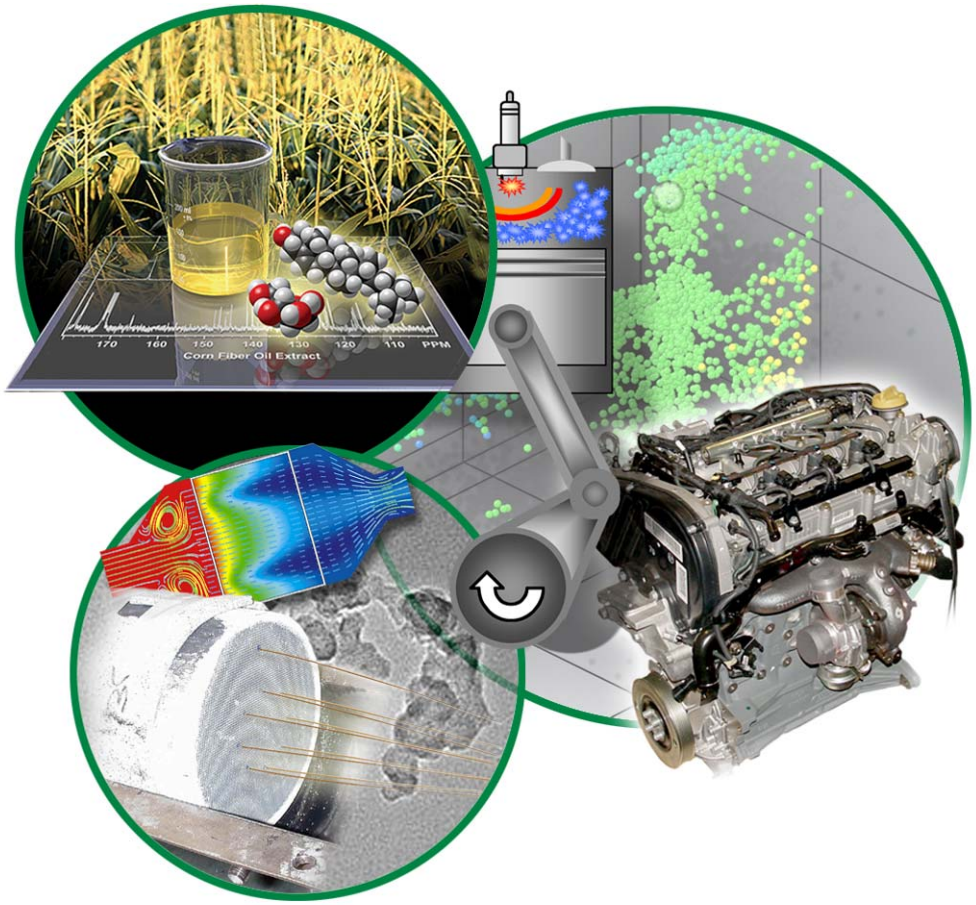
Light-Duty Diesel R&D, Targeting Barriers to Market Penetration

SAE Government-Industry Meeting, May 13, 2008



Ron Graves

Oak Ridge National Laboratory

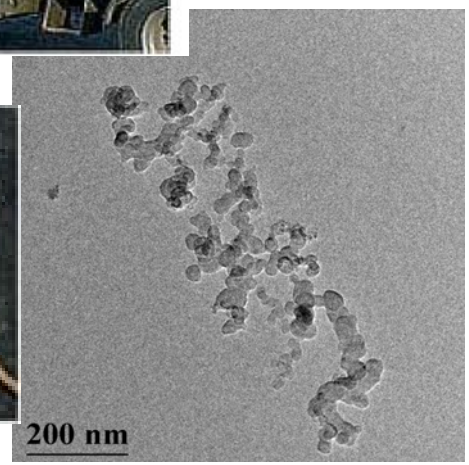
with contributions from other DOE labs

Presentation Outline

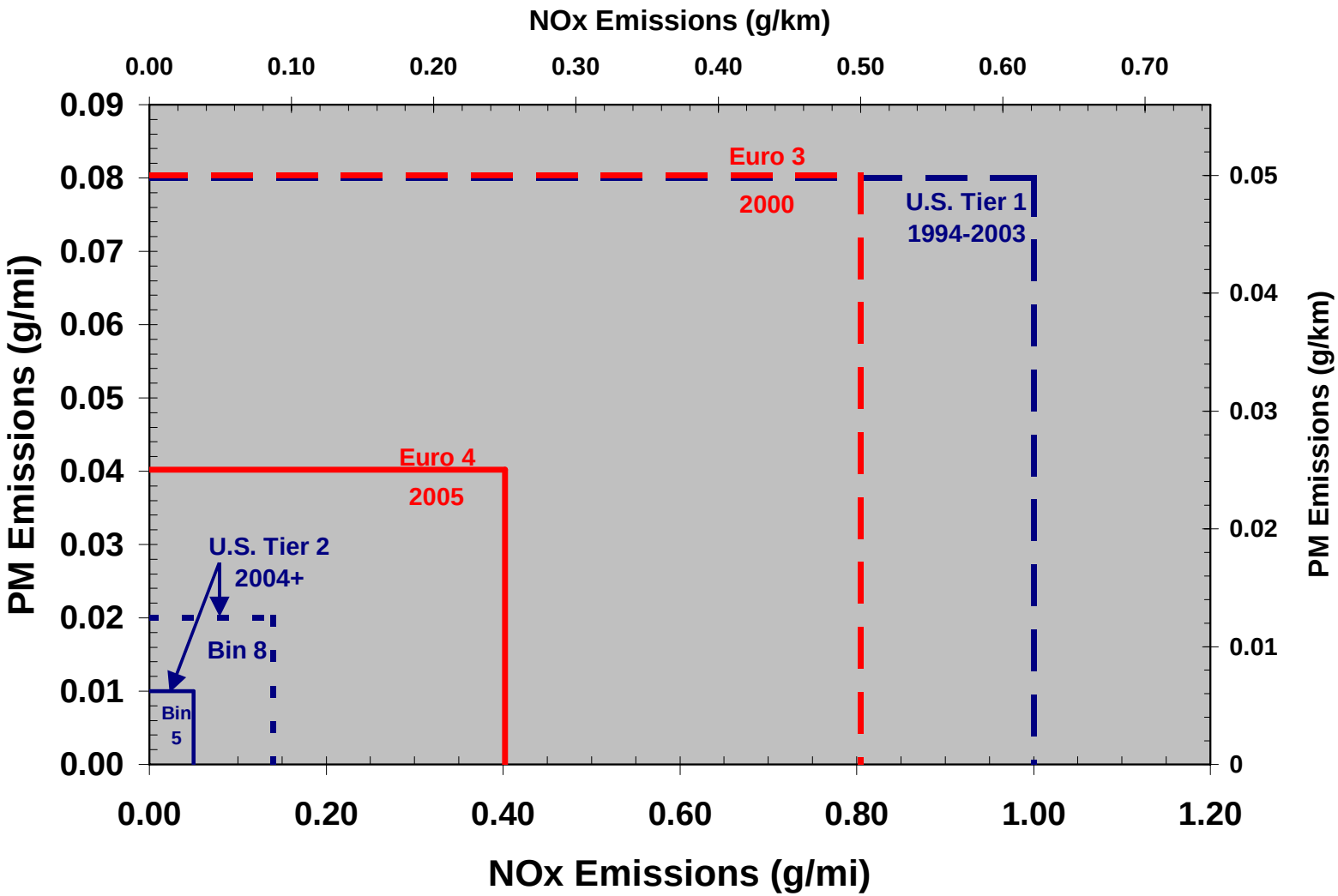
- **Barriers ten years ago**
  - **(real or perceived)**
- **Key breakthroughs or achievements to resolve those barriers, emphasis on DOE contributions**
- **Remaining issues in market penetration**
- **Ongoing R&D toward these**

