In-Cylinder Mechanisms of PCI Heat-Release Rate Control by Fuel Reactivity Stratification

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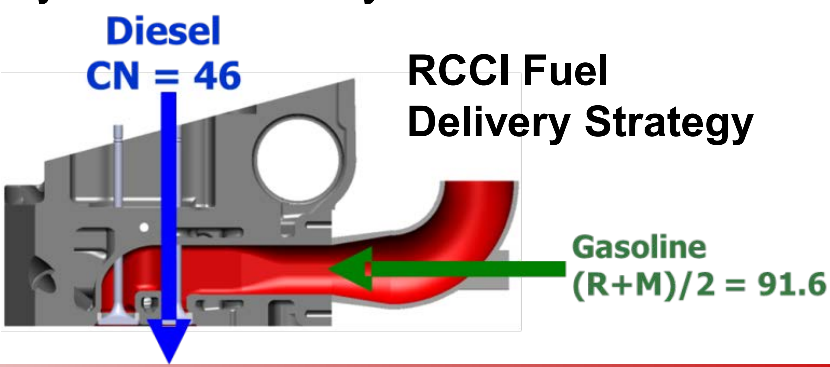
Outline

- Motivation and background
- Engine and experimental setup
- Identification of the mechanisms controlling RCCI energy release
  - Chemiluminescence imaging
  - Fuel tracer fluorescence imaging
- Controlling PCI heat release using fuel reactivity stratification
- Conclusions

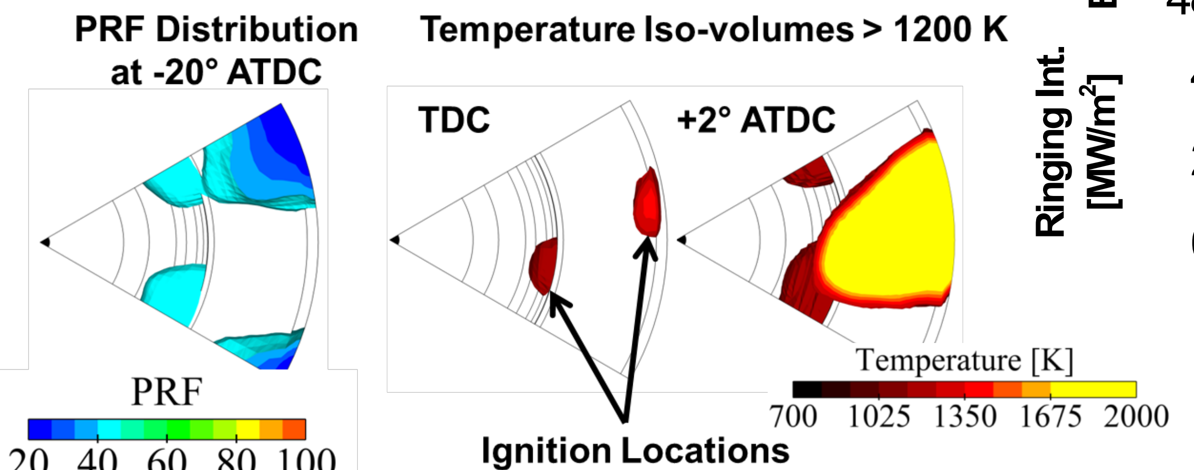
Motivation

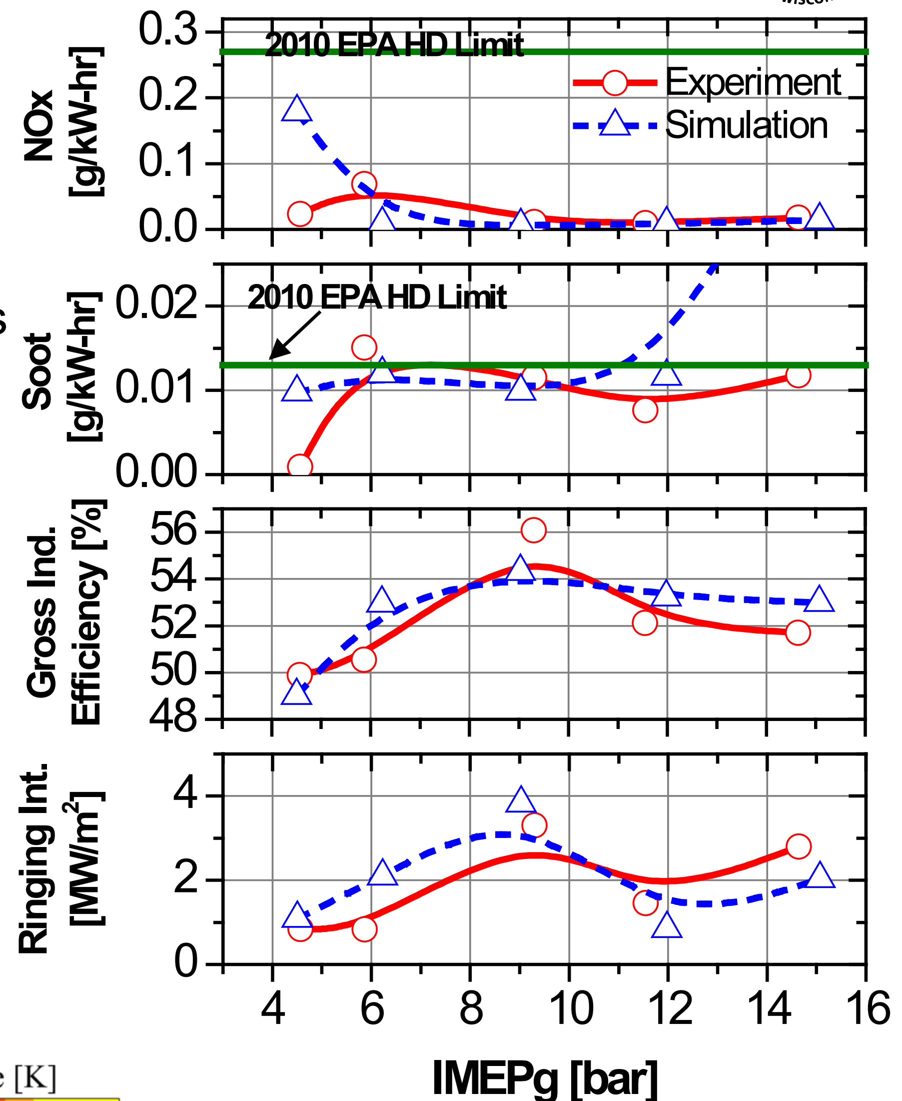
- Highly-premixed compression ignition (PCI) strategies (e.g., HCCI) offer attractive emissions and performance characteristics; however, in practice PCI strategies are generally confined to low-load operation due to
  - lack of adequate combustion phasing control
  - difficulties controlling the rate-of-heat release
- Metal engine experiments have shown that RCCI combustion using in-cylinder fuel blending allows low NOx and soot operation over a wide range of operating conditions
  - Combustion phasing is controlled by overall fuel reactivity
  - Rate-of-heat release is controlled by fuel reactivity stratification



Background – RCCI Combustion

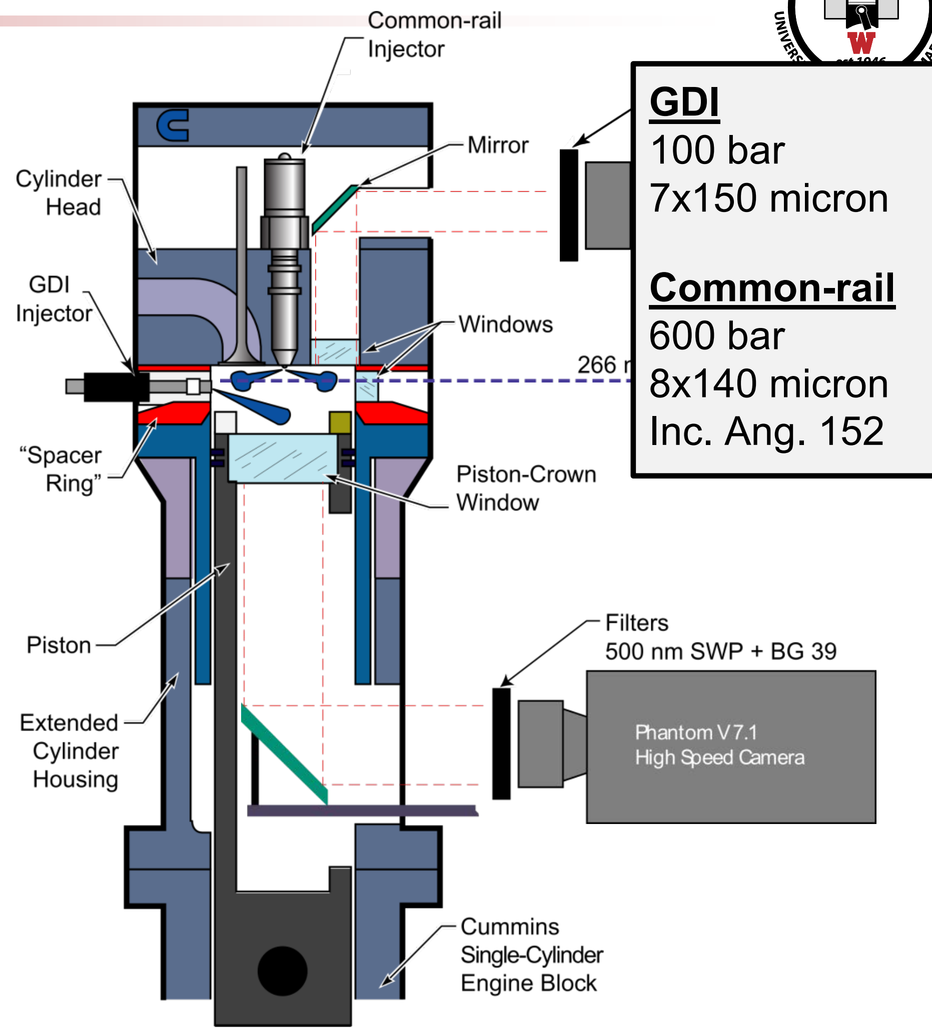
- Metal engine experiments have demonstrated **controlled** PCI combustion over a range of conditions
  - NOx and soot below the 2010 limits
  - GIE above 50% from 4 to 15 bar IMEP
- CFD modeling predicts that the energy release is controlled by the fuel reactivity stratification





