The Advanced Collaborative Emissions Study (ACES):Phase 3

D. Greenbaum[1], J. Mauderly[2], J. MacDonald[2] ,C. Tennant[3], R. Shaikh[1], M. Costantini[1], A van Erp[1]
[1]Health Effects Institute (HEI), [2]Lovelace Respiratory Research Institute, and [3]Coordinating Research Council (CRC)

Partners

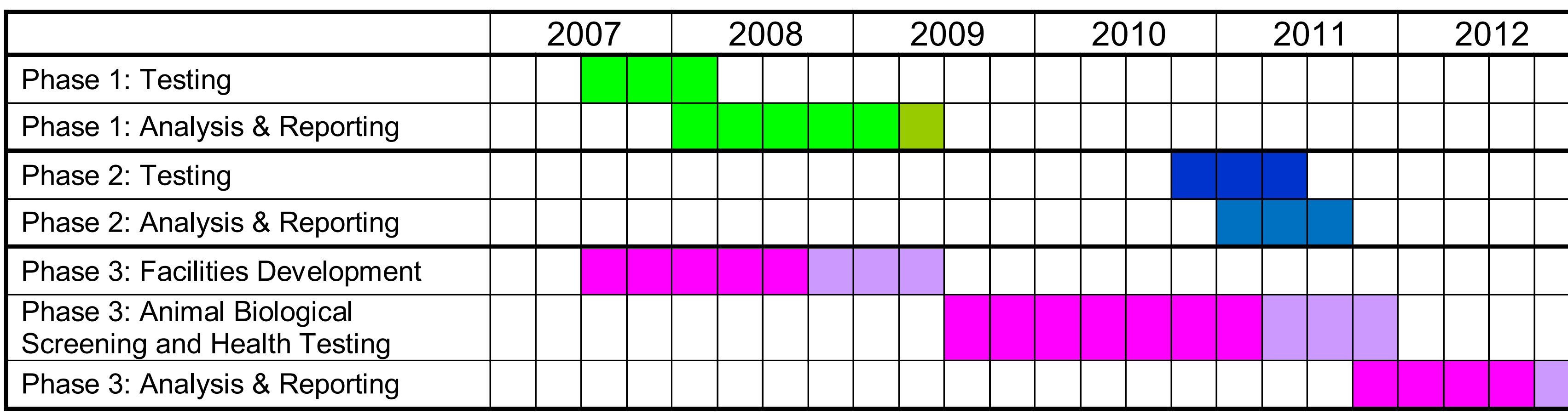
DOE OVT and NETL
Engine Manufacturers Association (EMA)
US Environmental Protection Agency (EPA)
California Air Resources Board (ARB)
American Petroleum Institute (API)
Aftertreatment Manufacturers
Coordinating Research Council (CRC)

Project Overview

<u>Phases:</u>

1. 2007 Engine Emissions Characterization (Southwest Research Institute (SWRI))
   - *CRC Technical Leader*
2. 2010 Engine Emissions Characterization (SwRI)
   - *CRC Technical Leader*
3. 2007/2010 Engine Health Effects Testing (Lovelace Respiratory Research (LRRI))
   - *Short Term biological screening and Long-Term Health Effects Test on 2007 Engines*
   - *HEI Technical Leader ; CRC Technical Monitor*

Overall Project Timeline



Why do we care about these results?

- New Generation diesel engines are highly fuel efficient and a likely significant contributor to enhanced fuel economy for the next 15 – 20 years IF they gain wide acceptance
- The combination of advanced-technology, compression-ignition engines, aftertreatment systems, reformulated fuels, and reformulated oils developed to meet the 2007/2010 emission standards will result in substantially reduced emissions.
- Substantial public health benefits and enhanced public acceptance and use are expected from these reductions.
- With any new technology it is prudent to conduct research to confirm benefits and to ensure that there are no adverse impacts to public health and welfare.

ACES Phase I Approach and Objectives

- Quantify the significant reduction in both regulated and unregulated emissions from advanced diesel engines,
- Provide regulated and unregulated emissions for this new engine technology,
- Provide initial guidance for ACES Phase 3 health study using the regulated and unregulated emissions information from ACES Phase 1

