



Automotive HCCI Engine Research

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DOE Office of Vehicle Technologies



Project ID: ACE006

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Overview

Timeline

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

Budget

- Project funded by DOE/VT
- FY11 funding: \$680k
- FY12 funding: \$680k

Barriers identified in VT Multi-Year Program Plan

- Inadequate fundamental knowledge of engine combustion:
 - Fuel injection, evaporation, and mixing;
 - Heat transfer and thermal stratification;
 - Ignition, low-temperature combustion, and emissions formation.
- Target goals for Advanced Combustion R&D (2015):
 - 25% Gasoline fuel economy improvement;
 - Achieve Tier II, Bin 2 emissions with < 1% thermal eff. penalty.

Partners

- Project lead: Richard Steeper, Sandia
- Industry:
 - GM & Ford (extensive technical interactions);
 - 15 Industry partners in DOE Working Group.
- University/National Lab:
 - Lawrence Livermore National Lab and University of Wisconsin:
 - KIVA model of automotive HCCI optical engine.
 - 6 National labs and 5 universities in DOE Working Groups.



Relevance: Objectives and Milestones

- **Overall objective:**

- Expand our fundamental understanding of low-temperature combustion (LTC) processes to remove barriers to the implementation of clean and fuel-efficient automotive HCCI engines.

- **Specific, multi-year objectives:**

- Quantify thermal and chemical effects of the negative valve overlap (NVO) fueling strategy, with the goal of increasing gasoline HCCI efficiency through extension of load range.

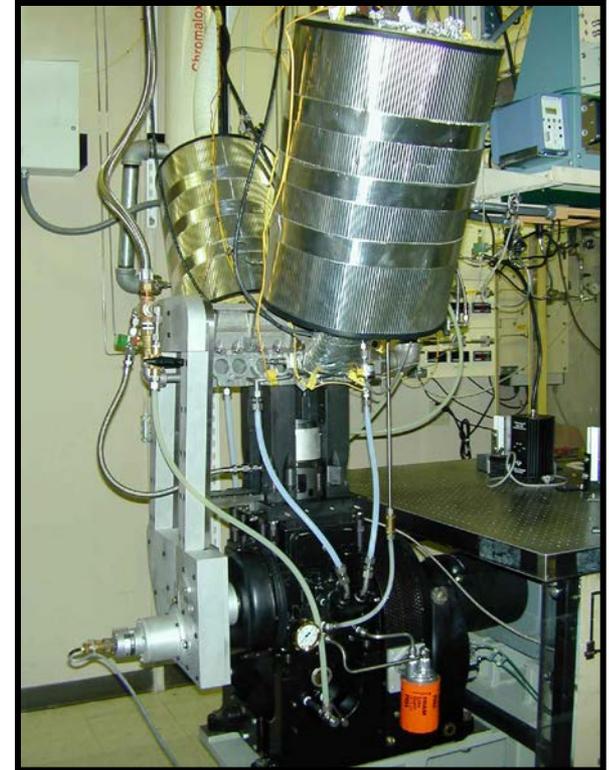
- Milestone: Perform engine experiments to examine chemical effects of NVO fueling on main combustion phasing.
 - Milestone: Perform seeding experiments to test combustion enhancement of specific NVO product species.

- Enhance and apply computer models in support of our automotive HCCI experiments.

- Milestone: Develop Chemkin-Pro piston/cylinder model with LLNL iso-octane mechanism to simulate NVO fueling reactions.
 - Milestone: Continue application of GT-Power and KIVA CFD models of the optical engine.

