Light-Duty Advanced Diesel Combustion Research

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This presentation contains no proprietary or confidential information

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Purpose of work

Over-riding goal:

Provide the physical understanding and predictive capabilities necessary to design high-efficiency, emissions-compliant combustion systems

Specific objectives (FY08 +):

- **Clarify the fundamental physical processes responsible for elevated CO and UHC emissions in low-temperature diesel combustion systems**
- **Facilitate development of improved models**
  - Examine the ability to predict in-cylinder UHC and CO distributions
  - Examine the impact of the turbulence model on mean flow structures

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Response to previous review comments

- "Not enough fundamental understanding of combustion developed"
  "Emissions data should not become a focus...the objective is optical measurements"
  "Approach needs more explanation," "Present a project schedule"
  - Benchmarking against metal test engine data and developing an engine-out emissions database to guide optical experiments is an essential aspect of the approach. Optical measurements and development of fundamental understanding, as well as a more detailed explanation of the approach, are included in this year's review materials
- "Would like to see a detailed comparison of the metal to the optical engine, supported by analysis"
  - A detailed comparison was made and is available in SAE 2008-01-1066
- "Good collaboration with GM...would like to see evidence that data are available to others"
  - We are planning to post data on Sandia's Engine Combustion Network web site as more detailed measurements become available. In the meantime, just ask for it
- "Need to incorporate more detailed analysis of combustion generated noise"
  - Noise reduction is the motivating factor behind current (joint with UW) research efforts incorporating multiple injection strategies

Barriers Addressed

- **Project focus on CO and UHC emissions directly impacts fuel efficiency**
- **Model validation and development impacts our ability to numerically optimize engines for efficiency and low emissions**
- **The above, and our emphasis on physical understanding, address barriers identified in:**

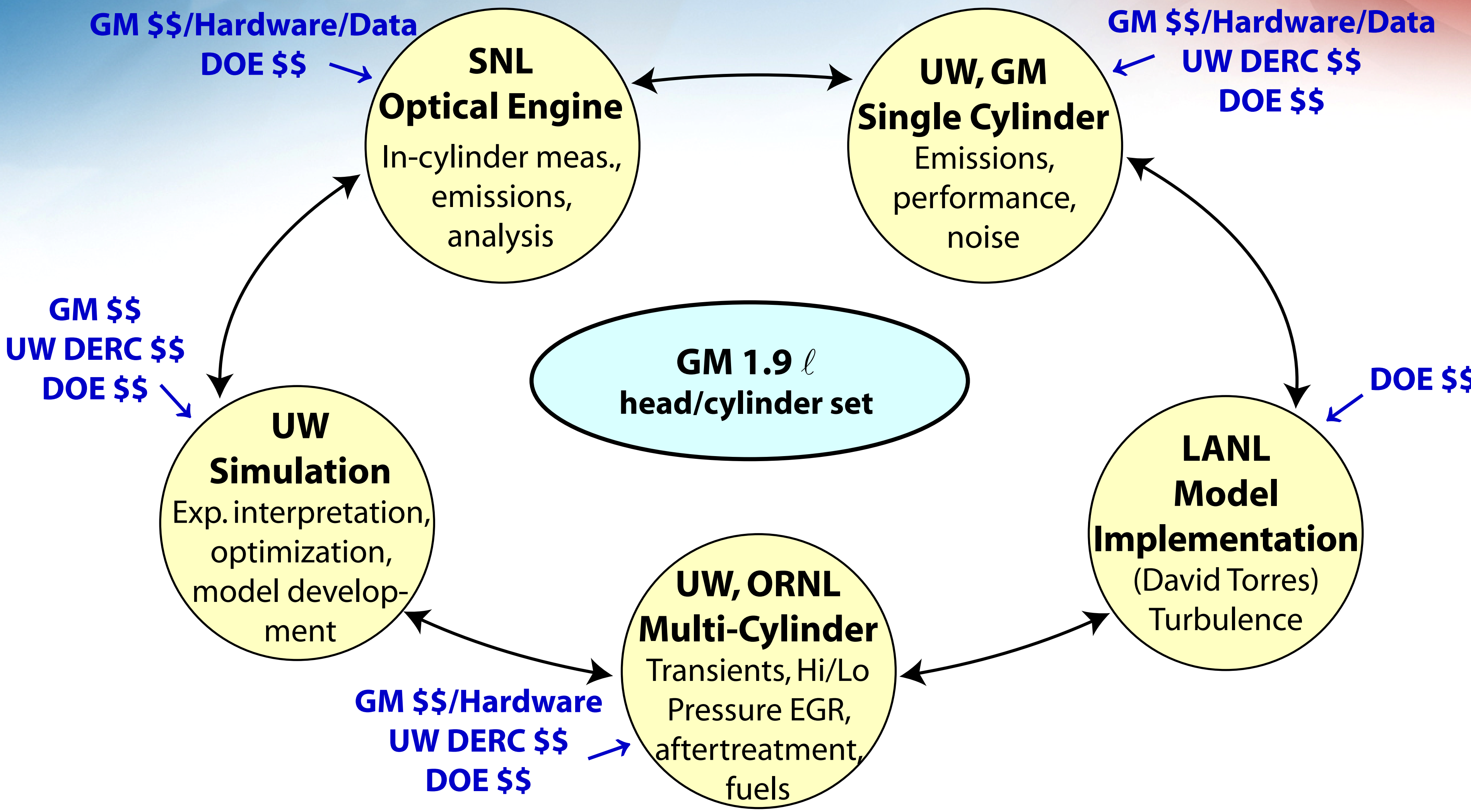
Light-duty powertrain roadmap:

- Barriers to low-temperature combustion technology development:
  - Inadequate understanding of fundamentals
  - Inadequate/inaccurate simulation capability
  - Need to address low load HC and CO emissions
- System cost barriers: reducing costs will require optimization

21st-Century Truck technical white paper:

- Barriers to efficiency: inadequate understanding and simulation capability
- Barriers to emissions compliance: inadequate understanding and simulation capability
- Barriers to non-petroleum fuel use: inadequate understanding of fuel property impacts on advanced combustion regimes (addressed by collaborative work at UW)

Approach (High-level)



- **Multi-institution effort focused on a single hardware platform**
- **Significant leverage of DOE funds by support from other sources**

Detailed approach (SNL/UW specific)

Core LTC program (80% of effort):

- GM 1.9 ℓ Design/Build
- EGR System Upgrade
- Emissions data base (boost study) 2007-01-4063
- Chemkin simulations of CO & UHC DEER 2007
- CO/UHC imaging study

Jan-Mar 2006	Apr-Jun 2006	Jul-Sep 2006	Oct-Dec 2006	Jan-Mar 2007	Apr-Jun 2007	Jul-Sep 2007	Oct-Dec 2007	Jan-Mar 2008	⇨	Future work

- Data analysis from previous engine build
- Fast-FID Cyclic var. study 2007-01-1837
- Metal Engine Benchmarking 2008-01-1066
- EGR components study 2008-01-1066
- Model comparison UHC & CO

Turbulent flow modeling assessment (20% of effort):

Jan-Mar 2006	Apr-Jun 2006	Jul-Sep 2006	Oct-Dec 2006	Jan-Mar 2007	Apr-Jun 2007	Jul-Sep 2007	Oct-Dec 2007	Jan-Mar 2008	⇨	Future work

- Dissipation modeling assessment 2007-24-1363
- Stress model comparison 2008-01-1363

Outline of technical accomplishments

- **Brief recap of FY007**

  - Clarify linkage to work done this fiscal year

- **Low-temperature combustion core program**

  - Homogeneous reactor modeling (Chemkin) to clarify influence of kinetics on UHC and CO yield
  - Experimental studies of in-cylinder UHC and CO distributions
  - Comparison with and assessment of model predictions

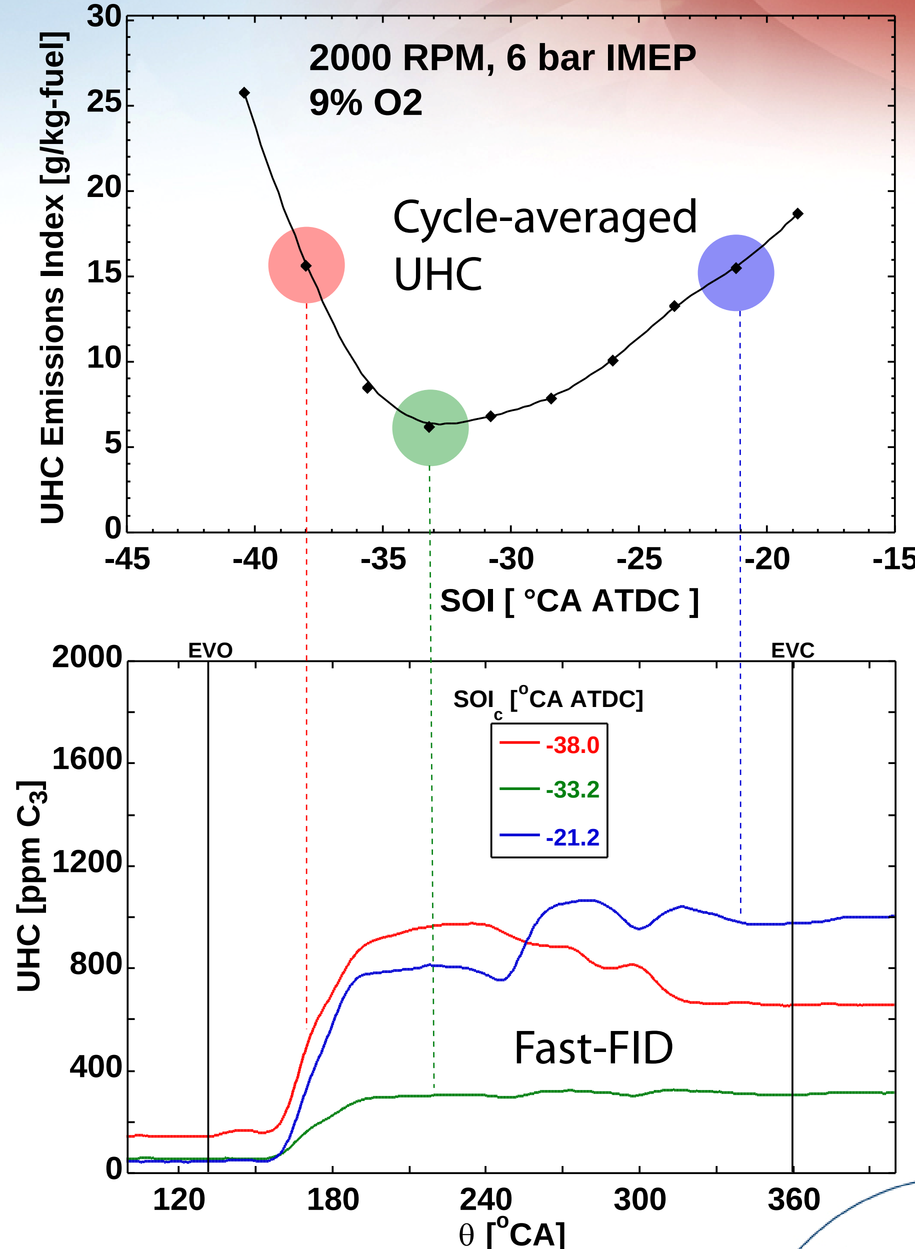
- **Turbulent flow modeling assessment**

