CATERPILLAR®

Development of Enabling Technologies for High Efficiency, Low Emissions Homogeneous Charge Compression Ignition (HCCI) Engines

Program Manager: Scott Fiveland

ACE038

DOE Contract: **DE-FC26-05NT42412**

DEDOE Technology Manager: Roland Gravel

NETL Project Manager: Carl Maronde

DOE Merit Review

Washington, D.C.

June 9th 2010

Collaborations

University of Wisconsin
Engine Research Center

Lund University

AEC MOU

CATERPILLAR®

- Program coordination
- Test/Analysis
- Truck/Machine system integration and packaging
- Combustion

Oak Ridge National Laboratory

- In-cylinder heat transfer
- Exhaust Availability
- Leverage advanced materials CRADA

Sandia National Laboratories

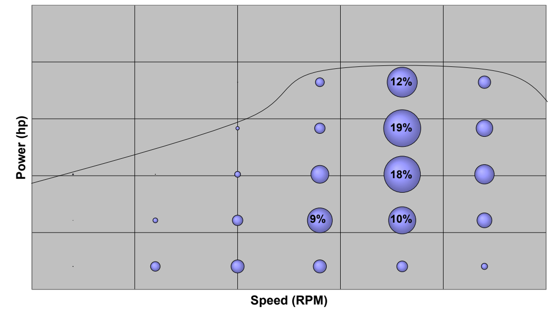
- Optical diagnostics
- Fuel spray and combustion
- Fuels effects

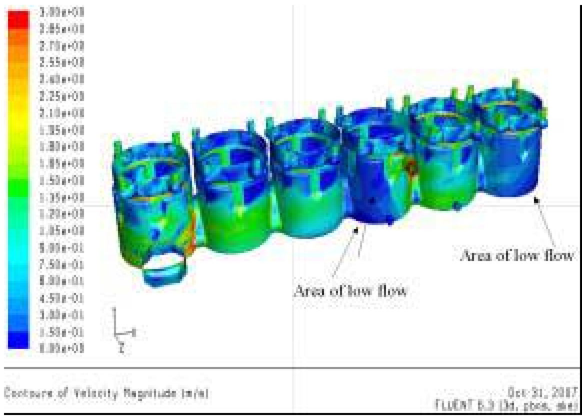
ExxonMobil Research and Engineering

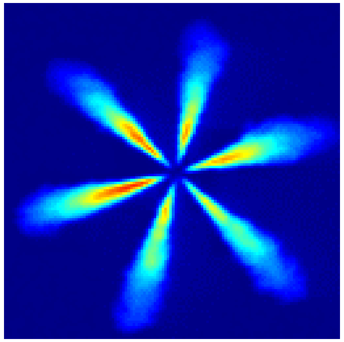
- Fuels effects
- Combustion Chemistry/modeling

Outline

- Program Overview/Purpose
- FY 2009 Milestones
- Technical Approach
- FY 2009 Program tasks







Program Overview

Timeline

- Start: 8/01/2005
- Finish: 7/31/10

Budget

- Total Project Funding (Phase 1,2)
  - DOE - $10,309K
  - Contractor - $10,309 (Phase 1,2)
- Funding received FY09 & FY10
  - DOE ~ $2,600[1]
  - Contractor ~ $2,600K

Partners

- Exxon-Mobil
- Sandia National Laboratory
- Oak Ridge National Laboratory

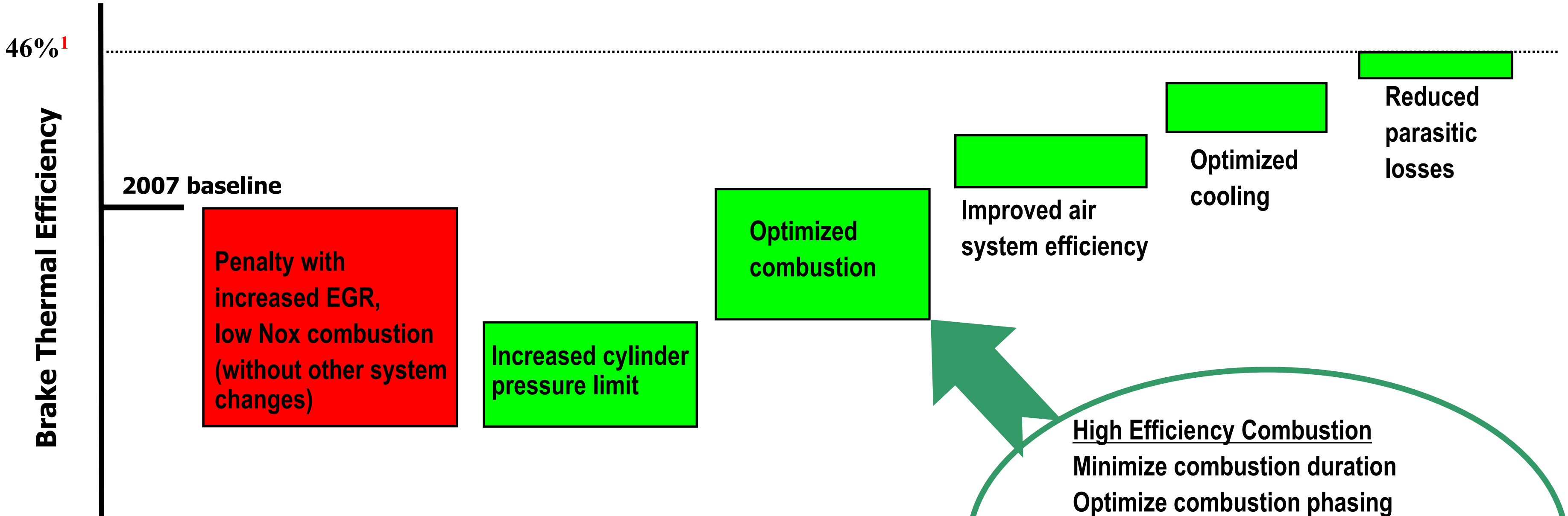
Technical Barriers

- **Mixture Preparation / Air Utilization**
  - Excessive HC,CO and soot emissions with HCCI – type combustion
  - Excessive soot at high BMEP (Ø > 0.8)
- **High heat rejection**
  - Increased EGR requirements
  - Increased in-cylinder heat transfer with HCCI
- **Power density / load capability**
  - Cylinder pressure and rise rate limits
  - High equivalence ratio at high BMEP
- **Robust combustion control**
  - Transient control of HCCI (PCCI)
  - Combustion feedback sensors
  - Combustion mode switching

[1] As per FY2008 & 2009 plan

Purpose of Work

- Assess production viable low temperature combustion technology building blocks to enable a low emissions and high thermal efficiency (46%[1]).



