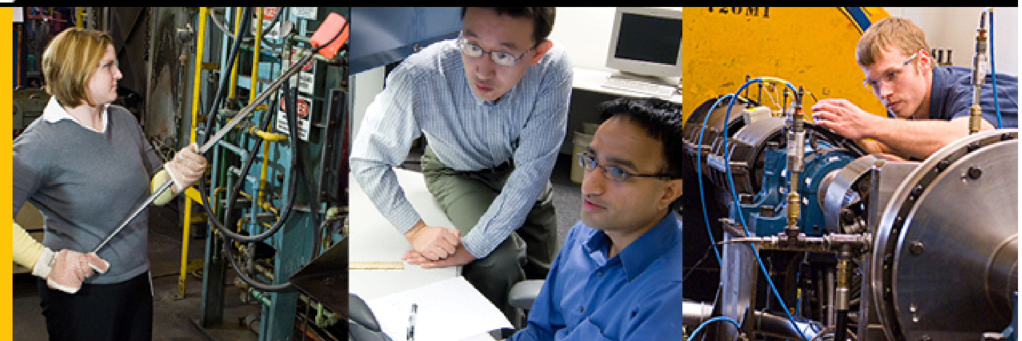


Development of Enabling Technologies for High Efficiency, Low Emissions Homogeneous Charge Compression Ignition (HCCI) Engines

Program Manager: David Milam

Caterpillar ®

DOE Contract DE-FC26-05NT42412

DOE Technology Development Manager: Roland Gravel

NETL Project Manager: Ralph Nine

DOE Merit Review

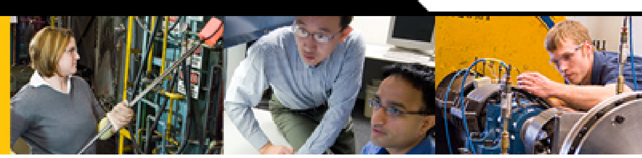
Washington, D.C.

February 26, 2008

This presentation does not contain any proprietary or confidential information

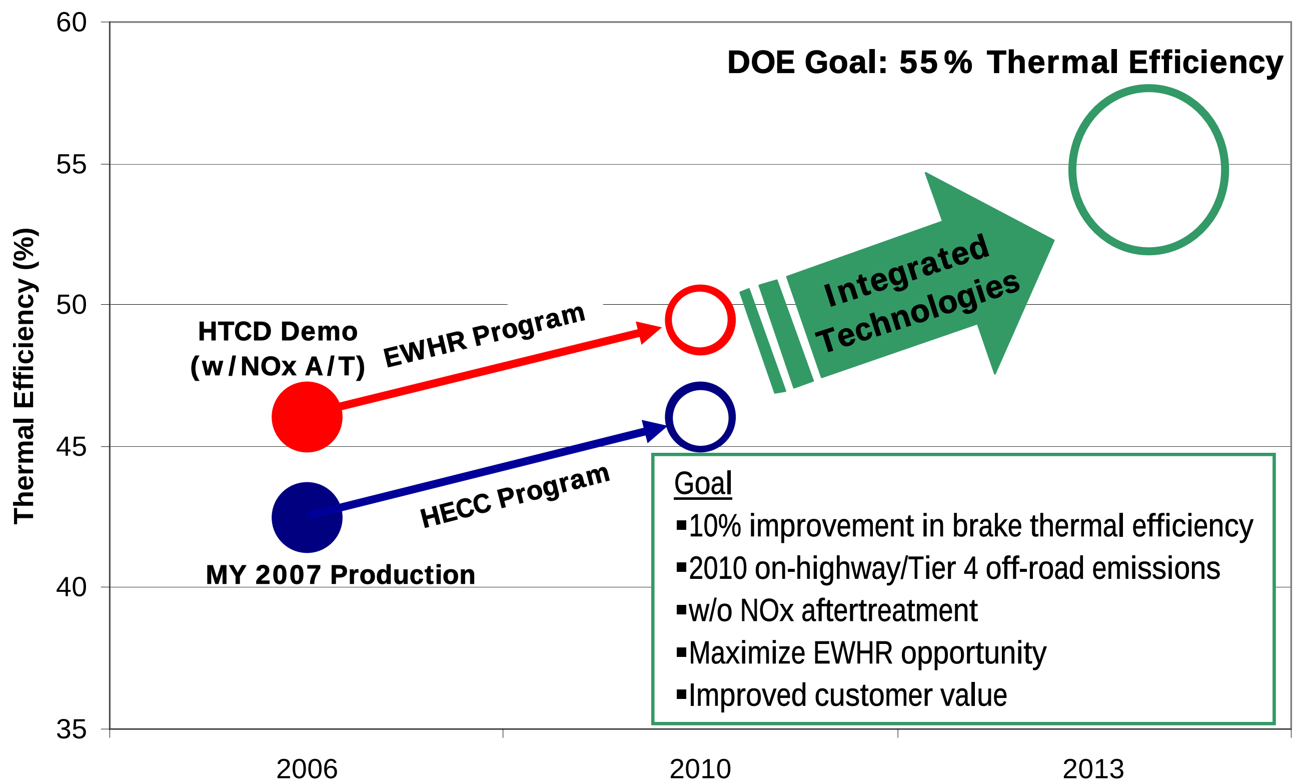
Outline

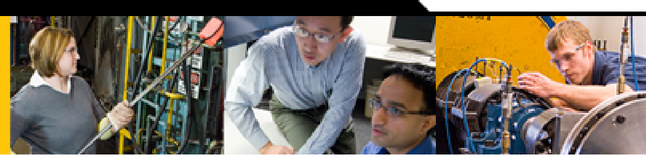
- Purpose of Work
- Previous Reviewer Comments
- Barriers
- Approach
- Performance Measures and Accomplishments
- Technology Transfer / Collaborations
- Publications/Patents
- Plans for Next Fiscal Year
- Summary



Purpose of Work

- Develop technologies to enable a low emissions, high efficiency, production viable, low-temperature combustion engine system





