ACE001: Heavy-Duty Low-Temperature and Diesel Combustion & Heavy-Duty Combustion Modeling

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Combustion Research Facility

Sandia National Laboratories

FY 2013 DOE Vehicle Technologies Program Annual Merit Review
Advanced Combustion Engine R&D/Combustion Research
8:30 – 9:00 AM, Tuesday, May 14, 2013

Sponsor: **U.S. Dept. of Energy, Office of Vehicle Technologies**

Program Manager: **Gurpreet Singh**

ACE001

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Heavy-duty combustion project overview

Timeline

- Project provides fundamental research that supports DOE/ industry advanced engine development projects
- Project directions and continuation are evaluated annually

Barriers

From DOE VTP Multi-Year Program Plan 2011–2015 (2010):

•2.3.A: Lack of fundamental knowledge of advanced engine combustion regimes

•2.3.B: Lack of cost-effective emission control

•2.3.C: Lack of modeling capability for combustion and emission control

Budget

- Project funded by DOE/VTP:
  FY12-SNL/UW: $700/115K
  FY13-SNL/UW: $670/115K

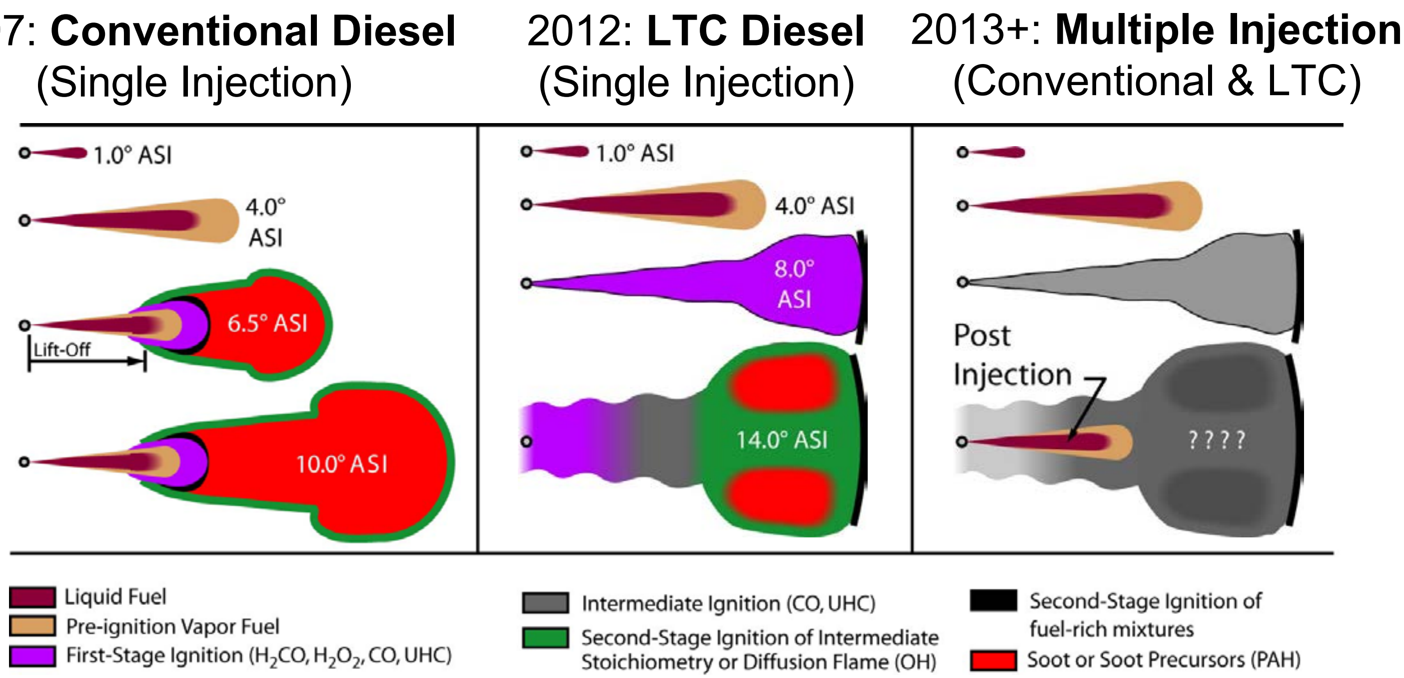
Partners

- University of Wisconsin, Delphi
- 15 industry partners in the AEC MOU
- Project lead: Sandia (Musculus)

Relevance/Objectives: HD In-Cylinder Combustion

Long-Term Objective

Develop the science base of in-cylinder spray, combustion, and pollutant-formation processes for both conventional diesel and LTC that industry needs to design and build cleaner, more efficient engines



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Current Specific Objectives:

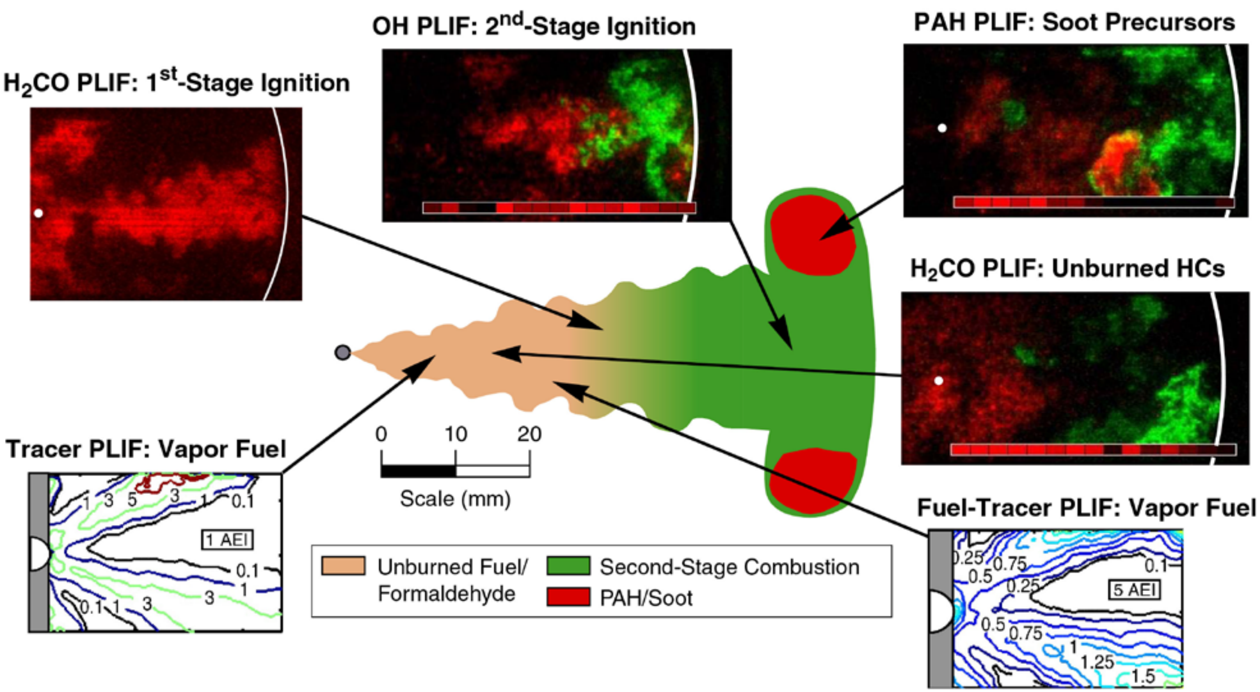
1. SNL – Show in-cylinder mechanisms that affect soot reduction by post-injections at fuel-efficient phasing
2. SNL – Evaluate efficacy and in-cylinder mechanisms of LTC combustion efficiency improvements by post-injections
3. SNL – Determine the 3-D interactions between close-coupled post-injections and residual main-injection soot
4. UW - Provide 3-D in-cylinder predictions to aid optical data interpretation for post-injection soot formation/oxidation

