Phase 1 of the Advanced Collaborative Emissions Study (ACES): Highlights of Project Finding




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ACES Phase 1 Objectives

- **Quantify the significant reduction in both regulated and unregulated emissions from four 2007 highway diesel engines,**
- **Provide detailed regulated and unregulated emissions for this new engine technology,**
- **Use ACES Phase 1 data to select one of the four engines for ACES Phase 3 exposure study,**
- **Provide initial guidance for ACES Phase 3 exposure study using the regulated and unregulated emissions information from ACES Phase 1**
  - **ACES Phase 3 exposure study is currently underway at the Lovelace Respiratory Research Institute (LRRI)**

Engines

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

CAT C13, by Caterpillar

Cummins ISX, by Cummins

DDC Series 60,
by Detroit Diesel

Mack MP7, by Volvo

Four Cycles Tested

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

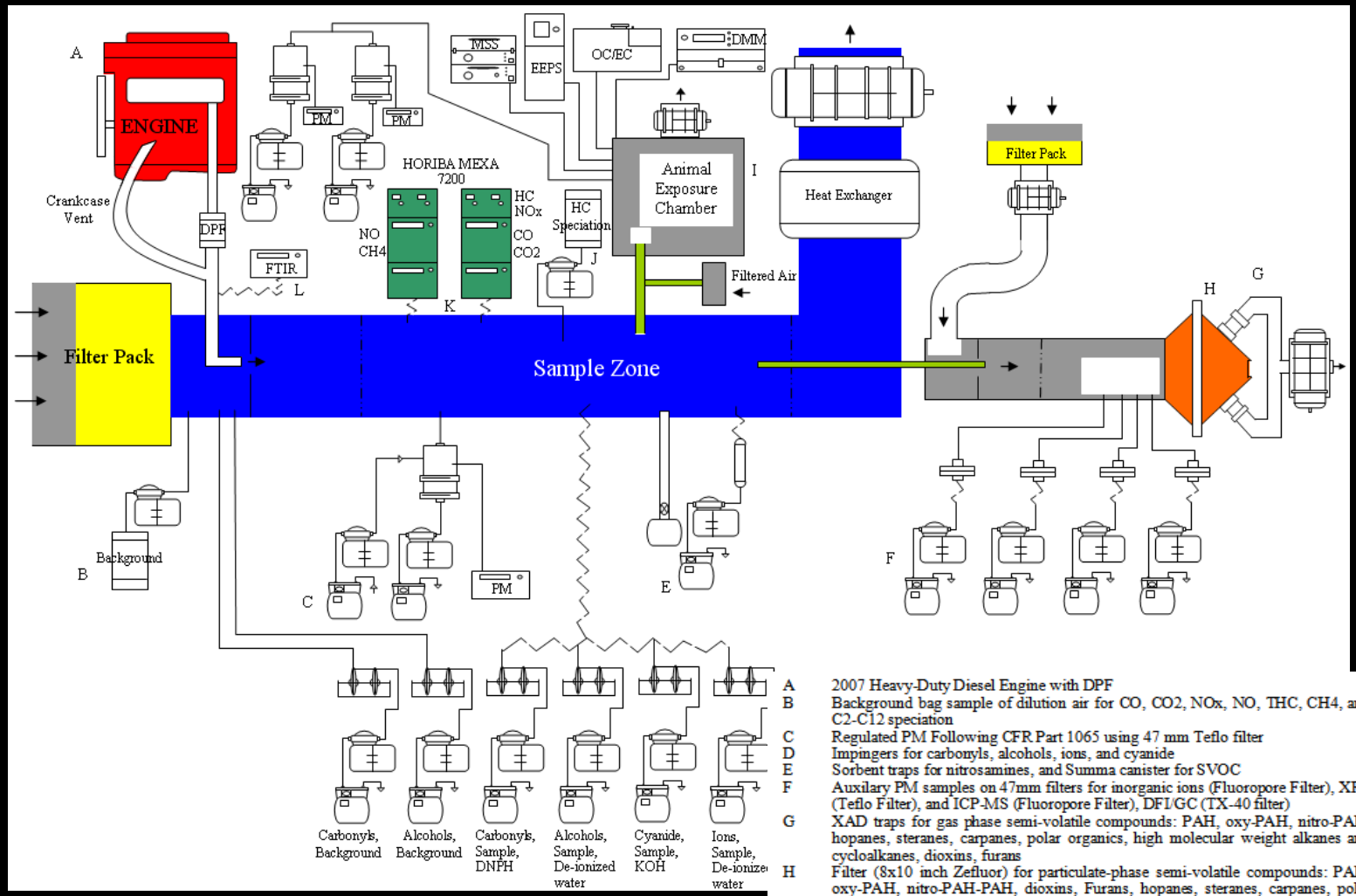
[b] Idle, creep, and transient portions of the CARB-5 Modes

