# Fuel Effects on Advanced Combustion Engines

**Charles J. Mueller**
*Combustion Research Facility*
*Sandia National Laboratories*

**Research Supported by**
**US DOE Office of Vehicle Technologies**
**Program Manager: Kevin Stork**

*FY 2008 DOE Vehicle Technologies Program Annual Merit Review Meeting*
*Bethesda North Marriott Hotel, Bethesda, MD*
*Wednesday, Feb. 27, 2008 (Salon G, 9:20 a.m.)*

*Note: this presentation does not contain any proprietary or confidential information*

# Outline

- Purpose of work
- Previous review comments addressed
- Technical barriers
- Approach to overcoming technical barriers
- Performance measures and accomplishments
- Technology transfer
- Publications and presentations
- Plans for FY 2009
- Summary

# *Purpose of Work: Develop the Engine-Combustion Science-Base Required for Maximum Petroleum Displacement*

- **Facilitate use of domestic, non-petroleum-based diesel fuels → >0.02 Mbpd**
  - Investigate the magnitude and origin(s) of the biodiesel $NO_x$ increase when operating under conventional and advanced combustion modes
- **Develop advanced combustion strategies to enable high-efficiency, clean-combustion (HECC) engines → 0.4 to ~3 Mbpd**
  - Overcome barriers to achieving early-direct-injection HECC
- **Establish fundamental understanding of fuel effects necessary for computational optimization of HECC engines**
  - Assist in efforts to provide reference and surrogate fuels for the diesel-engine research community

***Potential to reduce petroleum consumption by millions of barrels per day***

# *Responses to Recommendations from FY07 Review*

- **"This work is one of the most outstanding DOE funded efforts and should be maintained or expanded to enable advanced combustion… for heavy-duty engines."**
- **All noted weaknesses addressed:**
  - "Intake oxygen mole fractions of 8% aren't realistic."
    - Used 16.5% $O_2$ for biodiesel work, 15.0% for early-DI HECC study
  - "Not sure how much value was gained from testing fuels such as TPGME/water blends."
    - TPGME/water blend study has been completed and published
  - "Citation of external interactions was not supported in the described tasks."
    - Recent research results are shared with all members of Advanced Engine Combustion (AEC) Working Group at meetings twice a year
  - "Need more focus on testing of fuels that have a reasonable chance of being available in the marketplace."
    - Increasing responsibilities in Fuels for Advanced Combustion Engines (FACE) Working Group

# *Technical Barriers* and Relationship to FY08 Activities*

- **"Lesser-known combustion and emission-formation characteristics of non-petroleum-based fuels" and "efficiency typically reduced by measures to reduce $NO_x$ emissions"**
  - Biodiesel $NO_x$ research
- **"Apparent lack of cost-effective and innovative advanced engine concepts"**
  - Early-direct-injection HECC experiments, hardware upgrades
- **"Need better understanding of composition range of fuels and impacts on advanced combustion regimes"**
  - Development of FACE reference fuels
- **"Lack of adequate combustion understanding and simulation capability, especially for new combustion regimes"**
  - Development of surrogate fuels