10% Thermal Efficiency Improvement

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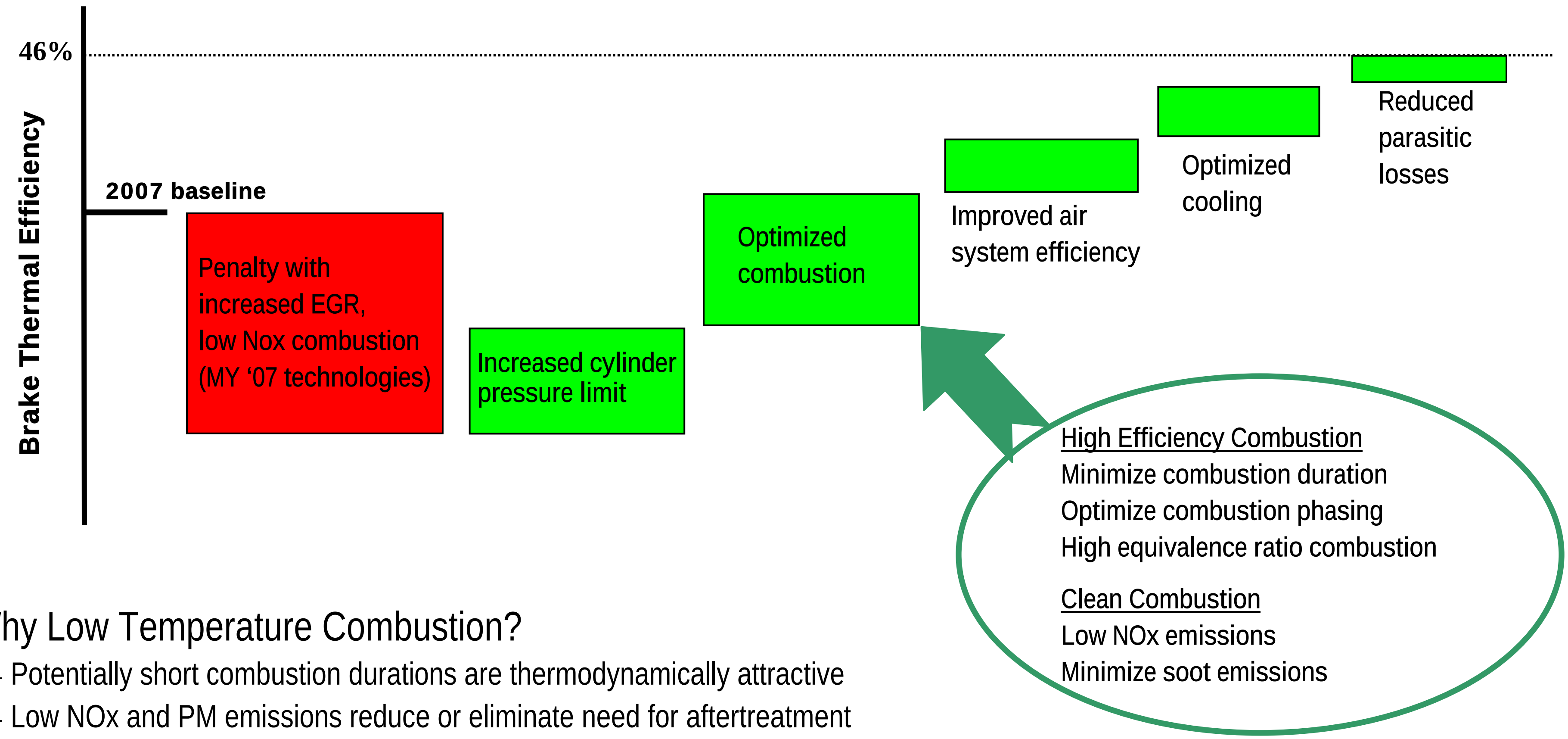
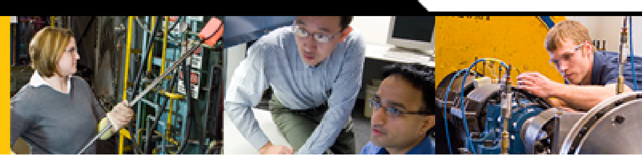


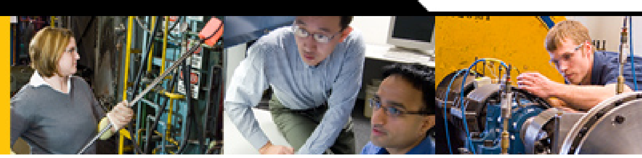
Why Low Temperature Combustion?

