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A Conceptual Model for Low-Temperature Diesel Combustion

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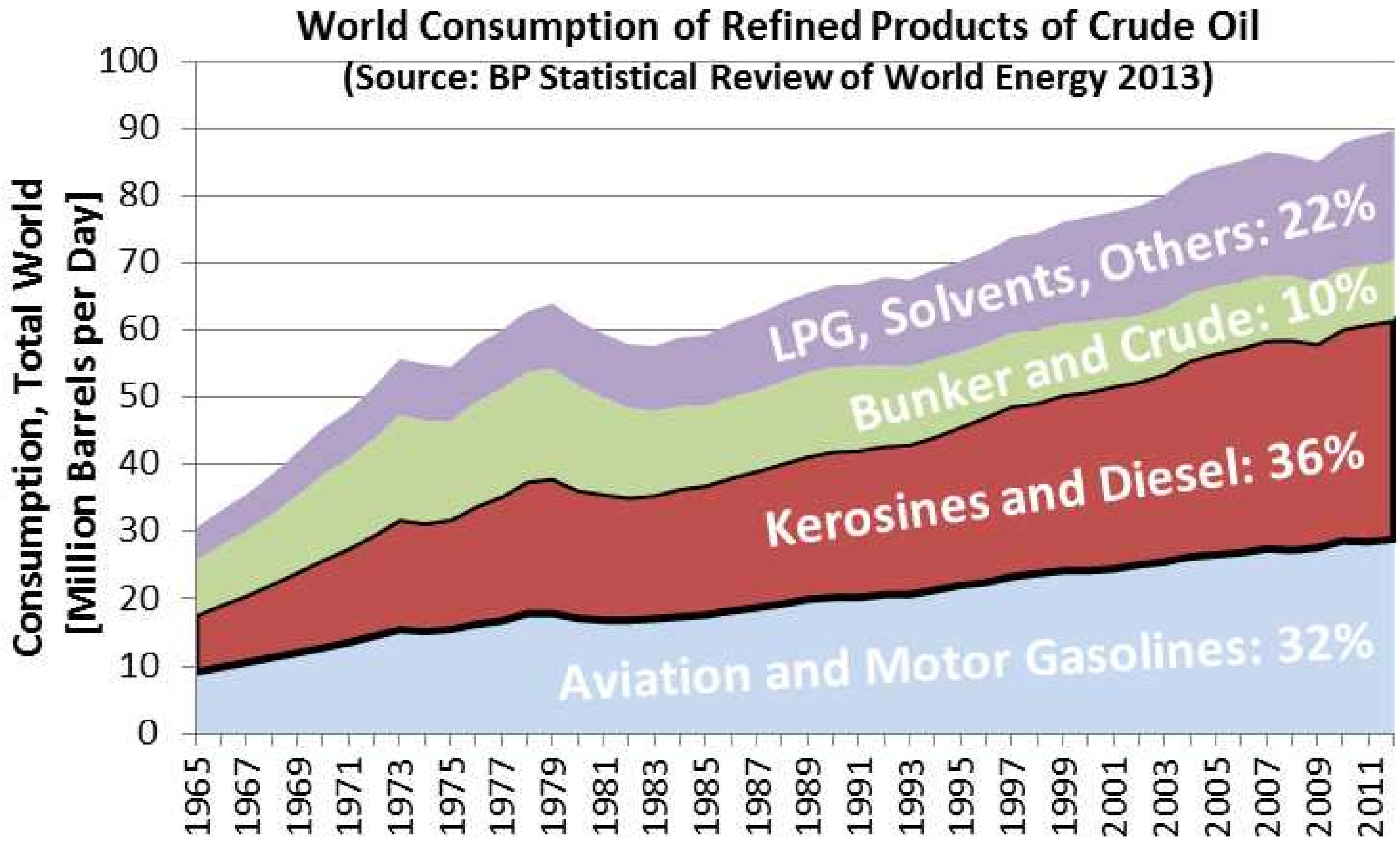
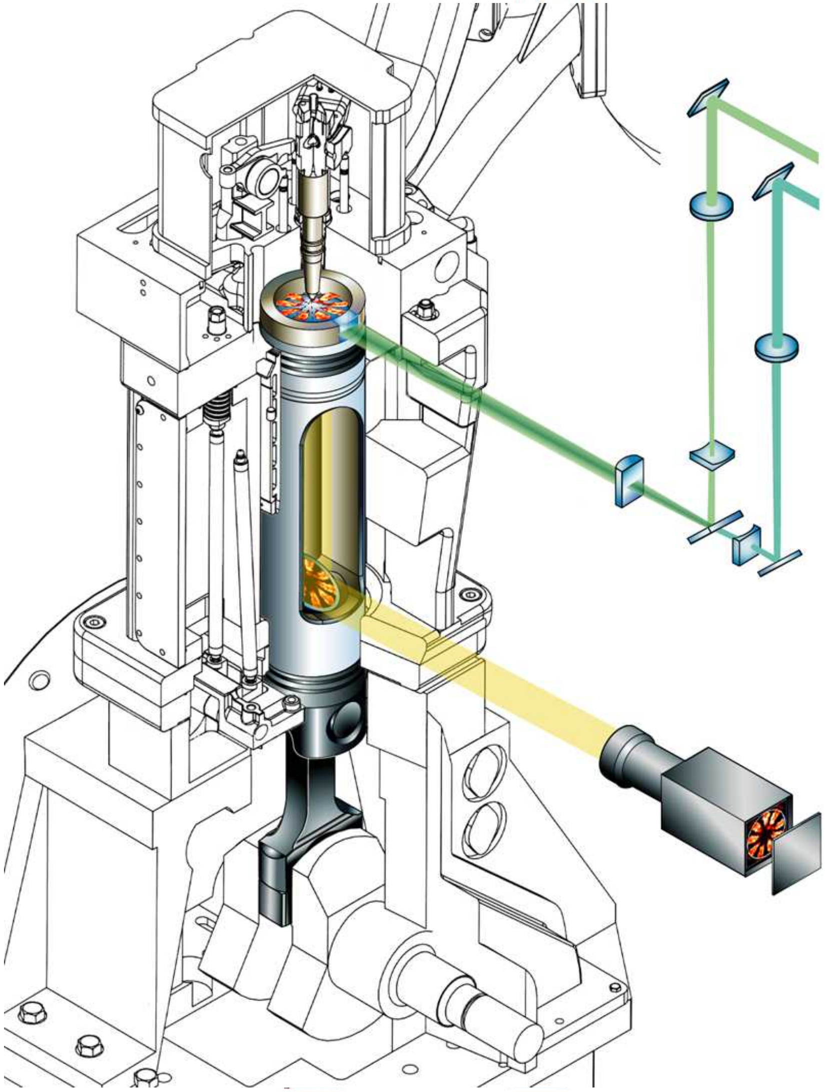
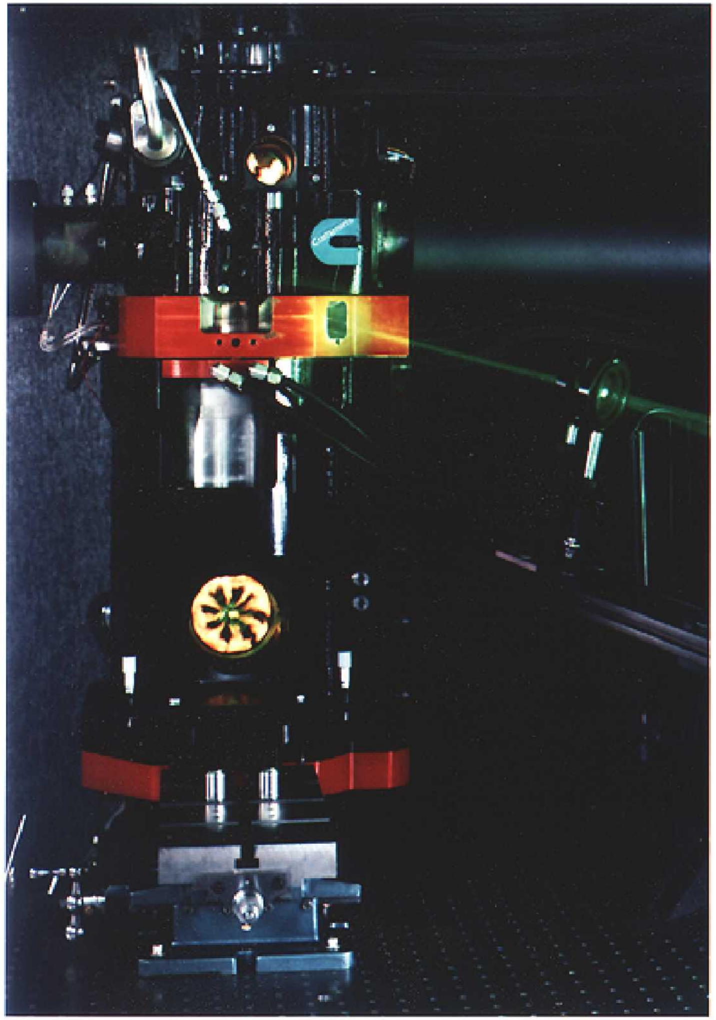
Combustion in transportation: air pollution, global warming, and resource depletion



