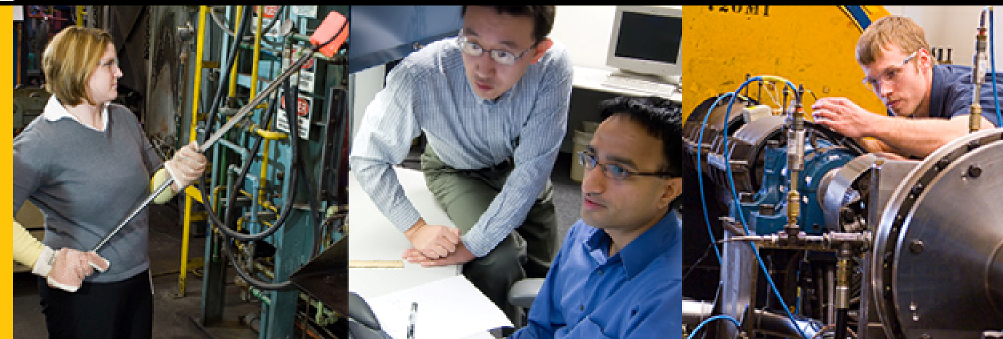


The Role of Advanced Combustion in Improving Thermal Efficiency

Chris Gehrke, Hari Sivadas, Tim Bazyn and David Milam – Caterpillar Inc

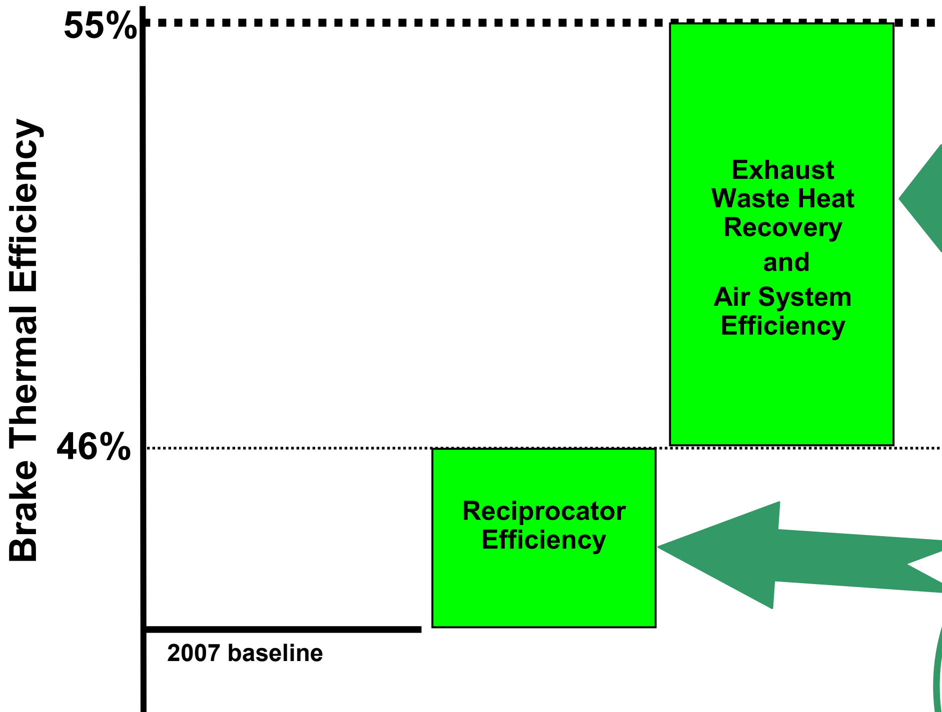
DOE Contract DE-FC26-05NT42412
DOE Technology Development Manager: Roland Gravel
NETL Project Manager: Carl Maronde

2008 DEER Conference
Dearborn, MI
August 4, 2008
Caterpillar Non Confidential

CATERPILLAR®

How much more reciprocator efficiency is needed?

T&SD Technology & Solutions Division



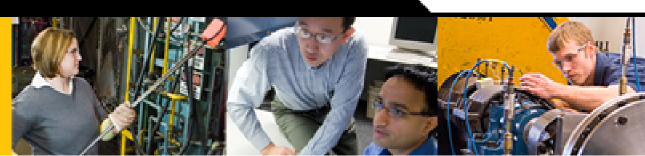
Aggressive heat recovery and component efficiency assumptions