Experimental Setup

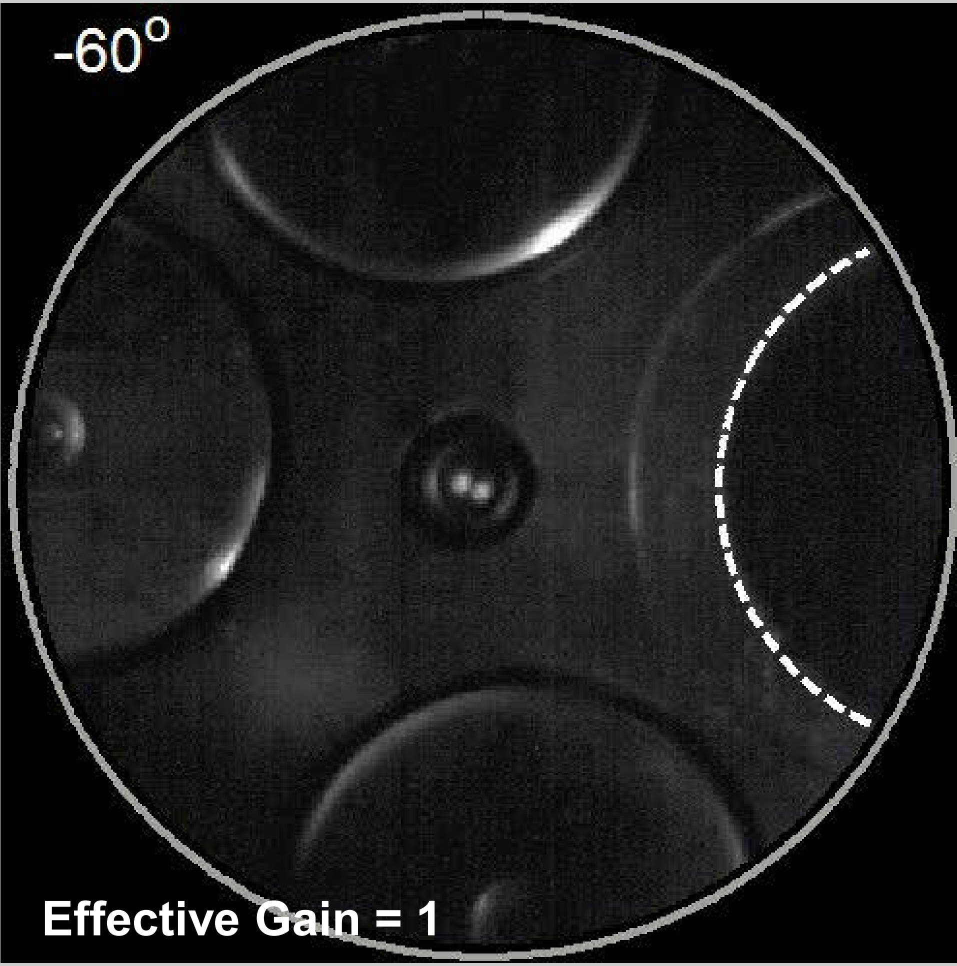
- RCCI engine experiments were performed in the Sandia heavy-duty optical engine
- Gasoline primary reference fuels (PRF) used for RCCI operation
  - iso-octane delivered with GDI early in the cycle (240° BTDC)
  - n-heptane delivered through the common-rail injector
- Ignition and reaction zone growth
  - High-speed combustion luminosity imaging
- Fuel distribution prior to ignition
  - Toluene fuel tracer PLIF

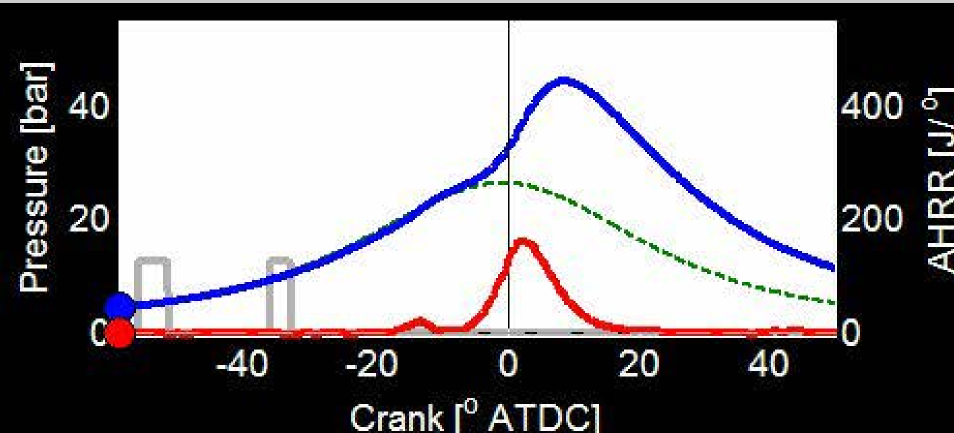


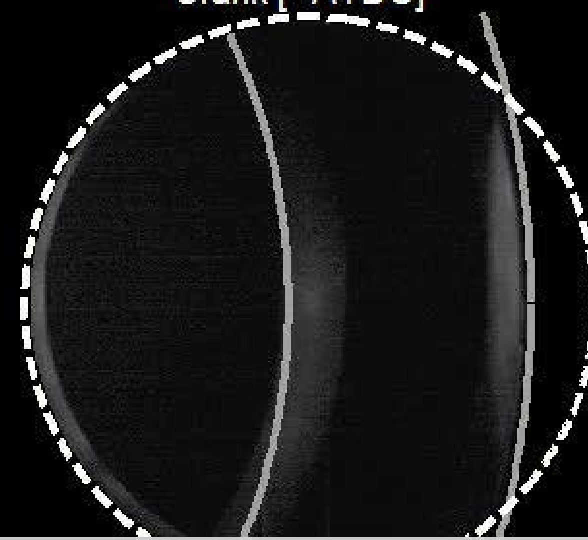
Engine	Cummins N-14
Bore x stroke	13.97 x 15.24 cm
Displacement	2.34 L
Geometric compression ratio	10.75

High-Speed Chemiluminescence Imaging

Load:	4.2 bar IMEP	GDI SOI:	-240°ATDC
Speed:	1200 rpm	CR SOI:	-57°/-37° ATDC
Intake Temperature:	90° C	Equivalence ratio:	0.42
Intake Pressure:	1.1 bar abs.	Iso-octane mass %:	64





