Impacts of Advanced Combustion, Fuels and Aftertreatment Technologies on Diesel PM Emissions and Mobile Source Air Toxics: A Ten-Year Retrospective

February 11, 2009

Chairman's Air Pollution Seminar Series

California Air Resources Board

Sacramento, CA

John Storey

Fuels, Engines, and Emissions Research Center

storeyjm@ornl.gov

865-946-1232

Managed by UT-Battelle
for the Department of Energy

Oak Ridge National Laboratory

Acknowledgements

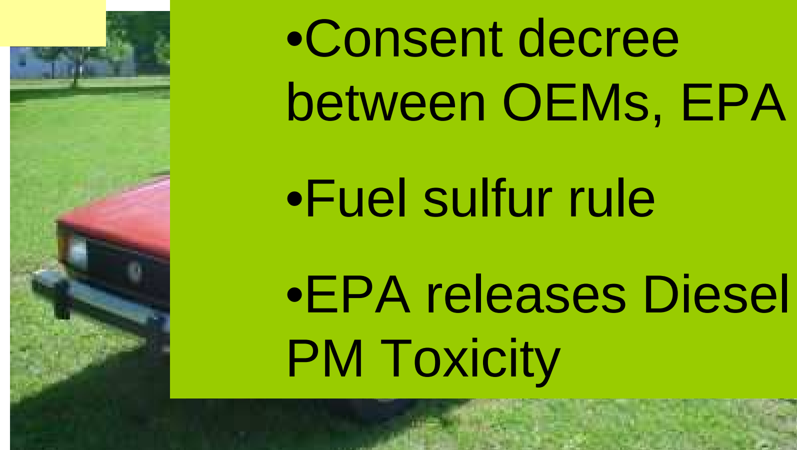
- **FEERC team:**
  - **Ron Graves (Director), Brian West, Jim Parks, Sam Lewis, Bruce Bunting, Stuart Daw, Scott Sluder, Robert Wagner, Teresa Barone, Norberto Domingo and many others**
- **DOE support: Office of Vehicle Technologies**
  - **James Eberhardt, Gurpreet Singh, Ken Howden, Kevin Stork, John Fairbanks**
- **EPA support: OTAQ**
  - **Dennis Johnson and Jim Blubaugh**
- **CARB – Alberto Ayala for inviting me**

Diesel and light-duty diesel have specific challenges in public, regulatory acceptance

- 1970's-90's tough for diesel
  - GM diesel problems
  - "Dump Dirty Diesel" Campaign
  - CARB interest in diesel replacement with natural gas

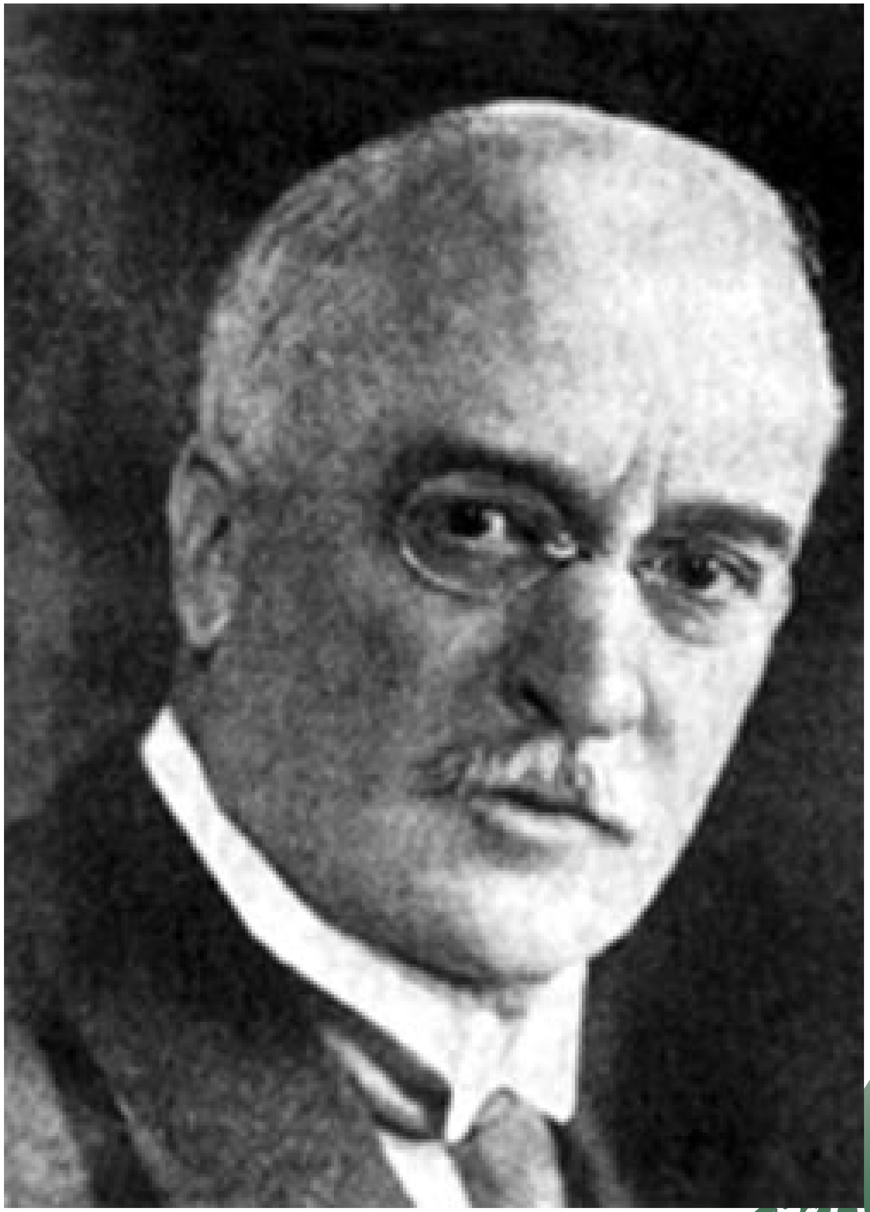
- 1998+ Government Response to Diesel Issues
  - DEER conference
  - Consent decree between OEMs, EPA
  - Fuel sulfur rule
  - EPA releases Diesel PM Toxicity

1979 Cadillac Diesel Sedan



1981 VW Rabbit Diesel Pickup

Who invented the diesel engine?



- **Rudolf Diesel 1858-1913**
- **Much more efficient than steam engines of the time**
- **Original vision – to run on vegetable oils!**
  - **biodiesel isn't such a new idea**
- **Died mysteriously on ferry to England 1913**

The path forward.....

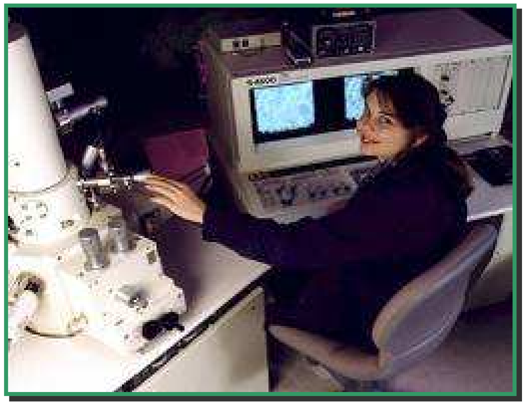
- Motivation, background of DOE and diesel
- Approach to lowering PM
  - Engine Hardware
  - Diesel Particulate Filters
- Current State-of-the-Art
  - Putting it all together into today's vehicle
  - Retrofit PM control
  - Ultralow sulfur diesel and Biodiesel
- Future
  - Modeling Emissions Control Systems
  - Advanced combustion modes
  - Link to CO_2 emissions and climate change

Oak Ridge National Laboratory

- Began as part of the Manhattan Project
- Nation's largest multiprogram energy laboratory
- World's first nuclear reactor and now leading producer of medical radioisotopes
- Nation's largest unclassified scientific computing facility
- Nation's largest science facility, the $1.4B Spallation Neutron Source
- Nation's largest concentration of open source materials research

Relevant Facilities

National Transportation Research Center



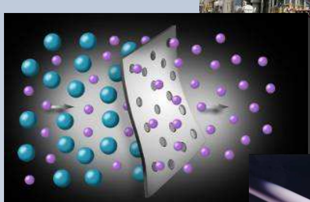
High Temperature Materials Laboratory

Transportation technology

Generation

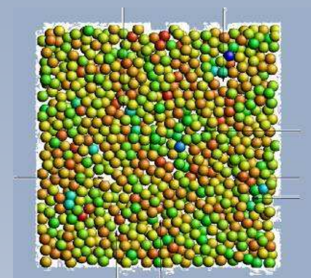

Alternative fuels

Refining




Hydrogen production

Storage and distribution



Hydrogen storage and transport

Batteries & Power electronics

Consumption

Internal combustion

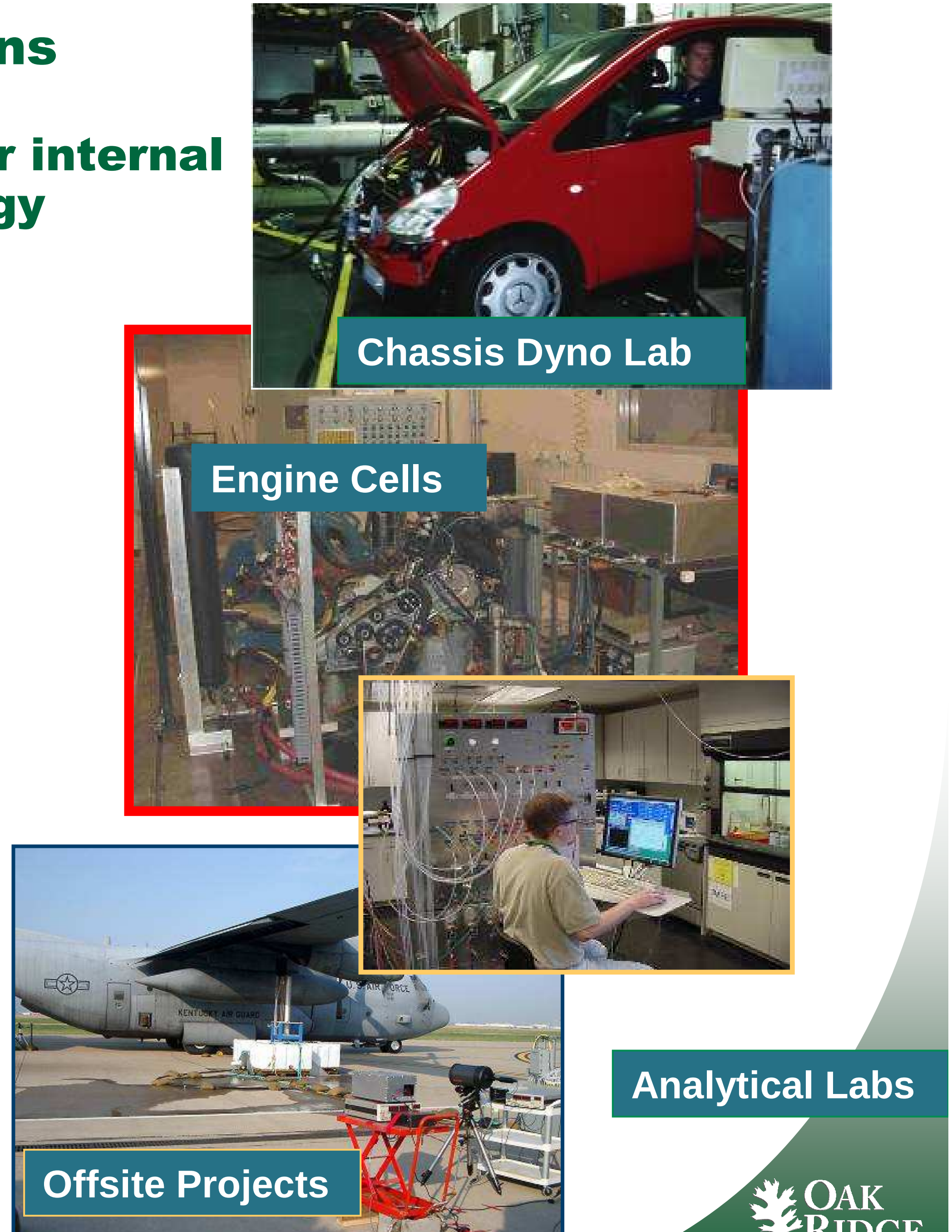
Hybrid Electric Vehicle


Fuel cells

Transportation system analysis

Fuels, Engines, & Emissions Research Center…. a comprehensive laboratory for internal combustion engine technology

- **A DOE National User Facility in the NTRC**
- **Focusing on alternative fuels, advanced combustion, and emission control R&D**
- **Unique or extraordinary diagnostic and analytical tools for engine/emission control R&D**
- **R&D from bench-scale to vehicle**
  - **Chemical/analytical labs**
  - **9 dynamometer stands: 25-600 hp**
  - **Chassis dynamometer**
  - **Full-pass engine controls support research**
  - **Emissions analysis with high resolution of time and species**
  - **Non-invasive optical and mass-spec diagnostics**
  - **Modeling & simulation**



The DOE's Transportation Agenda

- **Energy Security, Energy Efficiency**
  - **Energy Data Book and http://www.fueleconomy.gov**
  - **Energy Independence and Security Act (EISA, 2007)**
    - **36 Billion gal/yr of renewable fuels (2022)**
    - **Limits to corn-based ethanol**
    - **Focus on cellulosic ethanol**
- **Office of Vehicle Technologies**
  - **Light-duty engine efficiency goal: 42% (2007) 45% (2010)**
  - **Heavy-duty efficiency goal: 50% (2006); 55% (2013)**
  - **Meet applicable emissions**
- **Office of Biomass Programs**
  - **Production via Cellulosic sources (biomass)**
- **Office of Hydrogen, Fuel cells, and Infrastructure Technologies**
  - **Automotive fuel cell emphasis**

So why bring up the DOE vision?

- **DOE saw diesel engines as meeting their goal of energy efficiency and security**
  - **Heavy-duty engine efficiency program**
  - **Light Truck Clean Diesel program**
- **Emissions control was the enabling technology for diesel**
- **1998. DEER conference in Maine**
  - **Diesel Engine Emissions control Research**
  - **Organized by DOE (John Fairbanks)**
  - **< 100 attendees**
- **2008 DEER conference in Dearborn**
  - **> 1300 attendees**

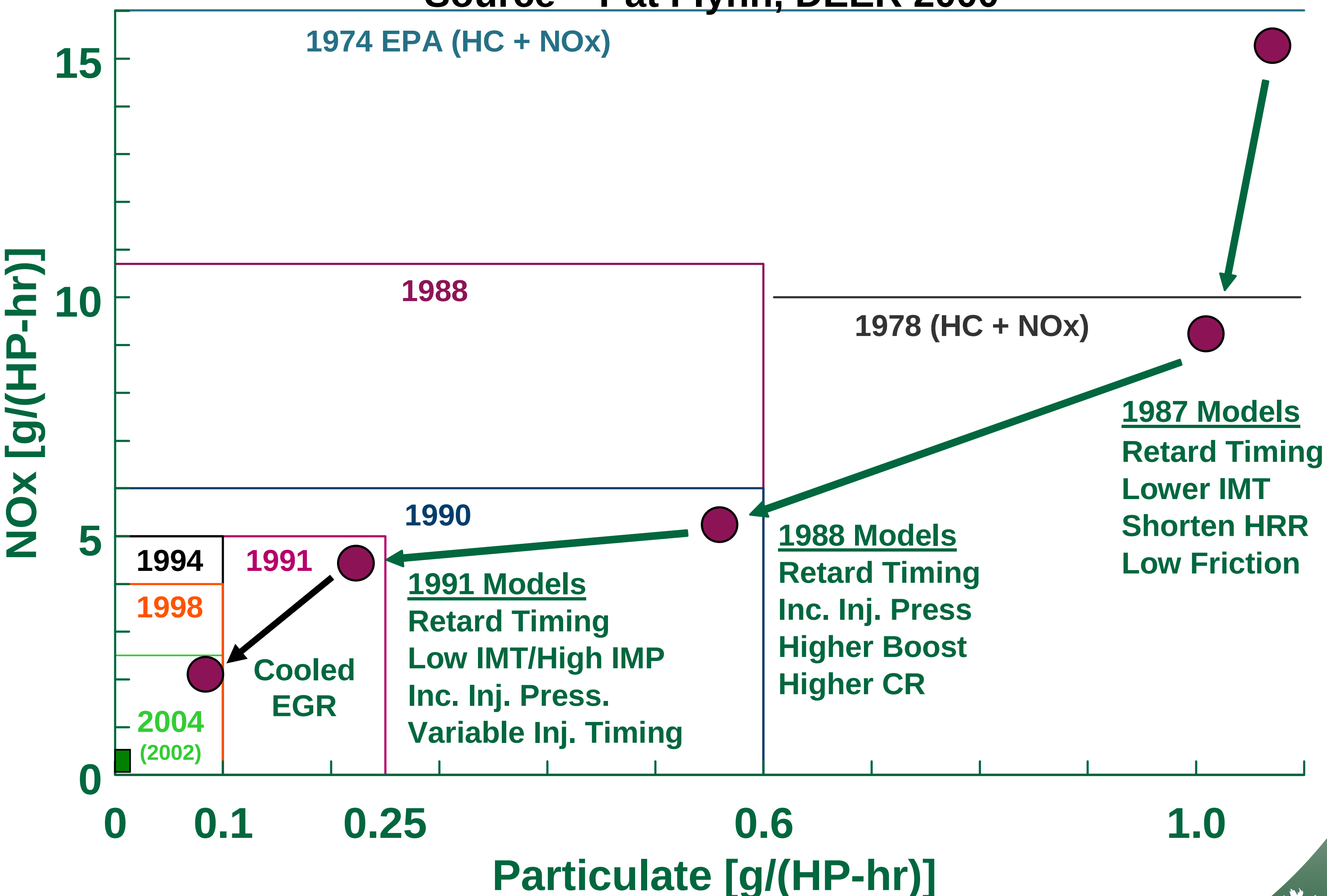
http://www1.eere.energy.gov/vehiclesandfuels/resources/proceedings/index.html

DEER conferences are comprehensive

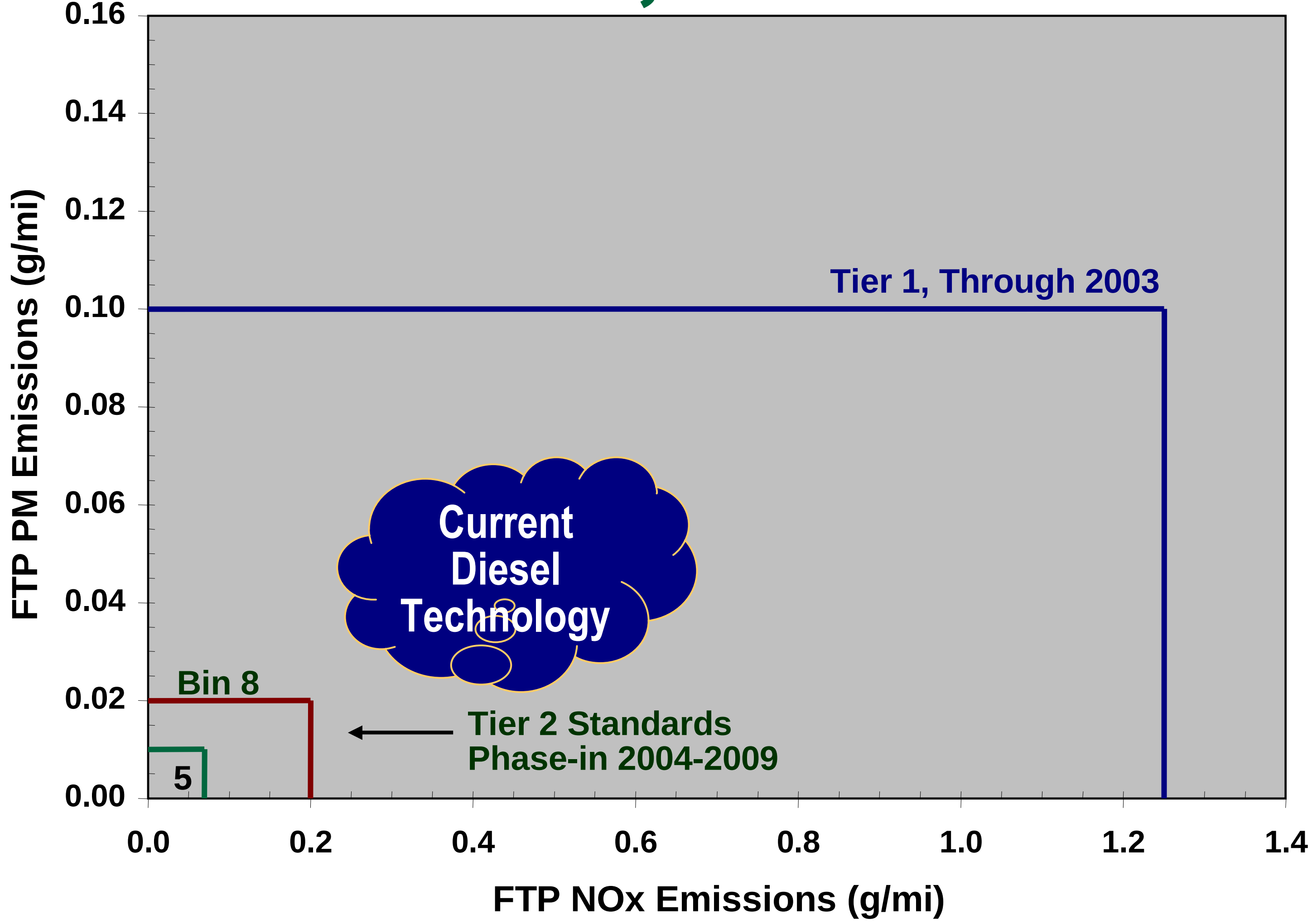
- **Industry, academia, National Labs, non-profit**
  - **Special session for environmental advocacy organizations**
- **Thrusts included health effects**
  - **First U.S. discussion of nanoparticles and health**
- **NOx and PM control sessions**
- **Now large focus on advanced combustion and energy efficiency**