Not currently practical for mobile applications

Needs to meet EPA 2010 and non-road Tier 4 emissions requirements

Current focus of HECC program

- Goal: minimum 10% improvement in reciprocator efficiency

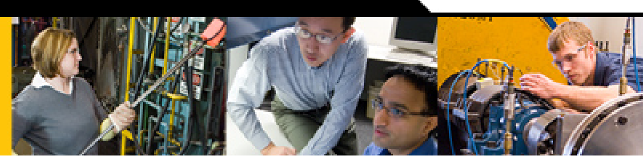


Objectives

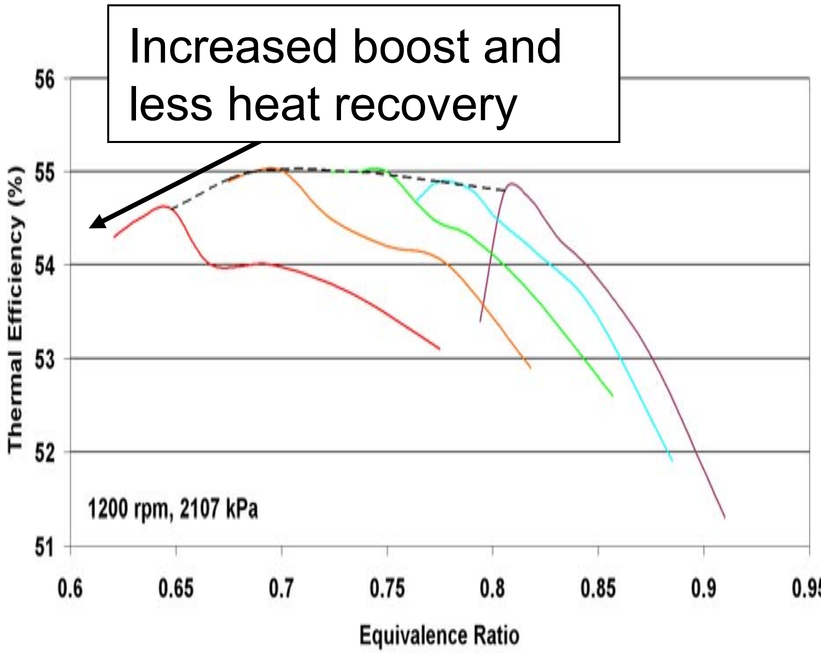
What are the combustion system challenges related to achieving higher brake thermal efficiency?

What are potential technologies to address these challenges?

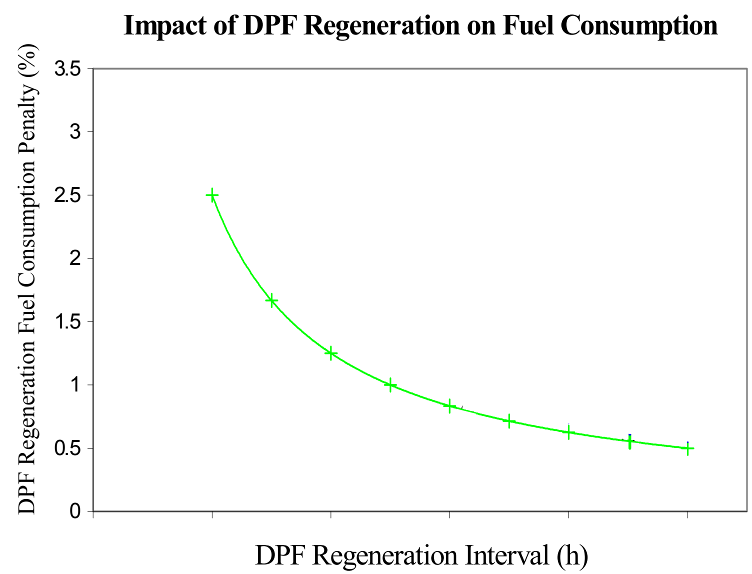
What are the barriers in making these technologies viable?



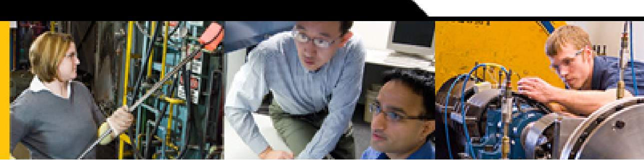
Need to Consider Other System Interactions



- Need to balance combustion system and heat recovery system requirements
  - Boost requirements
  - Equivalence ratio



- Need to minimize fuel consumption from aftertreatment regeneration
  - Minimize soot emissions



Impact of the Combustion System on Thermal Efficiency

T&SD Technology & Solutions Division

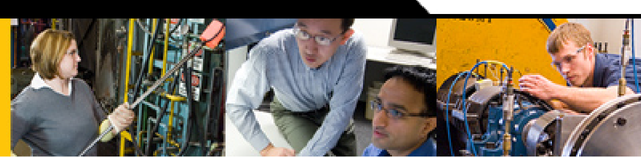
1. Efficiency of expansion work extraction → Maximize geometric expansion ratio, optimal combustion phasing, short combustion duration, minimize in-cylinder heat transfer

2. Quality of the exhaust energy to heat recovery devices → Minimize boost requirements vs. optimal equivalence ratio

3. Fuel consumption from A/T thermal management (ie. DPF regeneration) → Minimize soot emissions vs. optimal equivalence ratio

4. Engine parasitic loads
   - Cooling fan, fuel system

   → Minimize heat rejection, fuel injection pressure, etc.