CAT C13, by Caterpillar

Cummins ISX, by Cummins

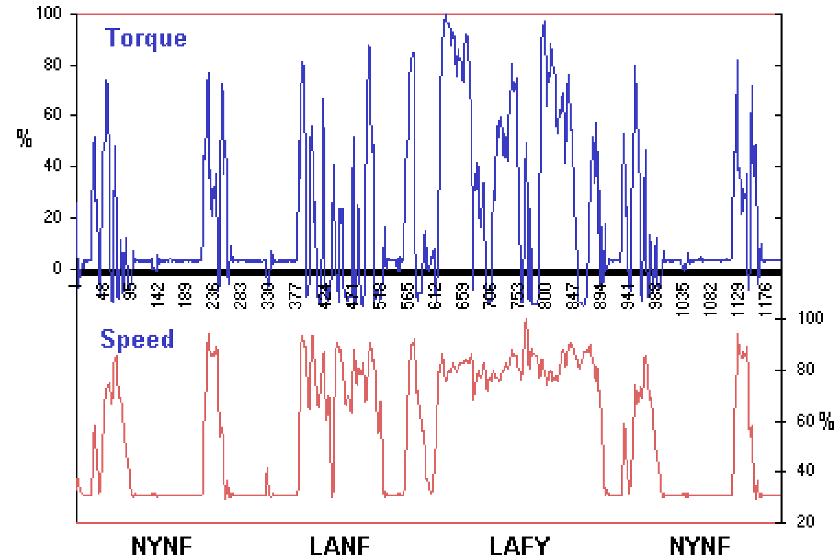
DDC Series 60, by Detroit Diesel

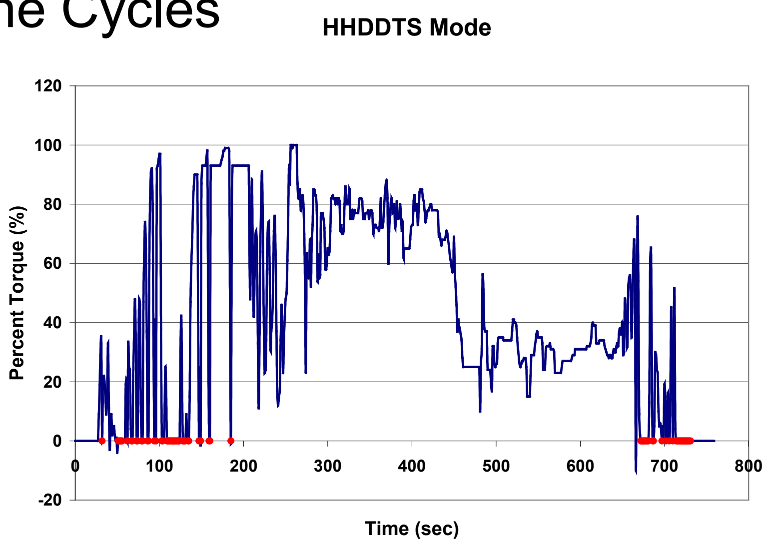
Mack MP7, by Volvo

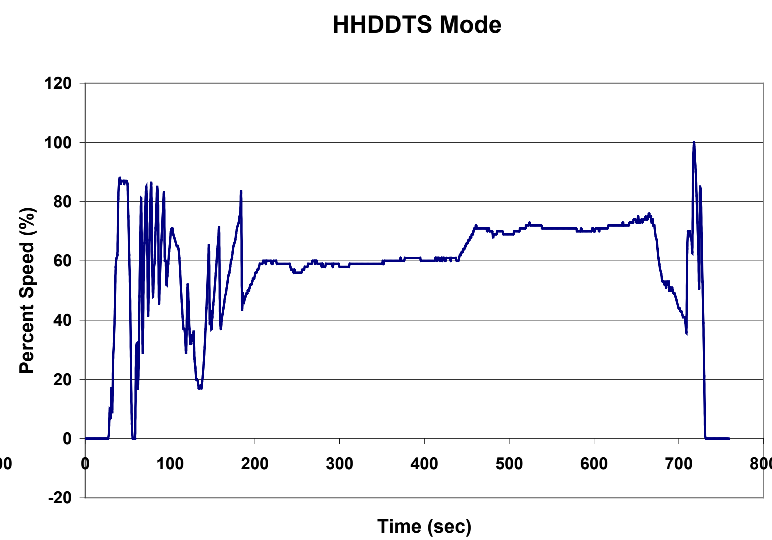
Phase 1 Approach: Test Cycles

- Foundation: HD-FTP
- CRC Project ACES-1
  - Conversion of CARB Chassis Cycles using E-55/59 data
  - Creep, Transient, 2 Cruise Cycles
- CRC Project ACES-1a
  - 16-hour test schedule based on HD-FTP & ACES-1/CARB Engine Cycles

FTP







Phase 1 Results: Regulated Emissions

- Relative to EPA 2007 regulated emissions limits, and based on the average FTP cycle emissions from all engines:
  - PM: **89 percent below** the 0.01g/hp-hr limit
  - CO: **98 percent below** the 15.5 g/hp-hr limit
  - NMHC: **95 percent below** the 0.14 g/hp-hr limit
  - NOx: **10 percent below** the 1.2 g/hp-hr average limit