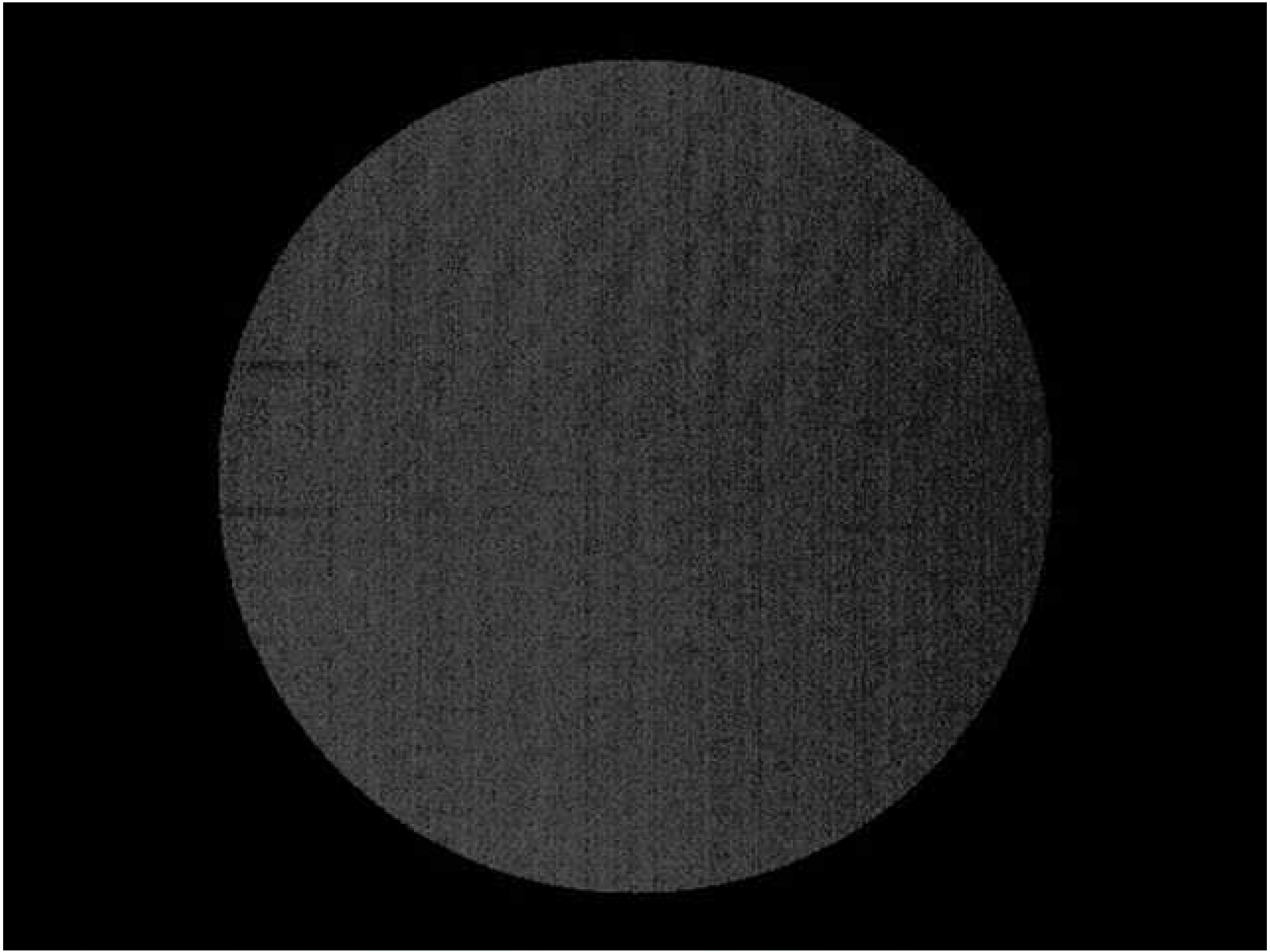
Analysis by Ecofys. All the data are for 2010.

Optically Accessible Heavy-Duty Diesel Engine



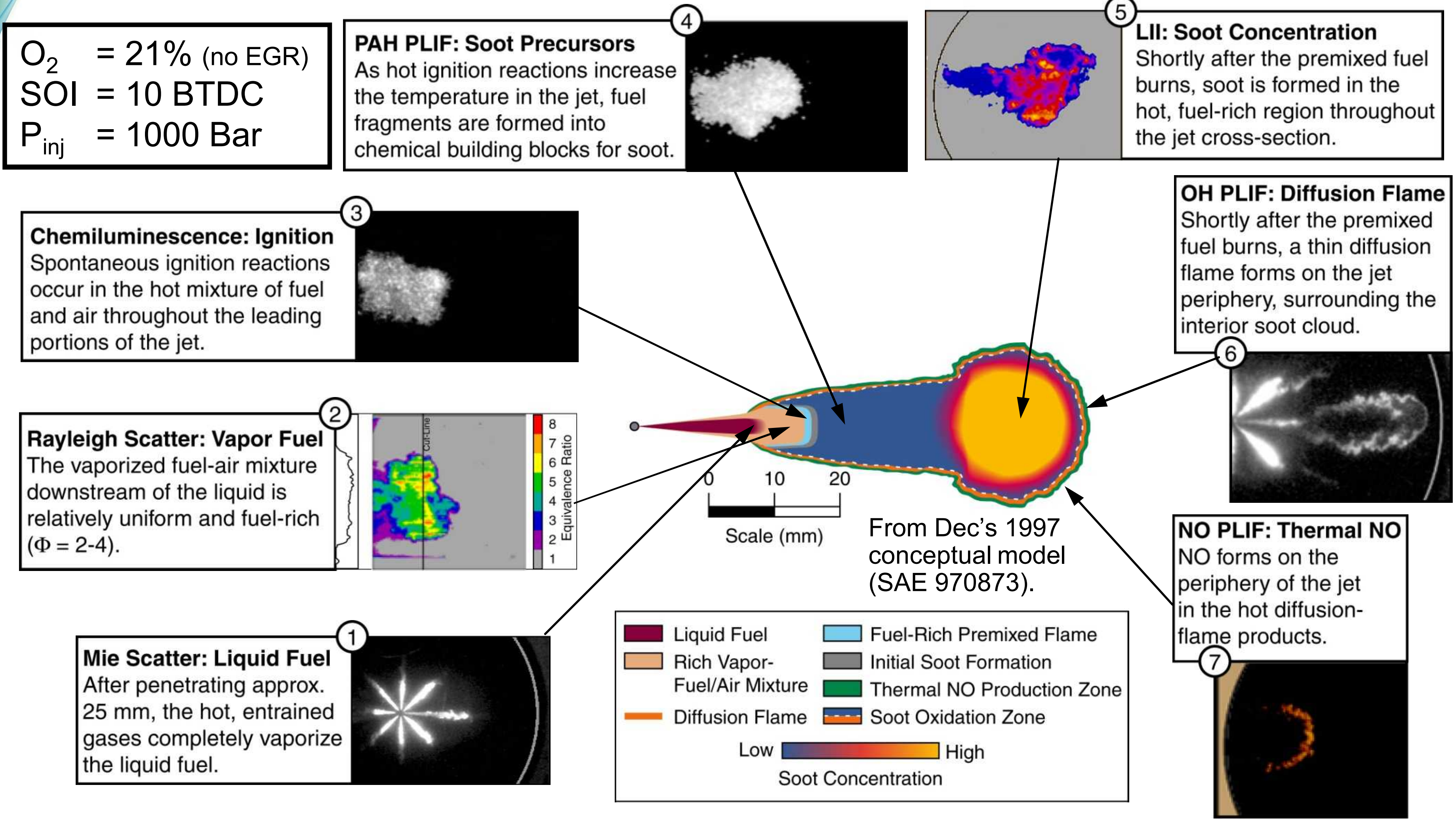


High Speed Luminosity of Diesel Combustion



Sandia’s diesel conceptual model describes mixing, combustion up to end of injection

O_2 = 21% (no EGR)
SOI = 10 BTDC
P_{inj} = 1000 Bar



① **Mie Scatter: Liquid Fuel**
After penetrating approx. 25 mm, the hot, entrained gases completely vaporize the liquid fuel.

② **Rayleigh Scatter: Vapor Fuel**
The vaporized fuel-air mixture downstream of the liquid is relatively uniform and fuel-rich (Φ = 2-4).

③ **Chemiluminescence: Ignition**
Spontaneous ignition reactions occur in the hot mixture of fuel and air throughout the leading portions of the jet.

④ **PAH PLIF: Soot Precursors**
As hot ignition reactions increase the temperature in the jet, fuel fragments are formed into chemical building blocks for soot.

⑤ **LII: Soot Concentration**
Shortly after the premixed fuel burns, soot is formed in the hot, fuel-rich region throughout the jet cross-section.

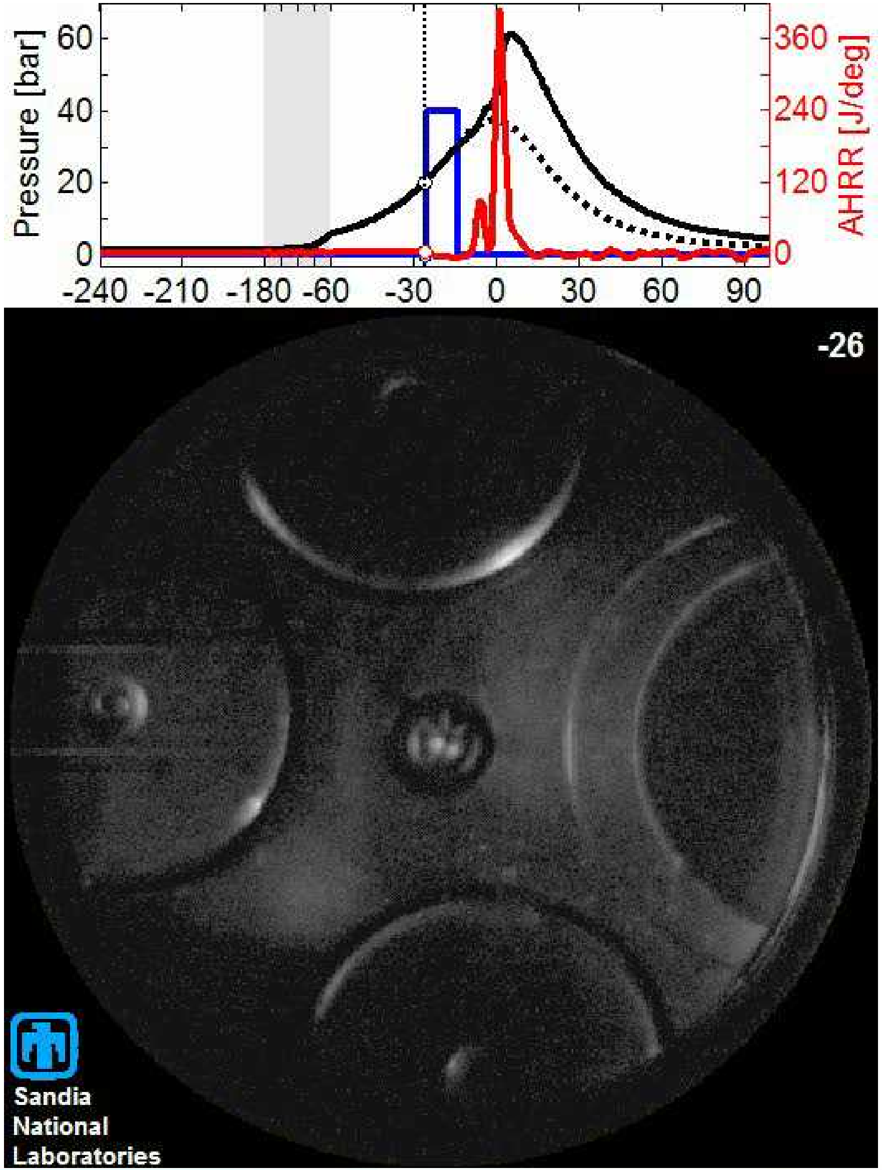
⑥ **OH PLIF: Diffusion Flame**
Shortly after the premixed fuel burns, a thin diffusion flame forms on the jet periphery, surrounding the interior soot cloud.

⑦ **NO PLIF: Thermal NO**
NO forms on the periphery of the jet in the hot diffusion-flame products.

From Dec’s 1997 conceptual model (SAE 970873).