Evolution of Heavy Duty Diesel Engine Emission Control

Source – Pat Flynn, DEER 2000



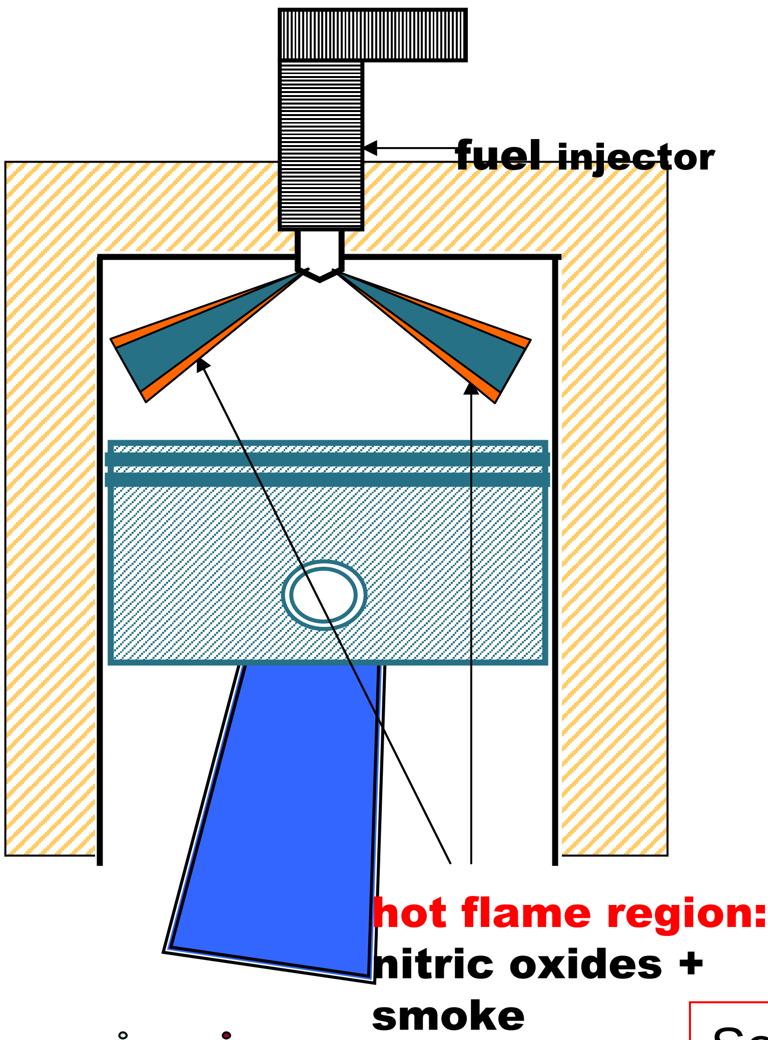
EPA's emissions standards require substantial PM and NOx reductions for automotive diesels, too.

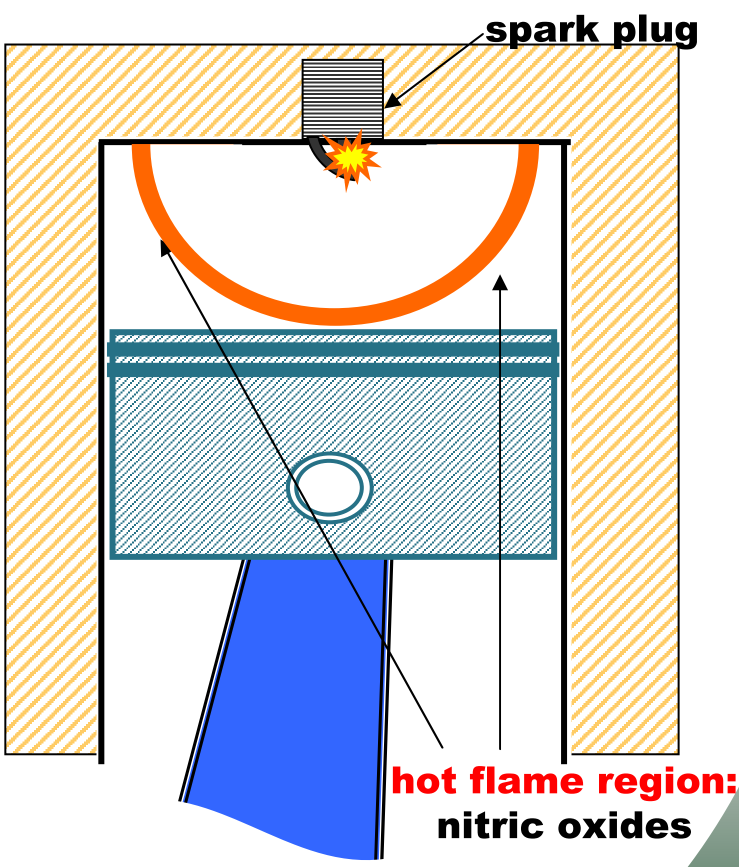


The path forward.....

- Motivation, background of DOE and diesel
- Approach to lowering PM
  - Engine Hardware
  - Diesel Particulate Filters
- Current State-of-the-Art
  - Putting it all together into today's vehicle
  - Retrofit PM control
  - Ultralow sulfur diesel and Biodiesel
- Future
  - Modeling Emissions Control Systems
  - Advanced combustion modes
  - Link to CO_2 emissions and climate change

How do diesels work, anyway?

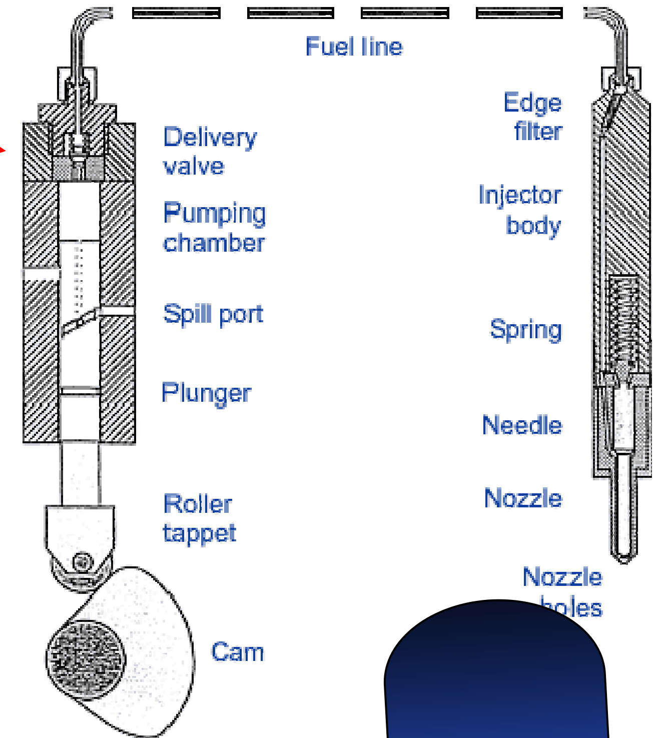


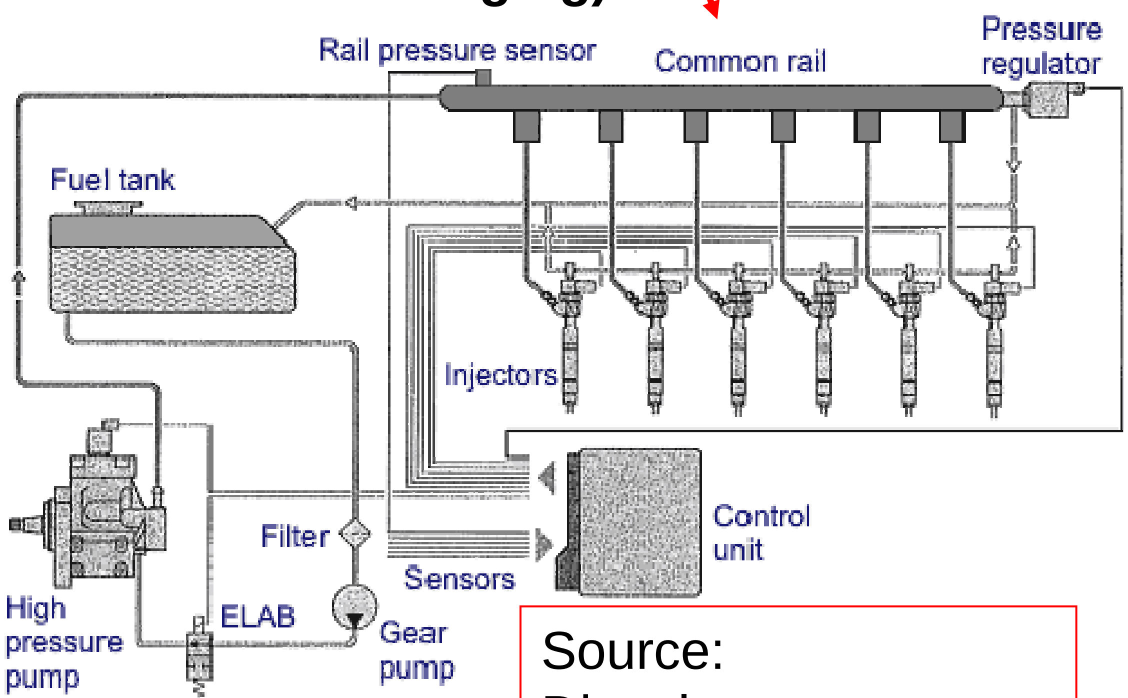


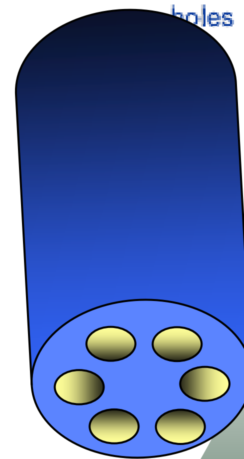
Source:Caterpillar, 2003

Fuel injection - key subsystem of diesel

- **Pump-line-nozzle ("ancient")**
- **Unit injectors**
- **Common rail (state of art)**
- **Piezo (combined with common rail emerging)**







Injector tip

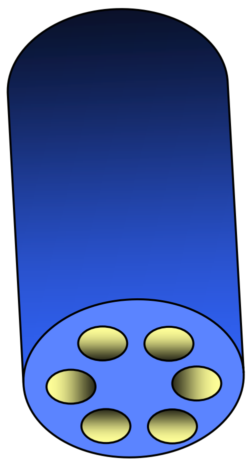
Source: Dieselnet.com

Injection pressure being increased to aid emission compliance

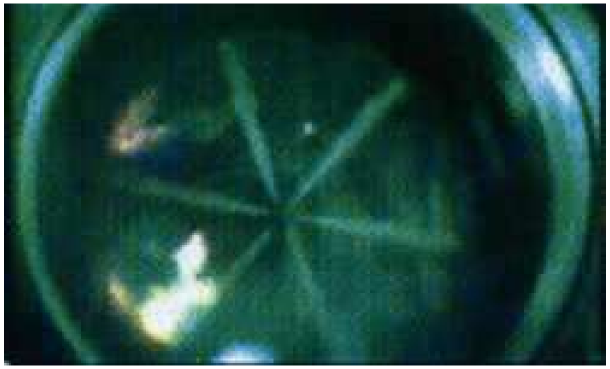
One bar=14.5 psi

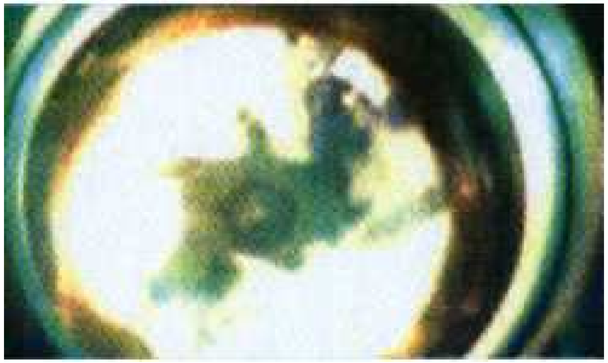
One Mpa=10 bar

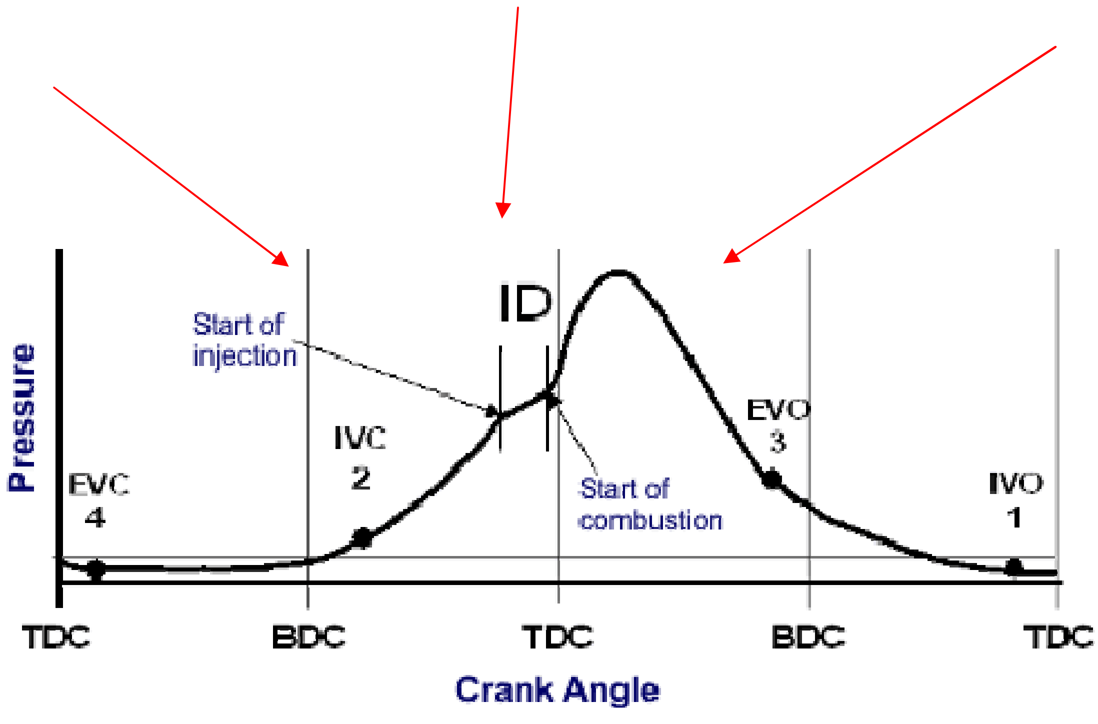
- **Mechanical unit injector=1000 bar (1981)**
- **"HEUI" =up to 1450 bar**
- **Early generation common rail=1350 bar**
- **Latest piezo common rail=1800 bar**
- **The future (Bosch and others) 2000 bar = 29,000 psi**
- **WHY?**
  - **Tiny, tiny holes (<200 μm) needed to make a fine spray, smaller particles**
  - **But, then pass ~ 1 gallon/hr through each hole!**



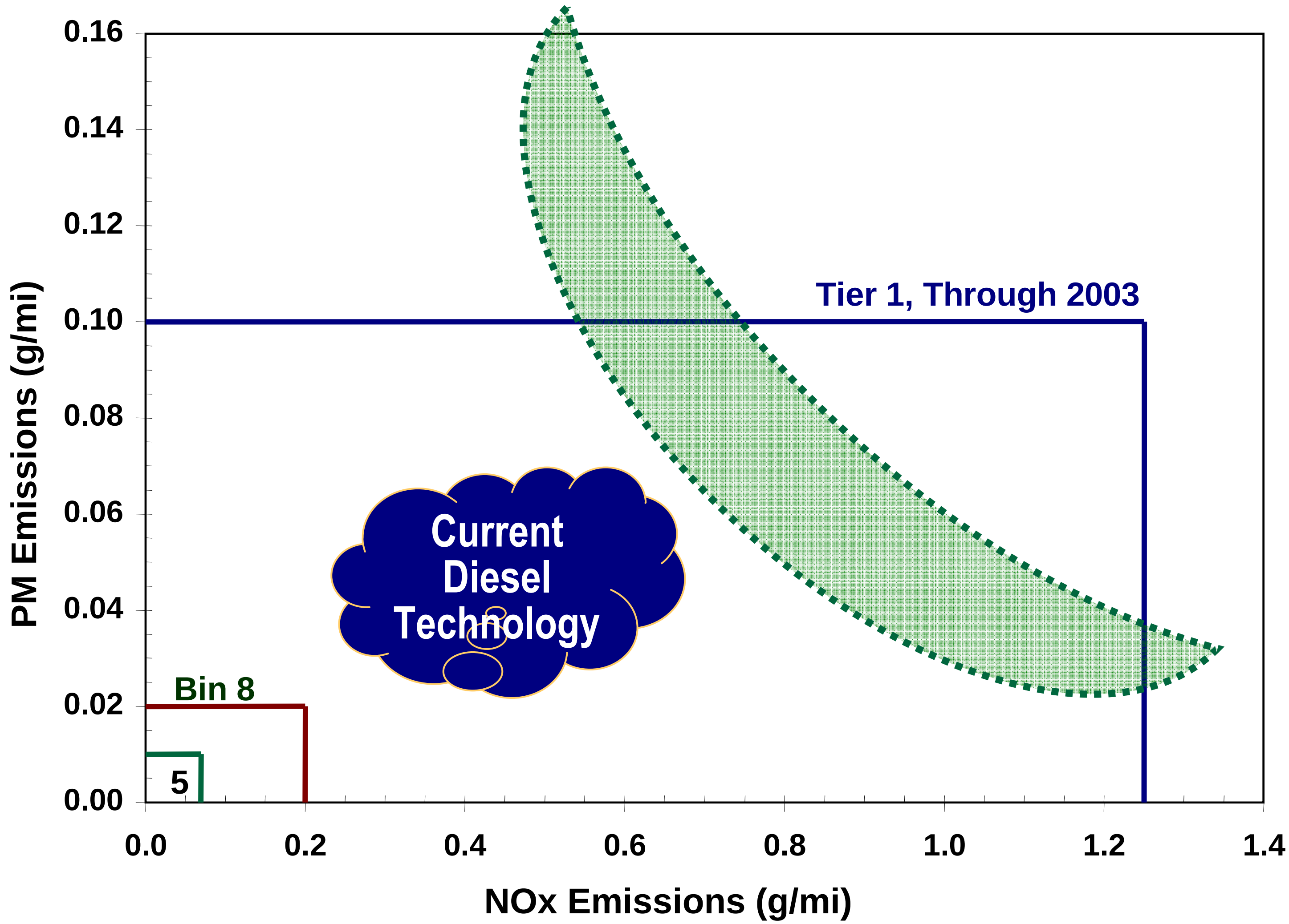
Sequence of diesel fuel injection and beginning of combustion