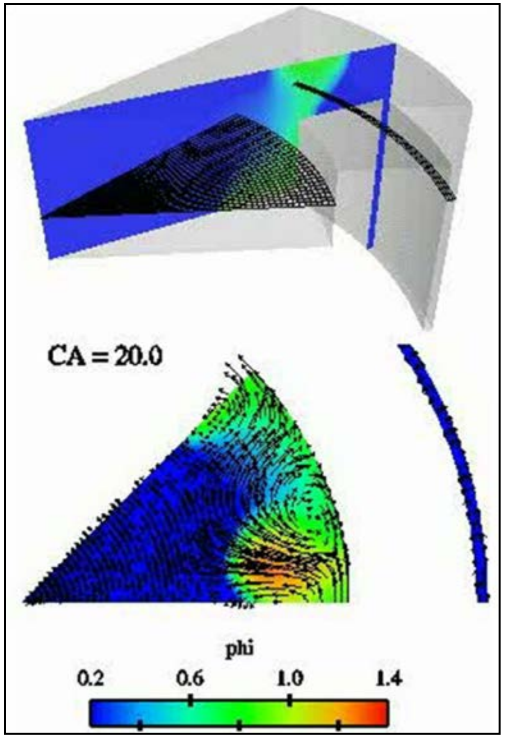
Milestones: Heavy-Duty In-Cylinder Combustion

1. (SNL) Evaluate the effectiveness and potential of small post injections to mitigate pollutant emissions and improve fuel efficiency
2. (SNL) Evaluate the three-dimensional post-injection soot interactions using multi-planar optical diagnostics
3. (UW) Compare post-injection combustion model predictions to optical data to validate models and interpret experimental results

Approach/Strategy: Optical imaging and CFD modeling of in-cylinder chemical/physical processes

- Combine planar laser-imaging diagnostics in an optical heavy-duty engine with multi-dimensional computer modeling (KIVA) to understand LTC combustion
- Transfer fundamental understanding to industry through working group meetings, individual correspondence, and publications





Collaborations

- All work has been conducted under the Advanced Engine Combustion Working Group in cooperation with industrial partners
  - Cummins, Caterpillar, DDC, Mack Trucks, John Deere, GE, International, Ford, GM, Daimler-Chrysler, ExxonMobil, ConocoPhillips, Shell, Chevron, BP, SNL, LANL, LLNL, ANL, ORNL, U. Wisconsin
- New research findings are presented at biannual meetings
- Tasks and work priorities are established in close cooperation with industrial partners
  - Both general directions and specific issues (e.g., UHC for LTC, post-injection soot-reduction)
- Industrial partners provide equipment and support for laboratory activities
  - FY2013: Delphi providing continued support for new injector

Technical Accomplishments & Progress (11 slides)

- Accomplishments for each of the four current specific objectives below are described in the following eleven slides

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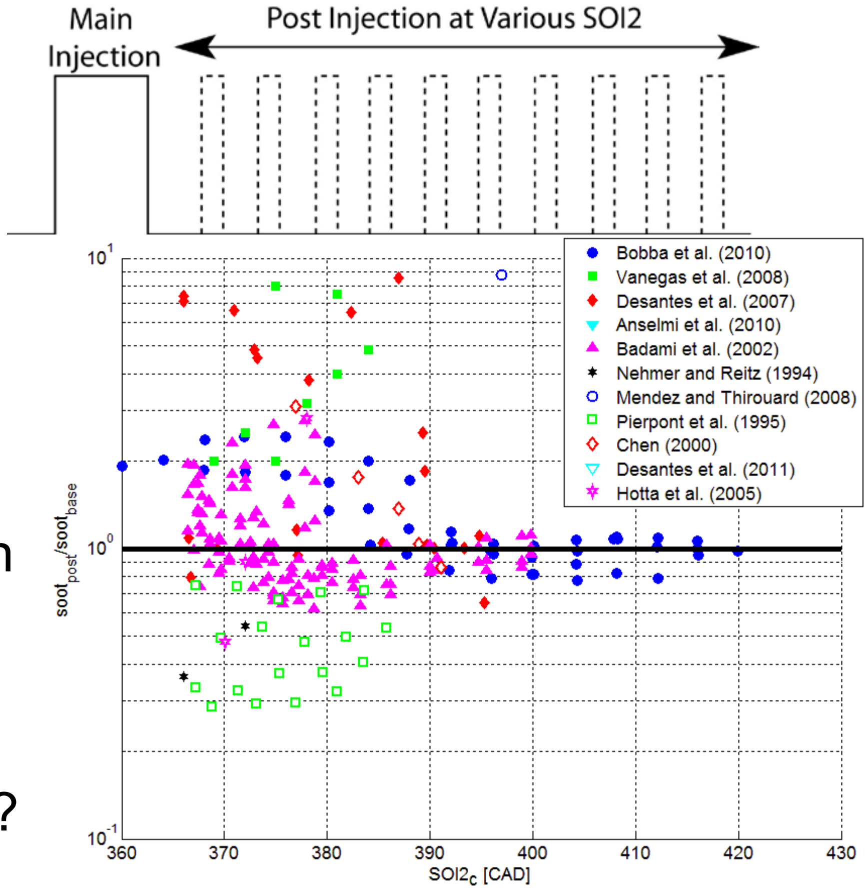
Post-injections can reduce soot at high fuel efficiency, but performance varies greatly