- 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



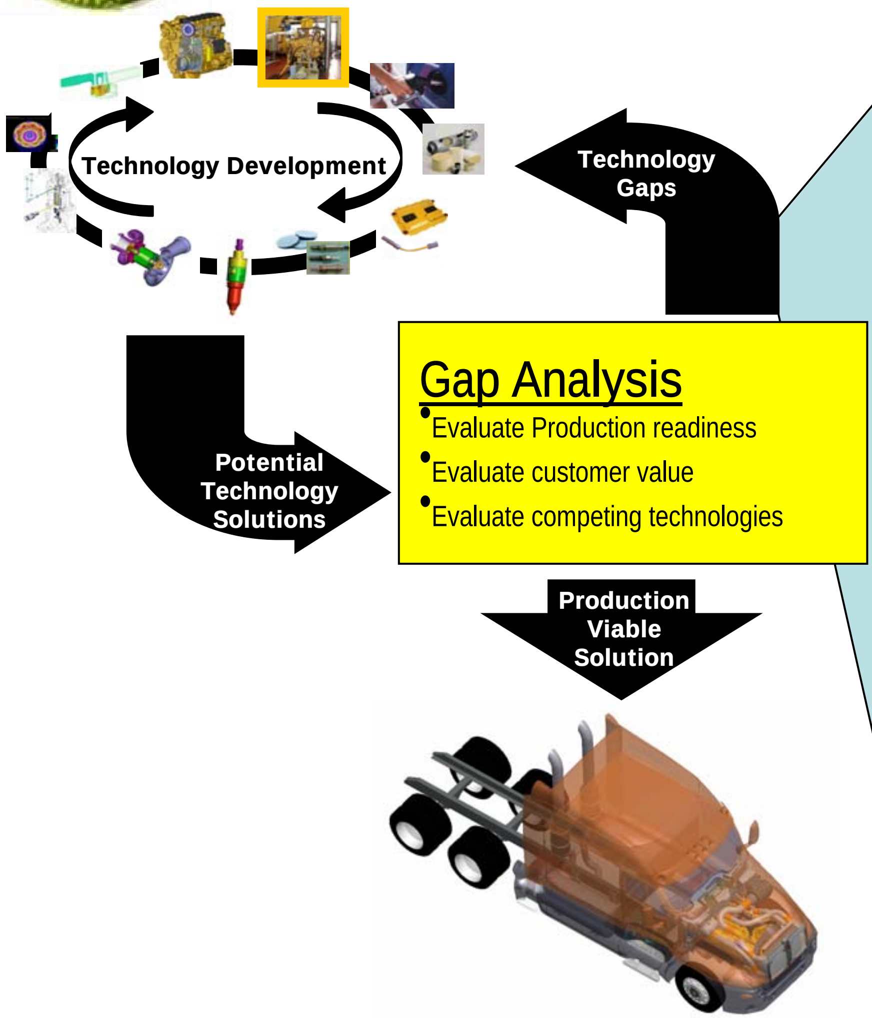
Previous Reviewer Comments

- "… insufficient discussion on meeting thermal efficiency targets."
  - Path to 10% improvement in thermal efficiency was presented earlier in this presentation.
- "… nothing was shown on how simulation is used to help direct investigations."
  - Engine simulation was key to identifying the path to 10% thermal efficiency improvement.

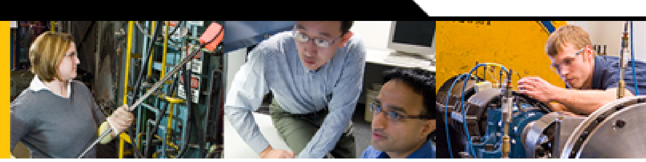


High-Efficiency, Clean Combustion Barriers

T&SD Technology & Solutions Division



- 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



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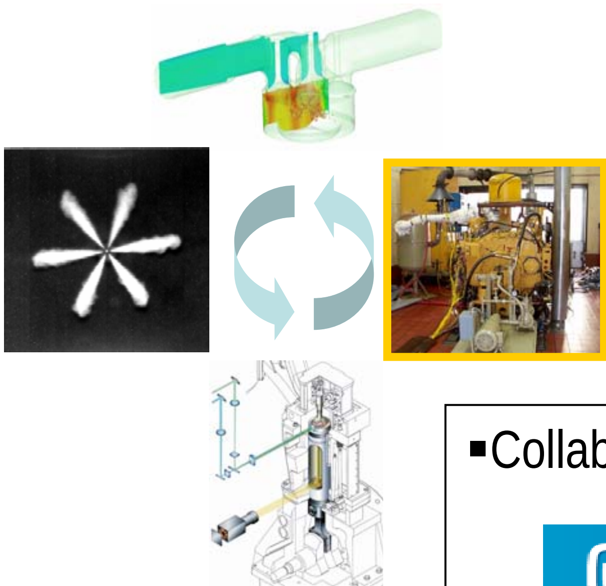
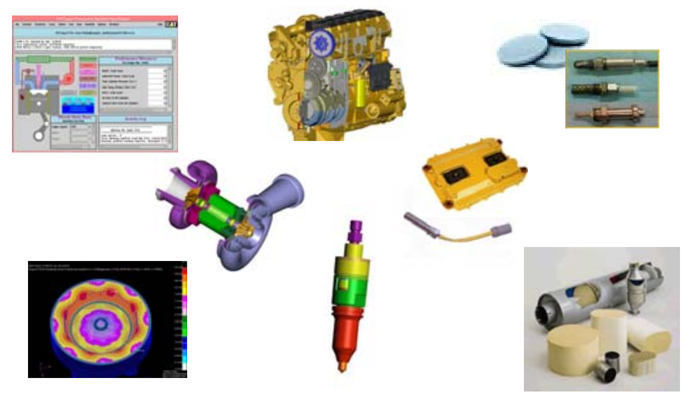
Systems approach to high-efficiency, clean combustion development