Reflecting back to major barriers ~decade ago

- **Emissions compliance**
  - **NOx (how?)**
  - **PM**
- **Cost**
- **Image of diesels by public**
- **Noise**
- **Fueling infrastructure**
- **Concern on health impacts**

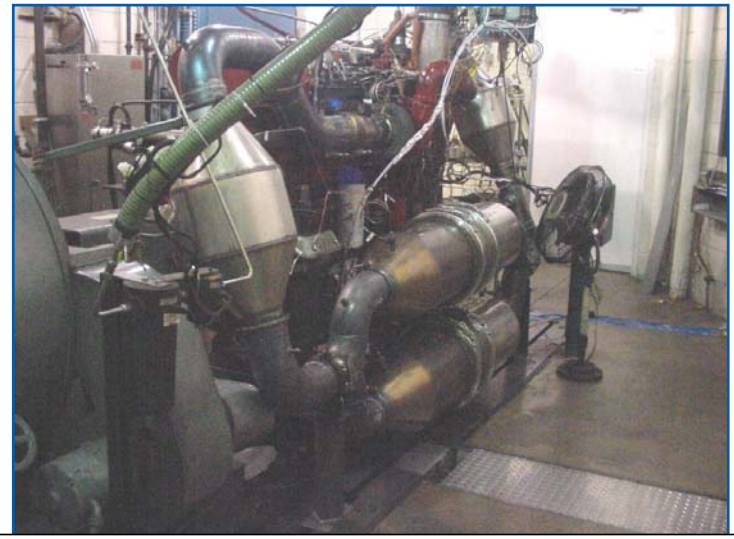


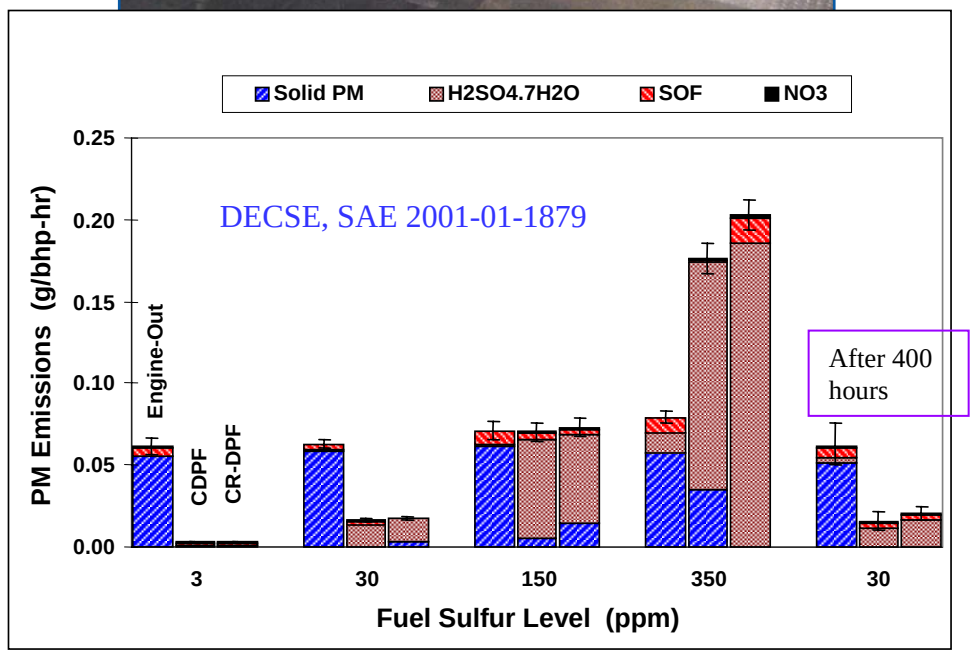
Tier 2 emissions regulations daunting challenge ten years ago…would require combustion, fuels, aftertreatment development