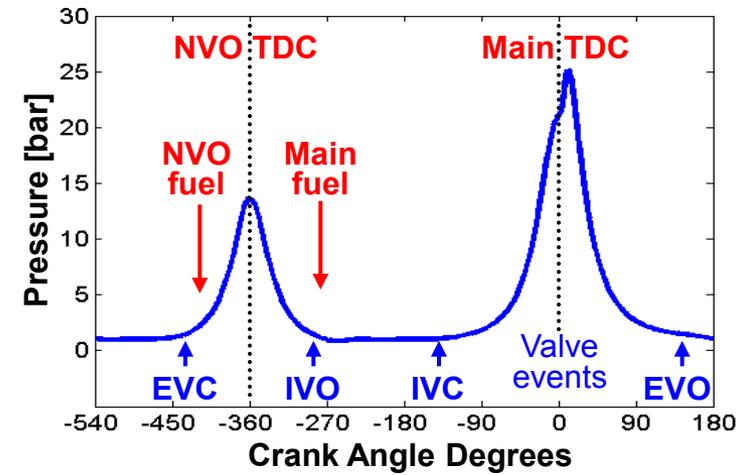
Approach

- Perform experiments in an optical engine equipped and configured for automotive HCCI combustion strategies.
- Develop and apply diagnostics to acquire in-cylinder measurements of fundamental physical processes.
- Apply suite of computer models to guide and interpret engine experiments.
- Leverage knowledge gained through technical exchange with DOE Vehicle Technologies program participants.



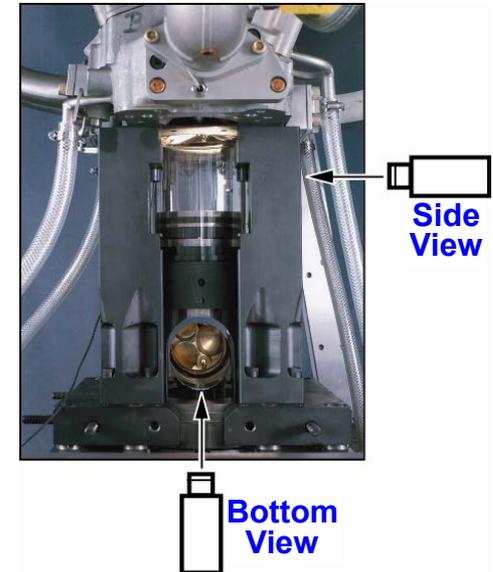
Technical accomplishments – FY12

- FY12 research focuses on gasoline HCCI negative valve overlap strategy:
 - NVO traps residuals to increase charge temperature, extending HCCI operation to lower loads.
 - Injecting fuel during NVO can modify both charge temperature and composition in order to further control the phasing of main combustion.
 - For mixed-mode (spark/HCCI) gasoline engines, this strategy is key to maximizing low-load efficiency.
 - Research has demonstrated the potential of NVO fueling, but the physical and chemical details need clarification.
- FY12 activities are divided into following sections:
 - Optical characterization of early versus late NVO fueling.
 - Measurement of effects of acetylene on HCCI combustion.
 - Modeling of HCCI-NVO combustion.



FY12 Accomplishments: Optical characterization of early vs. late NVO fueling

- Our prior heat release measurements showed unique effects associated with late NVO fuel injection.
 - Despite poor NVO combustion efficiency for late NVO SOI, it still significantly advances main combustion phasing.
 - One hypothesis is that late NVO SOI causes locally rich combustion, producing species that carry over to influence main combustion.
 - Examining this chemical effect is a key objective of our current research.
- This year, we conducted visualization experiments comparing early and late NVO injection.
 - High-speed camera recorded crank-angle-resolved videos from the side and bottom of the cylinder.
 - Videos captured spray and combustion processes during low-load HCCI-NVO operation.
- Highlights are shown in following slides...