Potential Combustion System Technologies

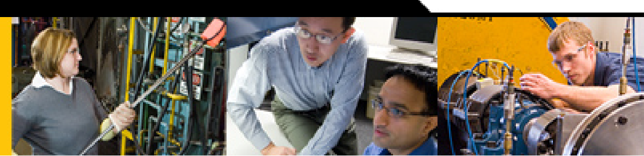
Combustion System Challenges

- Short, optimally phased combustion
- Tolerance for higher equivalence ratios
- Low soot emissions

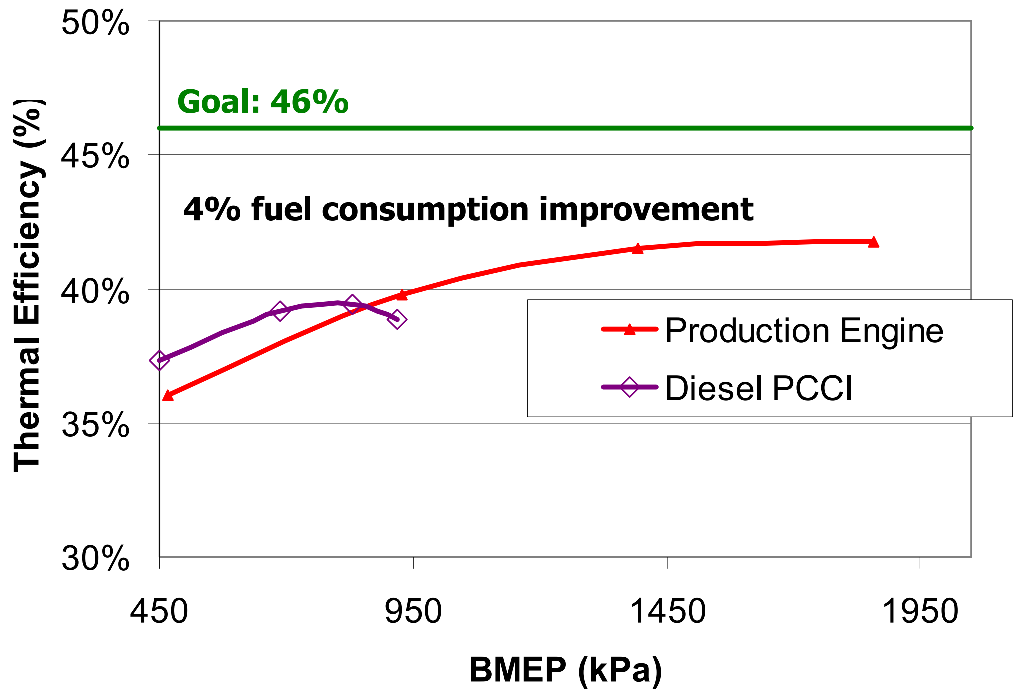
→ Premixed combustion (HCCI/PCCI)

- High BMEP mixing controlled combustion
- Compatible with HCCI/PCCI
- Low soot emissions

→ Lifted-flame diffusion combustion



Premixed Combustion (HCCI/PCCI)

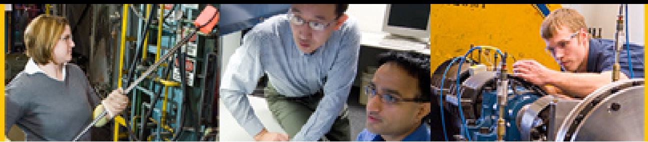


Advantages

- Short combustion duration
- Premixed → low smoke
- Low Temp Combustion
  → potential NOx benefit