Phase 1 Results: Unregulated Emissions

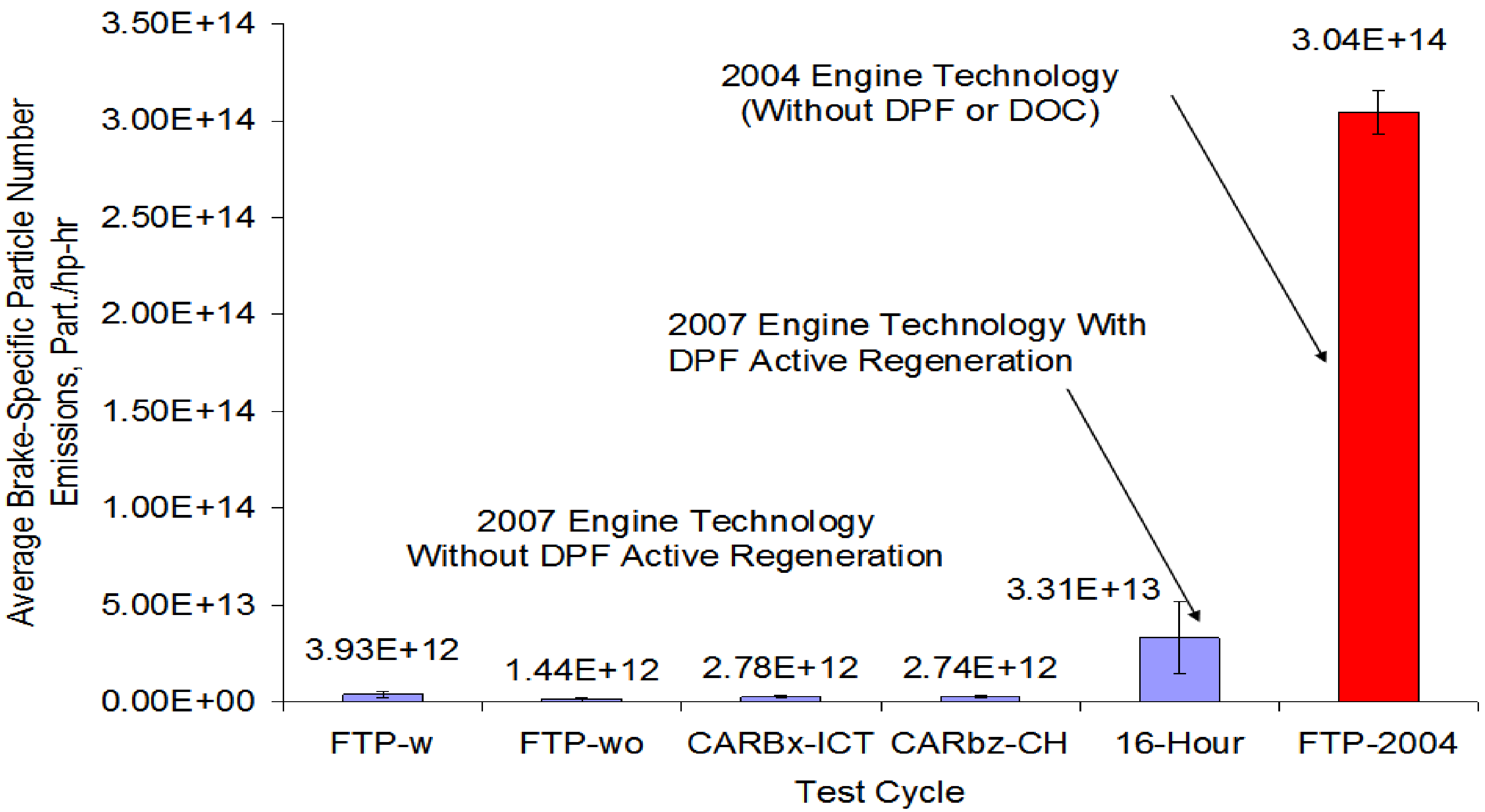
On a g/hr emission rate basis, the great majority of unregulated emission species were ***substantially below the level observed with 2004 engine technology*** used in CRC E55/59.

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

Average 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**

Summary – Phase 1 Results

- Regulated PM, CO, and NMHC emissions were at least 90% below the 2007 standard, and NO_x was 10% below standard
- Most unregulated emissions at least 90% below 2004 technology
- Average NO_2 emission of 0.68 g/hp-hr was 2 to 7 times higher than the emissions from 2004 engines
  - 2010 engine technology will force NO_2 emissions to be substantially lower than both 2007 and 2004 technology engines
- Particle number emissions average was at least 90% below 2004 technology engines, even when DPF regeneration occurred
- **One of the four engines (engine B) was selected to go on to health testing**
- **The final report issued June 30, 2009, available at http://www.crcao.com/publications/emissions/index.html**