<u>High Efficiency Combustion</u>
Minimize combustion duration
Optimize combustion phasing
High equivalence ratio combustion

<u>Clean Combustion</u>
Low NOx emissions
Minimize soot emissions

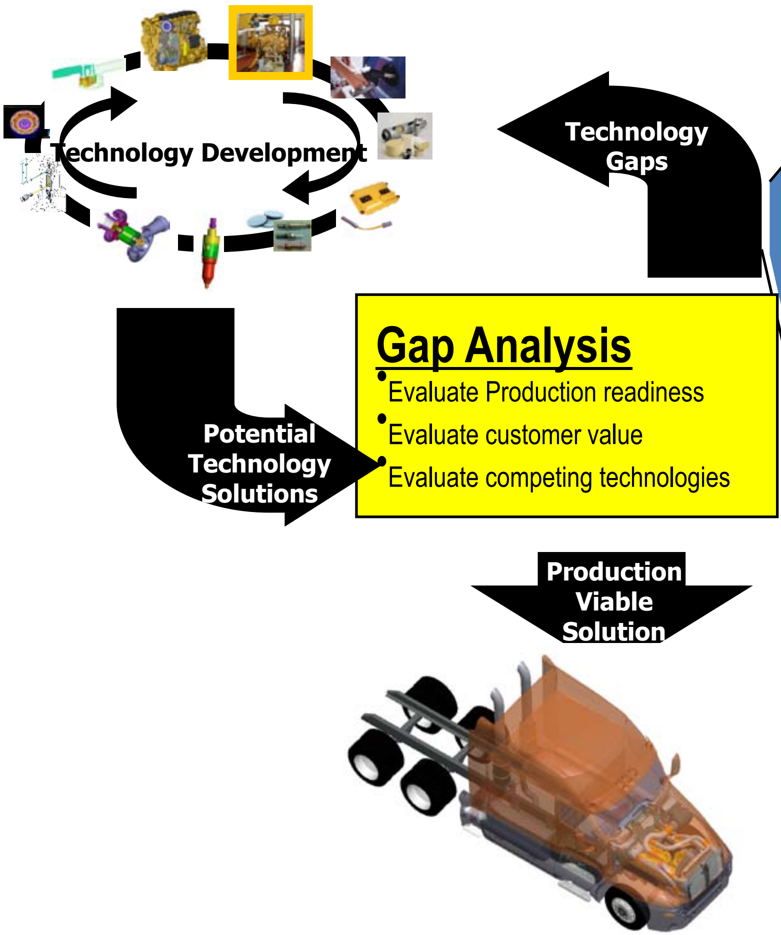
Why Low Temperature Combustion?

- Potentially short combustion durations are thermodynamically attractive
- Low NOx and PM emissions reduce or eliminate need for aftertreatment
    - →Reduced backpressure and lower cost
    - →Reduced regeneration cost

1 As Per Solicitation DOE Contract: **DE-FC26-05NT42412**

Technology Barriers

- Assess production viable low temperature combustion technology building blocks to enable a low emissions and high thermal efficiency (46%[1]).



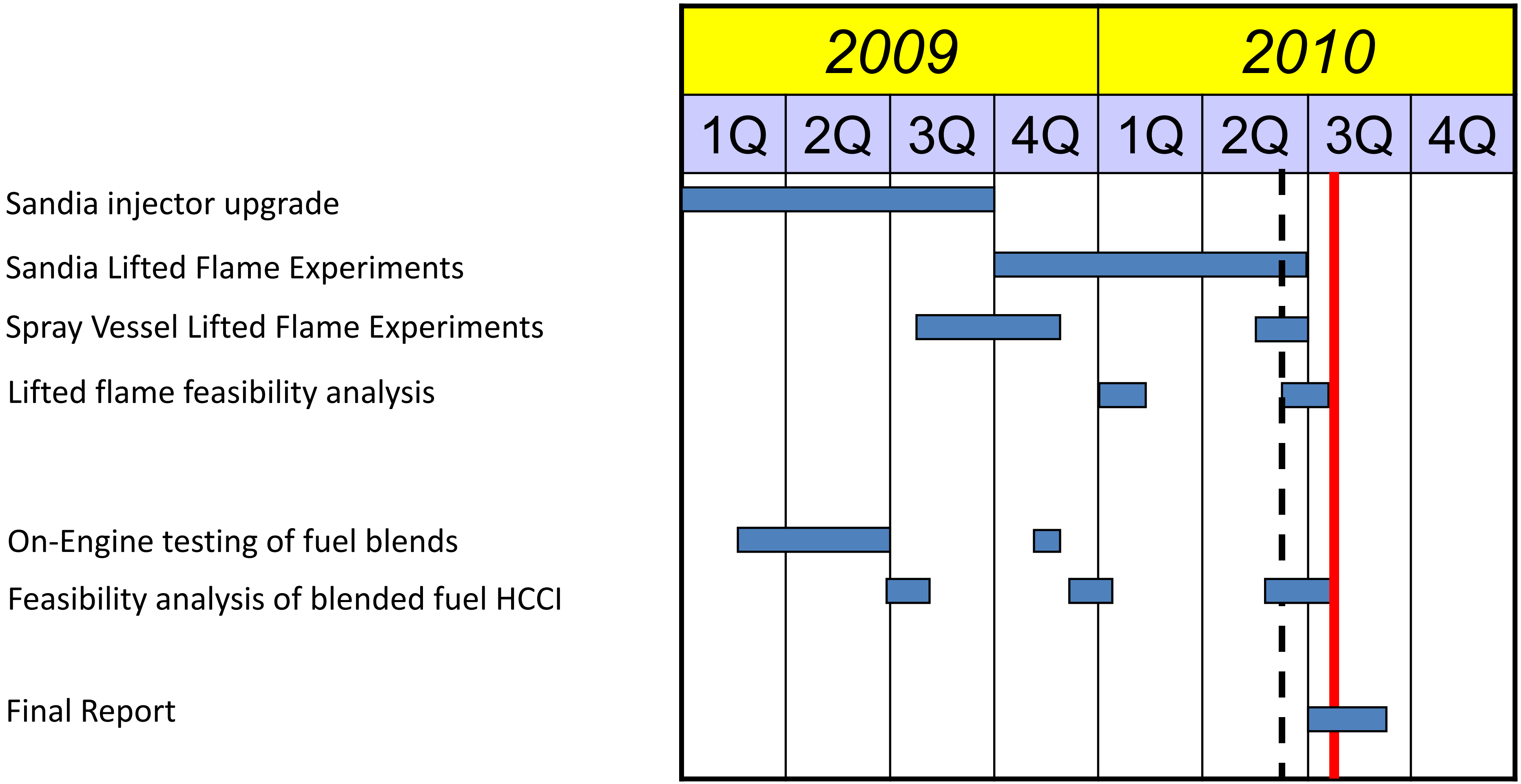
- **Mixture Preparation / Air Utilization**
  - Excessive HC,CO and soot emissions with HCCI – type combustion
  - Excessive soot at high BMEP (Ø > 0.8)
- **High heat rejection**
  - Increased EGR requirements
  - Increased in-cylinder heat transfer with HCCI
- **Power density / load capability**
  - Cylinder pressure and rise rate limits
  - High equivalence ratio at high BMEP
- **Robust combustion control**
  - Transient control of HCCI
  - Combustion feedback sensors
  - Combustion mode switching