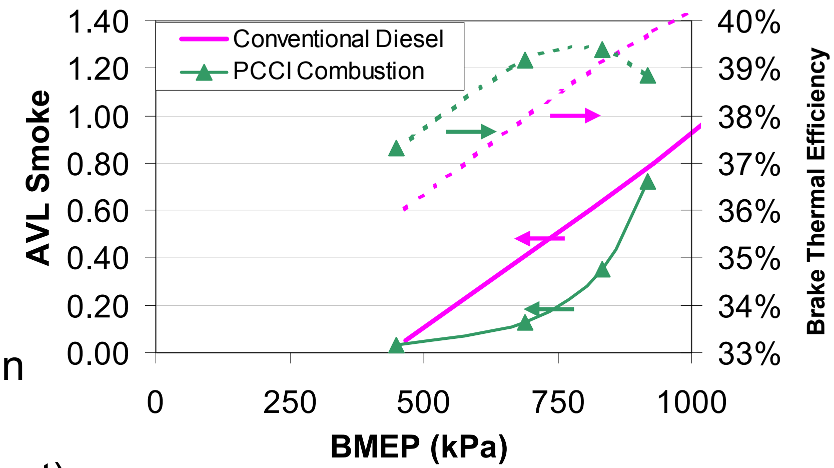
Challenges

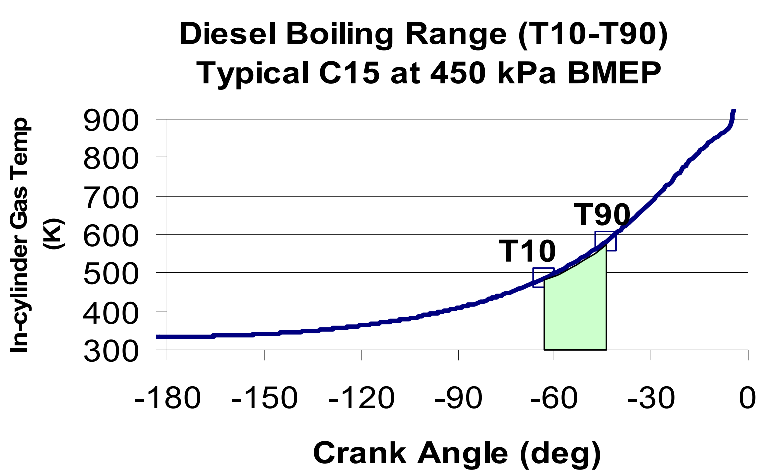
- Benefit limited to low load
- Need to transition to conventional diesel combustion at higher loads
- Combustion chamber / injector nozzle configuration must be compatible with conventional combustion

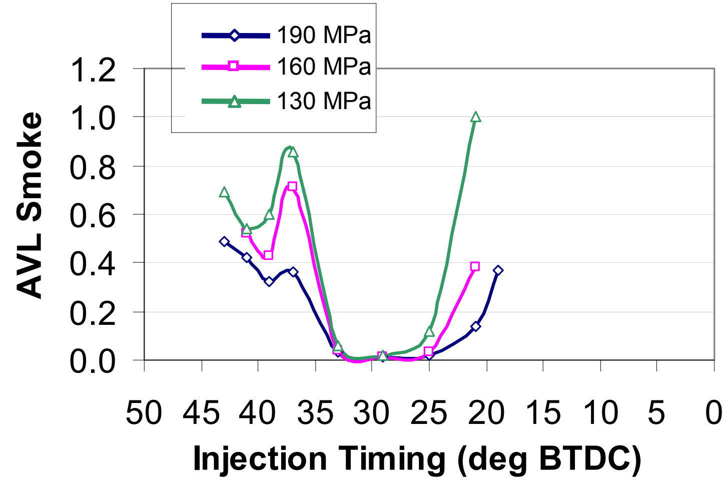


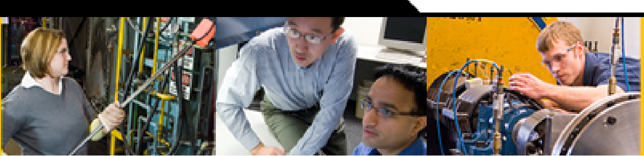
Technical Challenges with HCCI/PCCI

- Diesel PCCI operating range limited by
  - Smoke emissions
  - Non-optimal phasing (degrades BSFC)
- Technical Challenges
  - EGR/IVA insufficient to control diesel combustion phasing without sacrificing equivalence ratio
  - Low volatility of diesel fuel (liquid fuel impingement)