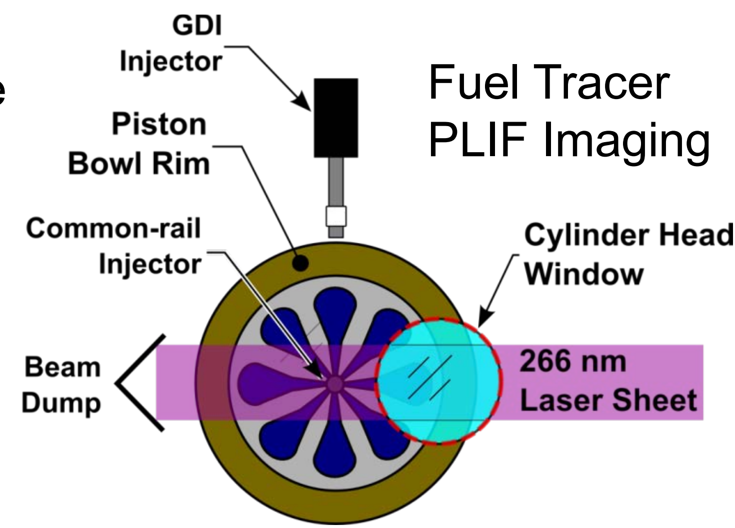


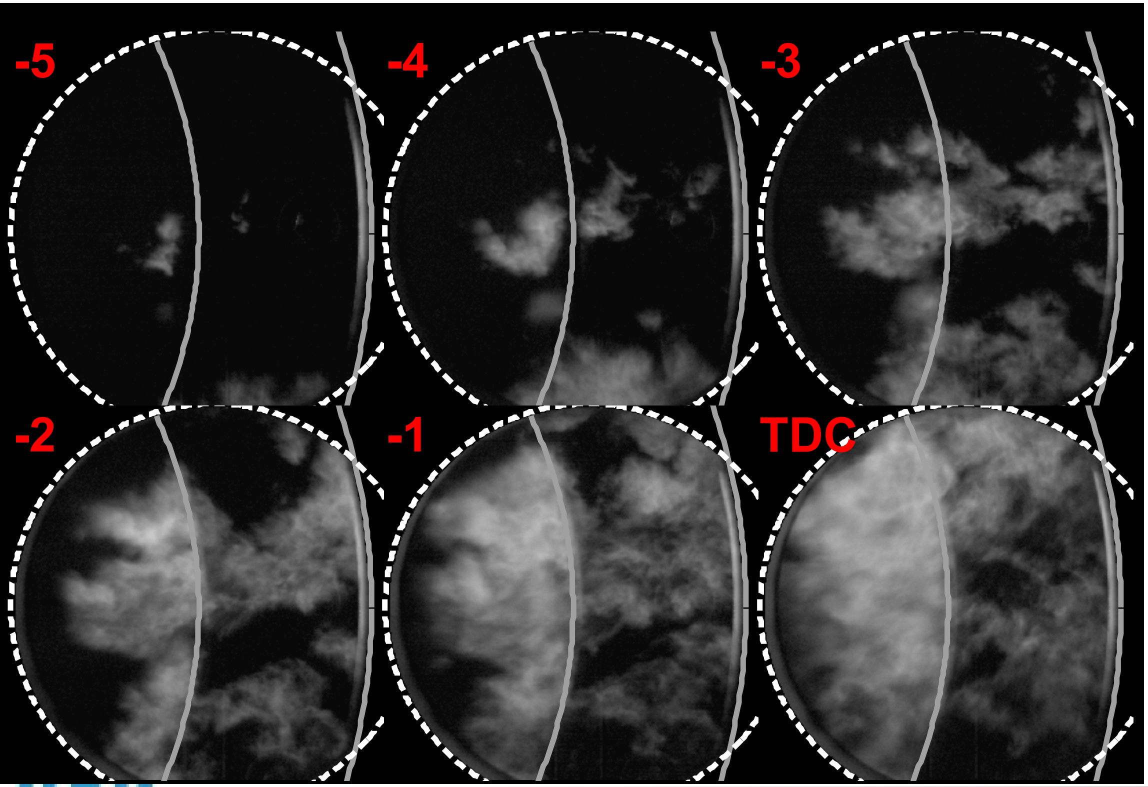
Piston Crown Window

Cylinder Head Window

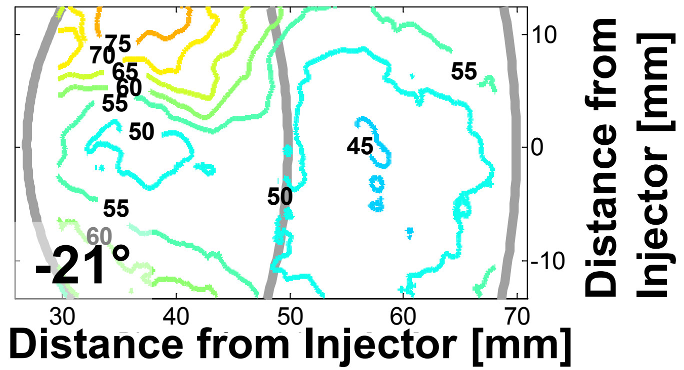
High-Speed Chemiluminescence Imaging

- Ignition occurs first near the bowl rim and in the squish and the reaction zone grows to consume the remainder of the charge
- Fuel PLIF imaging shows that the fuel reactivity is highest (i.e., PRF is lowest) in the squish and near the bowl rim





PRF (octane number) Distribution evaluated using PLIF imaging



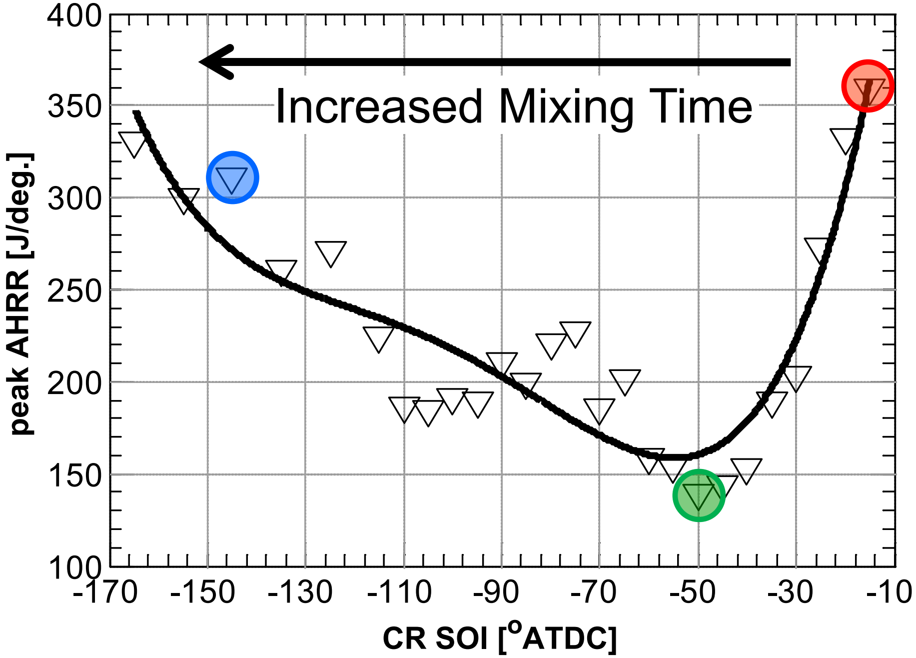
Fuel Reactivity Stratification

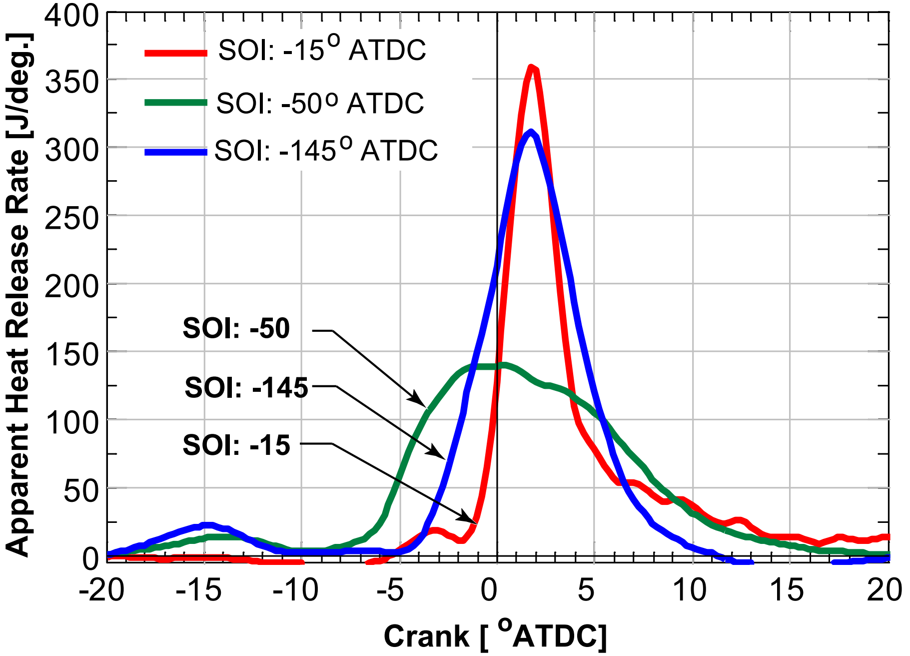
- Baseline results suggest that fuel reactivity stratification controls both the ignition location and combustion duration.
- Can fuel reactivity stratification be used to control the heat release rate?
- A common-rail (n-heptane) injection timing sweep was used to generate a range of stratification from very mixed (early SOI) to very stratified (late SOI)
- CA50 was held constant at 2° ATDC by adjusting the intake temperature

