

# Overview of the DOE Advanced Combustion Engine R&D

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Advanced Combustion Engine R&D Subprogram  
Vehicle Technologies Program

*2012 Annual Merit Review and Peer  
Evaluation Meeting  
DOE Vehicle Technologies Program and  
Hydrogen and Fuel Cells Program  
Washington, DC  
May 14-18, 2012*

## ***Vehicle Technologies Program Mission***

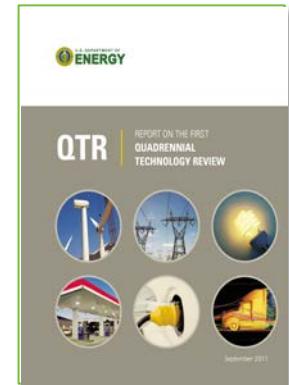
*To develop more energy efficient and  
environmentally friendly highway  
transportation technologies that enable  
the U.S. to use less petroleum.*

- ❑ Facilitate development of precompetitive technical knowledge base through investments in fundamental and applied R&D
- ❑ Undertake High-Risk Mid- to Long-Term Research
- ❑ Utilize Unique National Lab Expertise and Facilities
- ❑ Help Create a National Consensus
- ❑ Enable public-private partnerships to integrate R&D into industrially useful design tools

# Opportunity for Increased Internal Combustion Engine Efficiency

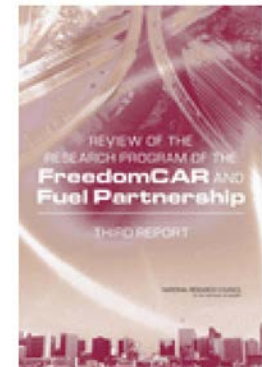
***Increasing the efficiency of internal combustion engines (ICEs) is one of the most promising and cost-effective approaches to improving the fuel economy of the U.S. vehicle fleet in the near- to mid-term.***

“The performance, low cost, and fuel flexibility of ICEs makes it likely that they will continue to dominate the vehicle fleet for at least the next several decades. ICE improvements can also be applied to both hybrid electric vehicles (HEVs) and vehicles that use alternative hydrocarbon fuels.” DOE QTR 2011<sup>1</sup>



DOE 2011

“...The internal combustion engine will be the dominant prime mover for light-duty vehicles for many years, probably decades ...” NRC Report 2010<sup>2</sup>



NRC 2010

<sup>1</sup> Quadrennial Technology Review, DOE 2011

<sup>2</sup> Review of the Research Program of the FreedomCAR and Fuel Partnership: 3rd Report, NRC 2010

**Strategic Goal:** Reduce petroleum dependence by removing critical technical barriers to mass commercialization of high-efficiency, emissions-compliant internal combustion engine (ICE) powertrains in passenger and commercial vehicles

## Primary Directions

- Improve ICE efficiency through **advanced combustion strategies and minimization of thermal and parasitic losses**
- Develop **aftertreatment technologies** integrated with combustion strategies for emissions compliance and minimization of efficiency penalty
- Explore **waste energy recovery** with mechanical and advanced thermoelectrics devices
- **Coordinate with materials and fuels teams** to enable clean, high-efficiency engines using hydrocarbon-based (petroleum and non-petroleum) fuels

**Benefits:** Advanced engines in conventional, hybrid electric vehicles (HEVs) and plug-in hybrid electric vehicles (PHEVs) will maintain significant share of the passenger car market for several decades



**No obvious alternative to ICE for over-the-road trucks in the foreseeable future**

Medium-duty and heavy-duty commercial vehicles account for a quarter of the fuel used (mostly diesel fuel)

## Performance Targets

	Light-Duty		Heavy-Duty	
	2010	2015	2015	2018
Engine brake thermal efficiency	45%		50%	55%
Powertrain cost	< \$30/kW			
NOx & PM emissions	Tier 2, Bin5	Tier 2, Bin2	EPA Standards	EPA Standards
Fuel economy improvement		25 – 40%	20%	30%

## Key Activities

- ❑ **Combustion and Emission Control R&D**
  - **Combustion Research**
  - Emission Control R&D
  - High Efficiency Engine Technologies
- ❑ **Solid State Energy Conversion**





