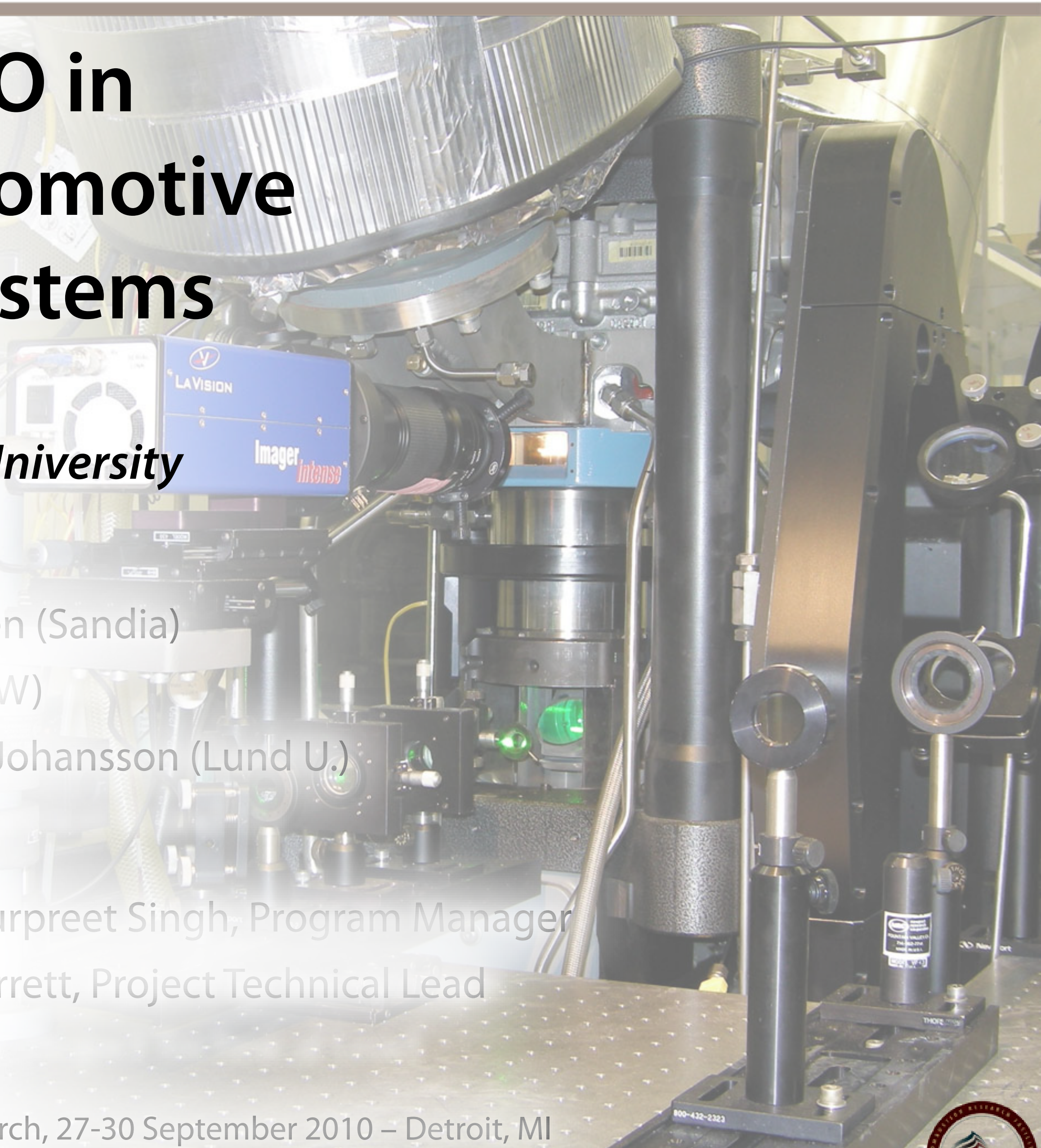
Sources of UHC and CO in Low Temperature Automotive Diesel Combustion Systems

Paul Miles
Sandia National Laboratories / Lund University



Co-workers:

- Isaac Ekoto, Mark Musculus, Ben Petersen (Sandia)
- Dave Foster, Youngchul Ra, Rolf Reitz (UW)
- Öivind Andersson, Ulf Aronsson, Bengt Johansson (Lund U.)

Sponsors:

- US Department of Energy, EERE-OVT, Gurpreet Singh, Program Manager
- General Motors Corporation, Russell Durrett, Project Technical Lead

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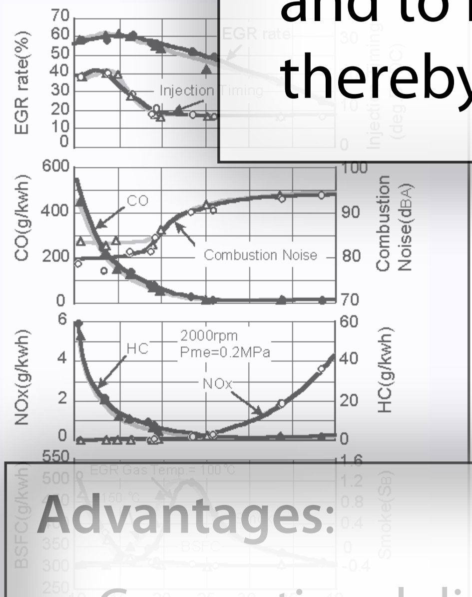
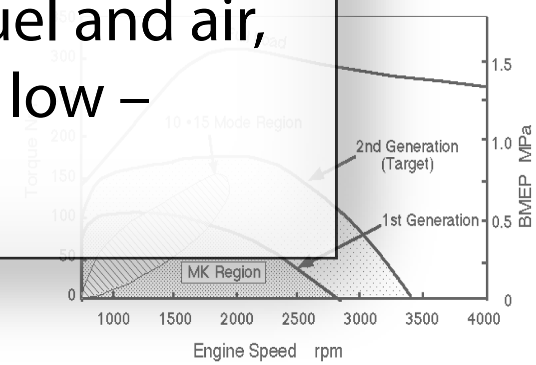
What are low-temperature combustion systems?

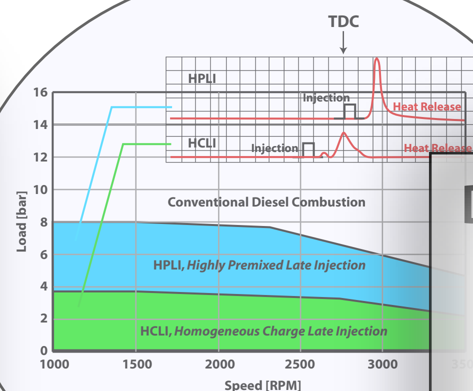
- Low Temperature combustion systems go by a variety of names (MK, PCI, PPCI, HECC, HCLI, Unibus, etc.)
- All of them strive to enhance premixing of fuel and air, and to keep peak combustion temperatures low – thereby avoiding NO_x and soot formation

Toyota "smokeless" combustion (SAE 2001-01-0655)





The Nissan MK system (SAE 2001-01-0200)



AVL HCLI systems (MTZ, Sept 2003)

Advantages:

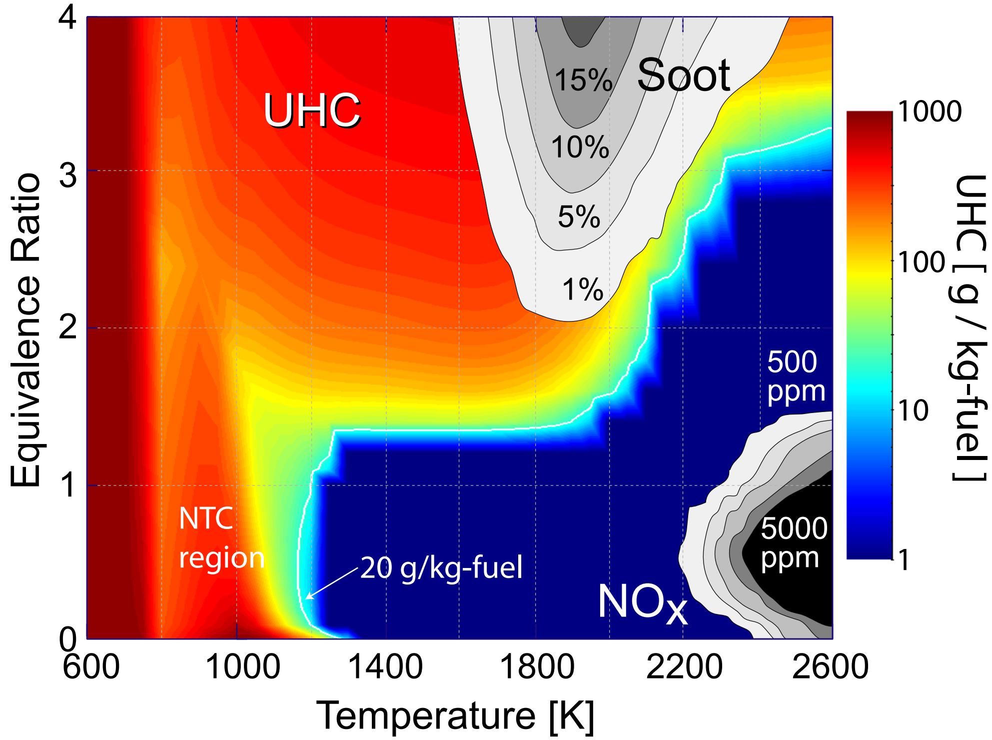
- Conventional diesel FIE & bowl geometry
- Combustion timing is controlled by fuel injection

Disadvantages:

- High UHC & CO emissions (efficiency penalty)
- Limited speed / load range

UHC can stem from both fuel-rich and fuel lean mixtures

Constant ϕ & T, P = 60 bar, Δt=2 ms, 21% O_2
Soot/NOx contours from Kitamura, et al., JER 3, 2002



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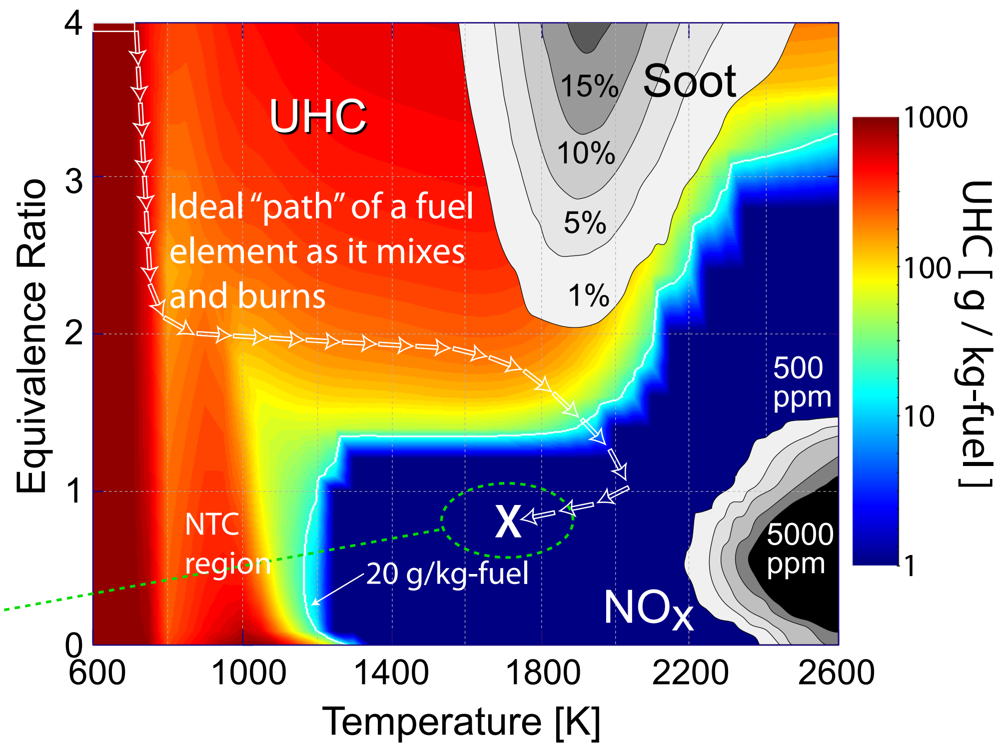
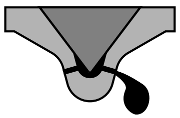


- For temperatures above ~1200 K, UHC oxidation in lean mixtures is complete (independent of EGR rate)

UHC can stem from both fuel-rich and fuel lean mixtures

Poor mixture formation:



- Low injection pressure
- Poor atomization
- Under or over-penetration
- Sac volume / hole dribble

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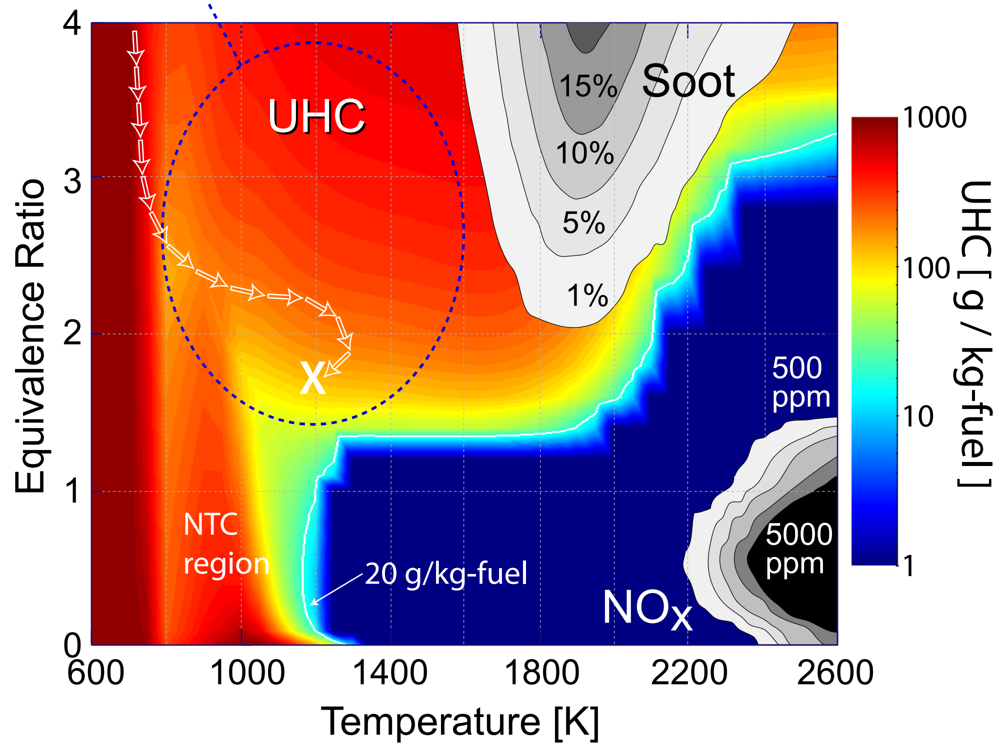

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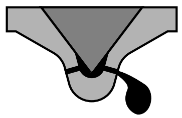