  - Impact of turbulence model on simulations of light-duty diesel combustion

2007 Recap

Fast-FID
Cyclic var. study
2007-01-1837

- Fast-FID provides crude in-cylinder spatial information on UHC
  - ➢ Guides optical measurement strategy, provides validation data
- Cycle-to-cycle fluctuations in UHC are small. Under-standing the mean cycle is of primary importance
  - ➢ Cycle-averaged optical mea-surements are relevant
  - ➢ Cycle-averaged simulations are relevant



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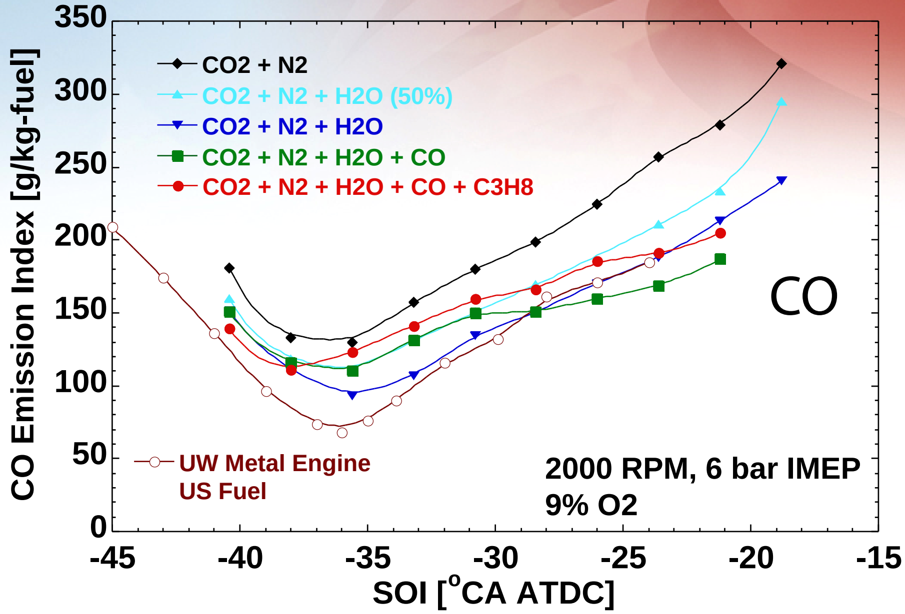
2007 Recap

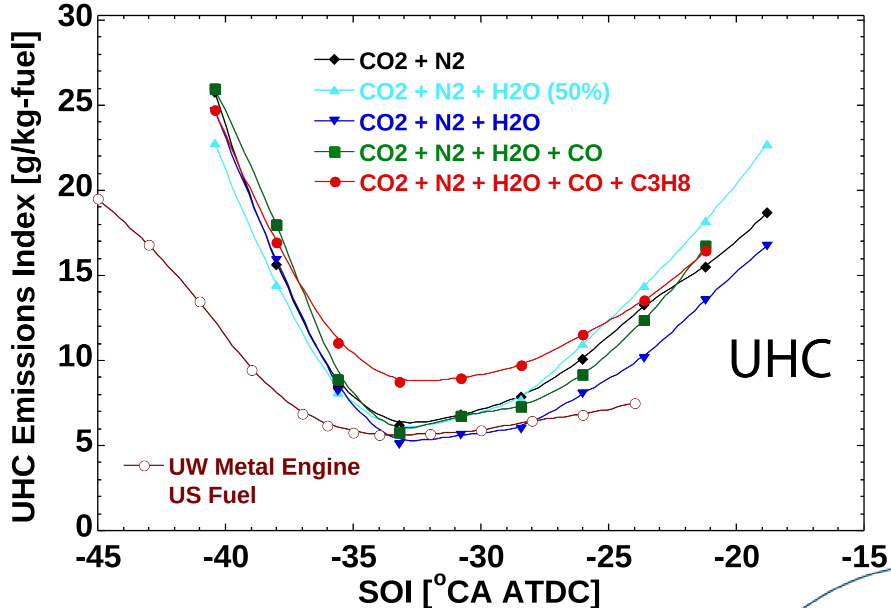
Metal Engine Benchmarking 2008-01-1066

EGR components study 2008-01-1066

- Combustion performance (pressure based) is closely matched
- Emissions agree well both in magnitude and in trends
- Detailed matching of EGR composition is of secondary importance

➢ Cautiously interpreted, optical engine data can provide relevant informa-tion on emissions processes





Metal engine data provided by Prof. David Foster, UW-ERC

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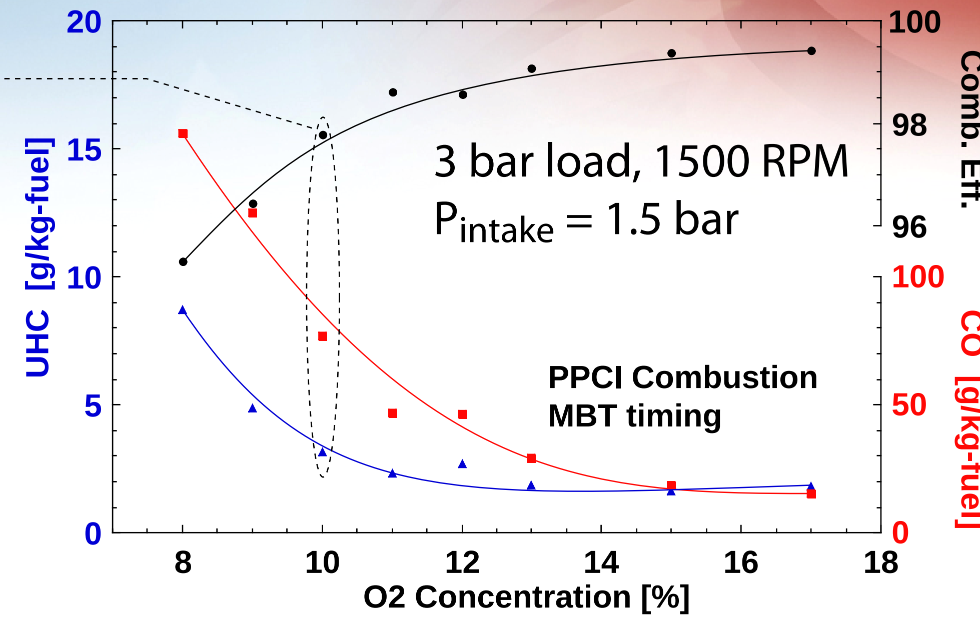
2007 Recap

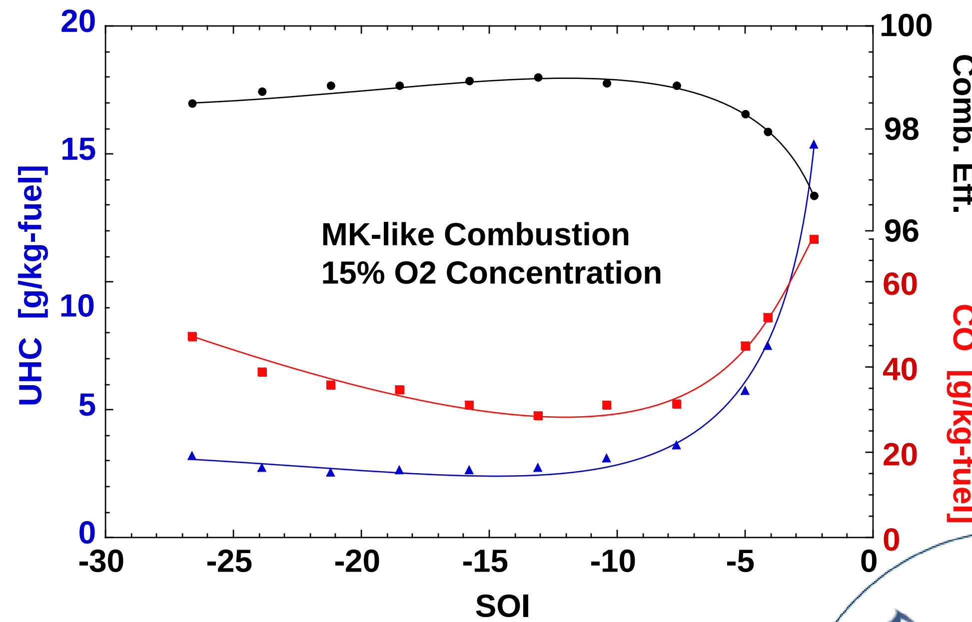
Emissions data base (boost study) 2007-01-4063

Operating condition for which in-cylinder measurements are presented below



- Investigated emissions, fuel economy, and combustion performance for a wide range of boost pressures, EGR rates, and injection timings

  - These data complement higher speed and load emissions and performance data obtained at UW, and provide guidance for optical studies