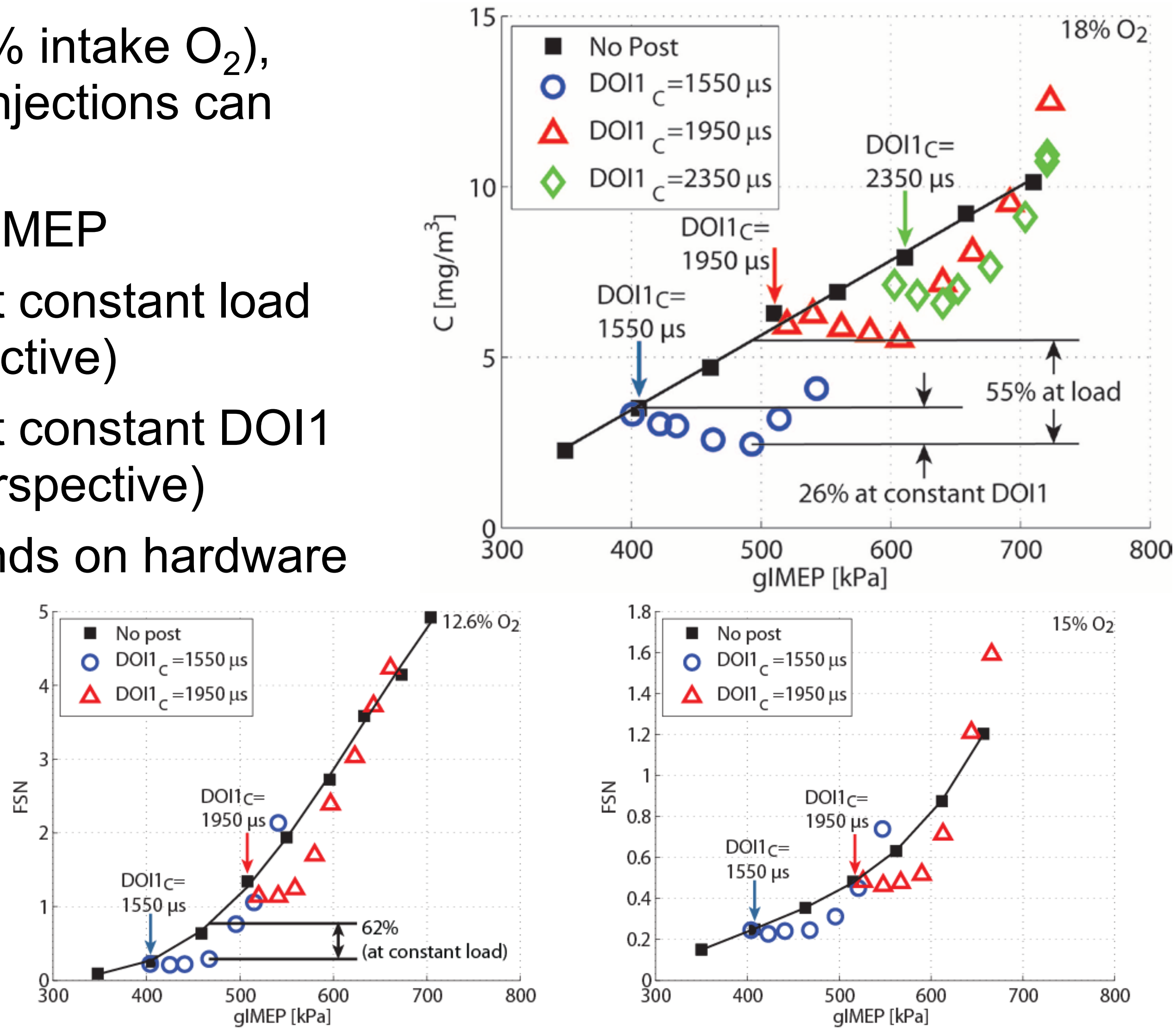
- One multiple-injection scheme of current interest: post-injections
  - Can reduce soot (or UHC)
  - Close coupled for efficiency
- Post injection defined as short injection (up to 20% of fuel) following main injection
- Literature shows large variation in soot reduction/increase by post-injections
- What injector/in-cylinder factors affect post-injection performance?



Can we develop a multiple-injection conceptual model for both conventional diesel and LTC to explain performance variations?

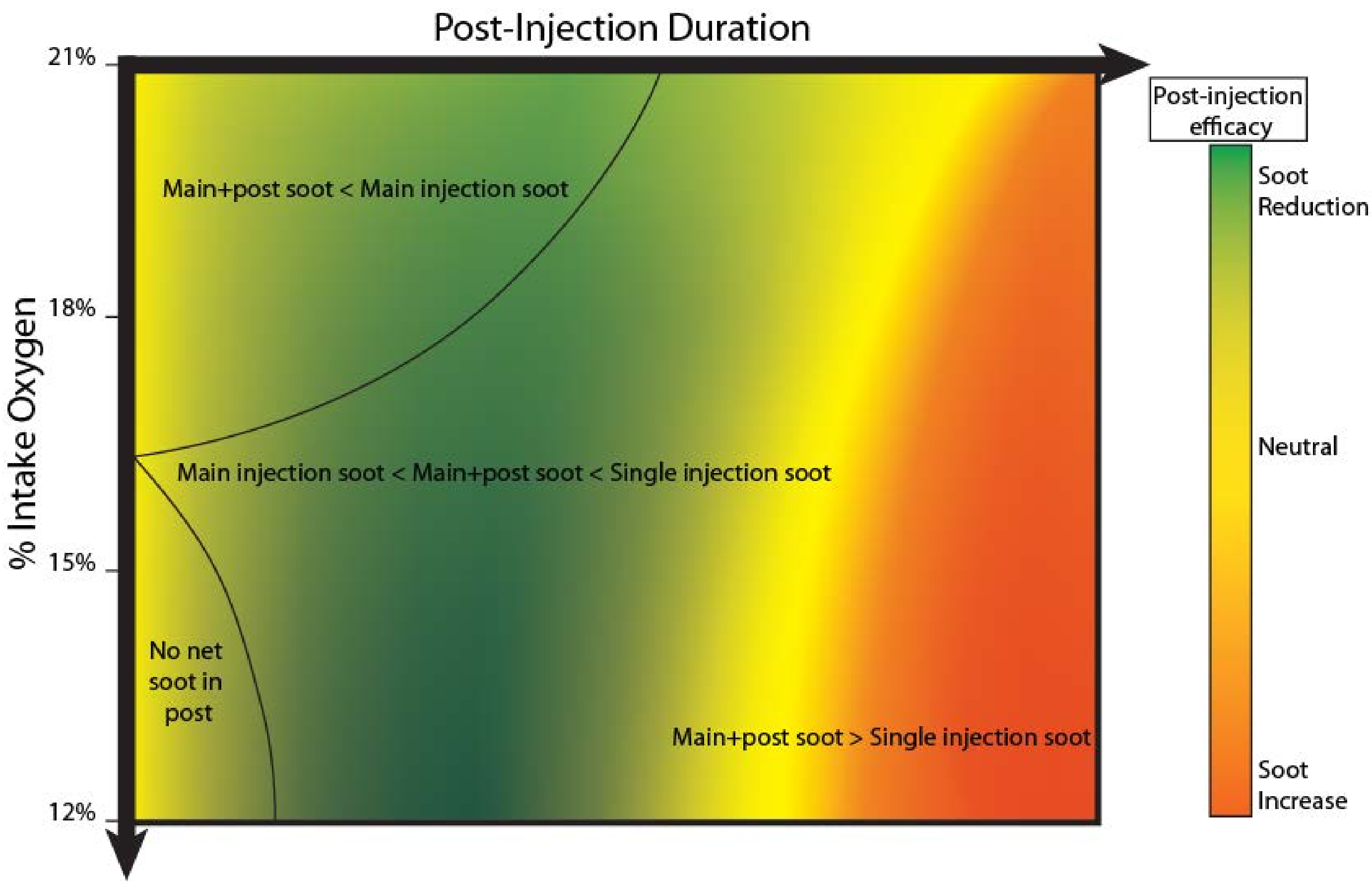
Injection duration and EGR affect close-coupled post-injection soot reduction, dwell unimportant

- At 20-30% EGR (18% intake O_2), close-coupled post-injections can reduce soot
- Example: 500 kPa gIMEP
    - 55% reduction at constant load (practical perspective)
    - 26% reduction at constant DOI1 (fundamental perspective)
    - Very likely depends on hardware
- At higher EGR, post injections are also effective
- Dwell between main and post injection has little effect for conditions tested