[1] As Per Solicitation DOE Contract: **DE-FC26-05NT42412**

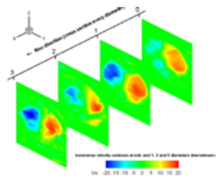
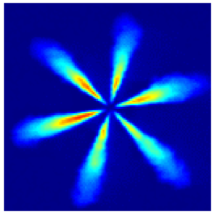
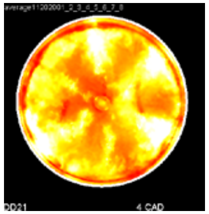
Key Focus Areas

- Combustion & Power Density
  - Characterize the HCCI combustion process & technology gaps using experiments & simulation (gap identification)
  - Investigate the use of fuel blending to improve the load range
  - Visualize early injection events in order to optimize the spray injection
  - Assess lifted-flame combustion (local premixing) as an emissions building block

2010 HECC Milestones



Technical Approach



Combustion Diagnostics

Combustion Modeling XFD

Air-System Development (ET/MEC)

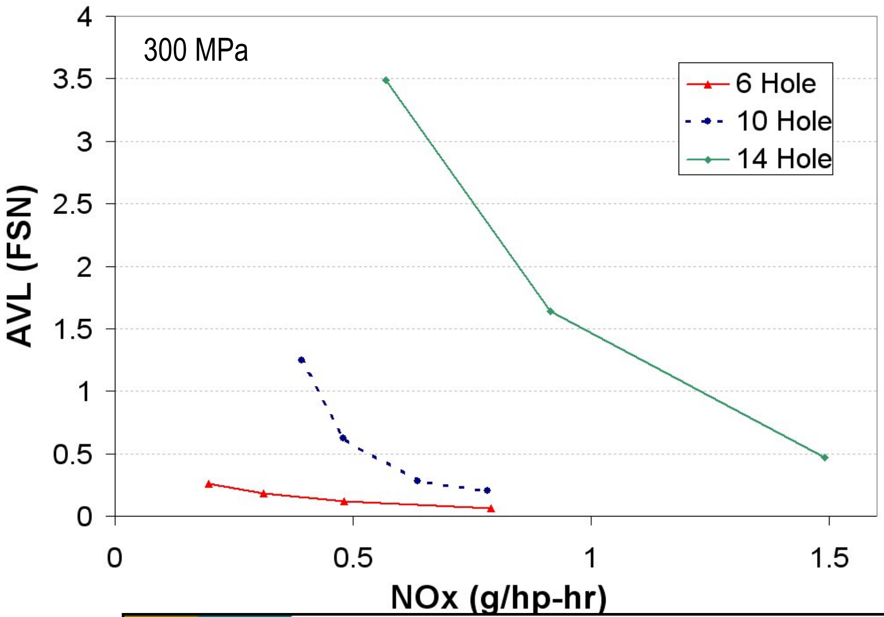
Injector Development (Fuel Systems, ACP)

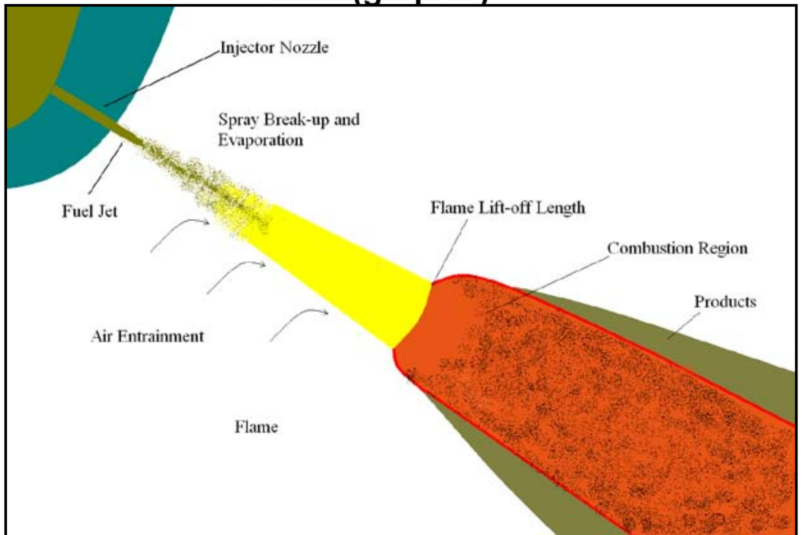
Combustion Development (GEDNA/LPSD Perkins/LEC/Solar)