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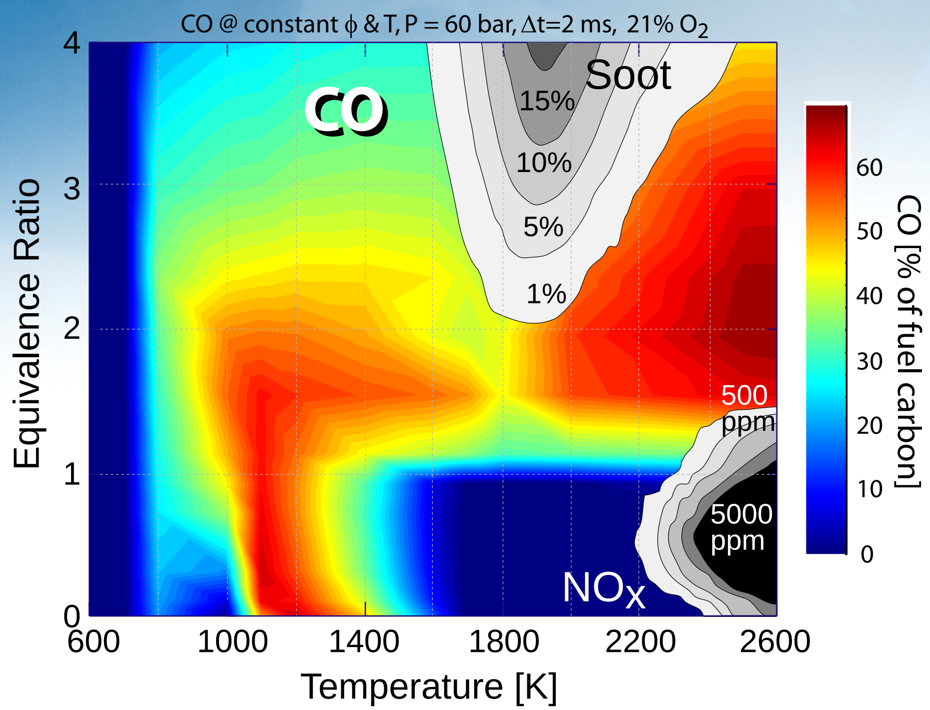
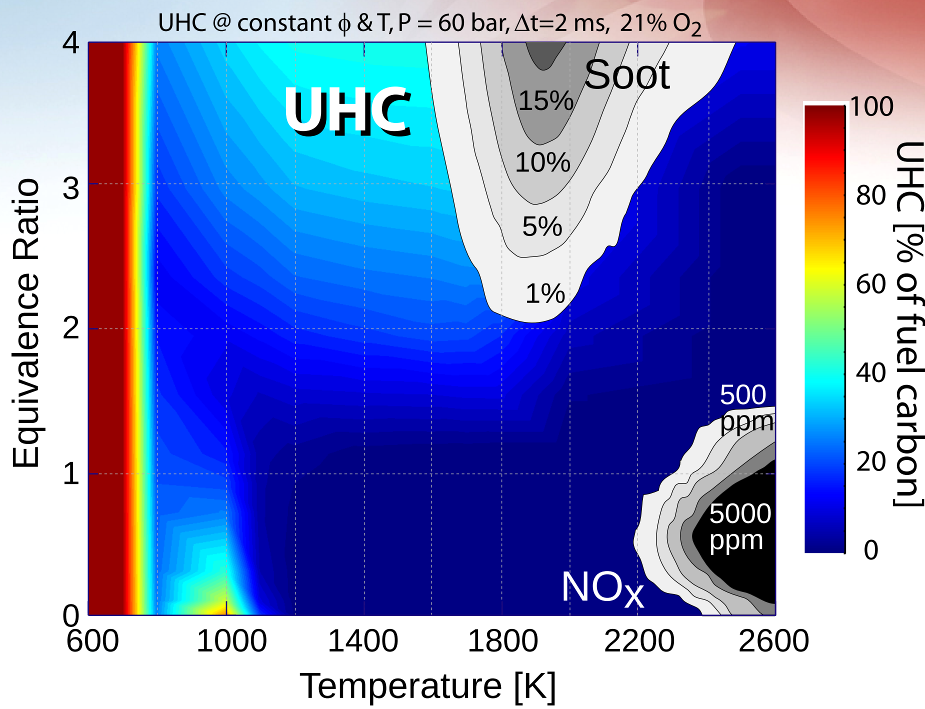
Kinetics studies clarify sources of CO and UHC





- Constant ϕ/T simulations are a simplification of engine combustion but provide guidance regarding sources of CO & UHC and help with interpreting experiments (results agree well with Park & Reitz, Comb. Sci. and Tech, 2007, and with Golovitchev, et al. ICE2007)
- Simulations extend previous results over a broader range of ϕ and T, in particular the T < 1400K lean region
- Rich and lean sources of both CO and UHC are clearly apparent, as are crevice/quench layer sources of UHC

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➢ Note that CO and UHC are often not collocated

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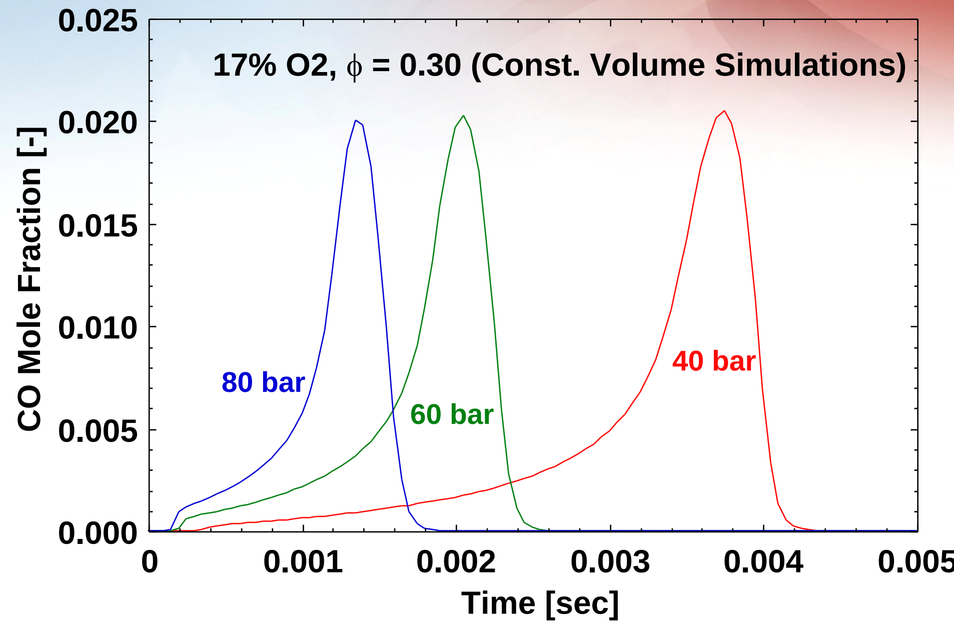
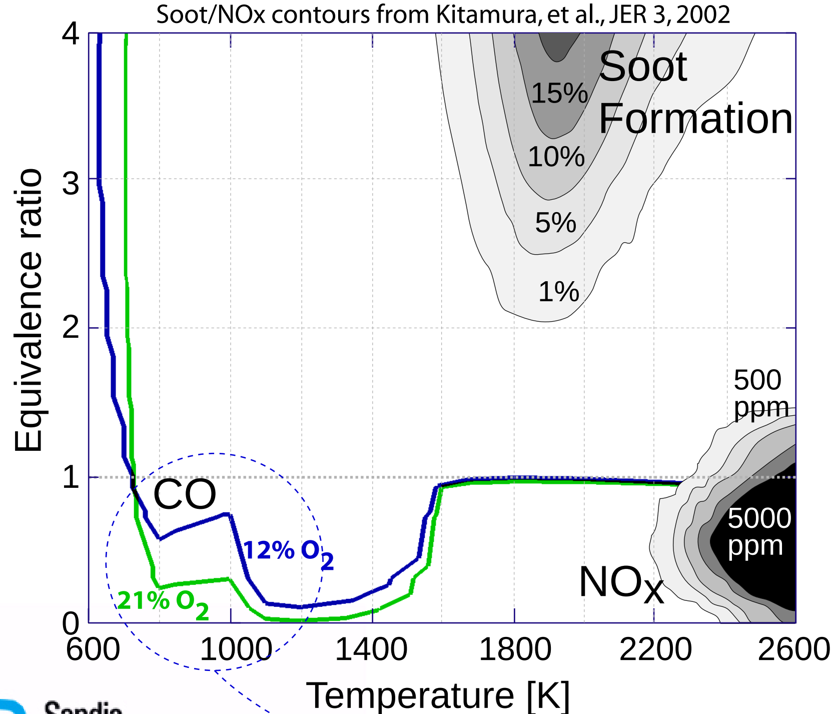
Pressure and dilution effects can be significant

Increased boost helps UHC and CO emissions by increasing:

- Global λ
- Mixing rates
- ➢ Reaction rates ⇨



CO isopleths 1% by volume (roughly 200 g/Kg-fuel), P = 60 bar, t = 2.0 ms
Soot/NOx contours from Kitamura, et al., JER 3, 2002



Increased dilution (with CO_2, H_2O & N_2):

- Has relatively small impact on high-to-moderate temperature CO yield
- Increases low temperature reaction rates of rich mixtures
- ➢ Most strongly influences reaction of lean, cool mixtures

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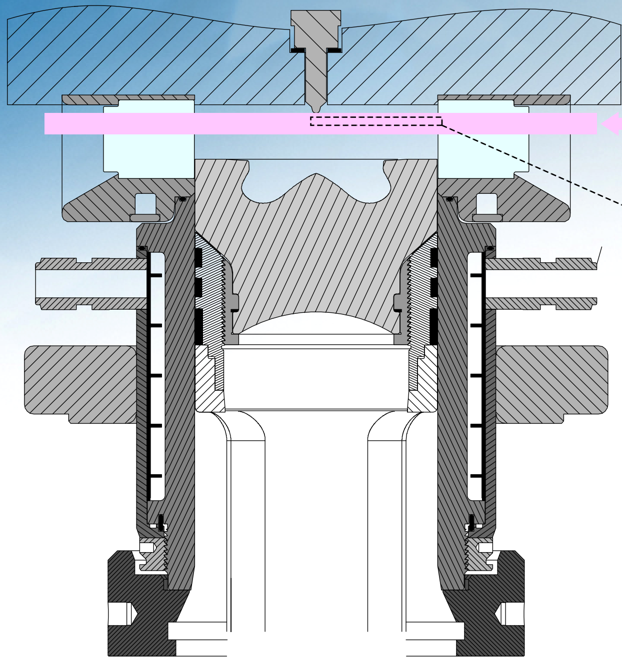
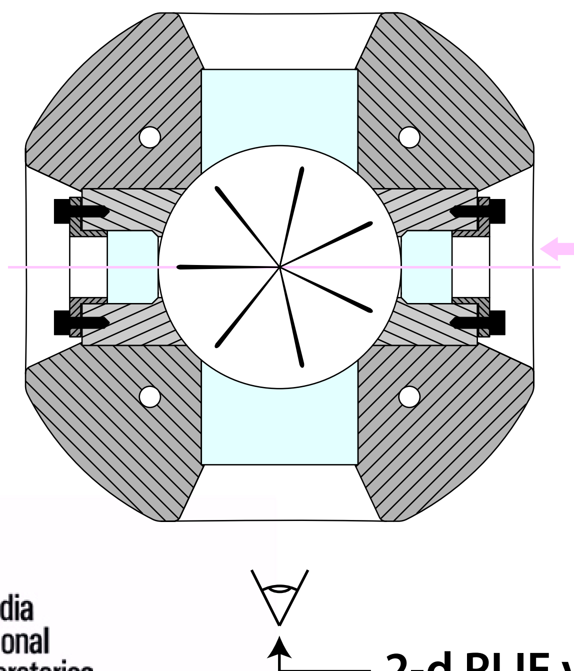
Engine and experiment