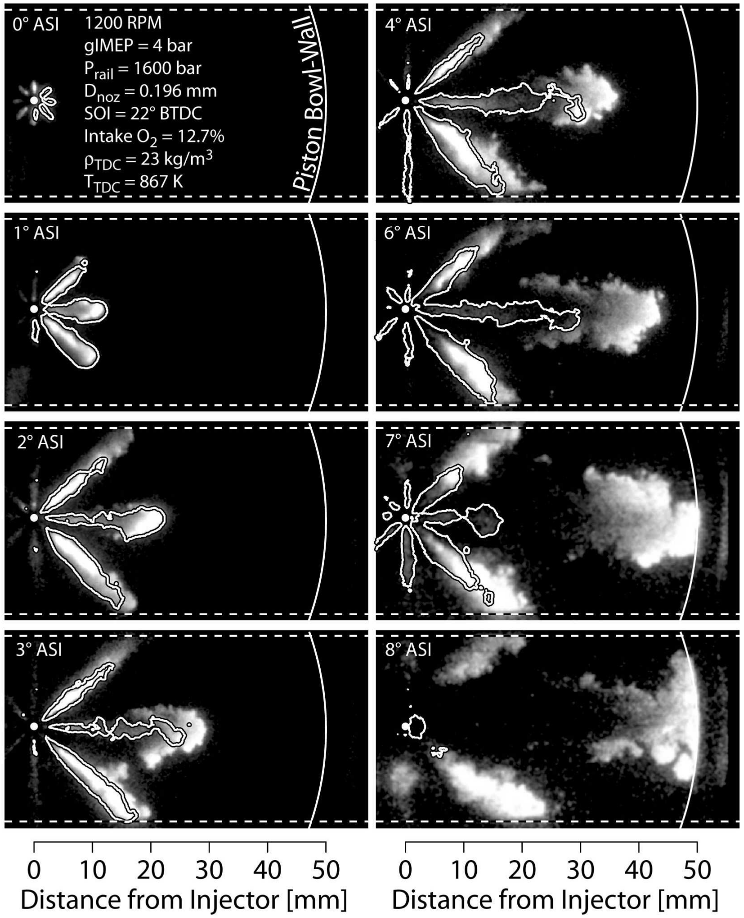
Low-temperature diesel combustion with EGR lowers soot & NOx, but increases CO and UHC

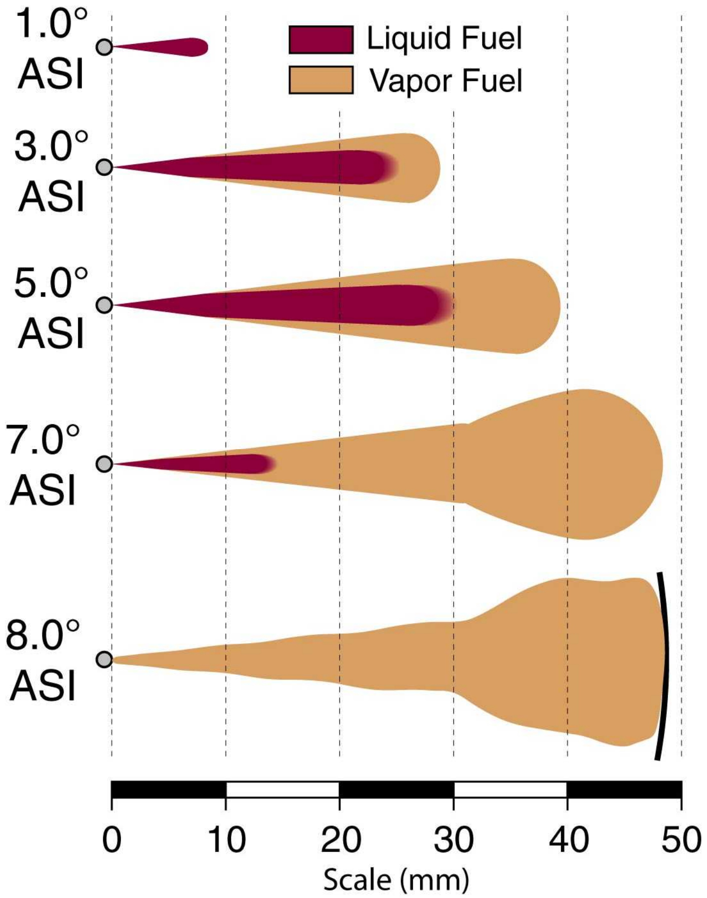
- Step 1: Dilute intake stream with recirculated exhaust gases (EGR) to lower combustion temperatures, and thereby reduce thermal formation of nitrogen oxides (NOx)
- Step 2: Inject fuel earlier (or later) to give it more time to mix before combustion to avoid fuel-rich regions that form soot (contributes to particulate matter, PM)
- Under some conditions, reduced heat transfer due to lower combustion temperatures can improve thermodynamic efficiency
- Unfortunately, other pollutant emissions, in particular carbon monoxide (CO) and unburned hydrocarbons (UHC) typically increase above regulated limits



LTC spray penetrates more quickly + longer liquid; liquid recedes after EOI, but before SOC

- Injection into lower density: faster spray penetration, longer liquid length
- Liquid recedes before SOC as vapor hits piston wall

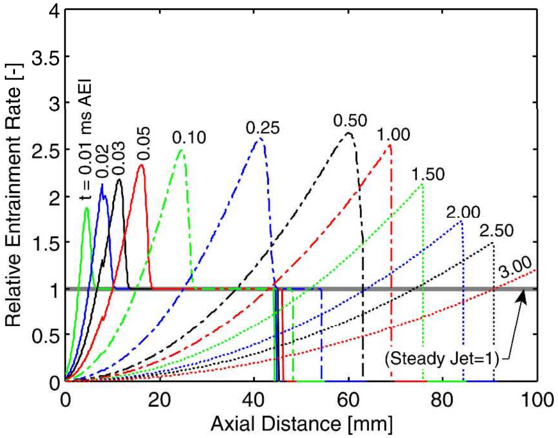




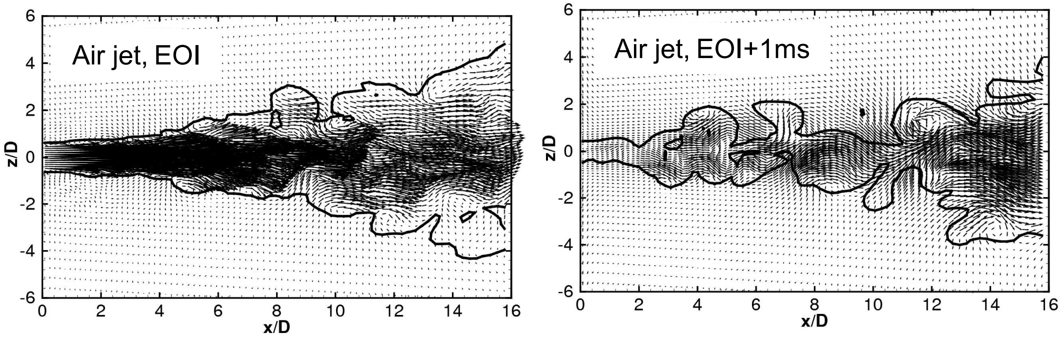
1-D analytic, KIVA RANS, and Sandia LES models predict wave of increased entrainment after EOI

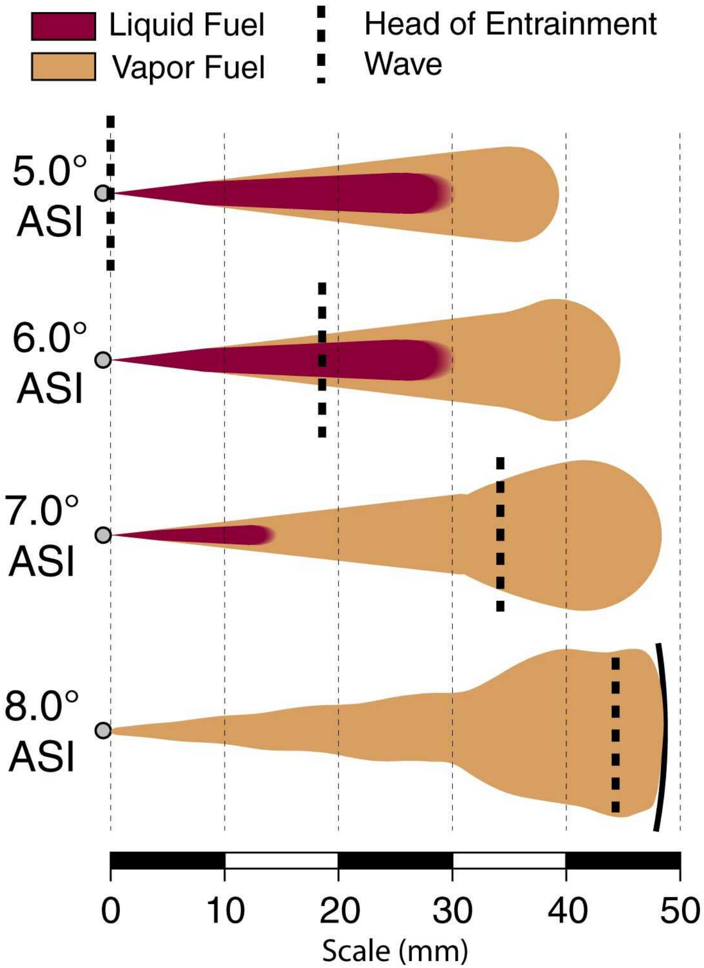
- Reduction in upstream jet velocity draws in more entrainment, which reduces velocity further, driving more entrainment, etc.
- LES (Oefelein, Hu): EOI ramp-down causes large flow structures to separate rather than collide; ambient fluid is entrained into gaps