[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.

Complex Experimental Setup and Very Detailed Emissions Characterization



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

Results

Regulated Emissions Relative to EPA 2007 Standard Based on FTP Transient Cycle

	2007 EPA Standard (g/hp-hr)	Average ACES Engine Emissions (g/hp-hr)	ACES Emissions % Reduction Relative to the 2007 Certification Standard
CO	15.5	0.33	98
NMHC	0.14	0.0064	95
PM	0.01	0.0011	89
NO_X	1.2 [a]	1.075	10

[a] Average value between 2007 and 2009, with full enforcement in 2010 at 0.20 g/hp-hr

Unregulated Emissions

On a g/hr emission rate basis, the great majority of unregulated emission species were much lower than the level observed with 2004 engine technology used in CRC E55/59.

Compounds	% Lower Than 2004 Engine Technology	
	16-Hour Cycle	CARBx-ICT
Single Ring Aromatics	82%	69%
PAH	79%	26%
Nitro-PAH	81%	49%
Alkanes	85%	84%
Polar	81%	12%
Hopanes/Steranes	99%	99%
Carbonyls	98%	78%
Inorganic Ions	38%	100%
Metals and Elements	98%	90%
Organic Carbon	96%	78%
Elemental Carbon	99%	100%
Dioxins/Furans[a]	99%	N/A

[a] Relative to 1998 Engine Technology

In general, the low exhaust temperature cycle CARBx-ICT showed less reduction for the hydrocarbon-based compounds, compared to the 16-Hour Cycle