T&SD Technology & Solutions Division

- Develop a fundamental understanding of combustion processes



- Develop advanced technologies to enable high thermal efficiency

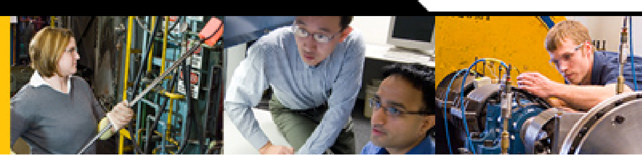


- Collaborate with technology experts

Sandia National Laboratories

ExxonMobil Research and Engineering

IAV Inc. Automotive Engineering



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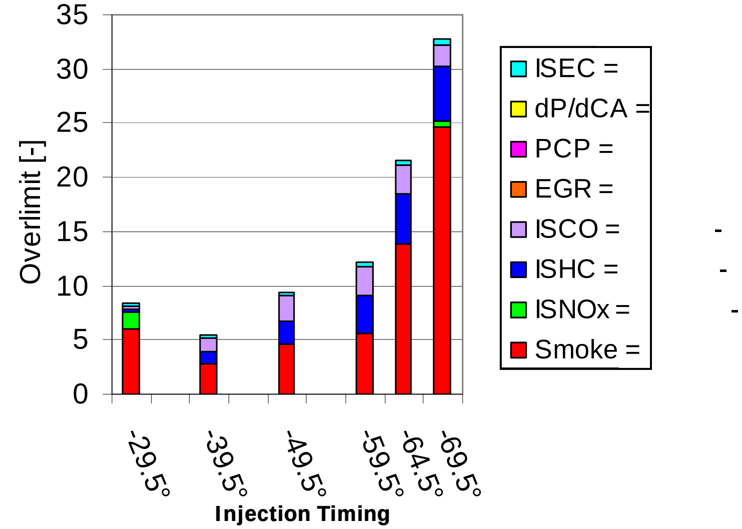
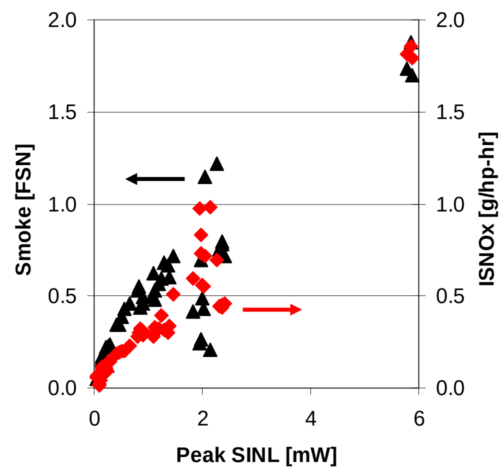
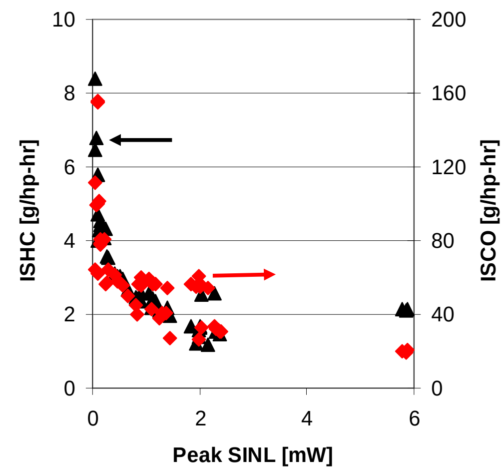
Optical Engine Testing with Sandia National Lab

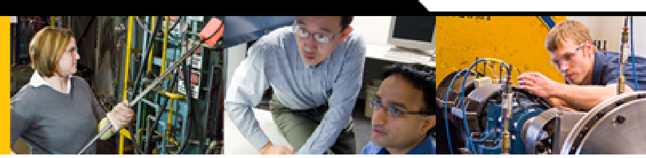
T&SD Technology & Solutions Division

- Objective:
  - Understand emissions and other trade-offs for early, narrow-angle injection strategy
- Approach:
  - Sweeps of 7 parameters: inj. timing, inj. pressure, equivalence ratio, EGR, intake temperature, load, and boost
  - Applied overlimit function to quantify proximity to compliance with emissions & other targets
  - Used spatially integrated natural luminosity (SINL) as measure of radiative heat transfer from combustion chamber
- Accomplishment:
  - Excessive smoke is primary barrier, followed by HC, CO, and NO_x (90% efficient oxidation catalyst assumed)
  - Emissions trends correlate well with peak SINL









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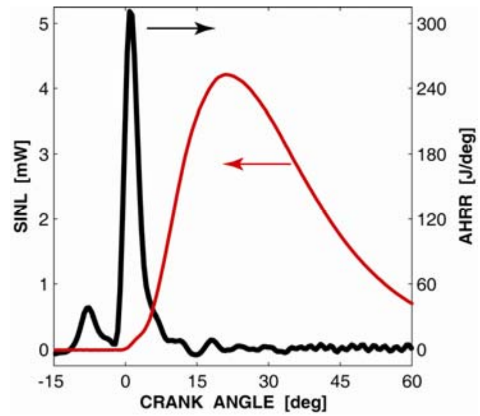
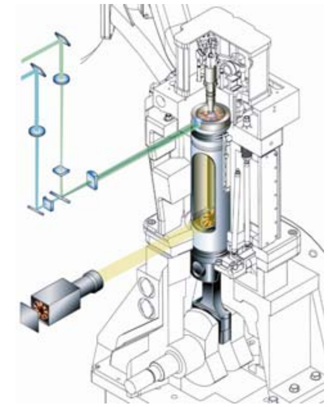
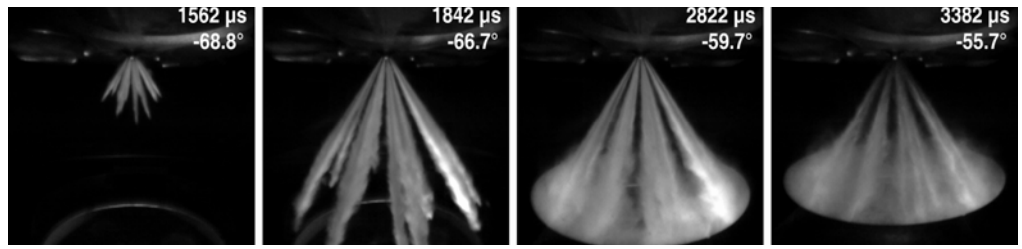
Optical Engine Testing with Sandia National Lab

- Objective:
  - Understand why emissions are well- correlated with peak SINL
- Approach:
  - Combine pressure-based analysis, SINL, spray visualization, and natural luminosity (NL) imaging diagnostics
- Accomplishment:
  - Peak SINL occurs after end of significant heat release
  - Spray visualization movies show liquid fuel impingement in piston bowl
  - NL movies show that pool fires from impinged fuel lead to high peak SINL
  - If pool fires ignite → higher smoke & NO_x from stoichiometric & rich regions
  - If pool fires don't ignite → slowly evaporating fuel film gives higher HC (& CO?)