1-D model →

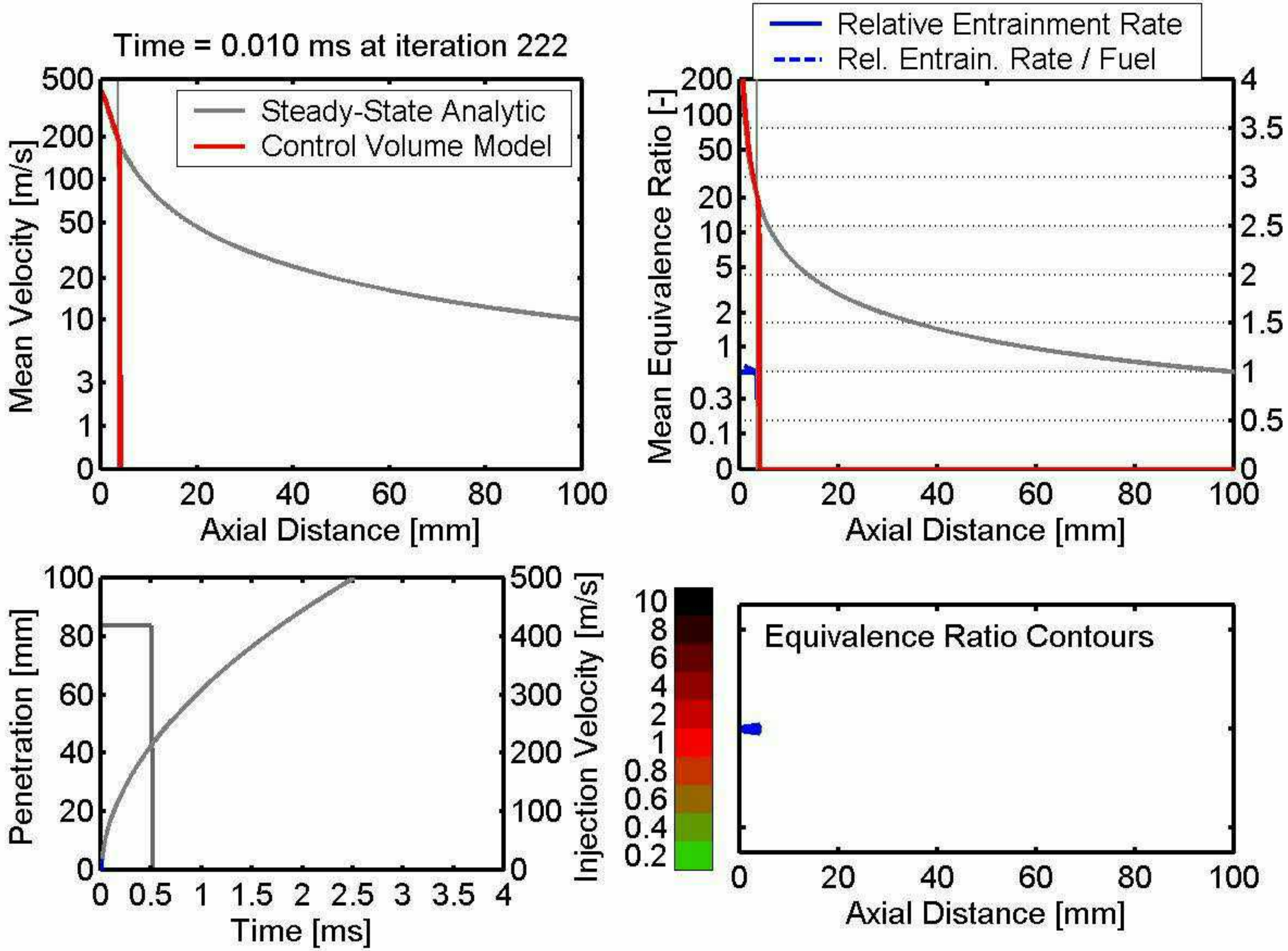


LES model ↓



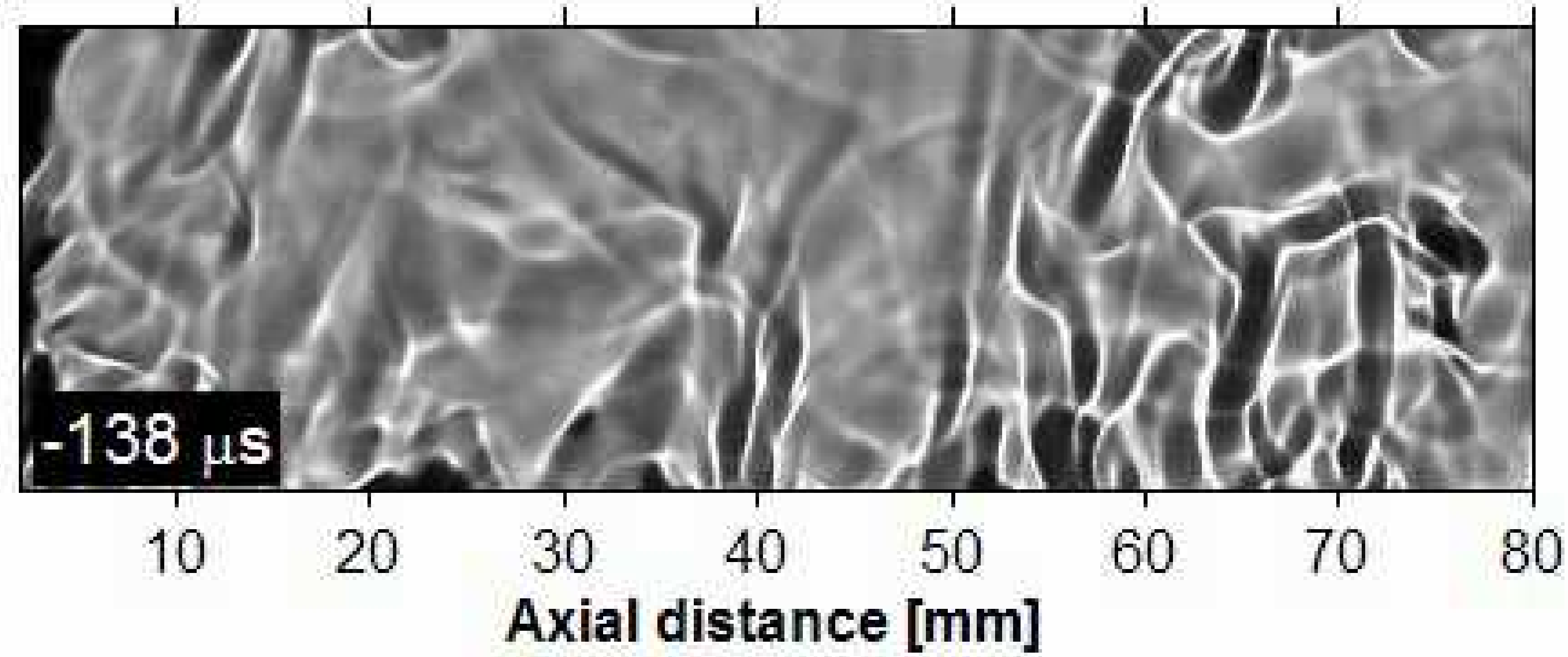


1-D jet model predicts "wave" of increased entrainment after EOI



Experiments show significant near-injector structural changes after EOI

- Upstream velocities decrease significantly after EOI, downstream velocities are higher
- Jet is tightly confined during injection, but large near-injector structures emerge after EOI



Diesel Shadowgraph (Lyle Pickett and coworkers, available at www.sandia.gov/ecn/)

LES air-jet model shows fluid-mechanical changes in jet structure and entrainment increase after EOI

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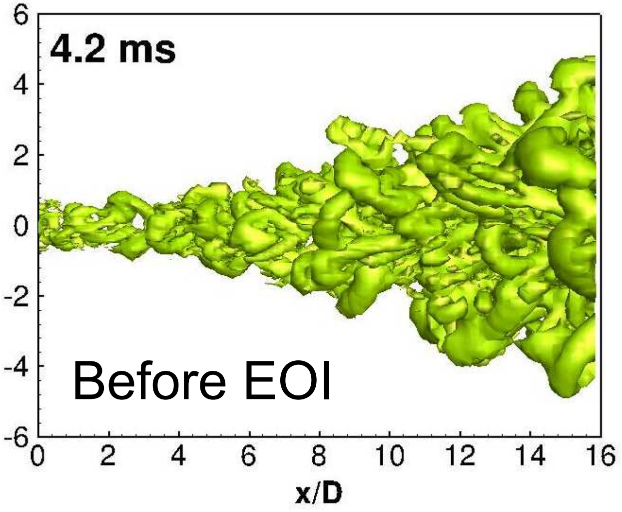
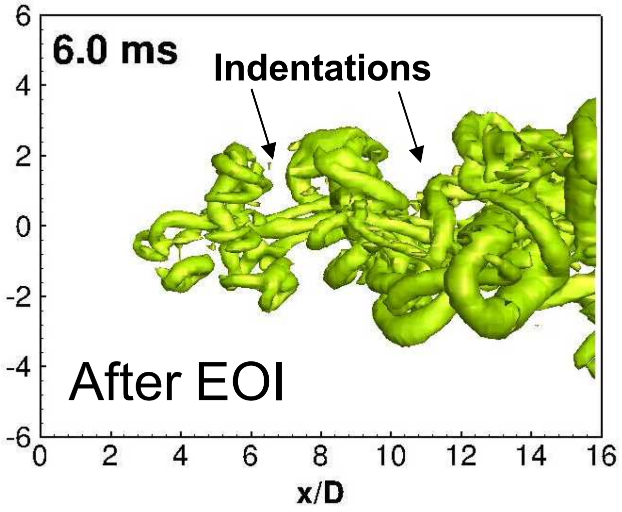
LES λ_2 visualization shows ambient engulfment between separating large-scale structures after EOI



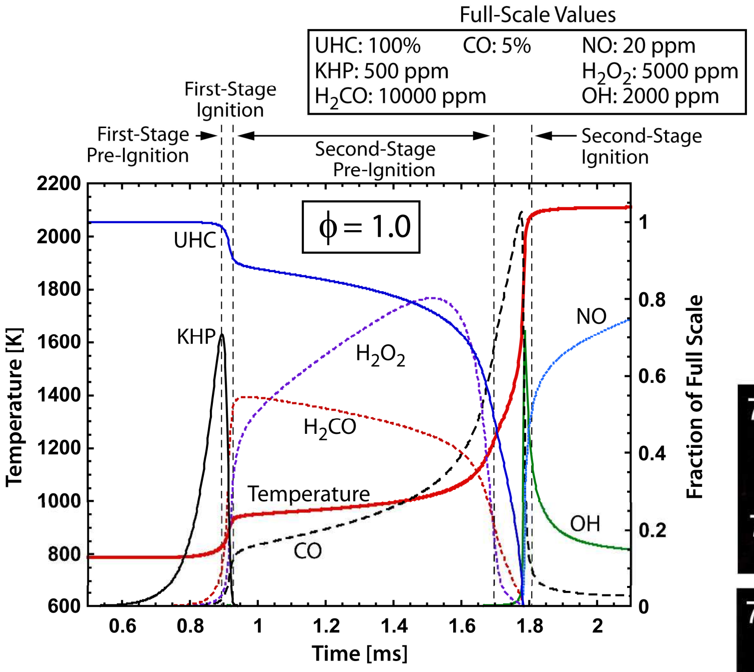


- $\lambda_2 \equiv$ 2nd-largest eigenvalue of $S^2 + \Omega^2$ (S and Ω $\equiv$ symmetric and anti-symmetric parts of ∇V)
- Vortex cores have $\lambda_2<0$, so $\lambda_2=0$ marks vortex core boundary, where azimuthal velocity is max.
- After EOI, vorticity, breakdown and turnover rates ↓, so large structure growth ↑
- Axial velocity inversion separates large structures, inhibiting coalescence
- Ambient fluid entrains into indentations between large structures (not apparent in RANS)
- Small-scale dynamics (scalar dissipation) decrease: not responsible for ↑ entrainment

