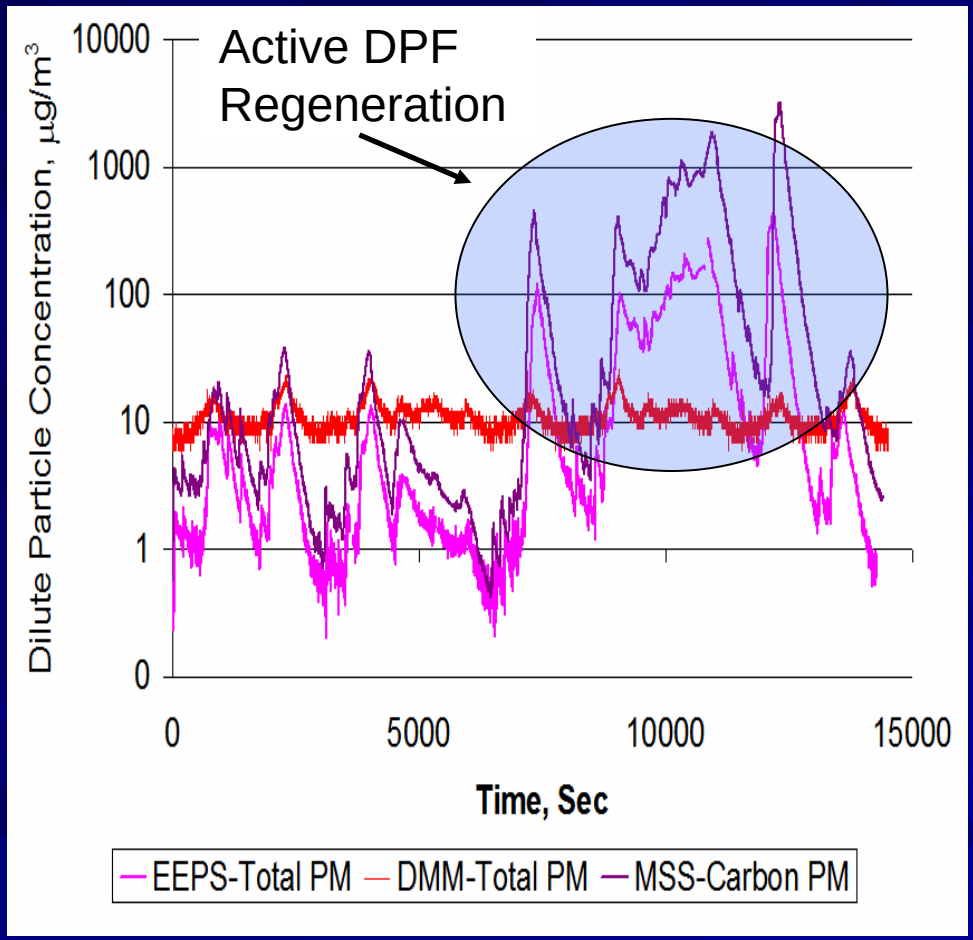
During Active Regeneration, sub-30 nanometer nanoparticle number exceeded 95 percent of the total number

Average Size Distribution with and without Active DPF Regeneration (16-Hour Cycle)



NMD is the geometric number mean diameter in nanometers

Mainly Volatile Particles During Active Regeneration



- The DMM-230 and EEPS showed a factor of 10 to 100 increase in total PM mass during regeneration
- The MSS soot measurement was not sensitive to the regeneration event, suggesting that little or no carbon particles were emitted
- These measurements enforce the PM mass composition results showing that the PM emitted was mainly volatile PM and not solid

Summary

- For 2007 DPF-equipped diesel engine technology:
  - Average particle number emissions without DPF regeneration were approximately 99 percent lower than a comparable 2004 engine technology without DPF
    - With DPF regeneration, number emissions average was approximately 90 percent lower
  - With DPF regeneration, number emissions average was approximately a factor of 10 higher than without regeneration
  - Real time particle number with regeneration was approximately a factor of 10 to 100 higher than without regeneration
  - During active DPF regeneration, sub-30 nm nanoparticles represented 70 to 95 percent of total particle number
- The exposure chamber used in this study may not be representative of all dilution and cooling schedules in the real world
- Particles formed downstream of the DPF are volatile hydrocarbon and sulfate that nucleate and grow during the dilution and cooling process. This was demonstrated in the PM composition analysis, and was also reinforced in the comparison made between EEPS and DMM "solid plus volatile mass" vs. MSS "solid particle mass"

Acknowledgments

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