"Lifted Flame" Combustion

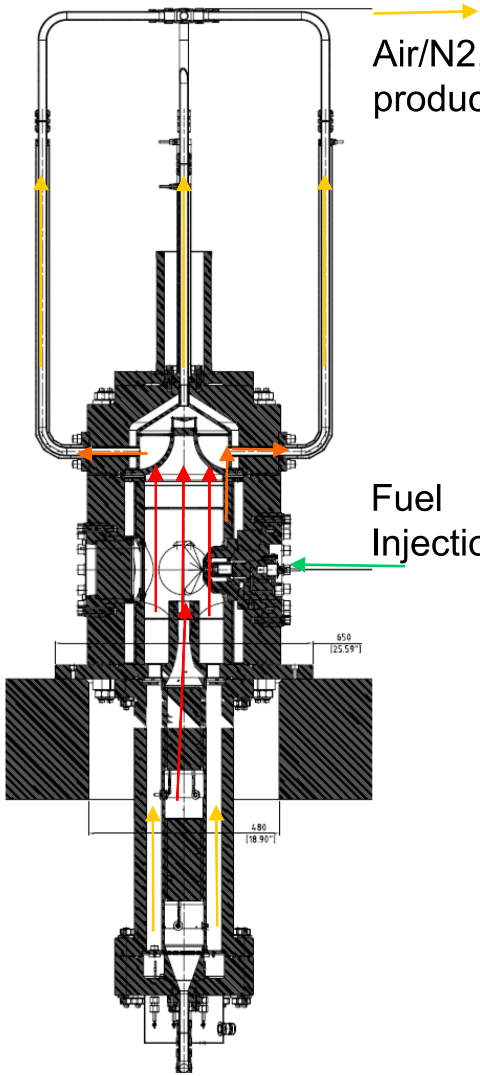
- General concept: increase air entrainment before the lifoff length of conventional Diesel combustion to avoid soot formation
- Previous work: demonstrated order of magnitude soot reduction with 6-hole nozzle, but nozzle lacked flow capacity for a 15 L engine
- Objective:
  - Understand the operational limits of achieving in-cylinder sootless lifted flames
  - Maximize the low soot benefit of "lifted flame" combustion through optimization of injector characteristics, in-cylinder conditions, and combustion chamber geometry
- Approach:
  - Investigate effect of plume interaction on flame liftoff and soot formation
  - Determine effect of transient in-cylinder environment on flame liftoff
  - Examine innovative combustion chamber and nozzle geometries

Effect of Increasing Number of Plumes on Emissions Performance

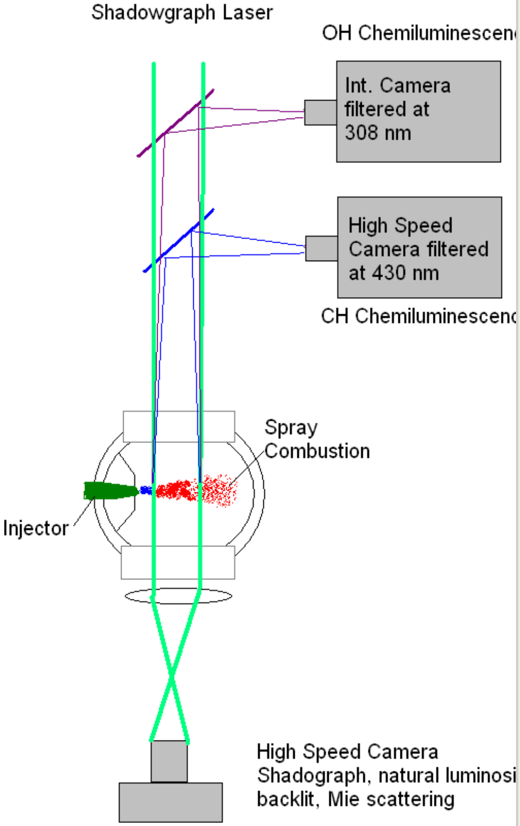


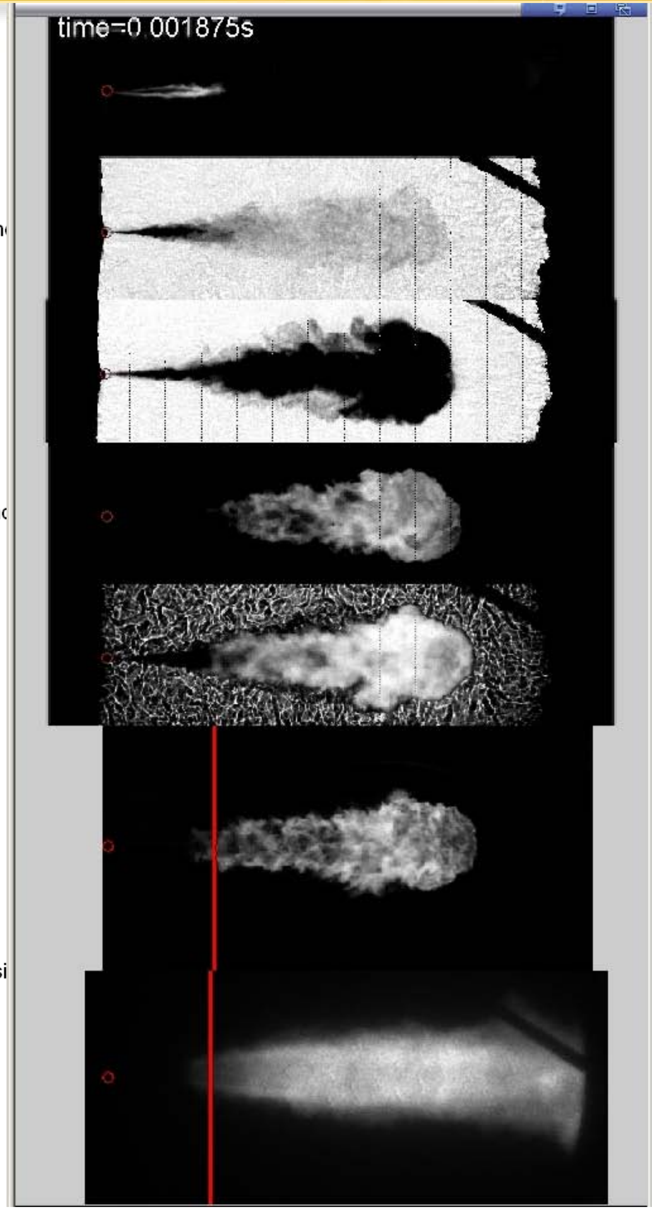


High Temperature Pressure Vessel (HTPV)