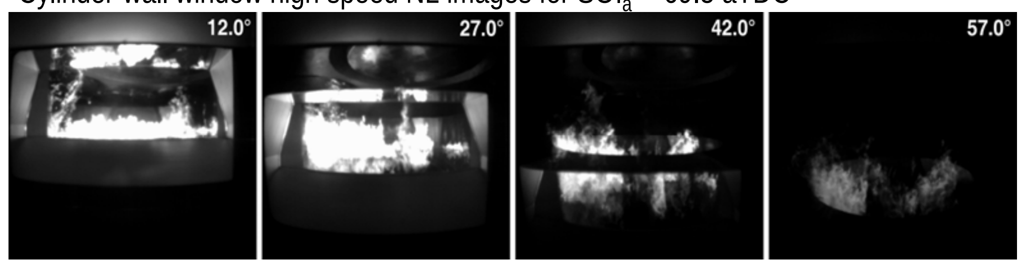




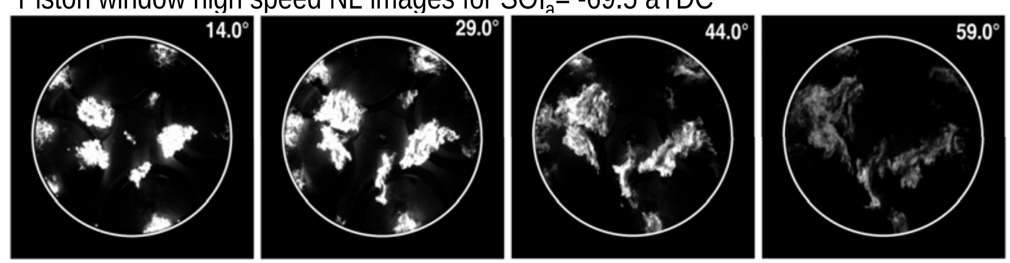
Cylinder-wall window spray visualization images for SOI_a= -69.5 aTDC



Cylinder-wall window high speed NL images for SOI_a= -69.5 aTDC



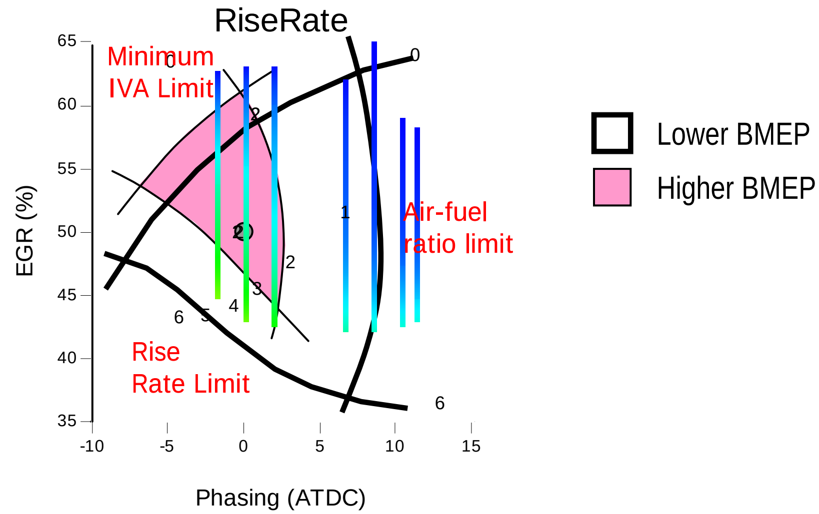
Piston window high speed NL images for SOI_a= -69.5 aTDC



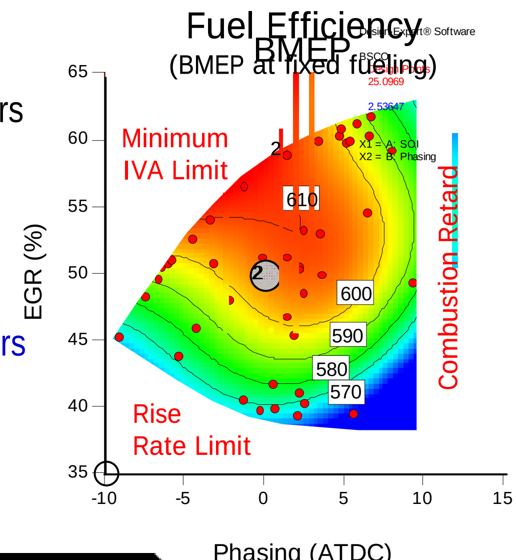
Single-Cylinder Engine Testing

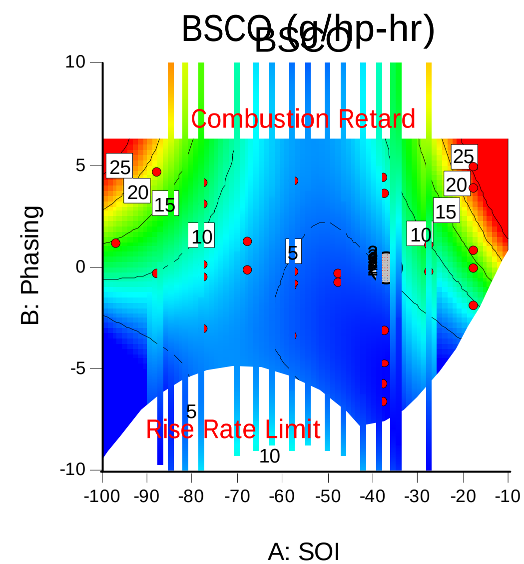
T&SD Technology & Solutions Division

- 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



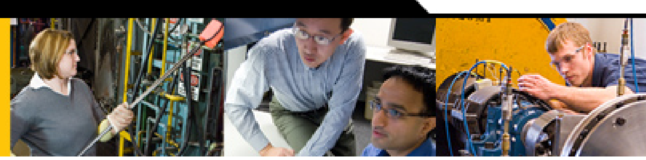
- Approach:
  - Extensive exploration of key control parameters
  - Generated response surfaces to key control parameters
- Accomplishments:
  - Established the effect of key control parameters on engine operating limits