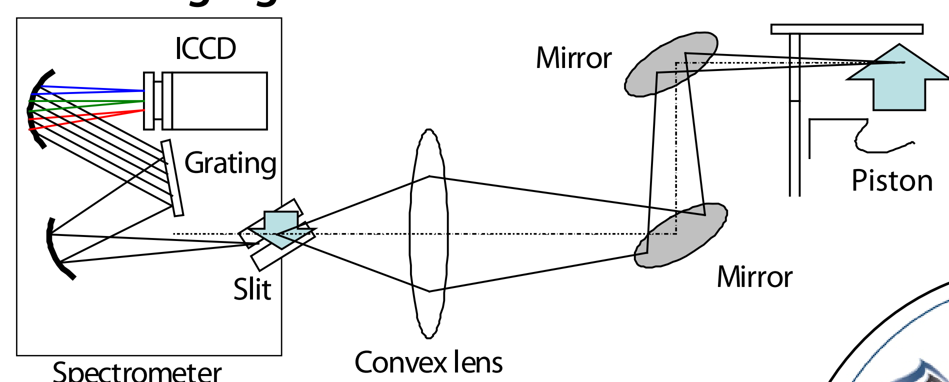
GM 1.9ℓ cylinder head	
Bore	82.0 mm
Stroke	90.4 mm
Geometric CR	16.7
Effective CR	14.0

Operating Conditions	
Speed	1500 RPM
Load	3.0 bar IMEP
P_{intake}	1.5 bar
T_{intake}	95 C

Bosch CRI2.2 Common Rail FIE	
Nozzle	7 hole, 149°, 440 [cm^3 / 30 s]
Rail Pressure	860 bar
Fuel	US #2 diesel fuel

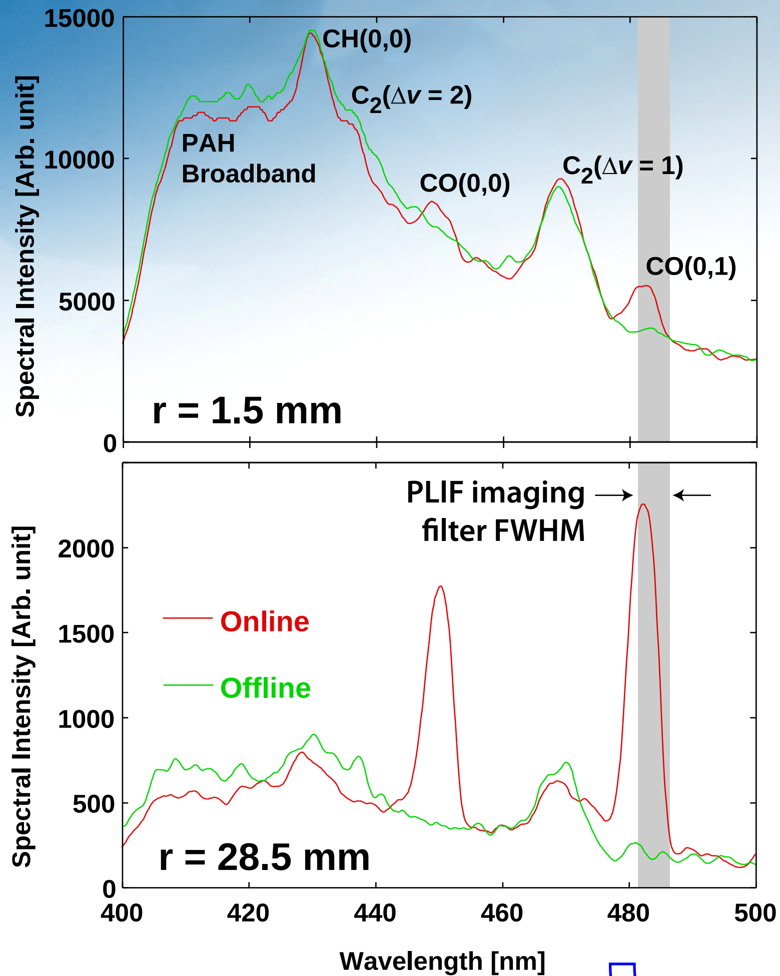
Laser Excitation	
On-line: 230.09 nm	Off-line: 230.18 nm
CO $B^1\Sigma^+ \leftarrow X^1\Sigma^+$ (0,0)+UHC	UHC

Line-imaging



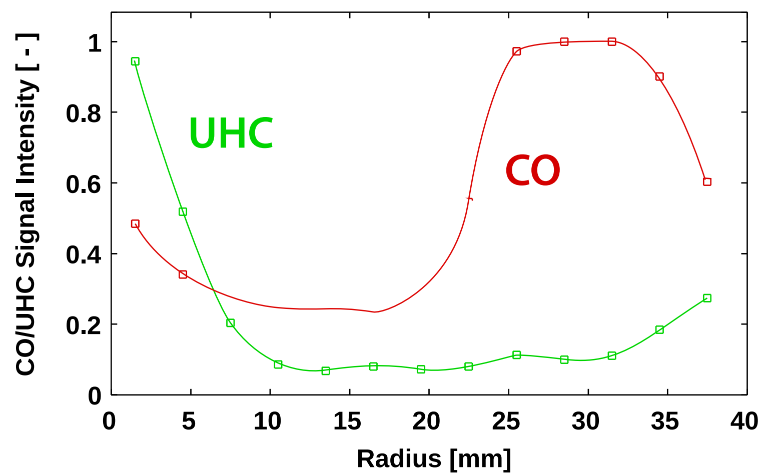
2-d PLIF viewing direction (full bore imaged, L = 483.9 ± 2.5 nm)

Spectral characterization & data analysis



- CO is unambiguously identified (on-line – off-line)
- Good statistical convergence required for on-line/off-line subtraction ➢ Cycle-averaged data
- Off-line signal (UHC) can vary significantly with spatial location and operating condition
- UHC signal dominated by broadband PAH back-ground, additional contributions from CH and C_2
- At constant pressure, change in CO fluorescent yield over a conservative range of T & P is 30–40%
- Irradiance dependency (absorption) adds add'l uncertainty

➢ Analysis yields a *qualitative* measure of CO and UHC distributions



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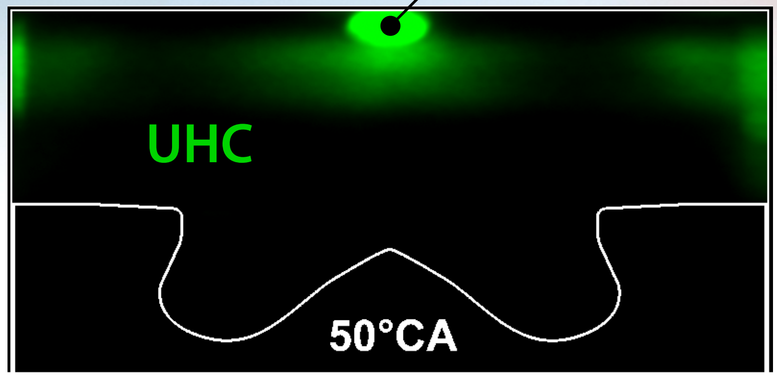
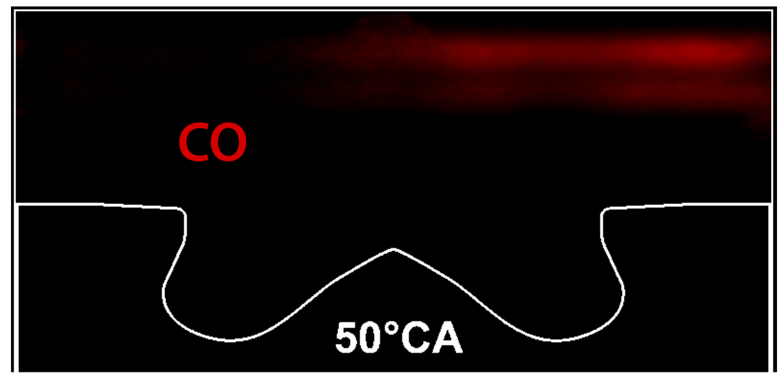
PLIF image processing

$$\frac{(\text{Off-line - Nat. luminosity})}{\text{Avg. Off-line Energy}} \Rightarrow$$



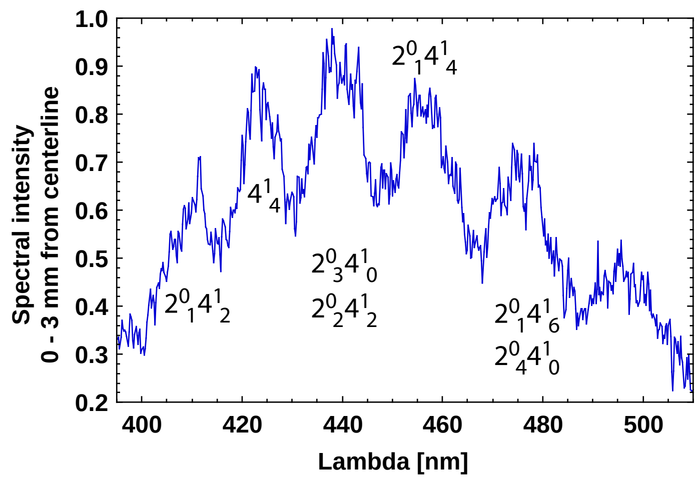
$$\left(\frac{(\text{On-line - Nat. luminosity})}{(\text{Avg. On-line Energy})^2} - \frac{(\text{Off-line - Nat. luminosity})}{(\text{Avg. Off-line Energy})(\text{Avg. On-line Energy})} \right) \Rightarrow$$