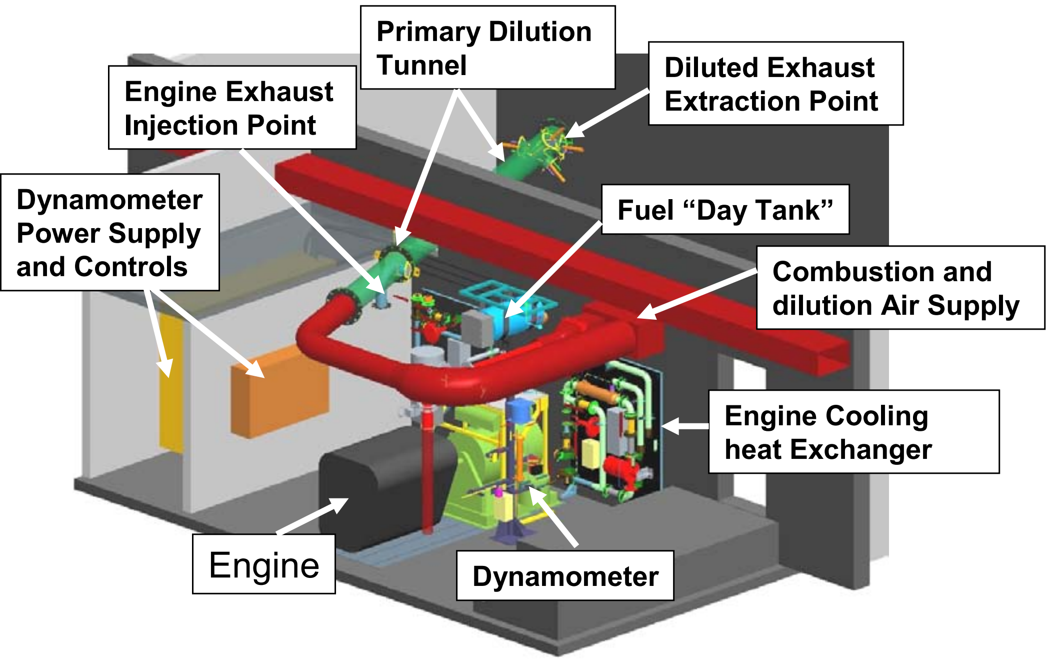
ACES PHASE 2: 2010 Compliant Engines Approach and Objectives

- 2010 engines will offer substantial improvements in NOx emissions
- Phase 2 will conduct Emissions Characterization in 2010 engines
- 2010 technology has evolved in multiple directions and, given credits, will not meet the specific requirements by that date
- CRC actively planning with manufacturers, agencies, other sponsors for start in early 2011

ACES PHASE 3 Health Bioscreening Approach and Objectives

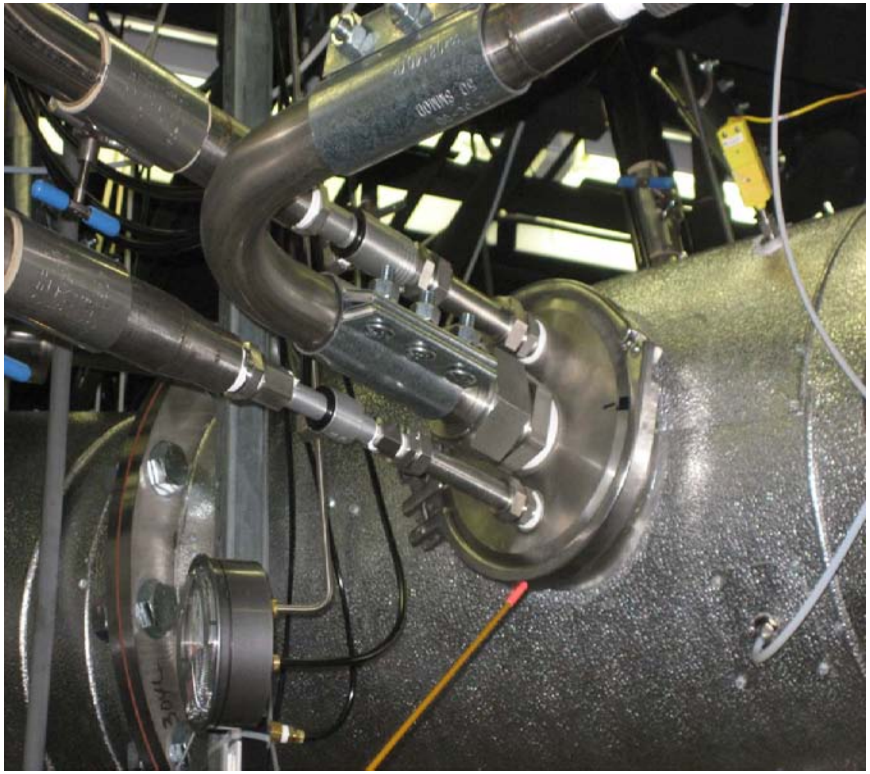
Phase 3A: Characterization of emissions and exposure atmospheres