Engine Technologies

Caterpillar Non-Confidential



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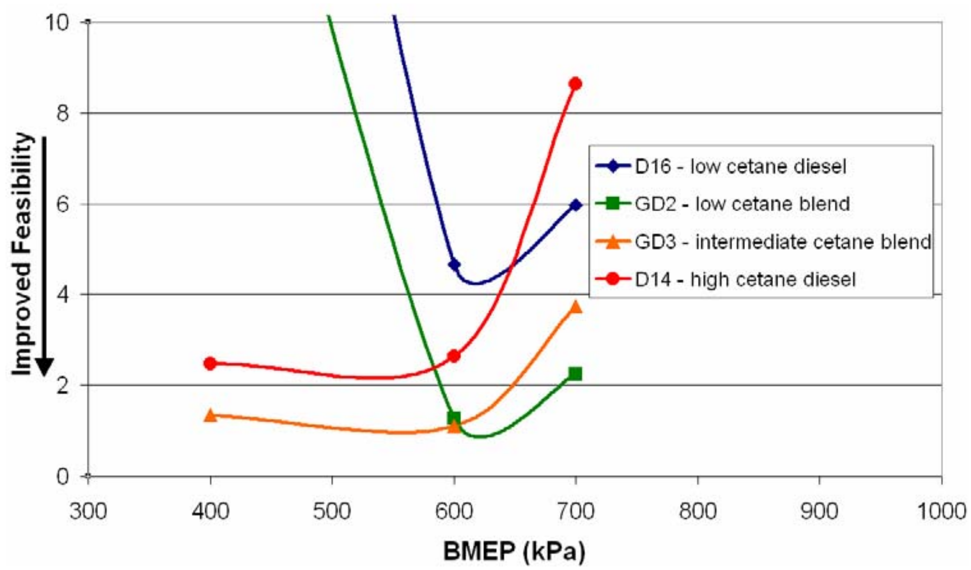
Fuel Property Investigation

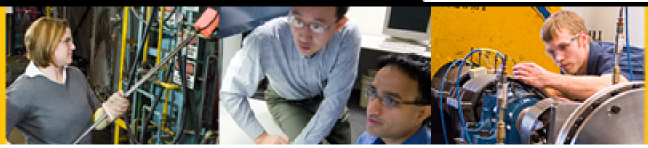
in collaboration with ExxonMobil

T&SD Technology & Solutions Division

- Objective:
  - Tailor fuel properties to engine operating conditions for low temp combustion
  - Establish impact of fuel properties on emissions with low temperature combustion
- Approach:
  - Tested diesel and gasoline/diesel blend fuels with varying derived cetane number
  - Overlimit function used to evaluate fuels
    - Compare combined effect on engine emissions and performance measures
- Accomplishments:
  - Gasoline/diesel blending is a feasible method to vary the ignition characteristics of the fuel
  - Improved engine emissions and performance with gasoline/diesel blends



The Overlimit is a function defined in: Cheng, A.S., Upatnieks, A., Mueller, C.J., “Investigation of Fuel Effects on Dilute, Mixing-Controlled Combustion in an Optical Direct-Injection Diesel Engine,” *Energy & Fuels* 21: 1989-2002 (2007).



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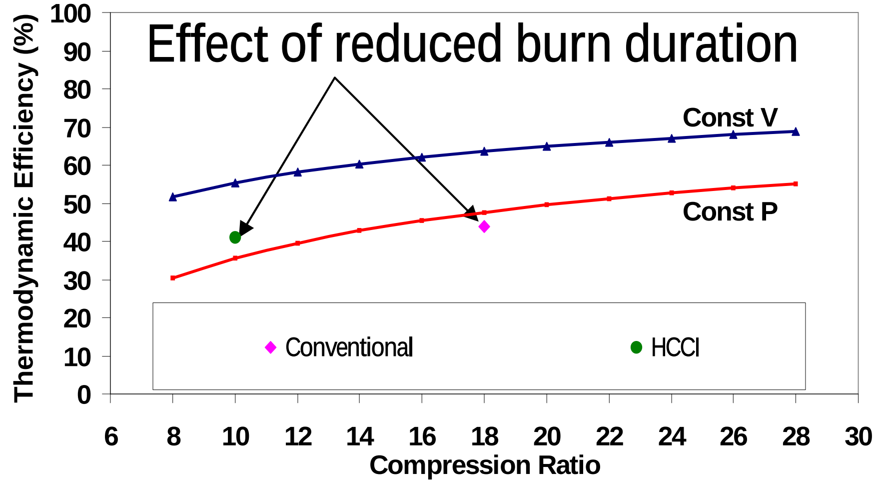
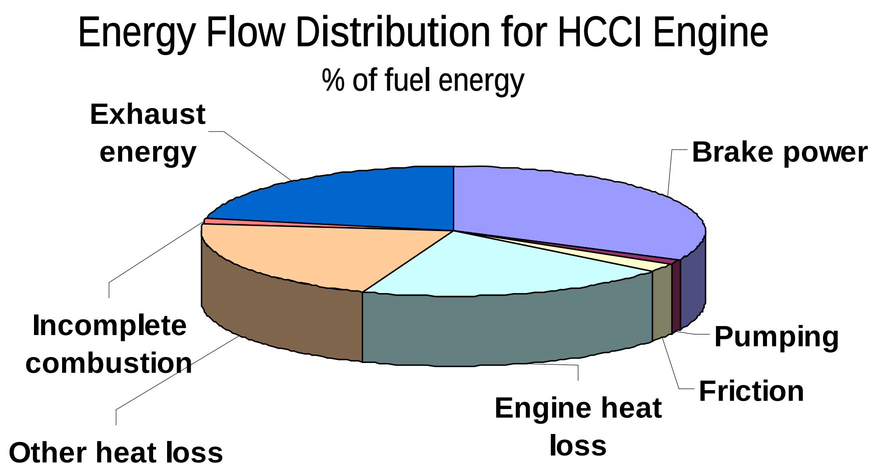
Thermal Efficiency Improvement