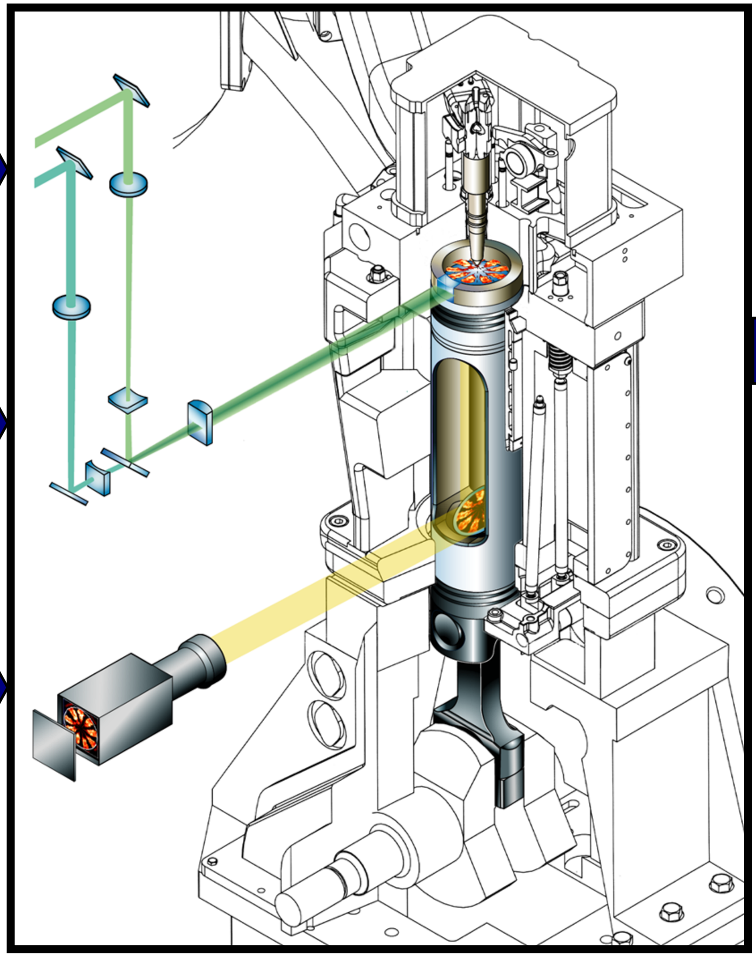
** From 21st-Century Truck Program Technical White Paper, Dec. 2006.*