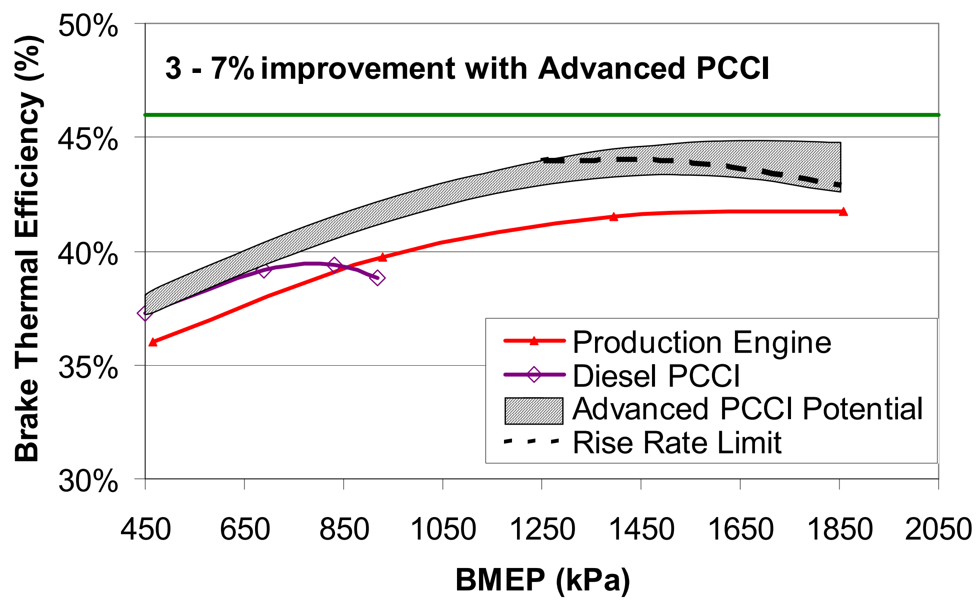




Thermal Efficiency Potential of HCCI/PCCI Combustion

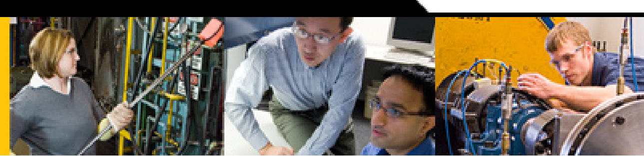
T&SD Technology & Solutions Division

- Need an alternative method of combustion phasing control to maintain the following …
  - optimal combustion phasing
  - sufficient compression ratio
  - acceptable equivalence ratio
  - sufficient pre-mixing



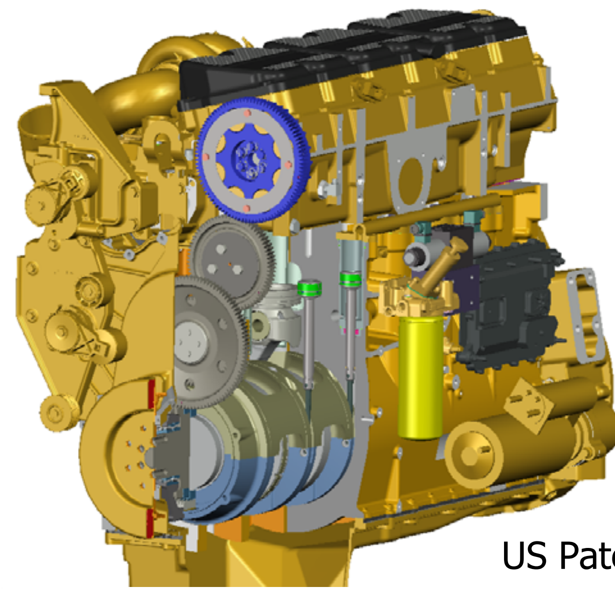
- Some NOx A/T potentially required to extend load range

- Cylinder pressure and rise rate constraints will limit load range and efficiency benefit
  - Conventional diesel combustion needed to reach full load (2100 kPa BMEP)

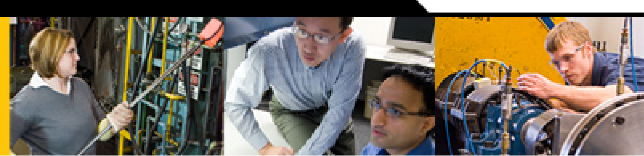


Technologies to Increase HCCI/PCCI Load Range

- Variable Compression Ratio
  - Effective means of extending load range at the expense of compression ratio
  - Optimal phasing does not outweigh expansion ratio loss to reach full load
  - May be adequate if using HCCI/PCCI only for NOx emissions control
  - Does not address diesel liquid fuel impingement