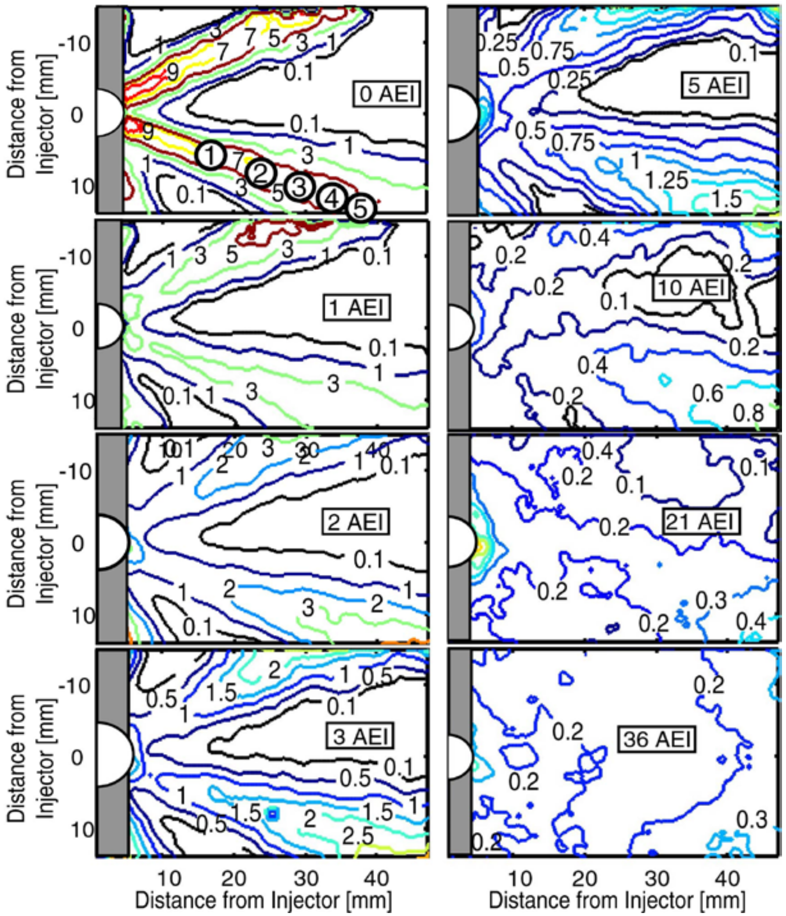
"Conceptual Chart" illustrates how EGR and post-injection duration affect soot reduction

- Color code indicates soot reduction for post-injection duration sweeps
- Moderate duration is optimal, long duration is detrimental, EGR limits post-injection duration range for soot reduction (more on how in slide 14)



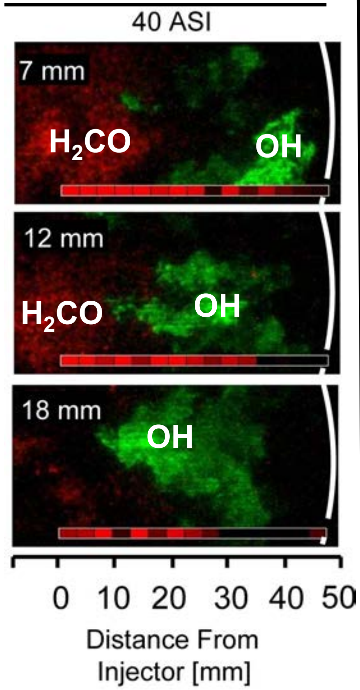
Previous work shows near-injector over-mixing leading to incomplete combustion and UHCs

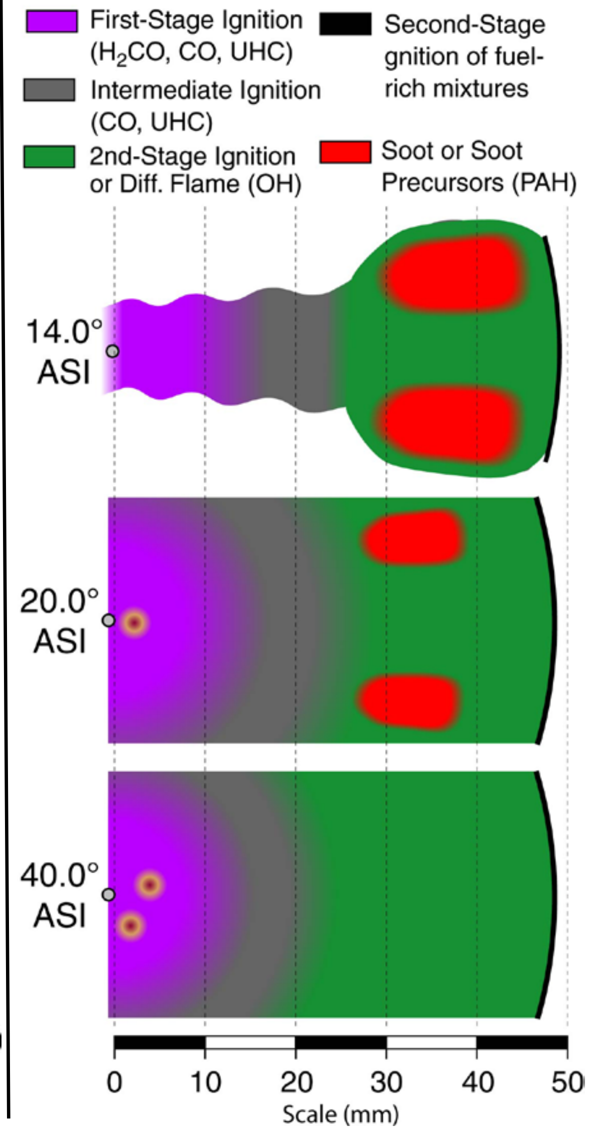
Toluene-LIF Vapor Fuel Concentration Measurements



LTC Conceptual Model

OH and Formaldehyde (H2CO) LIF

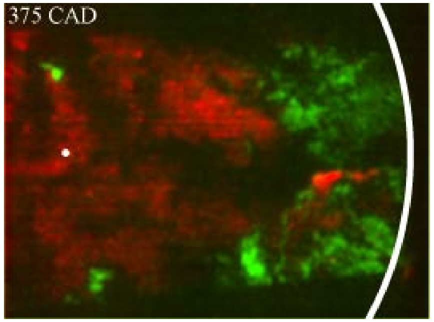




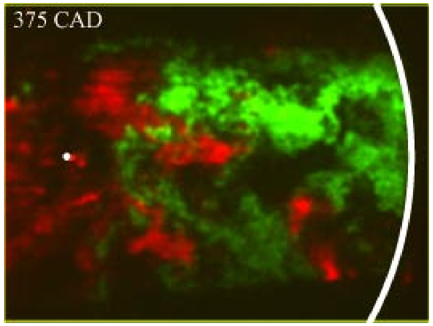
② New precise-delivery injection system shows range of post-injection efficacy for UHC reduction