# Approach: Understand Fuel Effects on In-Cylinder Processes Using Optical Engine and Advanced Diagnostics

**Modern Engine Hardware**

**Advanced Fuels**

**Guidance from Industry, Academia, Nat'l Labs**



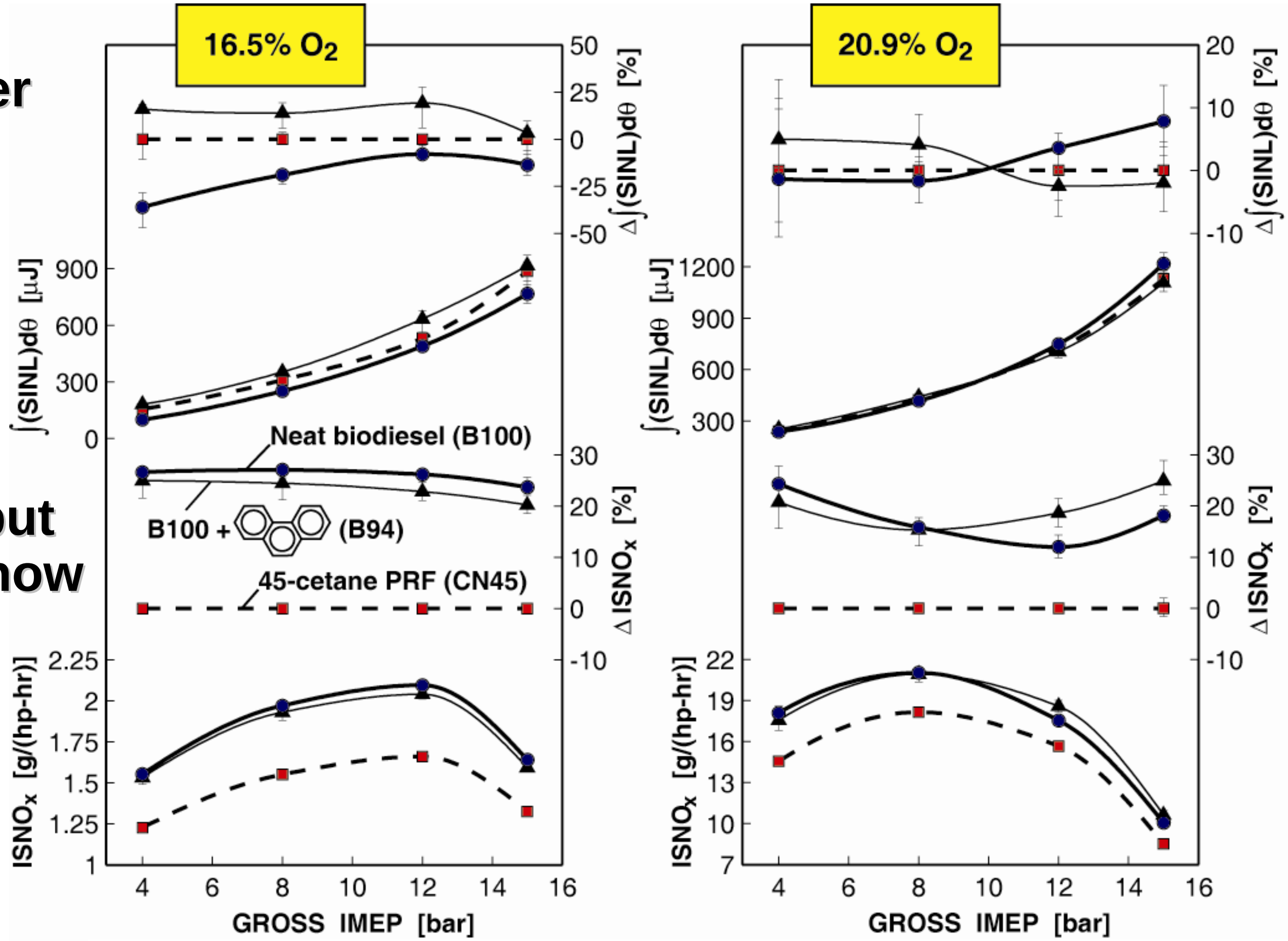
**Science-Base to Enable HECC Engines**

# *Performance Measures*

1. **Investigate $NO_x$ increase when fueling with biodiesel**
   - Magnitude of $NO_x$ increase in conventional and HECC operating modes
   - Effects of radiative heat transfer on $NO_x$ emissions
   - Insight into origins of biodiesel $NO_x$ increase (relevant for all fuels)
2. **Identify limiting processes in early-direct-injection HECC operation with diesel-boiling-range fuels**
   - Origin of increased smoke and $NO_x$ when injection timing is advanced
3. **Assist with design of reference and surrogate fuels**
   - To establish an intelligent foundation for fuel-effects studies in advanced combustion regimes (experimental and computational)
4. **Upgrade engine peak cylinder pressure capability by 50% (from 8.0 to 12.0 MPa)**
   - Complete fabrication of upgraded spacer ring and cylinder liner

# Accomplishment #1: Quantified Magnitude of Biodiesel $NO_x$ Increase under HECC Mode & Showed Role of Radiative Heat Transfer

- Biodiesel $NO_x$ increase is larger in HECC mode
- Changes in radiative heat transfer correlate with $NO_x$ changes for B100 and B94, but CN45 doesn't show same trend
- Radiative heat transfer effects important (but not only) factor