- World class injection test facility
- Capable of producing in-cylinder TDC-like conditions (1000 K, 15 MPa, 0-20% O_2 with balance N_2)
- Enables quantitative spatial measurements of
  - Heated sprays
  - Combustion experiments
- <u>Use:</u>
  - Evaluate combustion and fuel injector technologies
  - Validate CFD models with quantitative spatial information
  - Diagnose issues with engine combustion system hardware





MIE light scattering off of liquid drops – Non-Combusting (liquid spray behavior, liq. length)

Light blockage – Non-Combusting (liquid spray behavior, liq. length)

Light blockage –Combusting (liquid spray behavior, flame shape)

Broadband natural luminosity (soot location and amount)

Shadowgraph (spray vapor) + flame luminosity (soot visualization)

Light emission filtered at 430 nm CH* chemiluminescence

Transient flame zone visualization

Time-averaged light emission filtered at 308 nm

OH* chemiluminescence

Lift-off length measurement

C9 Bowl Size

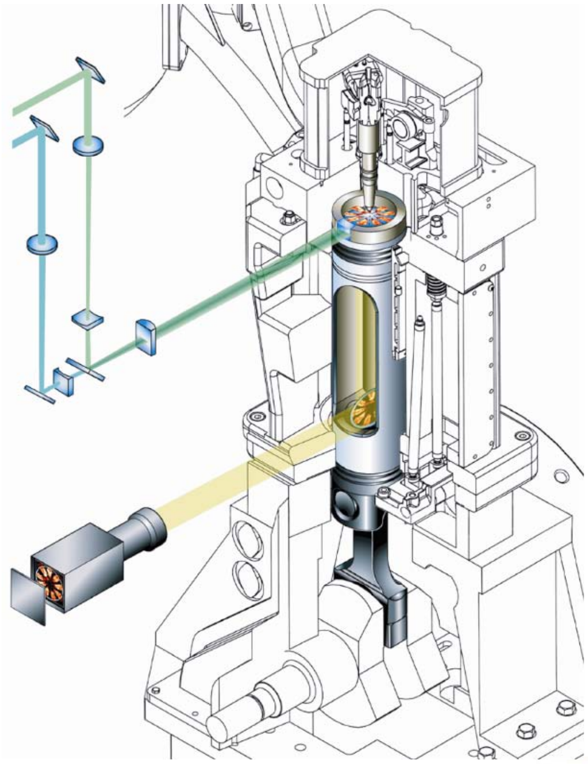
CATERPILLAR

Optical Engine Testing with Sandia National Laboratories

Sandia National Laboratories

Overall Objective: Lifted Flame Combustion

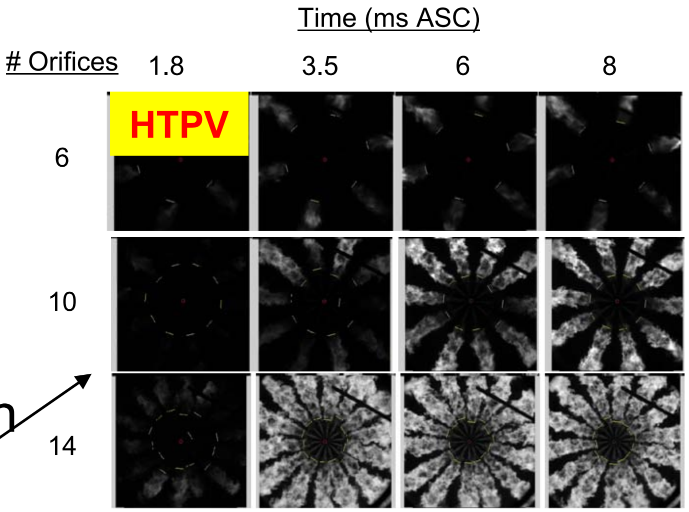
- 2010 Objective:
  - Investigate Plume-to-Plume interactions under engine conditions
- Approach:
  - Sandia Optical engine
  - 2009 update to common rail
- Accomplishments:
  - Transient images for lifted flame combustion taken
  - Show plume-to-plume interaction & gas recirculation

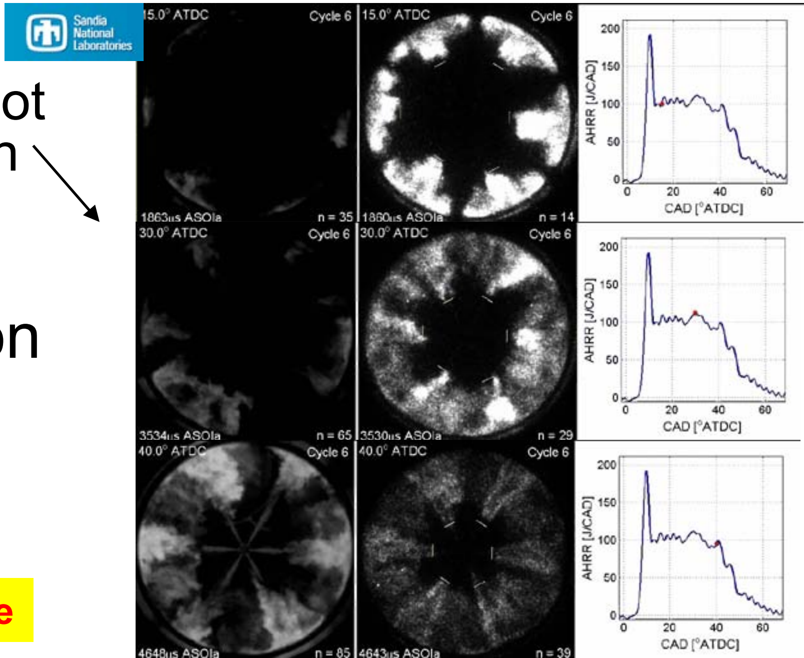


FY 2009

Technical Accomplishments

- Established the operational engine limits of the sootless lifted flame combustion regime
  - Ambient condition limit: refined knowledge of the required transient in-cylinder conditions to achieve liftoff lengths adequate for sootless combustion
  - Flame-flame interaction limit: closely spaced flame cause liftoff length retraction
  - Combustion gas re-entrainment limit: hot combustion gases being re-entrained in the jet causes liftoff length retraction
- Developed and analyzed two-row injector / separated bowl combustion system
  - Positive performance, but did not overcome plume spacing limitations to achieve sootless combustion