# Advanced Engine Combustion Research Supports DOE/Industry High-efficiency, Clean Engine Goals

U.S. DEPARTMENT OF  
**ENERGY**

Energy Efficiency &  
Renewable Energy

- ❑ **Goal:** To develop the knowledge base for low-temperature combustion (LTC) strategies and carry research results to products.
  - Science-base for advanced combustion strategies
  - Computational tools for combustion system design and optimization
  - Identify potential pathways for efficiency improvement and emission compliance
- ❑ Close collaboration with industry through the Advanced Engine Combustion MOU led by Sandia National Labs ***carries research to products.***



- ❑ **Cross cuts light-duty and heavy-duty engine R&D**
- ❑ **University research integrated with MOU**



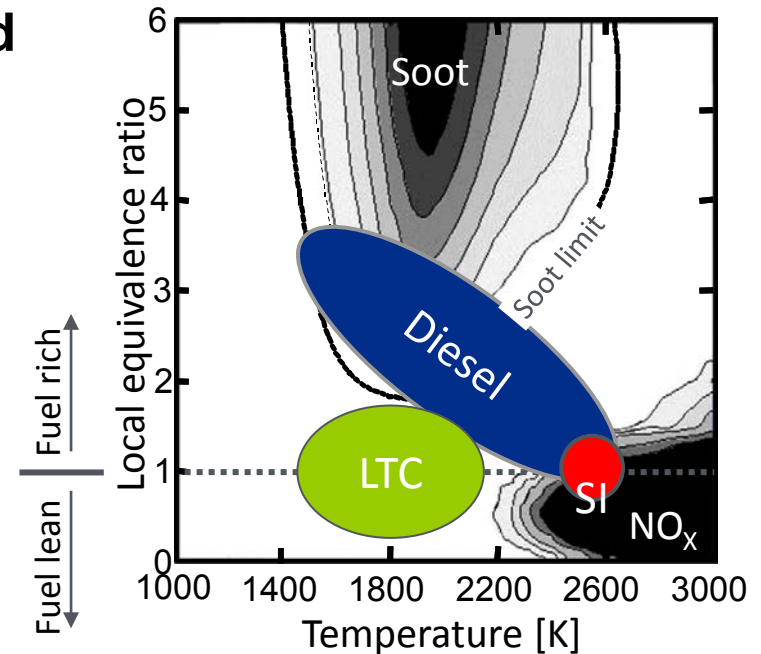
## Combustion Strategies Enabling Improved Efficiency and Very-Low Emissions

### □ Low-Temperature Combustion (LTC):

- Premixed-Charge Compression-Ignition (PCCI) (PPCI, PCI, MK, ...) – “mixed enough”
- Homogeneous-Charge Compression-Ignition (HCCI) – “heterogeneous enough”

□ Dilute Gasoline Combustion: Fuel-air mixing, ignition and flame propagation in stratified mixtures, stochastic misfire and knock challenges, fuels, emissions...

□ Clean Diesel Combustion: EGR, high-pressure and multi-pulse injection, lifted-flame combustion, post injections for in-cylinder and aftertreatment emission control,...



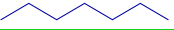

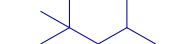
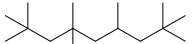
### – LTC Challenges:

- Combustion phasing
- Load range
- Heat release rate
- Transient control
- HC and CO emissions
- Fuel characteristics

# Research Tools Bridge Fundamentals to Application and Support Model Development

## ❑ Close coupled modeling and experiments

- Advanced diagnostics including optical, laser, x-ray, and neutron based techniques
- Combustion simulators
- Multi-dimensional computational models
- Fuel kinetics

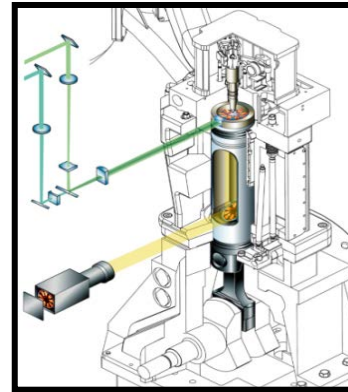
Gasoline PRF:	Diesel PRF:
n-heptane 	n-hexadecane 
iso-octane 	2,2,4,4,6,8,8 hepta-methylnonane 