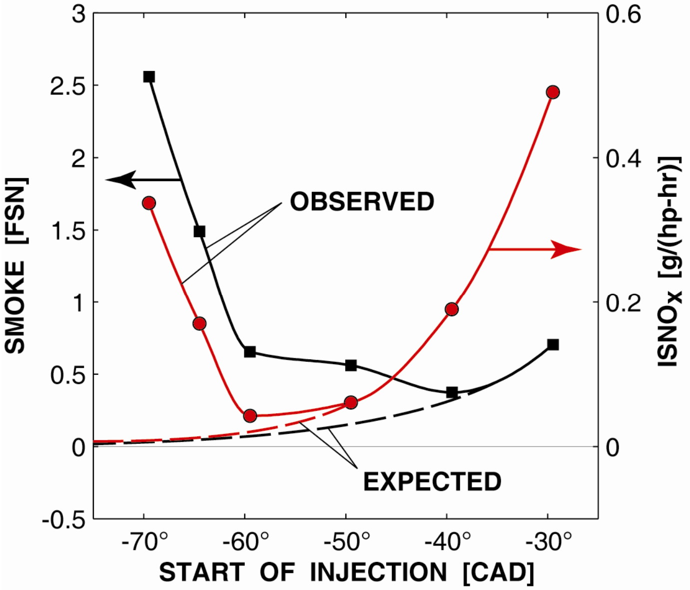



*SINL = spatially integrated natural luminosity (crank-angle resolved measure of radiative heat transfer)*

Sandia National Laboratories

# *Accomplishment #2: Determined Cause of High Smoke and $NO_x$ in Early-DI HECC Strategies with Diesel Fuel*

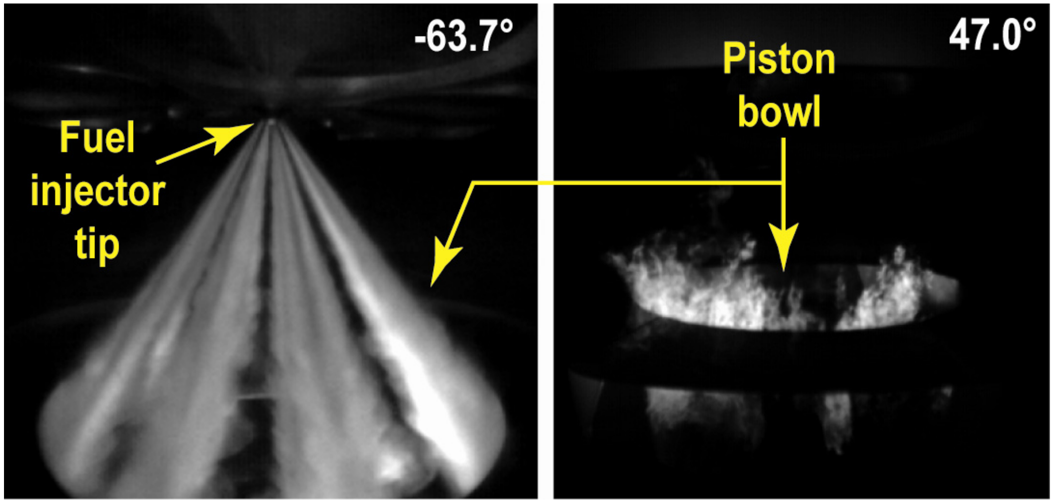
- **Pool fires = burning films of liquid fuel**
  - Emissions correlate with high SINL
  - High SINL occurs after AHRR ends
  - Origin of high SINL is pool fires
- **$\phi \geq 1$ pool-fire combustion produces soot and $NO_x$**
- **Increasing volatility of fuel could help avoid pool fires**