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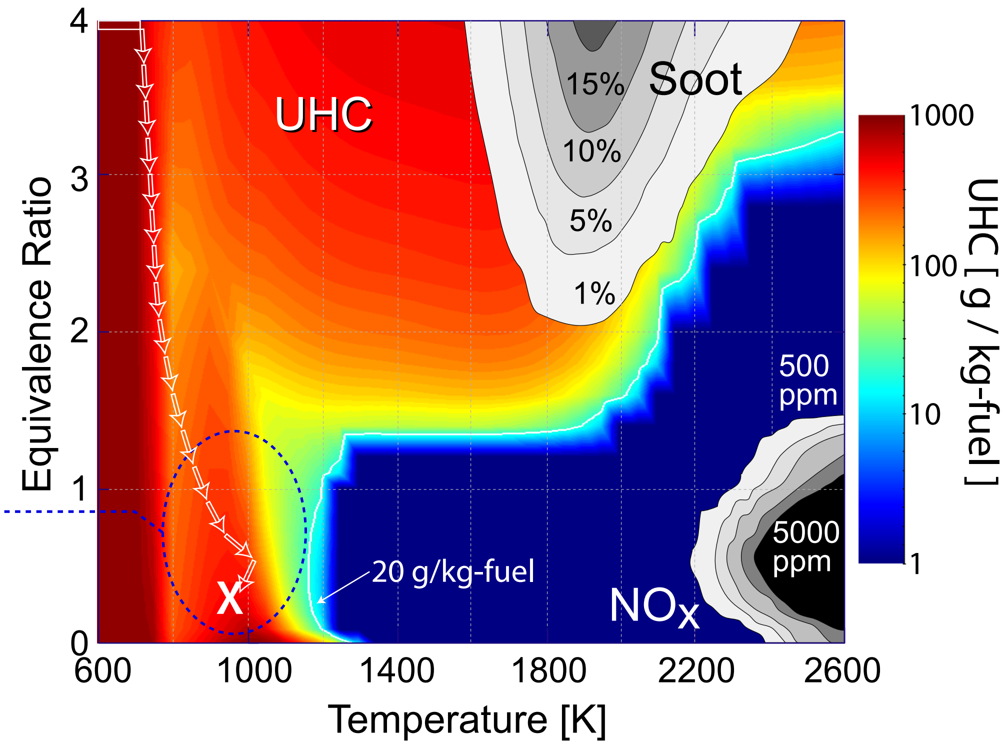
- Over-lean mixtures
  - Small nozzle holes
  - Excessive injection pressure
  - Excessive ignition delay



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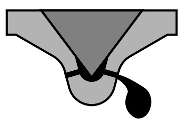
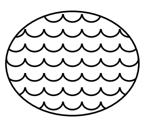


Cold quench layers
- Crevices
- Wall films



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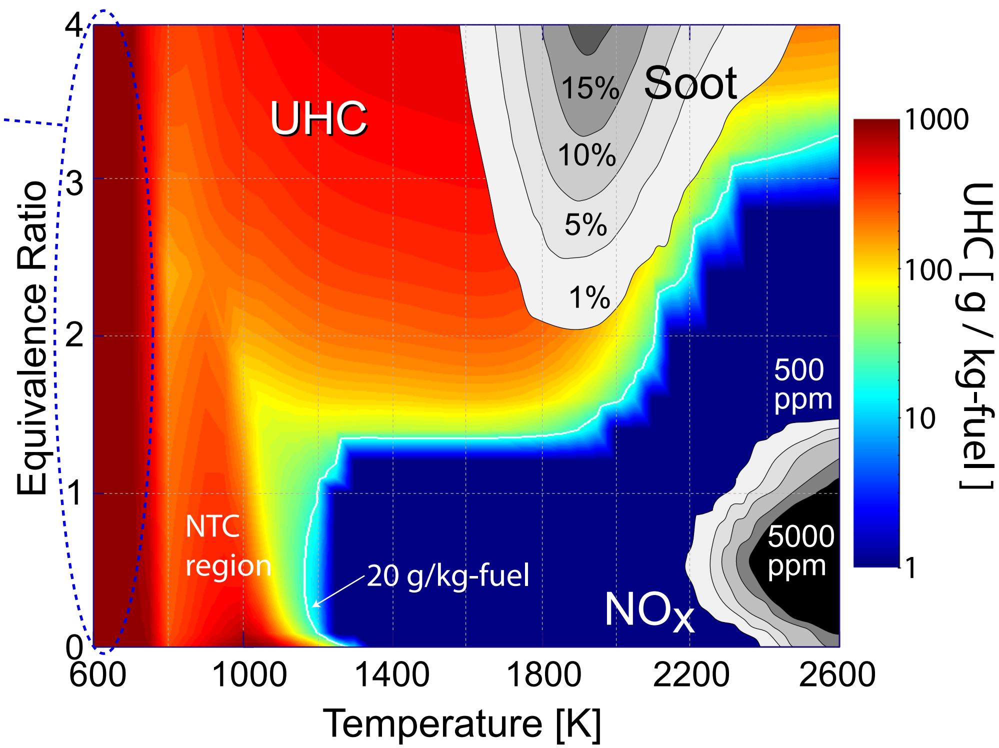

Bulk gas CO sources are similar to the bulk gas sources of UHC

Over-rich regions caused by poor mixture formation (typical of high load – CO emissions track soot emissions

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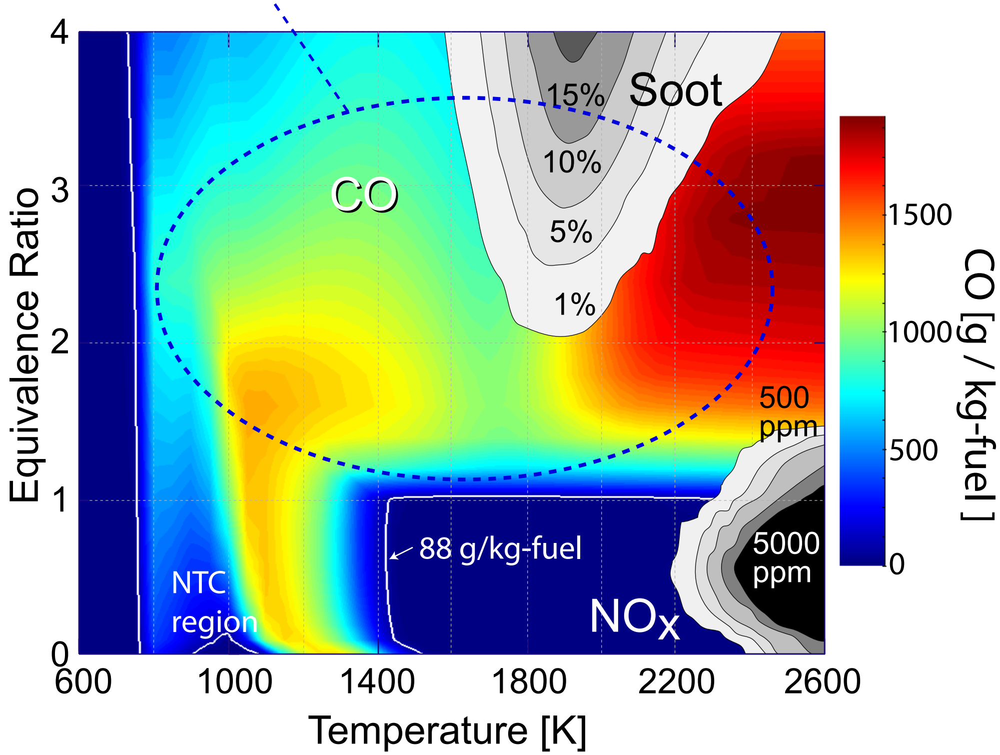

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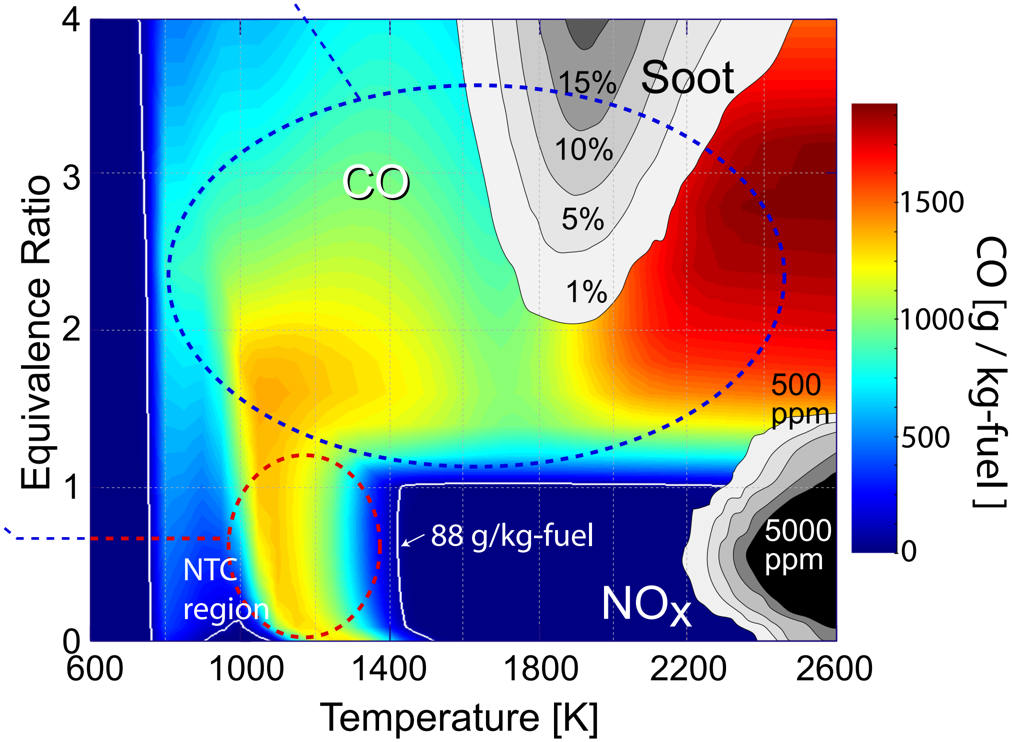
Constant ϕ & T, P = 60 bar, Δt=2 ms, 21% O_2
Soot/NOx contours from Kitamura, et al., JER 3, 2002

- Over-lean mixtures

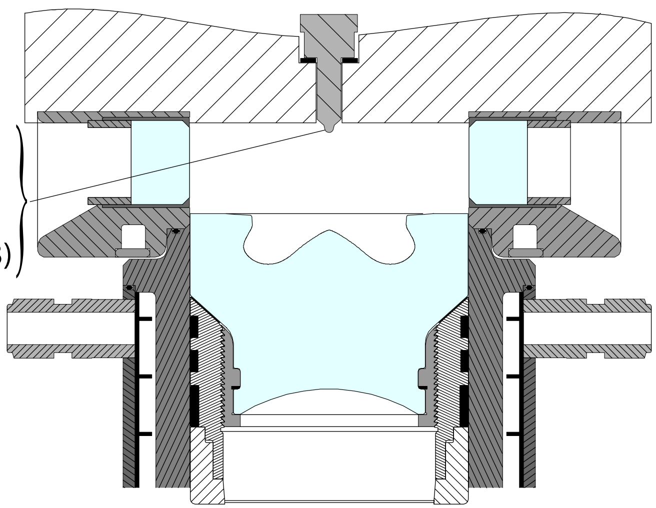
  (typical of light load – CO emissions correlate with τ_{ign}

- For temperatures above ~1450 K, CO oxidation in lean mixtures is complete (independent of EGR rate)



Sandia's light-duty optical engine facility

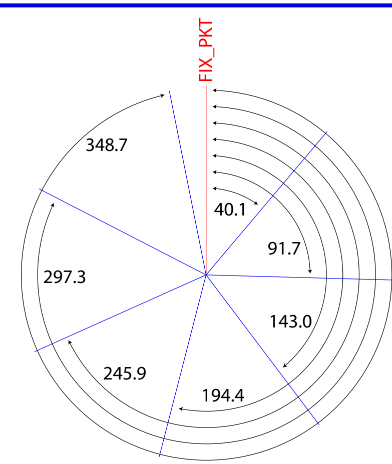
860 bar rail pressure
7-Holes, 0.14 mm
Included angle = 149°
Mini Sac (Vol. = 0.23 mm3)



Based on production GM 1.9L head
Bore = 82.0 mm, Stroke = 90.4 mm

The optical piston retains the same bowl geometry and valve-pockets as a production intent piston; only the crevice land height is larger

The Bosch CRI2.2 nozzle hole layout has also been modified to facilitate optical studies



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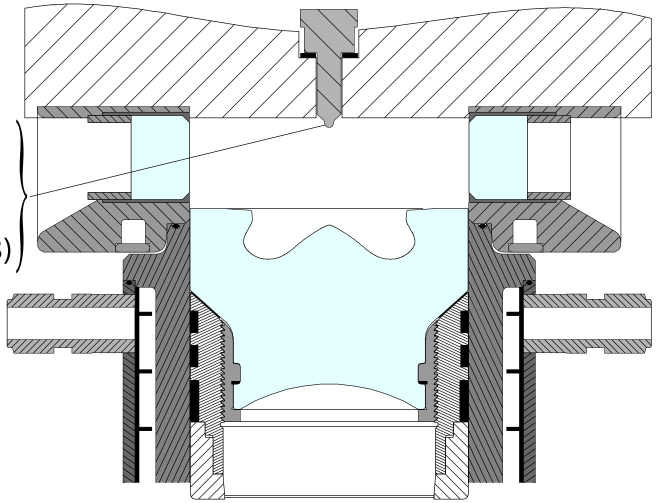

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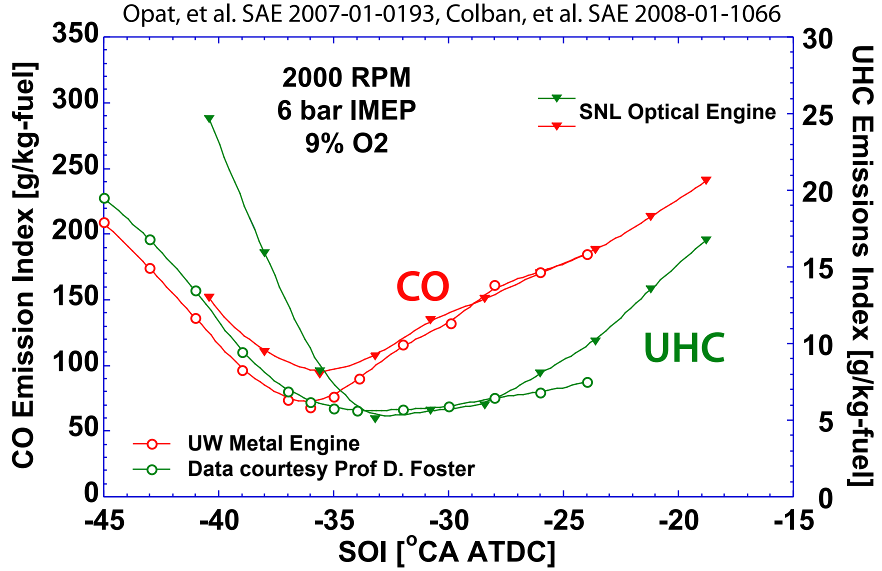

Both pressure history and emissions behavior are well-matched to metal test engines

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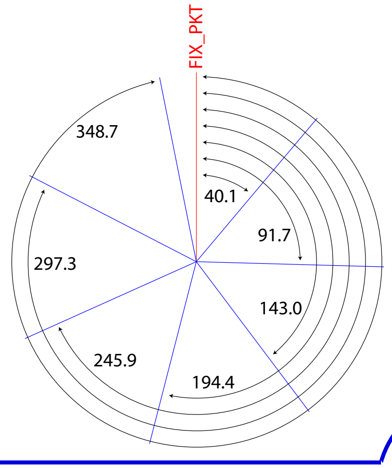
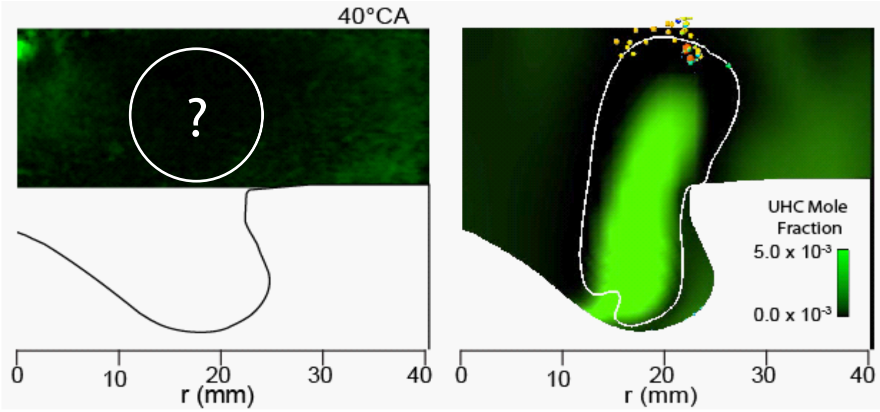