- Multi- and single-cylinder engines

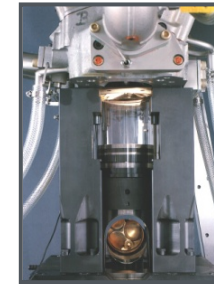
## ❑ Close collaboration between industry, national labs and universities

## ❑ Cross-cuts light- and heavy-duty R&D

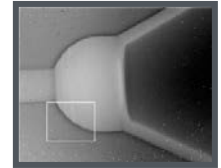
Leading to engine CFD modeling tools widely used in industry



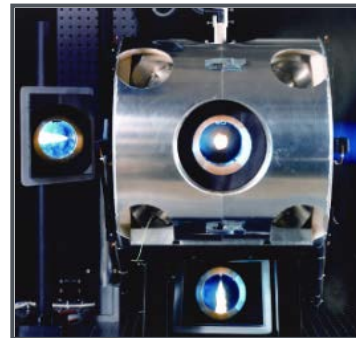
Optical Engines



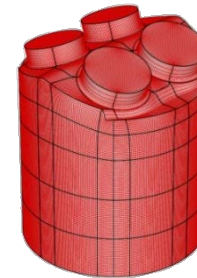
HCCI & Lean-burn Gasoline



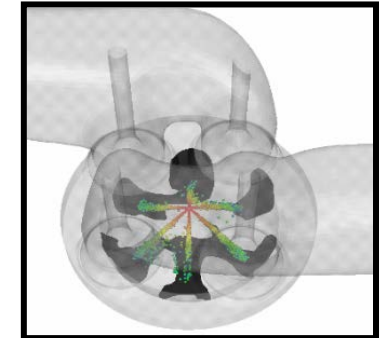
Nozzle Sac X-Ray Image



LTC Simulator



3-Million Cell LES Grid



Engine Simulation





## ❑ University Research in Advanced Combustion and Emission Control

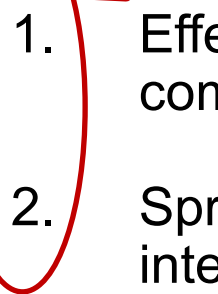
- 2 – 3 years
- Research Areas of Interest:
  - Lean-burn and low-temperature combustion strategies
  - Reduce nitrous oxide and particulate matter emissions in lean-burn combustion
  - Reduce combustion inefficiencies
  - Reduce hydrocarbon and carbon monoxide emissions for low temperature and lean-burn combustion

## ❑ Universities selected:

- *Michigan State*
  - *Regents of the U. of Michigan*
  - *Board of Regents of the U. of Wisconsin*
  - Michigan Tech
  - U. of Houston
  - U. of Connecticut
- } *Combustion*
- } Emission Control

# Identified Industry Barriers For Advanced Engines

## Highest priorities – PreSICE workshop focus

- 
1. Effect of stochastic nature of in-cylinder flow on engine combustion, performance and emissions
  2. Spray modeling and experimentation in dense spray and nozzle internal flow regions, including physics like cavitation and flash boiling
  3. Surface chemistry and physics for high-efficiency, low-temperature catalysis and filtration
  4. Fundamental understanding of near-wall processes (e.g., flow, heat transfer, diffusion, chemistry, wall films)
  5. High-pressure, dilute combustion including turbulence-chemistry interaction and extremes of equivalence ratio, dilution, and turbulence

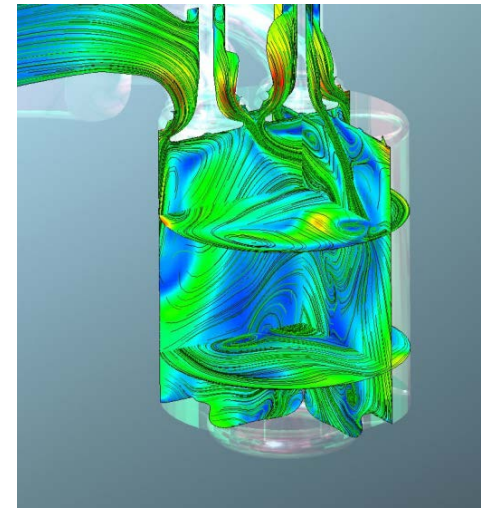
**All can be mitigated or overcome through science-based modeling**