Phase 3B: Conduct of animal studies

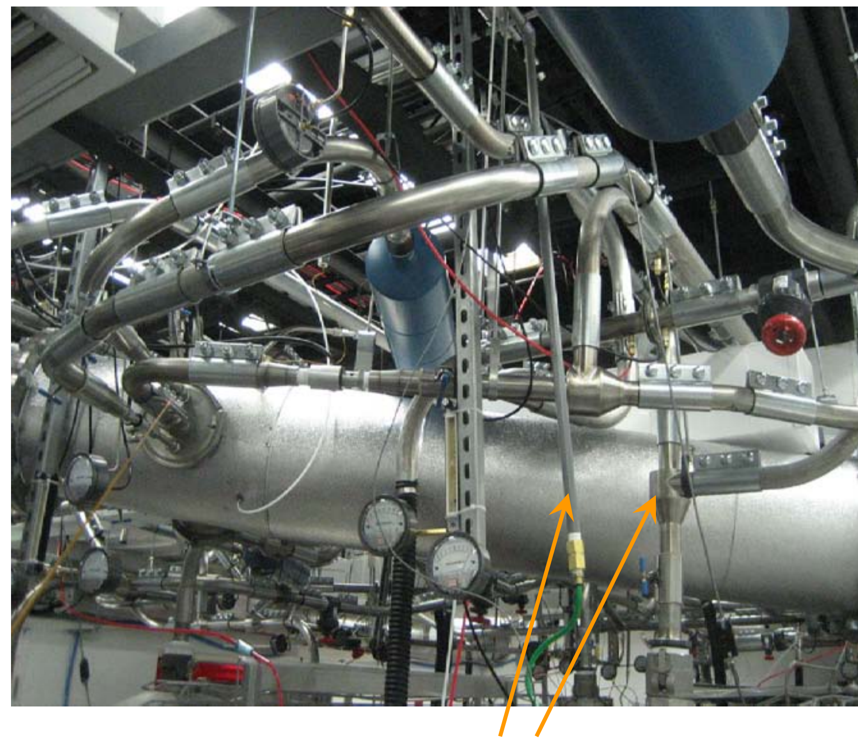


dynamometer

dilution tunnel and exhaust stacks



primary dilution port



secondary dilution

Engine Control Room

Adjusting Dilution

Checking & Cleaning Chambers

Examining Mouse

Lovelace


DANGER
DANGER

PHASE 3A

- **2007-compliant "engine B' "** (selected from four candidates)
  - **Installed at LRRI**
  - **Confirmed that engine/control systems met performance criteria**
- **Evaluated diluted emissions in empty animal chamber, and compared to SwRI results** (using same fuel)
  - **Emissions = exhaust + crankcase blow-by**
  - **FTP, SS modes 1, 3 & 5, ACES cycle**
  - **Constant pressure primary dilution tunnel**
- **Determined dilutions required to meet targets set by HEI**
  - **Dilutions set to achieve 4.2, 0.8 & 0.1 ppm NO_2**
  - **Dilutions ≈ 40:1, 210:1 & 1680:1**
- **Characterized chamber atmosphere in detail**
- **Evaluated chamber temperatures & operating reliability**

EXPOSURE ATMOSPHERES

(from 40 daily measurements 2/22 – 4/15/10)

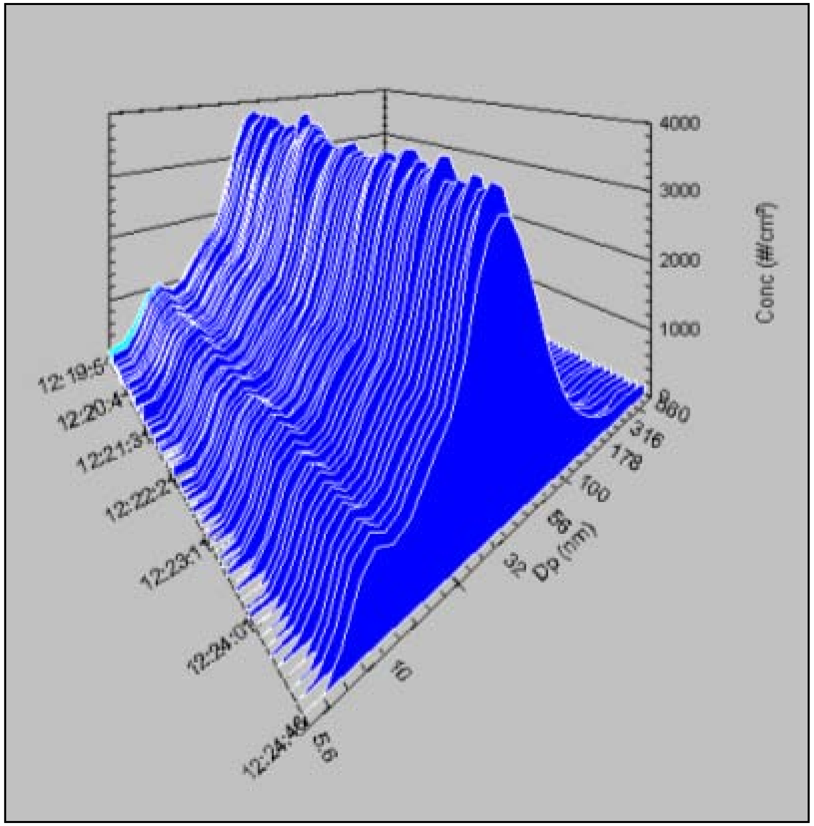
Gases (ppm)	High Mean	High SD	Medium Mean	Medium SD	Low Mean	Low SD
(NO_2 target)	4.2		0.8		0.1	
NO_2	4.19	0.74	0.87	0.19	0.10	0.04
NO	5.06	0.67	0.93	0.21	0.10	0.05
NOx	9.25	1.34	1.80	0.39	0.19	0.08
CO	6.9	1.1	*nmd**		*nmd*	
THC	0.4	0.3	*nmd*		*nmd*	
CO_2	3818	263	*nmd*		*nmd*	
PM (μg/m³)						
Inlet filter	9	3	3	2	1	1
Chamber filter	38	20	43	59	34	17