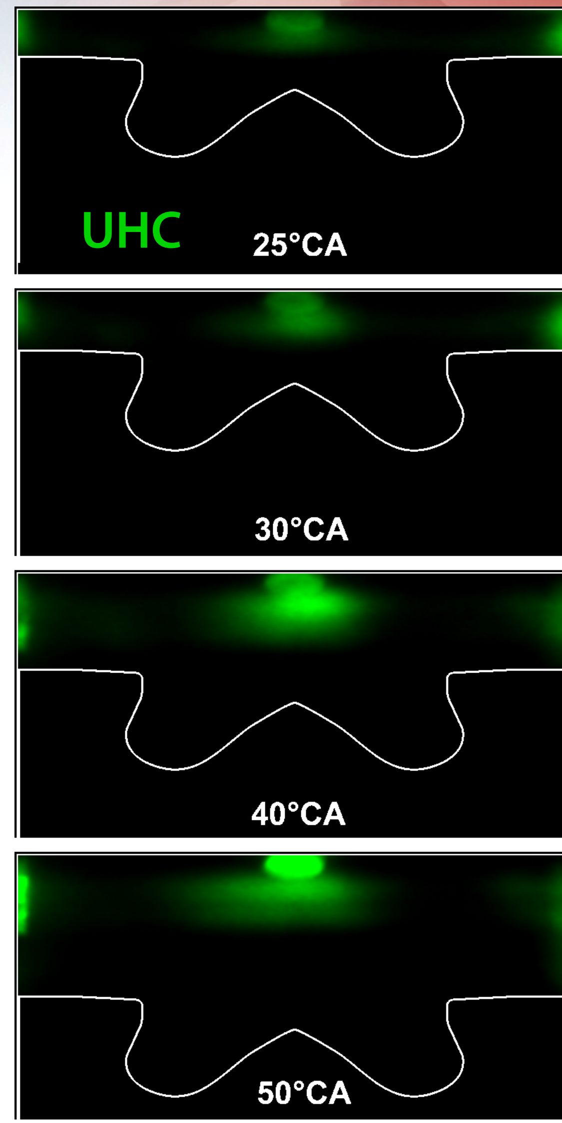
- Images are corrected for distortion, bowl position shown to scale
- Note strong beam absorption apparent in CO image
  - Restrict attention to RHS only
  - CO near cylinder centerline under-estimated
  - Absorption strongest when UHC is high

Baseline UHC: 9% O2, SOI=-26.6 (PPCI)

- UHC dominated by centerline region. Consider:
  - Musculus et al. SAE 2007-01-0907
  - Spatial contraction/expansion at higher/lower loads
  - Temporal evolution of CO signal (next viewgraph)
  - Spatial relationship to CO signal
  - Observed CH_2O fluorescence when excited at 355 nm



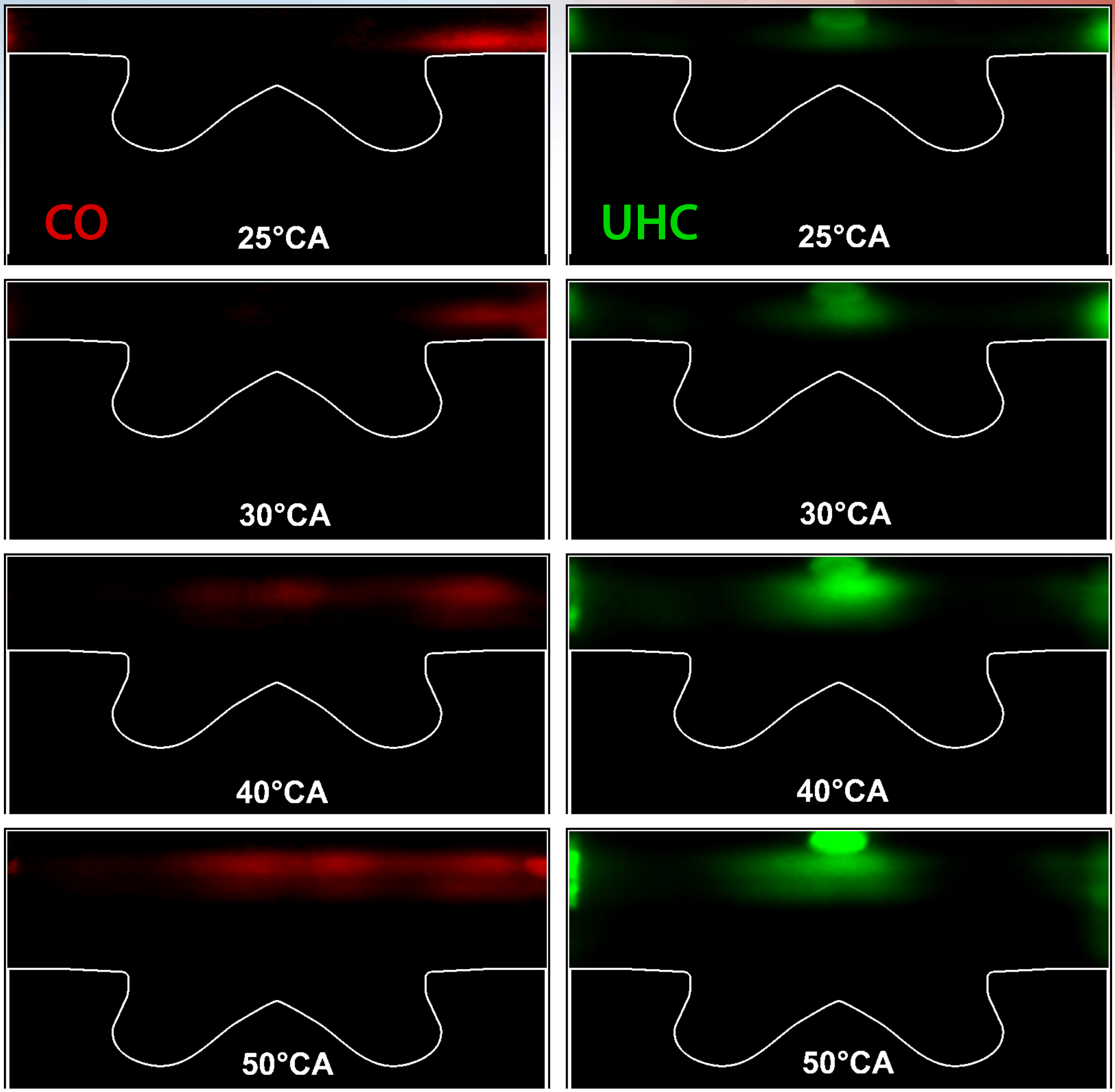
➢ Centerline UHCs dominated by over-lean mixture



- Crevice volume UHCs, volume weighted, are comparable
  - Top ring land crevice > 3X metal engine crevice
  - Based on load sweep results, crevice UHC mixtures are lean

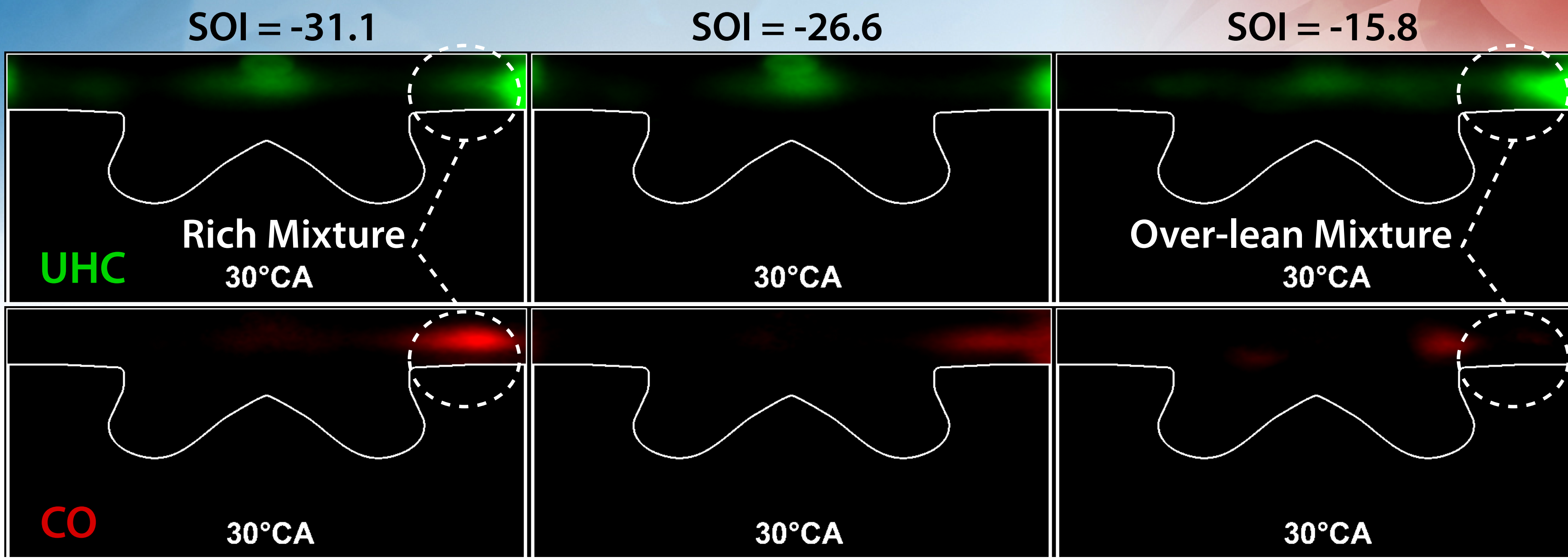
Baseline CO: 9% O2, SOI=-26.6 (PPCI)

- CO is generally not collocated with UHC — as anticipated from homogeneous reactor modeling
- Centerline CO appears late:
  - Unlikely to be caused by mean flow transport
  - Consistent with slow oxidation of lean mixture
- CO is broadly distributed in the squish volume and dominates
  - CO in the absence of UHC consistent with rich, T>1400K regions or lean, 1000K < T < 1400K regions
  - Results from load sweep point to lean mixture



- CO at intermediate radii, at crank angles of 50° and beyond, may be due to efflux from the bowl