Recap from DEER 2008:

In early-injection (PCI-like) combustion systems, UHC is observed:

- Near the injector
- In the squish volume
- In mixture leaving the bowl



50 cycle average image

Predicted UHC

Simulations suggest that rich mixture leaving the bowl dominates, but this is only infrequently observed in the experiments

CO is mainly found within the squish volume

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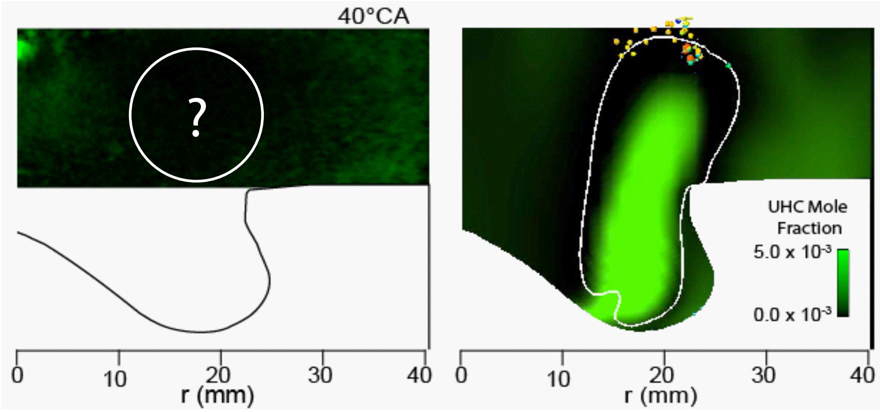

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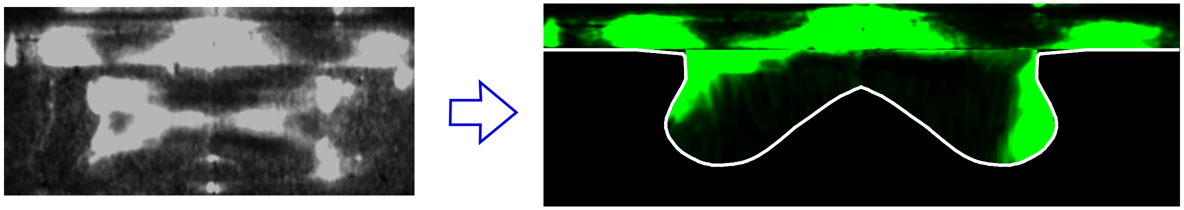
In our recent work, we have applied a variety of measurement techniques to:

- Identify the cause of the discrepancy between experiments and model
- Approximately quantify the magnitude of the UHC from various sources
- Improve the accuracy of in-cylinder CO measurements (eliminate interference)
- Examine the impact of load, O_2, SOI, and fuel type

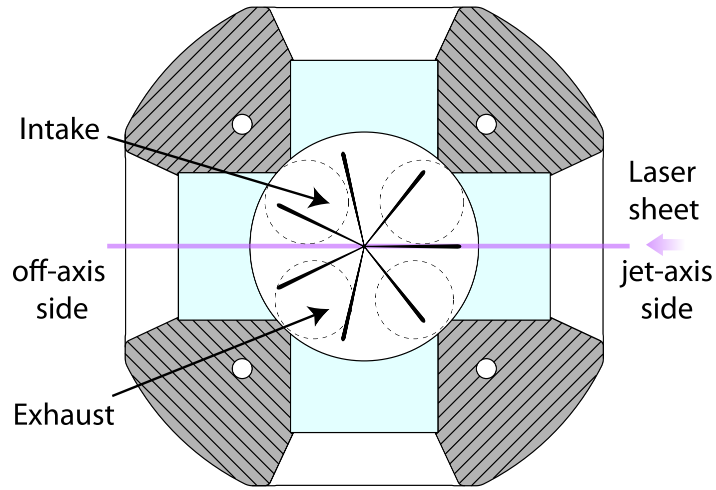
Complementary optical diagnostic techniques are used to image UHC and CO

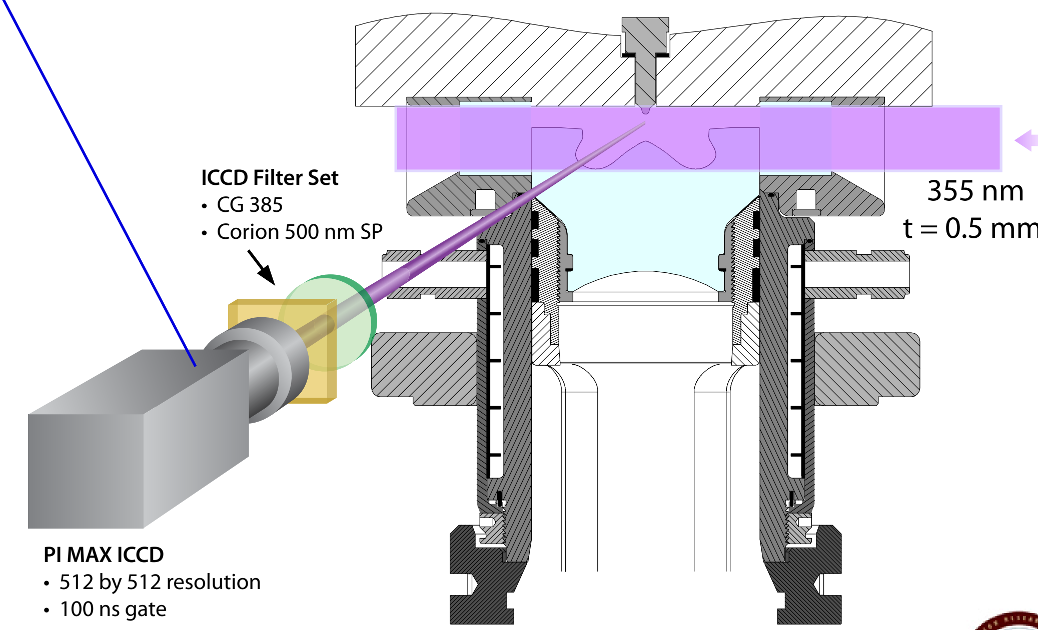
355 nm PLIF images capture CH_2O and PAH
(Parent fuel and products of ϕ>2 combustion)



Before correction

After correction a near seam-less image is obtained





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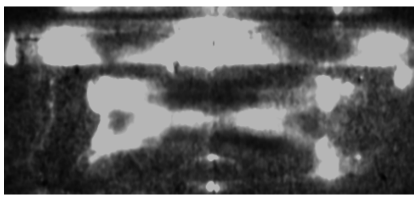

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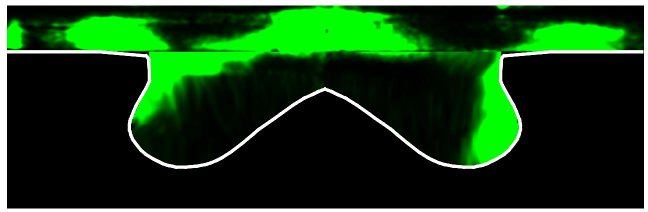

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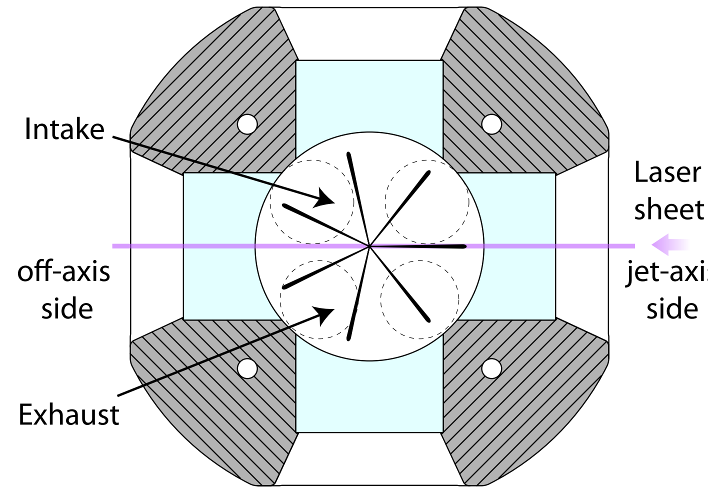
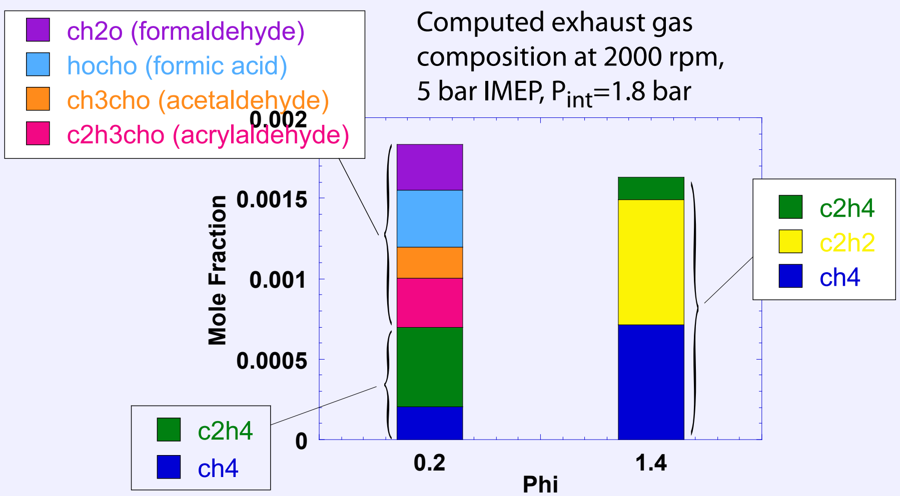
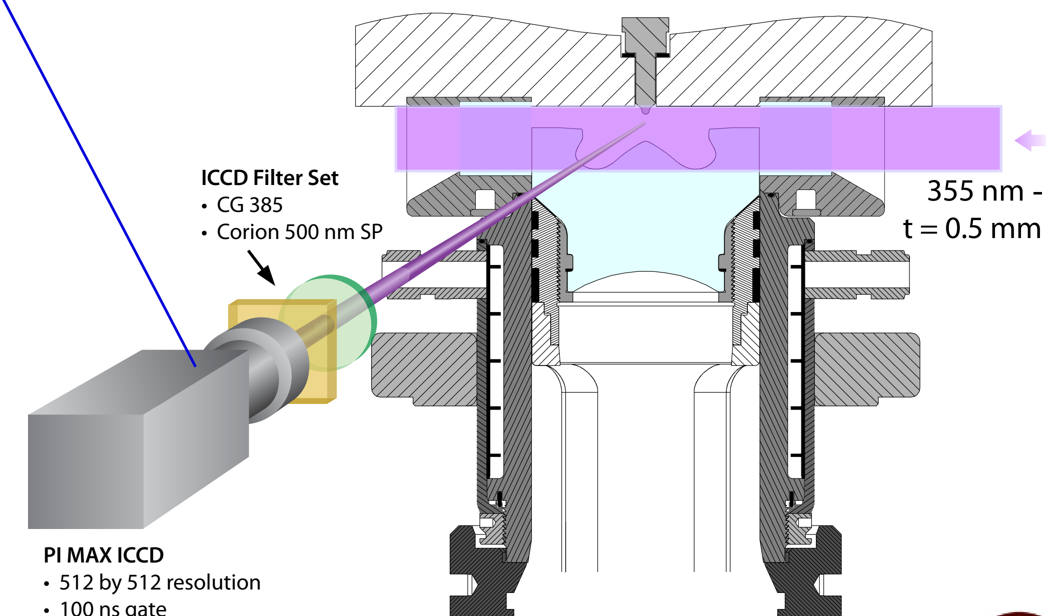


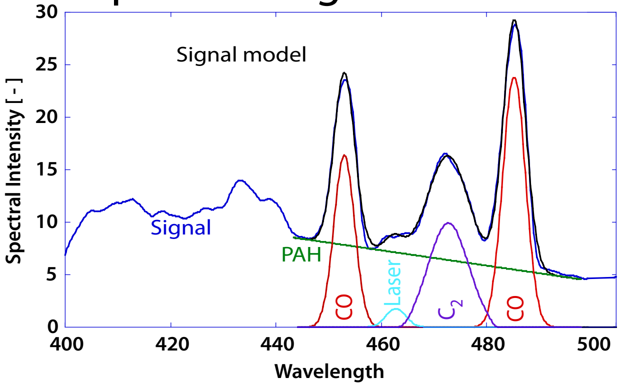


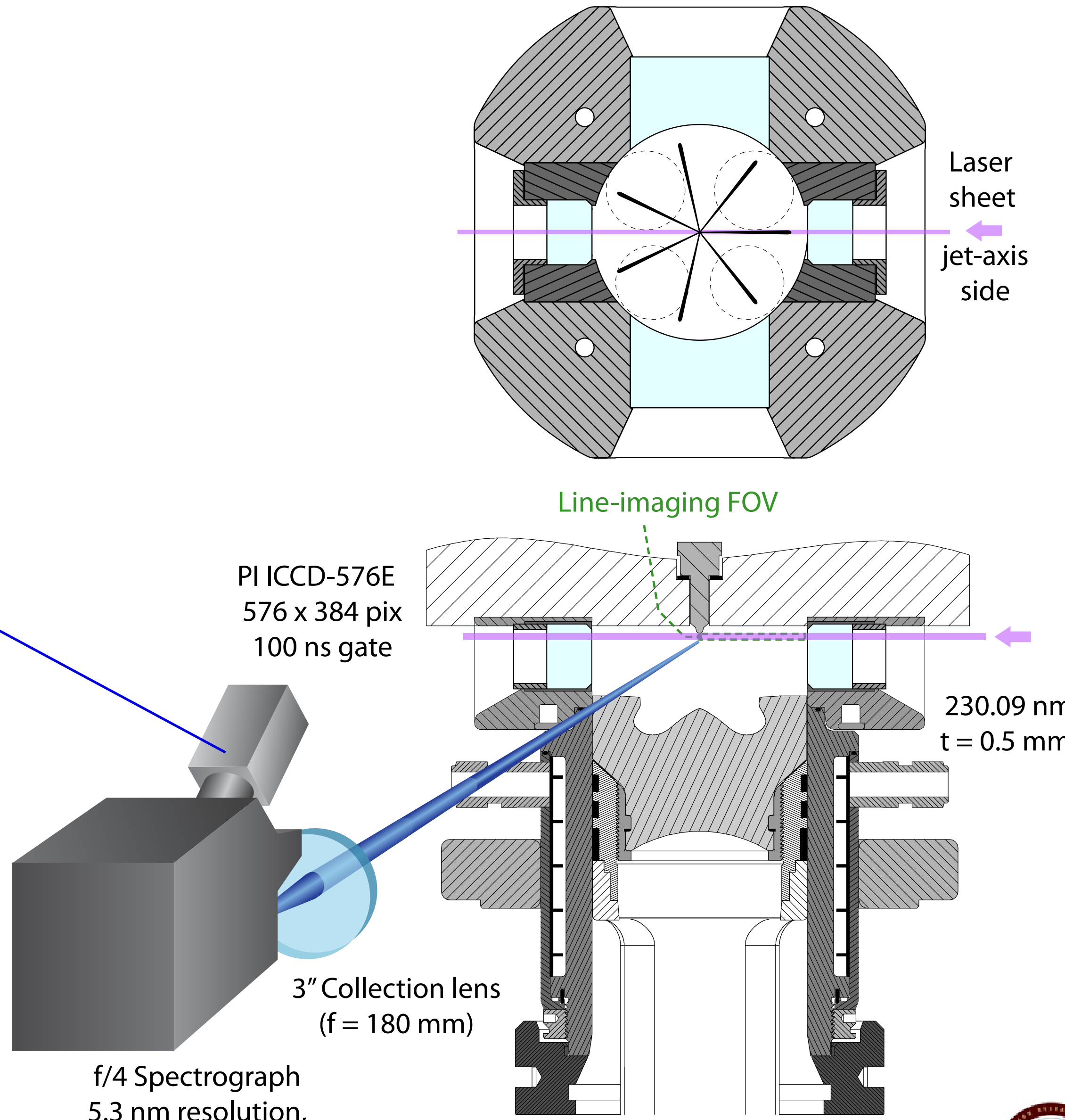
Rich mixture UHC consists of C_2H_4, C_2H_2, and CH_4—species which are not excited at 355 nm -



Deep-UV radiation excites CO and UHC inaccessible with 355 nm radiation

Spectrally-resolved data are obtained at each point along a line...