Engine speed	1200 rpm
Gross IMEP	4.2 bar
Intake temperature	73 to 100 °C
Intake pressure	1.1 bar abs.
Inlet oxygen concentration	21 vol. %
CR SOI	-165° to -15° ATDC
GDI SOI	-240° ATDC
n-heptane mass (CR)	36%
iso-octane mass (GDI)	64%
Premixed equivalence ratio	0.27
Overall equivalence ratio	0.42

Fuel Reactivity Stratification

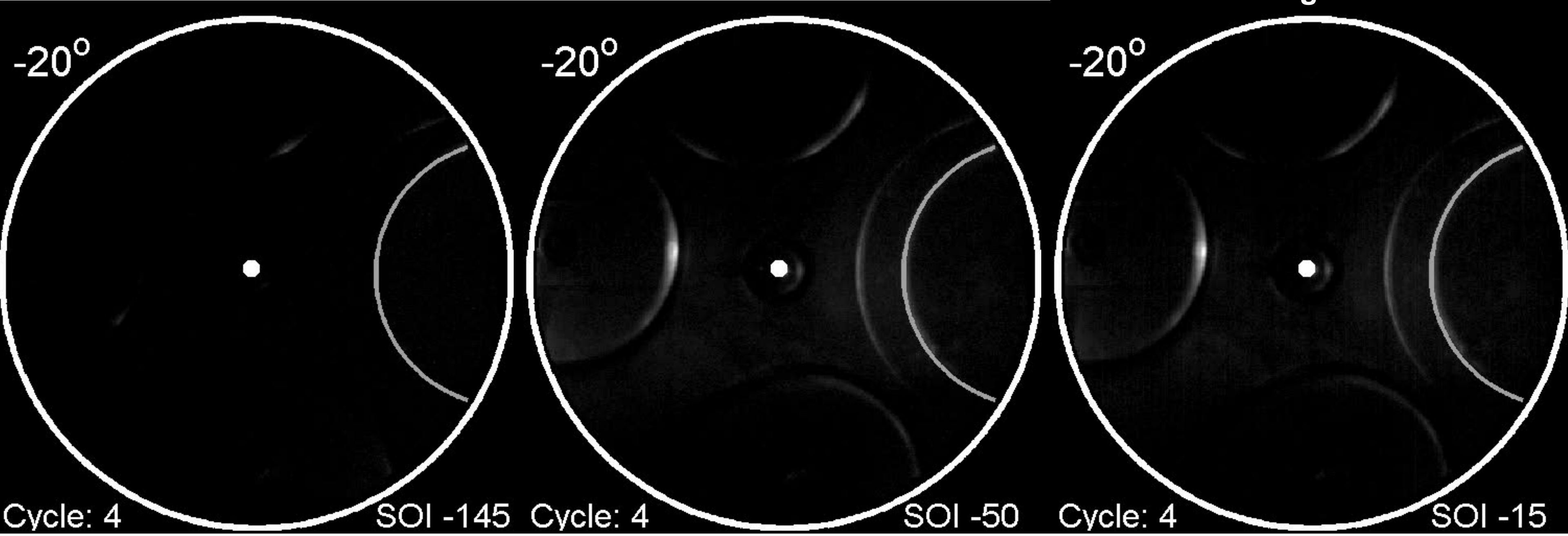
- Minimum in the peak heat release rate is observed near an SOI of 50° BTDC
- Combustion becomes violent at very early and near TDC injection timings
  - Diesel-like injection timings perform poorly for dual-fuel operation
- Combustion rate can be controlled by controlling mixing time



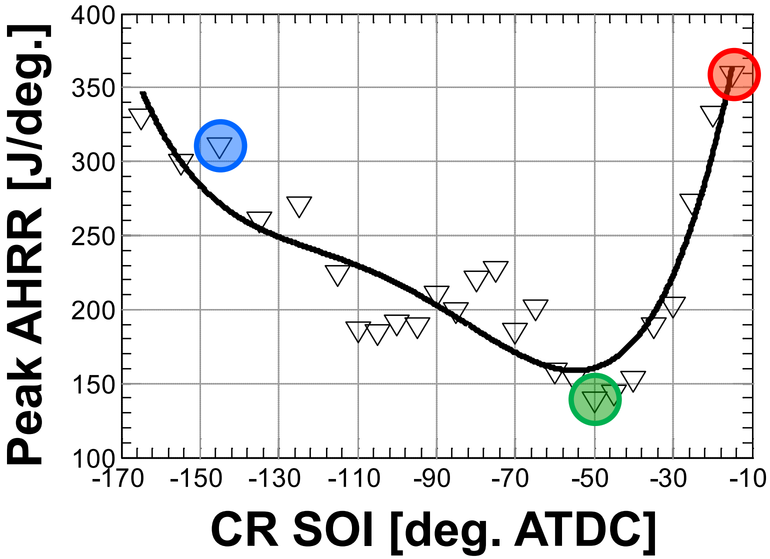


Fuel Reactivity Stratification

Camera Settings are constant

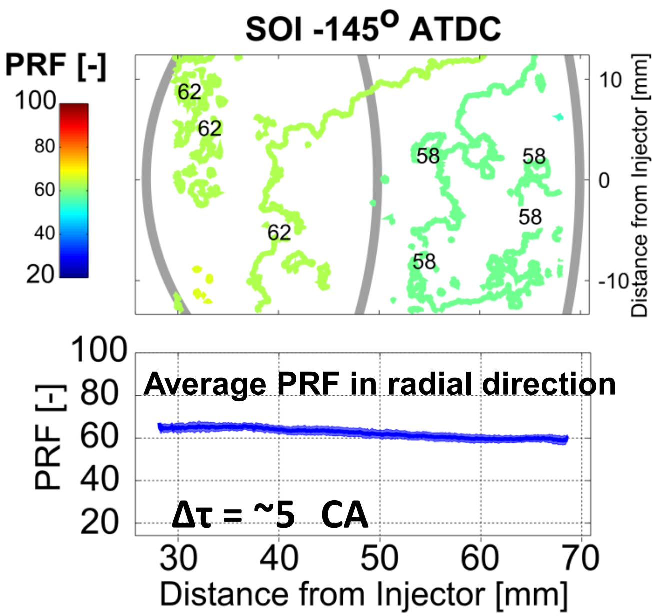


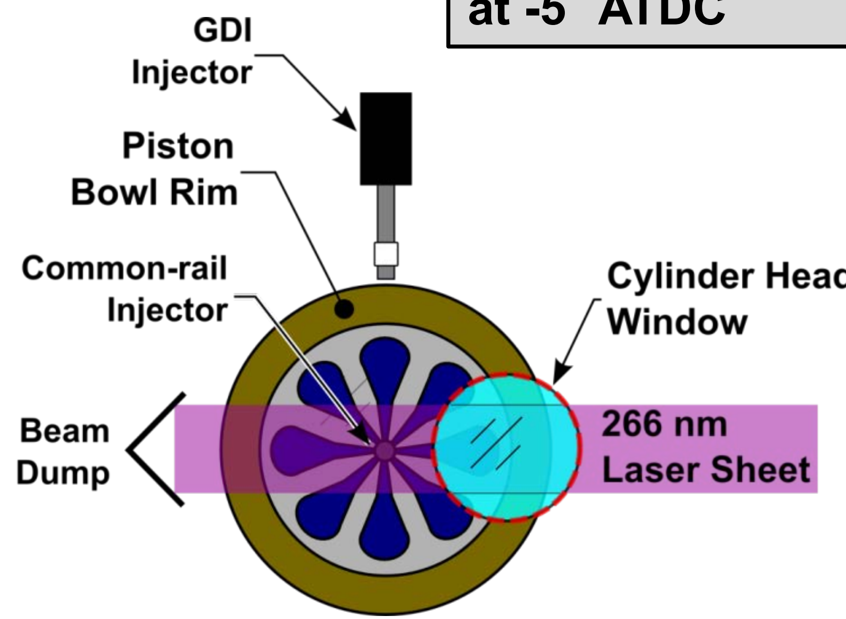
- **Early injection:** Random ignition locations and volumetric combustion
- **Mid injection:** Controlled energy release from the piston bowl rim inward
- **Late injection:** Ignition near the bowl rim followed by rapid heat release throughout the jet



Fuel Reactivity Stratification

PRF Maps shown at -5 ATDC





- **Early injection:** Charge is very well mixed (near global PRF) → Under stratified charge results in rapid energy release (HCCI-like)
- **Mid injection:** Spatial gradient in ignition delay results in controlled energy release
- **Late injection:** Jet-like structure with many near stoichiometric regions (jet has nearly uniform ignition delay) → Rapid energy release in jet