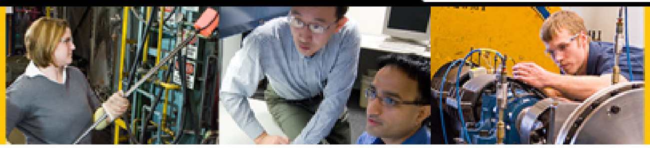
T&SD Technology & Solutions Division

- Objective:
  - Compare energy flow of HCCI engine and 2007 conventional on-highway diesel engine
  - Quantify heat rejection differences between HCCI and conventional combustion
  - Identify opportunities to increase engine thermal efficiency by utilizing low temperature combustion



- Approach:
  - Detailed system wide and individual component wide analysis of energy and availability flow
  - Engine system simulation to evaluate thermal efficiency building blocks
- Accomplishments:
  - Completed energy flow analysis for a multi-cylinder engine running in HCCI mode
  - Identified opportunities for reducing heat losses including in-cylinder heat rejection
  - Identified opportunities for optimally recovering wasted energy





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Collaborations - External

T&SD Technology & Solutions Division

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

University of Wisconsin Engine Research Center

Lund University

AEC MOU

Sandia National Laboratories

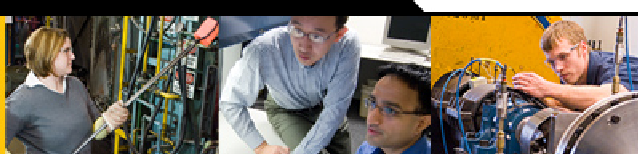
- Optical diagnostics
- Fuel spray and combustion
- Fuels effects

ExxonMobil Research and Engineering

- Fuels effects
- Combustion Chemistry/modeling

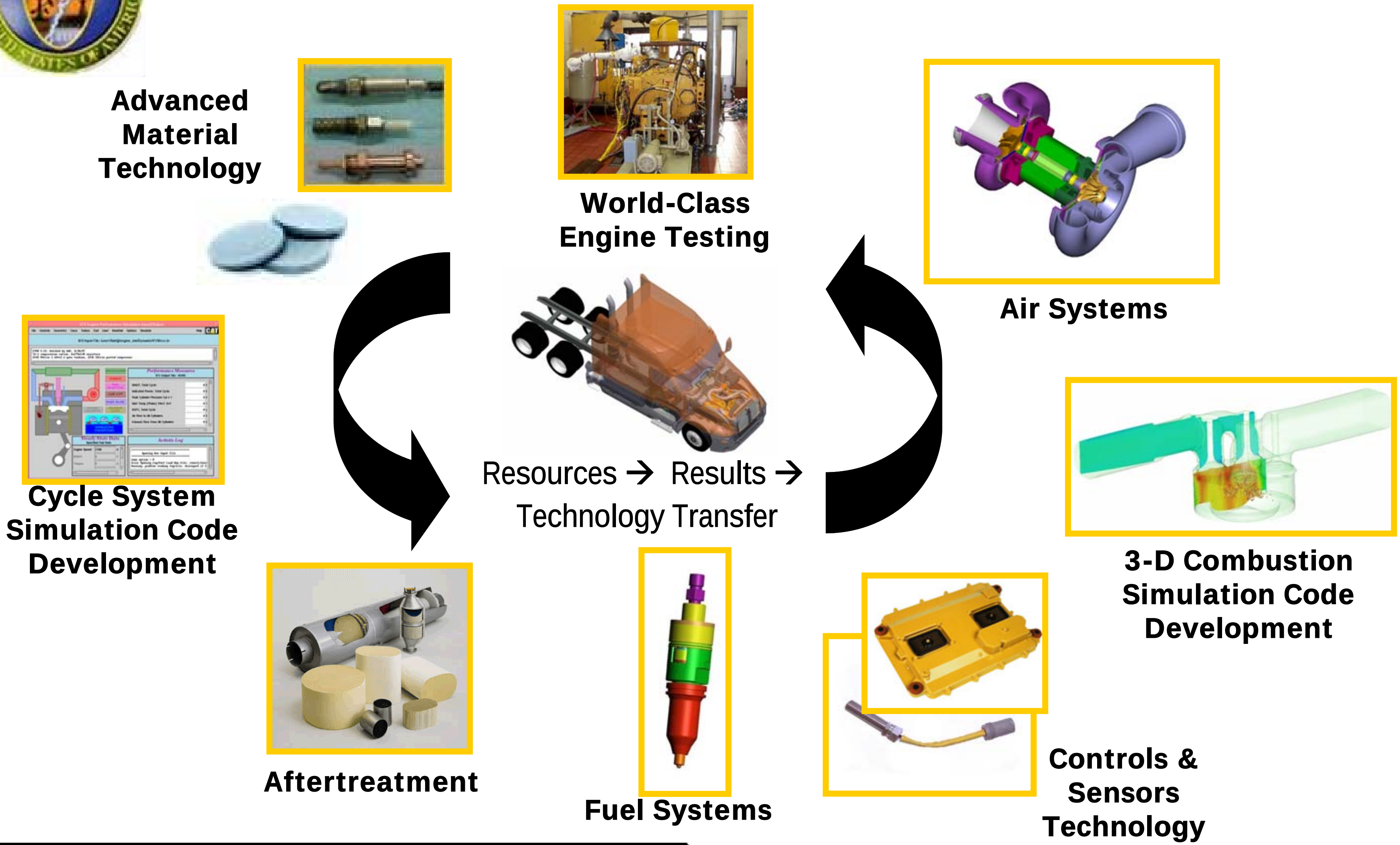
IAV Inc. Automotive Engineering

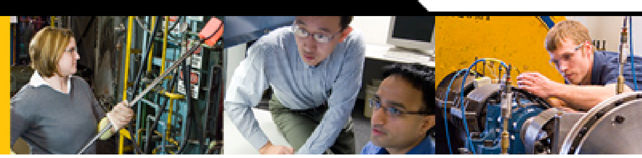
- Closed loop control
- Transient controls
- Vehicle calibration
- Sensors