SOI Sweep CO & UHC: 9% O2

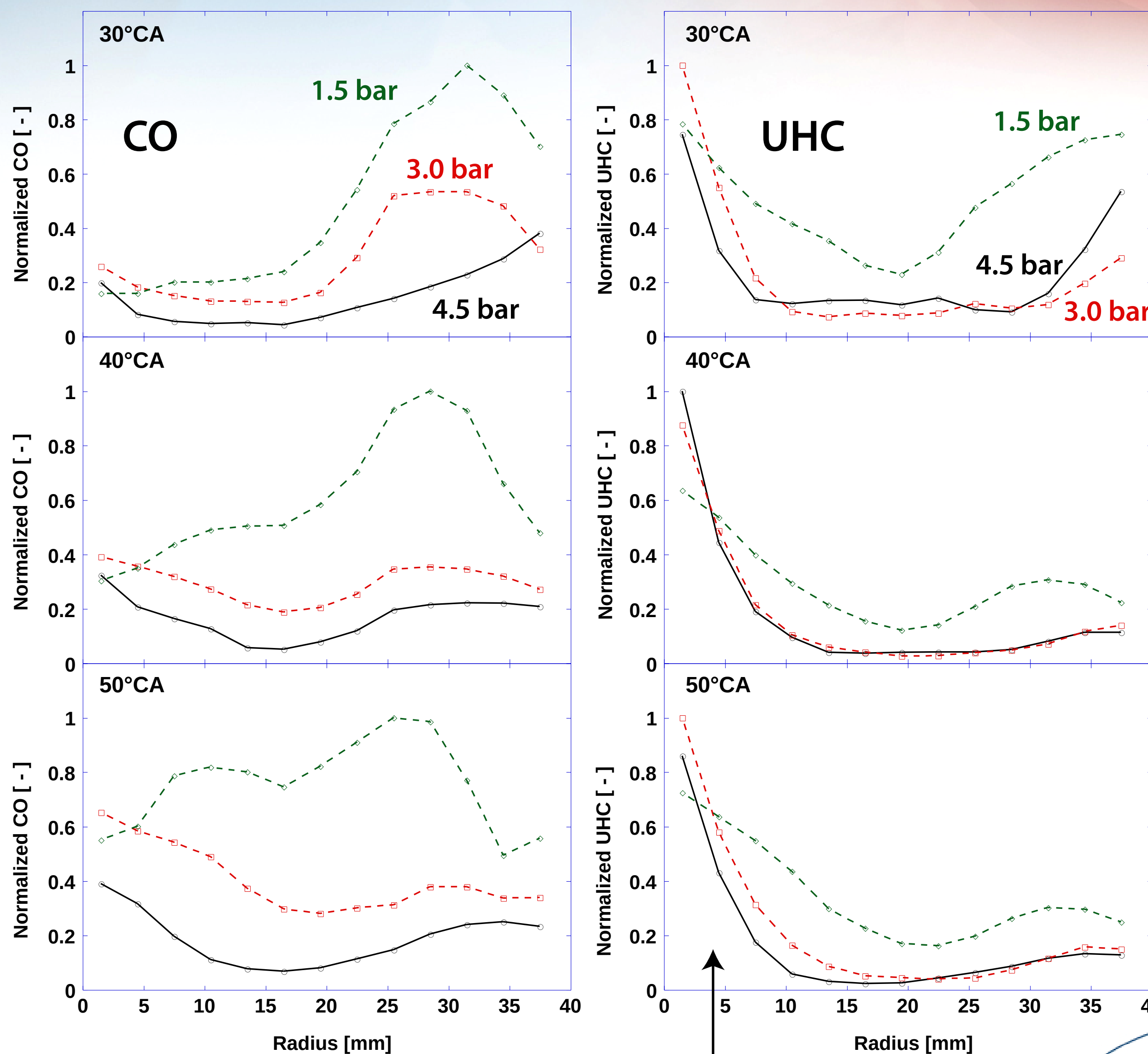


- Minimum squish volume UHC observed at baseline (MBT timing) (beam absorption makes relative centerline signal levels assessment difficult)
- With advanced timing, increased UHC and increased CO over the baseline case is only consistent with rich mixture
- With retarded timing, increased UHC with decreased CO is consistent with over lean mixtures or very rich mixtures

  Spray targeting, knowledge that the baseline squish region is lean, and displacement of CO toward the (higher-temperature) bowl region all point to over-lean mixture

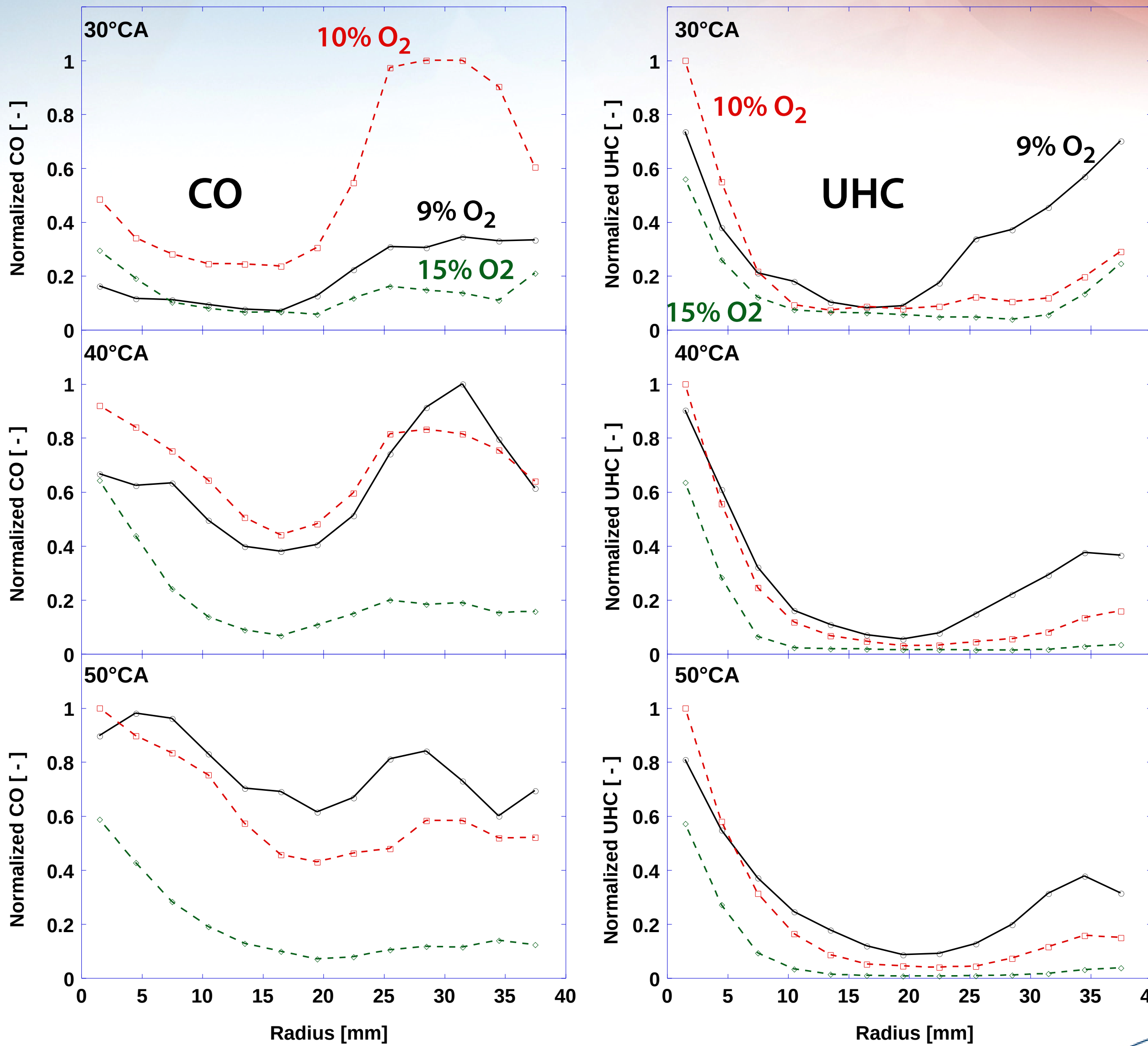
Load Sweep CO & UHC: 9% O2

- CO in the squish volume decreases with increased load
  - ➢ Even at the highest load, squish volume CO dominates over centerline CO
- UHC in the squish volume also decreases
  - ➢ At the baseline load and below, the squish volume mixture is fuel lean
  - ➢ Over-lean regions are not problematic at the baseline load
  - ➢ Over-rich regions are not problematic at the highest load
- Spatial contraction of centerline UHC with increased load is consistent with lean mixture

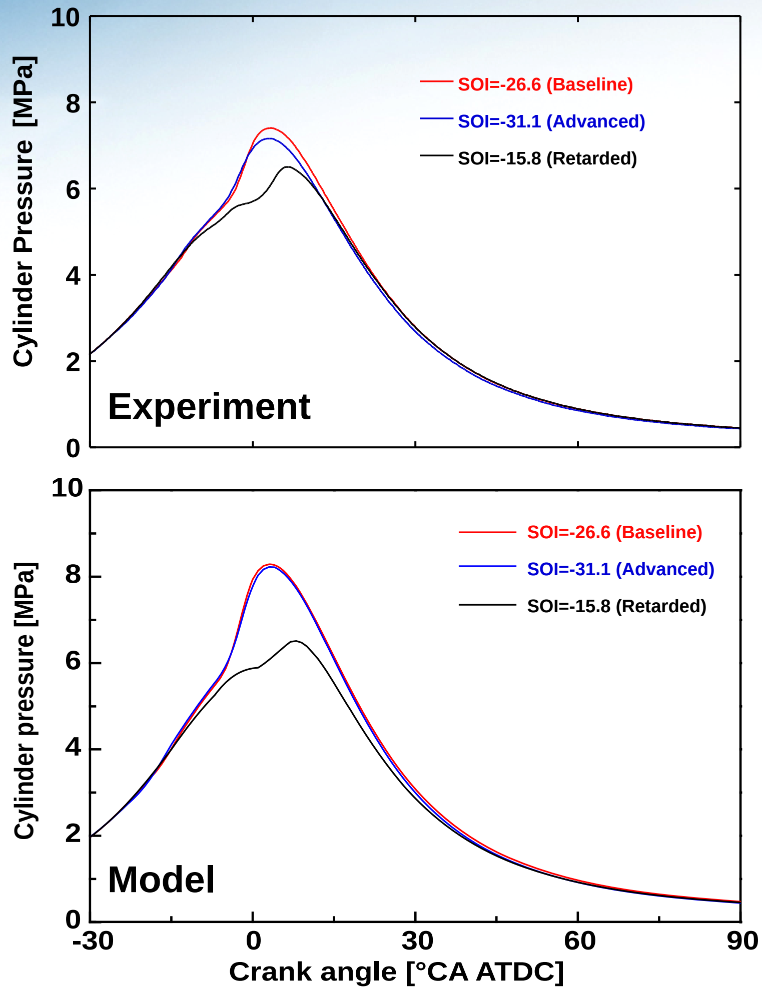


EGR Sweep CO & UHC: Baseline load & SOI

- UHC is generally increased throughout the clearance volume with decreased O_2
  - ➤ Large increase in squish volume UHC at low O_2 (recall reactor simulations show largest sensitivity to O_2 in lean, cool regions)
  - ➤ Some indication that crevice UHC oxidation occurs at high O_2 concentration
- Early on, clearance volume CO is lower at the lowest O_2 (slow oxidation of UHC)
- Late in the cycle, CO levels are higher throughout the cylinder at low O_2