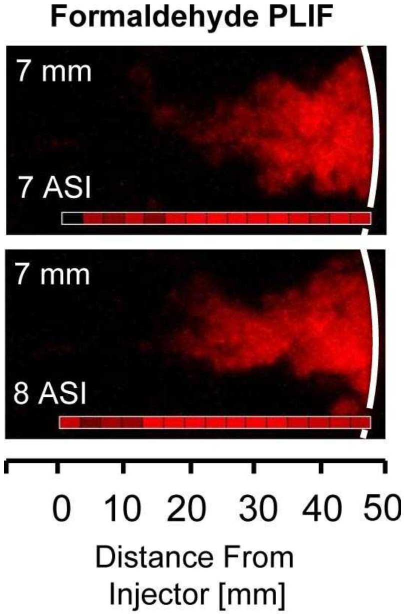
LES predictions imply that boundary conditions (rate-shaping), which affect large-scale structures can be tailored to achieve a desired mixing state

First-stage ignition in downstream vapor fuel, partially burned fuel (UHC, CO) throughout jet

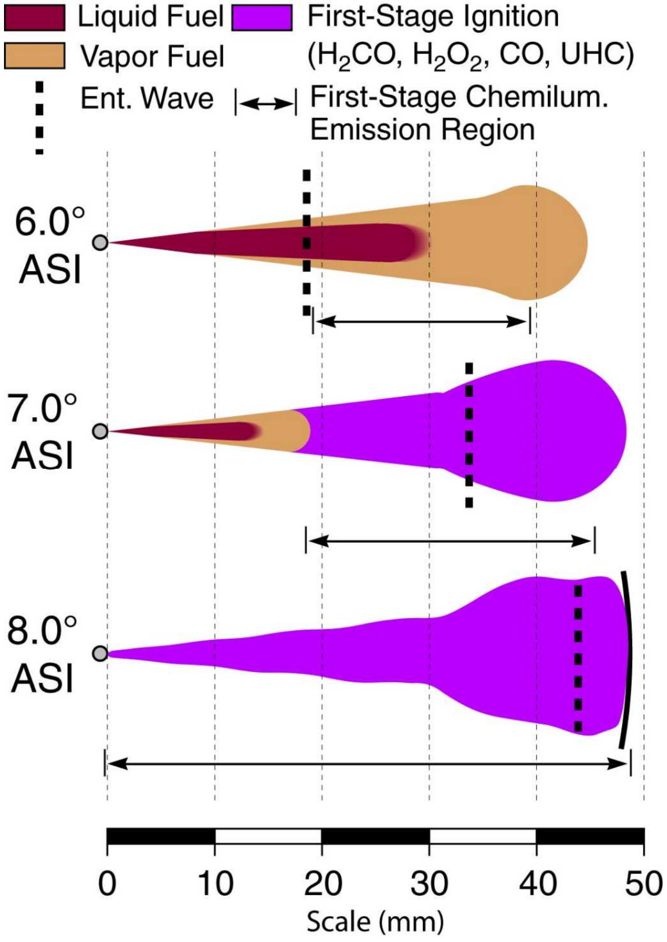
- LLNL chemical kinetics model: formaldehyde at 1st-stage ignition
- Experiments: Formaldehyde fluorescence at 1st stage, throughout jet



← Model

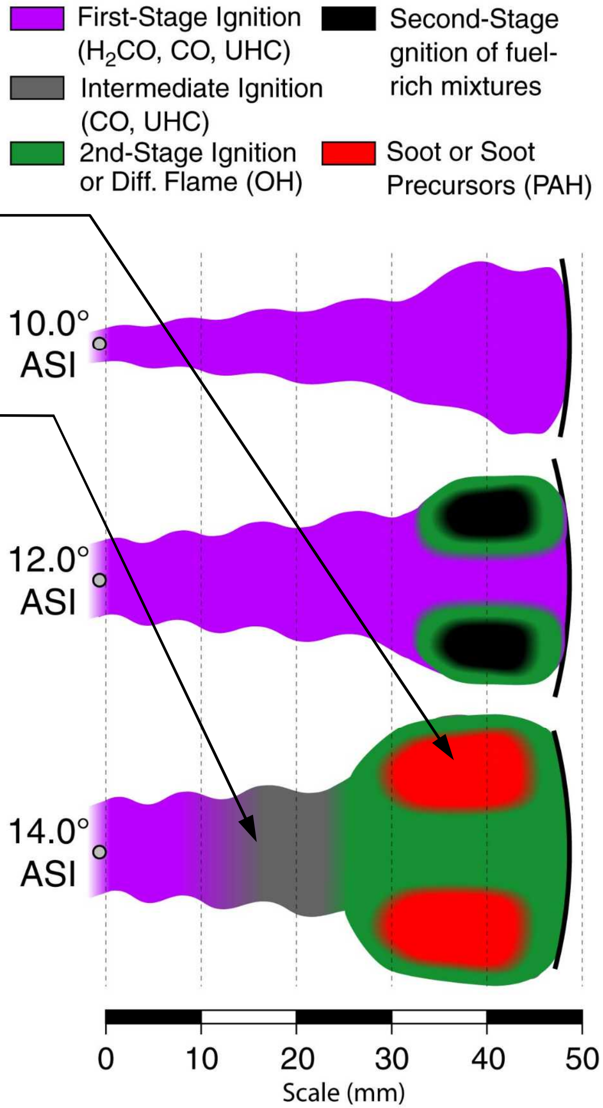


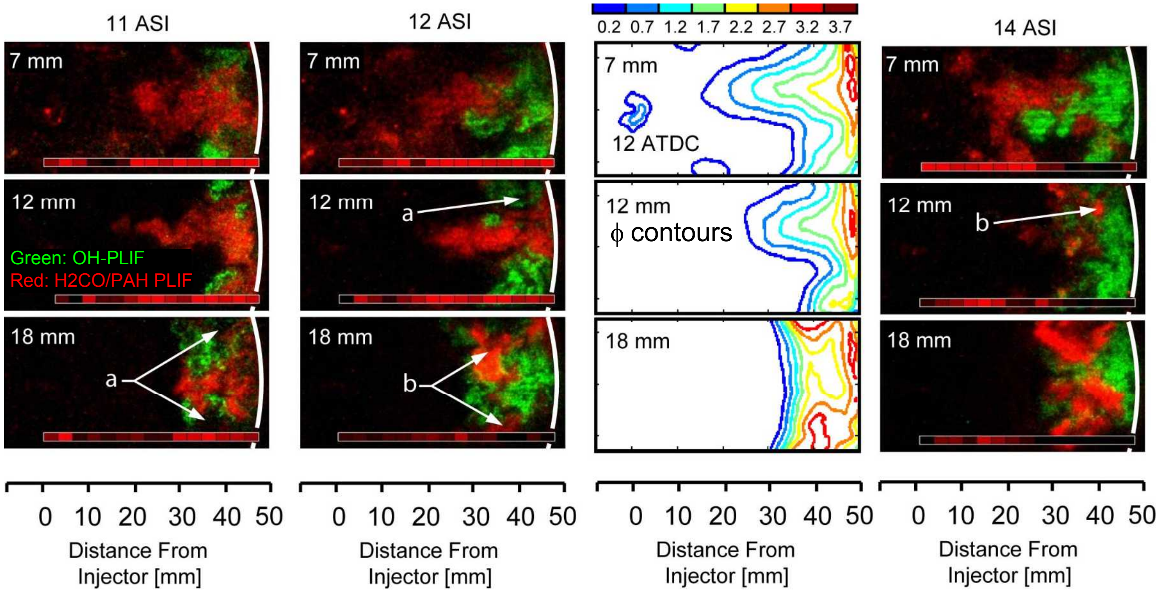
Experiment →



Second-stage ignition downstream where ϕ~1, followed by soot in rich pockets at head of jet

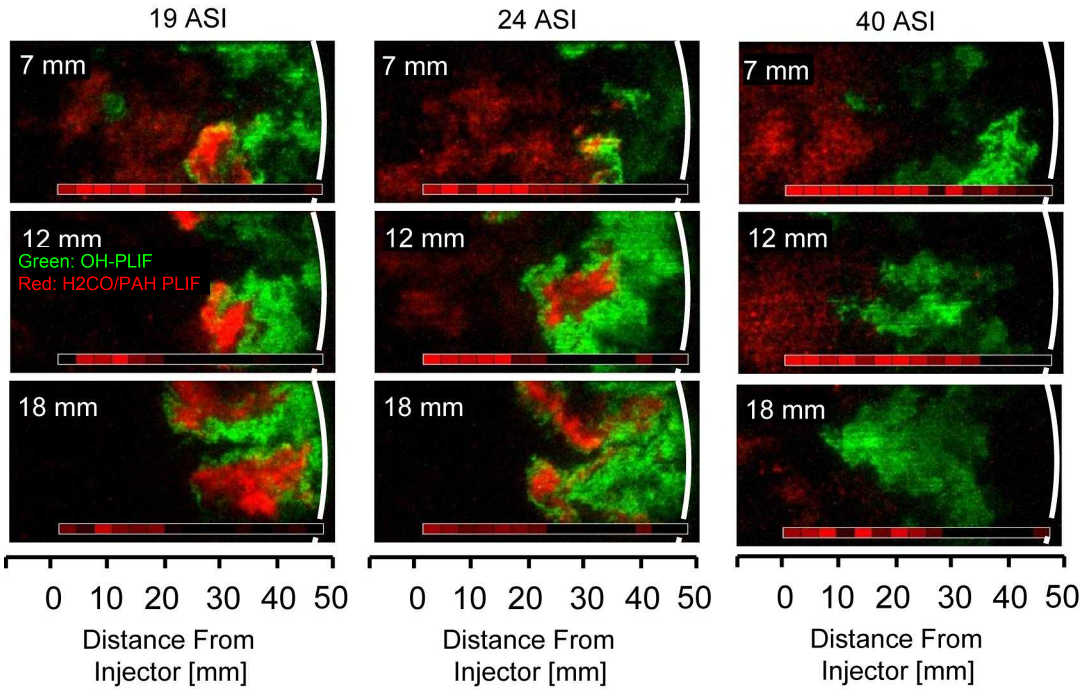
- Simultaneous PLIF of OH (green) and formaldehyde/PAH (red) show 2nd-stage ignition across most of downstream ϕ~1 jet
- Soot and PAH form in ϕ>2 pockets
- In lean upstream regions, experiments and LLNL kinetics simulations show partially burned fuel (CO, UHC, formaldehyde)