Collaborations - Internal

T&SD Technology & Solutions Division





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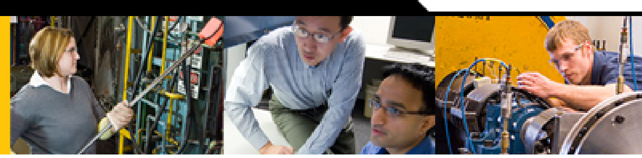
Publications, Presentations, Patents

T&SD Technology & Solutions Division

- 2007 DEER Presentation, “Heavy Duty Low Temperature Combustion Development Activities at Caterpillar”, Chris Gehrke, Michael Radovanovic, Doug Frieden, Eric Schroeder, Parag Mehresh, David Milam, Glen Martin, Charles Mueller and Paul Bessonette

- August 2007 AEC/HCCI Working Group Meeting Presentation, “DOE High Efficiency Clean Combustion”, Glen Martin and Charles Mueller

- Patent Applications
  - 2006- 11/498,001 - “Strategy for extending the HCCI operating range using low cetane number diesel fuel and cylinder deactivation
  - 2006- 11/584,889 - “Mixed high and low pressure EGR in HCCI engine”
  - 2007- 11/657,940 - “Power balancing cylinders in HCCI engine”
  - 2007- 11/699,522 - “Ignition timing control with fast and slow control loops”
  - 2007- 11/699,523 - “Recipe for high load HCCI operation”



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Activities for Next Fiscal Year

Refine strategy to achieve 55% thermal efficiency

- Determine best utilization of HCCI and other low temperature combustion technologies
- Integration of exhaust waste heat recovery technologies

Identify and develop technologies to improve mixture preparation

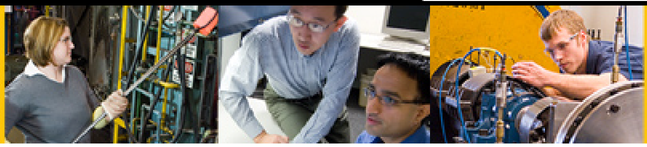
- Investigate injection strategy, spray characteristics and fuel property effects on mixture preparation and combustion
- Investigate air motion and stratification impact on mixture preparation and combustion

Increase load range and thermal efficiency

- Investigation of diesel/gasoline fuel blending as a means to increase load range and thermal efficiency of HCCI
- Investigate other low temperature combustion regimes for high BMEP operation

Identify and develop technologies to reduce heat losses

- Investigate concepts to reduce in-cylinder heat transfer
- Evaluate concepts to reduce/recover heat from EGR system



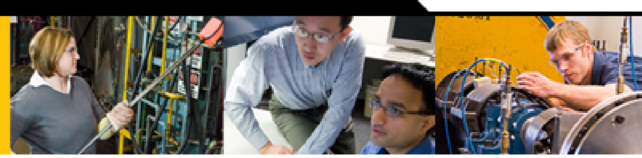
Summary

- Focused on achieving 10% improvement in thermal efficiency without NOx aftertreatment to meet 2010 on-highway / Tier 4 off-road emissions standards

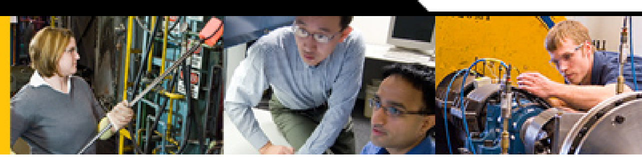
- Combine understanding of low temperature combustion fundamentals with development of enabling technologies to deliver a production viable, high-efficiency, clean combustion engine.

- Technical Accomplishments
  - Identified liquid fuel impingement as a significant factor in engine emissions
  - Established relationship between key control parameters and engine operating limits
  - Gasoline/diesel blending is a feasible method to vary the ignition characteristics of the fuel
  - Completed energy audit of HCCI engine and compare to conventional diesel engine
  - Completed design changes to variable compression ratio engine to reduce parasitic losses

- Collaborations key to success
  - Sandia providing key insight into combustion through optical engine explorations
  - ExxonMobil collaboration leading to improved understanding of fuel property effects on HCCI combustion
  - IAV collaboration providing advanced transient controls insight



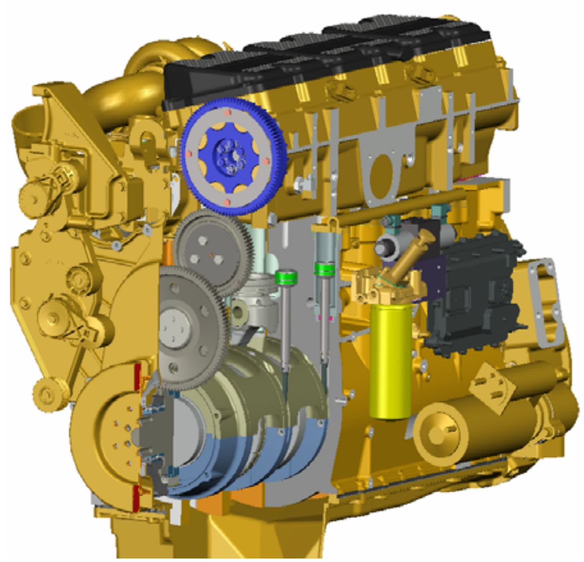
Back-up Slides



Thermal Efficiency Improvement (cont.)

T&SD Technology & Solutions Division

- Objective:
  - Establish thermal efficiency benefit of a variable compression ratio (VCR) engine using diffusion combustion
  - Reduce parasitic losses associated with VCR engine
- Approach:
  - Compared performance of to production C15 to quantify parasitic losses
  - Conducted teardown inspection of engine
- Accomplishments:
  - Identified root causes of increased parasitic losses associated with VCR mechanism
  - Identified design changes to reduce parasitic losses by 5%



VCR - US Patent Application 2006/0112911