- Single injection: complete comb. (OH, green) downstream, but much UHC (H_2CO, red) near inj.
- Post injection: complete comb. closer to injector (more green), but not 100% (red remains)

Single Injection

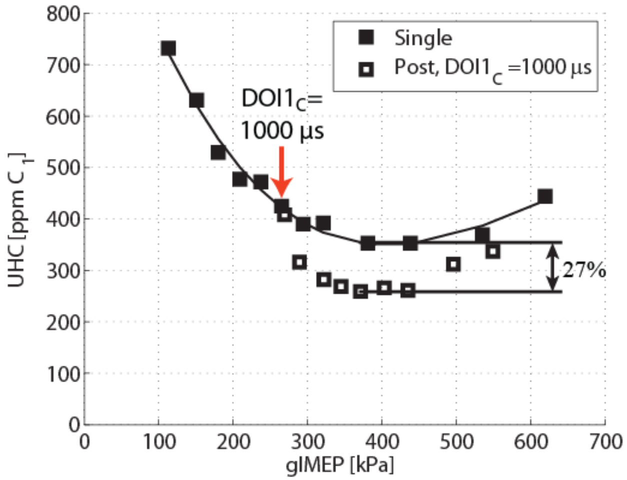


Two Post Injections

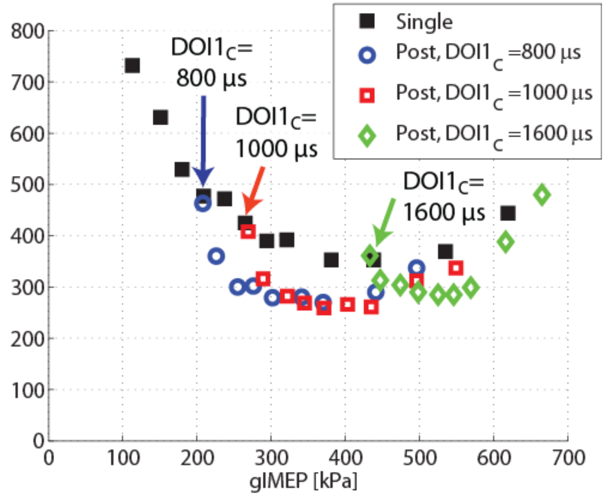


- New injector (added last year) provides more precise fuel, allowing design-level mapping of load/duration and multiple post-injections

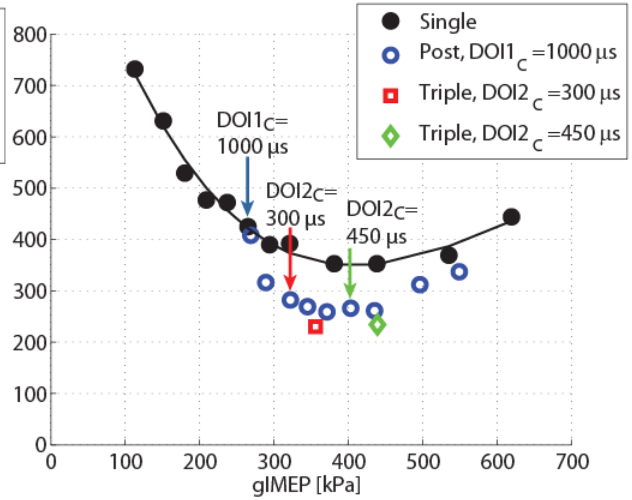
- 27% UHC at low load



Similar at other loads

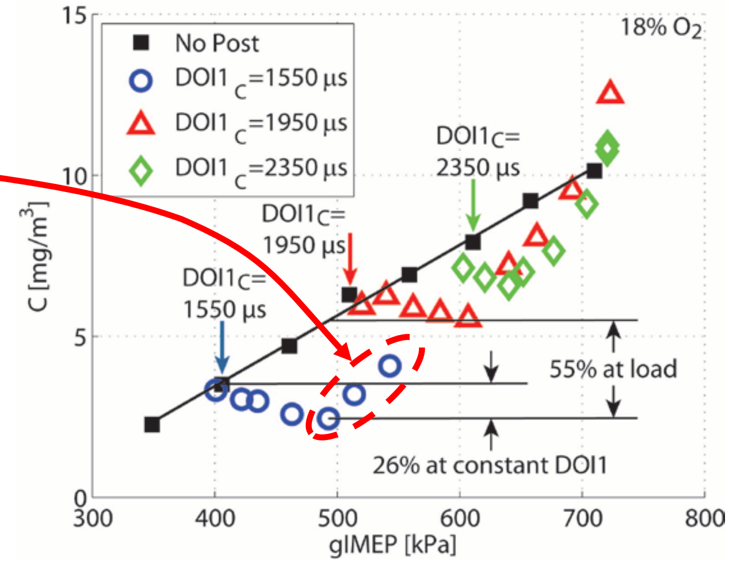


Two post-injections

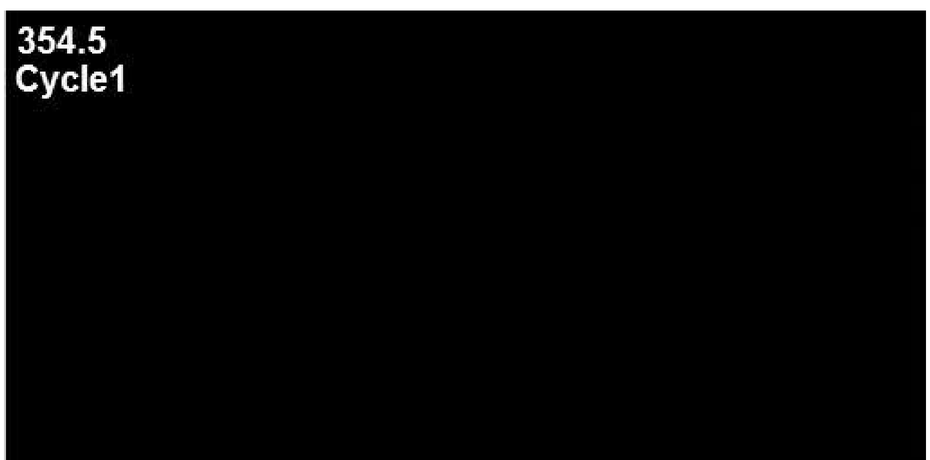


High-speed imaging: re-entrainment of main-inj. soot may limit post-injection soot reduction

- Moderate-duration post injections have optimal soot reduction; longer post injections yield increasing exhaust soot
- Hints from high-speed soot luminosity:
    - Moderate post injection *appears to pass over* main-injection soot
    - Longer post-injection *appears to entrain* main-injection soot
    - Line-of-sight diagnostic, needs confirmation