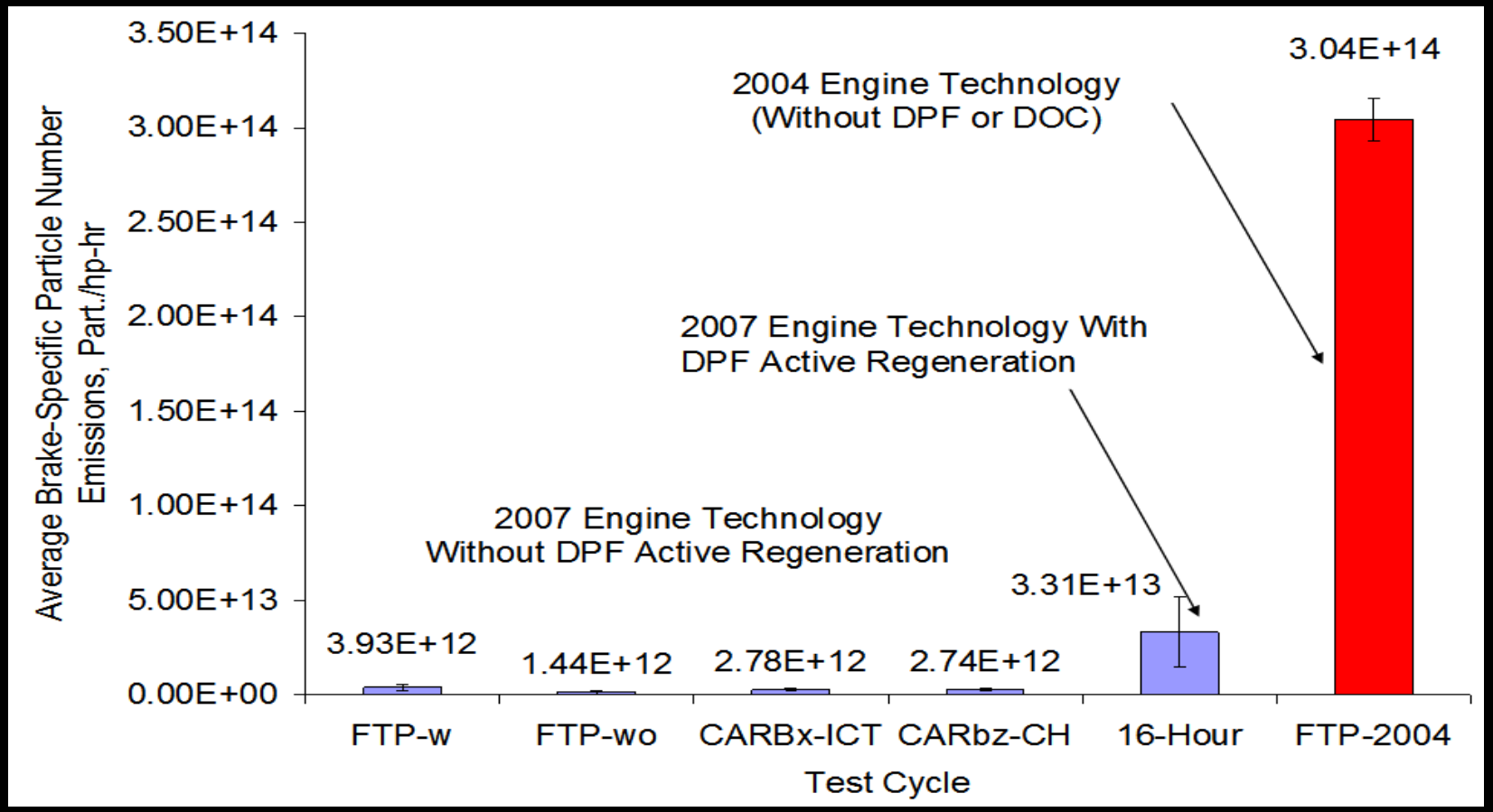
NO_2 Emissions

- Average NO_2 to NO_x ratio determined for the ACES engines during the FTP transient cycle was 68 %
  - Ratio was much higher than typical ratios (4% to 15%) for 2004 technology engines

- Due to the catalyzed DOC/DPF or catalyzed DPF without DOC, the ACES engines emit 2 to 7 times higher NO_2, compared to a 2004 engine technology (2.4 g/hp-hr NO_x limit) emitting NO_2 in the range from 0.096 to 0.36 g/hp-hr