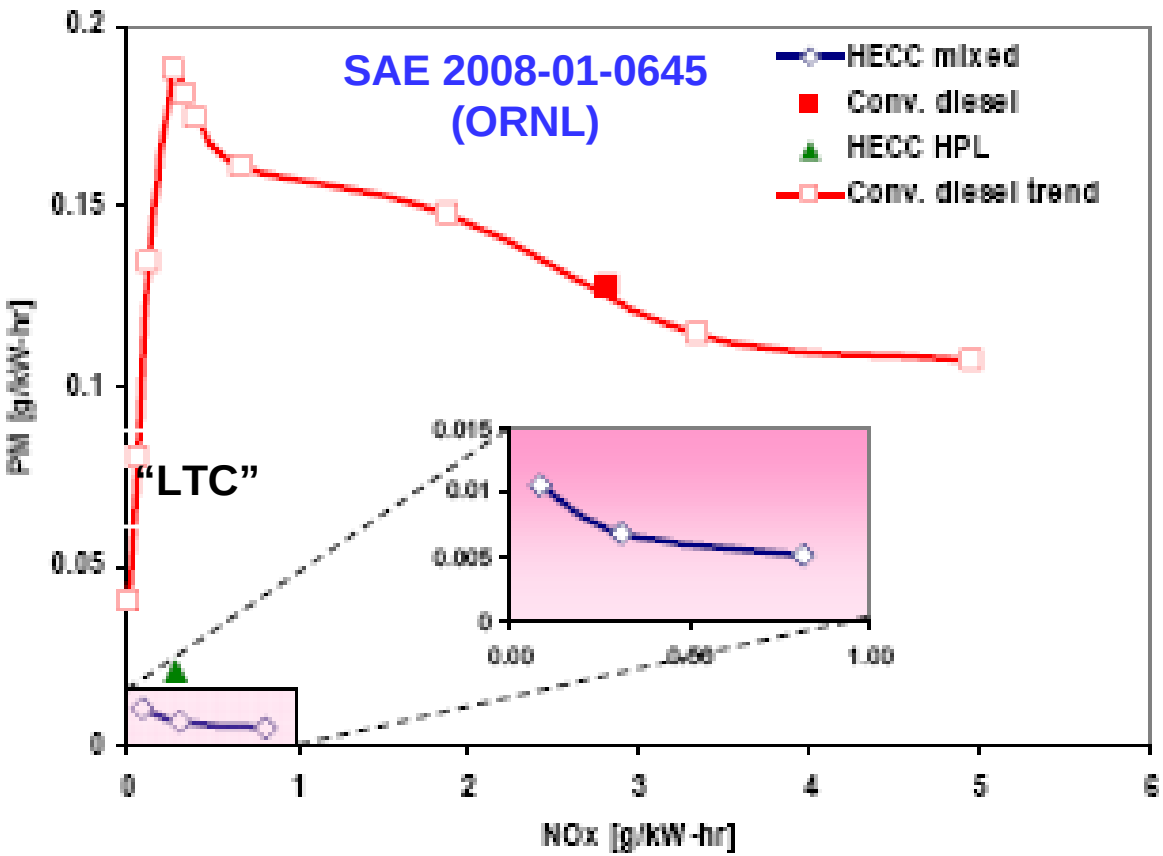
EPA ruling on diesel sulfur was key step on path to clean light-duty diesels.

- **Intense data gathering on sulfur effects supported by DOE 1997-2004.**
  - **Diesel Emission Control Sulfur Effects (DECSE)**
  - **APBF-DEC**
  - **DOE worked with EPA and ~50 govt/industry organizations**
  - **Important part of foundation of diesel sulfur rulemaking**





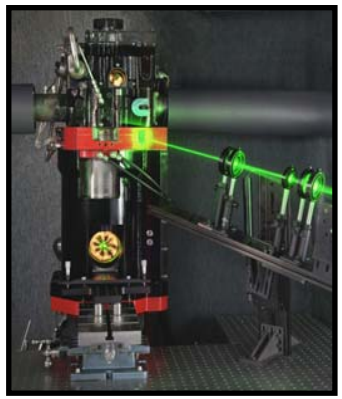
Worldwide efforts in engine technology and combustion research yielded major engine-out emission reductions

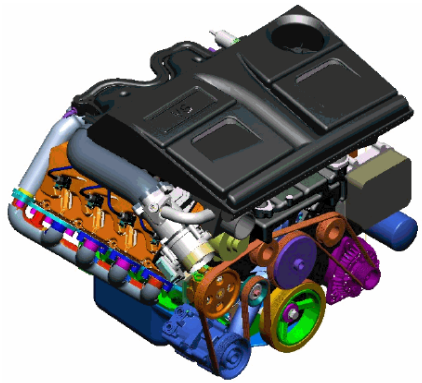


- **Low engine-out emissions key path to compliance**
- **Potentially best overall energy efficiency**
- **Helps manage cost of any catalyst-based aftertreatment system**
- **Critical to noise control**

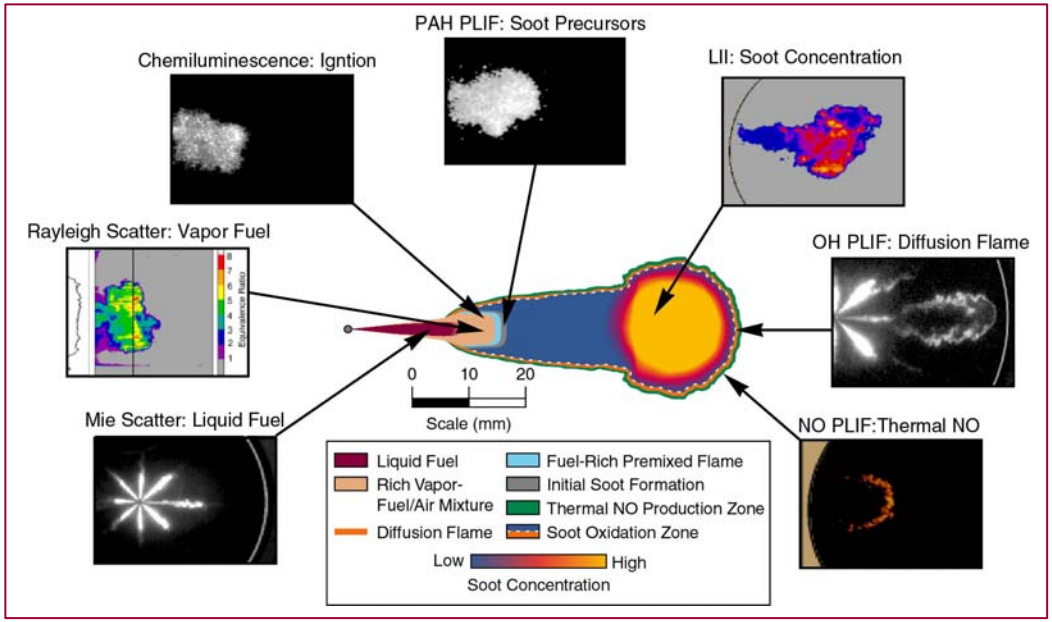
DOE contributed with complimentary efforts in industry, labs, universities