**not measured daily*

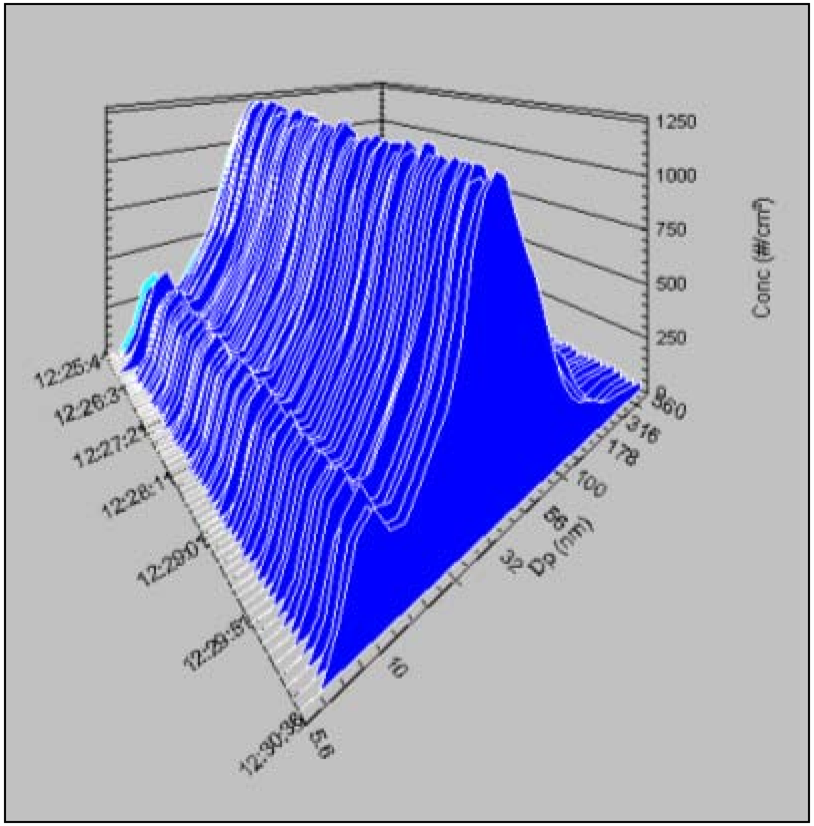
The first detailed characterization is complete.