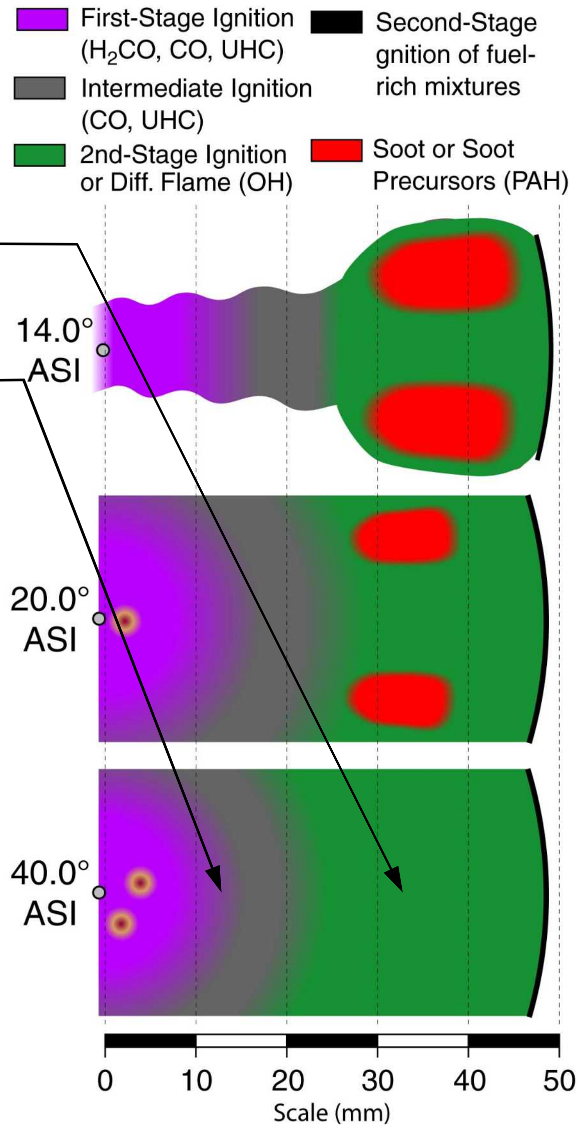




Late cycle: soot pockets largely oxidize, formaldehyde, CO, UHC remain upstream

- Late in cycle, simultaneous PLIF of OH (green) and formaldehyde/PAH/soot LII (red) show soot pockets surrounded OH
- Soot pockets are mostly oxidized by 40º ASI
- Partially burned fuel (CO, UHC, formaldehyde) remain late in cycle



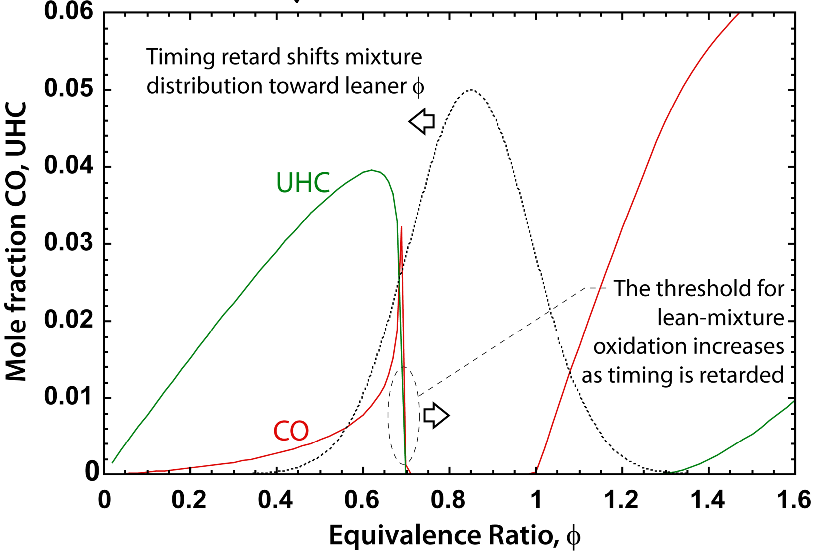


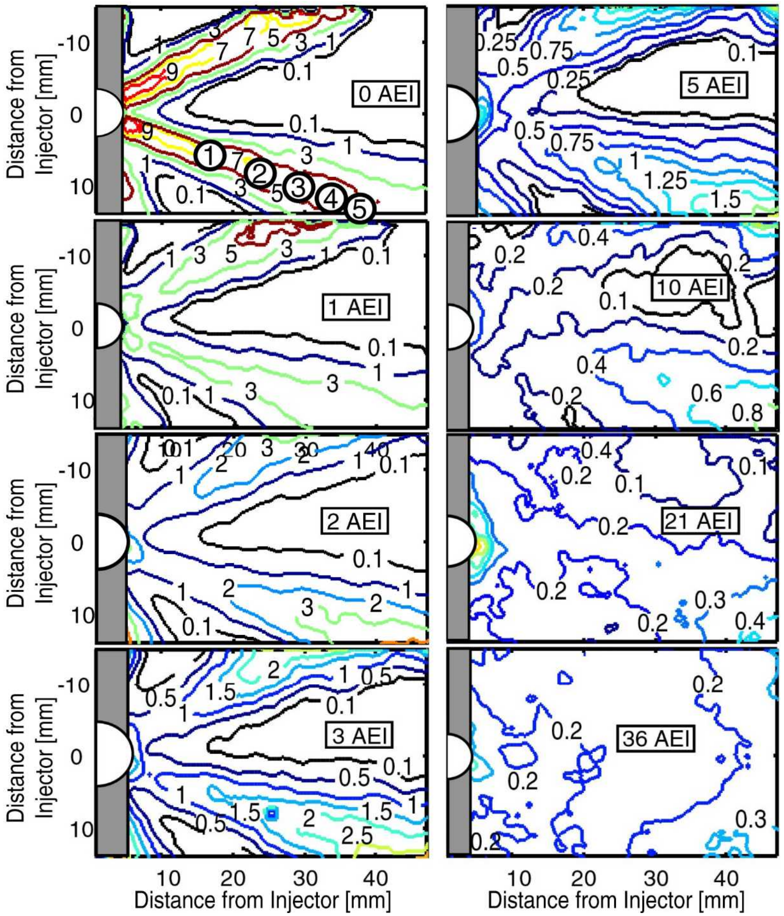
Experiments show over-lean regions near injector, where kinetics models predict partial combustion

- Experiments: vapor-fuel tracer-PLIF shows lean mixtures near injector where combustion-PLIF shows late-cycle formaldehyde and CO
- LLNL kinetics models: Lean mixtures have long dwell between first- and second-stage ignition, with UHC and CO persisting to exhaust

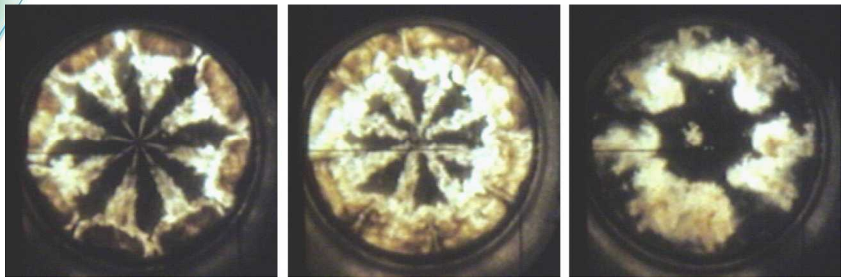
Kinetics Model
↓

ϕ from experiment →



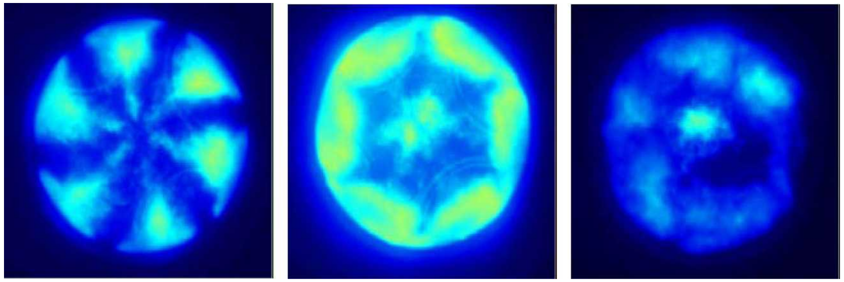


Injector dribble is not universal in the literature, but it is not uncommon either



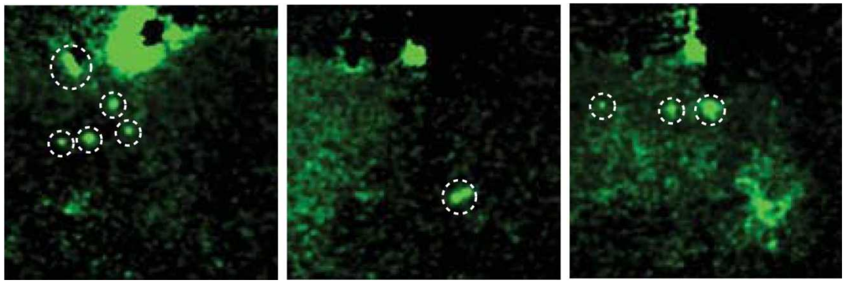
SAE 930971 (Dec, Sandia)

- Heavy-duty, diesel reference fuel
- Cam-driven, mini-sac injector
- Late soot at center



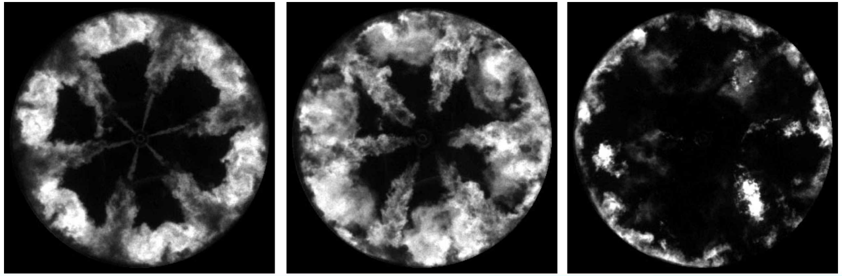
SAE 2005-01-3845 (Taschek et al., Aachen)

- Light-duty, diesel fuel
- Common-rail, mini-sac injector
- Conceptual model: Inj. sac vapor → soot



SAE 2009-01-1446 (Ekoto et al., Sandia)

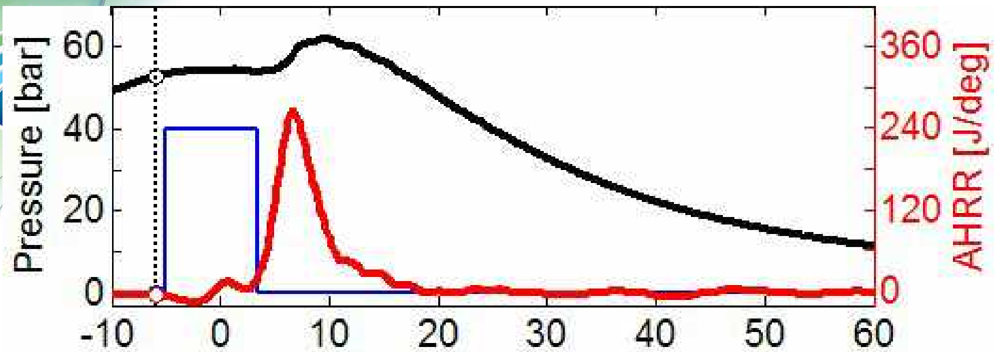
- Light-duty, diesel fuel
- Common-rail, mini-sac injector
- Side-view PLIF, bright fuel droplets late



SAE 2001-01-2004 (Mueller et al., Sandia)

- Heavy-duty, diesel reference fuel
- HEUI, VCO injector
- No late soot at center (but sometimes yes)