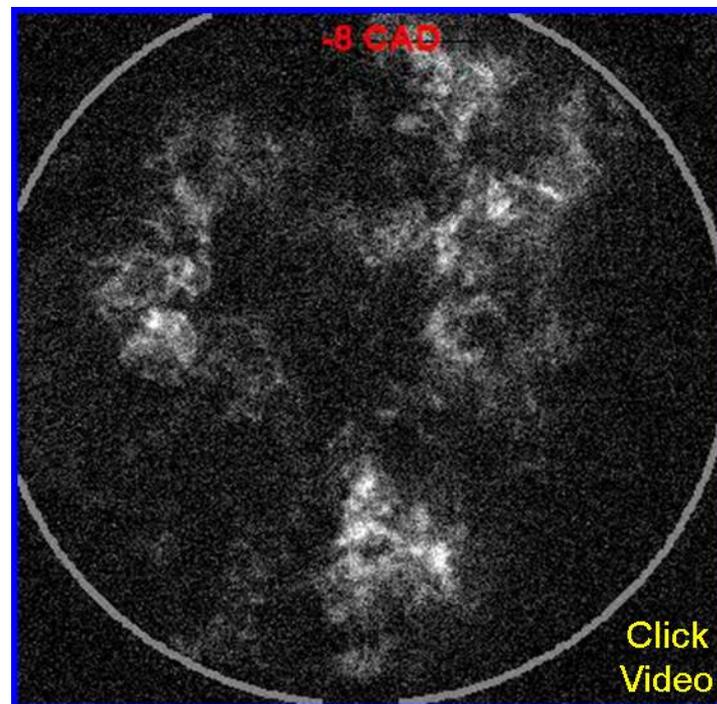


Optical experiment conditions	
Neg. valve overlap (CAD)	150 CAD
Residual gas fraction (%)	50 %
Split-fuel-injection mass (mg of iso-octane)	NVO: 1.5 Main: 7.8
Fuel-air equiv. ratio (-)	NVO: 0.43 ; Main: 0.46
NVO start of injection (CAD bTDC-NVO)	Early: 70 Late: 25

* SOI: start of injection.

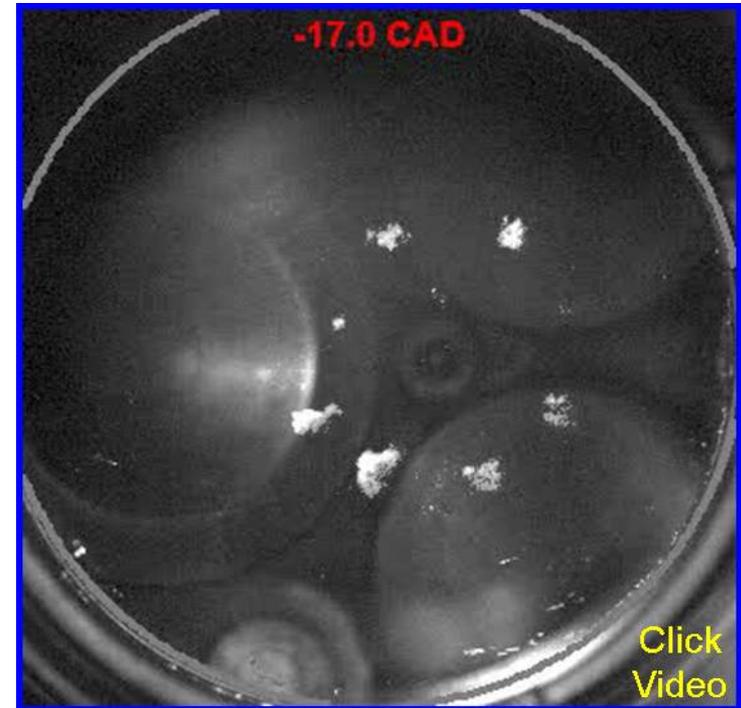
Early NVO fuel injection: Combustion imaging.

- Experiment setup
 - Camera images visible NVO combustion luminosity.
 - NVO fuel injection is early (70 bTDC), soon after exhaust valve closure.
 - Spray imaging (not shown) indicates minimal spray impingement on piston top for these conditions.
- Typical video of early NVO combustion:
 - Burn is quick, faint, and distributed (volumetric).
 - Appearance is similar to main HCCI combustion.
 - Localized flames occur only in vicinity of injector tip.
- For our lean conditions, we conclude that:
 - Despite short time scale of NVO recompression, early NVO sprays normally evaporate, mix, and burn well.
 - Relatively complete combustion of early NVO fueling implies it is useful primarily for adding sensible energy to intake charge (rather than reactive species).
- Performance of late NVO fueling is distinctly different than early NVO fueling...



Late NVO fueling: Formation of liquid fuel films.