***15-hole, dual-included-angle nozzle: 5 x 35° plus 10 x 70°, all orifices 105-$\mu$m diam.***

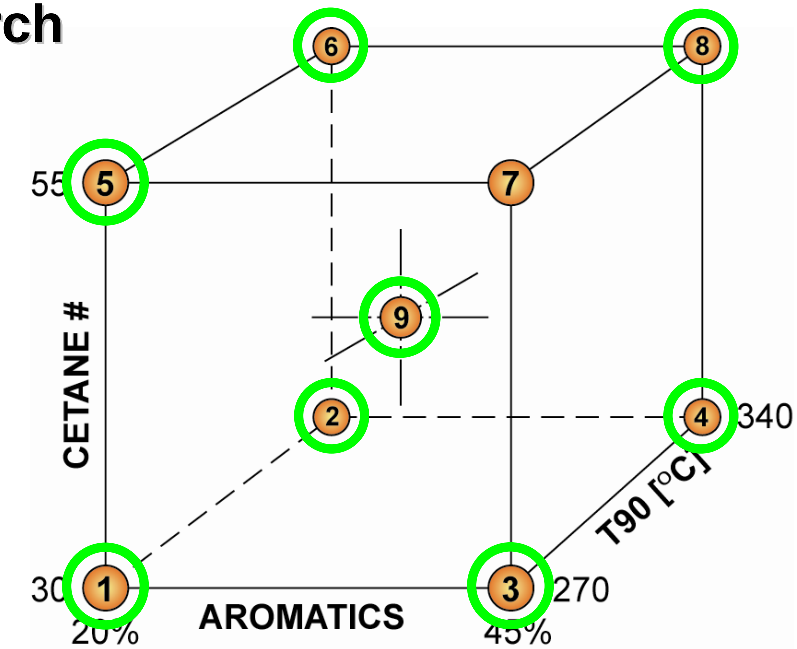
***1450 bar peak inj. pressure***
***Start of injection = -69.5°***

***1200 rpm***
***15.0% $O_2$ (50% EGR)***
***4.82 bar gross IMEP***
***$\phi$ = 0.39***



# Accomplishment #3: Continuing to Assist Researchers Studying Fuel Effects on HECC Operating Modes

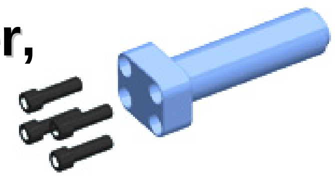
- **Developing common, publicly available, well-characterized reference fuels for experimental and computational studies**
- **FACE fuels for experimental research**
  - Reference fuels blended from actual refinery streams
  - 8 of 9 fuels have been produced, all will be available soon