NOx PM Trade-off curve has been moving



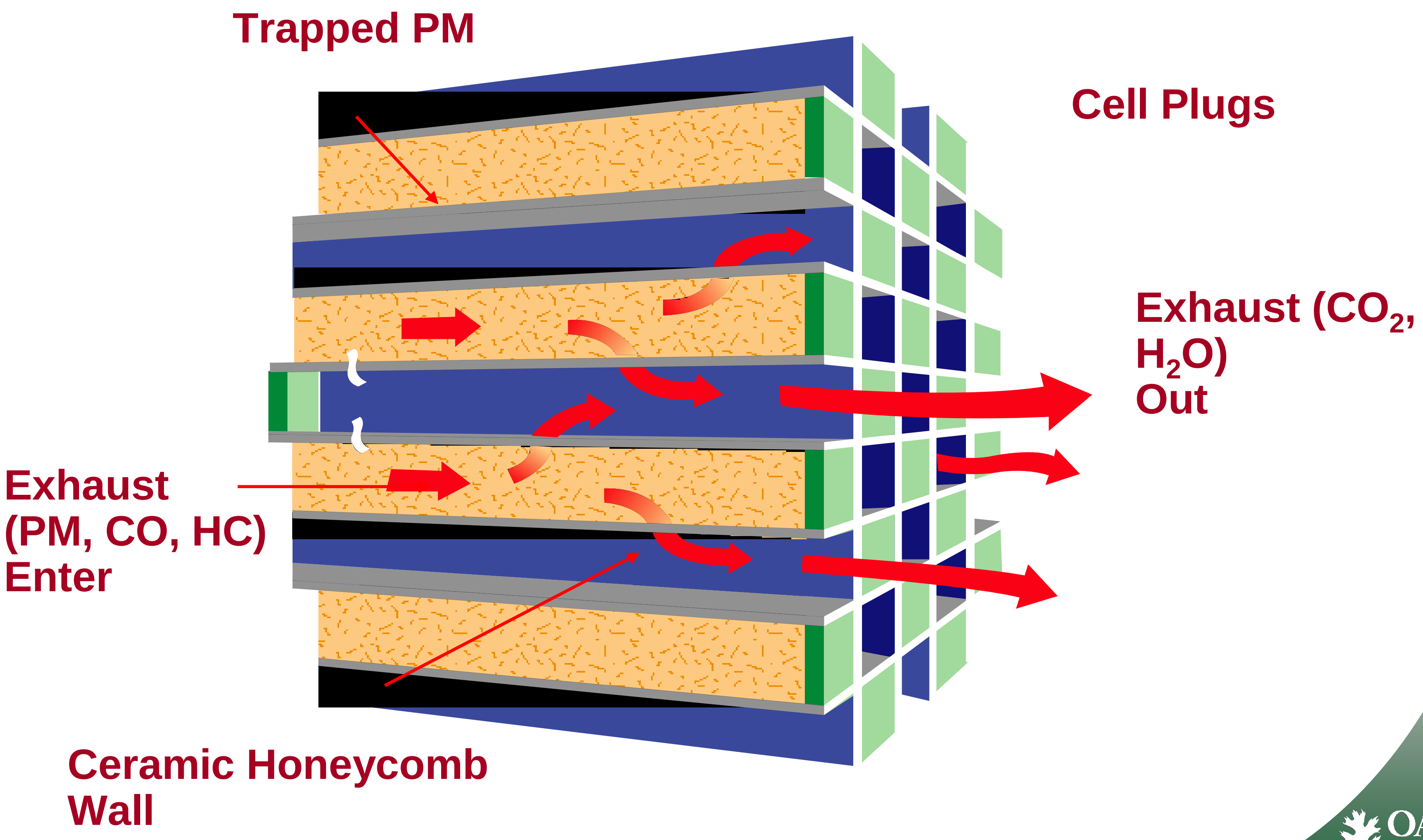
The path forward…..

- Motivation, background of DOE and diesel
- Approach to lowering PM
  - Engine Hardware
  - Diesel Particulate Filters
- Current State-of-the-Art
  - Putting it all together into today's vehicle
  - Retrofit PM control
  - Ultralow sulfur diesel and Biodiesel
- Future
  - Modeling Emissions Control Systems
  - Advanced combustion modes
  - Link to CO_2 emissions and climate change

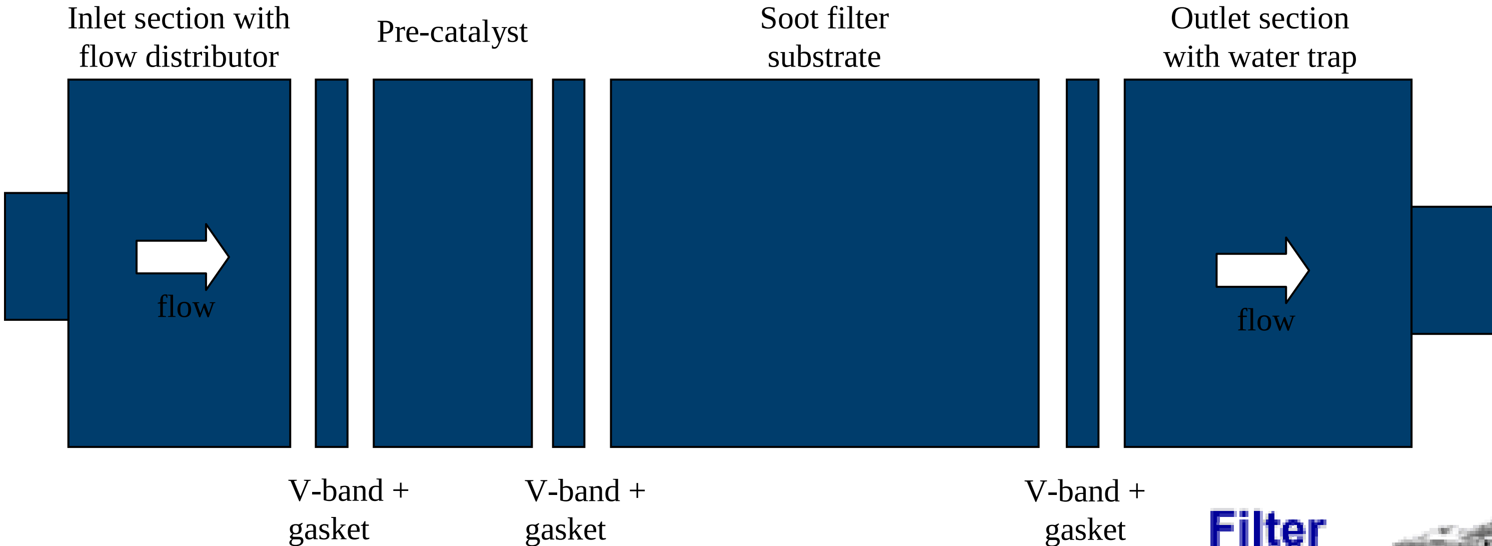
Diesel PM control – Diesel Particulate Filters (DPF) and Diesel Oxidation Catalysts (DOC)

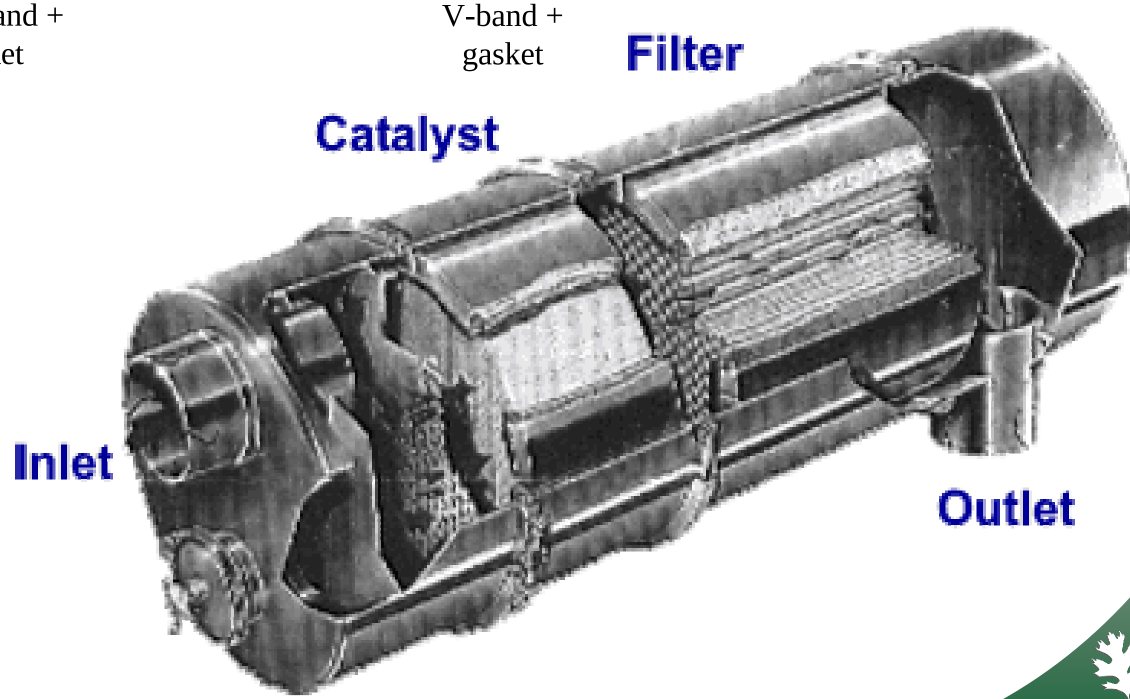
- **DOCs use precious metal catalyst to burn off organic fraction**
  - **Typical PM mass reduction is 30%**
  - **Used on heavy-duty pickup trucks in 90's**
- **First DPF on a car – 1985 Mercedes 300 for California market (not a success)**
  - **Need 700 ℃ to burn off soot with exhaust O_2**
- **Electrically-heated DPF's in early 1990's**
- **Early systems used DOC + DPF**
  - **$NO \rightarrow NO_2$, then the NO_2 oxidizes the soot**
- **Later DPFs use catalytic coating**
  - **Catalyst on DPF converts NO to NO_2, NO_2 oxidizes soot**

Diesel Particulate Filter uses ceramic honeycomb to trap PM



DPF Assembly can replace muffler





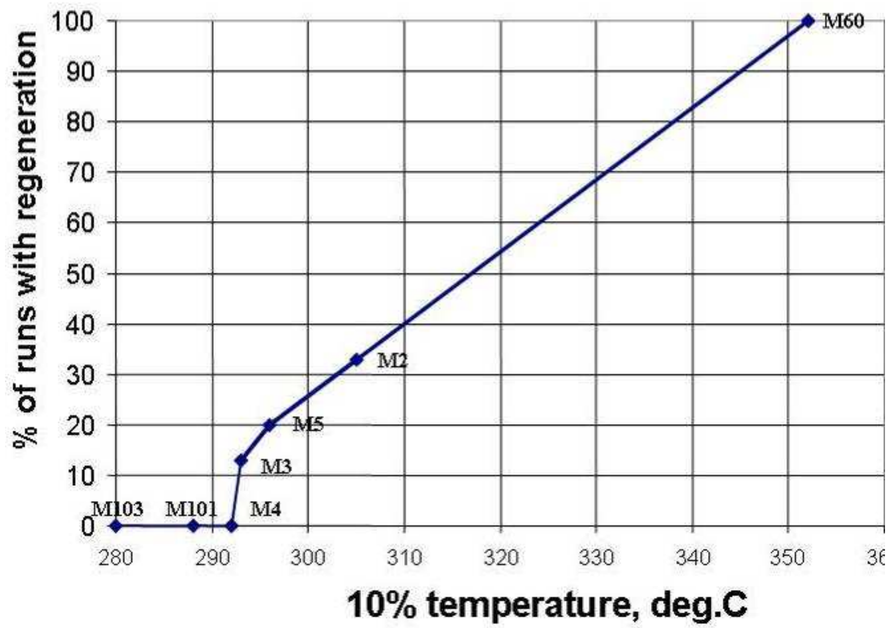
Oak Ridge National Laboratory

Early DPF field study in 2001 in NYC

Uncontrolled Regeneration

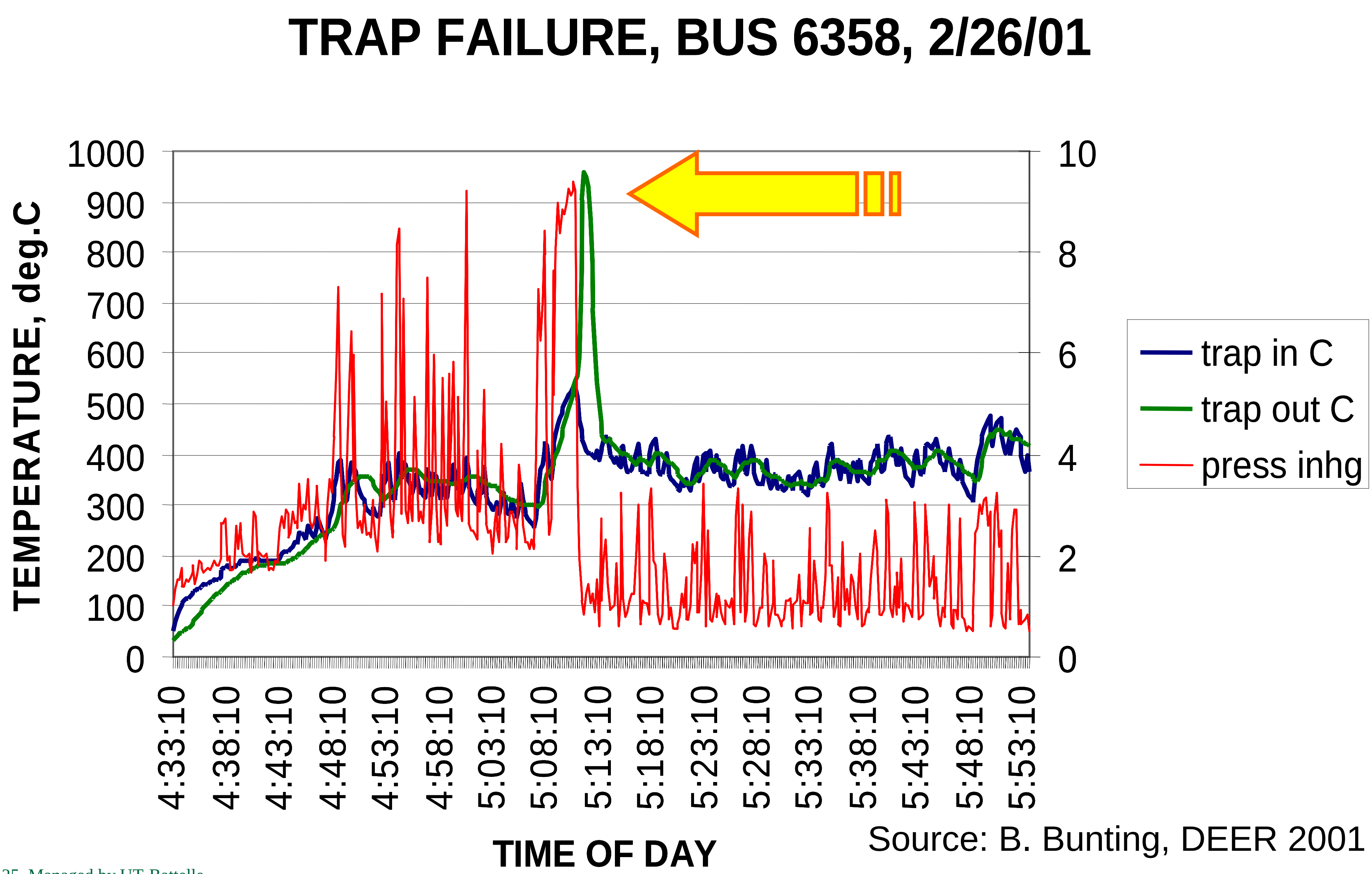
- **Occurs when DPF accumulates excess soot**
- **Excess soot can be lit off during high load (hill, ex-way).**
- **If engine drops to idle during this burning, exhaust flow too low**
- **Internal DPF temperatures high enough to melt ceramic.**

Figure 14, temperature / regeneration line, winter NYC



Source: B. Bunting, DEER 2001

Trap failure is very rapid, typically

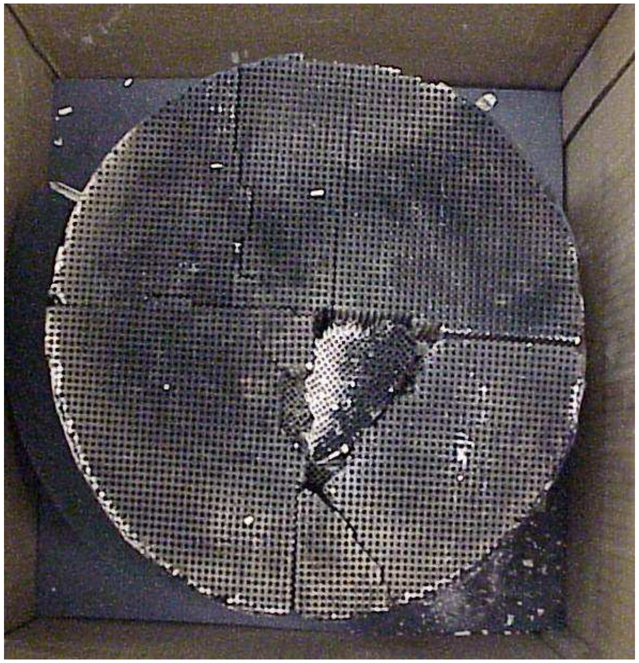


Source: B. Bunting, DEER 2001

What we are trying to prevent - Uncontrolled Regeneration

Hi Temp - Melting

Temp Gradients - Fracture



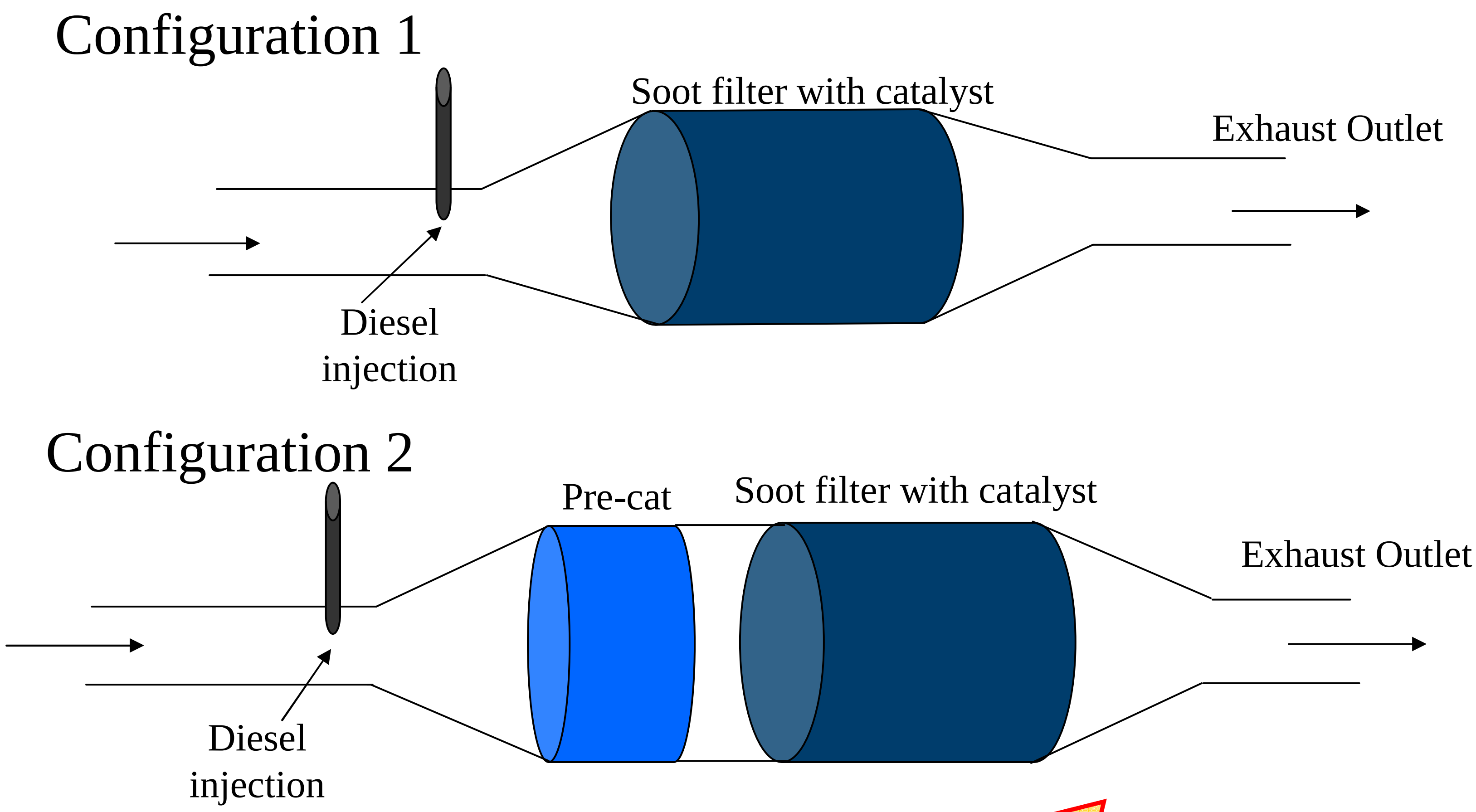
Low load operation

➡ Excessive soot loading

➡ High load operation ignites soot

➡ ***UNCONTROLLED REGENERATION***

Solution: active regeneration controls when the DPF is regenerated



More of a slow burn than a flame thrower

...........Evolution into a system...