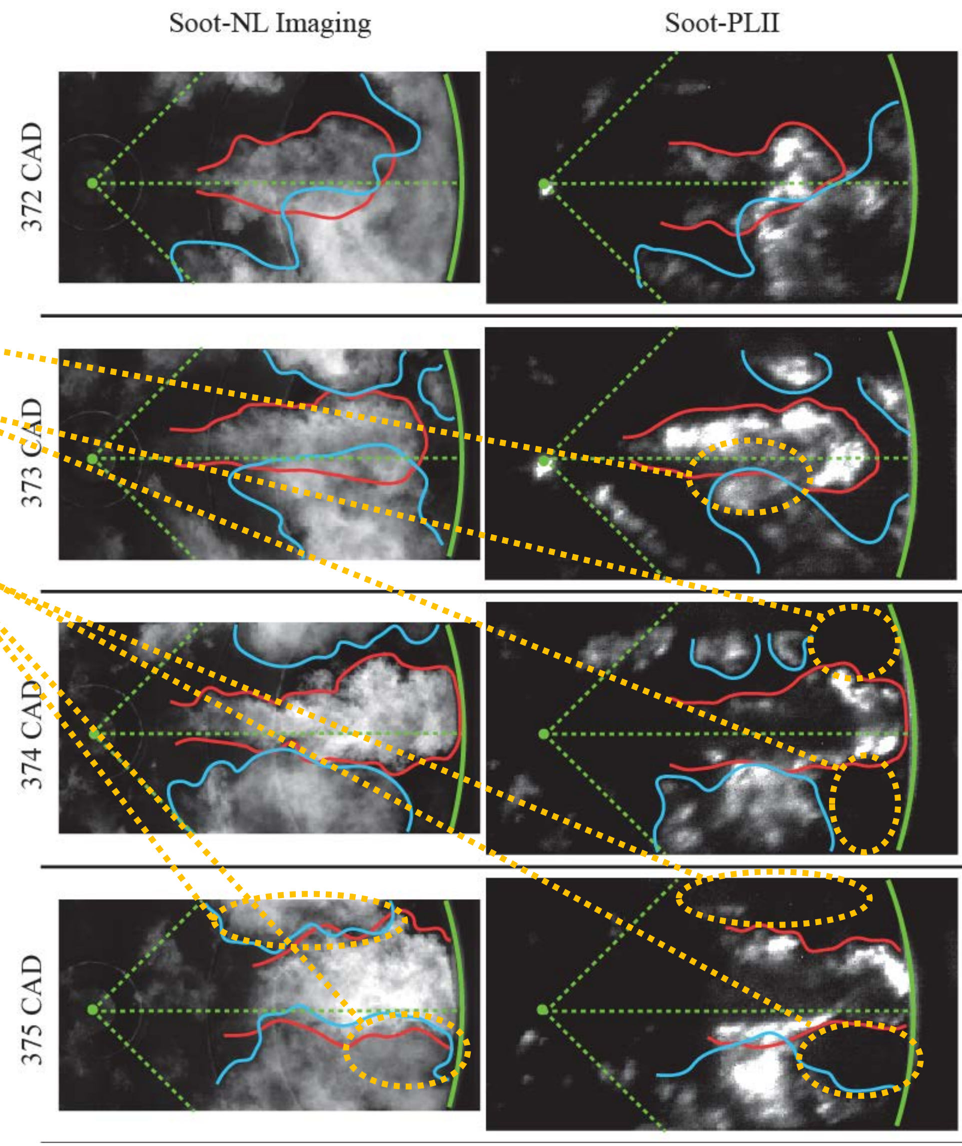
Minimum-soot post-injection



Longer post-injection

Planar laser-induced incandescence on jet axis: post-injection "clips" main-injection soot

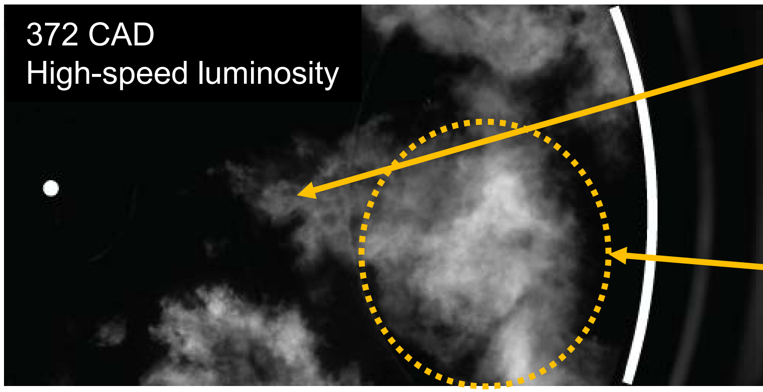
- Laser-sheet diagnostics help to interpret line-of-sight images
- Planar soot-LII simultaneous with high-speed luminosity:
  - slight interaction on jet axis
  - post-jet displaces main-soot?
- Single plane does not provide whole picture of soot interaction

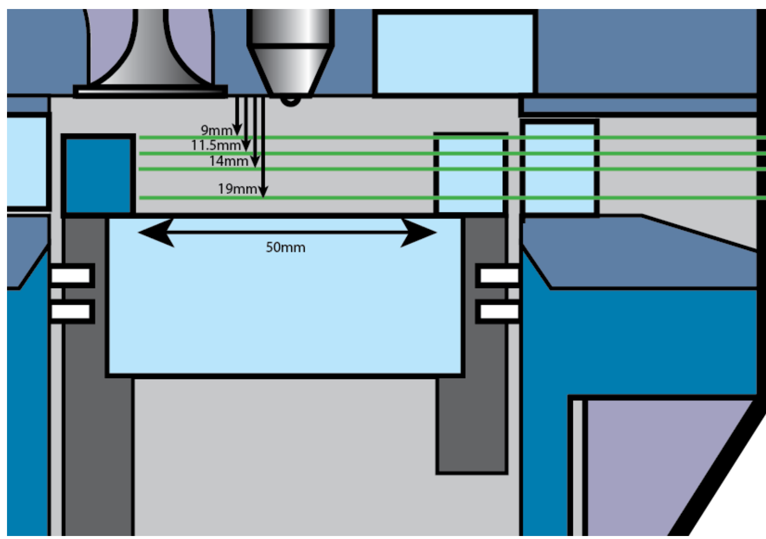


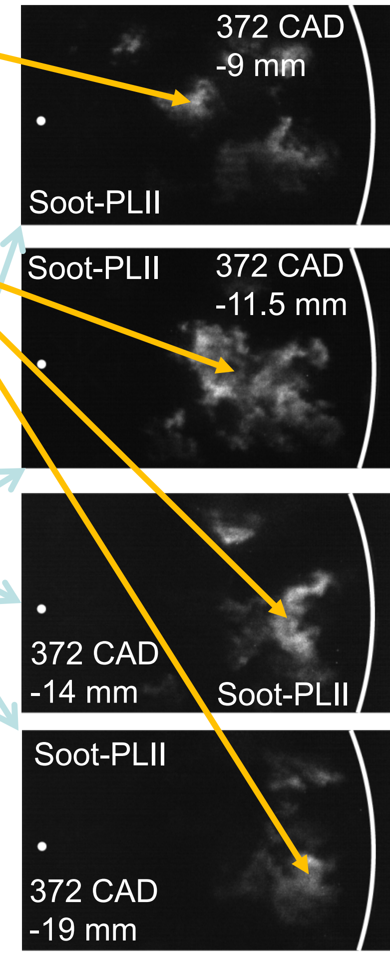
Minimum-soot post-injection

Multi-planar soot-LII provides view into three-dimensional shape of soot-cloud interactions

- Horizontal laser sheet aligned at four different distances from firedeck
- Soot-PLII at each elevation helps discriminate main and post soot





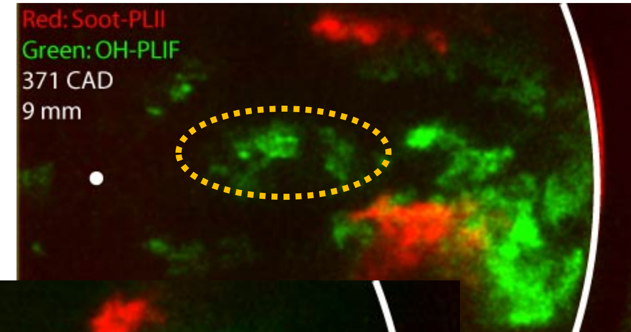


Multi-plane soot-PLII is helpful, but discerning main- from post-soot is often difficult.