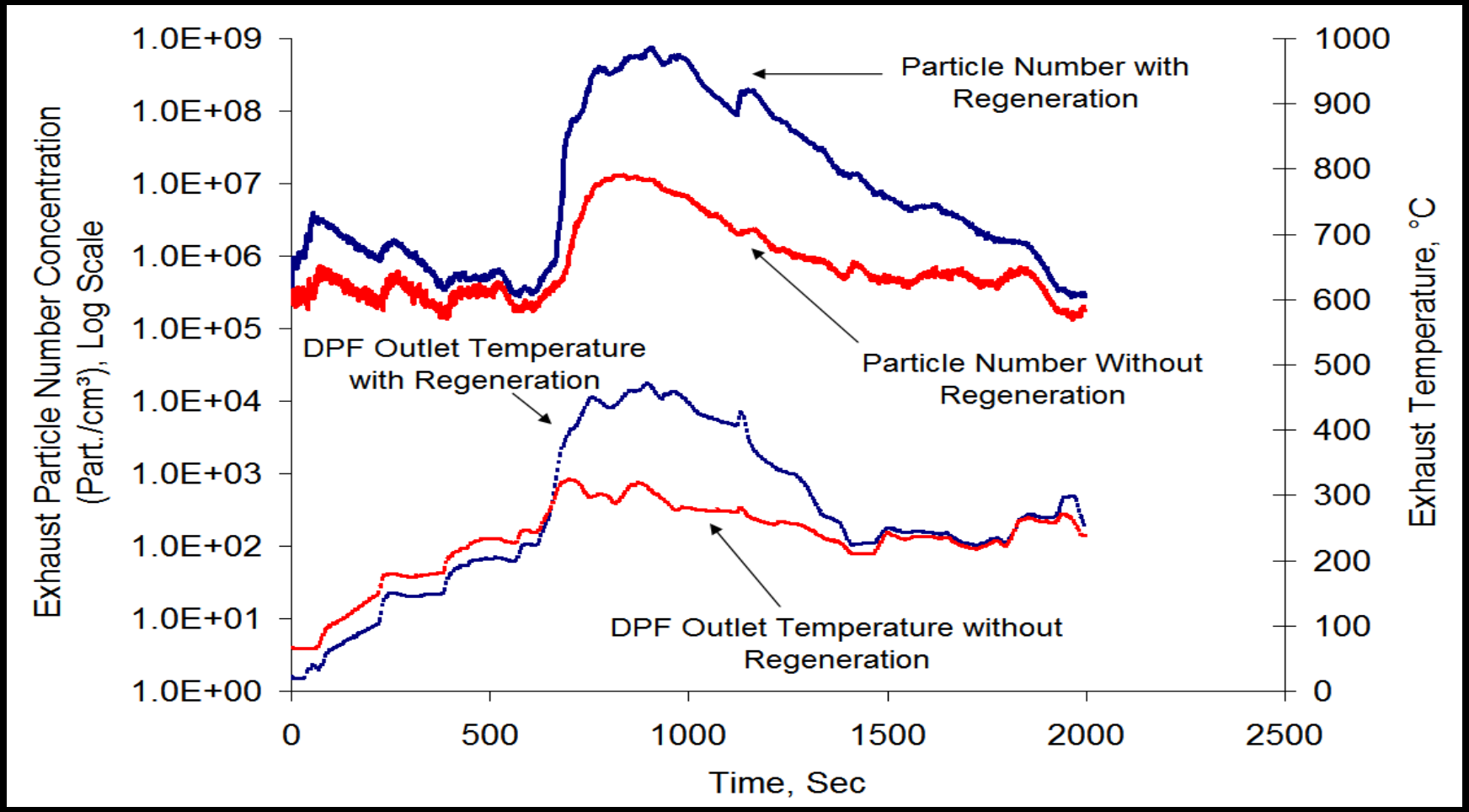
- 2010 NO_x emissions limit of 0.20 g/hp-hr will eliminate this temporary increase in NO_2 from highway engines