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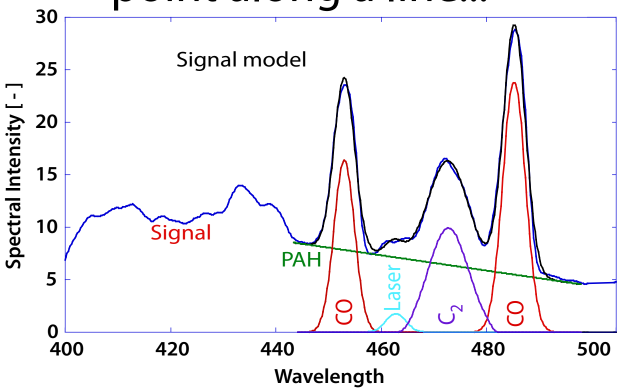
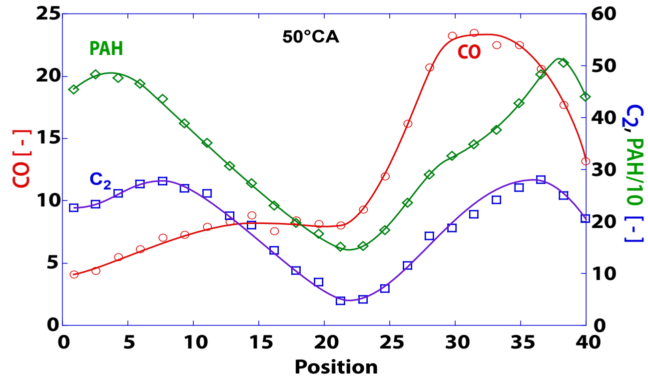
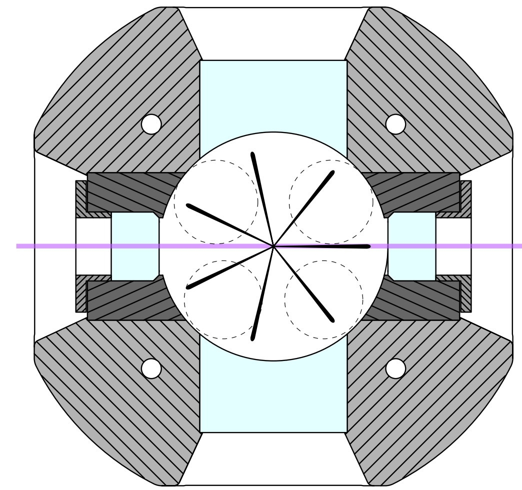
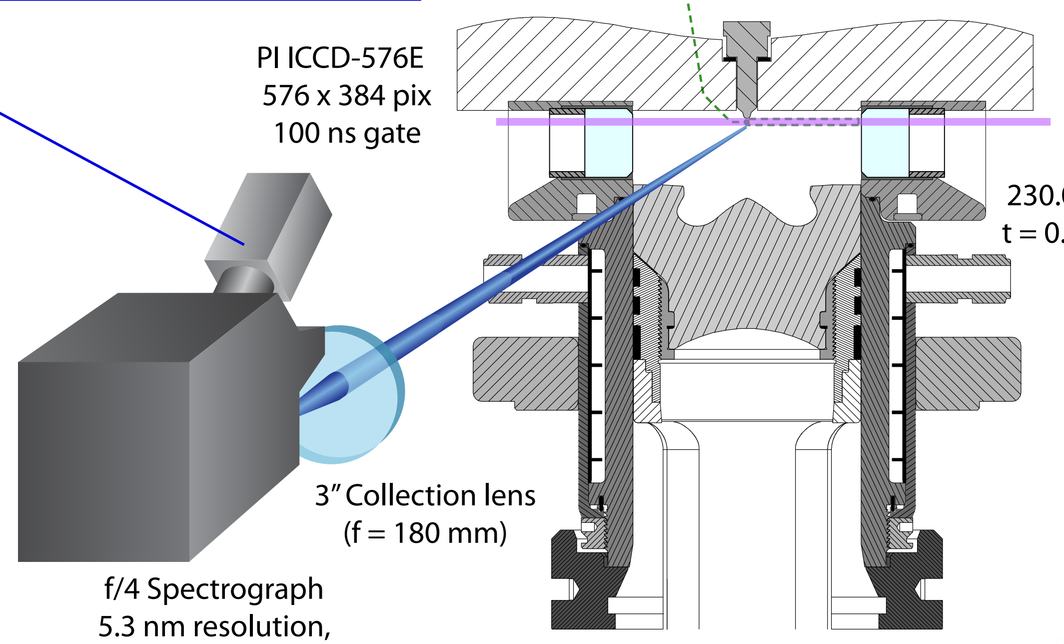


...providing radial profiles of CO, C_2, and PAH





Line-imaging FOV



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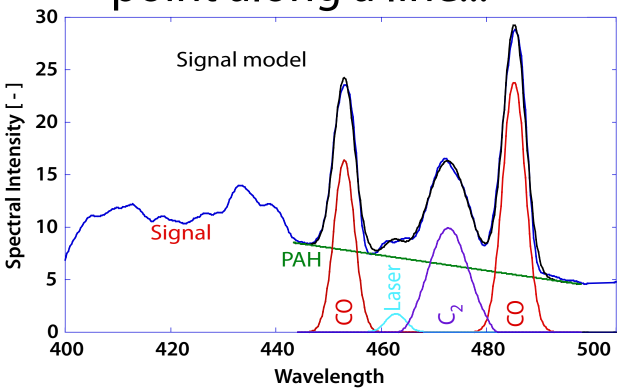

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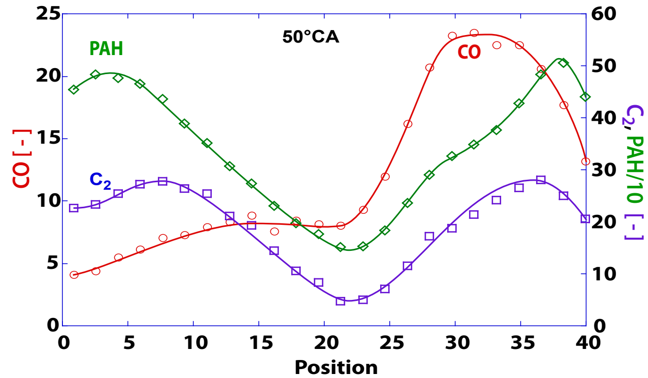
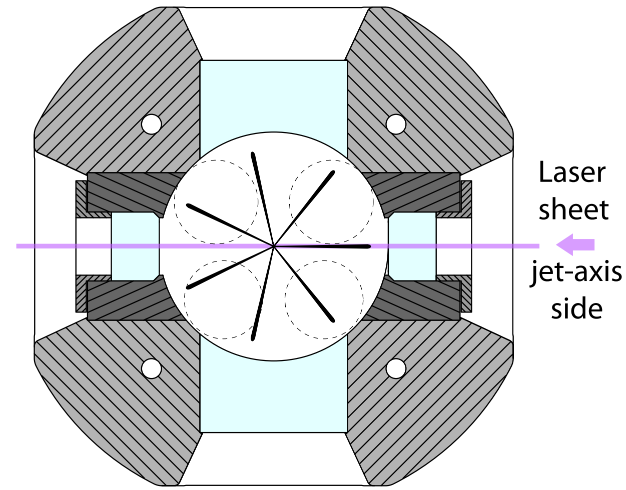
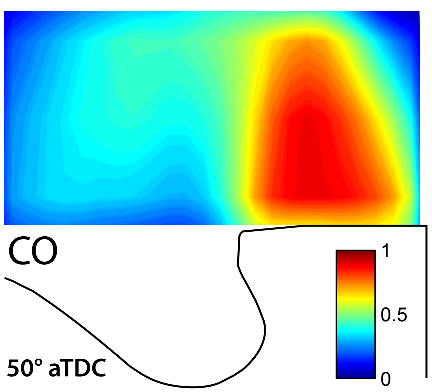
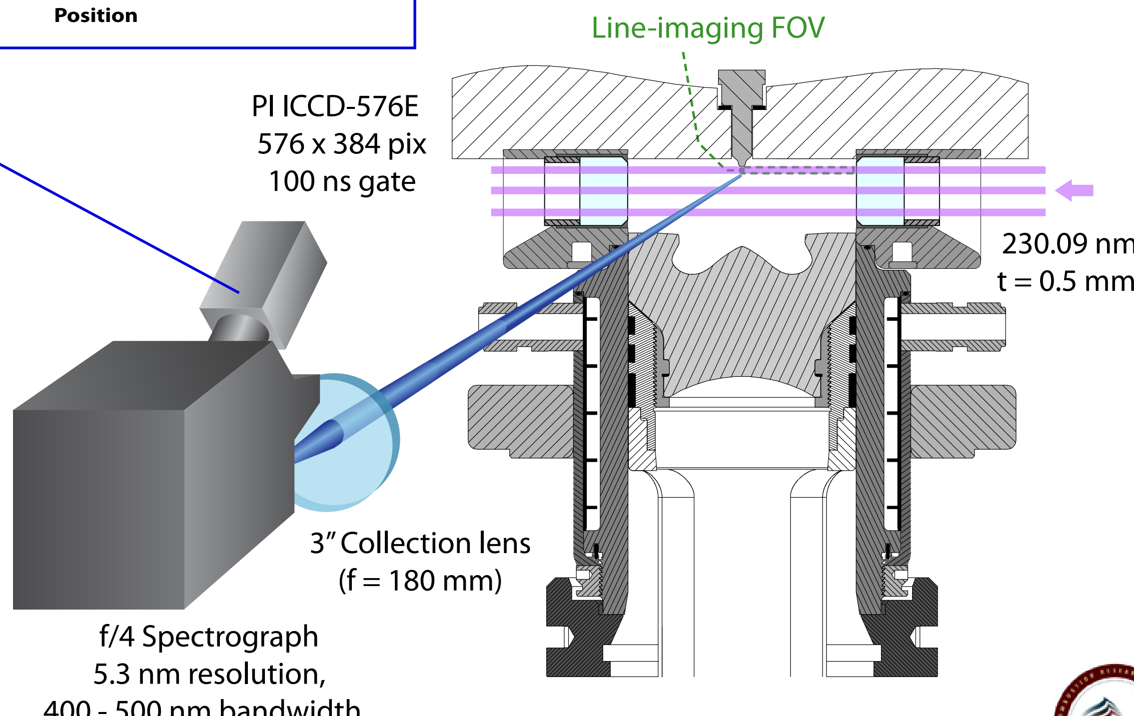




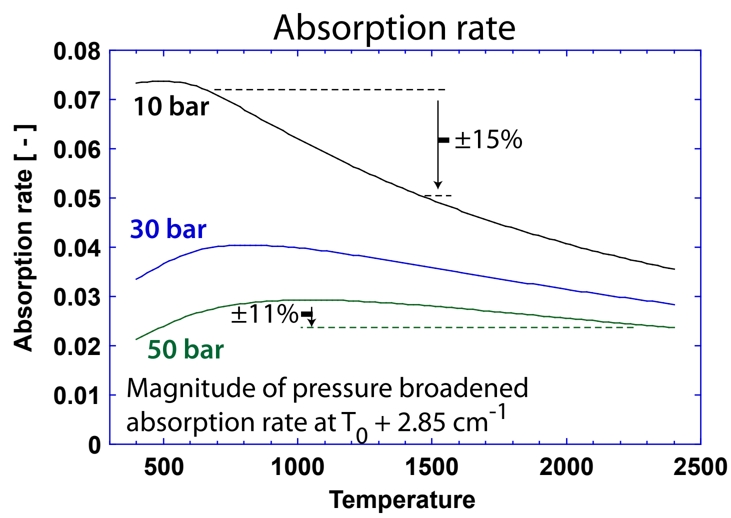


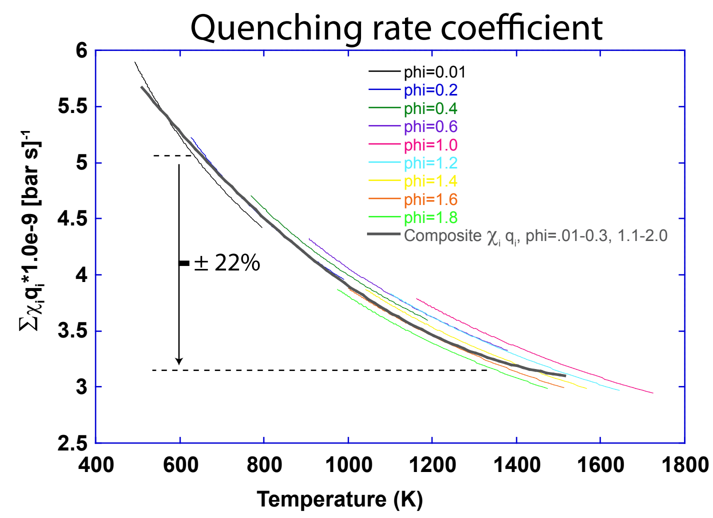
Smoothing splines are fit to profiles measured at multiple heights, yielding a 2-d image

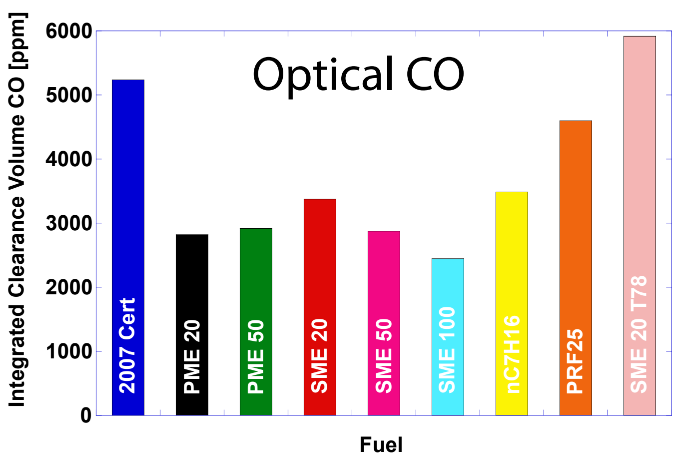


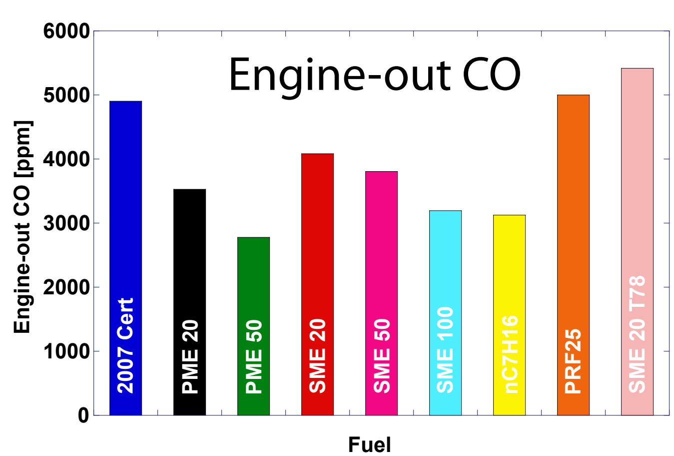
The CO LIF results are semi-quantitative – lending credence to the measured spatial distributions