- **Light-truck clean diesel program, 1997-2004**
  - **Multiple prototype engines in demo vehicles**
  - **Commercialization announced by Cummins/Chrysler, 2006**
- **Complimentary heavy truck R&D factor in early 2010 heavy pickup compliance**
- **Combustion MOU, 2003-present, coordinated by Sandia**
- **University Combustion Teams**

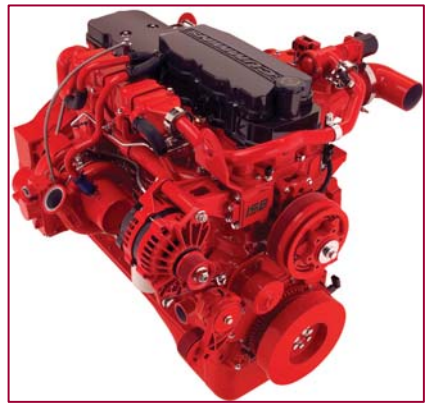


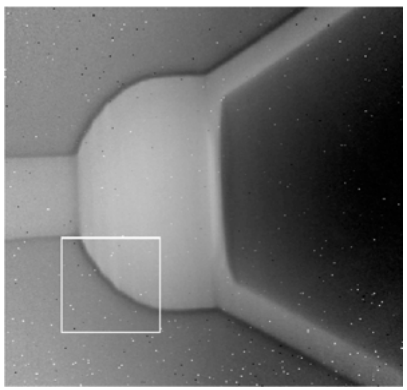


Source: Cummins, DEER 2004



Understanding and models of diesel combustion allowed fully virtual engine development. SNL, LLNL, LANL

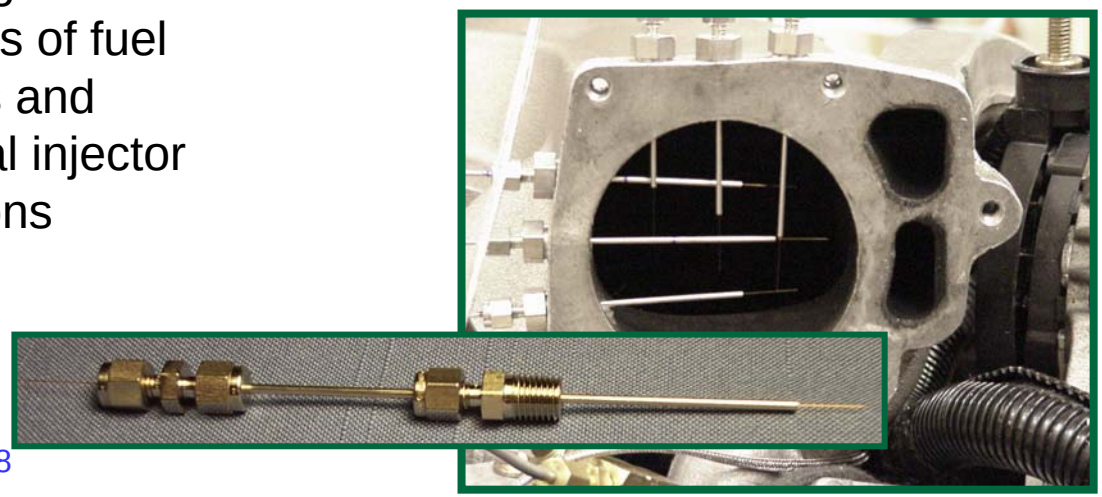




X-ray image of an injector nozzle, revealing the internal structure and operation.

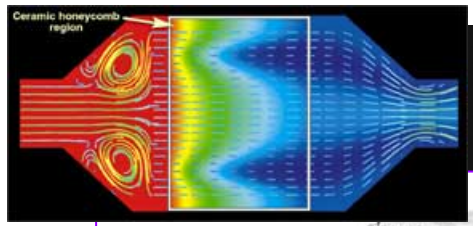
Adv Photon Source (ANL) lending new insights of fuel sprays and internal injector functions

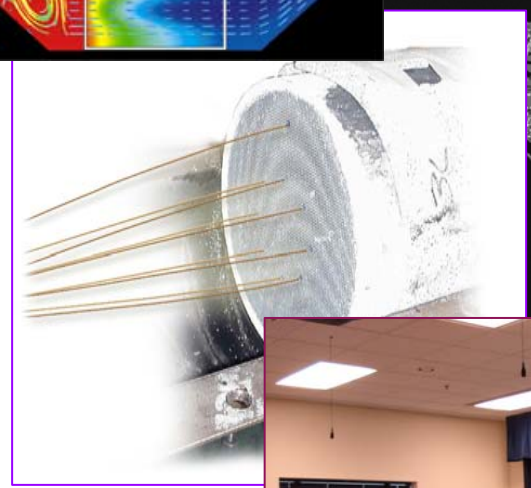
Capillary inlet mass spec (ORNL) used to study EGR mixing and distribution

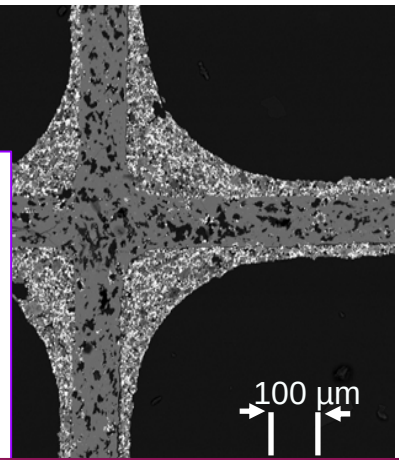


Crosscut lean exhaust emission reduction simulation (CLEERS), govt-industry team providing focus for emission control R&D since 2001

- **Non-competitive forum for sharing information on technical barriers and breakthroughs**
- **Encompasses DPF, LNT, SCR. www.cleers.org**
- **Typical ~ 70% private sector participation, international participation**
- **Research prioritization survey**
- **Creation of kinetic data and std protocols**
- **Emphasis on minimizing "fuel penalty" associated with achieving emission levels**
- **Aging and poisoning mechanisms**