THE EXPOSURE SYSTEM HAS LITTLE EFFECT ON PARTICLE SIZE DISTRIBUTION

Particle number vs diameter with time during 75% throttle at 1800 rpm



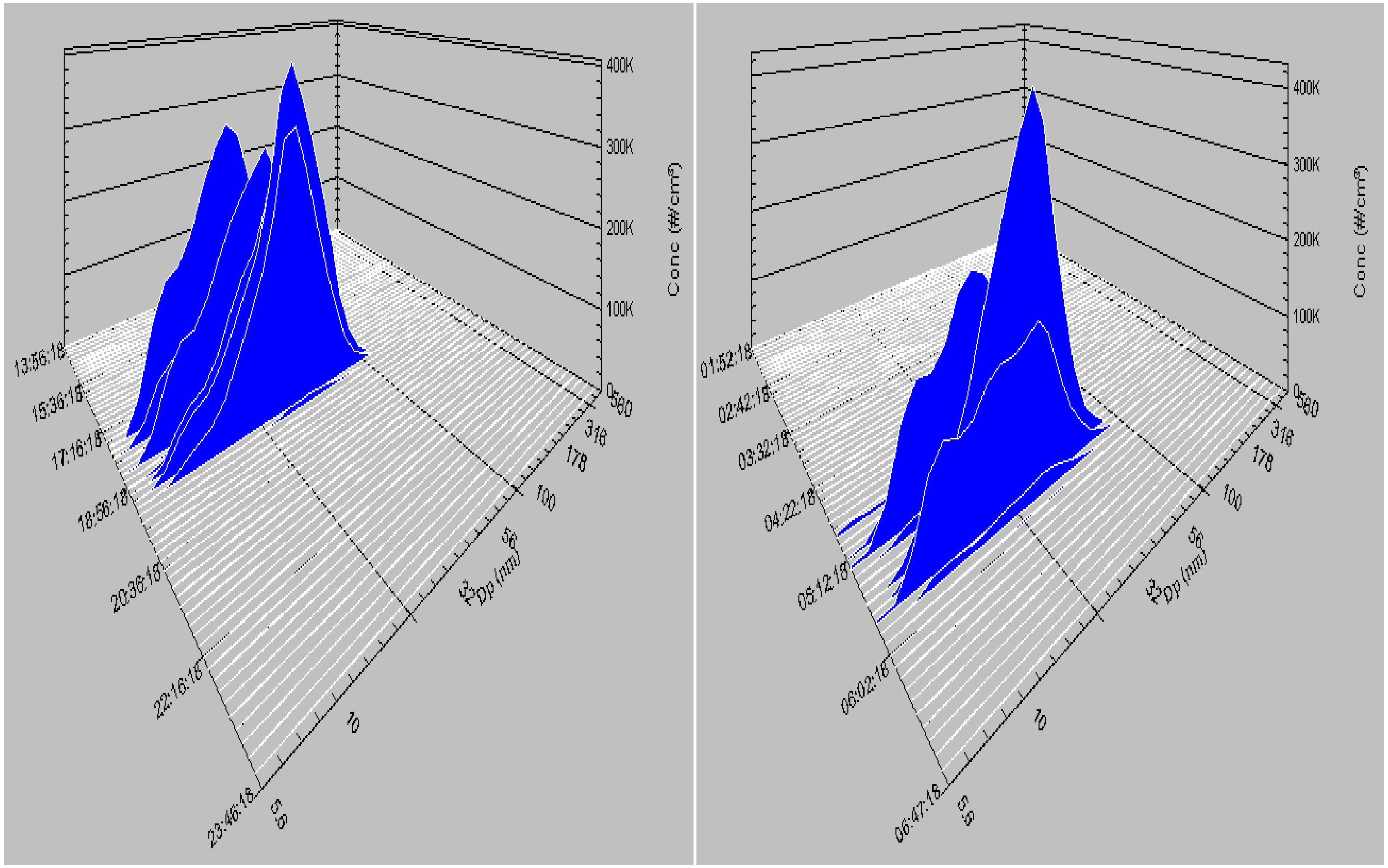
Primary Dilution tunnel



High Level Exposure Chamber

EFFECT OF PARTICLE TRAP REGENERATION

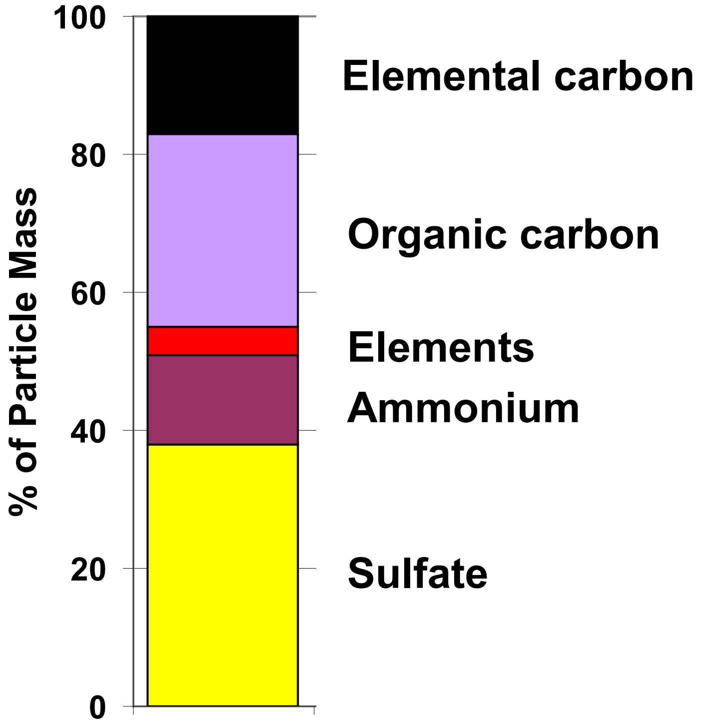
- **Very little PM is emitted except during regeneration**
- **Regeneration occurs twice during 76% of 16-hr cycles, once during 24%**