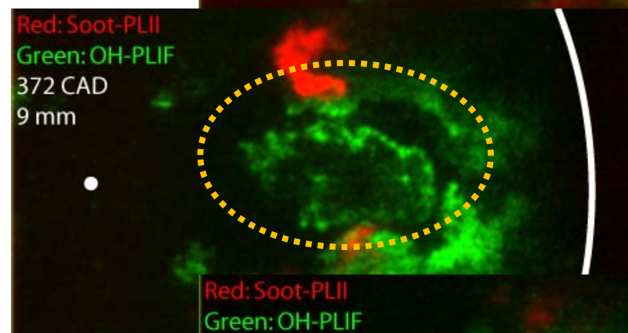
We need a separate indication of jet boundaries.

Adding OH-PLIF to soot-PLII shows post-injection displacing and mixing with main-injection products

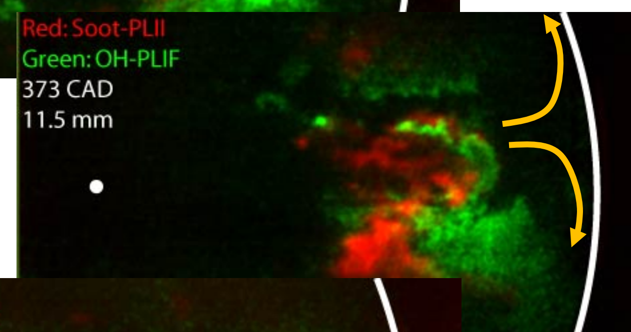
Post injection is first evident in OH-PLIF (green) at its ignition event



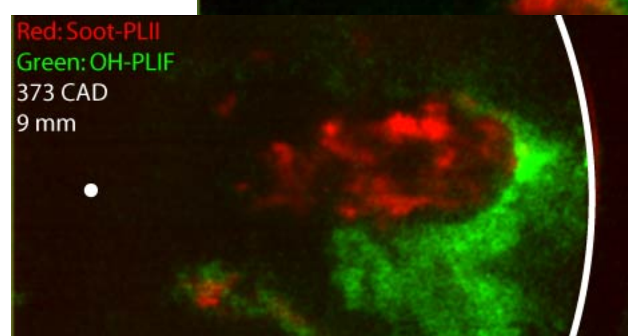
As post injection penetrates, (1) it often closely resembles conventional diesel conceptual model, and (2) it often displaces main-injection products, with OH-free zone (black) outside post-jet



- Soot (red) later forms throughout post-jet cross section as main-injection products are further displaced, but not always...

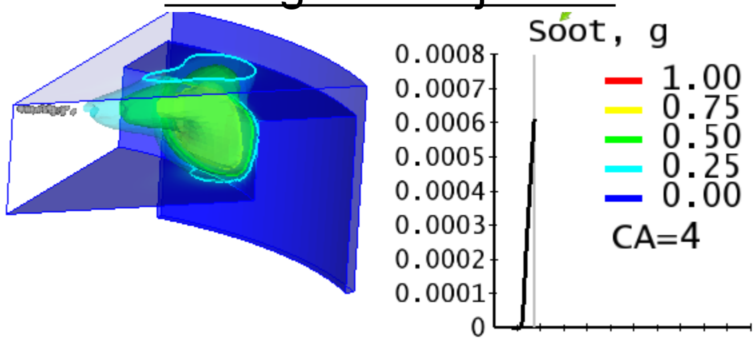


Some cycles show uniform OH with the post-jet combining with main products; no distinct boundary: cycle-to-cycle variations could be important

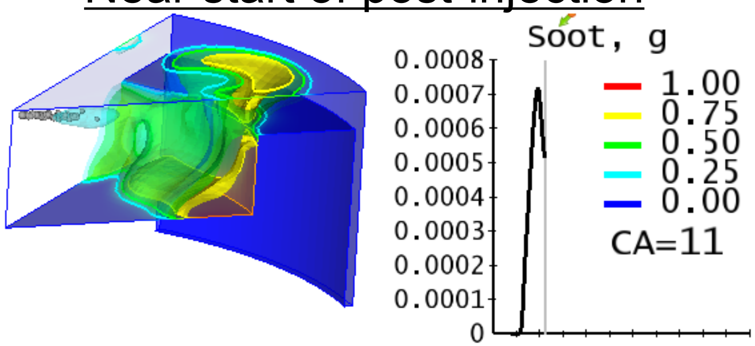


UW: KIVA CFD predicts measured exhaust soot trends well, provides full 3-d soot distribution