- **Gasoline vehicle emissions control evolved into a system**
  - **Tailpipe approach with oxidation – early 70's**
  - **Air pumps added, late 70's**
  - **A/F ratio control + fuel injection – 80's**
  - **Now completely tied together**
- **Diesel engine system**
  - **Better control of fuel injection**
  - **DPF with Active Regen**
  - **EGR for NOx control**

What's Missing?

Fuel – the missing link

- **DPF development well on its way by 2001**
  - **But PM mass was higher with pump fuel**
- **Sulfur was the culprit – made sulfate aerosol in the exhaust pipe**
- **DOE had several large research efforts to address sulfur effects 1999-2002**
  - **DECSE (Diesel Emissions Control- Sulfur Effects)**
  - **DVECSE (Diesel Vehicle Emissions Control – SE)**
- **Result: EPA required 15 ppm S in 2006**
- **Analogous to tetraethyl lead removal**
  - **Driven by concerns for catalytic converter**
  - **Lower lead levels in people was a byproduct**

The path forward.....

- Motivation, background of DOE and diesel
- Approach to lowering PM
  - Engine Hardware
  - Diesel Particulate Filters
- **Current State-of-the-Art**
  - **Putting it all together into today's vehicle**
  - **Retrofit PM control**
  - **Ultralow sulfur diesel and Biodiesel**
- **Future**
  - **Modeling Emissions Control Systems**
  - **Advanced combustion modes**
  - **Link to CO_2 emissions and climate change**

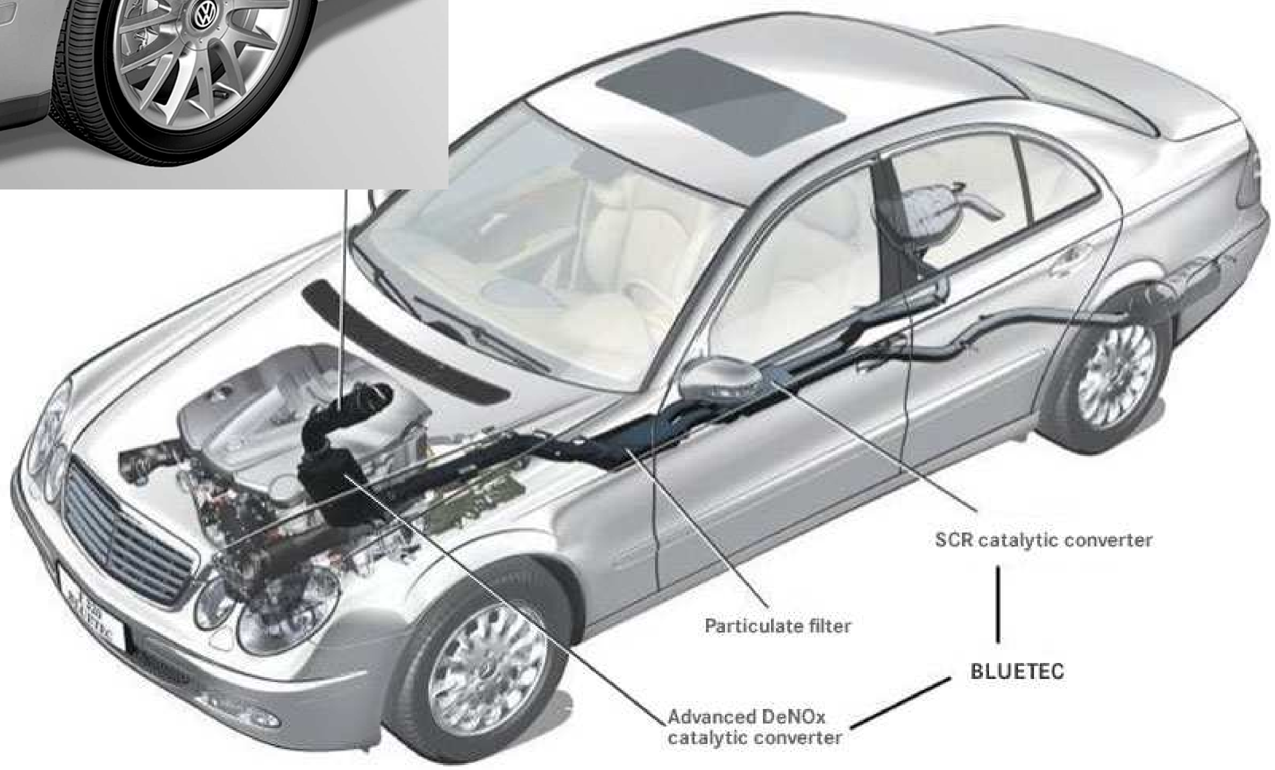
The dirty diesel of the past is giving way to clean diesel technology

2008 Dodge Ram 2500 Pickup meets 2009 standards

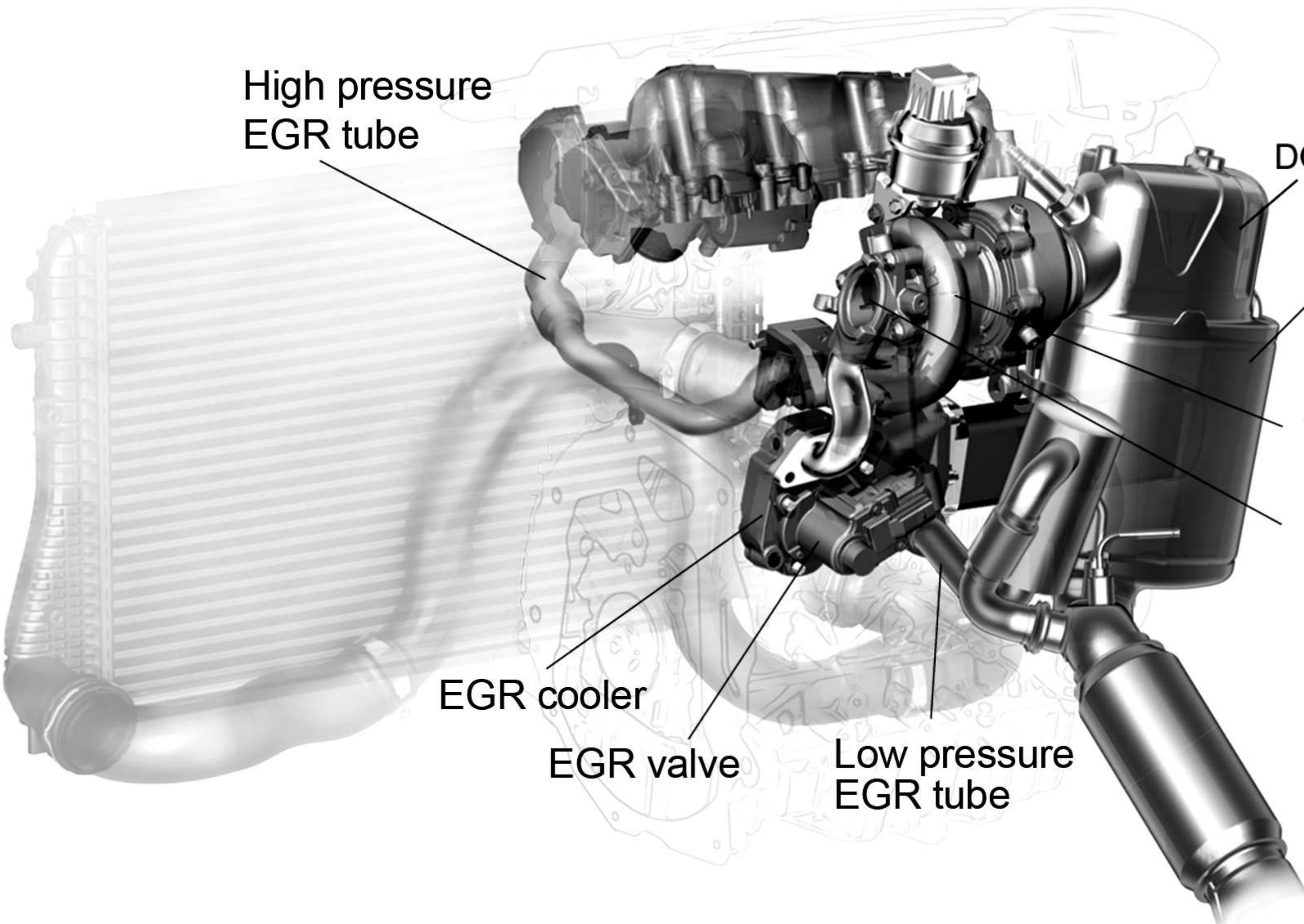
Clean diesel cars available now

VW Jetta TDI

Mercedes E320
Bluetec



VW's emissions controls a marvel of packaging



Source: Internationales Wiener
Motorensymposium 2008

Almost 40% improvement in MPG

2009 Volkswagen Jetta	2009 Volkswagen Jetta
	
Diesel Vehicle	**Gasoline Vehicle**

New EPA MPG

Diesel			Regular Gasoline		
29 City	33 Combined	40 Hwy	20 City	24 Combined	29 Hwy

Annual Petroleum Consumption
(1 barrel=42 gallons)

11.9 barrels | **14.3 barrels**

Source: fueleconomy.gov

Oak Ridge National Laboratory

Diesel fuel then and now…

- **1998: Low sulfur diesel rule in effect, largely for PM control. < 500 ppm S, ~450 ppm true**
  - **California: ~150 ppm S due to low aromatics**
- **2006: Ultralow sulfur diesel for diesel emissions control < 15 ppm S, ~ 8 ppm true**
  - **How? The magic of hydrogen. Result is higher cetane fuel - good for older engines**
- **Biodiesel: How does it affect PM emissions?**
  - **Generally lower PM mass, higher solubles**
  - **Alters behavior of DPF → ULSD ≠ B5 ≠ B20**

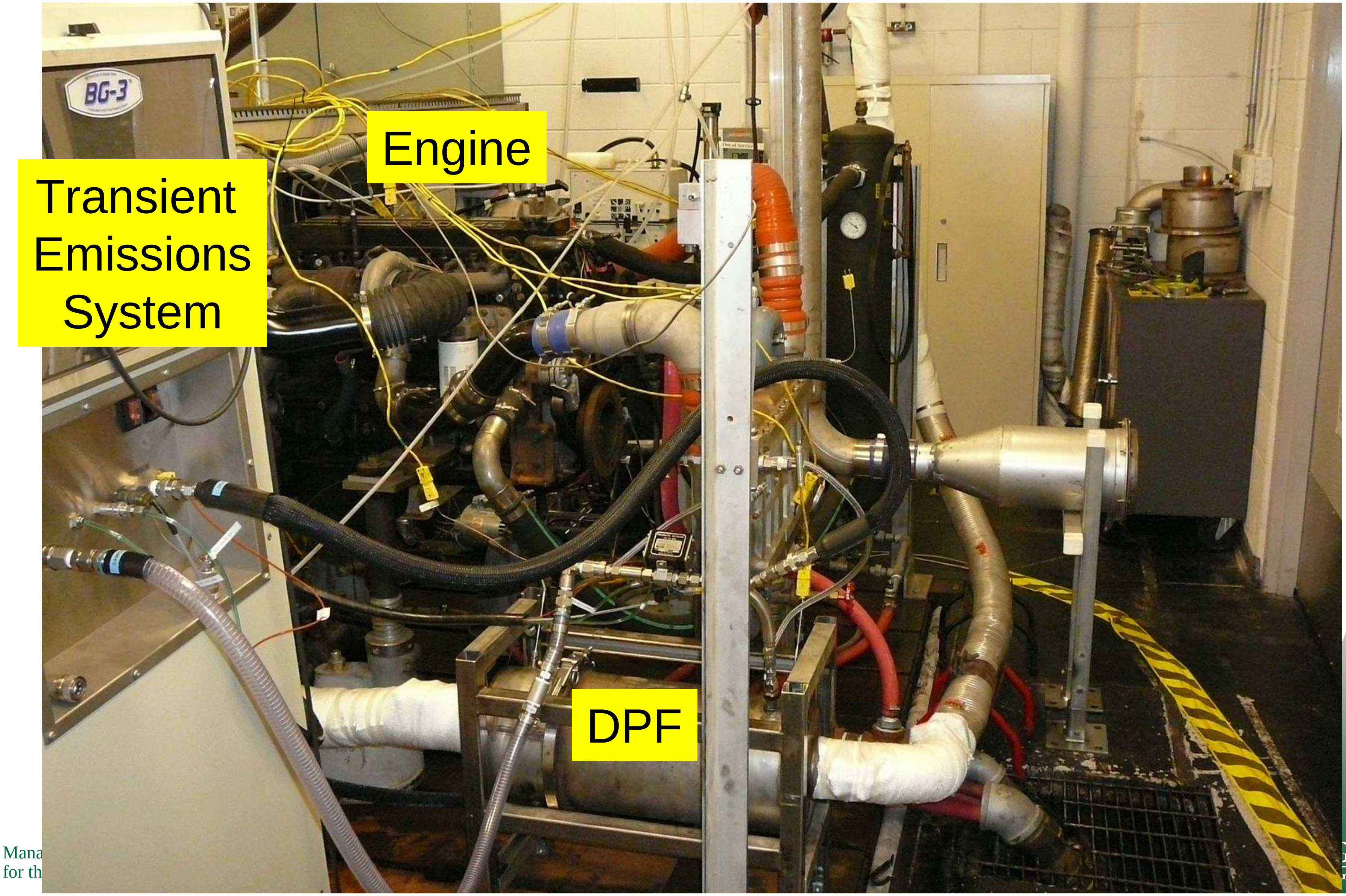
The path forward.....

- Motivation, background of DOE and diesel
- Approach to lowering PM
  - Engine Hardware
  - Diesel Particulate Filters
- Current State-of-the-Art
  - Putting it all together into today's vehicle
  - Retrofit PM control
  - Ultralow sulfur diesel and Biodiesel
- Future
  - Modeling Emissions Control Systems
  - Advanced combustion modes
  - Link to CO_2 emissions and climate change

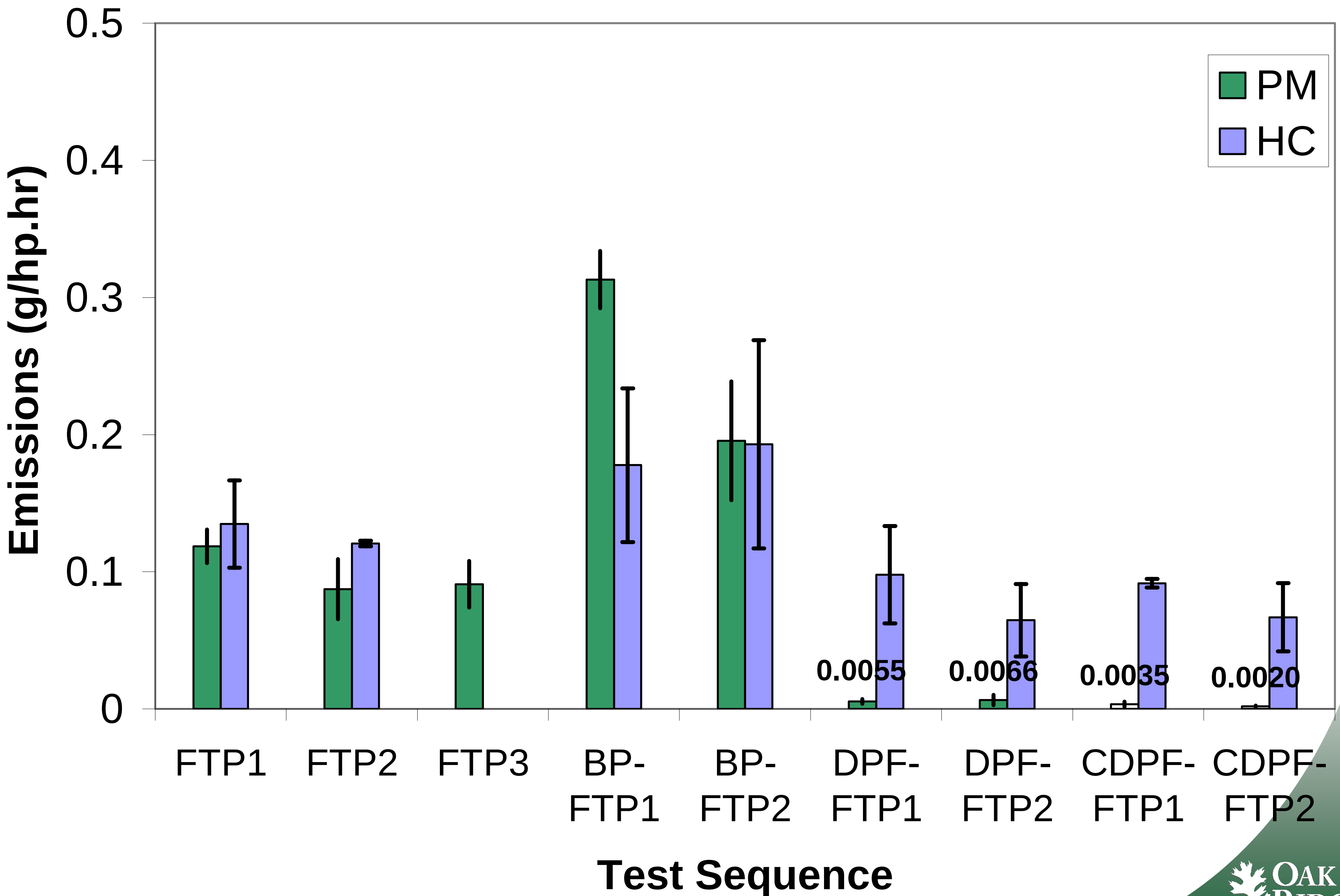
Diesel PM retrofit

- **Diesel oxidation catalysts (DOC) popular**
  - Low cost, “bolt-on” solution
  - ~30% PM reduction
- **Diesel Particulate Filters (DPF) offer best PM removal**
  - Require maintenance, off-vehicle regeneration
- **Crankcase emissions filtration**
  - Crankcase breather significant source
- **ORNL-EPA project examined both**
  - Field-aged DPF from schoolbus
  - Crankcase PM mass and size