LTC PCCI: Injector Dribble

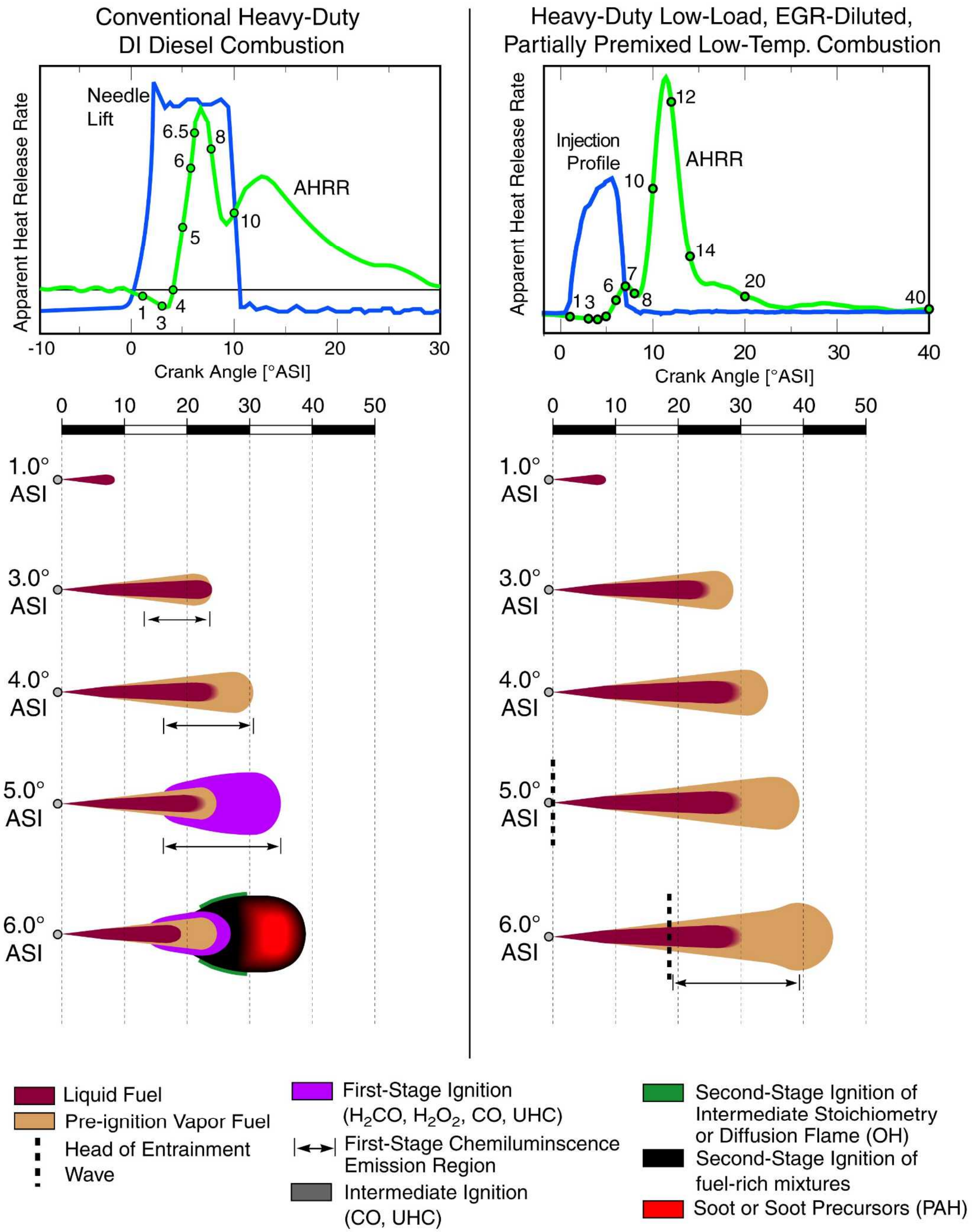


- Diesel PRF (realistic boiling pt)
- Droplets emerge from different holes each cycle
- “Sparkling” could be flash-boiling events or tumbling ligaments

Fuel	Diesel PRF CN42.5
Intake	13% O_2
Load	3 bar IMEP
Intake T	78 C
Intake P	2.14 bar
CR SOI	-5° ATDC
Speed	1200 rpm
Engine r_C	10.75
View	35 mm square
Framing	14400 fps
Filter	None

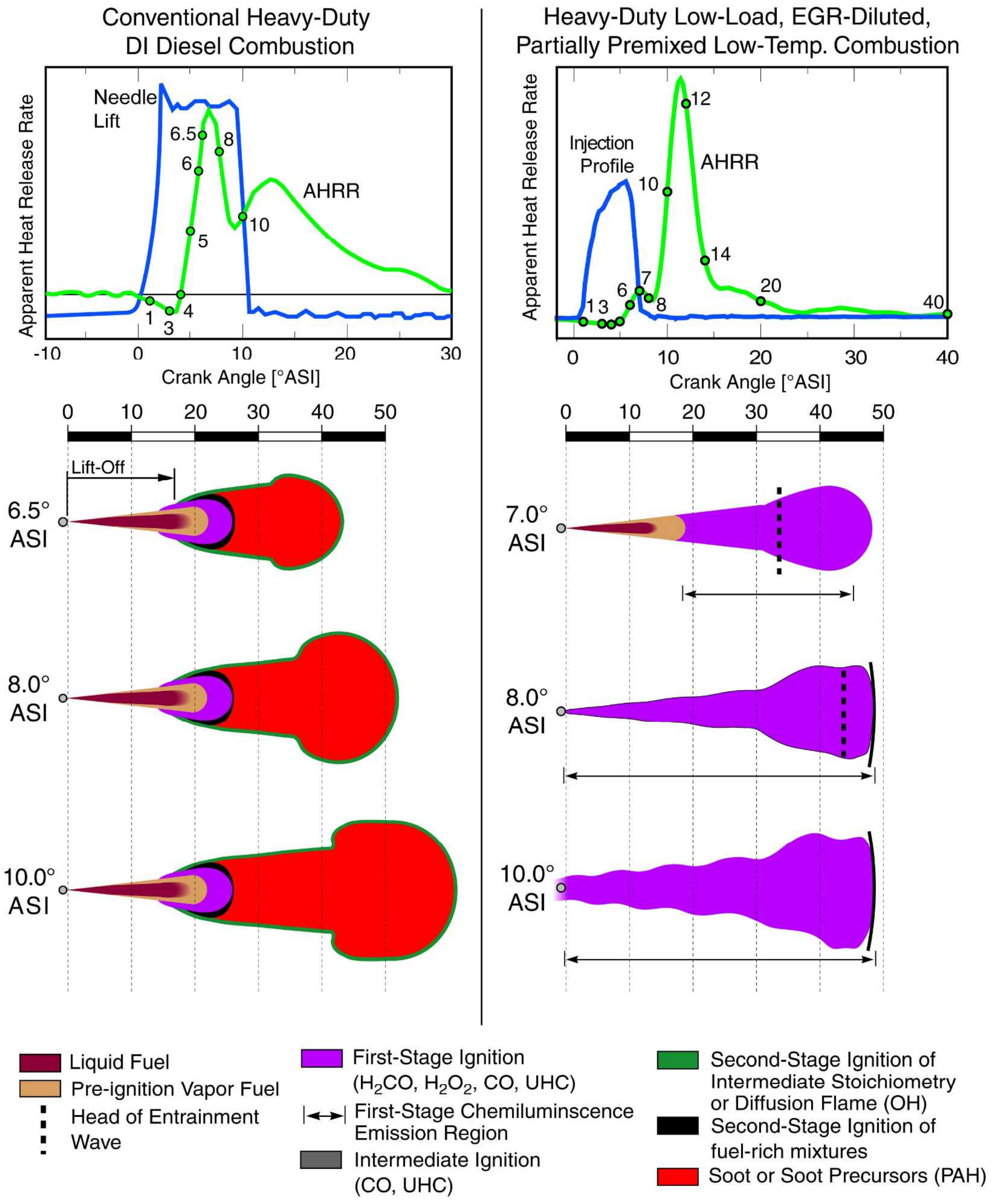
HD Conv. vs. LTC: 0-6 ºASI

- Early penetration and vaporization are similar for conventional and LTC
  - Liquid fuel penetration is longer for early-injection LTC (cooler, lower density ambient)
- First-stage ignition occurs sooner for conventional diesel, during injection, in downstream jet
- Conventional second-stage ignition in rich mixtures yields early soot formation
- As LTC injection ends, entrainment is temporarily boosted in traveling wave



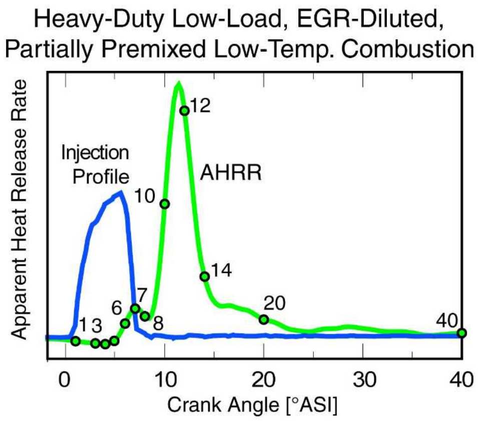
HD Conv. vs. LTC: 6-10 ºASI

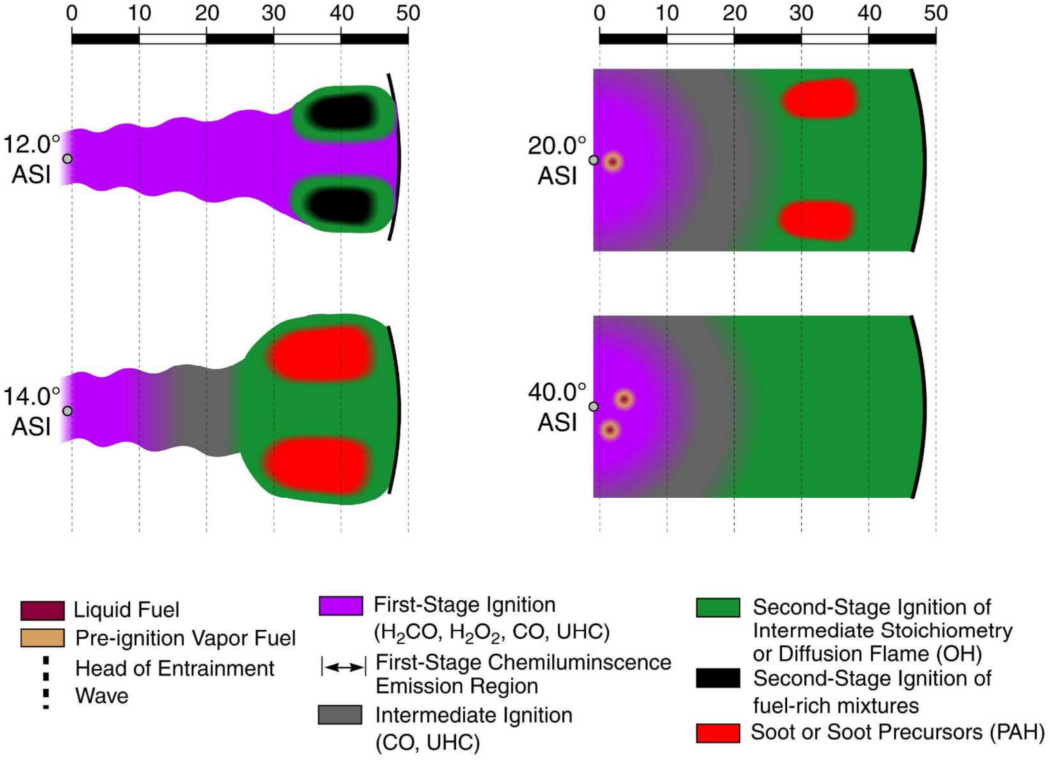
- Conventional diesel jet enters “quasi-steady” period, characterized by fuel-rich, soot-filled interior surrounded by diffusion flame
- After-injection entrainment increase causes liquid-length recession in LTC jet
- First-stage ignition occurs throughout most of LTC jet, from lean upstream mixtures to richer downstream mixtures.