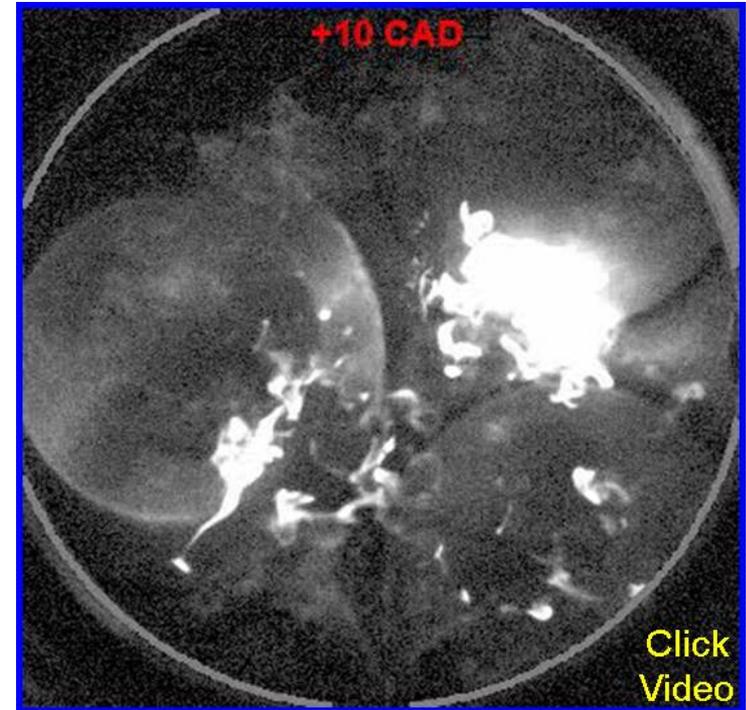
- Experiment setup
 - Camera records Mie scattering from the NVO fuel spray.
 - NVO injection is late (25 bTDC).
 - Combustion suppressed via N_2 ambient.
- Video shows a typical late NVO spray.
 - Spray impinges on piston, forming persistent fuel films.
 - As NVO SOI is retarded, the extent of impingement depends on competing effects of piston proximity and increasing charge density.
- The most evident consequence of late injection is the appearance of rich flames...



Spray visibility enhanced by differencing spray image with non-spray image, increasing contrast, and then superimposing the result.

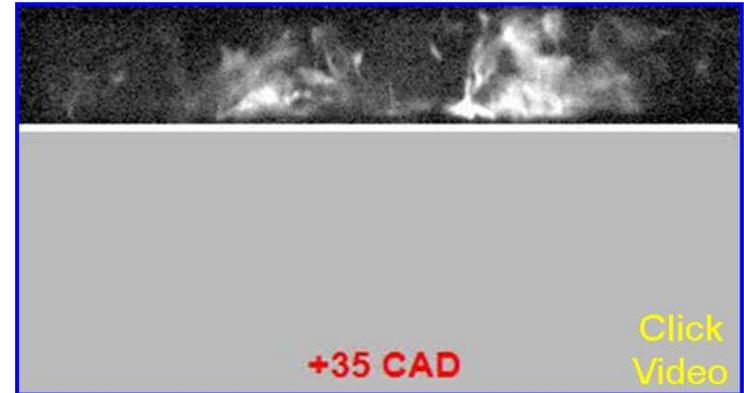
Late NVO fueling: Combustion imaging.

- Experiment setup:
 - Combustion luminosity imaging of late NVO SOI.
- Bright yellow flame luminosity is a consistent marker of late NVO injection.
 - Ignition occurs as for early SOI cases, but initial volumetric combustion subsequently ignites liquid fuel.
 - Luminosity is mainly due to soot incandescence which persists nearly to end of NVO.
- Addition of side-view camera is needed to establish location of the rich flames...



Late NVO fueling: Combustion imaging.

- Side-view camera indicates that rich flames are attached to the piston top.
- All NVO injections later than about 30 bTDC produce this localized rich combustion.
- Significance of visualization results:
 - Rich flames as seen with late NVO fueling are normally avoided in an engine due to soot emissions. But species produced during NVO reforming are not directly exhausted, and may offer benefits for control of main combustion.
 - Supported by OEM interest, we are investigating the potential benefits of chemical reforming during NVO fueling as an extension to more conventional thermal strategies.
- As a means of examining effects of NVO reformed species, we have been conducting seeding experiments, described in next section.





FY12 Accomplishments: Acetylene seeding experiments

- Rationale for seeding experiments:

- Prior year experiments demonstrated apparent chemical effects of late NVO injection on main combustion phasing.
- Further, in the imaging experiments just presented, late NVO fueling is linked to rich flames.
- Since acetylene is a known product of rich flames and a known ignition enhancer, we hypothesize its role as a reformed NVO product that can help control main combustion.
- Seeding experiments were thus designed to test the hypothesis in a simplified environment.