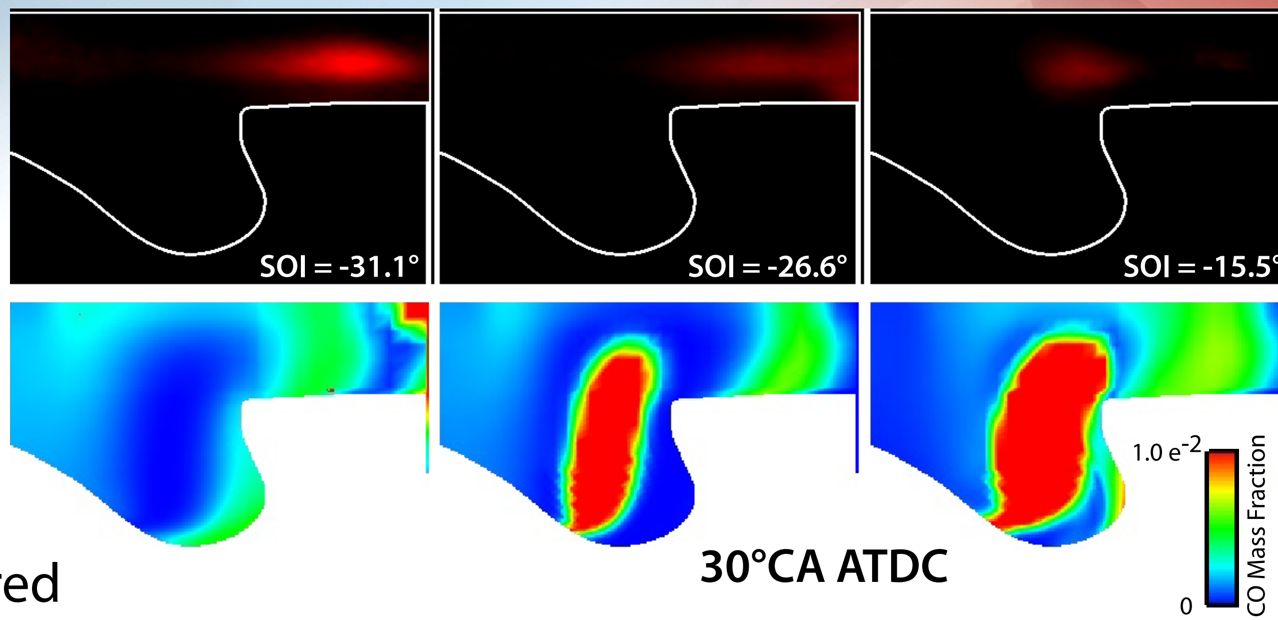


Model Assessment: Background



- Model employs measured experimental geometry (no CR adjustment)
- KIVA-Chemkin interface
  Reduced (34 species, 74 reactions) n-C_7H_{16} mechanism (SAE 2004-01-0558)
- Model visualization cut-plane corresponds to experiments

CO Model Comparison: SOI Sweep



The Good:

- Spatial distribution of CO within the clearance volume is generally captured

The Bad:

- Trends in squish volume CO as SOI changes are not captured
- No experimental evidence of crevice volume CO with advanced injection
- Delayed appearance of centerline CO not predicted (not shown)

Insights:

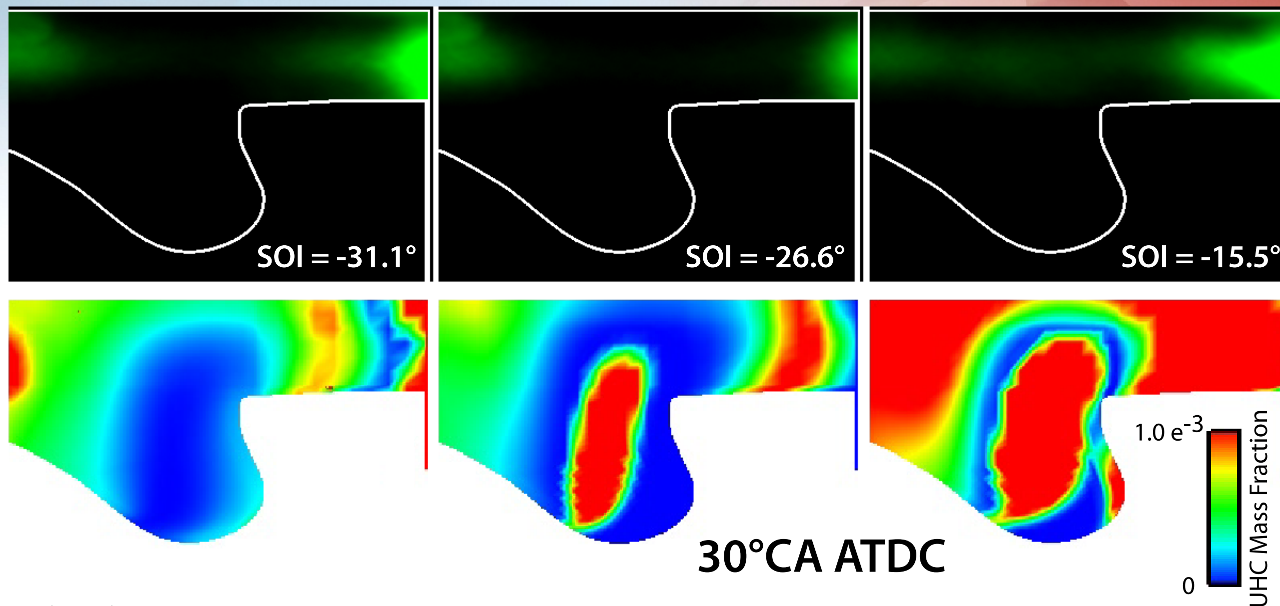
- The model predicts significant CO within the bowl—an area that was not experimentally accessible
- The model suggests that squish volume CO is *transported* there

(i.e., it does not arise from fuel injected into the squish volume)

UHC Model Comparison: SOI Sweep

The Good:

- Bi-modal spatial distribution of UHC within the clearance volume is generally well-captured



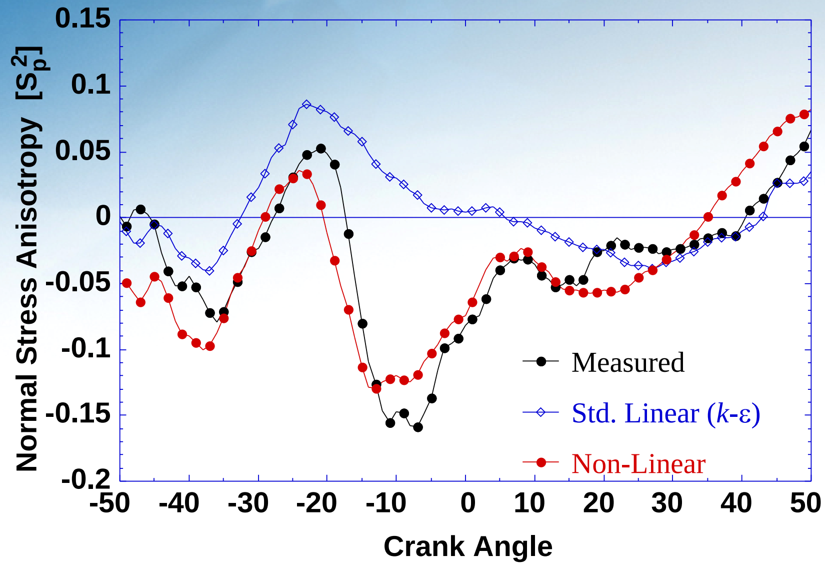
The Bad:

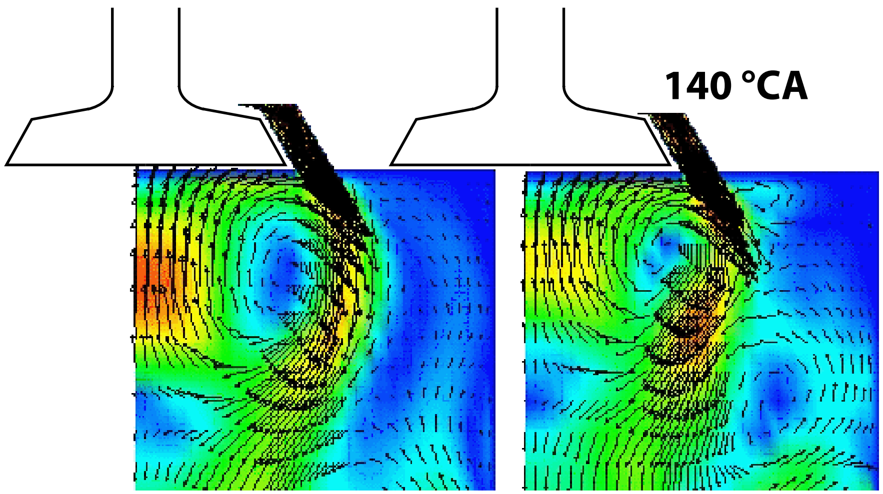
- No crevice volume UHC predicted at the later injection timings
- The model shows significant spatial collocation of UHC and CO, which is not supported by the experiments or the detailed kinetic modeling
- UHC bowl efflux with advanced SOI not captured (cf. CO distribution)
- Note: trends in centerline UHC may be obscured by beam absorption

Insights:

- Like CO, the model predicts significant UHC within the bowl—this *is* accessible to fuel LIF studies employing 355 nm excitation

Flow modeling study – motivation





Linear **(k-ε)**

Non-Linear **(Shih, et al.)**

- Previous work has demonstrated that the turbulent stresses are modeled significantly better with a non-linear stress model

  (n.b.- this is still a 2-eq. model and adds little to the computational cost)

- Engine intake flow modeling demonstrates that the stress model can profoundly impact the mean flow

➢ Will the turbulence model similarly impact flow structures important to the combustion process?