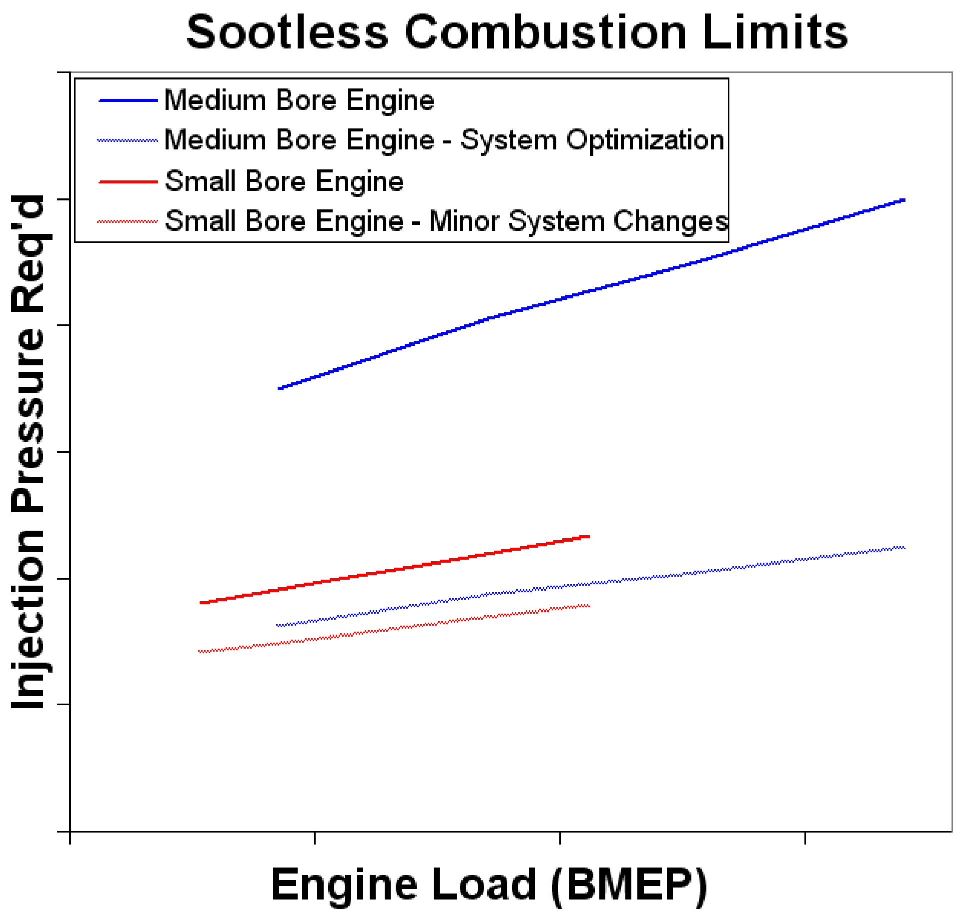


50% load, 1500RPM, 6 hole nozzle

Technical Accomplishments

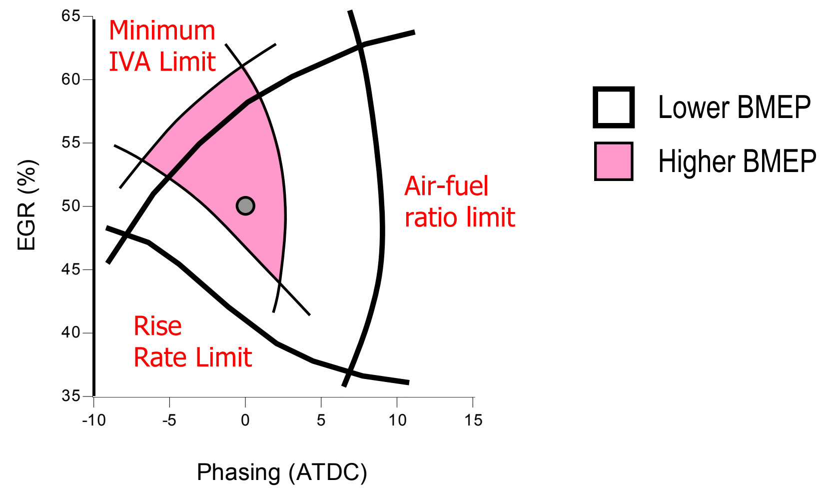
Sootless combustion limits applied to system analysis showed the requirements for achieving sootless combustion

- Identified small bore engines as natural first adopter of this technology
- Small bore engines have a clear advantage because of smaller load range and inherently smaller orifices
- System level changes required for practical medium bore application