Conclusion

Split-Injection RCCI Combustion

- Chemiluminescence imaging showed that ignition generally occurred in the downstream portion of the jet and moved gradually upstream towards the center of the combustion chamber
- Fuel-tracer PLIF imaging showed that the fuel distribution (i.e., PRF number) correlates with the observed ignition location(s) and reaction zone progression

Heat-Release Rate Control Using Reactivity Stratification

- Fuel reactivity stratification controls the energy release and the gradient in the stratification controls the direction of reaction zone growth
  - At early injection timings, the charge is **too mixed** and the ignition delay is nearly constant throughout the chamber
  - At late injection timings, the charge is **too stratified** and the ignition delay in the n-heptane jet is nearly constant
- Using fuel reactivity stratification, the heat release rate can be tailored to maximize efficiency while meeting engine platform constraints (e.g., combustion noise)

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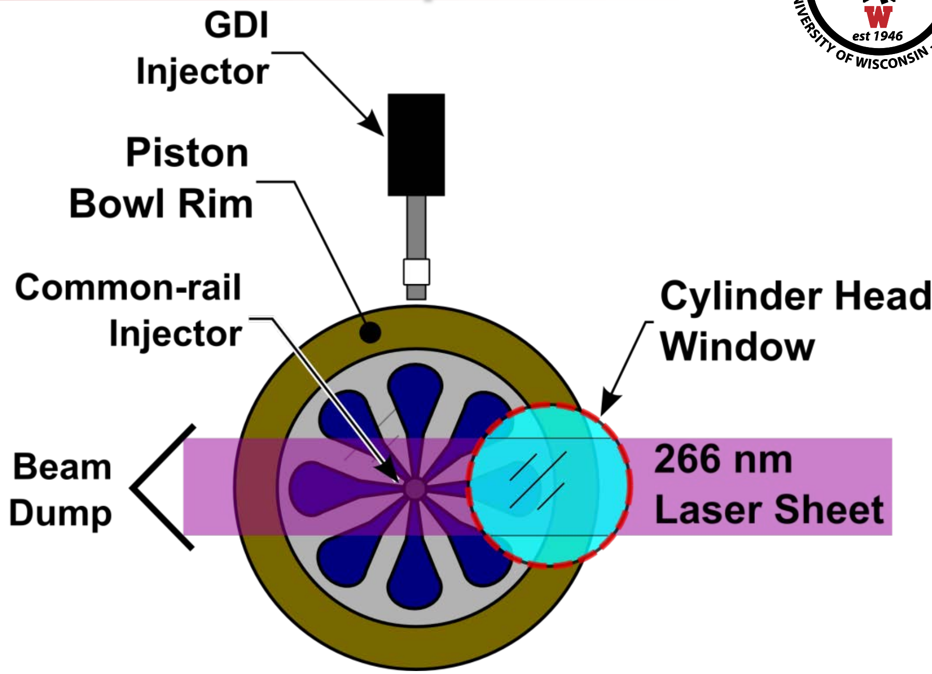
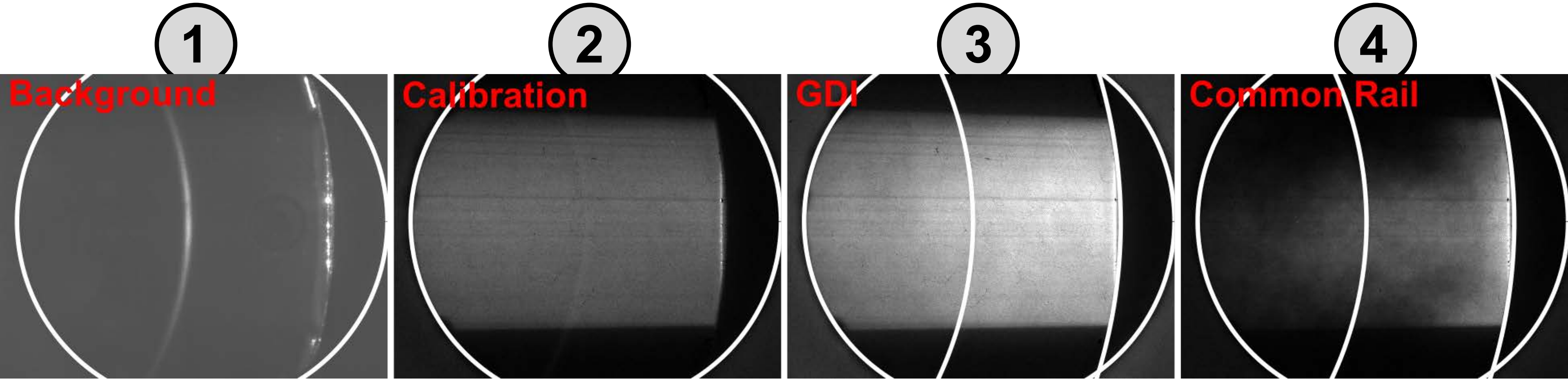
Backup Slides

Toluene Fuel Tracer PLIF - Setup

Image Acquisition

- Images were acquired in sets of 4
  1. Background image
  2. Uniform calibration image
  3. GDI distribution image
  4. Common-rail distribution image



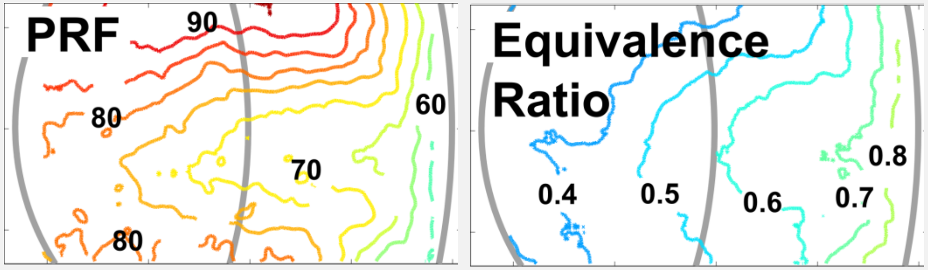


Toluene Fuel Tracer PLIF - Setup

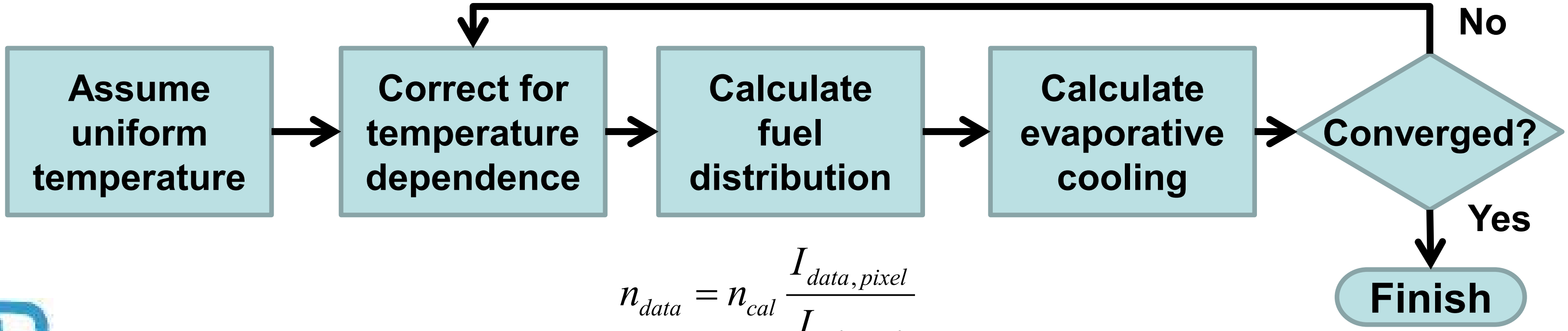
Image Processing

- Temperature correction
  - Fluorescence quantum yield decreases with increasing temperature
  - Absorption cross section increases with increasing temperature
- Images are then processed iteratively accounting for evaporative cooling and real gas properties

Ensemble averaged GDI and common-rail images are combined to calculate overall PRF and equivalence ratio distributions



$$PRF = \frac{m_{GDI} / \rho_{\mathrm{ic8h18}}}{m_{GDI} / \rho_{\mathrm{ic8h18}} + m_{CR} / \rho_{\mathrm{nc7h16}}}$$