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Model results courtesy of C. Son and C. Rutland, UW-ERC

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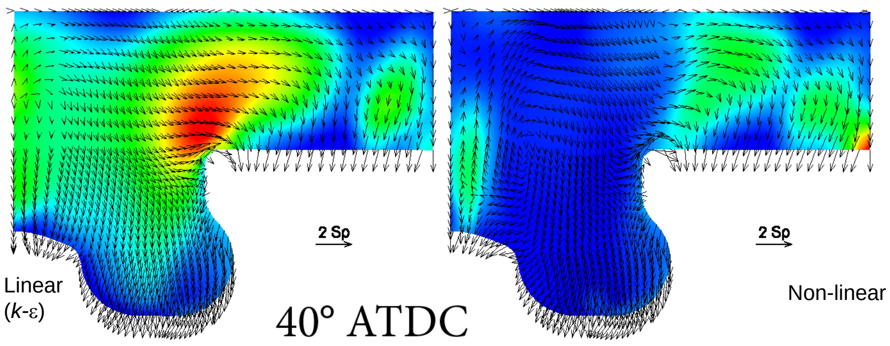
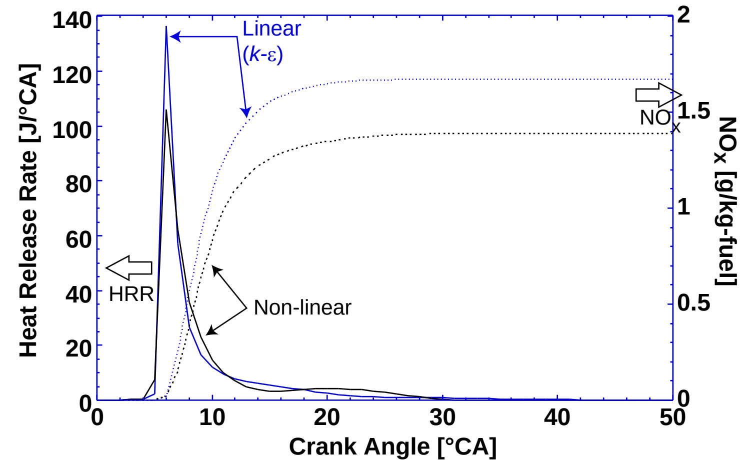
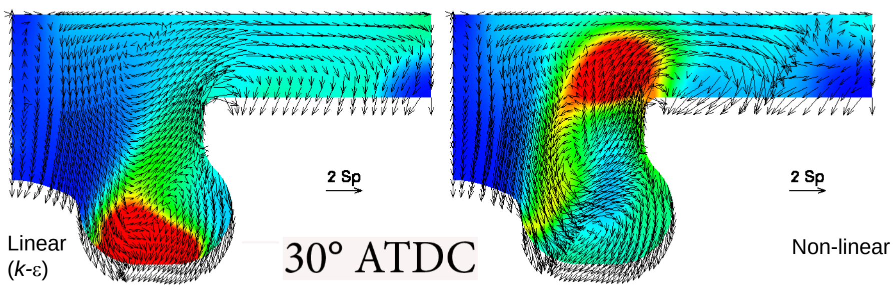
Flow modeling dramatically impacts combustion



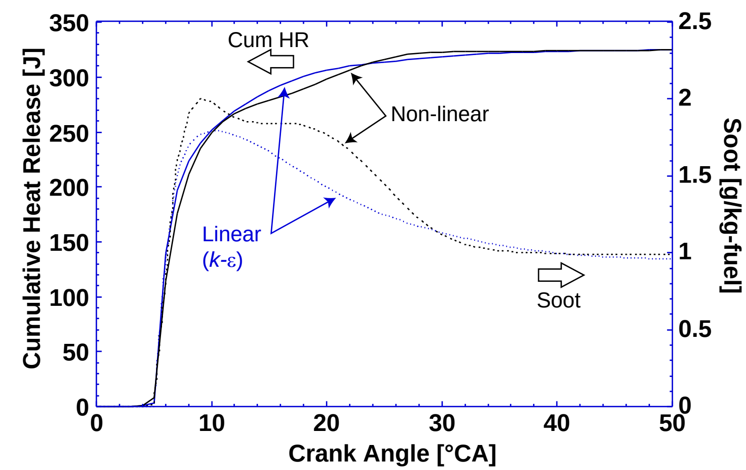
Motored mean flows change little, but turbulent energy distributions (bkg) differ greatly



Changes in early mixing lead to differences in heat release and NO_x formation



In-cylinder spatial distributions of soot (bkg) change significantly



Late-cycle mixing impacts both heat release and soot oxidation

- Future work will focus on providing validation data for both velocity and scalar (soot) fields

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Technology transfer

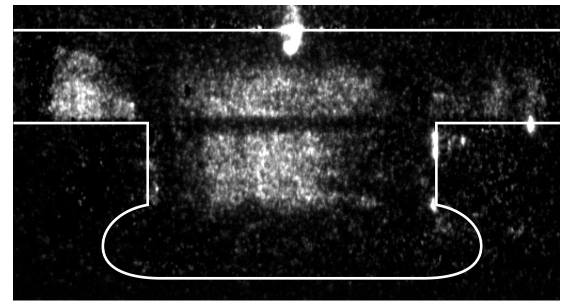
- **Close collaboration with GM, GM sponsored work at UW**

  Results communicated & directions discussed by teleconference approximately every 6 weeks
- **Integrated experimental/modeling program directly identifies preferred models and leads to incorporation of advanced models into industry accessible codes**
  - Assessment of simulations of UHC and CO distributions—kinetics models, liquid film modes
  - Incorporation of alternative turbulence models into KIVA (David Torres, LANL)
- **One-on-one discussions with individual industrial partners**
  - Direct provision of experimental data
  - Establishment of research tasks and priorities
- **Lund University / Volvo:** (B. Johansson / Ö. Andersson) - Collaboration in understanding both light- and heavy-duty engine fluid mechanics; Chemkin simulations to support data interpretations and diagnostic development
- **Research results reported at bi-annual working group meetings with:**

- DaimlerChrysler	- Ford	- General Motors
- Caterpillar	- Cummins	- Detroit Diesel
- Mack Trucks	- International	- John Deere
- General Electric	- Energy companies	

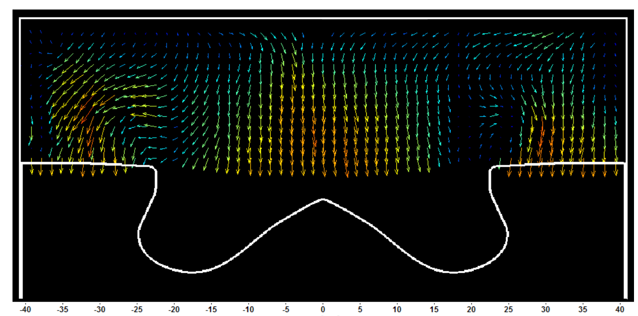
Activities for next fiscal year...

- Continue application of CO/UHC LIF diagnostics to additional operating conditions
  - Late injection (MK-like) operating regimes
  - Higher speeds and loads (ultimately will be limited by soot)
- Extend UHC imaging by:
  - Obtaining measurements within the bowl (excitation with 355 nm)
  - Following the temporal evolution of the UHC distributions from SOI onward



Sample single-cycle UHC PLIF image
355 nm excitation, 9% O2

- Commence with full-field flow measurements
  - Better understand the evolution of scalar fields (i.e., CO & UHC)
  - Provide accurate ICs for numerical simulations
  - Assess the accuracy of flows predicted by various turbulence models



Sample mean flow field, motored, 45°ATDC

- Proceed with in-depth comparison and assessment of models
- Continue to collaborate with GM-UW CRL and support their metal engine fuel effects work

Summary

- Better understanding of CO and UHC emissions directly impacts fuel efficiency; Model improvement impacts numerical optimization for low emissions and efficiency
- Research approach
  - Connects multiple institutions and leverages DOE funding
  - Closely links experimental studies with numerical simulations
  - Supports advanced model development for both combustion and flow processes
- Technical Accomplishments
  - Fundamental kinetics studies support experimental data interpretation
  - Experiments directly identify rich/lean regions, sources of CO and UHC, model strengths and shortcomings
  - Modeling studies demonstrate importance of flow modeling to combustion predictions
- Information and technology are transferred to industry through teleconferences, DOE meetings, one-on-one discussions, model improvement and model implementation into accessible codes, and extensive publications and presentations
- Next fiscal year will
  - Extend CO and UHC investigations to higher speed/load and late-injection LTC regimes, provide imaging of UHC distributions within the bowl
  - Provide accurate flow initial conditions (also validates induction calculations)
  - Experimentally assess the accuracy of simulations performed with various combustion and flow models

Publications & Presentations (Mar 2007 – Feb 2008)

- “In-Cylinder Imaging of CO and UHC in a Light-Duty Diesel Engine Operating under PPCI Low-Temperature Combustion,” SAE offer 08SFL-0473, submitted to SAE Powertrain, Fuels and Lubricants Spring meeting, July 2008.
- “A Detailed Comparison of Emissions and Combustion Performance between Optical and Metal Single-Cylinder Diesel Engines at Low Temperature Combustion Conditions,” SAE Paper 2008-01-1066, to be presented at the SAE World Congress, April 2008.
- “Experimental Assessment of Reynolds-Averaged Dissipation Modeling in Engine Flows,” SAE Paper 2008-01-0046, to be presented at the SAE World Congress, April 2008.
- "Effect of Intake Air Pressure on Emissions from an Automotive Diesel Engine Operating in Low Temperature Combustion Regimes," SAE Paper 2007-01-4063, SAE Powertrain, Fuels and Lubricants Fall meeting, Oct. 2007.
- "Optimization of Injector Spray Configurations for an HSDI Diesel Engine at High Load ," Submitted to ASME J. Gas Turbines and Power, October, 2007.
- "Assessment of Reynolds-Averaged Dissipation Modeling in Engine Flows," SAE Paper 2007-24-0046, SAE-Naples 8th International Conference on Engines for Automobiles, Sept. 2007.
- “On sources of CO and UHC emissions in low-temperature diesel combustion regimes,” Invited presentation at the 2007 Homogeneous Charge Compression Ignition Combustion Symposium, Sept. 2007.
- “Sources and mitigation of CO and UHC emissions in low-temperature diesel combustion regimes: Insights obtained via homogeneous reactor modeling,” 13th Diesel Engine Efficiency and Emissions Research Conference, DEER 2007, Aug. 2007.
- "On the Cyclic Variability and Sources of Unburned Hydrocarbon Emissions in Low Temperature Diesel Combustion Systems," SAE Paper 2007-01-1837, Joint JSAE/SAE International Fuels and Lubricants meeting, July 2007.
- "Fuel Injection and Mean Swirl Effects on Combustion and Soot Formation in Heavy-Duty Diesel Engines" SAE Paper 2007-01-0912, SAE World Congress, April 2007.
- "The Influence of Fuel Injection and Heat Release on Bulk Flow Structures in a Direct-Injection, Swirl-Supported Diesel Engine," Experiments in Fluids, March 2007.