Average Total Particle Number Emissions



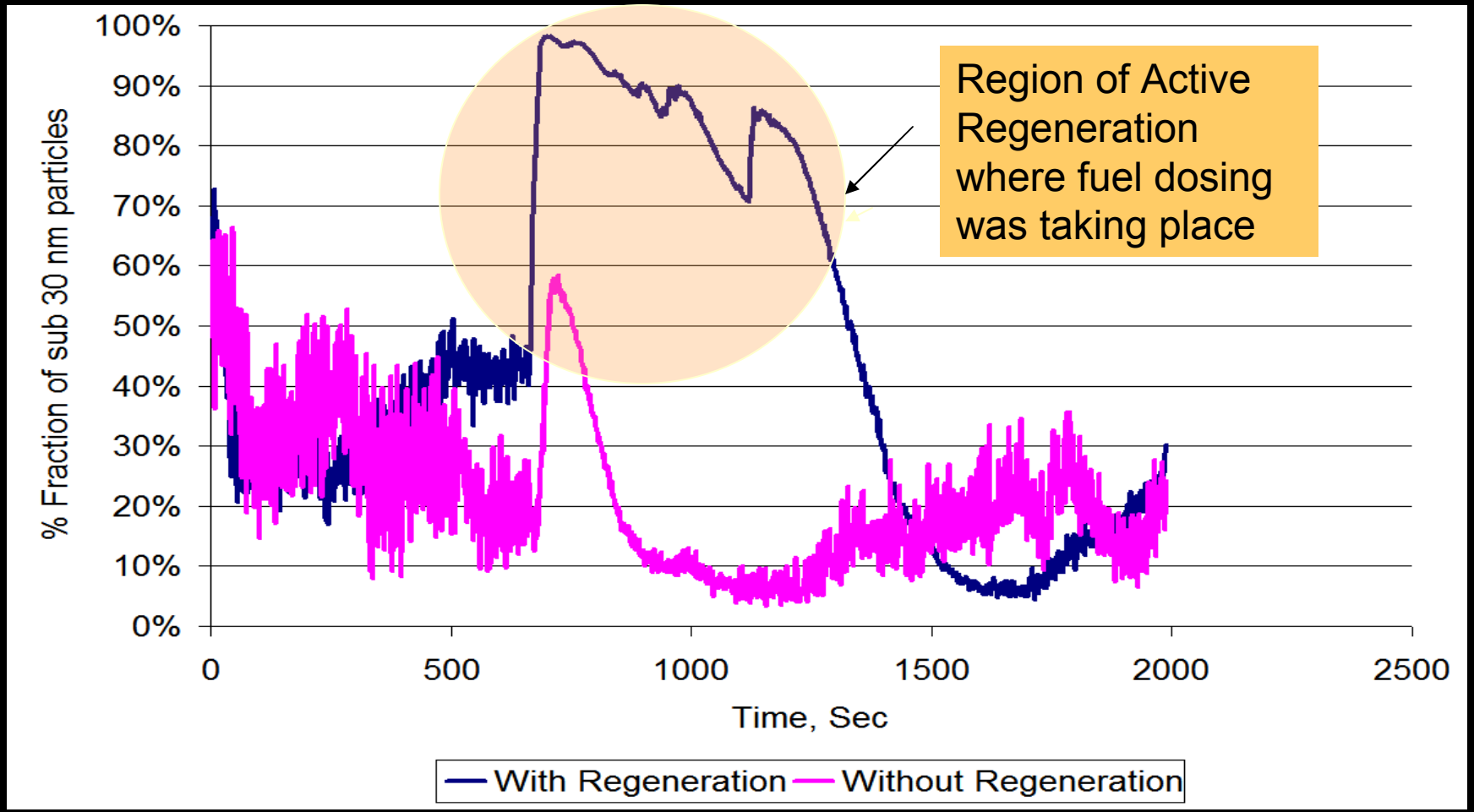
- With regeneration, the particle number emissions average was approximately 90 percent lower than the level emitted by a 2004 engine technology, and without regeneration it was approximately 99 percent lower
- Average Particle number with regeneration was more than a factor of 10 higher than that without regeneration (Note that there was no difference in PM mass emissions)