We apply temperature and pressure corrections to the CO absorption and quenching rates







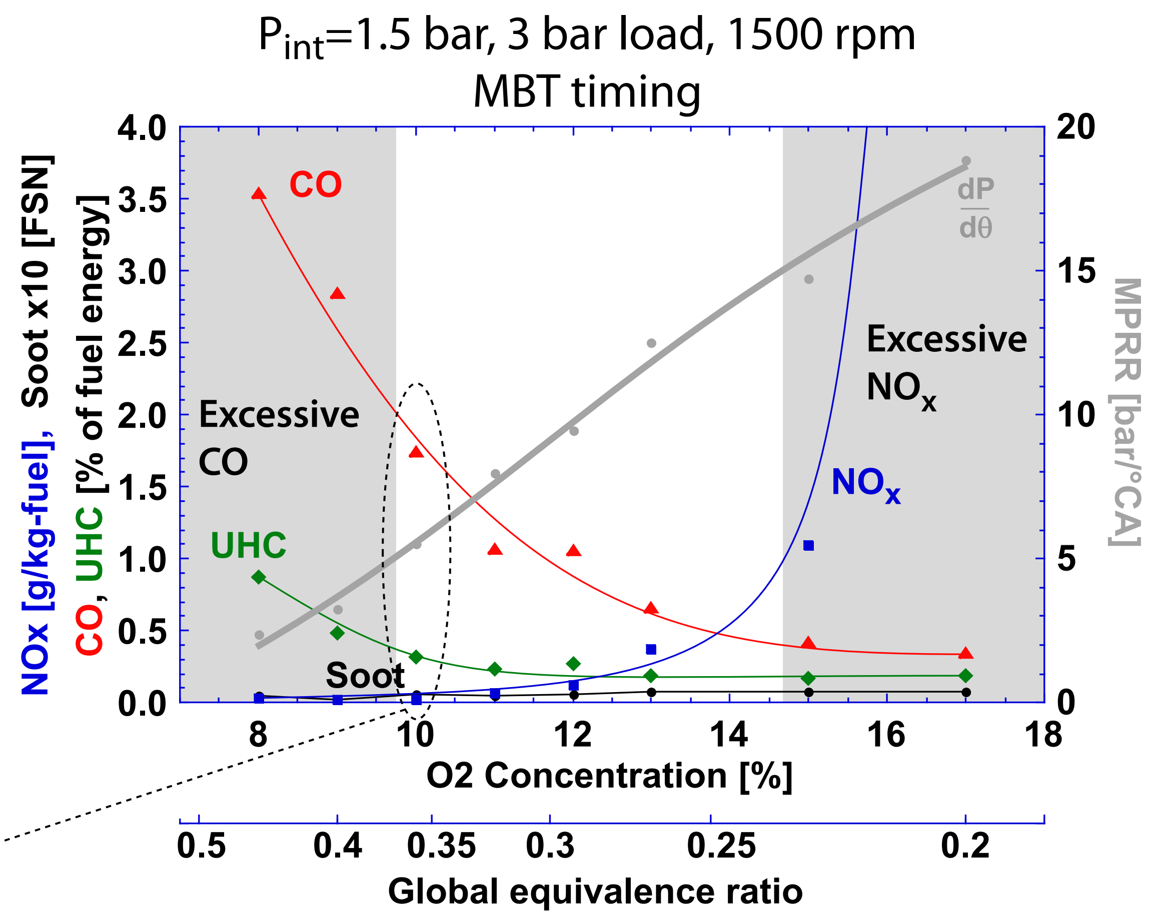


Despite remaining uncertainties, the magnitude and the trends of the spatially-integrated optical data match engine-out emissions well

Optical measurements are used to identify the actual in-cylinder sources of UHC and CO

Potential UHC/CO sources:

- Injector sac dribble -
- Crevice UHC and wall films -
- Poor mixture formation - (over-rich regions)
- Excessively lean regions



We examine a single, early injection (PCI-like) operating condition at a 10% O_2 concentration, where combustion efficiency is still ≈ 98%

Injector leakage is clearly observed in the images

Potential UHC/CO sources:

- **Injector sac dribble** ✓
- Crevice UHC and wall films
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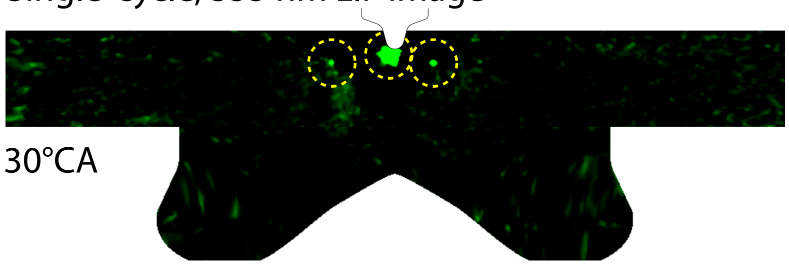
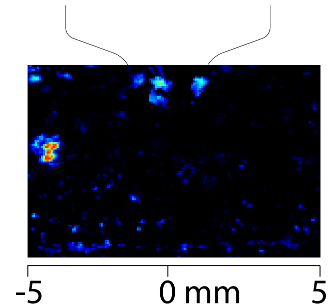
Single-cycle, 355 nm LIF image



Intense LIF near the injector indicates parent fuel & spherical droplets...



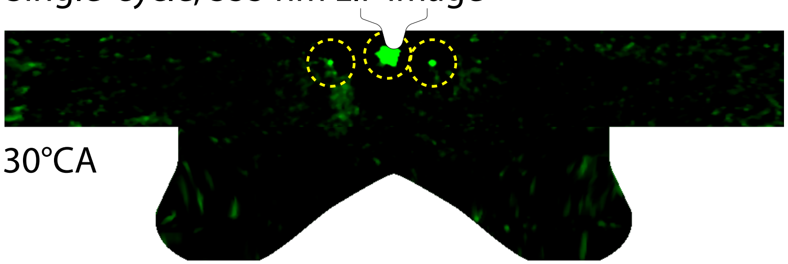
...that are also seen in elastic scatter images

Injector leakage is clearly observed in the images – and implied by the emissions behavior

Potential UHC/CO sources:

- **Injector sac dribble** ✓ 15%
- Crevice UHC and wall films
- Poor mixture formation (over-rich regions)
- Excessively lean regions

Single-cycle, 355 nm LIF image



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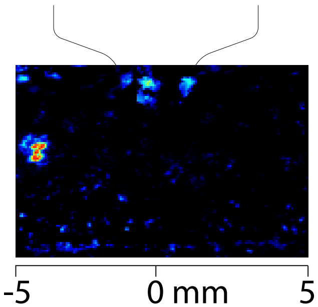
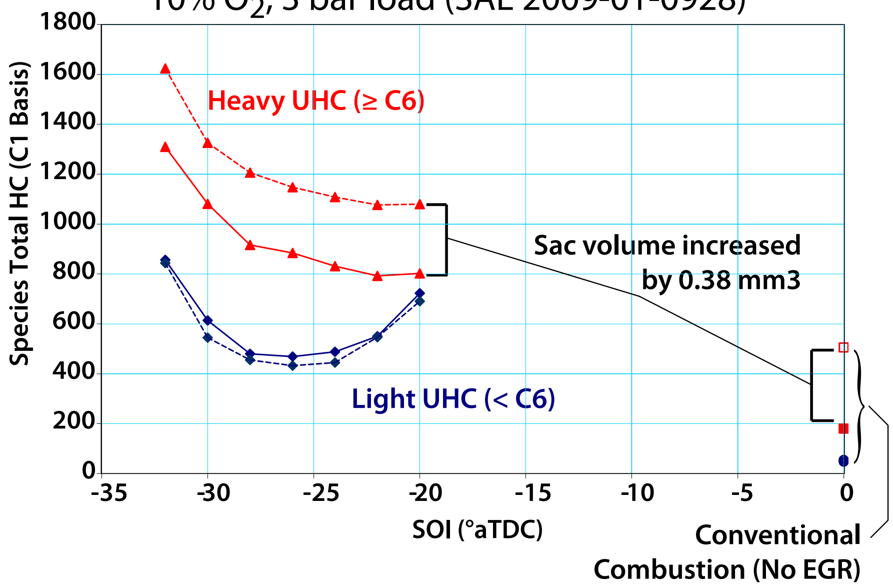


...that are also seen in elastic scatter images

10% O_2, 3 bar load (SAE 2009-01-0928)



Emissions measured with various sac volumes indicate that a typical minisac nozzle yields ~ 0.02 mg UHC (15% of UHC emissions)

UHC stemming from piston-top fuel films and from the ring-land crevice are also observed

Potential UHC/CO sources:

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- **Crevice UHC and wall films -** ✓
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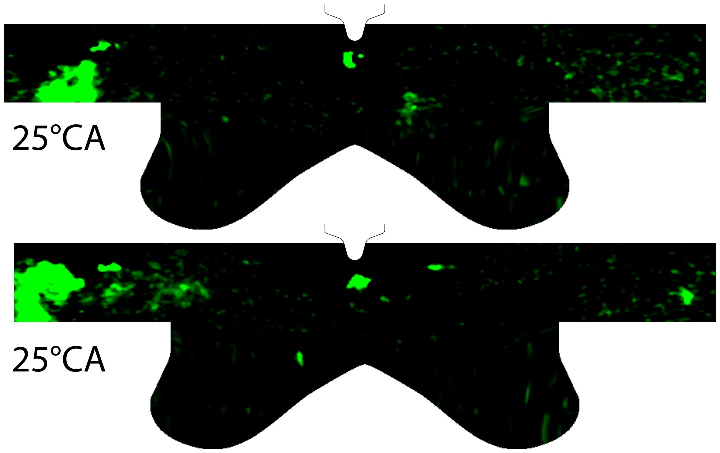
Single-cycle, 355 nm LIF images, 3 bar load



UHC from piston top films is observed during expansion...

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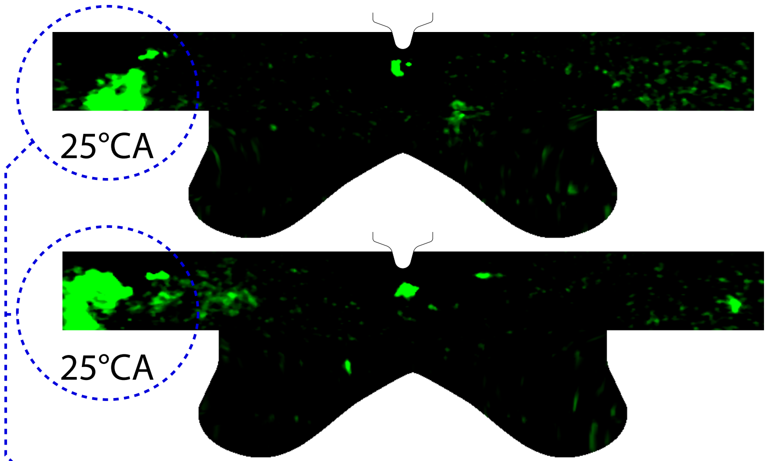
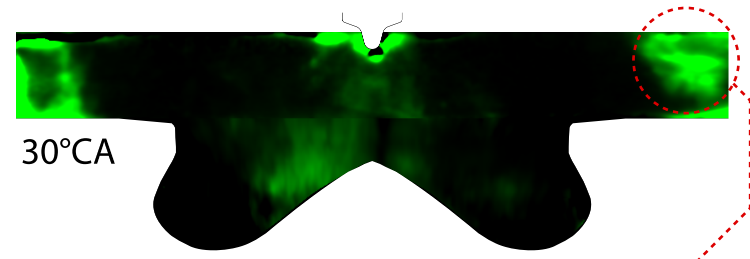


UHC from piston top films is observed during expansion...

Cycle-averaged, 355 nm LIF image, 4.5 bar load



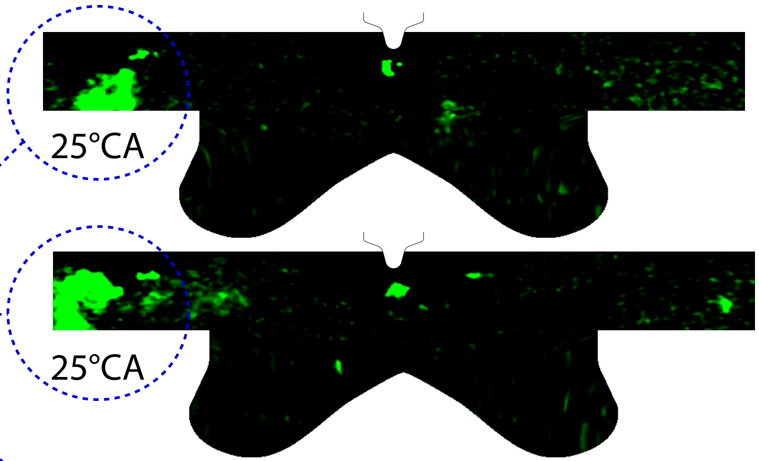
...as is UHC embedded in crevice flows

UHC stemming from piston-top fuel films and from the ring-land crevice are also observed

Potential UHC/CO sources:

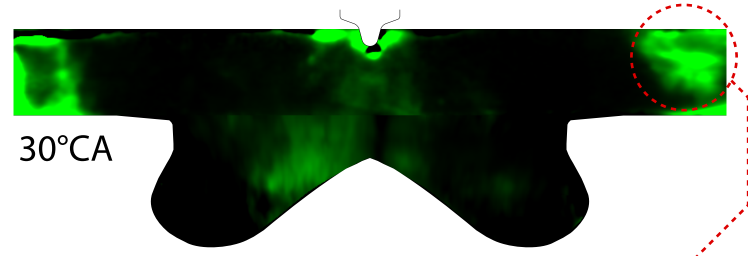
- Injector sac dribble ✓ 15%
- **Crevice UHC and wall films** ✓ 20%
- Poor mixture formation (over-rich regions)
- Excessively lean regions

Single-cycle, 355 nm LIF images, 3 bar load



UHC from piston top films is observed during expansion...