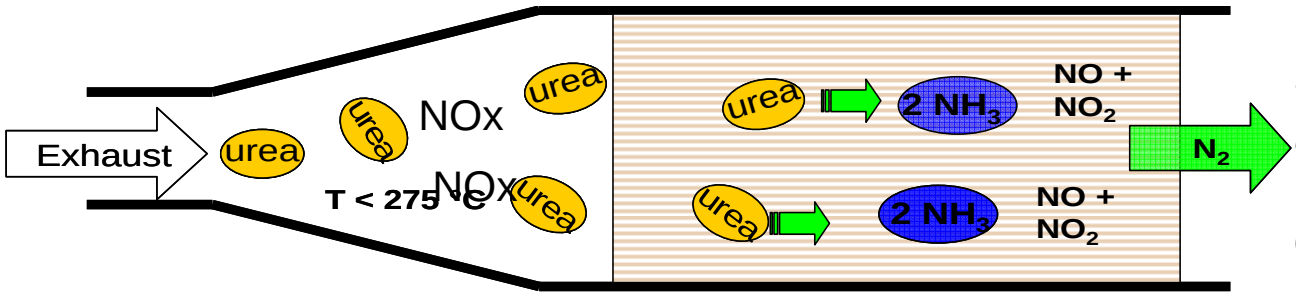






10th CLEERS workshop at U Mich., Dearborn

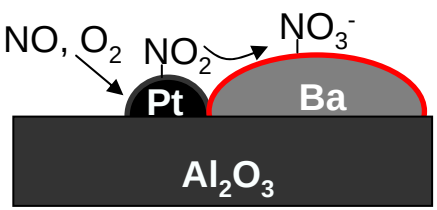
Again, world-wide efforts achieved commercial introduction of urea-SCR and LNT based systems



+ other products: ammonia, N_2O, HCN, cyanuric acid, ammeline

Lean A/F

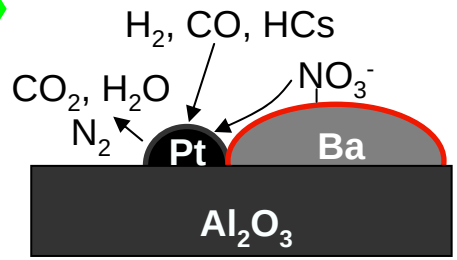
≳85% of time



NO_x stored as nitrate "storage"

Rich A/F

≲15% of time



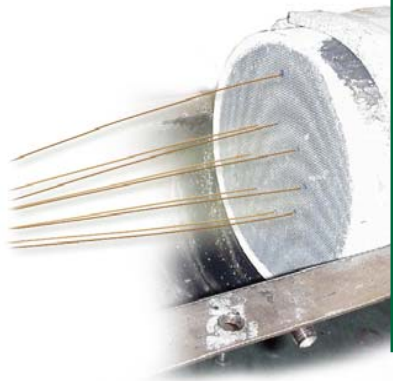
NO_x released & reduced "regeneration"

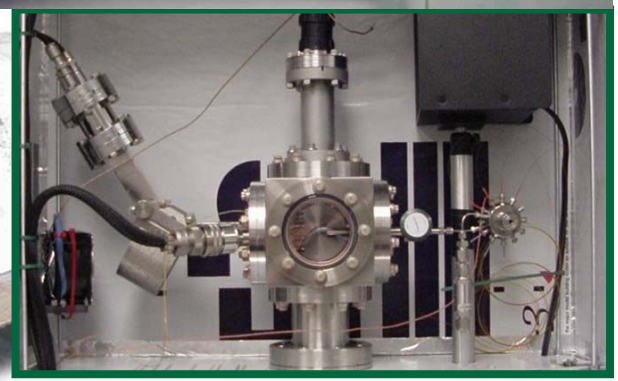
Citing some specific outcomes in DOE projects

PNNL CLEERS research…"key to interpreting many features of these uniquely complex catalytic systems".

Ford, ExxonMobil demonstrate low-emission urea SCR vehicle and co-fueling approach (Mack truck demo vehicle) SAE 2002-01-290

GM, BASF study 1000s LNC formulations via combinatorial methods



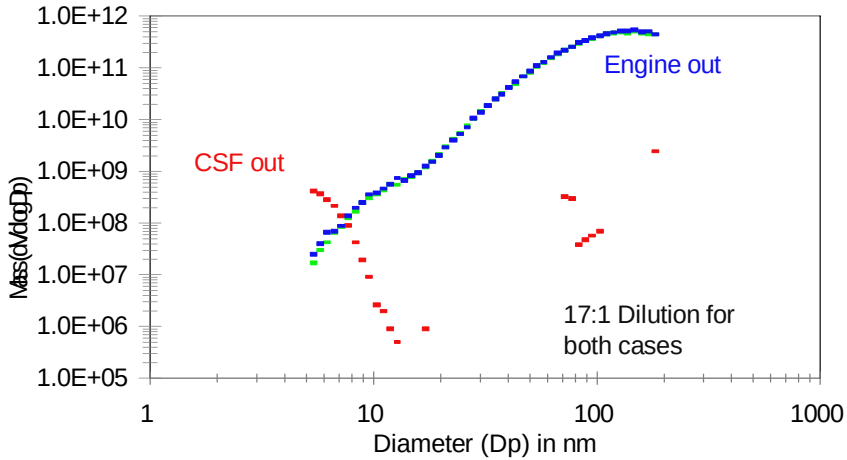


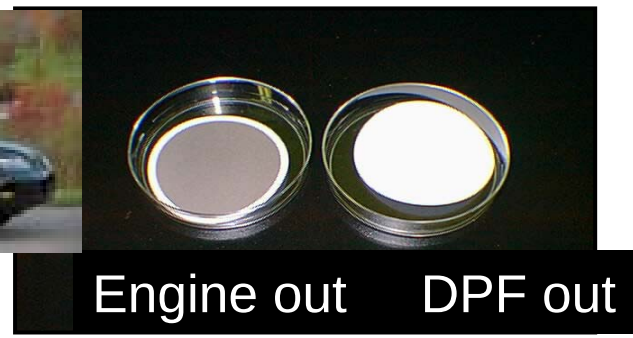
ORNL materials research addressed mechanisms of DPF degradation and catalyst aging

"The SpaciMS changed the way we think about tuning engine combustion."