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



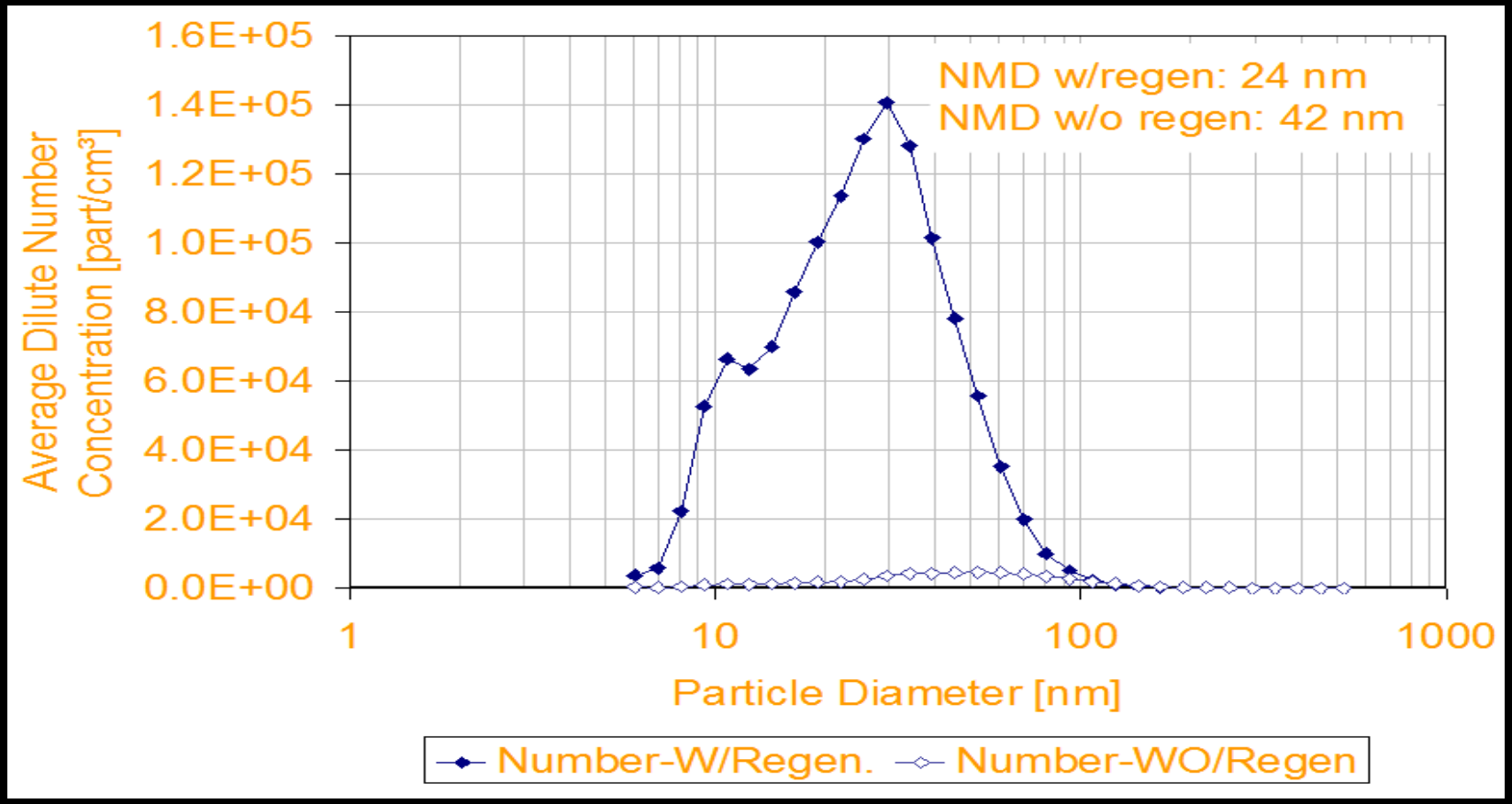
During DPF regeneration, real time particle number in exposure chamber increased by a factor of 10 to 100, compared to the condition without DPF regeneration . Number count w/o regen. increases above 300C.