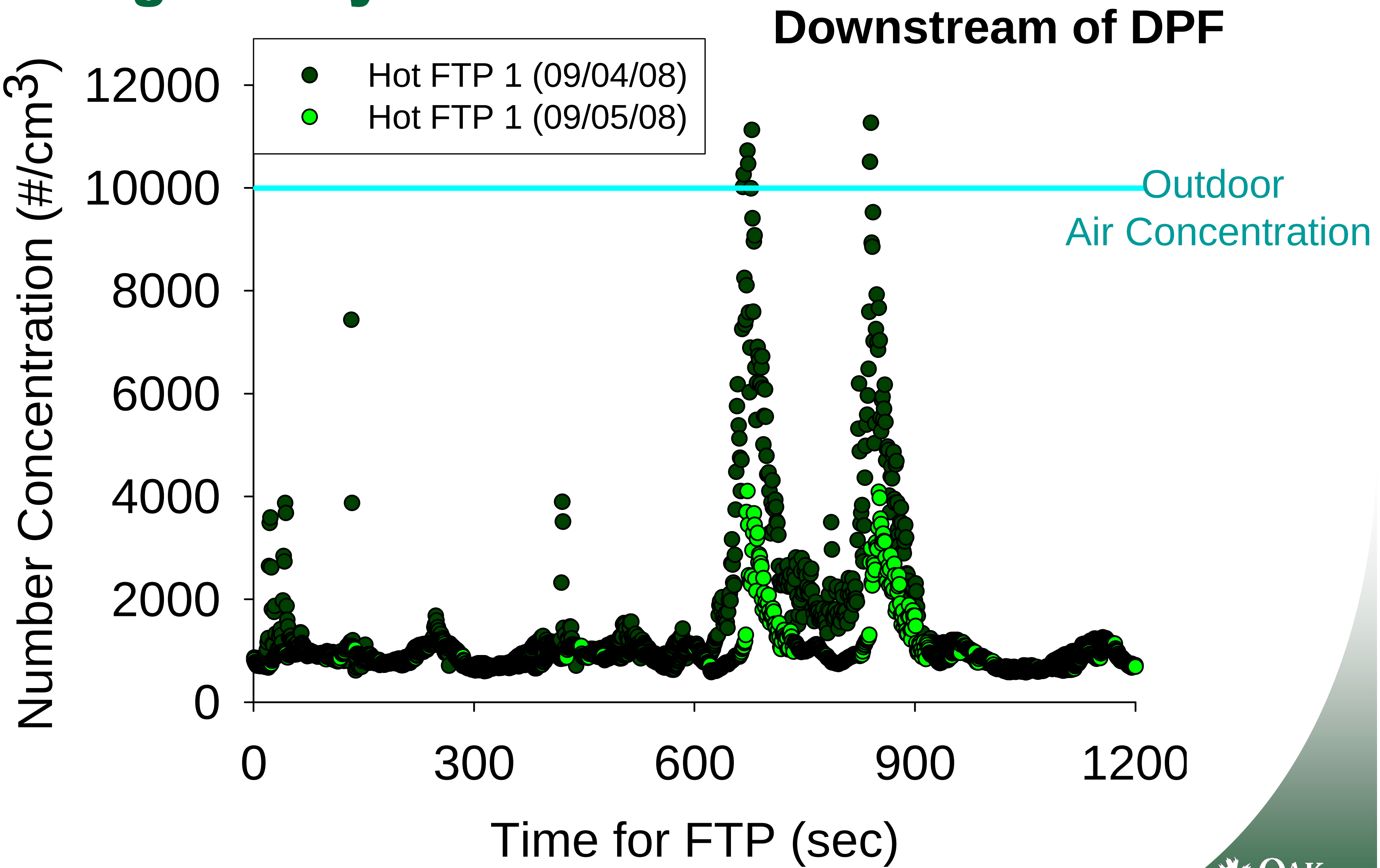
Extensive setup of 1999 Cummins B5.9 was necessary to carry out project



PM and HC go down with DPF

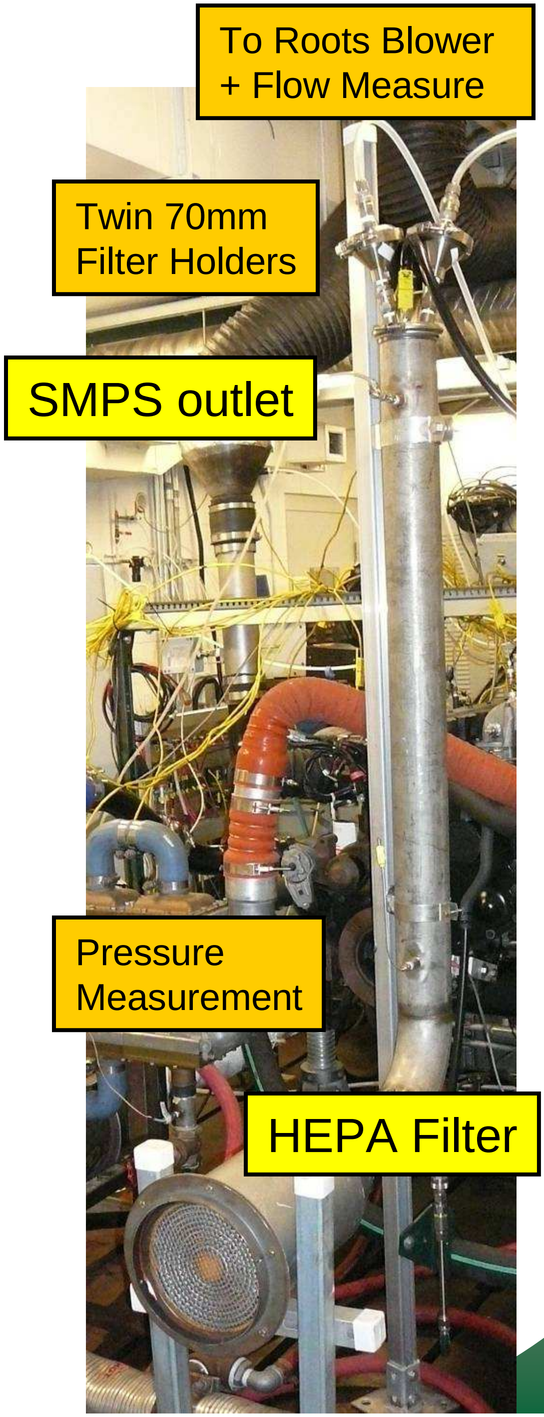


Total Particle Number Concentration During FTP Cycles

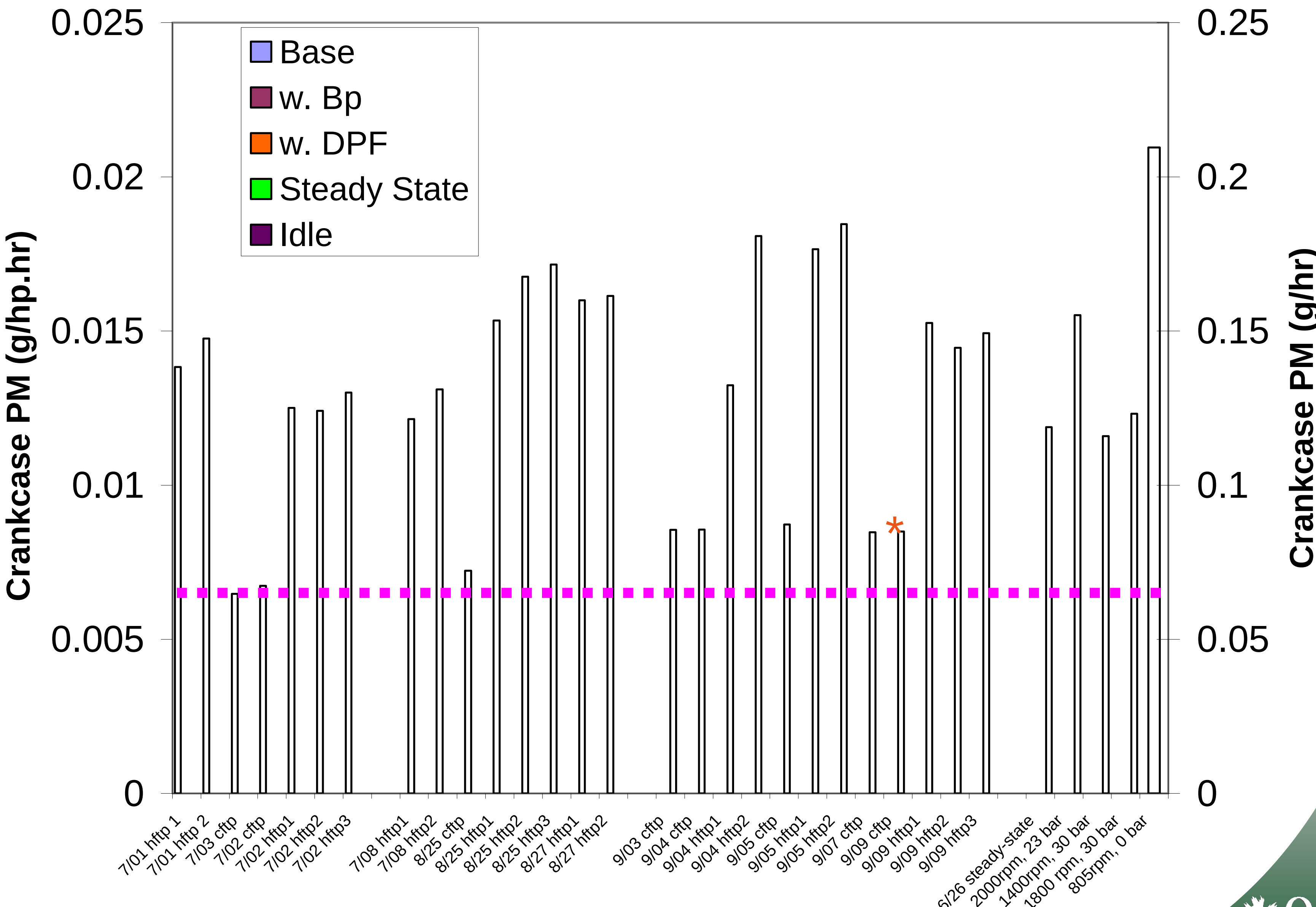


Unique sampler design imposes no vacuum or pressure on crankcase

- **All of PM collected**
- **$\Delta p < 0.5"$ H_2O observed at inlet of tunnel**
- **PM as much as 18% of regulated limit**



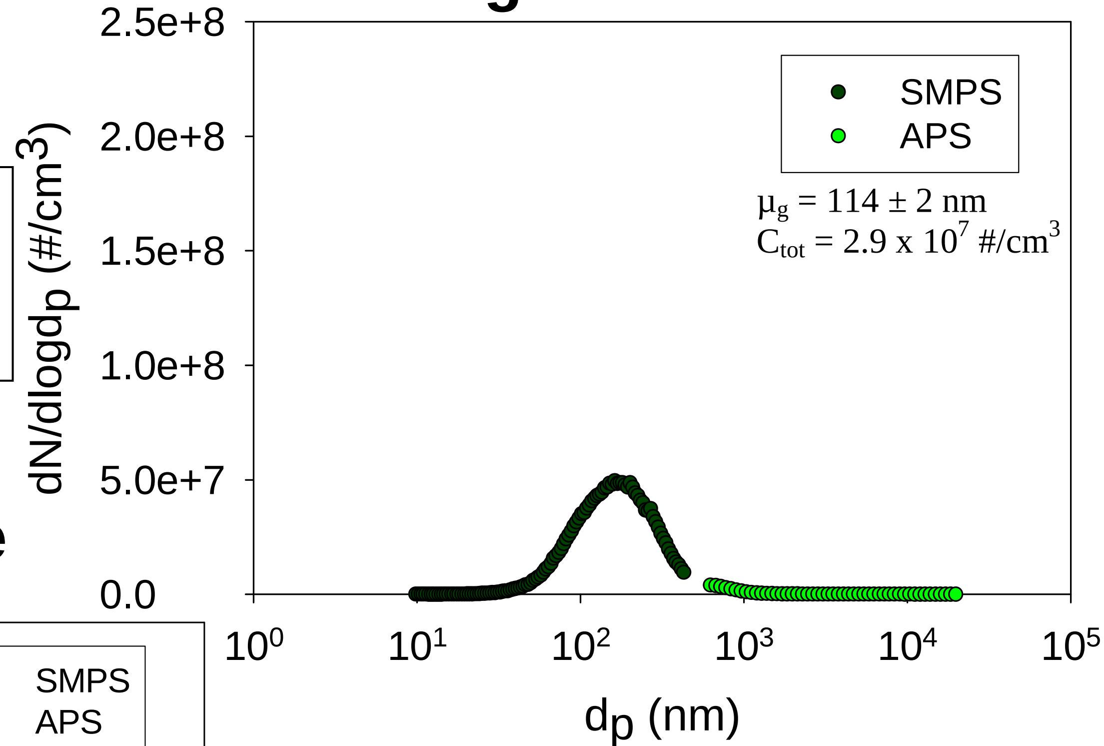
PM emissions from draft tube significant



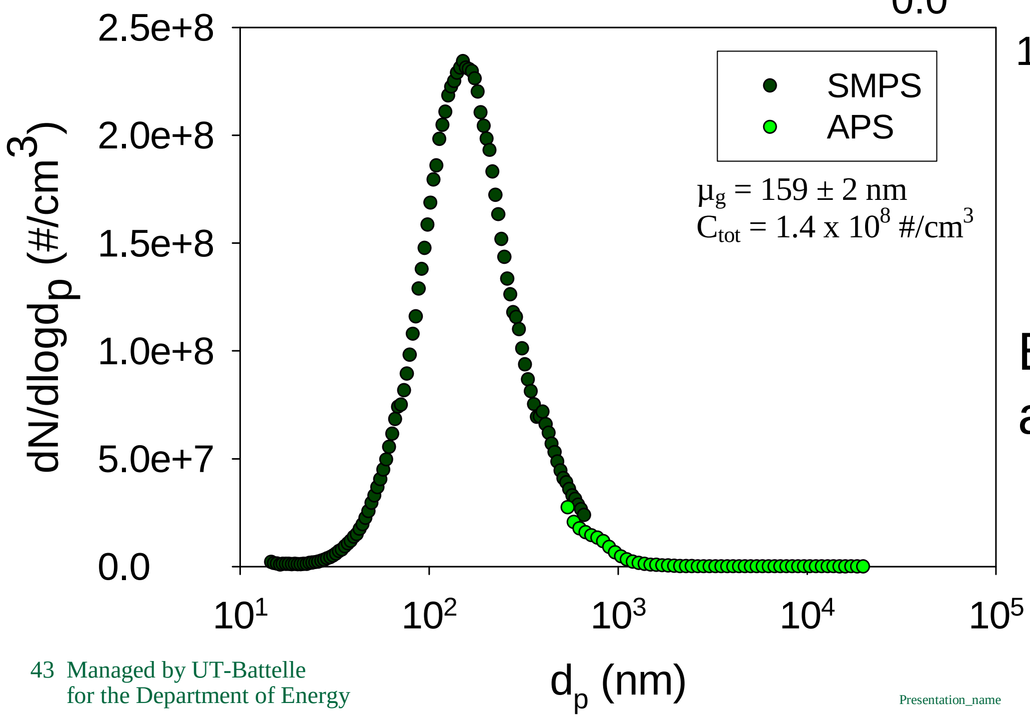
Crankcase Emissions Number-Size Distribution

Rated Torque
1400 RPM, 300 ft.lbs
(similar to 100% A on 13 mode)

Engine Baseline



Increased Backpressure



Backpressure 280 mbar
at rated speed (1400 RPM)

Findings from Retrofit DPF Study

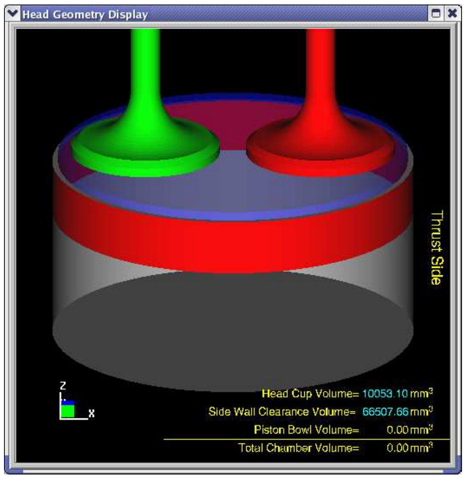
- **Field aged DPF (3+ years in service) as received evaluation**
  - **DPF very efficiently removing PM**
  - **Clean DPF: higher number concentrations until soot layer builds**
- **Crankcase emissions – mostly oil droplets**
  - **PM mass emissions = 3 X DPF out emissions**
  - **PM size shows significantly larger particles**
- **Crankcase PM treatment complements DPF retrofit**
- **Model Year 2007 and beyond closes the crankcase**

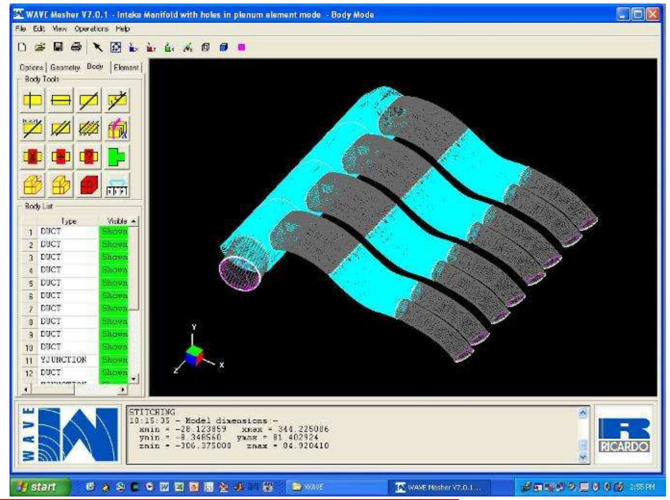
Presentation at 2009 CRC On-Road Emissions Workshop

The path forward.....

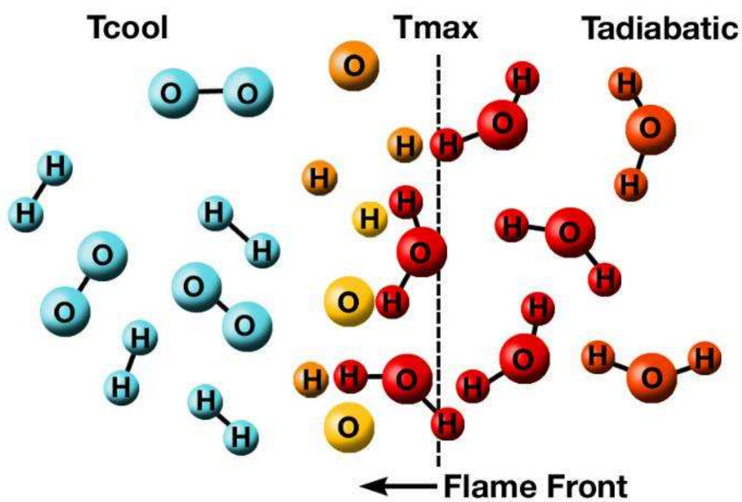
- Motivation, background of DOE and diesel
- Approach to lowering PM
  - Engine Hardware
  - Diesel Particulate Filters
- Current State-of-the-Art
  - Putting it all together into today's vehicle
  - Retrofit PM control
  - Ultralow sulfur diesel and Biodiesel
- **Future**
  - **Modeling Emissions Control Systems**
  - **Advanced combustion modes**
  - **Link to CO_2 emissions and climate change**

Modeling used extensively to improve combustion efficiency, emissions





Increased use of computational tools

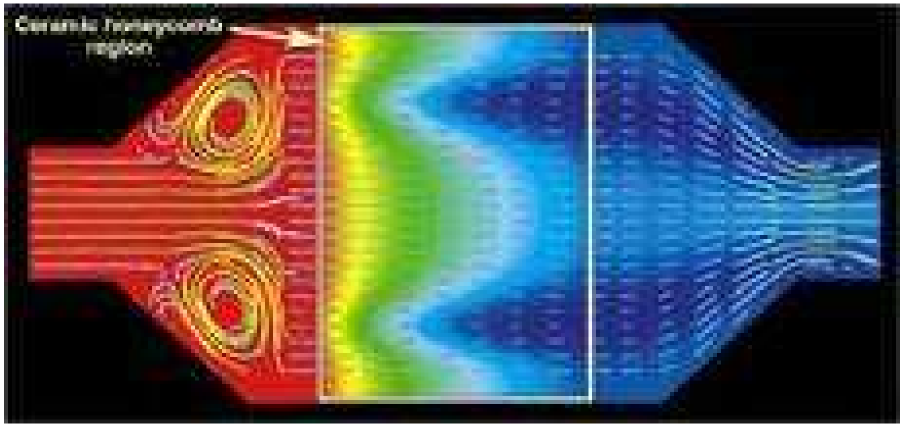


Addressing the fundamental losses of combustion flames

Catalyst Modeling takes off from 2000 on….