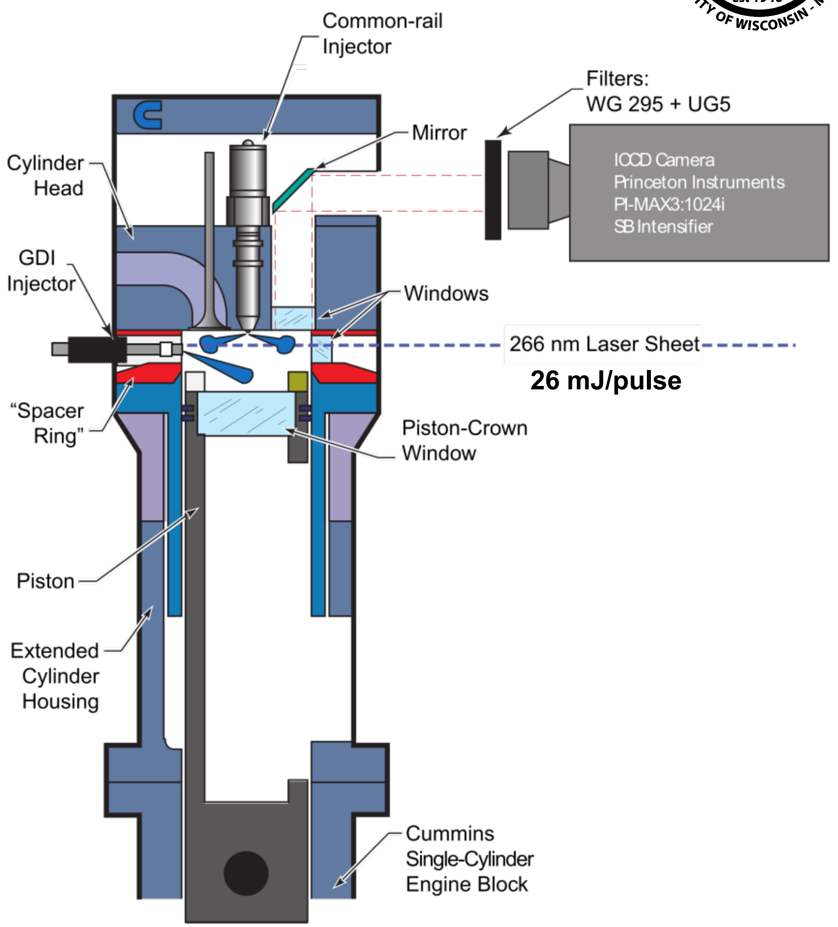


$$n_{data} = n_{cal} \frac{I_{data,pixel}}{I_{cal,pixel}}$$

Toluene Fuel Tracer PLIF - Setup

Engine	Cummins N-14
Bore x stroke	13.97 x 15.24 cm
Displacement	2.34 L
Geometric compression ratio	10.75

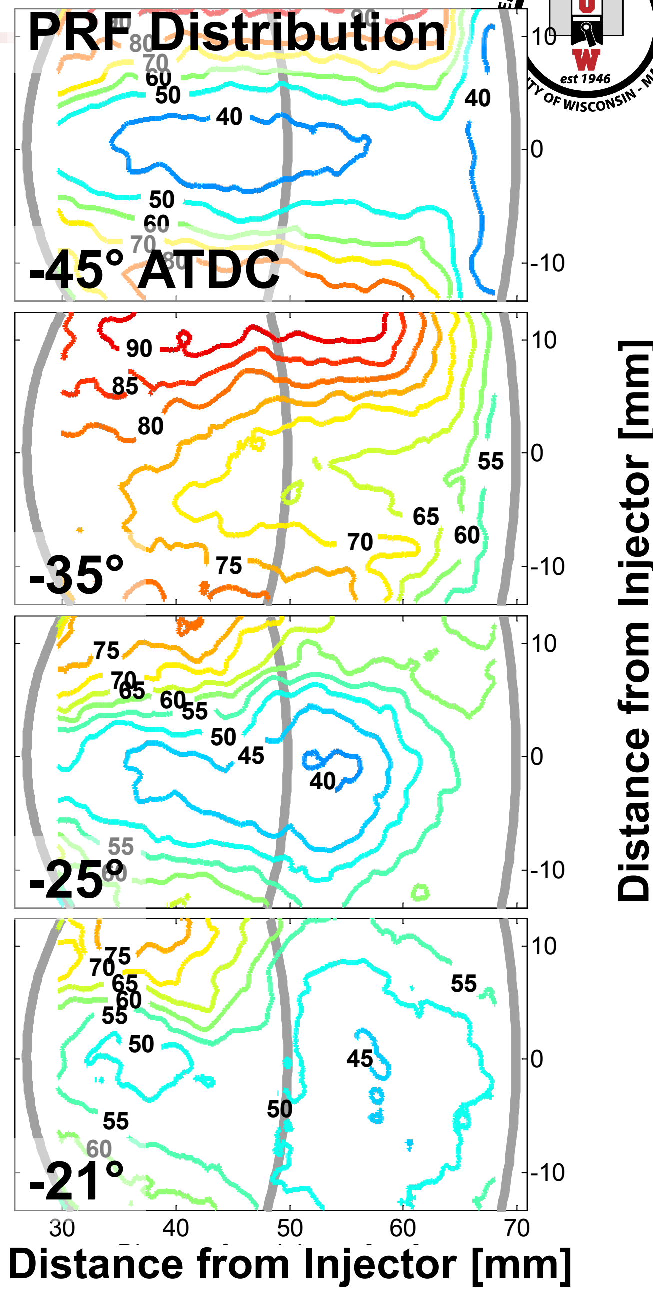
- 4th harmonic of an Nd:Yag laser (266 nm) was formed into a thin horizontal sheet using an f=-50 mm cylindrical lens followed by an f=500 mm plano-spherical lens
- Sheet was positioned 10 mm below the firedeck
- Fuel was doped with 1% toluene by volume
- An intensified CCD camera sensitive in both the UV and visible ranges was used to image the toluene fluorescence
- Engine was operated using 100% nitrogen (i.e., inert) to avoid oxygen quenching of the toluene fluorescence

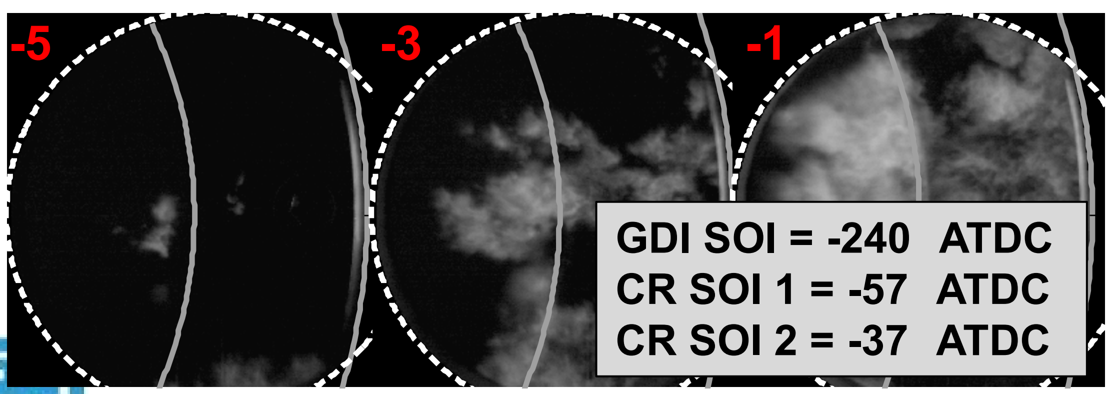


GDI SOI	-240° ATDC
CR SOI1/SOI2	-57°/-37° ATDC
TDC density	11.1 kg/m^3
N_2 Dilution	100%

Toluene fuel tracer PLIF

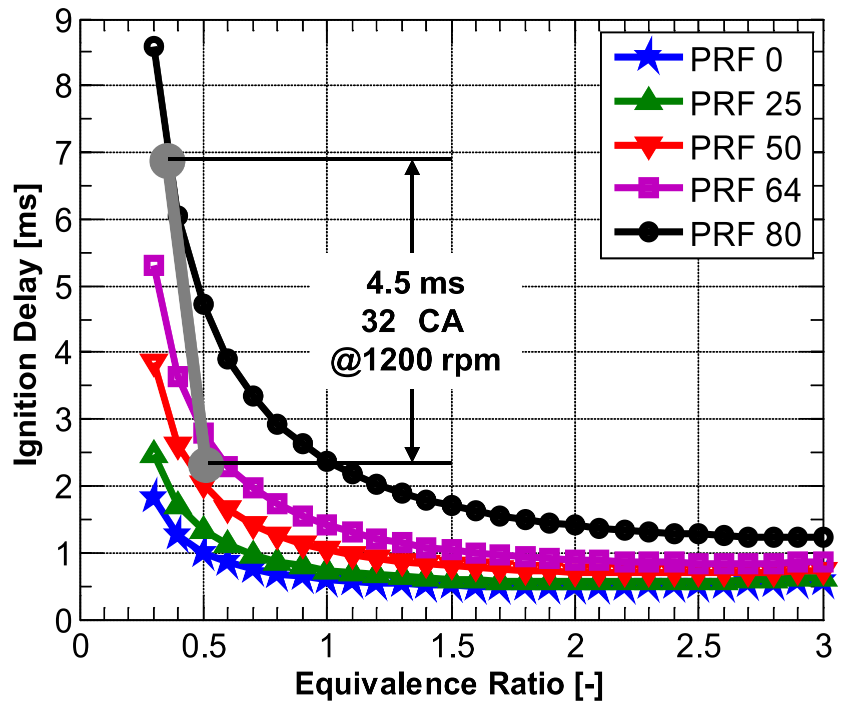
- Vapor fuel from the first common-rail injection penetrates to the liner (liquid length is near bowl rim)
- Downstream portion of the jet mixes to around a 50-50 blend of iso-octane and n-heptane by the time of the second injection. PRF number increases towards the nozzle
- Second injection enhances gradient in fuel reactivity → downstream near PRF 45 and upstream out of jet near PRF 75
- Fuel distribution prior to ignition correlates with observed ignition location and reaction zone progression