Research and PR made Clean Diesel the new image and reality

- **New round of emission characterization and health impacts**
  - **Greater risk associated with high-emitter gasoline vehicles**
  - **Gasoline-derived PM equal to diesel PM in LA Basin**
  - **Mass PM emissions from DPF equipped diesels among lowest of any type engine**
  - **DOE supporting HEI-EMA-CRC ACES. >100 peer-reviewed articles from DOE sponsored works**
- **EPA diesel retrofit program, release of health impacts report**
- **Diesel Tech Forum, DOE, industry modern diesels in hands of public…ride & drive events**

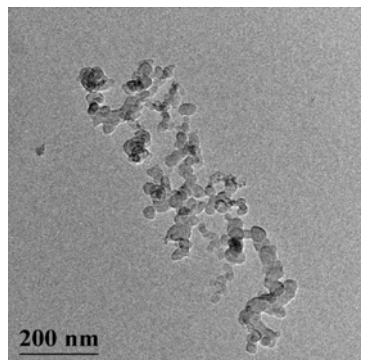




So how are we doing after ~ ten years?

- **Emissions compliance**
  - **NOx**
  - **PM**
- **Cost**
- **Image of diesels by public**
- **Noise**
- **Fueling infrastructure**
  - **Urea acceptance**
- **Concern on health impacts**

SmartWay™ Transport Partnership
U.S. Environmental Protection Agency



Thus, potential market barriers needing additional targeted R&D

- **Cost**
- **Another phase of emissions reductions?**
  - **Equivalency with lowest emission vehicles?**
  - **NAAQS impacts**
  - **Number-based PM requirement?**
- **Hybrid-electric vehicles…integration with diesels or competition for market share?**
- **Are fuel properties ok for the long term?**

Cost reduction?
Leaps in fuel efficiency and petroleum displacement rarely come without cost

- **Fuel cells' major hurdle**
- **Hybrid electric vehicle cost premium**
- **Ethanol and other fuels subsidies**
- **….and diesels**
  - **Additional engine component content**
  - **Non-traditional catalytic aftertreatment (not TWC)**
  - **What is going on with diesel fuel price?**

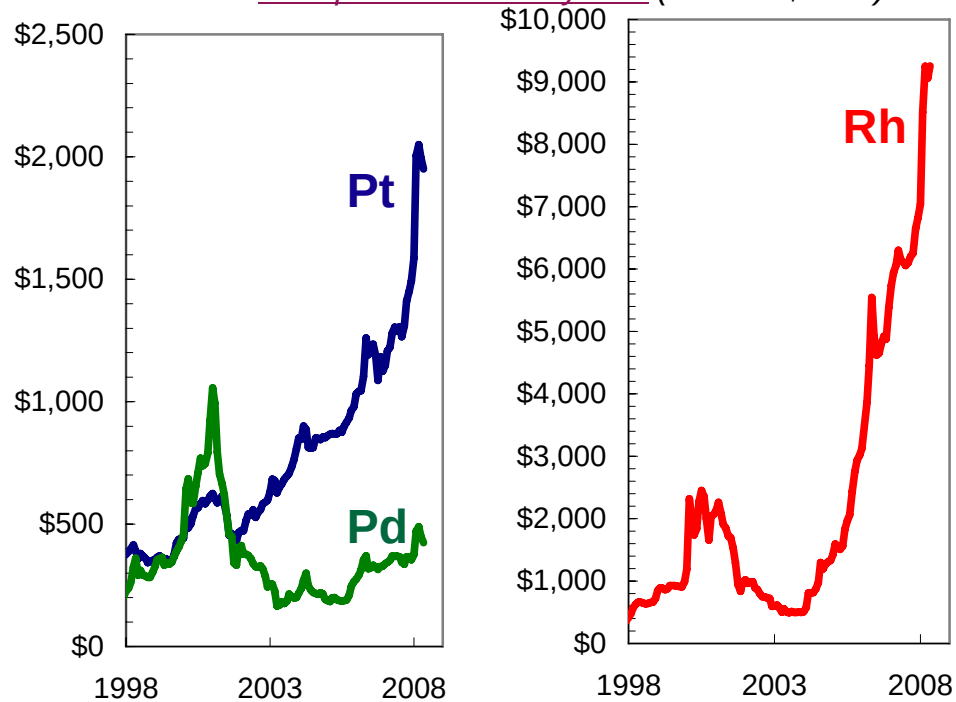
Diesel cost reduction...how?

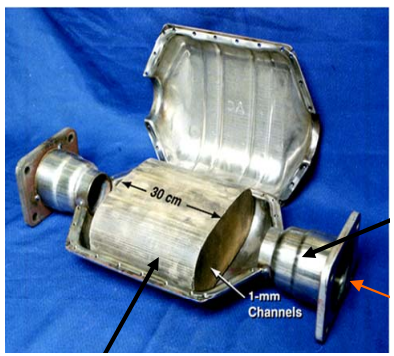
- **Lessen the need for aftertreatment via advancements in combustion (fuels?)**
  - **Expand range of High-efficiency clean combustion**
- **Lower the PGM content needed in the emission control devices**
  - **Develop improved materials**
  - **Better engine-aftertreatment integration**
  - **Devices with less catalyst content**
- **Further increase the diesel efficiency cost-effectiveness to shorten the payback period (without high-cost components)**
  - **Can we lower the cost of any components?**

Cost of Catalytic Diesel Emissions Control tied to PGM prices.
Expect Progress If Research Continues

- **"Dieselization" Costs:**
  - **Engine, Aftertreatment**
- **R&D decreases precious metal content**
  - **Current gasoline 1/3 1970's levels**
- **Pt/Rh/Pd mined in Russia, Zimbabwe, South Africa**
  - **Volatile price history**
  - **Pt increased more than 2x since 2005, Rh more than 3x**

Source: www.platinum.matthey.com (costs in $/T.O.)