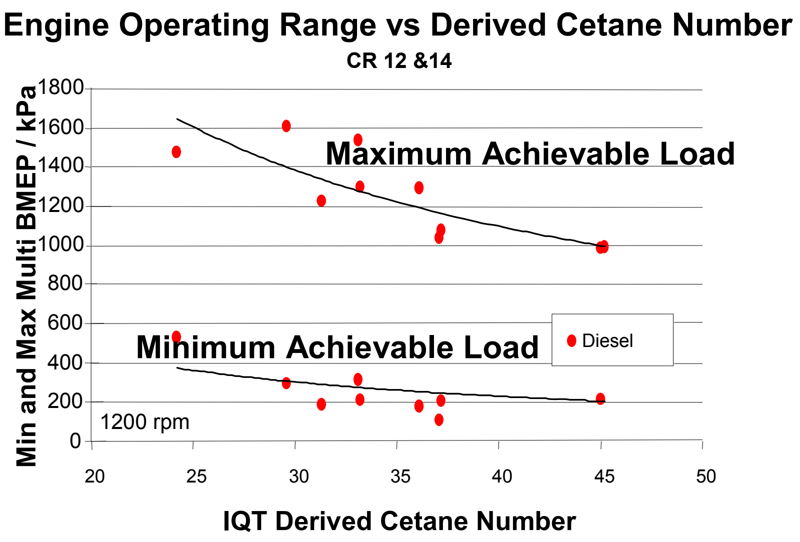
US Patent 7,370,613

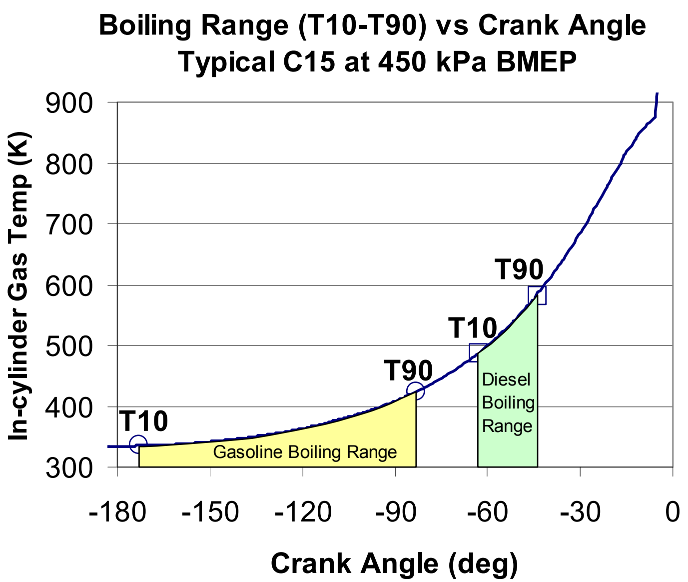


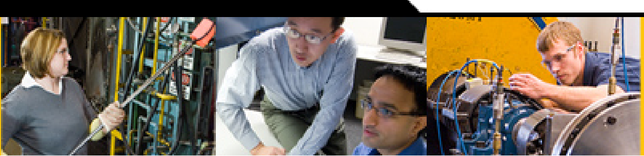
Technologies to Increase HCCI/PCCI Load Range