Sub-30 nm Nanoparticle Formation During Active Regeneration



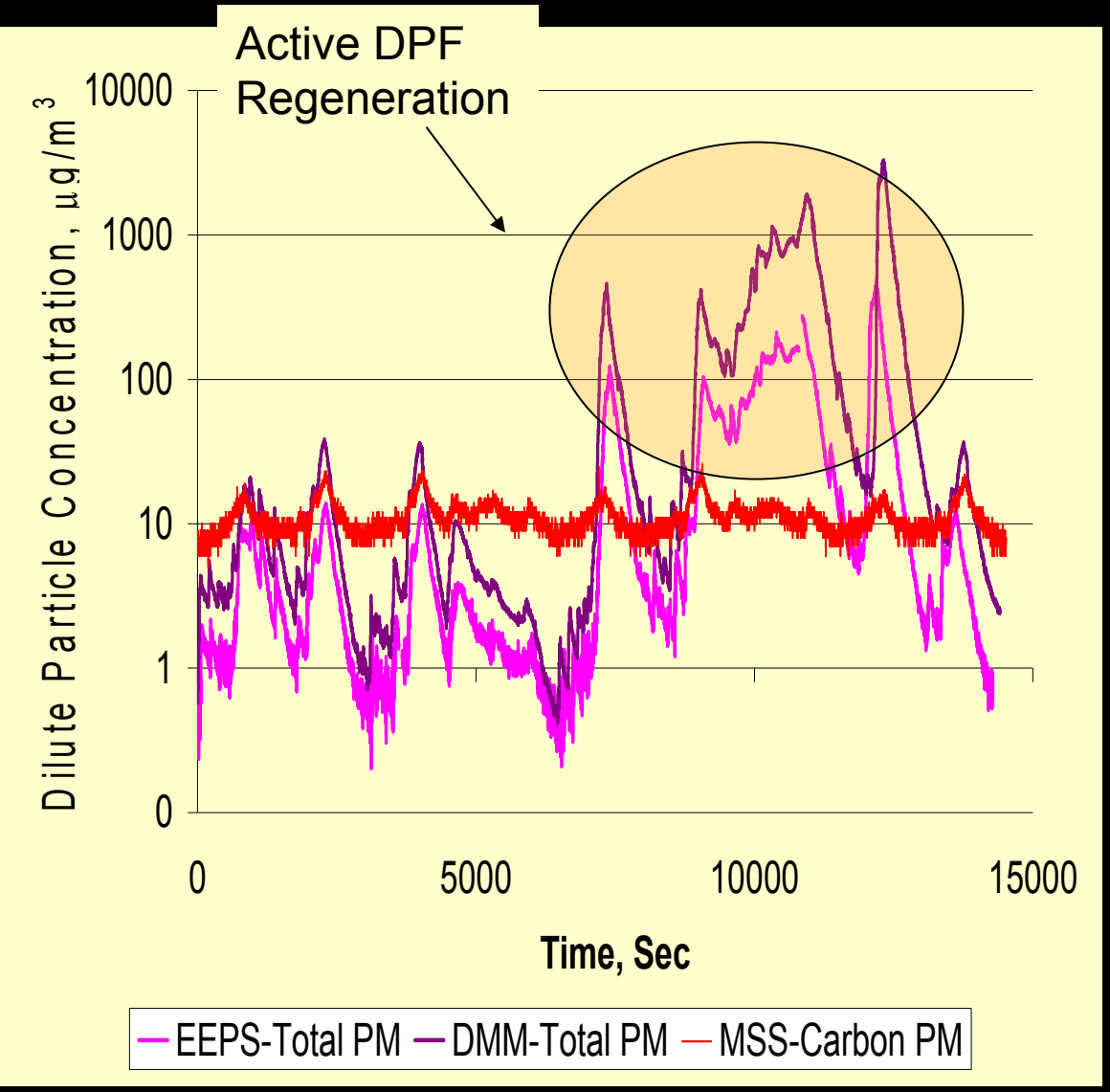
During Active Regeneration, sub-30 nanometer nanoparticle number dominated particle number emissions, and exceeded 95 percent of the total number