NOx Adsorber Catalyst

•Precious metal ~$1.0-1.5K/unit

•Regeneration efficiency a function of precious metal

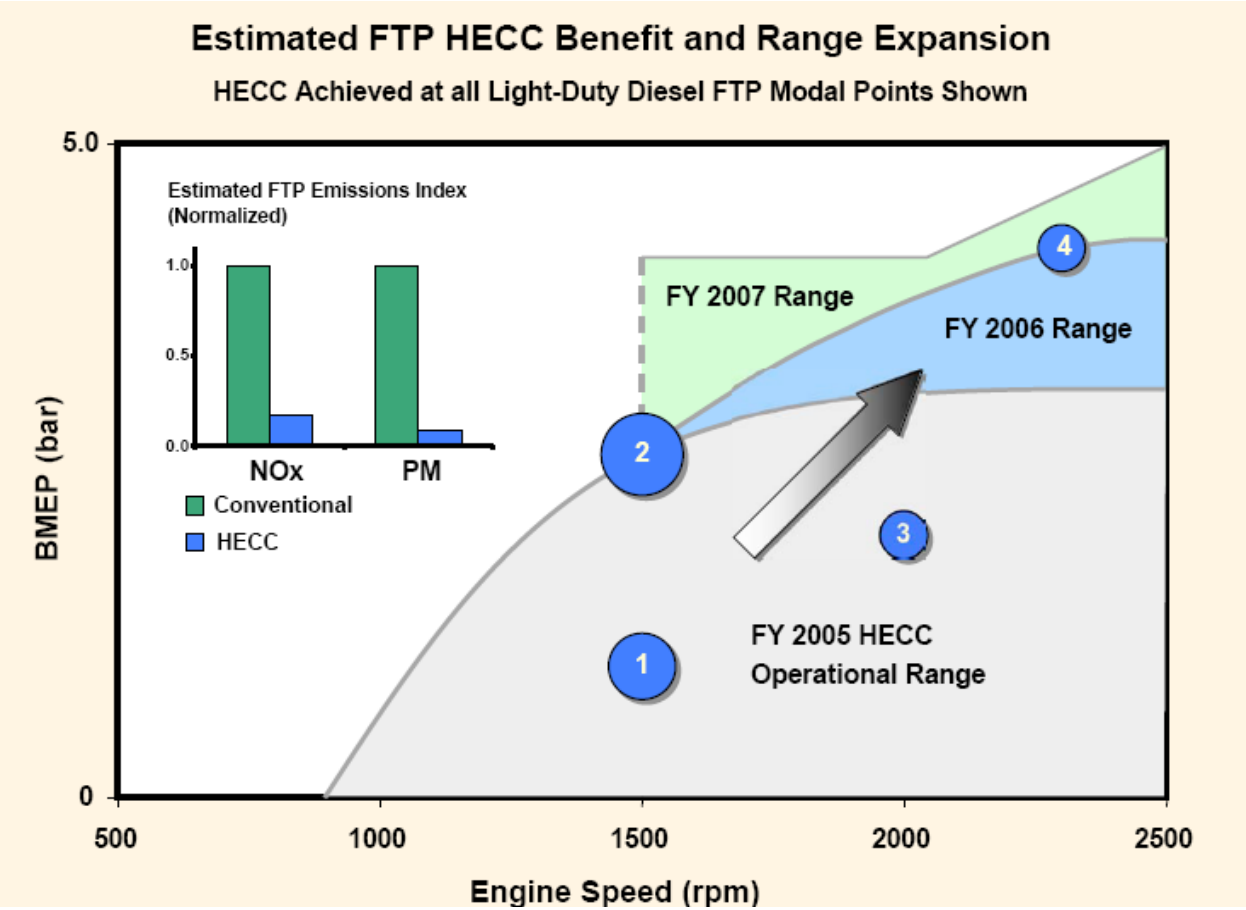
Urea SCR

•Require precious metal based diesel oxidation catalyst - $500-1000 /unit

Diesel Particulate Filter

•$1K - $1.5K /unit in Pt

Next wave of engine and combustion research for further reduced emissions, and higher efficiency

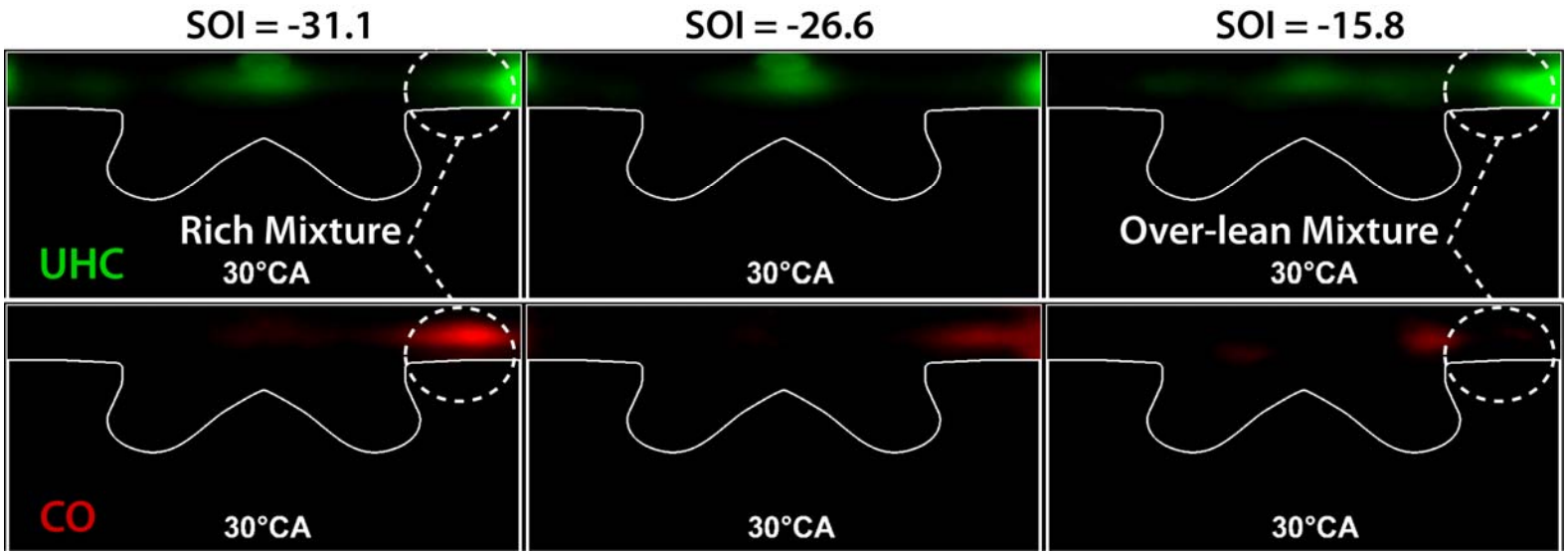


- **Expand "HECC" range**
- **Target emissions equivalency?**
- **Does urea SCR change our thinking on combustion vs catalysis?**