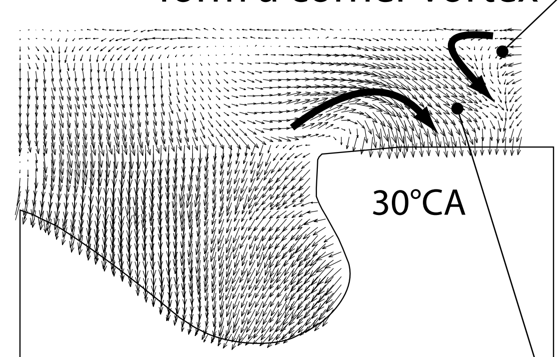
Cycle-averaged, 355 nm LIF image, 4.5 bar load



...as is UHC embedded in crevice flows

Measured flow structures identify the origin of UHC

Ring-land crevice flows form a corner vortex



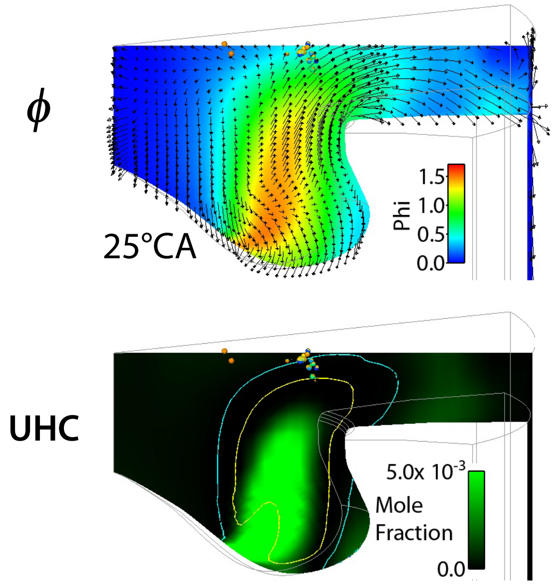
Fluid in this region was expelled from the bowl earlier

As reported previously, rich mixture pockets within the bowl are only sporadically observed

Potential UHC/CO sources:

- Injector sac dribble ✓ 15%
- Crevice UHC and wall films ✓ 20%
- **Poor mixture formation (over-rich regions)** ✓ ?
- Excessively lean regions

Multi-dimensional simulations indicate the majority of UHC is embedded in rich mixture in the lower, inner bowl regions



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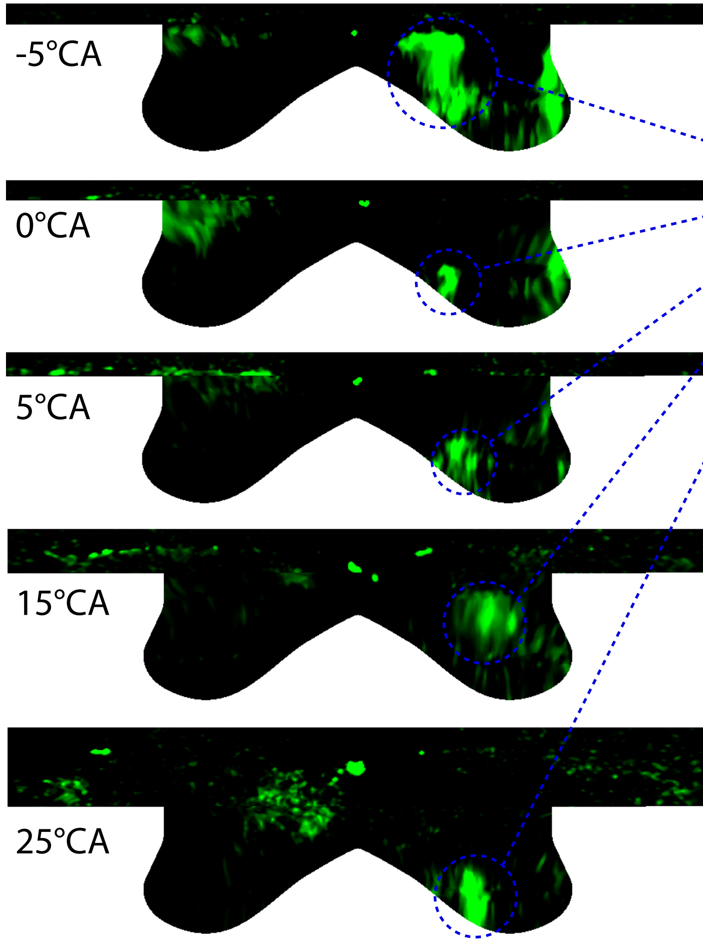
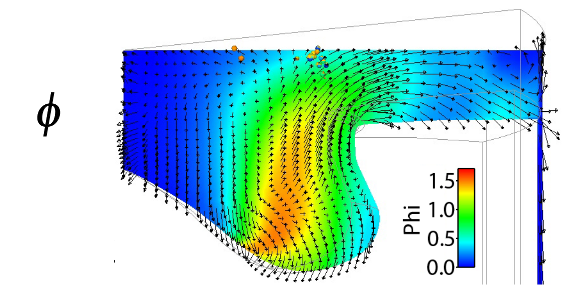
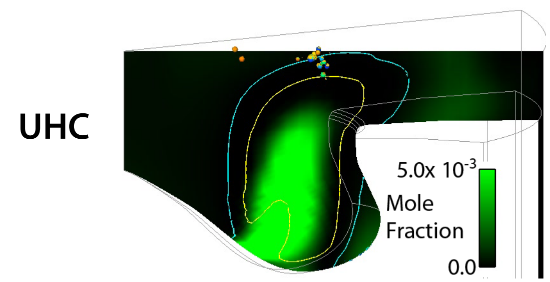
Single-cycle, 355 nm LIF images, 3 bar load



Selected, atypical cycles exhibiting lower, inner bowl fluorescence (~ 1 cycle in 5)

Multi-dimensional simulations indicate the majority of UHC is embedded in rich mixture in the lower, inner bowl regions



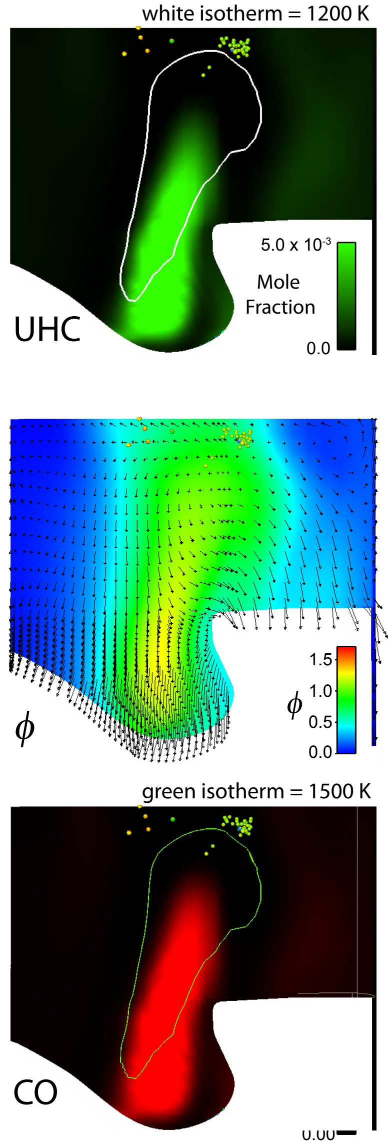


Fluoresence from this lower-bowl region is only seen *infrequently*

Deep-UV LIF can detect rich mixture CO (and UHC?) that is inaccessible at 355 nm

Potential UHC/CO sources:

- Injector sac dribble ✓ 15%
- Crevice UHC and wall films ✓ 20%
- **Poor mixture formation (over-rich regions)** ✓ ?
- Excessively lean regions



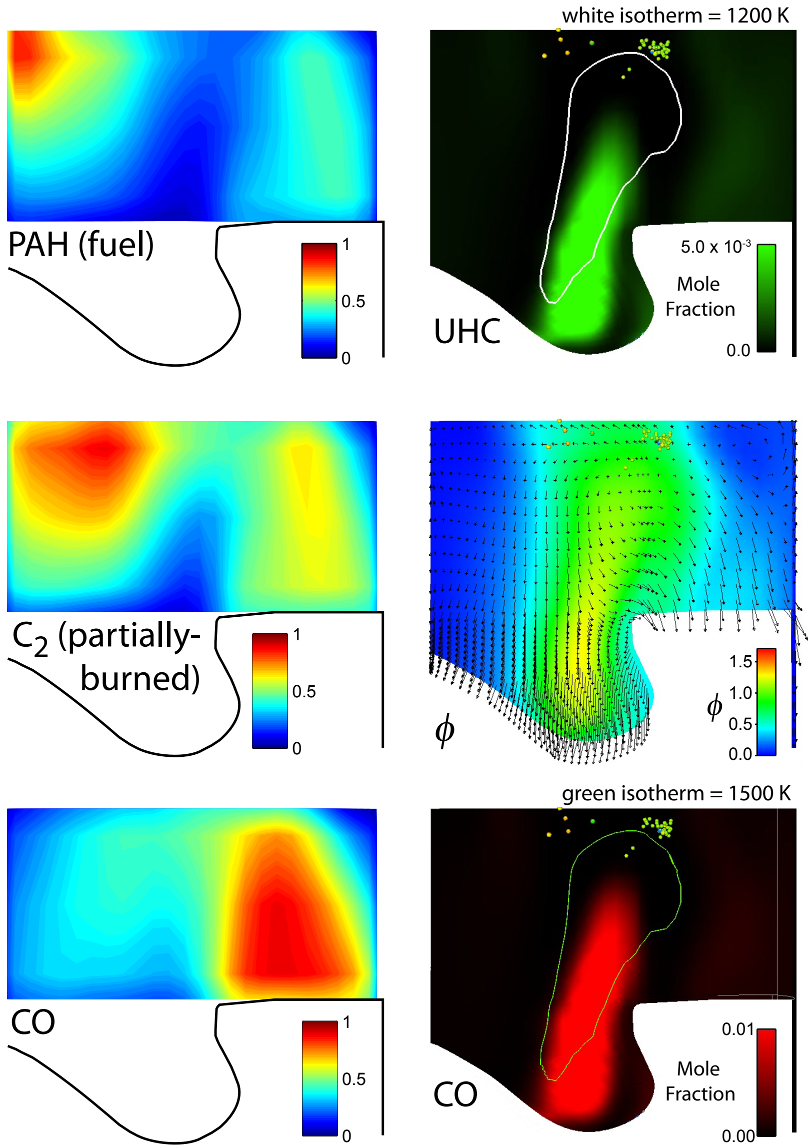
Simulation

The predictions of rich bowl mixture persist into expansion...

Deep-UV LIF can detect rich mixture CO (and UHC?) that is inaccessible at 355 nm

Potential UHC/CO sources:

- Injector sac dribble ✓ 15%
- Crevice UHC and wall films ✓ 20%
- **Poor mixture formation (over-rich regions)** ✓✗? ✓5%
- Excessively lean regions



Deep-UV LIF　　Simulation -

(UHC/CO distributions at 50° aTDC)

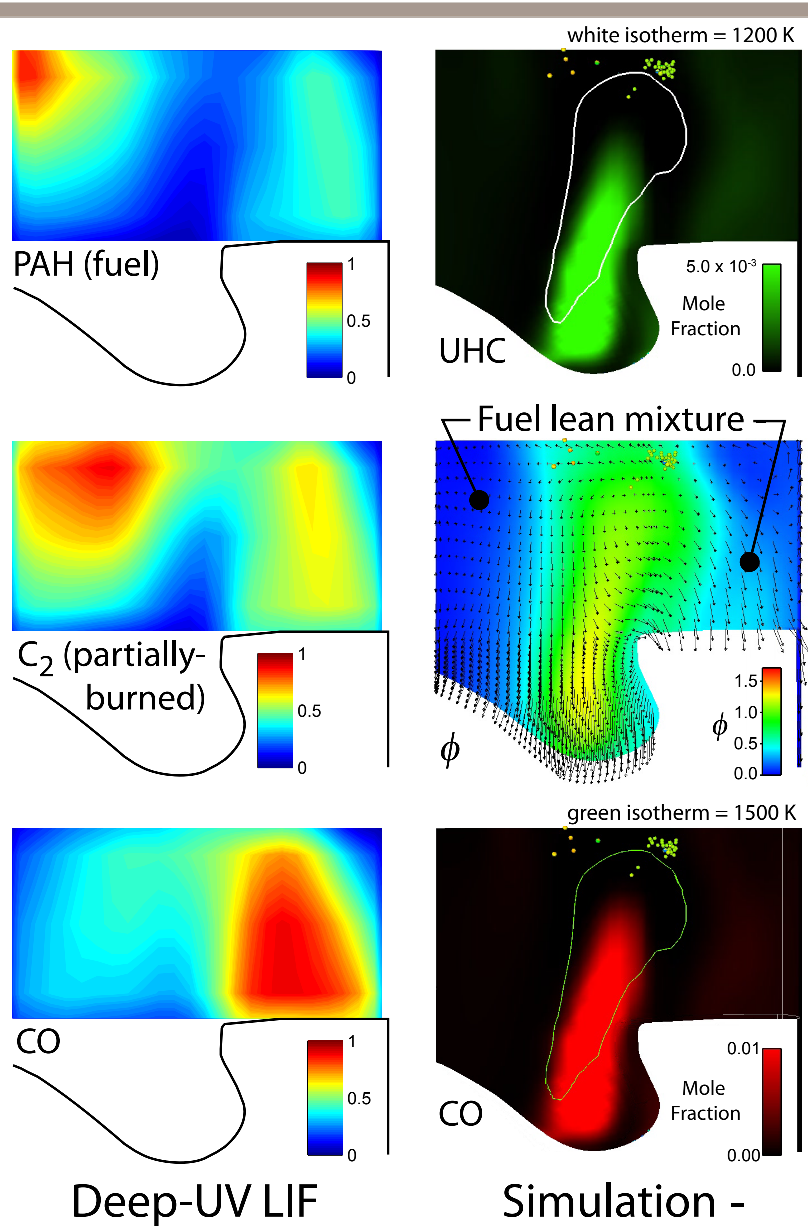
The predictions of rich bowl mixture persist into expansion...

...but the measurements show that *the flow exiting the bowl is clean*

Deep-UV LIF can detect rich mixture CO (and UHC?) that is inaccessible at 355 nm

Potential UHC/CO sources:

- Injector sac dribble ✓ 15%
- Crevice UHC and wall films ✓ 20%
- Poor mixture formation (over-rich regions) - ✓✗? ✓5%
- **Excessively lean regions** ✓? 60%



(UHC/CO distributions at 50° aTDC) -

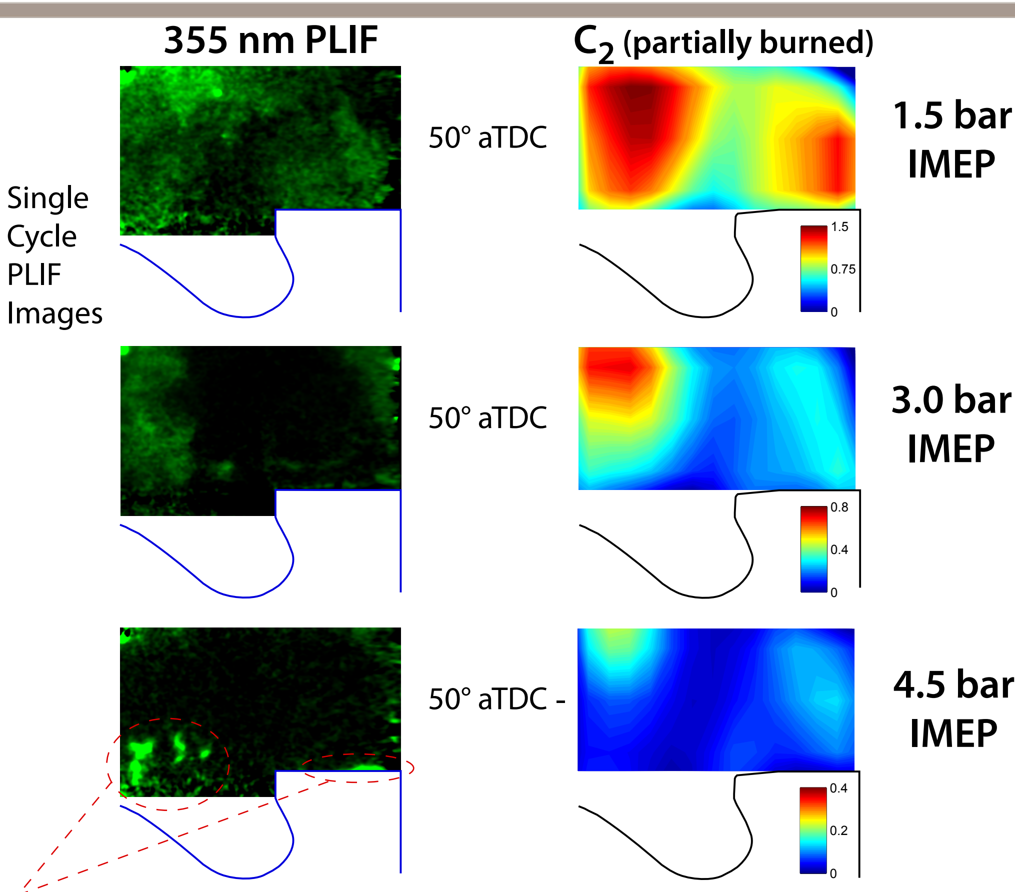
The predictions of rich bowl mixture persist into expansion...