HD LTC:
10-40 ºASI

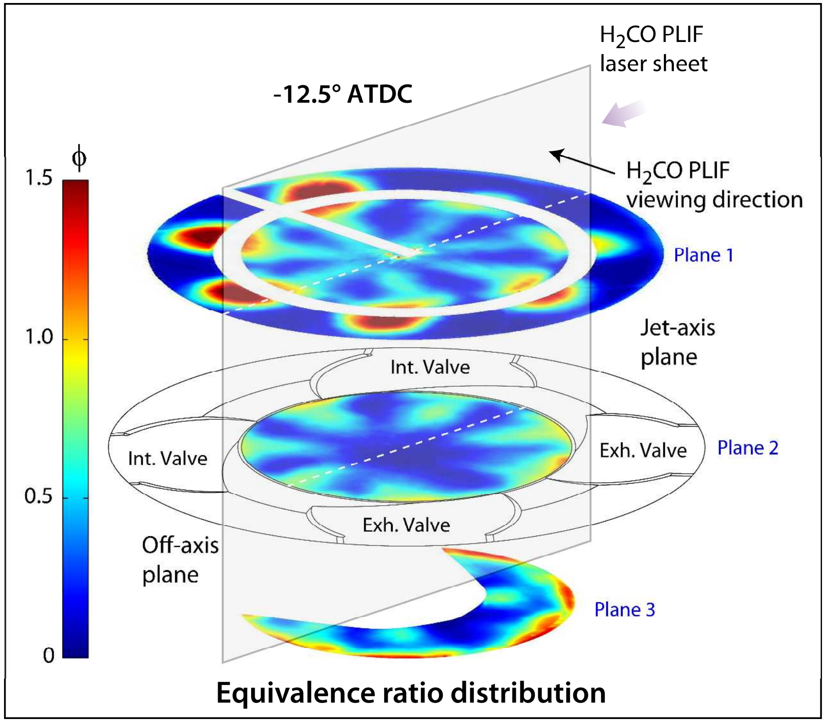
- Second-stage ignition occurs after EOI, in the downstream jet
- At “threshold-sooting” conditions, soot forms in fuel-rich pockets near the piston bowl-wall
- Late in the cycle, most bulk soot oxidizes
- Fuel-lean upstream regions do not achieve second-stage ignition, and contribute to UHC and CO emissions
- Injector “dribble” deposits fuel-rich droplets within fuel-lean field near injector


Heavy-Duty Low-Load, EGR-Diluted, Partially Premixed Low-Temp. Combustion

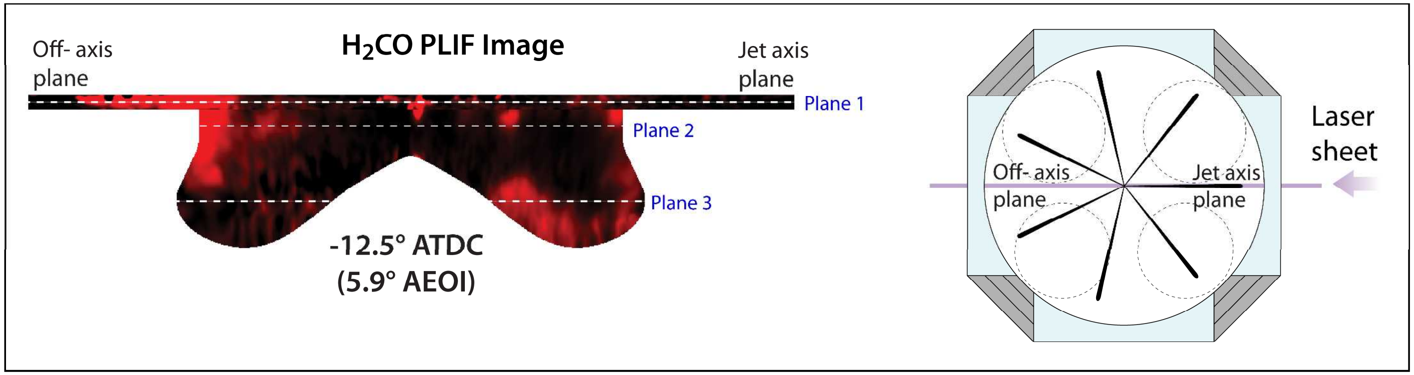


Light Duty: Swirl transports mixtures away from jet axes, first-stage ignition throughout jet

- For light-duty, swirl transports mixtures off the jet axes
- Like heavy-duty, light-duty jet is lean upstream and fuel-rich close to bowl
- Piston bowl contour redirects jet, with rich mixtures at lip and in piston bowl
- First-stage ignition (H_2CO PLIF) occurs nearly simultaneously throughout jet



Equivalence ratio distribution

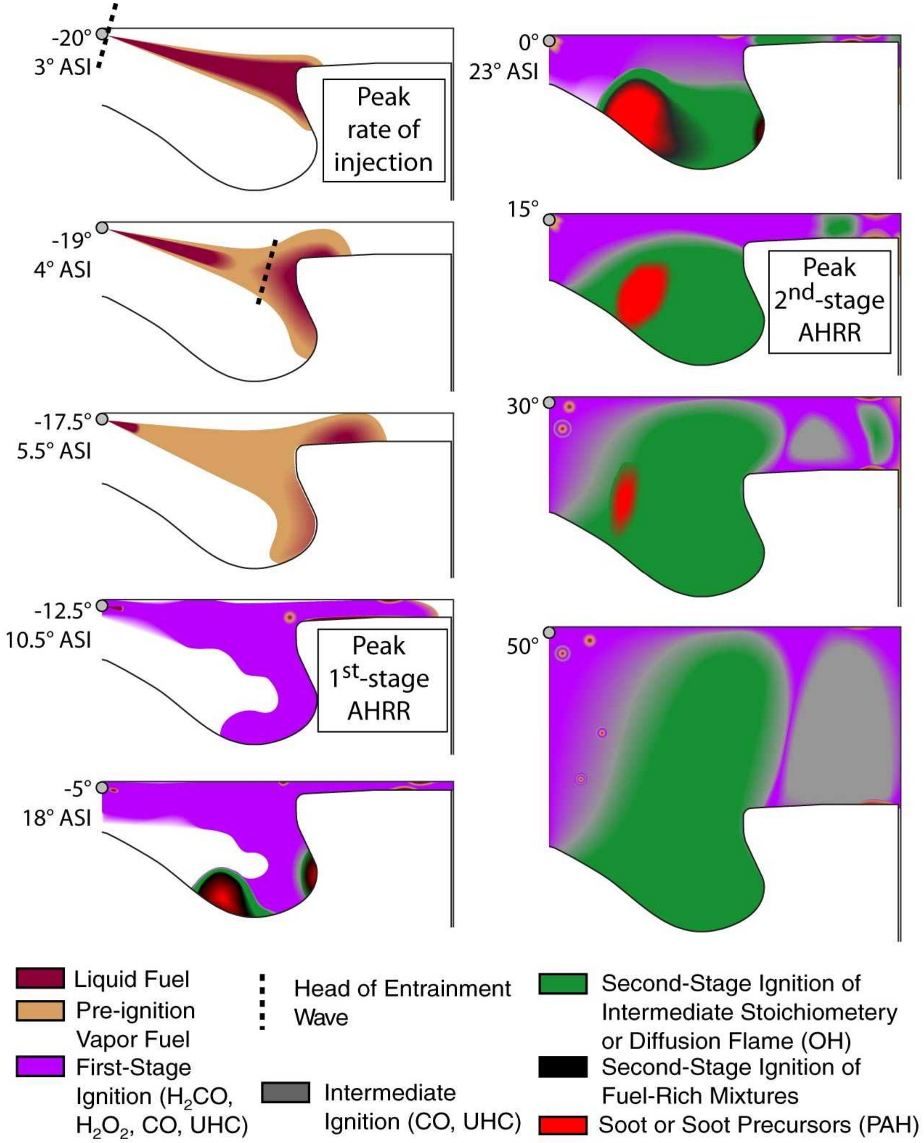


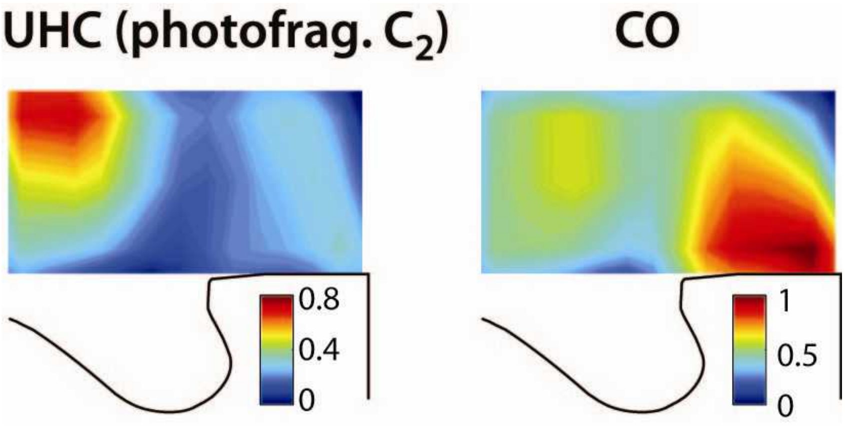
H_2CO PLIF Image

-12.5° ATDC (5.9° AEOI)

Light Duty: Interaction with piston bowl and reverse squish play more prominent role

- In light-duty engines, liquid fuel impinges on piston, especially for early injection
- Jet is split by lip of piston bowl, with rich mixtures mostly in bowl
- Reverse-squish pulls lean near-injector mixtures into squish: incomplete combustion + late film vaporization → CO, UHC





Review article summarizes heavy- and light-duty low-load EGR-diluted partially premixed LTC