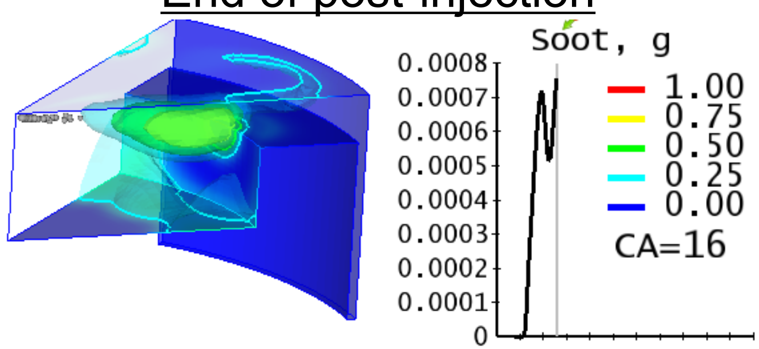
During main-injection

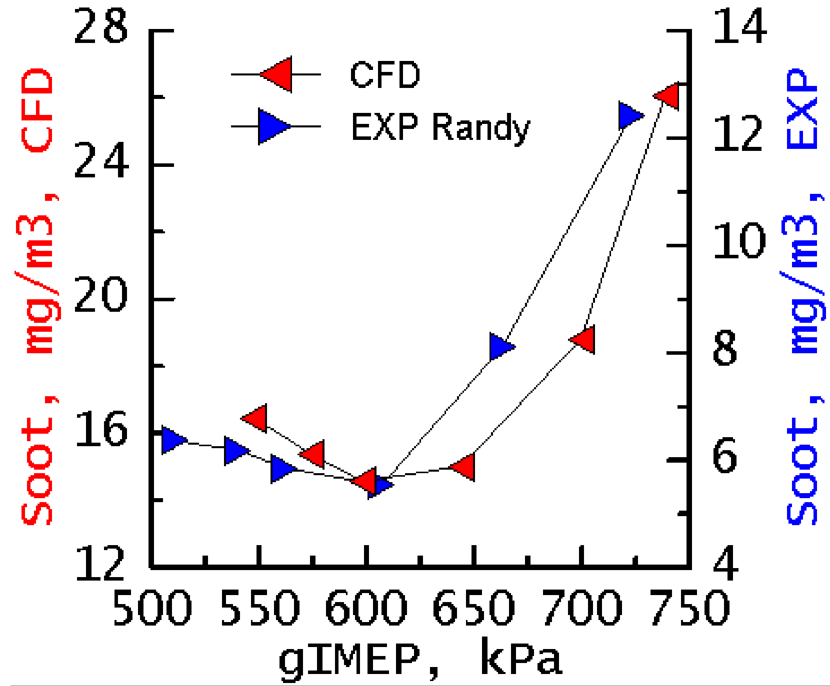


Near start of post-injection



End of post-injection

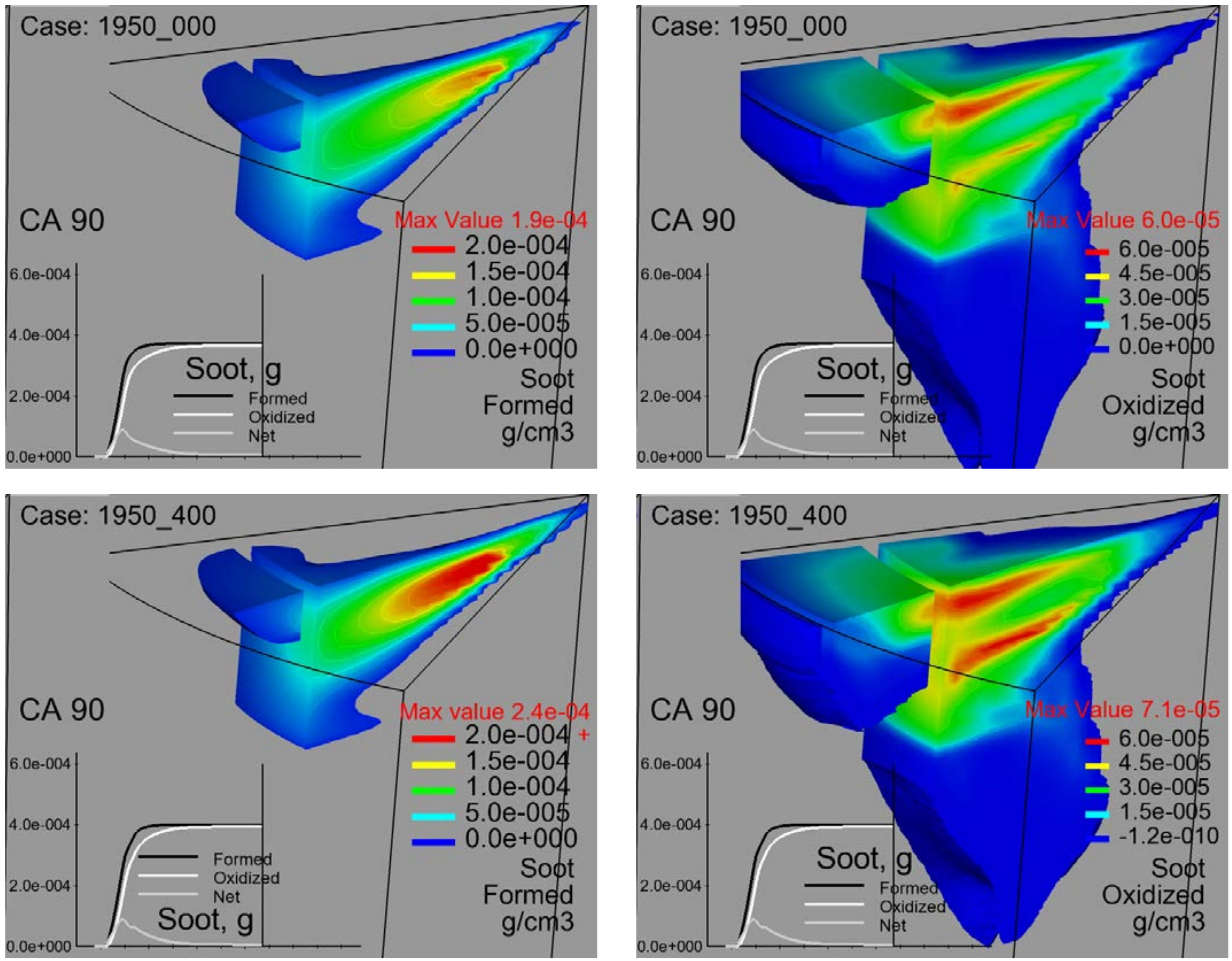




CFD	KIVA3V-ERC
Ignition	Shell
Combustion	Char. Time Comb (CTC)
Spray breakup	KH-RT
Turbulence	RNG k-epsilon
Soot formation	Hiroyasu
Soot oxidation	NSC

After validation with in-cylinder optical data, CFD predictions can provide additional insight

Cumulative Soot Formation | Cumulative Soot Oxidation



Single Injection

- Soot formation in jet cross-section
- Oxidation in diffusion flame on jet periphery

Post Injection

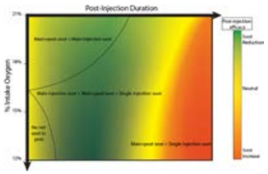
- Increased soot formation in jet cross-section
- Increased oxidation in post-jet diffusion flame

Future Plans: Multi-injection conceptual model, heat-transfer diag., and fuel-injection technology

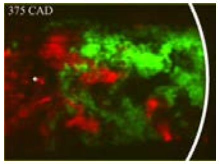
- Continue building a conceptual-model understanding of multiple-injection processes for both conventional diesel and LTC
  - Multi-injection schedules (pilot, post, split) deployed by industry
  - Use optical geometry more similar to metal engines (expense limit)
  - Compare with metal engine data where possible (industry partners)
  - Identify mechanisms and critical requirements (injector rate-shaping, dwell, duration, etc.) to improve emissions and efficiency
- Determine how combustion design affects heat transfer and efficiency
  - Measure spatial and temporal evolution of heat transfer across range of combustion modes; correlate to progression of in-cylinder combustion processes
- Continue to explore and upgrade fuel-injection technologies
  - Injection rate-shaping likely very important for performance, and higher load than our current injector capability is of interest

Heavy-Duty Combustion and Modeling Summary

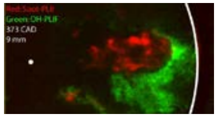
Improved understanding of in-cylinder spray, combustion, and pollutant-formation to help industry build cleaner, more efficient engines

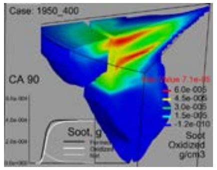
1. 

(SNL) Developed conceptual framework of exhaust soot-reduction dependencies for close post-injections

2. 

(SNL) Quantified post-injection load, duration, and dwell effects on LTC exhaust UHC; identified in-cyl. processes

3. 
(SNL) Showed main-post interactions via multi-plane soot and OH; 1st step to multi-inj. conceptual model

4. 

(UW) Achieved good agreement between CFD and experiments; provided insight into 3-d in-cyl. processes