...but the measurements show that *the flow exiting the bowl is clean*

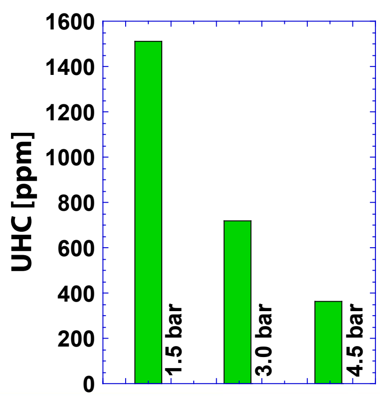
UHC and CO are dominated by bulk gas mixture near the injector and in the squish volume

...the simulations indicate that these mixtures are fuel-lean

Load sweeps confirm that the near-injector and squish volume regions are fuel lean & dominant



Rich mixture and films are more common at higher load

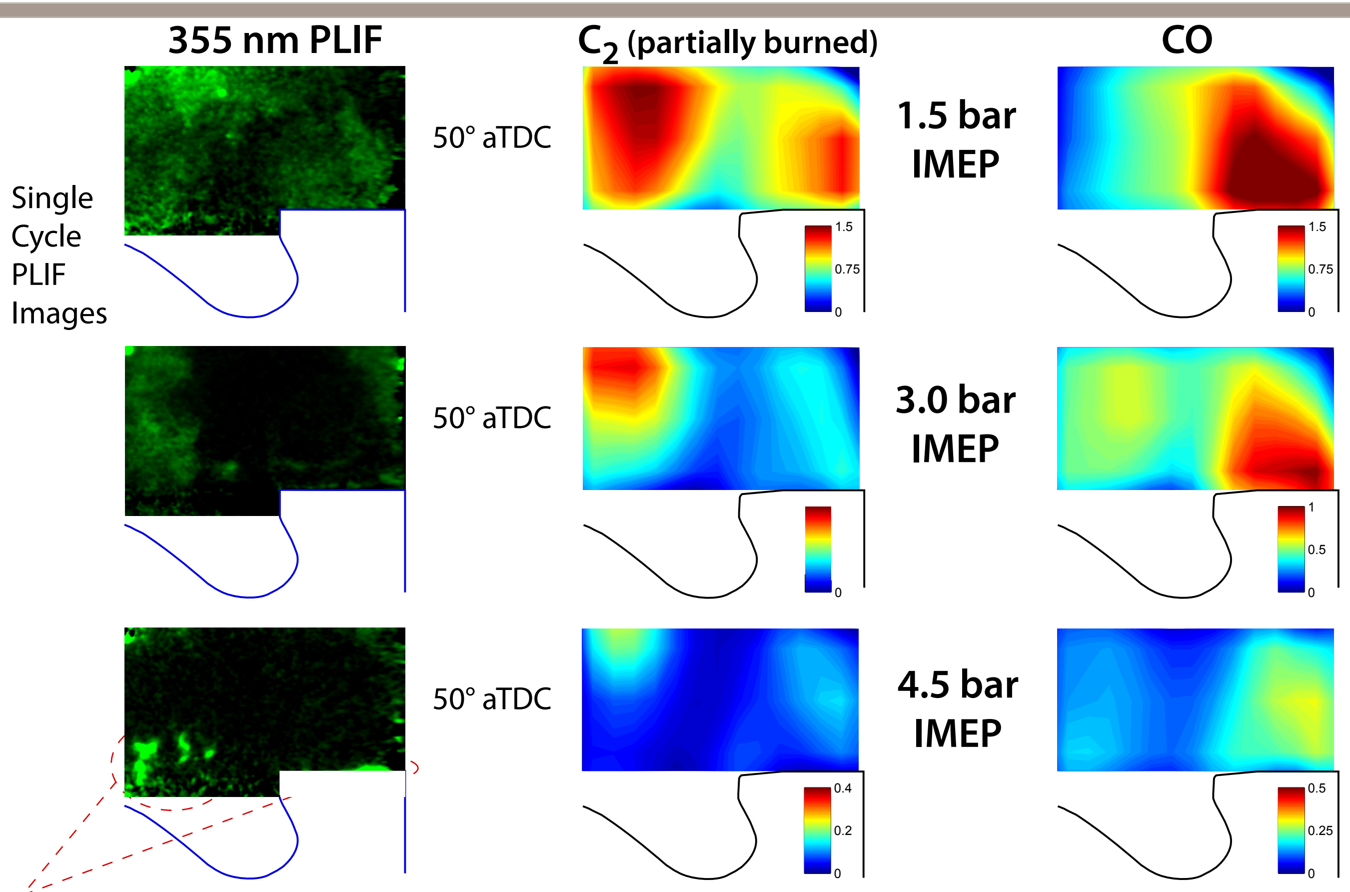


Partially-burned UHC near the injector and in the squish volume decreases with increasing load...

...as do engine-out UHC emissions

- Excessively lean regions ✓ 60%

Load sweeps confirm that the near-injector and squish volume regions are fuel lean & dominant



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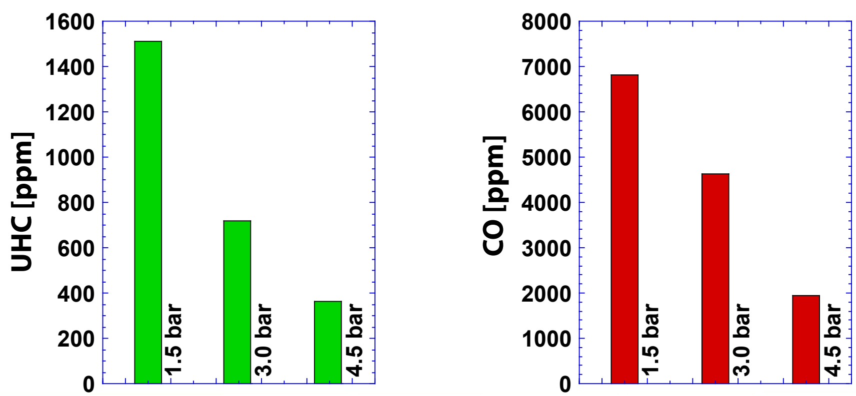


- Excessively lean regions ✓ 60%

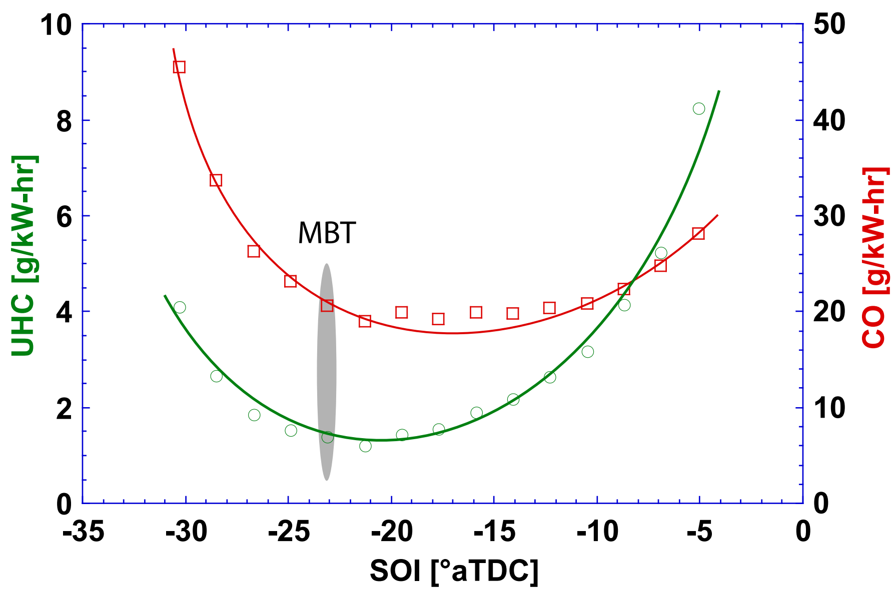
Partially-burned UHC near the injector and in the squish volume decreases with increasing load...

...as do engine-out UHC emissions -

CO near the injector first increases as UHC oxidation improves, then is oxidized at the highest load

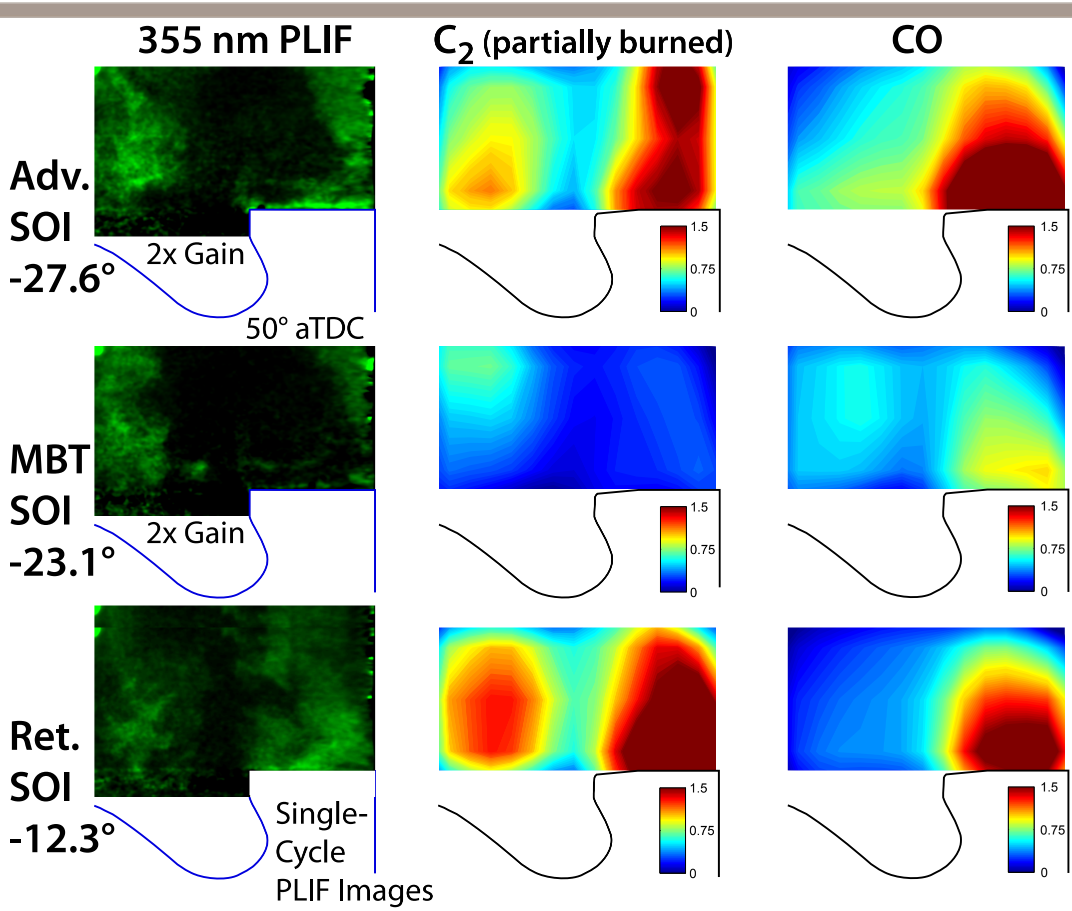
Increased load always improves the squish volume CO oxidation -

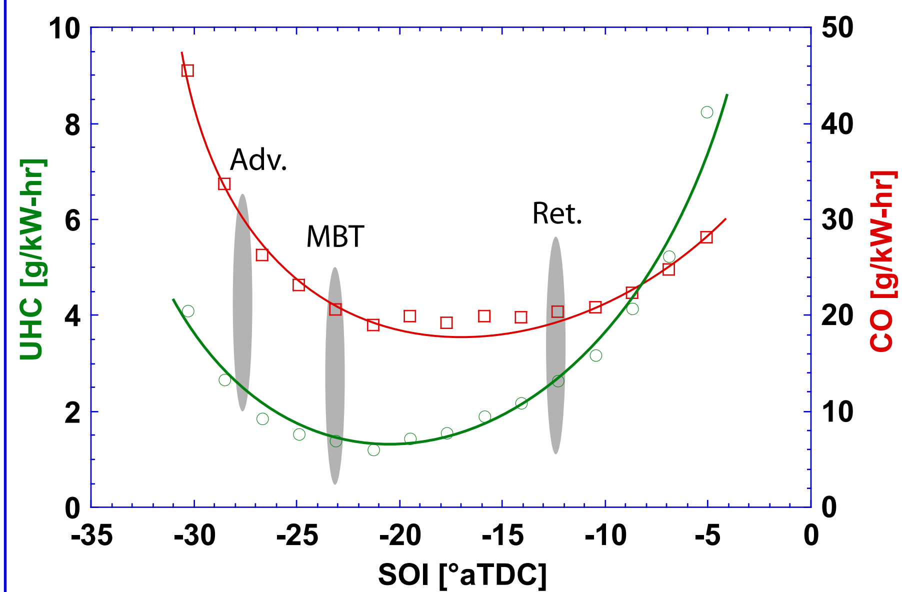
Emissions increase with timing retard or advance



UHC and CO emissions are mimimized near MBT timing

Emissions increase with timing retard or advance ... but the source locations are the same



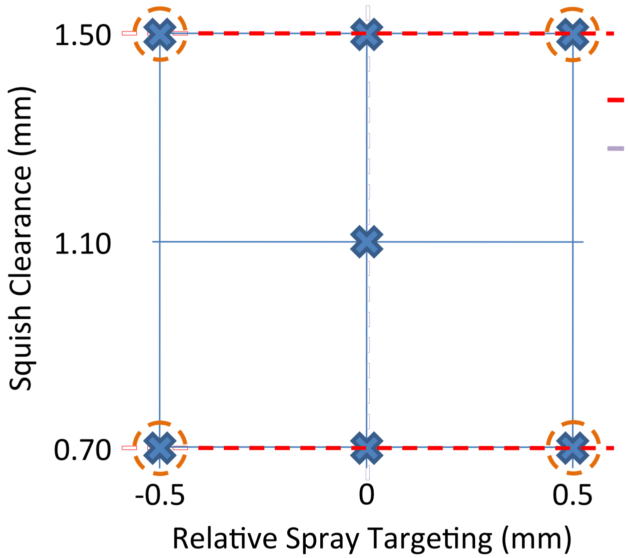


UHC and CO emissions are mimimized near MBT timing

With both advanced and retarded SOI, the dominant source of increased UHC and CO is the squish volume

- With advanced SOI, the squish volume mixture near the piston top is likely rich
- With retarded SOI, very lean squish volume mixtures increase emissions (rich bowl mixture is seen more frequently in the single-cycle PLIF images)