Wagner et al, ORNL, DOE Advanced Combustion Engine Annual Report, 2007

HC and CO control, efficiency loss in expanded LTC regions not fully resolved. Source: Sandia

Low-temperature diesel combustion relies on high EGR rates and low peak combustion temperatures to lower soot and NOx emissions. This creates additional challenges in achieving complete combustion

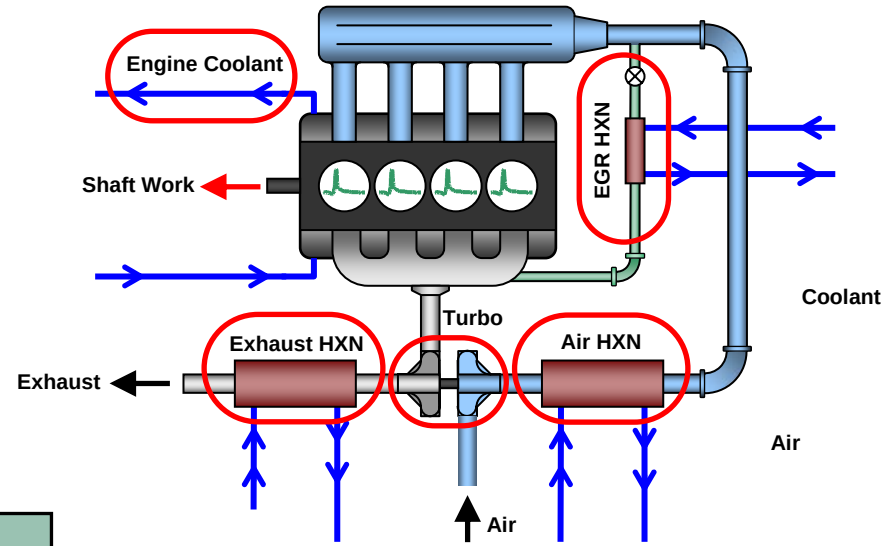


Recent progress in DOE laboratories has resulted in the first direct imaging of CO and UHC within the engine—indicators of incomplete combustion. Understanding the in-cylinder behavior is required to devise strategies to improve efficiency

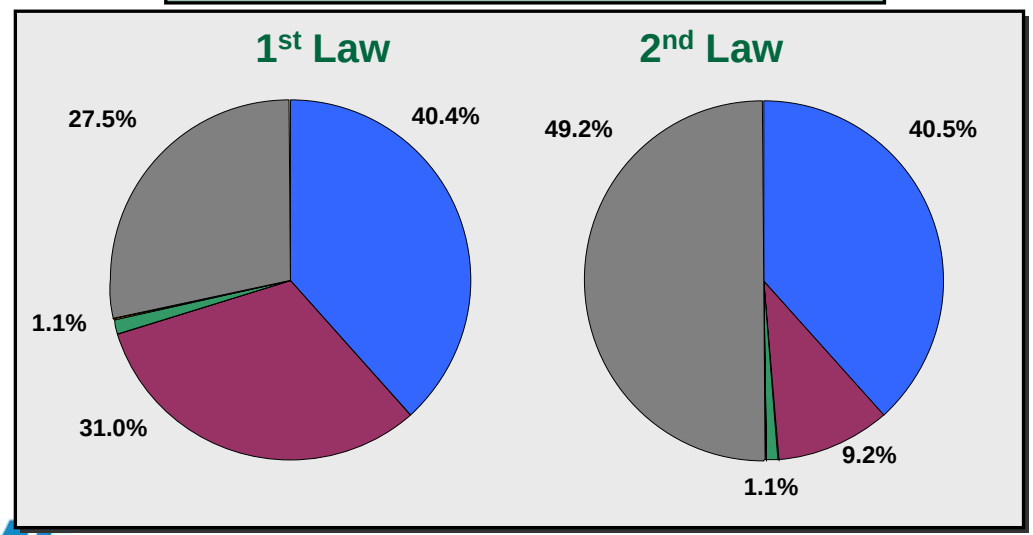
Look for the other efficiency opportunities

- **Fraction of fuel energy/availability apportioned to**
  - **Exhaust**
  - **Friction losses**
  - **EGR and charge-air cooler losses**
  - **Coolant losses (from block)**
  - **"Other": convective and radiant heat loss, mixing, combustion irreversibility, etc.**

Many potential sources of 'waste' energy



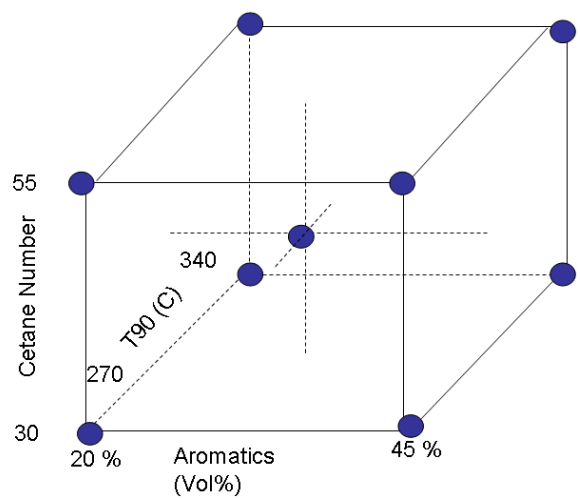
Peak Efficiency, 2250 rpm, 18 bar



Researching fuels for advanced combustion engine (FACE) interactions

Design and produce sets of research fuels that can provide common linkages among many combustion and emissions control activities.

- **Diesel fuel matrix includes 9 fuels with varying:**
  - **Cetane Number**
  - **Aromatic Content**
  - **90% Recovery Temperature**
- **The diesel matrix fuels are complete**
- **Combustion evaluations getting underway.**
- **Gasoline set being designed, trial blends**



Fuels being extensively charfacterized

Acknowledgements

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