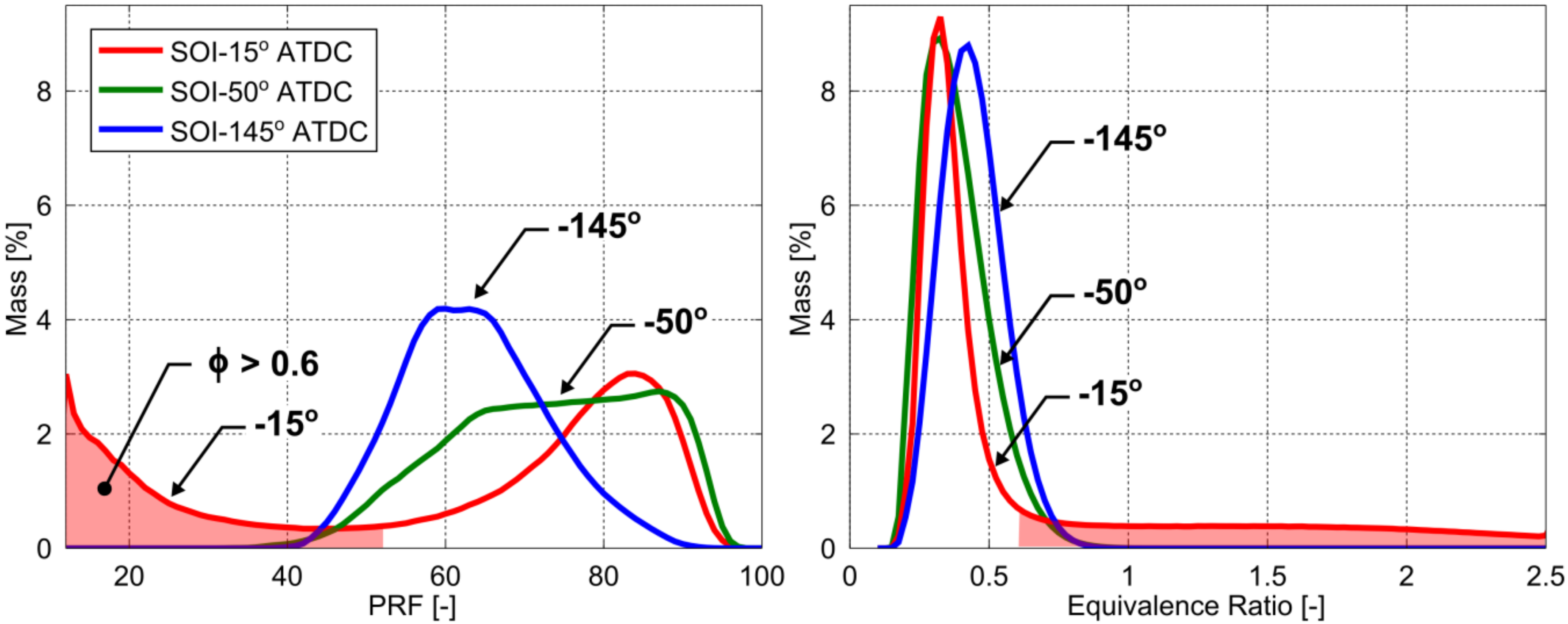
Ignition Delay

- Constant volume ignition delay using the SENKIN code and a reduced PRF mechanism
- The initial conditions correspond to representative TDC conditions from the current experiments
  - initial pressure = 27 bar
  - initial temperature = 837 K, and
  - 21% intake oxygen concentration).



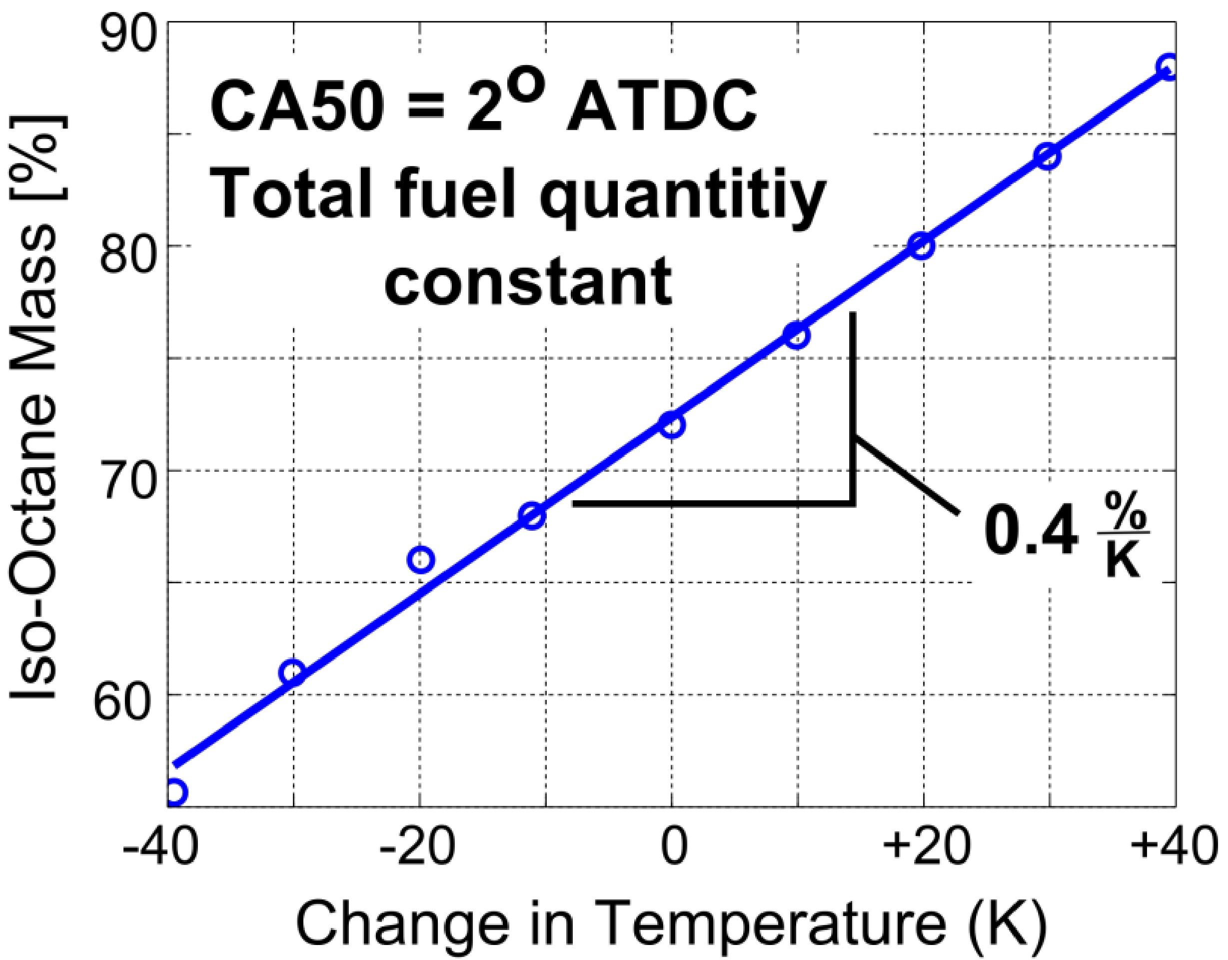
PRF and Equivalence Ratio PDFs

- PDFs calculated from the each single-shot image (40 per set) and averaged to provide a representative PRF and equivalence ratio distribution for each case