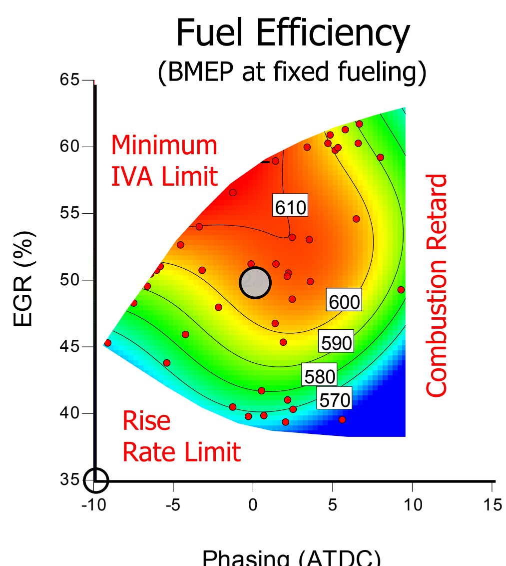
Single-Cylinder Engine Testing

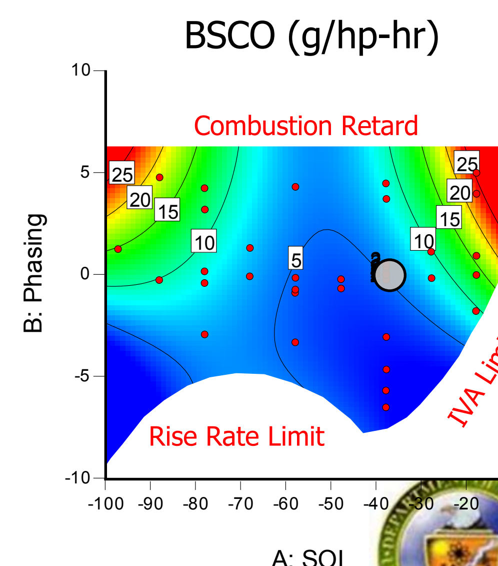
- Objective:
  - Quantify the fundamental relationships between control parameters and engine performance and emissions
  - → Input to 0-d combustion model for engine system simulation and basis for model based control
  - → Define optimal combustion mode for improved thermal efficiency



- Approach:
  - Extensive exploration of key control parameters
  - Generated response surfaces to key control parameters

- Accomplishments:
  - Established the effect of key control parameters on engine operating limits
    - EGR, IVA etc.
  - Demonstrated 4% BSFC improvement @ BMEP < 750kPa

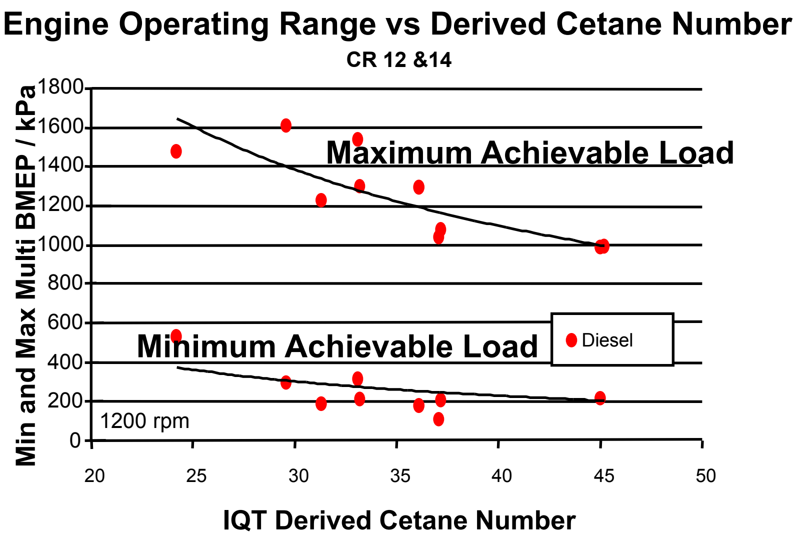


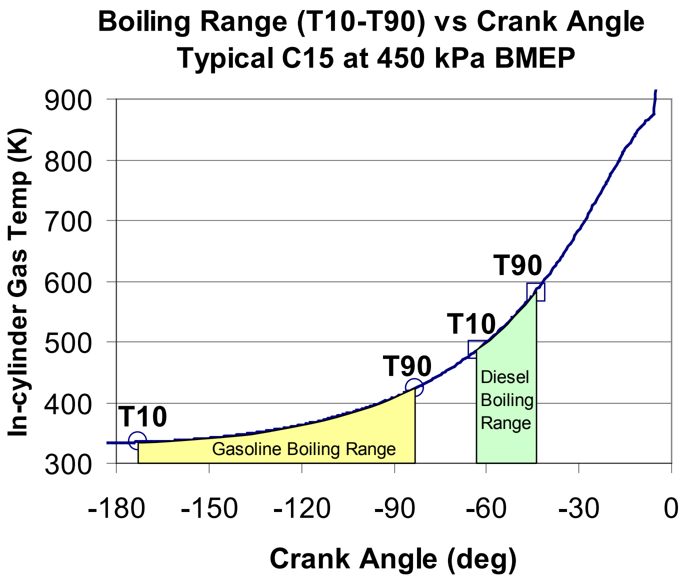


Background work, FY 2007 & Early 2008

PCCI Combustion – Fuel Blending Technologies to Increase HCCI/PCCI Power Density & Load Capability

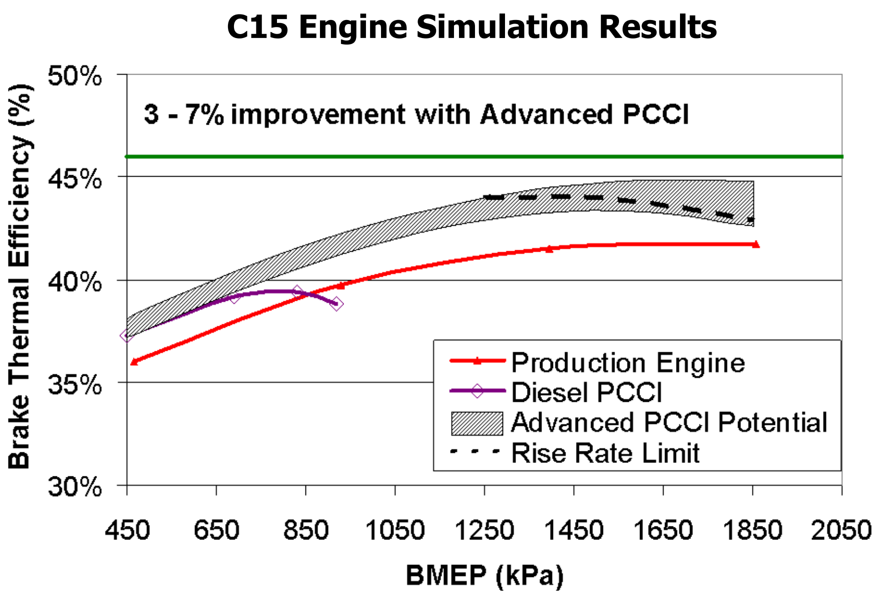
- Fuels
  - Load range is affected by cetane number
  - High volatility fuel increases the injection window (mixing)
  - No commercially available fuel meets all requirements
  - Investigating diesel / gasoline fuel blends