T&SD Technology & Solutions Division

- 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



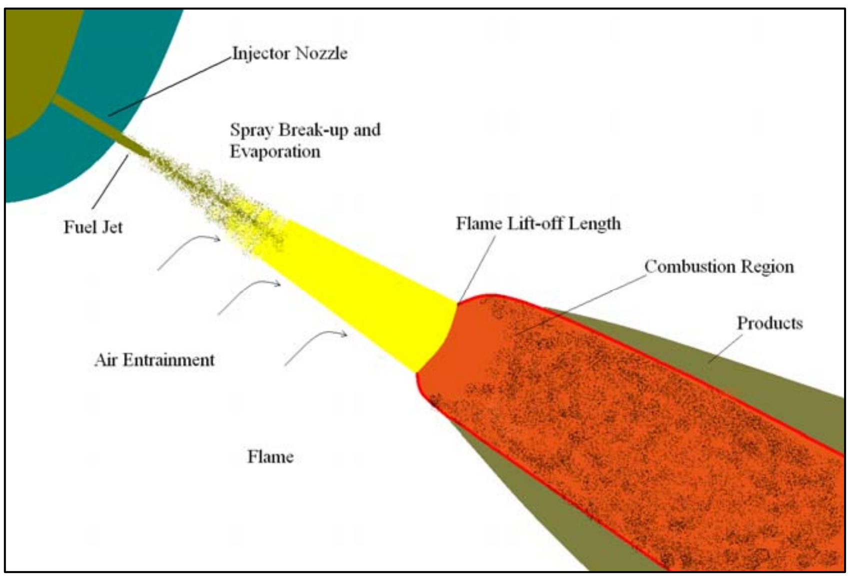


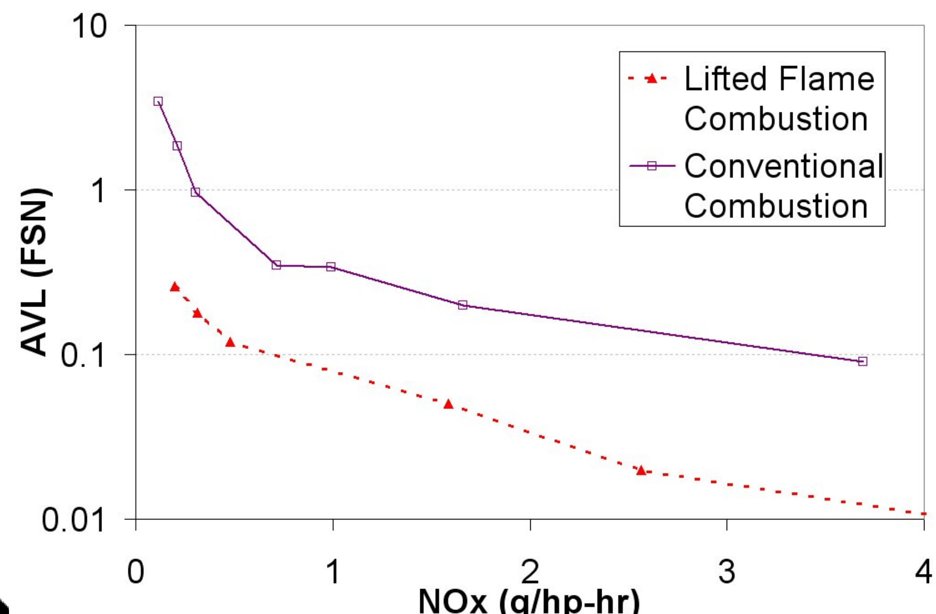


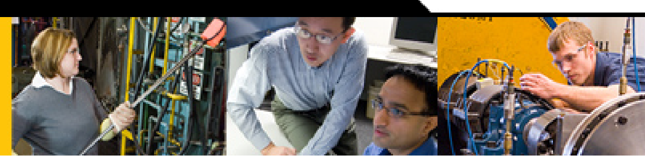
CATERPILLAR®

“Lifted Flame” Combustion

- Low soot combustion technology
  - Entrain enough air prior to liftoff length (equivalence ratio <2) such that soot is not formed in combustion region (SAE 2001-01-0539)
- Requires small injector orifices
  - Increased compatibility with PCCI/HCCI
- Order of magnitude smoke reduction







Challenges with Lifted Flame Combustion

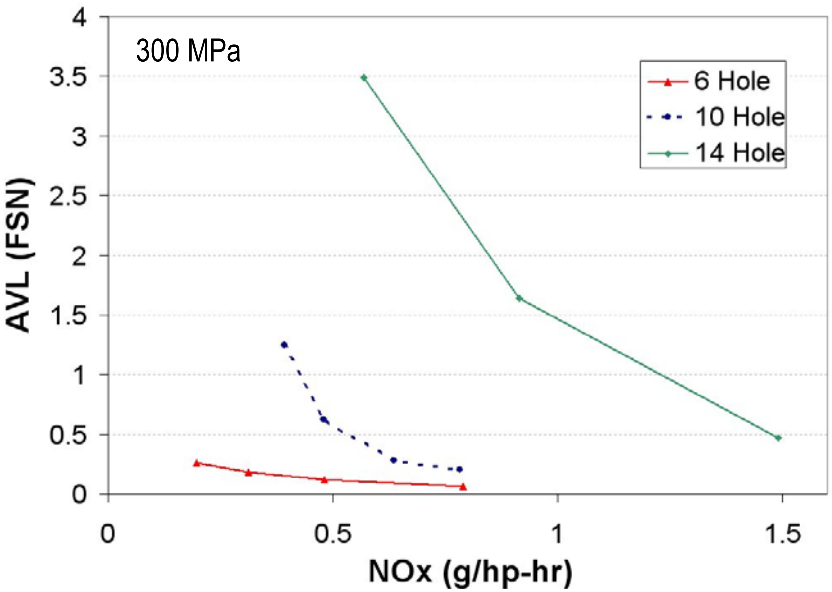
T&SD Technology & Solutions Division

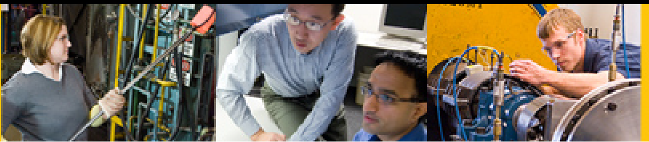
- Technology does not easily scale up with engine size
  - Potentially compatible with mid-range and smaller sized engines with current injection pressure capability and hole sizes.
  - Need more holes or higher injection pressure for heavy-duty application
  - for 15L, ~500 MPa injection pressure w/ 6 holes
    or 12 holes at 300 MPa

- Smoke emissions become problematic with increased number of holes

- Are spray plume interactions to blame?