# Priority Research Directions: Stochastic Processes and Sprays

## □ Development and validation of models to enable simulation of stochastic processes

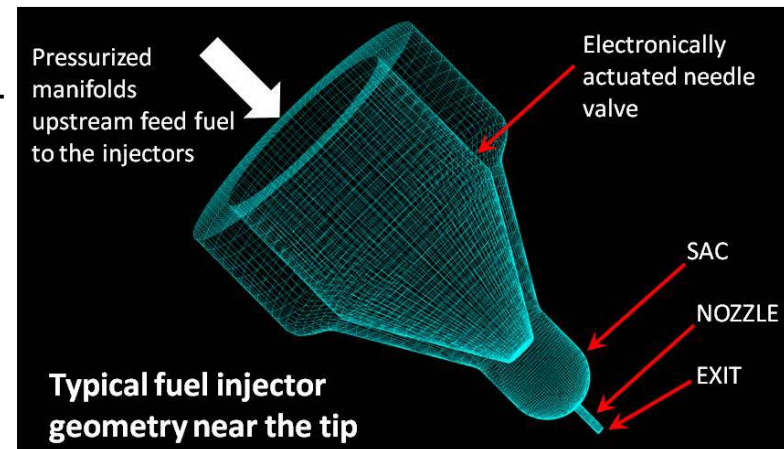
- Sub-grid scale models for unresolved processes
- Reduced chemical kinetic mechanisms
- New theoretical frameworks / efficient numerical approaches

Complex in-cylinder flow during intake stroke in diesel engine



## □ Optimization of fuel-preparation strategies (in-cylinder injection, mixing and combustion)

- Injection timing and strategy (single/multiple-pulse, etc.)
- Primary-breakup, atomization, dense spray dynamics
- Secondary-breakup, particle deformation, coalescence
- Dilute drop dynamics, vaporization, combustion
- High-pressure thermodynamically supercritical flow



# Engine Combustion Network (ECN) Improves Understanding of Fuel Spray CFD (SNL)



## Challenge:

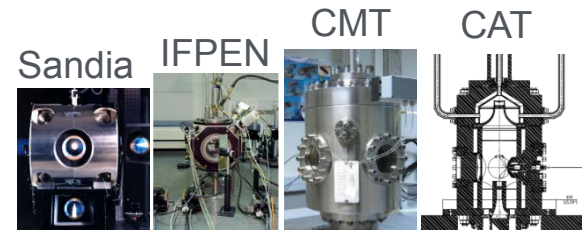
- Development of high-efficiency engines requires improved CFD predictive capabilities for combustion system design
  - Accurate spray modeling in DI engines is a critical challenge.

## Approach:

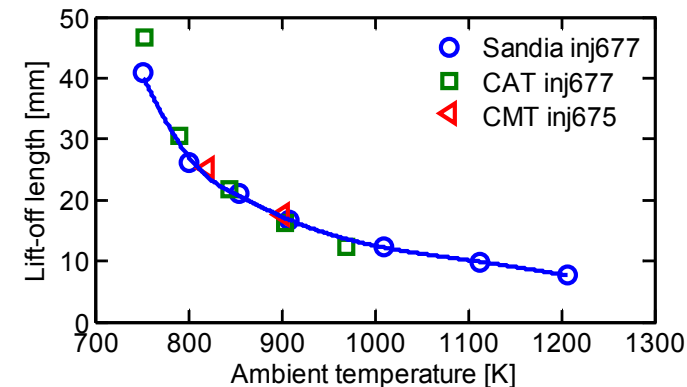
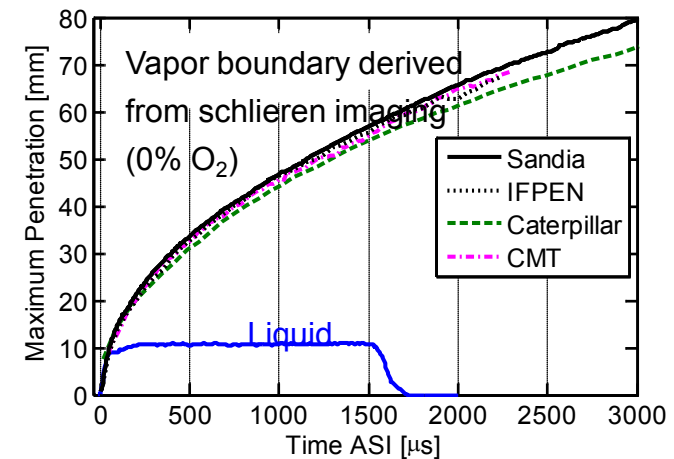
- A multi-institution, international collaboration develops comprehensive, highly vetted datasets for model development - initially focused on fuel sprays