- Experimental design

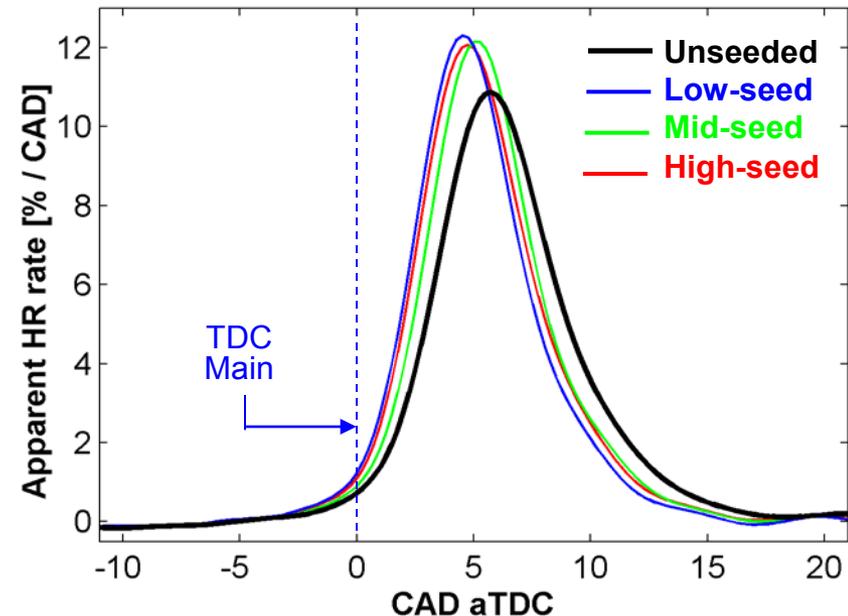
- Primary fuel: iso-octane.
- Single main fuel injection only, no NVO fueling.
 - This removes uncertainty of NVO product composition;
 - Lack of NVO heat release can be compensated for by increasing intake air temperature.
- Acetylene (C_2H_2) is seeded into intake air stream.
 - Seed concentration is varied, but total fuel energy is held constant by adjusting iso-octane mass.
 - Also, main combustion phasing is held constant by adjusting intake air temperature.
 - These constraints remove confounding influences to better isolate the effect under investigation.

Effect of C_2H_2 on heat-release rates.

Experimental matrix:

- Two low loads.
- Three seeding levels plus the unseeded base case.
- Graph illustrates the clear enhancement of main combustion heat release due to C_2H_2 .
 - Seeded data show a significant increase in peak apparent HR rate over unseeded case.
 - The difference in phasing of HR rate is due to the different shape of the curves.
 - HR rate does not appear sensitive to seeding level.
 - These curves represent higher load conditions, but lower load results are similar.
- To further quantify the seeding data, we next look at cycle temperatures: any enhancement of reactions by C_2H_2 should reduce in-cylinder temperatures required to achieve our target phasing.

Seeding experiment conditions	
Total fuel, C_8H_{18} equiv.	9 & 11 mg/cycle
C_2H_2 seeding levels	0, 0.3, 0.7, & 1.1 mg/cycle (0, 1200, 3000, 4500 ppm*)
Residual gas fraction	50%
CA50**	5.5 CAD aTDC