Gasoline / Diesel Fuel Blend Testing

- Objective:
  - Assess ability of ‘modified’ fuel properties to increase load range
  - Improve thermal efficiency by increasing the load range of PCCI combustion
  - Reduce soot emissions in diffusion combustic regime
- Approach:
  - Test multiple gasoline / diesel fuel blends wit a range of derived cetane number on single-cylinder test engine.
  - Characterize impact on combusting spray using optical techniques in high-temperature spray vessel
- Accomplishment:
  - Testing currently in-progress (March – April)
  - Results currently being processed



FY 2009

Approach

- Test multiple gasoline / diesel fuel blends with a range of derived cetane number on single-cylinder test engine.

		Diesel	Diesel + Gasoline	Gasoline
Density at 60°F (g/cm^3)		0.83	0.78	0.75
Derived Cetane number		43.2	25.9	14.9
Vapor pressure at100 °F (psi)		0.1	7.1	9.4
Distillation (°F)	10%	408	142	125
	50%	504	280	217
	90%	595	536	304

Thermal efficiency

$$\eta_{fc} = \frac{W}{m_f Q_{LHV}} = \left(\frac{W}{Q_{chem} - Q_{hl}}\right)\left(\frac{Q_{chem} - Q_{hl}}{Q_{chem}}\right)\left(\frac{Q_{chem}}{m_f Q_{LHV}}\right) \quad (1)$$

$$= \left(\frac{W}{Q_{chem} - Q_{hl}}\right)\left(\frac{Q_{chem} - Q_{hl}}{m_f Q_{LHV}}\right) \quad (2)$$

$$= \eta_{wc}\eta_{hl}\eta_{comb} = \eta_{wc}\eta_{hr} \quad (3)$$

Heat rejection eff. (chemical to thermal)

Work conversion eff. (thermal to mechanical)

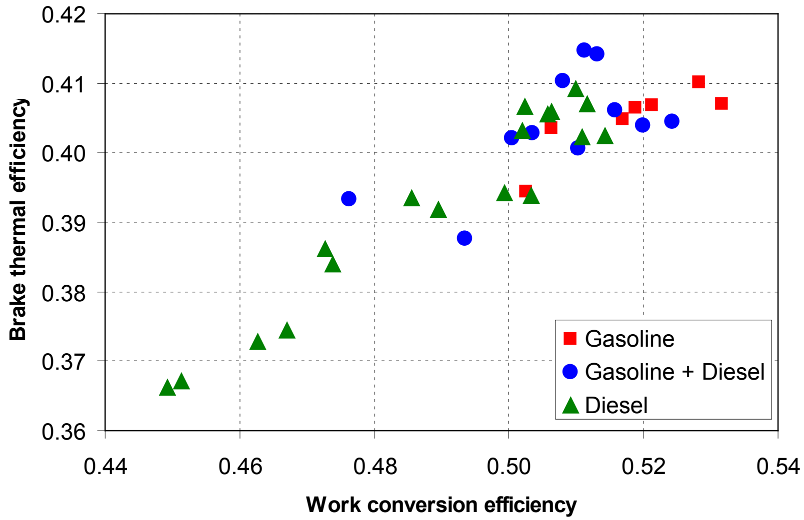
Accomplishment

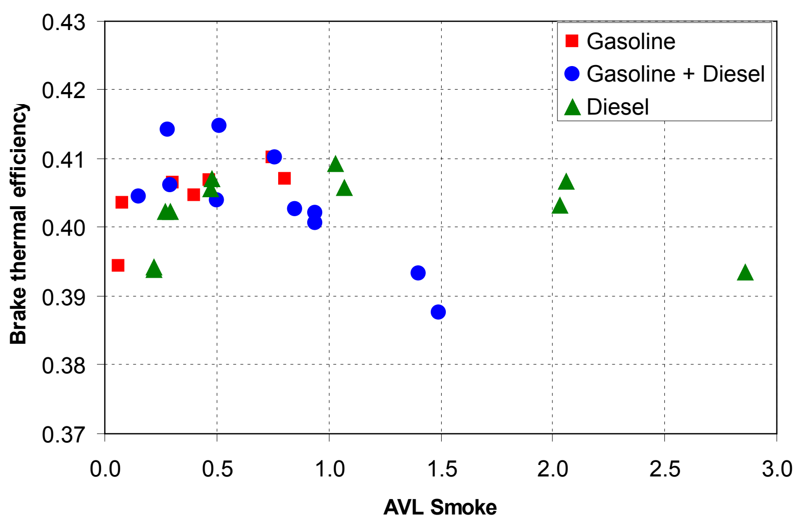
1200rpm 55% load

- Gasoline (or gasoline diesel blend) could lead better work conversion efficiency by achieving fast combustion. However, gasoline blending marginally improved thermal efficiency due to high pressure rise rate and heat transfer loss.

- Gasoline blending achieves better efficiency at lower smoke emission.

- Technology gap; Controlling pressure rise rate (initial reaction) was a barrier limiting thermal efficiency of gasoline blending.





Summary

- Performance - HCCI/PCCI (low temperature combustion) potentially offers increased thermal efficiency with reduced requirements for DPF regeneration. Demonstrated 4% BSFC improvement below 750 kPa BMEP. Low load fuel economy benefit will be application dependent
- Control - Inability to adequately control combustion phasing and liquid fuel impingement limits the load range and thermal efficiency benefit of diesel HCCI/PCCI
- Fuel Chemistry - Fuel blending (gasoline & diesel) is one method to increase load
- Combustion - Lifted flame combustion is a potential low-soot diffusion combustion technology that is compatible with HCCI/PCCI. Demonstrated order of magnitude soot reduction. Plume-to-Plume interaction is a challenge and is being investigated.