## Findings:

- Initial diesel “Spray A” conditions investigated
  - Initial and boundary conditions tightly specified
- Experimental and modeling results compared at the first face-to-face ECN workshop (53 participants from 14 countries, 16 more via webcast) held May 13-14, 2011
- Data comparisons show feasibility of controlled, repeatable experiments at multiple facilities
  - Unique capabilities of each institution can be leveraged to accelerate model development and validation*



Spray A measurements at 4 institutions



**Funding Opportunity Announcement (FOA)** - for near and mid-term projects in technology areas that support the vehicle technologies mission and goals.

- Area of Interest 6A - Solid State Thermoelectric Energy Conversion Devices
- Area of Interest 6B - Enabling Technologies for Engine and Powertrain System



Awardees	R&D Focus
General Motors LLC	Develop and demonstrate a novel technology that enables the use of high dilution in the combustion chamber significantly improving the fuel economy of vehicles compared to conventional engines
MAHLE Powertrain LLC	Develop a next-generation combined ignition/turbo-charging concept that will enable the implementation of ultra lean-burn technology to engines, improving efficiency and significantly reducing the formation of pollutants such as oxides of nitrogen (NOx).
Filter Sensing Technologies, Inc.	Develop and demonstrate low-cost, robust sensors and controls that reduce the overall cost and complexity of engine and emission control systems, while delivering tangible performance benefits. The initial focus will be on U.S. heavy-duty vehicles
Eaton Corporation	Develop and demonstrate advanced component technology for heavy-duty diesel engine waste heat recovery systems that are capable of improving the fuel economy of heavy-duty vehicles

## Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) Programs Topics FY 2012 Phase I (Release 3)

- Topics Released: Monday, March 5, 2012
- Funding Opportunity Announcement Issued: Monday, April 3, 2012
- Pre-Application Due Date: Tuesday, May 1, 2012
- Feedback Provided on Pre-Applications: Tuesday, June 5, 2012
- Application Due Date: Tuesday, July 3, 2012

### Vehicle Technologies Program topics:

- (a) High-energy, high-power electric drive vehicle batteries
- (b) Catalyst materials for exhaust aftertreatment
- (c) Engine boosting technologies**
- (d) Differential compression and expansion technologies**
- (e) Subsystem component technologies**
- (f) Thermoelectric technologies**
- (g) Materials for traction drive motor laminations, cores, or structures.

## NSF/DOE PARTNERSHIP ON ADVANCED COMBUSTION ENGINES



**National Science Foundation  
Directorate for Engineering**  
Division of Chemical, Bioengineering,  
Environmental and Transport Systems



**U.S. Department of Energy,  
Vehicle Technologies Program**

- ❑ A Partnership to leverage the complementary DOE and NSF missions<sup>1</sup>.
- ❑ Two broad areas: *Advanced Combustion Engines*; and *Emissions Control Strategies*
- ❑ Research to focus on understanding the fundamental thermal/fluid/chemical processes and how improved understanding will enable ICE efficiency gains.
- ❑ Collaborations with industry, and other academic and/or national laboratories that provide complementary experimental/modeling/facility capabilities.

<sup>1</sup>DOE Mission - Deployment and Commercialization

NSF Mission - Fundamental Research and Education

# Advanced Combustion Engine R&D Budget by Activities

U.S. DEPARTMENT OF  
**ENERGY**

Energy Efficiency &  
Renewable Energy

Major Activities	FY 2010	FY 2011	FY 2012	FY 2013 Request
<b>Advanced Combustion Engine R&amp;D</b>	<b>\$57,600K</b>	<b>\$57,600K</b>	<b>\$58,027K</b>	<b>\$55,261K</b>
<b>Combustion and Emission Control</b>	47,239	47,239	49,320	47,505
<b>Solid State Energy Conversion</b>	8,748	8,748	8,707	7,756
<b>SBIR/STTR</b>	1,613	1,613	--	--

## Thank You!

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