Two regenerations during single 16 hr cycle at <u>high</u> exposure level

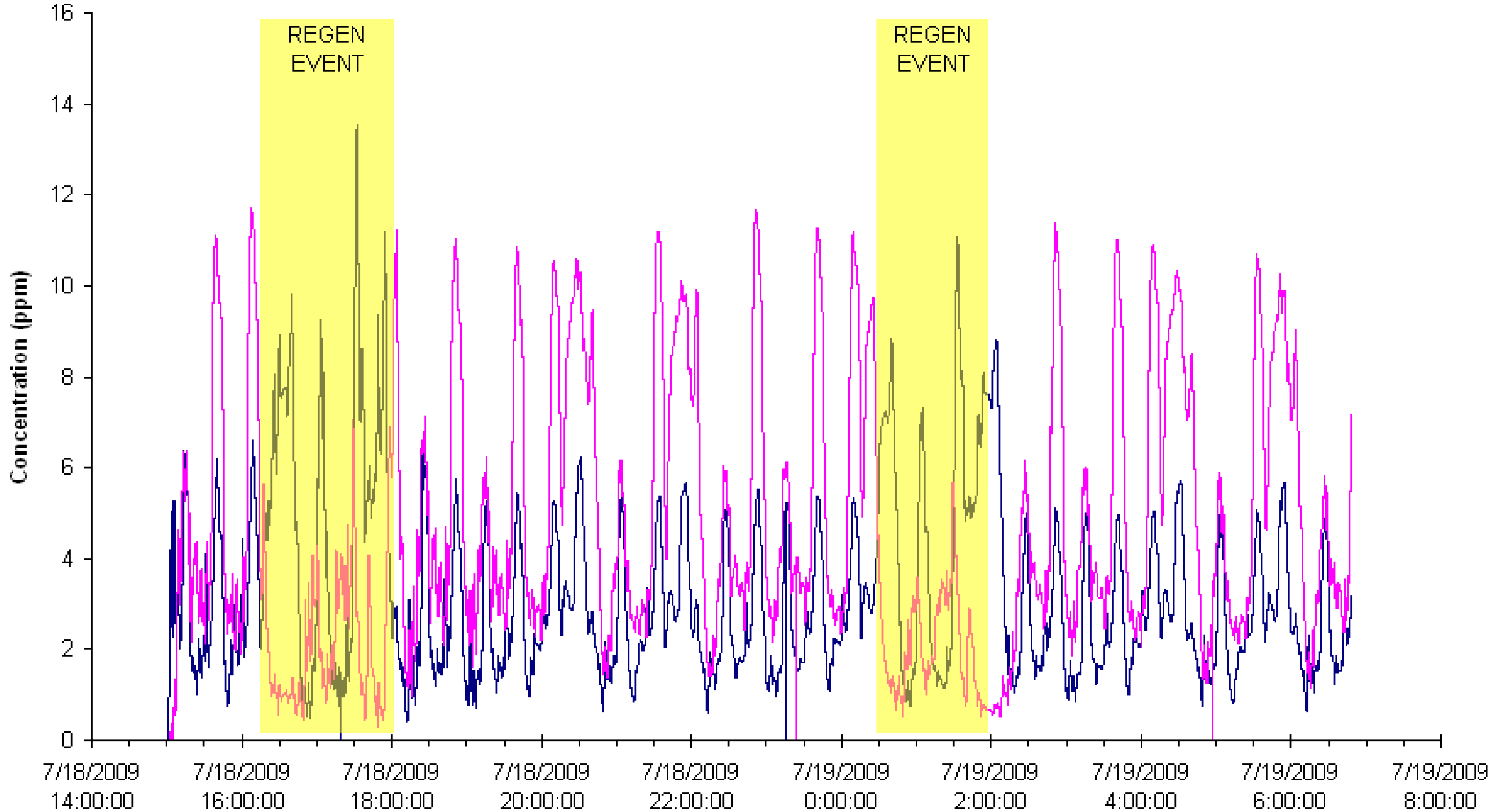
PARTICLE COMPOSITION

Measured in high level chamber without animals



EFFECT OF REGENERATION ON GASES

- NO ↑ and NO_2 ↓ during regeneration - other gases are affected less



NO and NO_2 in high level chamber on day with 2 regenerations

MOUSE BIOSCREENING STUDY

- **Expose 132 mice/group 16 hr/day, 5 days/wk for 13 weeks**

  C57Bl/6

- **Three dilutions of whole emissions + clean air controls**

  Target mean NO_2 of 4.2, 0.8 & 0.1 ppm

  Commercial fuel from local supplier (Chevron)

  Engine lube oil same as at SwRI (Lubrizol)

  Engine maintenance per mfg. direction

- **40 mice/group allocated for evaluations at 1 and 3 months**

  Bronchoalveolar lavage | **Cell proliferation**

  Hematology* | **Serum chemistry***

  Histopathology ***3 mo only*

- **80 mice/group allocated for evaluations at 1 & 3 months by 5 ancillary studies**

  Blood and tissue collections

STATUS: 1 and 3 month exposures now complete

Evaluation and Analysis underway

RAT BIOSCREENING STUDY

- **Expose 280 rats/group 16 hr/day, 5 days/wk for 24-30 months**
  Harlan HsdRccHan:Wist (Wistar)
- **Three dilutions of whole emissions + clean air controls**
  Same dilution targets as for mice (4.2, 0.8 & 0.1 ppm NO_2)
- **200 rats/group committed to long-term carcinogenesis bioassay**
  Expect ~60+% survival to 30 mo
- **80 rats/group allocated for evaluations at 1, 3, 12, & 24 months**

Bronchoalveolar lavage	**Cell proliferation**
Hematology*	**Serum chemistry***
Pulmonary function*	**Histopathology**

***Not measured at 1 mo**

- **Blood and tissue collected from same rats for 5 ancillary studies**

STATUS: 1 and 3 month Exposures Complete; Analysis Underway

Long-term exposures continuing

Ancillary ACES Studies

- Additional endpoints in animals allocated to intermediate sacrifices and unassigned animals
  - Systemic and vascular inflammation; blood coagulation
  - Genotoxicity
- Measurements to be made in mice at 1 & 3 months and in rats at 1, 3, 12 and 24 months
- 3 diesel exhaust concentrations and control group
- Five Teams:
  - **Jeffrey Bemis**, *Litron Laboratories*
  - **Lance Hallberg**, *University of Texas*
  - **John Veranth**, *University of Utah*
  - **Daniel Conklin**, *University of Louisville*
  - **Qinhua Sun**, *Ohio State University*

SCHEDULE

- One and Three Month Exposures Complete
- Evaluation Underway at LRRI and Five Ancillary Labs
- Report Expected to Enter HEI review – Early 2011
- First ACES Health Results later next year!

For further information, contact:

Maria Costantini
Principal Scientist
Health Effects Institute
mcostantini@healtheffects.org
617-488-2302

Chris Tennant
Deputy Director
Coordinating Research Council
ctennant@crcao.org
678-795-0506 x105