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



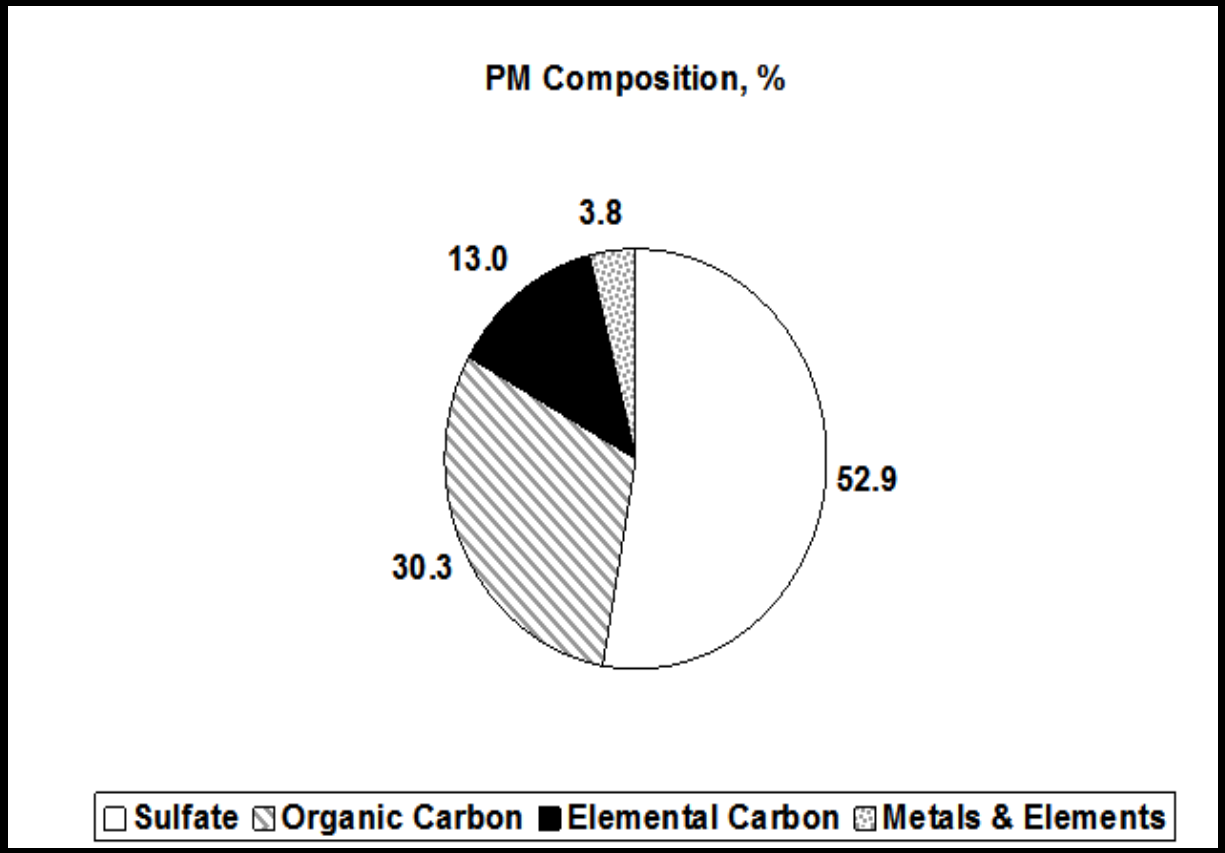
NMD is the geometric number mean diameter in nanometers

Mainly Volatile Particles During Active Regeneration



- The DMM-230 and EEPS showed a an 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

Sulfate and Organic Carbon Dominate PM Composition of 16-Hour Cycle



- 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

Summary-1

- Regulated PM, CO, and NMHC emissions were at least 90% below the 2007 standard, and NO_x was 10% below standard
- Most unregulated emissions were at least 90% below 2004 technology engines
- Average NO_2 emission of 0.68 g/hp-hr was 2 to 7 times higher than the emissions from 2004 engines
  - However, 2010 engine technology NO_x limit of 0.20 g/hp-hr will force NO_2 emissions to be substantially lower than both 2007 and 2004 technology engines

Summary-2

- Average particle number emissions with DPF regeneration were approximately 90 percent lower than a comparable 2004 engine technology without DPF
  - Without DPF regeneration, number emissions average was approximately 99 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
- Elemental carbon represented only 13 % of the very low total PM mass. Sulfate was the dominant composition at 53 %, followed by organic carbon at 30 %.

Final Note

- The final report is now a public document available at www.crcao.com
- An ACES webinar coordinated by Diesel Forum is scheduled for September 9th, from 1:30 to 3:00 PM
- Three separate peer-reviewed articles will be published on ACES Phase 1 by June, 2010, and will cover:
  - Regulated emissions and GHG
  - Unregulated emissions
  - Particulate matter mass, number, size, and composition

Acknowledgments

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