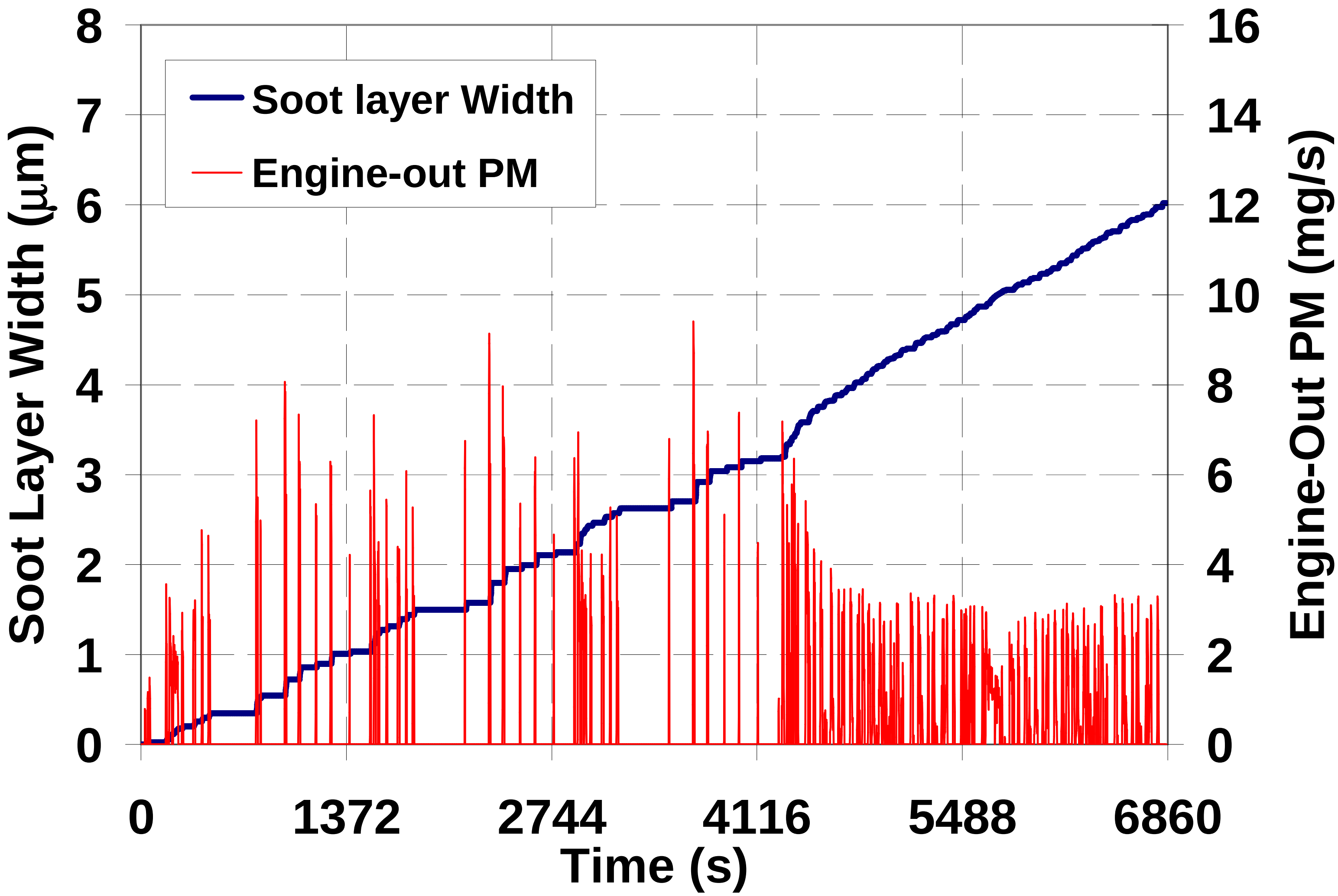
Cross-Cut Lean Exhaust Emissions Reduction Simulations

CLEERS



- **Objective to improve ability to simulate advanced emissions controls**
- **CLEERS (cleers.org) has annual workshops and working groups for NOx and PM control**
- **Broad participation from industry, academia, labs**
- **Past presentations available on the web site**
  - **Created and maintained by ORNL**

Modeling Extended to Engines, Vehicles



- Modeling the growth of the soot layer in a DPF during a drive cycle
- No active regeneration of the filter (DPF)

Source: ORNL Systems Modeling, 2008

The path forward.....

- Motivation, background of DOE and diesel
- Approach to lowering PM
  - Engine Hardware
  - Diesel Particulate Filters
- Current State-of-the-Art
  - Putting it all together into today's vehicle
  - Retrofit PM control
  - Ultralow sulfur diesel and Biodiesel
- **Future**
  - Modeling Emissions Control Systems
  - **Advanced combustion modes**
  - **Link to CO_2 emissions and climate change**

High Efficiency Clean Combustion (HECC)

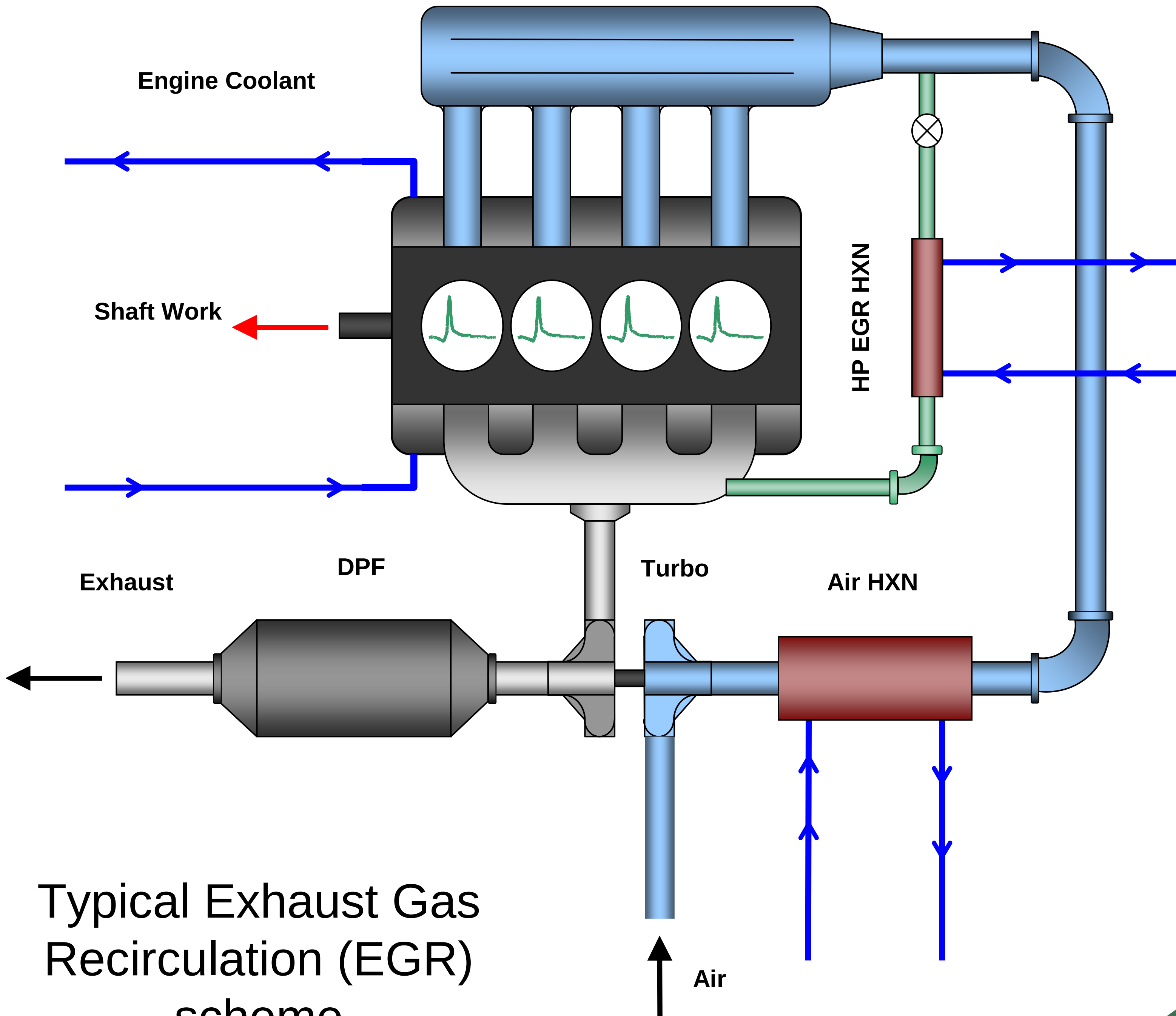
- **HECC includes**
  - **Homogeneous Charge Compression Ignition (HCCI)**
  - **Premixed Charge Compression Ignition (PCCI)**
  - **others**
- **Improve powertrain system efficiency by lowering performance requirements for post-combustion emissions controls.**

Objectives of ORNL efforts

- **Detailed emissions characterization for understanding combustion regimes and environmental impact.**
  - **Hydrocarbon speciation (MSATs!)**
  - **PM characterization**

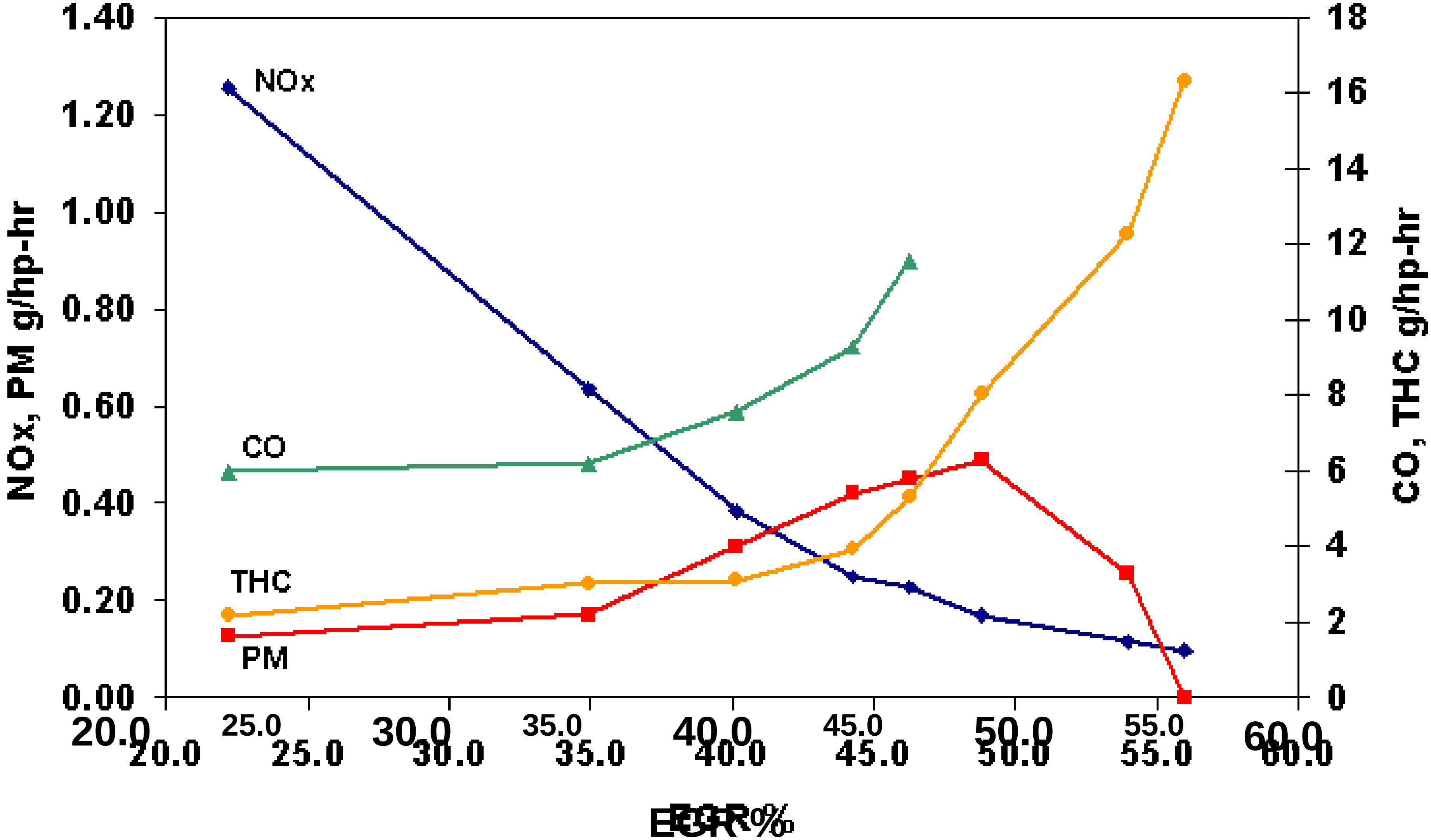
Exhaust Gas Recirculation (EGR) key to advanced combustion modes

- **EGR on most diesel engines since 2002**
- **How does EGR work?**
  - **Lowers NOx by diluting charge (air) with exhaust gas – lowers peak combustion temperature**
  - **Typically <u>increases</u> PM**
- **High levels of EGR result in lower NOx and PM**

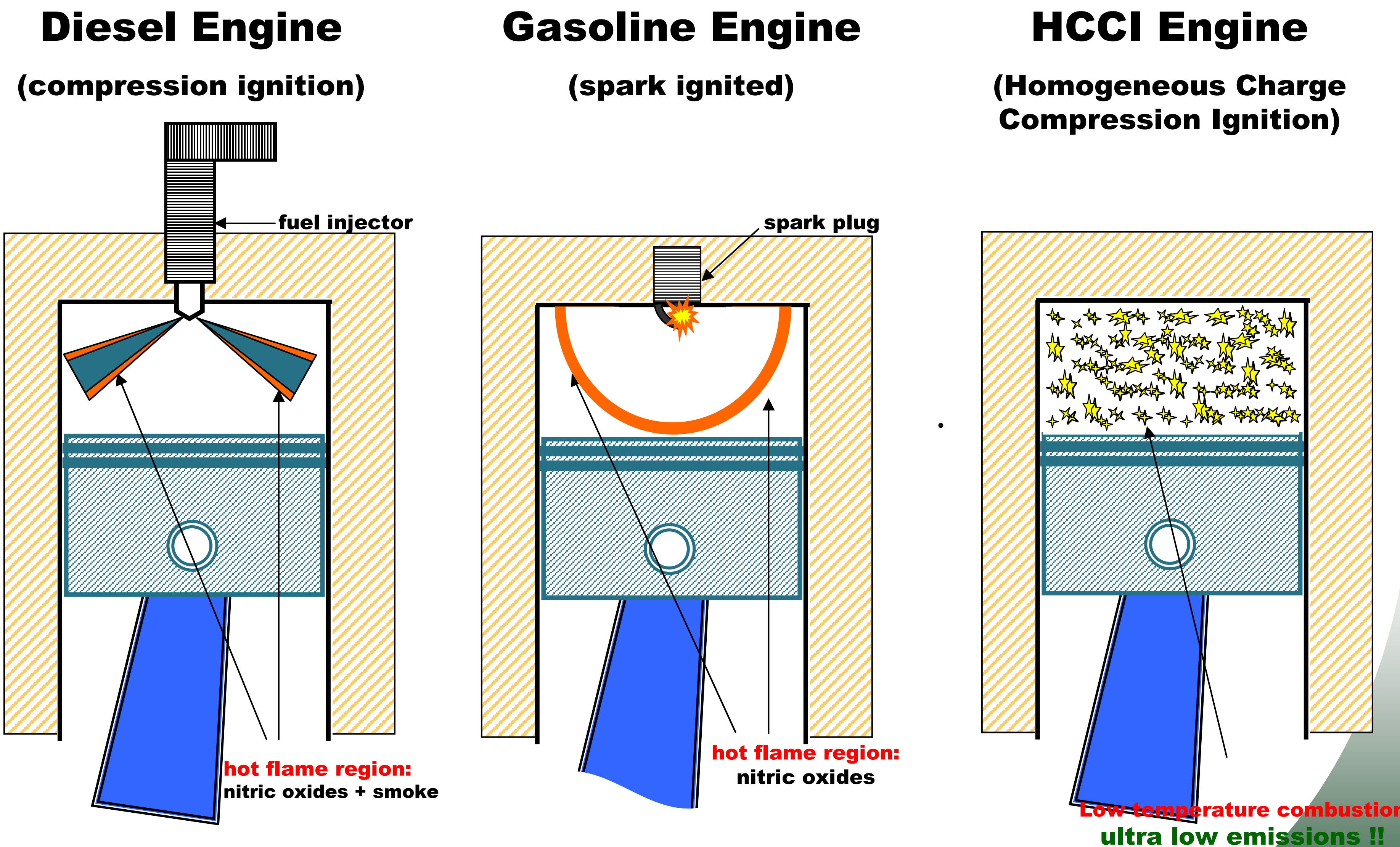


Typical Exhaust Gas Recirculation (EGR) scheme

Motivation – 1999 study with VW TDI engine

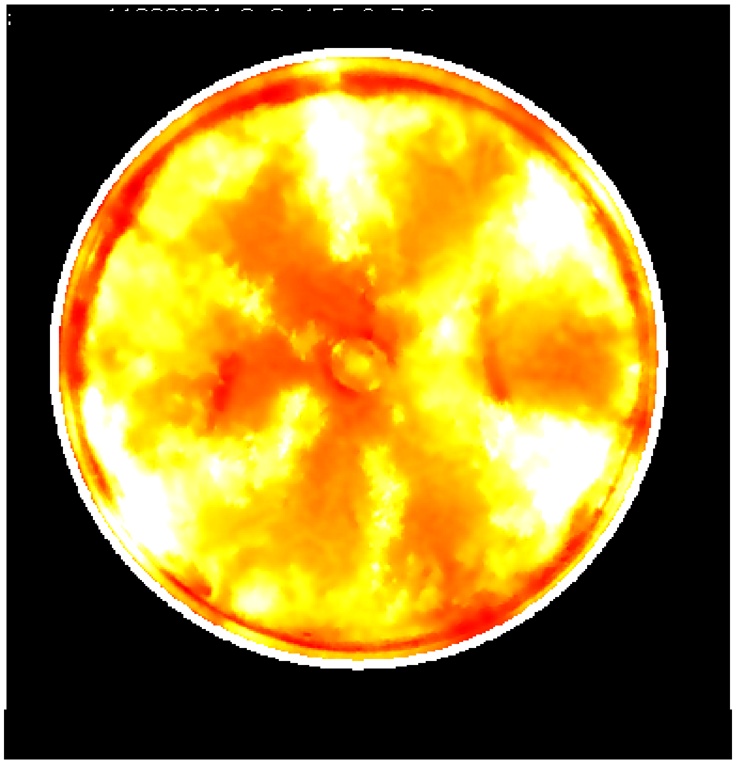


What is this High Efficiency Clean Combustion?