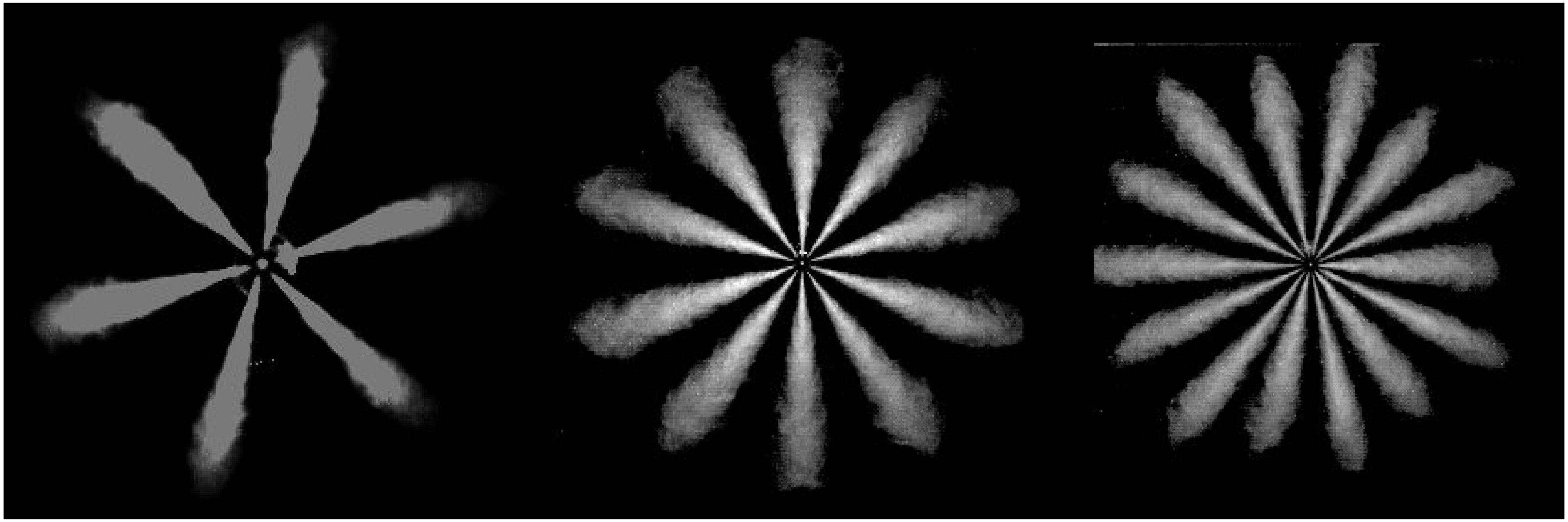
Effect of Increasing Number of Plumes on Emissions Performance





CATERPILLAR®

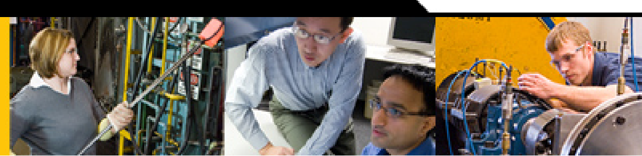
Challenges with Lifted Flame Combustion



6 hole | 10 hole | 14 hole

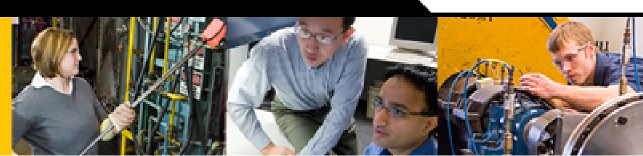
- No significant differences in non-evaporating spray characteristics

- Next Step: Investigate evaporating and combusting sprays



Summary

- To achieve 55% brake thermal efficiency, the efficiency of the combustion system / reciprocator must be increased.
- HCCI/PCCI (low temperature combustion) potentially offers increased thermal efficiency with reduced requirements for DPF regeneration. Demonstrated 4% BSFC improvement below 750 kPa BMEP.
- Inability to adequately control combustion phasing and liquid fuel impingement limits the load range and thermal efficiency benefit of diesel HCCI/PCCI
- Lifted flame combustion is a potential low-soot diffusion combustion technology that offers increased compatibility with HCCI/PCCI. Demonstrated order of magnitude soot reduction.
- Many challenges must be solved to achieve a production viable, high thermal efficiency combustion system



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

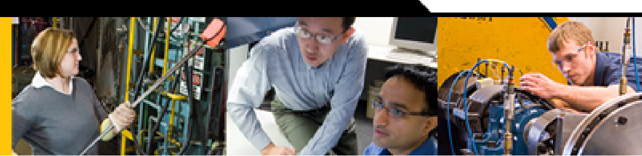
- Optical diagnostics
- Fuel spray and combustion
- Fuels effects

ExxonMobil Research and Engineering

- Fuels effects
- Combustion Chemistry/modeling

IAV Inc. Automotive Engineering

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



Disclaimer

The work described in this presentation, conducted under the Caterpillar / DOE cooperative research agreement, was conducted by the Technology and Solutions Division (T&SD) of Caterpillar Inc. The cooperative research described in the presentation was done to evaluate proof-of-concept for technologies that meet EPA 2010 on-highway emissions with the potential to improve peak brake thermal efficiency by 10%. Cursory consideration was given to which technologies may have some ability to be commercialized by the engine divisions of Caterpillar which have commercialization responsibility. The process to validate technologies as commercially viable was not in the scope of the program, nor was it undertaken. Commercialization aspects such as cost/benefit analysis, reliability, durability, serviceability and packaging across multiple applications were only considered at a cursory level. Until such analysis is completed,any attempt to imply commercial viability as a result of the material in this presentation is not justified.