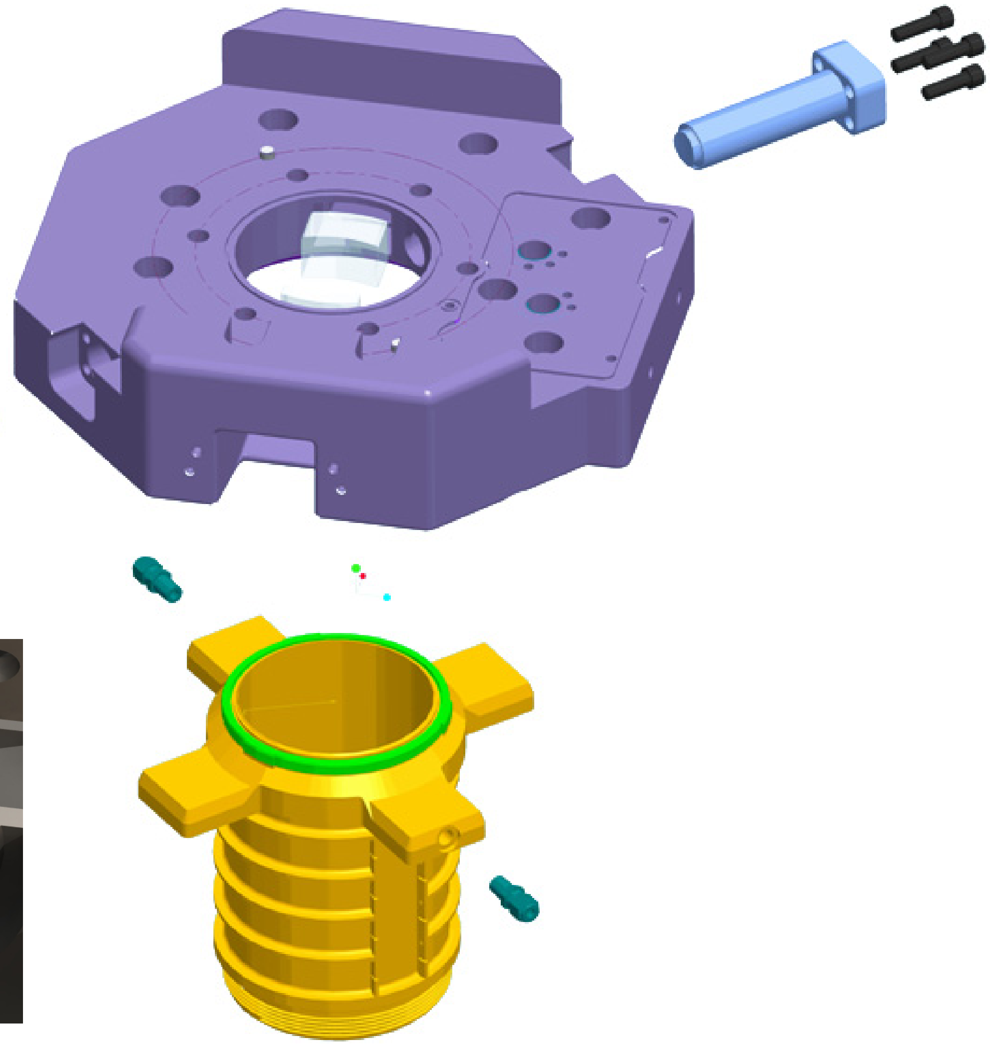


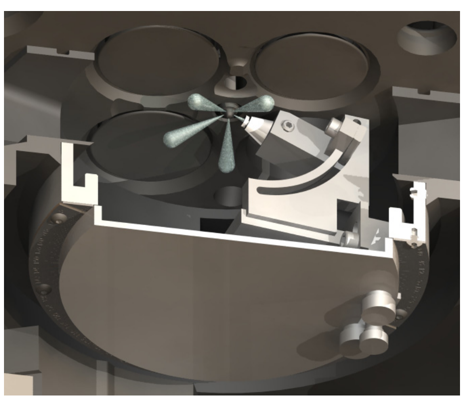

- **Surrogate fuels for computational engine design and optimization**
  - I am team leader of FACE chemical-kinetics activity, also active member of Diesel Surrogates Working Group
  - Create/evaluate diesel surrogates
  - Active teaming with experts in kinetic modeling (W. Pitz *et al*. at LLNL)

# Accomplishment #4: Increased Peak Cylinder Pressure Capability of the Optical Engine by 50% (from 8.0 to 12.0 MPa)

- 20-MPa-capable upgrades to spacer ring and cylinder liner are complete
- New custom hydraulics for liner-support system fabricated
- Also: in-cylinder, orifice-specific injection rate meter completed and tested







Sandia National Laboratories

# *Collaborations and Tech Transfer (1 of 2)*

- **Advanced Engine Combustion (AEC) Working Group:**
  - OEMs: *Caterpillar, Cummins, DaimlerChrysler, Deere, Detroit Diesel, Ford, General Electric, General Motors, International, Mack/Volvo*
  - Energy Companies: *British Petroleum, Chevron, ConocoPhillips, ExxonMobil, Shell Global Solutions*
  - National Laboratories: *Lawrence Livermore, Oak Ridge, Argonne, Los Alamos, National Renewable Energy Laboratory*
- **Fuels for Advanced Combustion Engines (FACE) Working Group:**
  - Labs: *Battelle, Coordinating Research Council, LLNL, National Centre for Upgrading Technology (Canada), NREL, ORNL, PNNL*
  - Energy/petrochemical companies: *British Petroleum, Chevron, Conoco Phillips, ExxonMobil, Marathon-Ashland*
  - Engine OEMs: *Cummins, Ford, General Motors, International*
  - Academia: *West Virginia University*

# *Collaborations and Tech Transfer (2 of 2)*

- **Diesel Surrogates Working Group:**
  - *US Dept. of Defense, Caterpillar, Drexel University, ExxonMobil, NIST, Princeton University, Stanford University*
- **DOE HECC Research:**
  - David Milam and Michael Radovanovic, *Caterpillar*
  - Chris Wright, *ExxonMobil*
  - Not part of DOE Fuels R&D Program but collaboration adds value
- **Biodiesel Combustion and Emissions:**
  - Prof. André Boehman, *Pennsylvania State University*
  - Prof. A.S. (Ed) Cheng, *San Francisco State University*
  - Bill Pitz, *Lawrence Livermore National Laboratory*