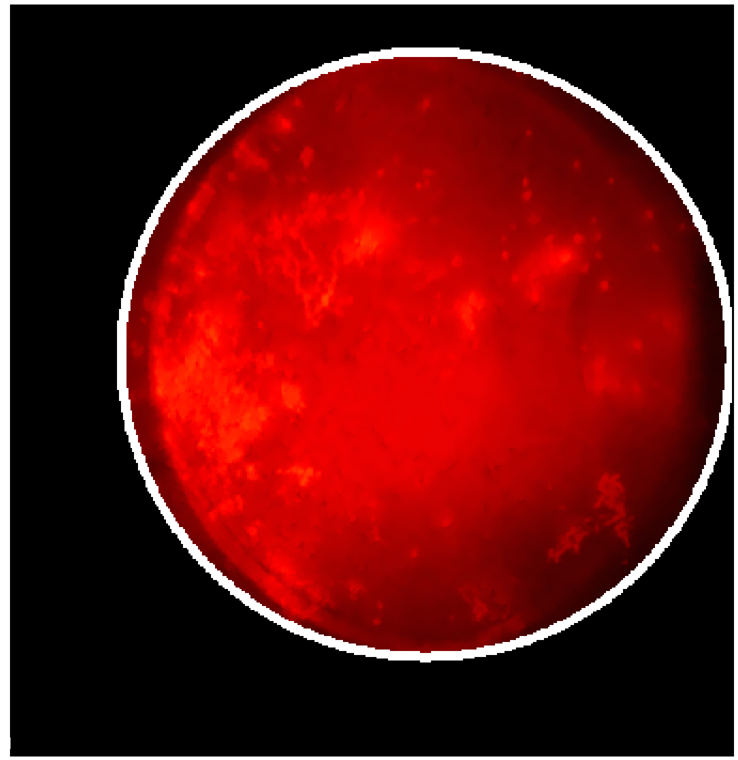


Source:Caterpillar, 2003

Images of Conventional and HCCI
Source: Caterpillar, DEER Conference, 2002



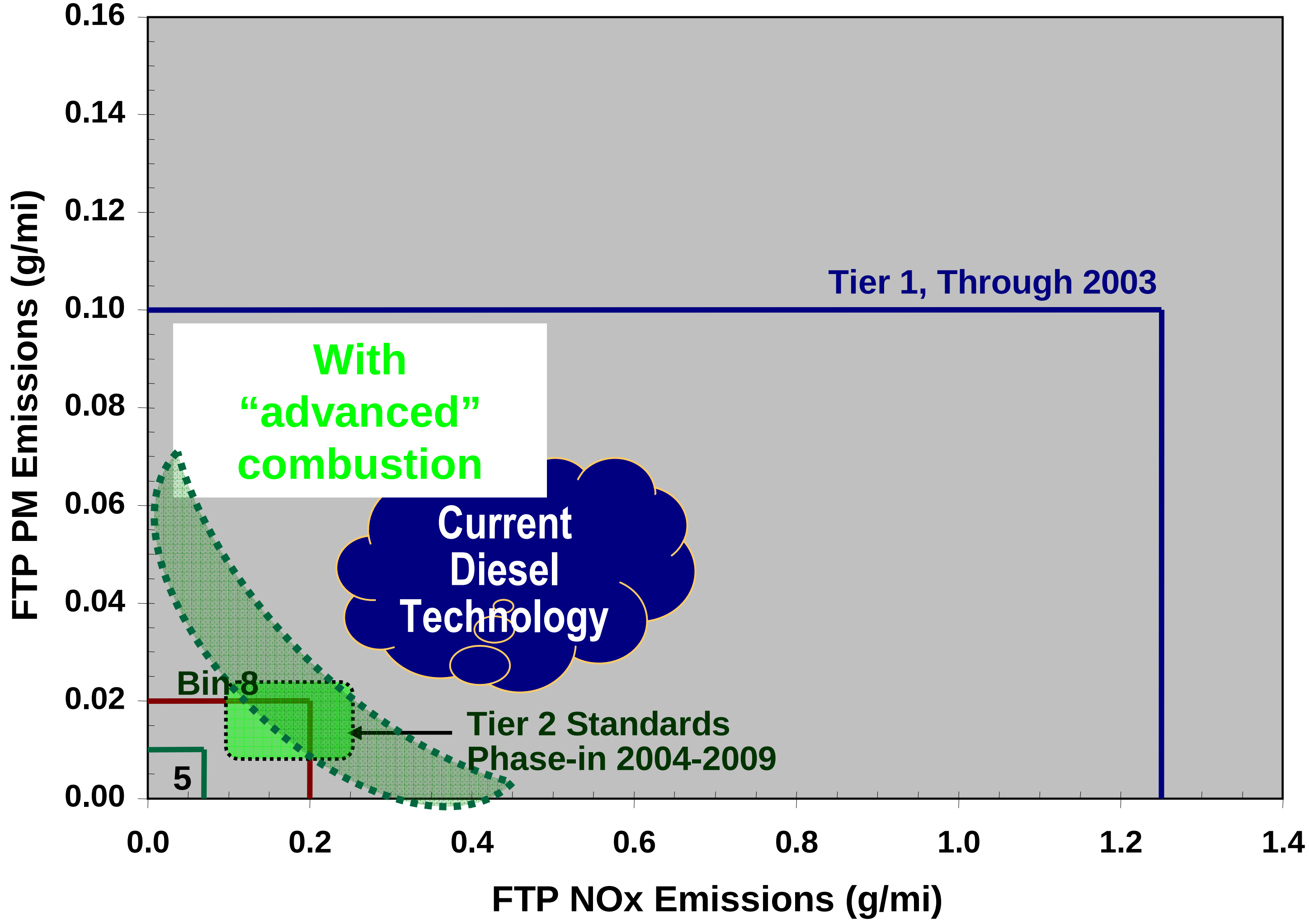
Conventional



Diesel HCCI

PCCI = Pre-mixed charge compression ignition

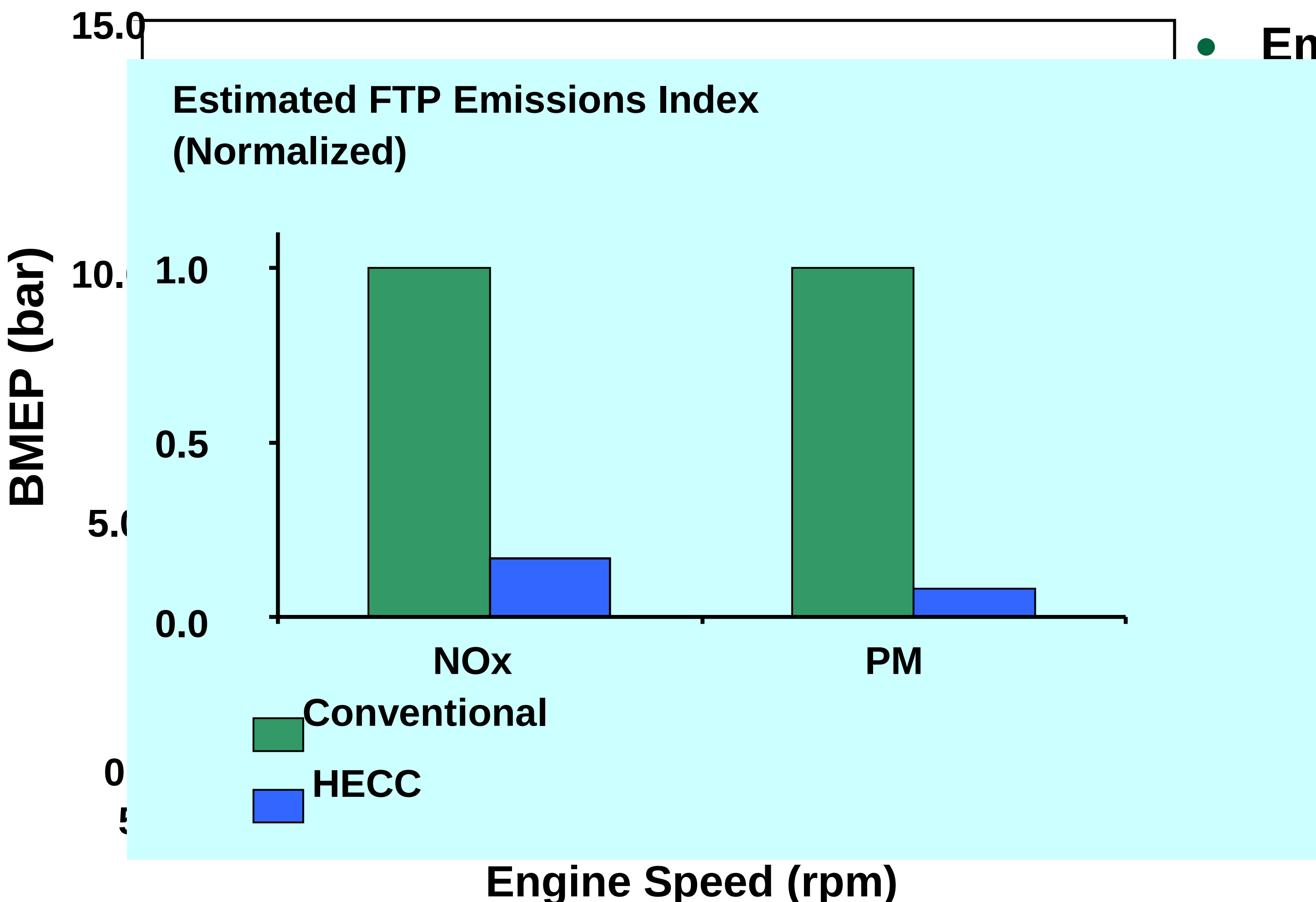
Advanced combustion changes the NOx-PM trade-off curve



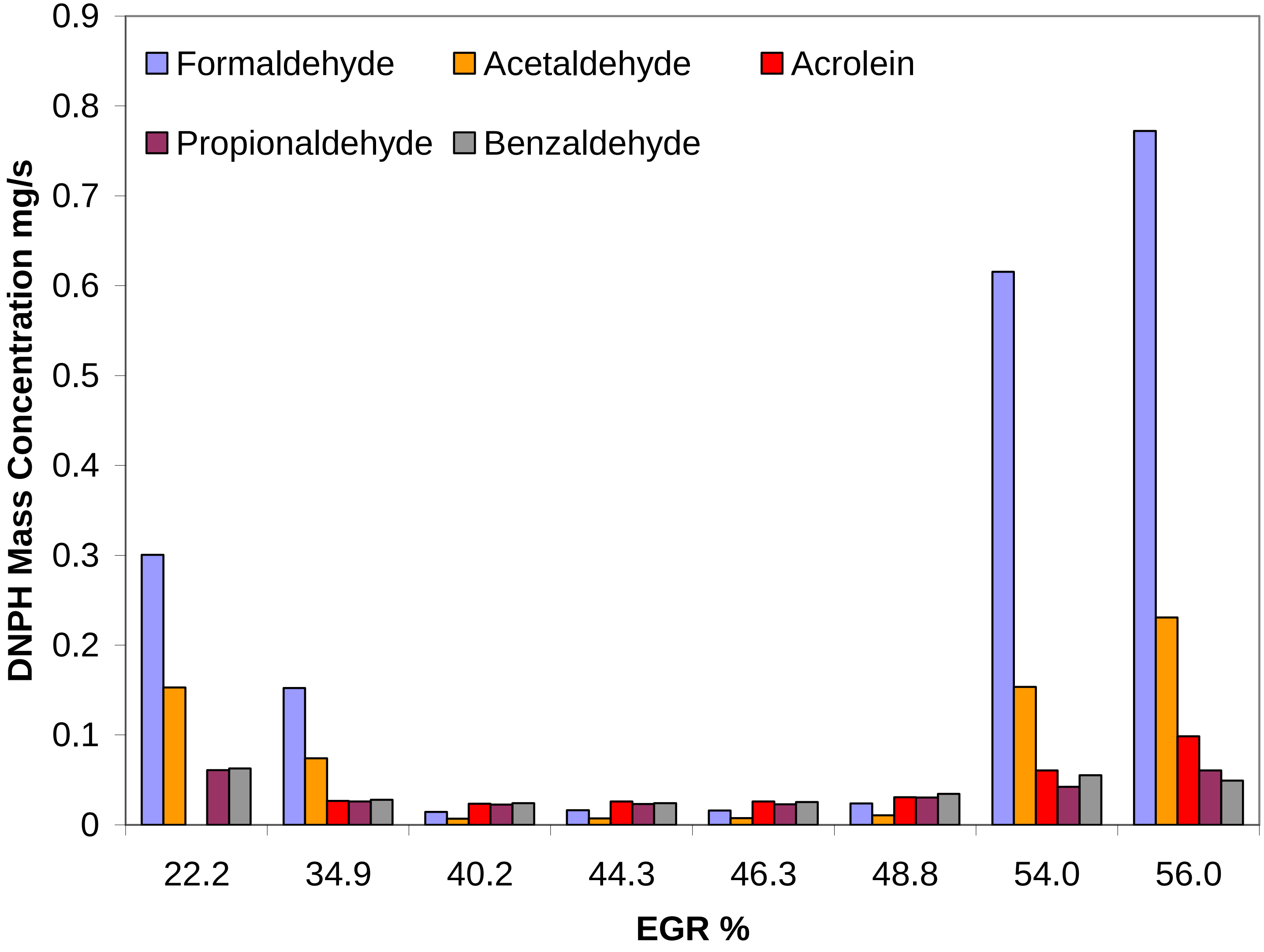
Steady state modes used with HECC to <u>approximate</u> Light-duty FTP cycle.

What about HCs and CO?

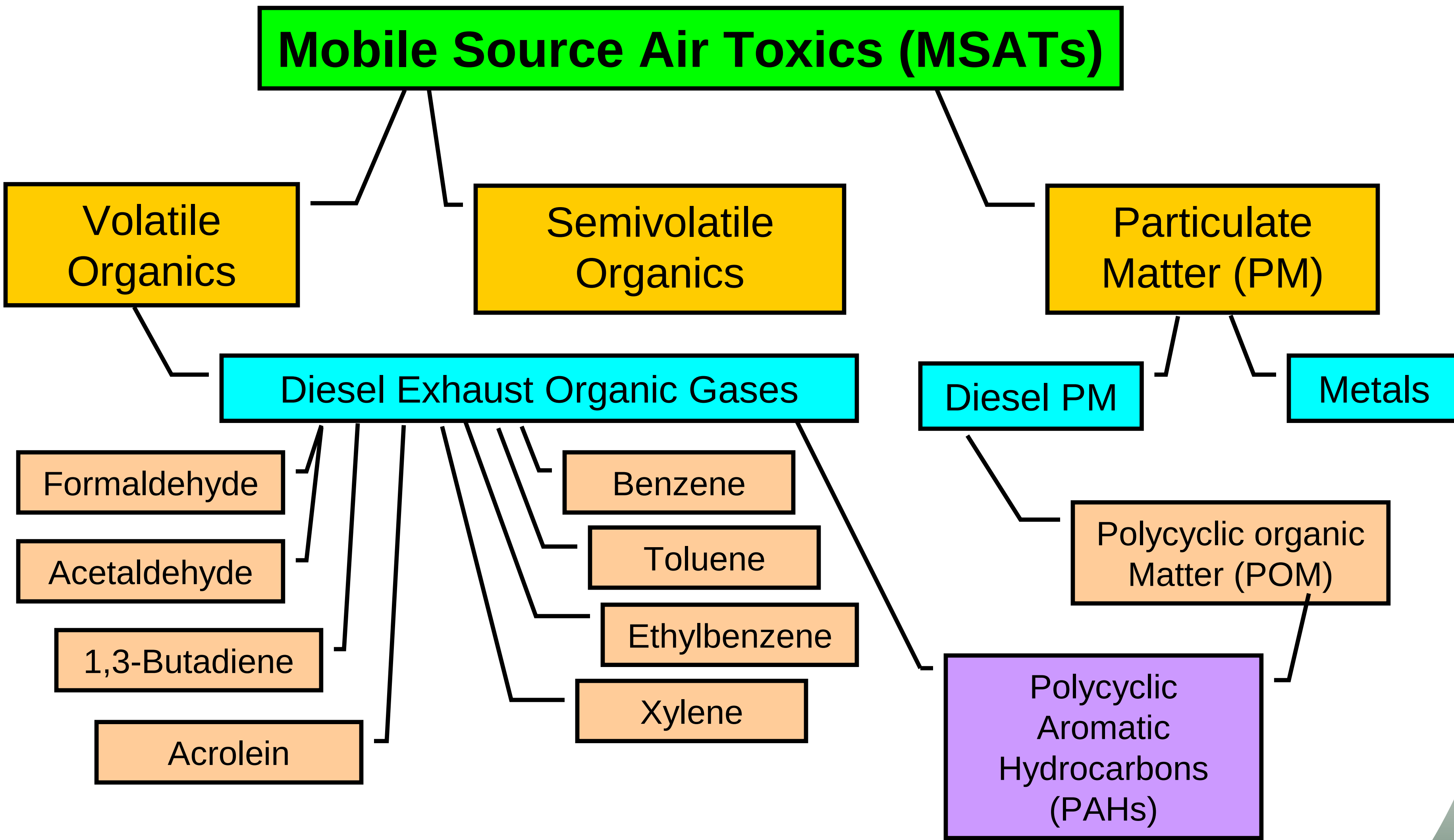
- **BSFC equivalent to baseline operation.**
- **Emissions lower**



High EGR = high formaldehyde and acetaldehyde formation.

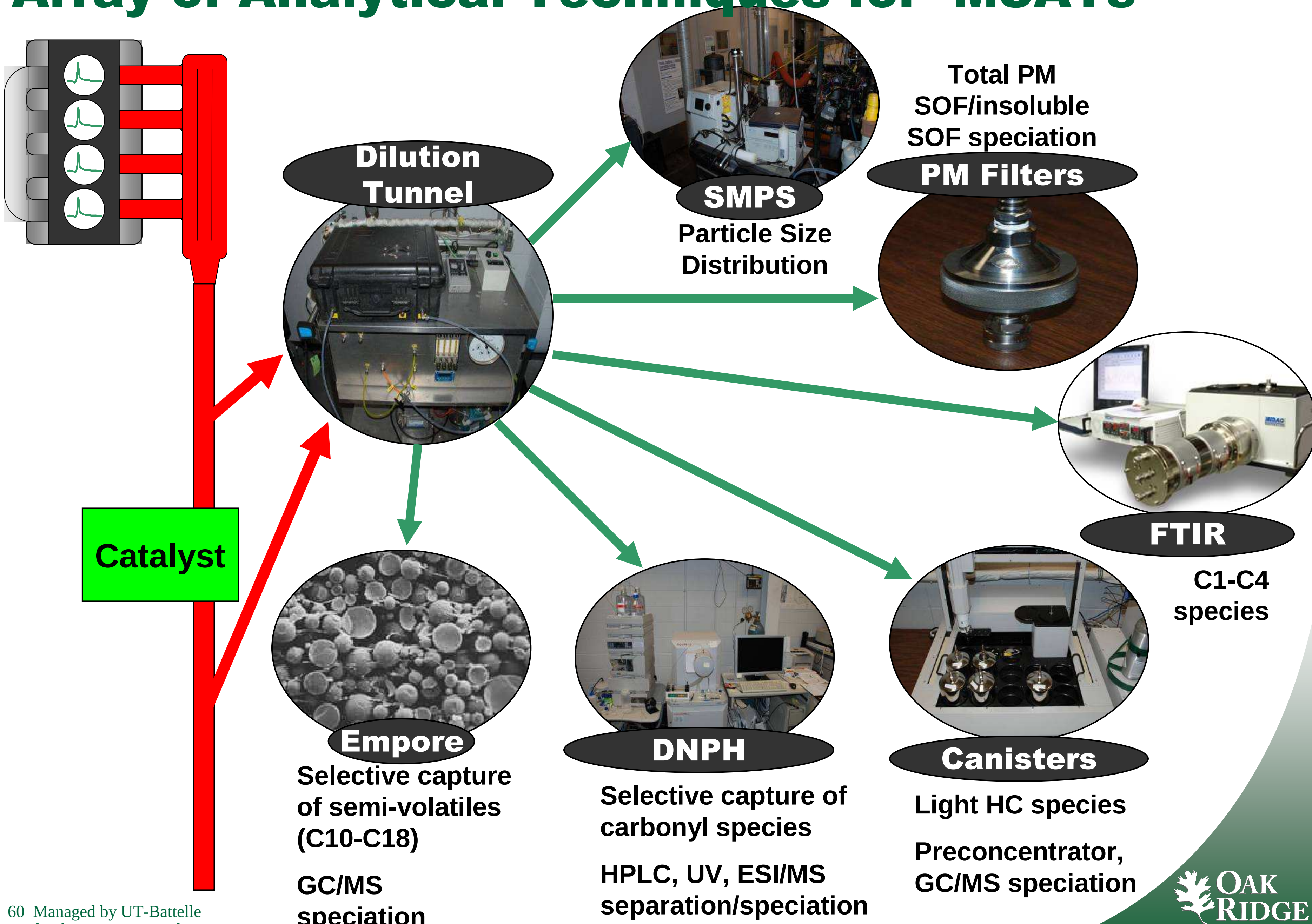


What are Mobile Source Air Toxics (MSATs)?