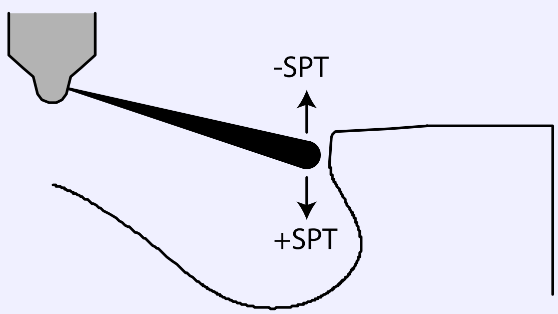
Squish volume emissions are minimized by small squish heights and low spray targeting



DOE courtesy of Öivind Andersson, Lund University

Response surface design with seven test points and one replicate (i.e., the entire test matrix was measured twice)

Spray targeting definition:



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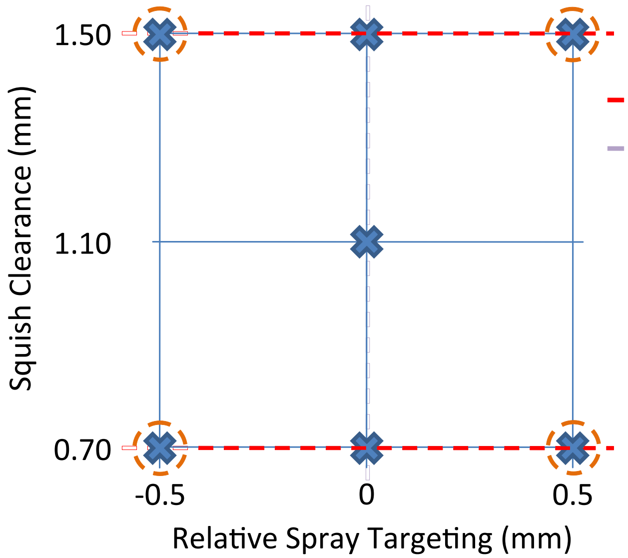
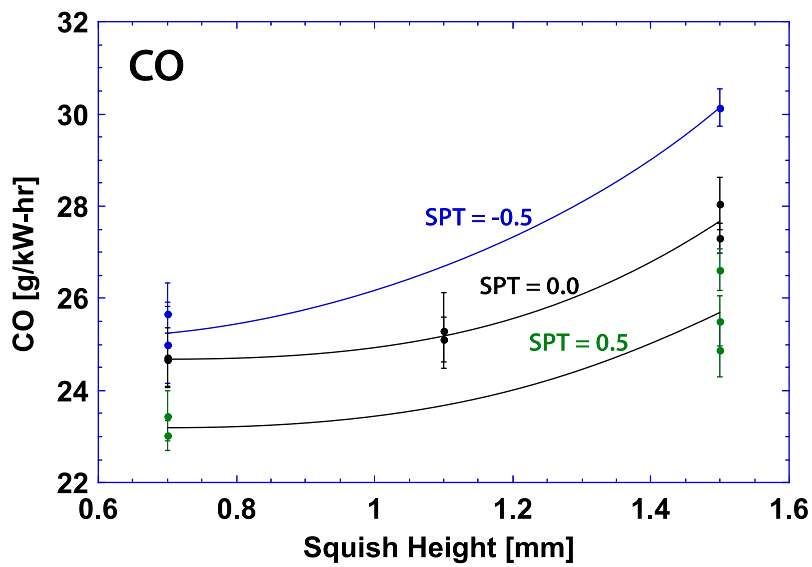
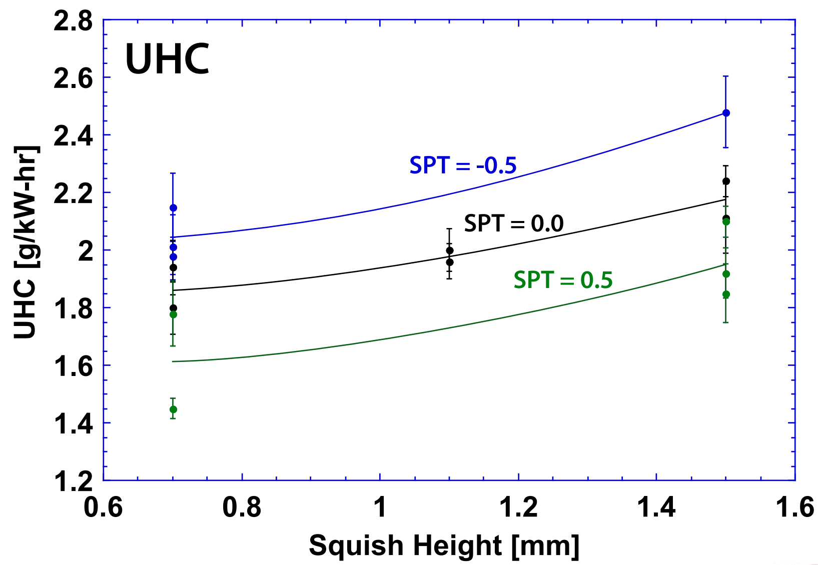


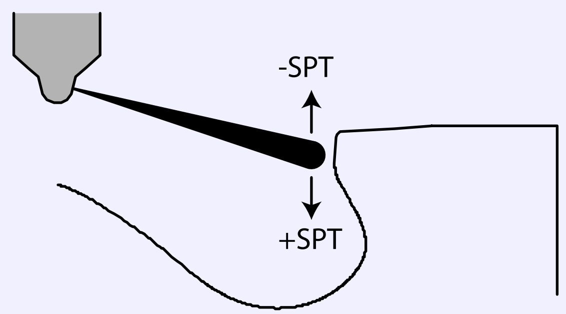
DOE courtesy of Öivind Andersson, Lund University



Response surface design with seven test points and one replicate (i.e., the entire test matrix was measured twice)



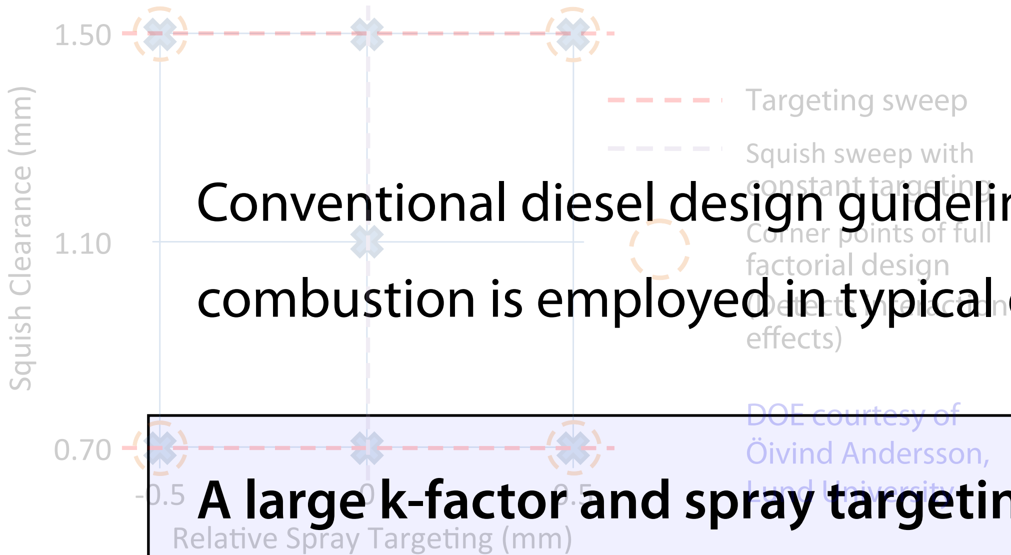
Spray targeting definition:

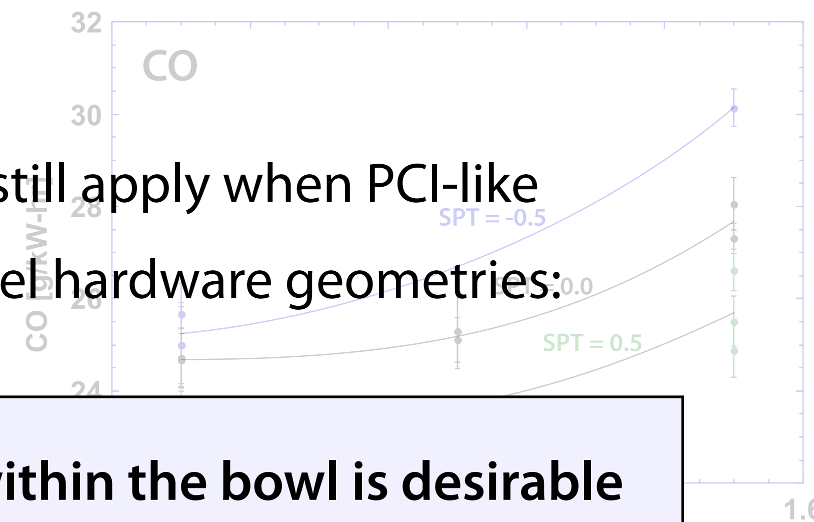


Squish volume emissions are minimized by small squish heights and low spray targeting

Conventional diesel design guidelines still apply when PCI-like combustion is employed in typical diesel hardware geometries:

A large k-factor and spray targeting within the bowl is desirable





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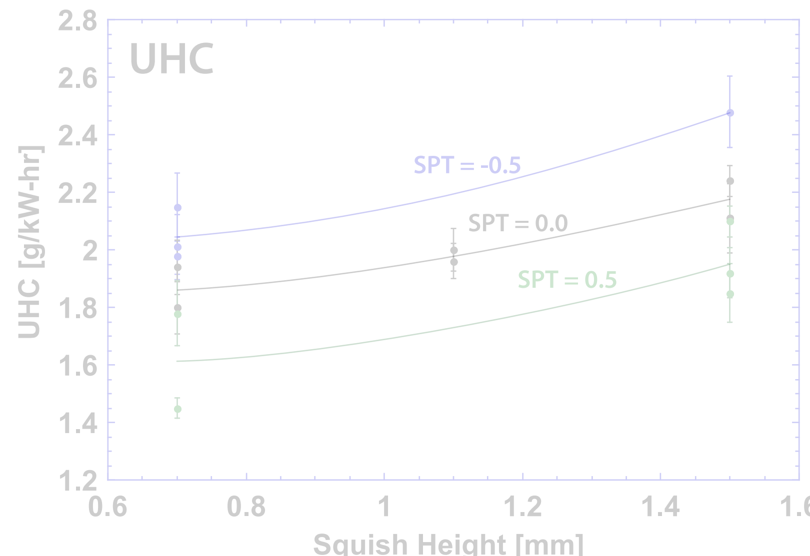
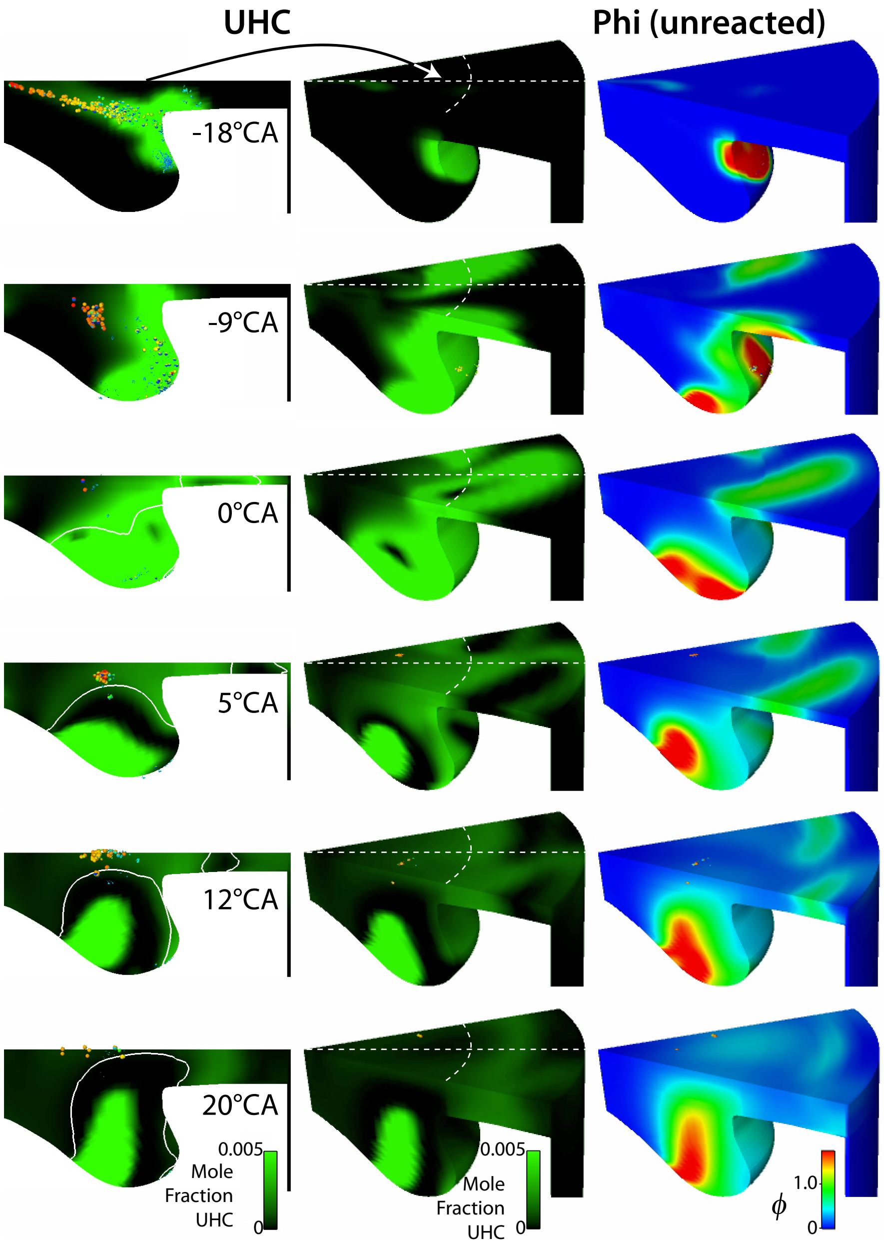


Only a portion of the fuel in the squish volume is placed there by the injection event



- With SOI ≈ -23° (our baseline case), fuel vapor is injected into the squish volume
- The squish flow does not force the fuel back into the bowl, although no squish volume fuel remains in the jet-axis plane
- As peak HTHR approached, UHC in near stoichiometric mixture is fully oxidized
- A large amount of lean mixture UHC, from between two fuel jets and the tail of each individual jet, is positioned near the bowl rim
- The reverse squish flow and gas expansion in the bowl forces this mixture into the squish volume
- Lean mixture from near the bowl rim is the dominant source of squish volume UHC, with a remnant of fuel injected into the squish volume

Summary

- Optical measurements obtained in an engine with realistic geometry, operating in an early-injection (PCI-like) combustion regime at a speed and load typical of an urban drive cycle, have identified the following sources of UHC and CO emissions:
  - Lean mixtures near the cylinder centerline and in the squish volume (~ 60%)
  - Cool mixture expelled from the ring-land crevice & piston top fuel films (~ 20%)
  - Fuel associated with nozzle dribble and poor atomization near EOI (~ 15%) -
  - Rich mixtures within the bowl (~ 5%)
- Simulation predictions that rich mixtures are a dominant source of UHC and CO emissions are not supported experimentally. At higher loads, or with different engine geometries, however, there is clear evidence that rich mixtures are of greater importance
- Lean mixture within the squish volume appears to be dominated by fluid from the edges and tails of the fuel jets, forced into the squish volume by gas expansion in the bowl and the reverse squish flow
- Simulations have become useful design tools, but further improvement is required to accurately capture LTC UHC and CO emissions behavior