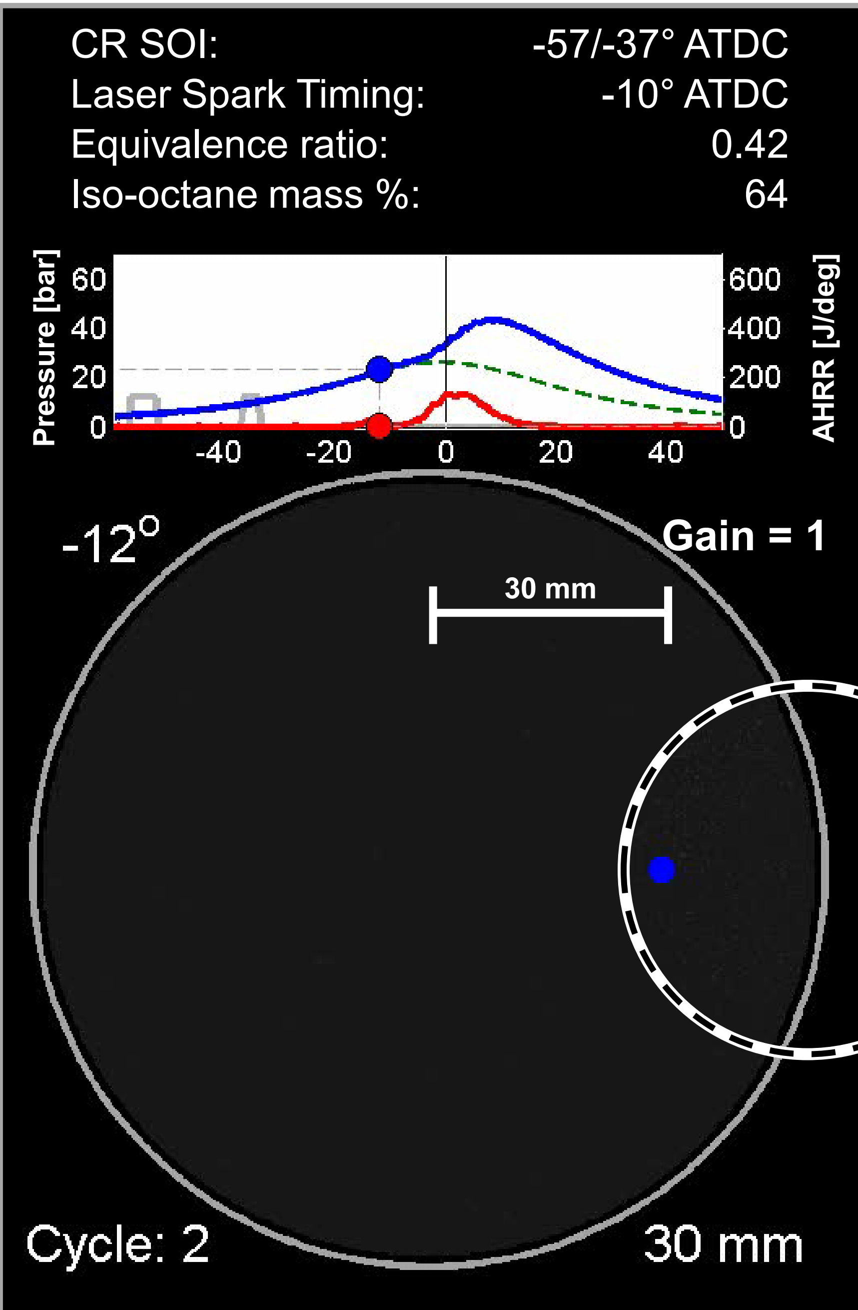


Background – RCCI Combustion

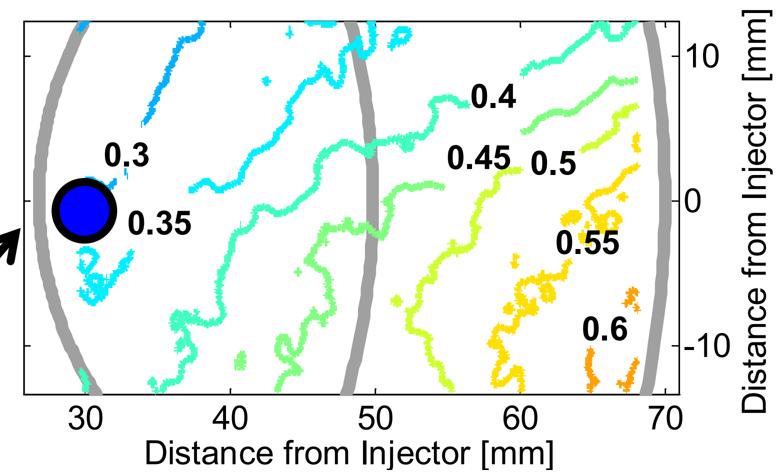
- Relative ratios of more- and less reactive fuels controls combustion phasing (e.g., effective cetane number)



Mechanism of reaction zone growth



Average Equivalence Ratio at **-10° ATDC**

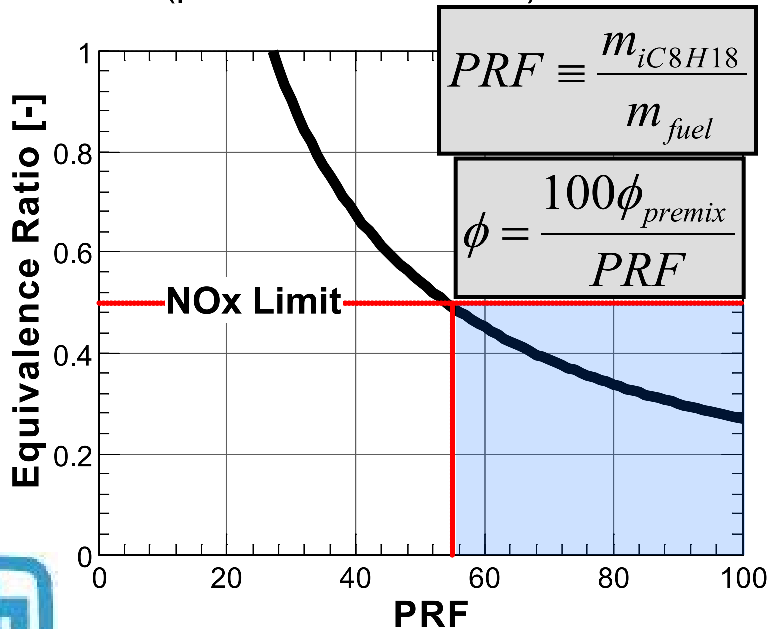


- Laser ignition is most consistent at the 30 mm location
  - Equivalence ratio **increases** with **increasing** distance from injector
  - Upstream regions are likely too lean to consistently support flame propagation

Laser ignition location is 13 mm below firedeck

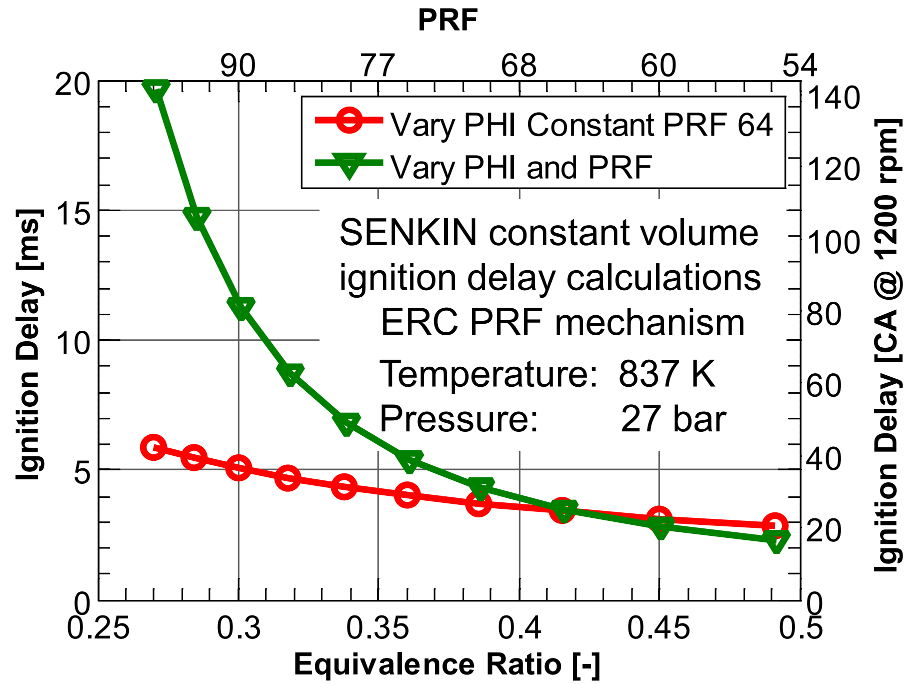
Fuel Reactivity Stratification

- Fuel reactivity (PRF) and equivalence ratio stratification are coupled.
- NOx bounds the upper limit of equivalence ratio stratification at φ=0.5 (Dec. et al. SAE 2006-01-0629)
- In the present study the equivalence ratio can vary from 0.27 to 0.5 (i.e., premixed to NOx limit)
- The equivalence ratio range to avoid NOx formation corresponds to a PRF range of 100 (premixed iso-octane) to 54



$$PRF \equiv \frac{m_{iC8H18}}{m_{fuel}}$$

$$\phi = \frac{100\phi_{premix}}{PRF}$$



Constant volume ignition delay calculations suggest that PRF stratification dominates equivalence ratio stratification at the present conditions