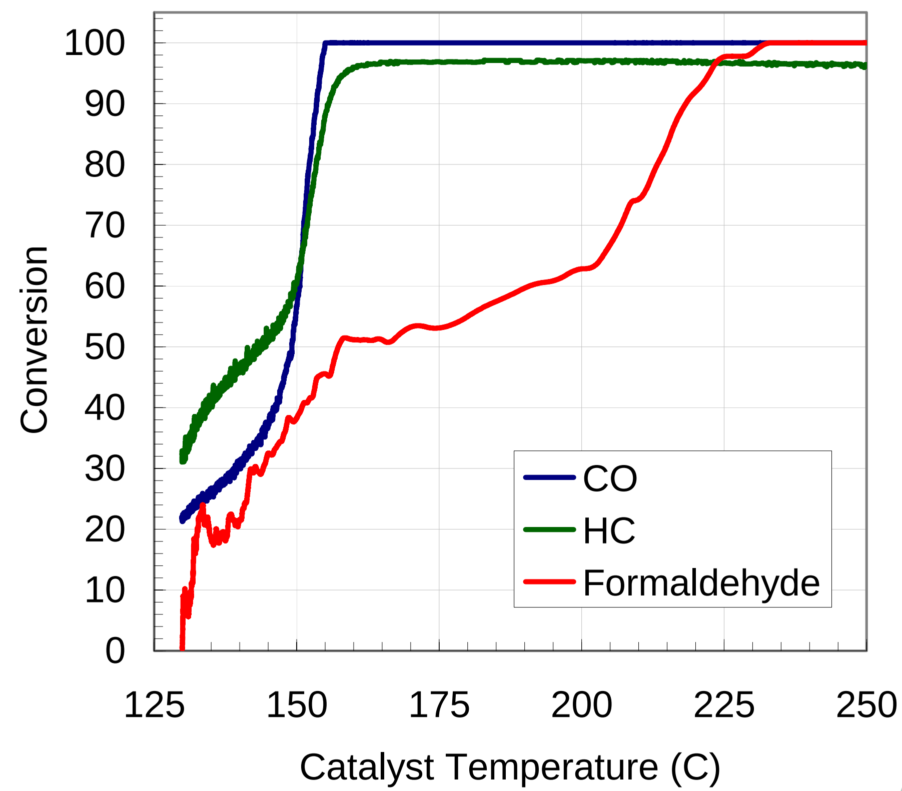
OAK RIDGE National Laboratory

Array of Analytical Techniques for MSATs



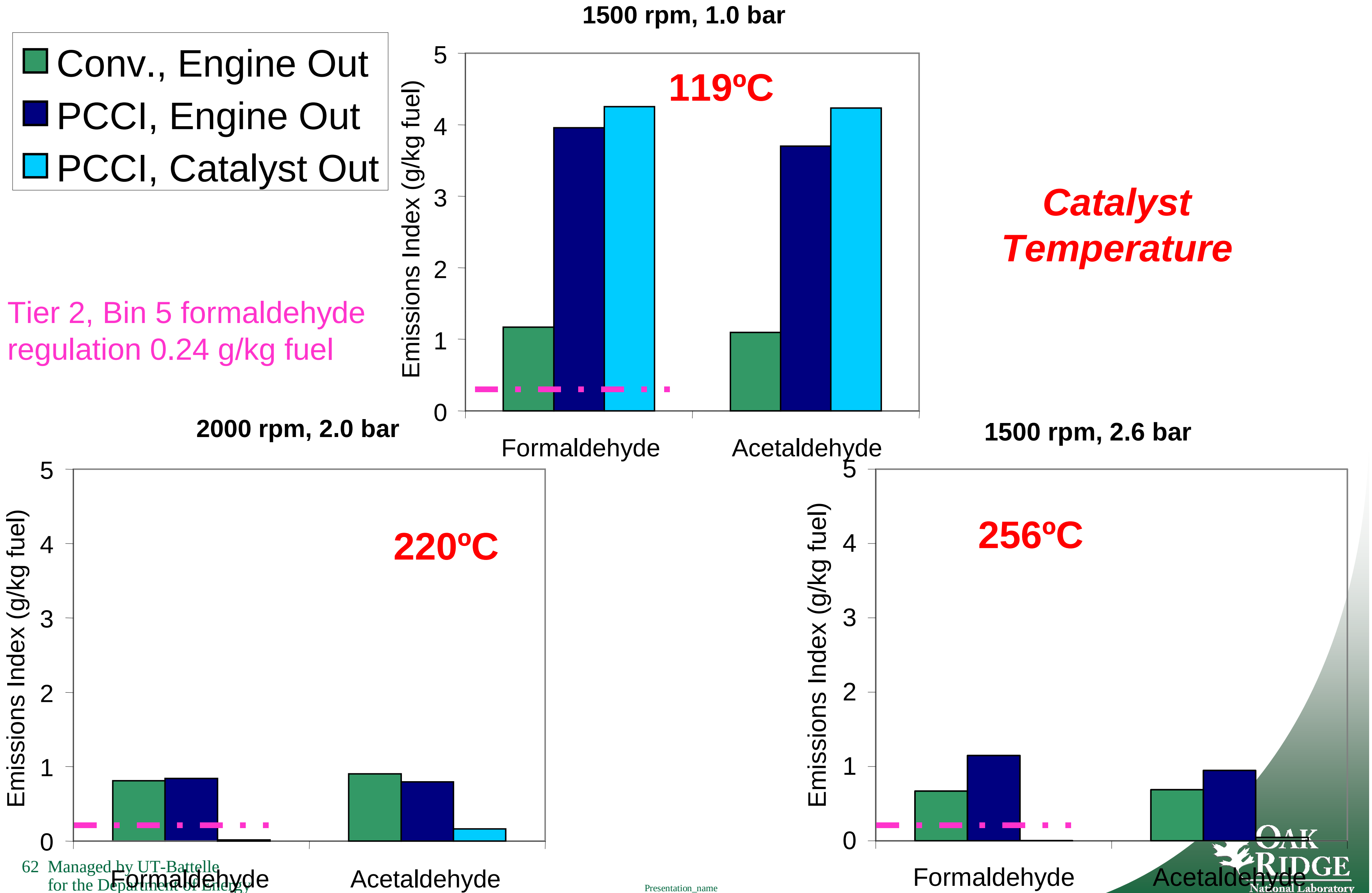
DOC Oxidation of Formaldehyde Not Complete Until ~225ºC

- **CO, HC, and formaldehyde oxidation efficiency as a function of catalyst temperature**
  - **CO oxidation enables higher oxidation of HCs and formaldehyde**
  - **Formaldehyde oxidation not complete until 225ºC**
- **Engine at 1500 rpm/ 1.0 bar during cool down of catalyst from previous higher load operation**



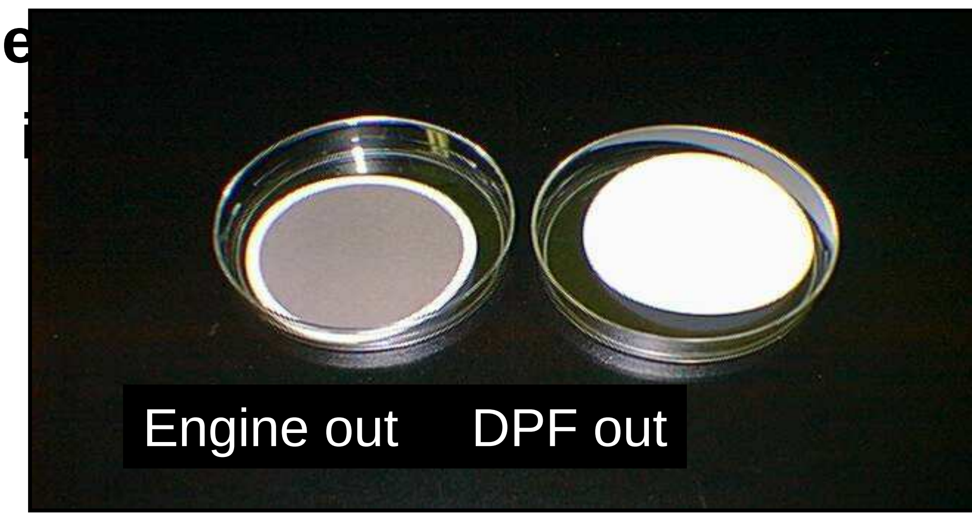
- **Thermal management can enable DOC to be kept at temperature where suitable CO/HC/Formaldehyde oxidation occurs, but…**
  - **What is the efficiency penalty associated with maintaining formaldehyde oxidation vs. CO/HC oxidation?**

Low catalyst temperature presents challenges for tailpipe aldehydes in PCCI mode



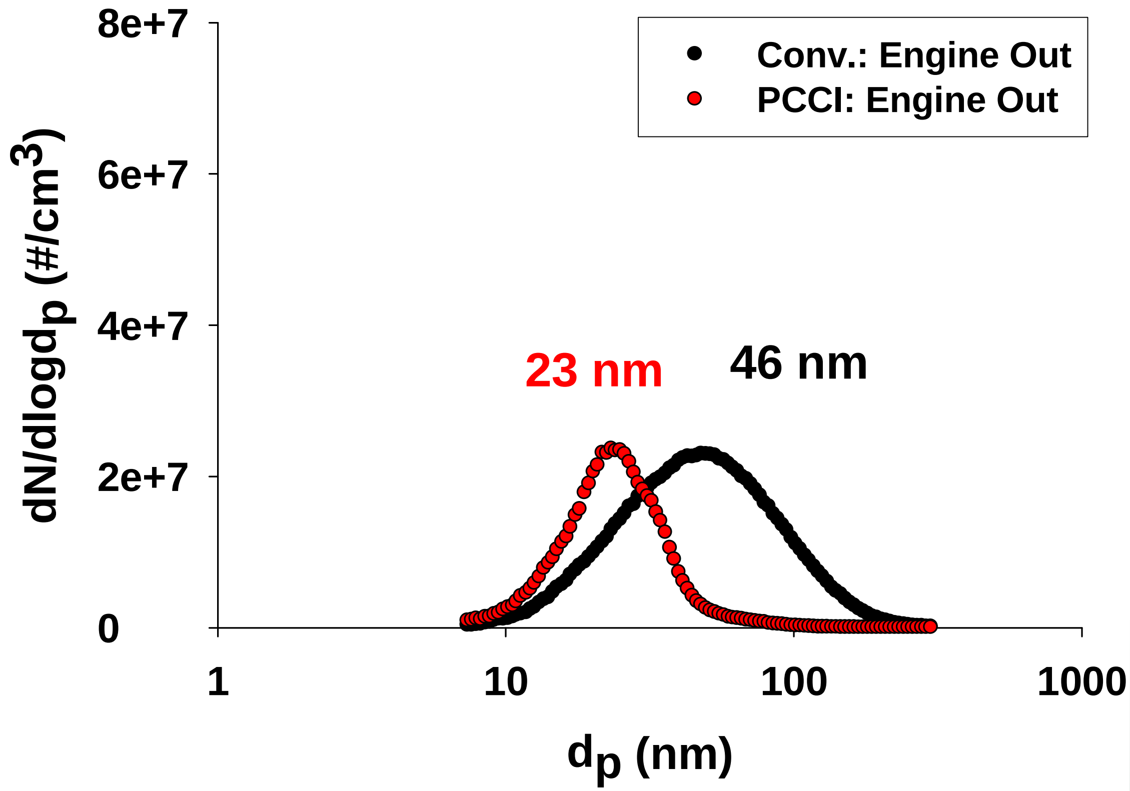
Particle size measurements

- **Why measure particle size?**
  - **Nanoparticles linked to health effects**
  - **Number of particles may be more important than mass**
    - **Modern engines reduce PM size to reduce mass**
- **With DPFs, PM mass measurement difficult**
  - **Europe ... ed regs**
  - **CARB i ... stem as well**

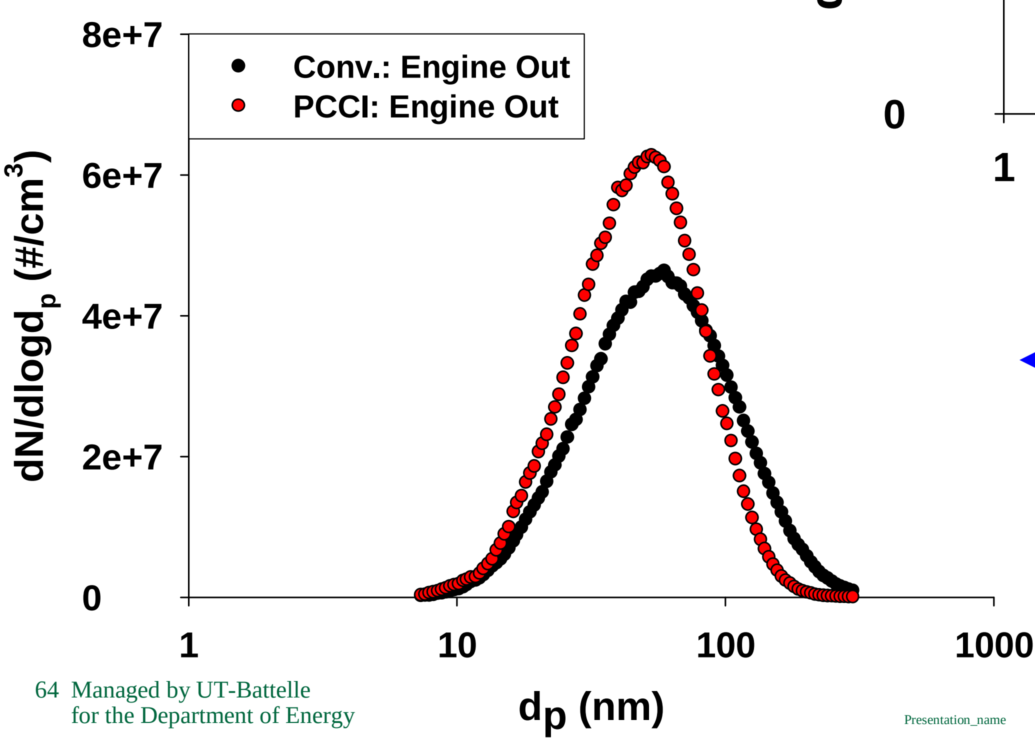


PCCI PM smaller in size at low load and medium load

Numbers are similar, but PCCI particles much smaller



Number of particles > 100 nm decreases



Oak Ridge National Laboratory

The path forward.....

- Motivation, background of DOE and diesel
- Approach to lowering PM
  - Engine Hardware
  - Diesel Particulate Filters
- Current State-of-the-Art
  - Putting it all together into today's vehicle
  - Retrofit PM control
  - Ultralow sulfur diesel and Biodiesel
- **Future**
  - Modeling Emissions Control Systems
  - Advanced combustion modes
  - **Link to CO_2 emissions and climate change**

What does all of this mean for greenhouse gas emissions?

- CO_2 directly related to fuel efficiency
  - Engines have been getting more efficient, but..
  - …PM emissions controls reduce efficiency
    - Backpressure, fuel needed for active regeneration
- N_2O and CH_4 emissions can be a concern
  - Catalyst systems can make N_2O
  - Advanced combustion can make more CH_4
- 2010 regulations could be paradigm shift
  - Urea-SCR NOx removal efficiency could allow higher fuel efficiency

Summary

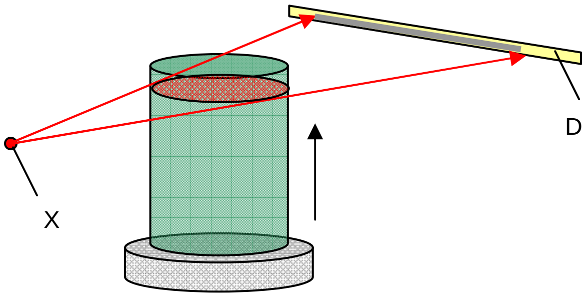
- **Engines, PM control have advanced considerably in ten years**
- **DPFs close to 99% efficient**
- **Retrofits showing good durability**
- **Packaging of systems remains a challenge**
- **DOE continues to push technology for better efficiency**

Resources

- **DEER presentations**
  - http://www1.eere.energy.gov/vehiclesandfuels/resources/proceedings/index.html
- **CLEERS**
  - http://cleers.org
- **Society of Automotive Engineers**
  - www.sae.org
- **Health Effects Institute**
  - **2008 Mobile Source Air Toxics report at** www.healtheffects.org

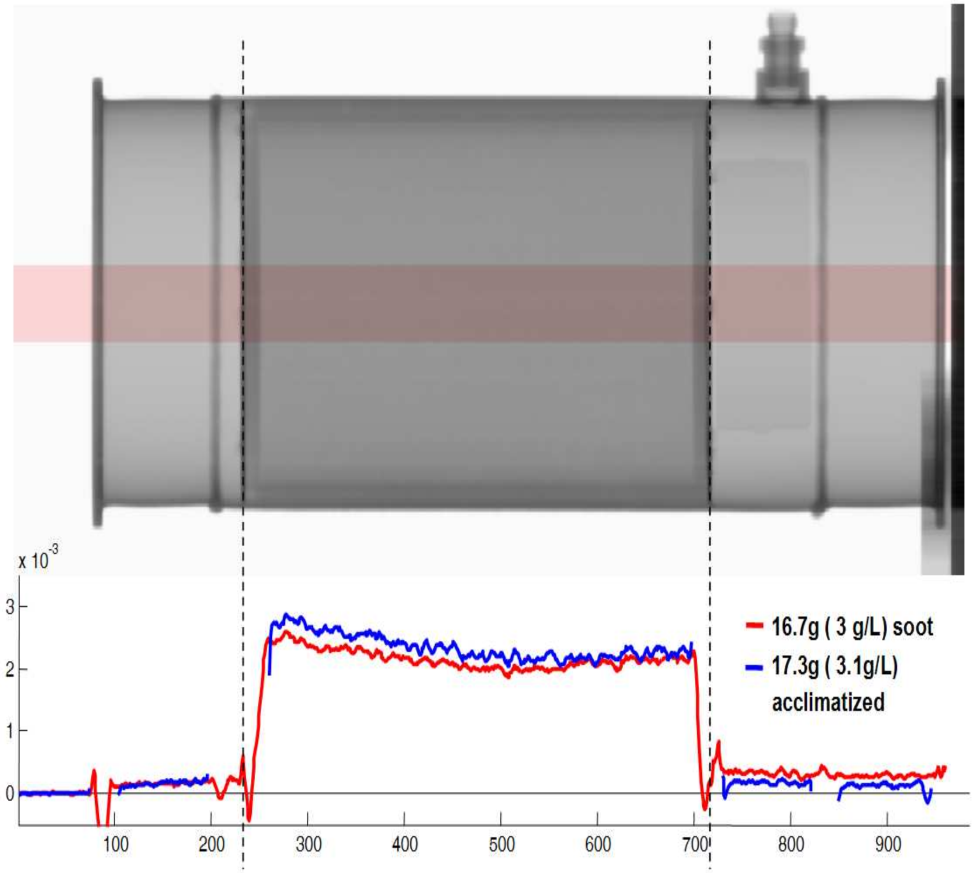
Extra slides

X-Ray Imaging Scouting Study Approach: Measurements with commercial 3D x-ray

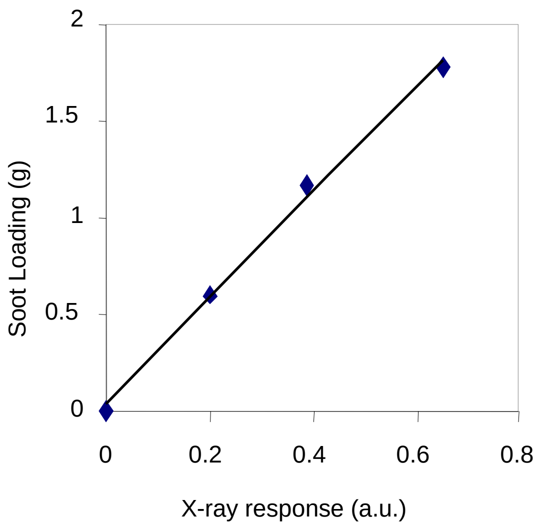


- **MDXi400 by 3D-XRAY, Ltd on site NTRC March-May 08**
- **Rotating platform & X-ray fan beam give 3D profiles**
- **Used for defect detection in catalytic monolith production**
- **Examined cracks, thermal damage, washcoat uniformity, soot & ash DPF deposition**
- **Responds to CLEERS poll interest in DPF monitoring**

Significant Results (6): Confirmed measurement of DPF soot

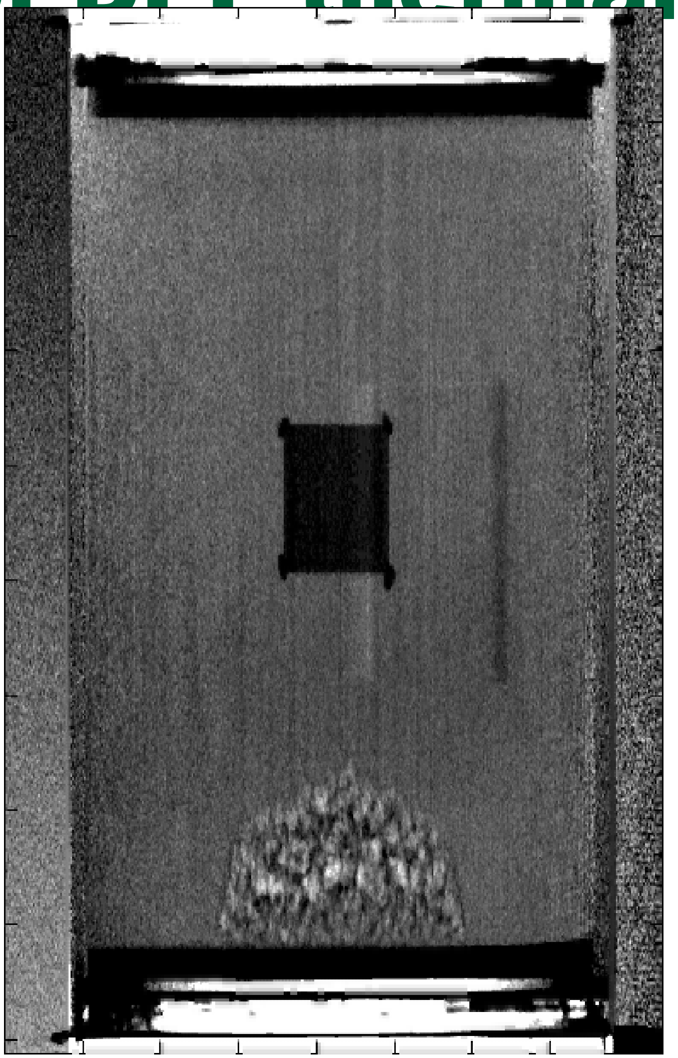


- 6-in OD uncoated DPF (in can)
- Loaded for 5 hours on Mercedes 1.7-L engine with ULSD fuel
- Quantitative detection of axial soot loading variations thru can wall



Linear calibration curve

Significant Results (7): Also confirmed ability to image details of DPF thermal damage



- 150mm DPF in can
- Thermal damage (by OEM) induced near exit
- Expect to be highly useful for model/OBD validation