# Publications and Presentations Since Last Merit Review Meeting

- Mueller, C.J. and Upatnieks, A., "Operational Characteristics of Oxygenate-Water Fuel Blends Studied in an Optical DI Diesel Engine with Simulated Exhaust Gas Recirculation," SAE Technical Paper 2007-01-2017.
- Cheng, A.S., Upatnieks, A., and Mueller, C.J., "Investigation of Fuel Effects on Dilute, Mixing-Controlled Combustion in an Optical Direct-Injection Diesel Engine," *Energy and Fuels*, **21:**1989-2002, 2007.
- Mueller, C.J., "Optical-Engine Investigations of High-Efficiency, Clean-Combustion Strategies Using Advanced Liquid Fuels," *Proc. of DOE Fuels Technologies Program Review*, DOE Office of FreedomCAR and Vehicle Technologies Annual Report, 2007.
- Mueller, C.J., Martin, G.C., and Boehman, A.L., "On the Origins of the Biodiesel $NO_x$ Increase," manuscript in preparation, 2008.
- Martin, G.C., Mueller, C.J., Milam, D.M., Radovanovic, M.S., and Gehrke, C.R., "Early-Direct-Injection, Low-Temperature Diesel Combustion Utilizing a 15-Hole, Dual-Row, Narrow-Included-Angle Nozzle," submitted to SAE Fall Powertrain and Fluid Systems Meeting, 2008.
- Kempenaar, J.G., Mueller, C.J., Shollenberger, K.A., and Lakshminarasimhan, K., "In-Situ Injection-Rate Measurement of a Multi-Orifice Nozzle," ASME Paper FEDSM2008-55047, submitted to ASME Fluids Engineering Conference, Jacksonville, Florida, August 10-14, 2008.

***11 presentations (including 3 invited plenary) since last review***

# *FY09 Research Directions*

- **Study effects of fuel volatility on transient liquid-phase fuel penetration for time-varying in-cylinder conditions and injection rate**
  - Single-component fuel
- **Investigate fuel-volatility effects on early-direct-injection HECC**
  - Are pool fires still limiting factor for efficiency and emissions compliance?
- **Explore mixing-controlled HECC using diesel fuel and < 40% EGR**
  - Small (< ∅110-μm) orifices are essential
- **Engine hardware upgrades**
  - Finish design and fabrication of 20-MPa-capable optical piston, connecting rod, and balancing masses
  - Work with Caterpillar to design 20-MPa-capable, variable-swirl cylinder head with new common-rail fuel system
- **Continue active collaborations**
  - AEC, FACE, and Diesel Surrogates Working Groups; also DOE HECC activities

# *Summary*

- **Project demonstrates a solid, proven approach to overcoming key technical barriers to achieving HECC → significant petroleum displacement**
  - Optical engine + advanced diagnostics + engine-out emissions meas'mts
  - Fundamental understanding of fuel effects on in-cylinder processes governing efficiency and emissions
- **Project is a key resource for producing timely results on HECC fuel effects**
  - Heat transfer differences play important role in biodiesel $NO_x$ increase
  - Liquid fuel impingement and pool fires are key barrier to early-DI HECC
  - Assisting with formulation of reference and surrogate fuels
  - Hardware upgrades are essential for studying emerging technologies
- **Project builds on past successes, is responsive to reviewers' feedback, has many active collaborations to facilitate tech. transfer, and has a clear vision for future work**

# *Acknowledgments*


**Caterpillar (David Milam, Michael Radovanovic) – *support, advice***

**Dr. Glen C. Martin – *post-doc***

**Dr. Brian T. Fisher – *post-doc***

**Dr. Krishna Lakshminarasimhan – *former post-doc***