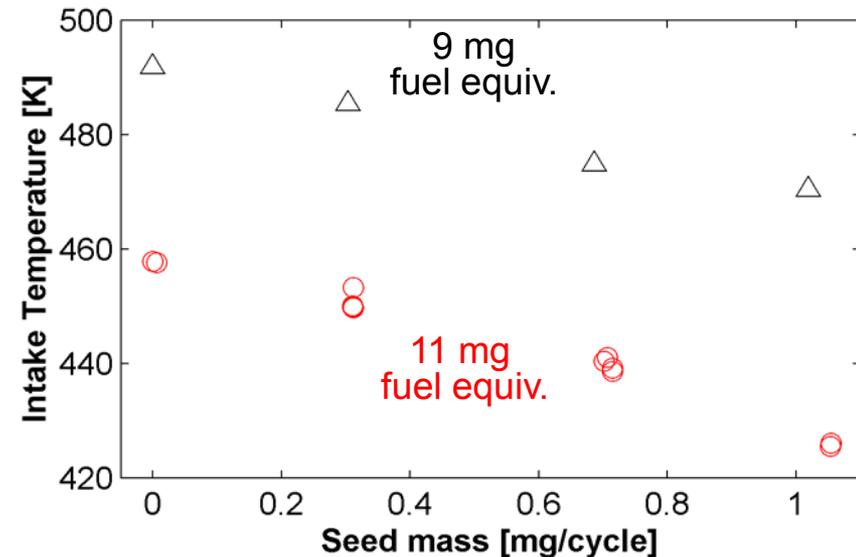


* ppm C_2 as measured in intake stream.

** CA50: Crank angle location of 50% heat-release point.

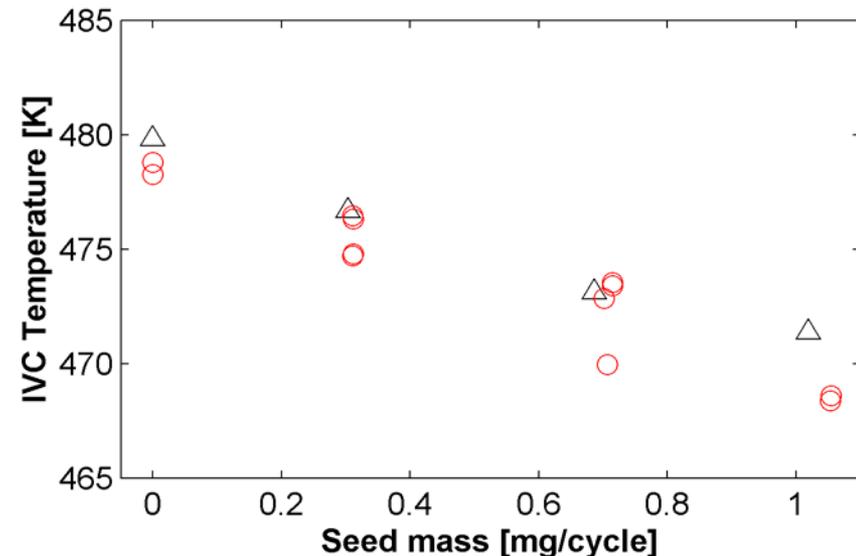
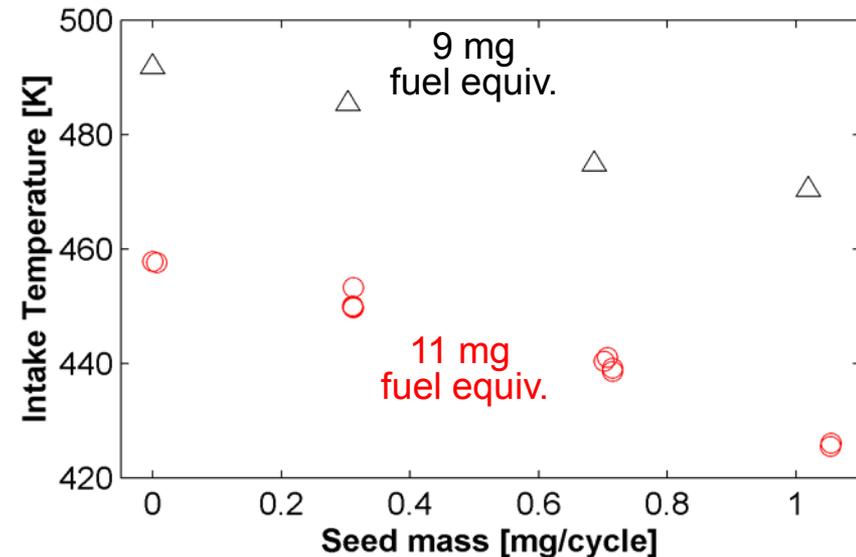
Effect of C_2H_2 on cycle temperatures.

- Plot shows intake temperatures required to maintain CA50 phasing.
 - Data represent 2 loads and 4 seeding levels.
 - Points shown are filtered (based on our specified CA50) from large database of results.
- As seeding level increases, we can achieve target phasing using significantly lower T_{INTAKE} .
 - At max seeding, intake temperatures are 25-30 K colder than the unseeded cases.



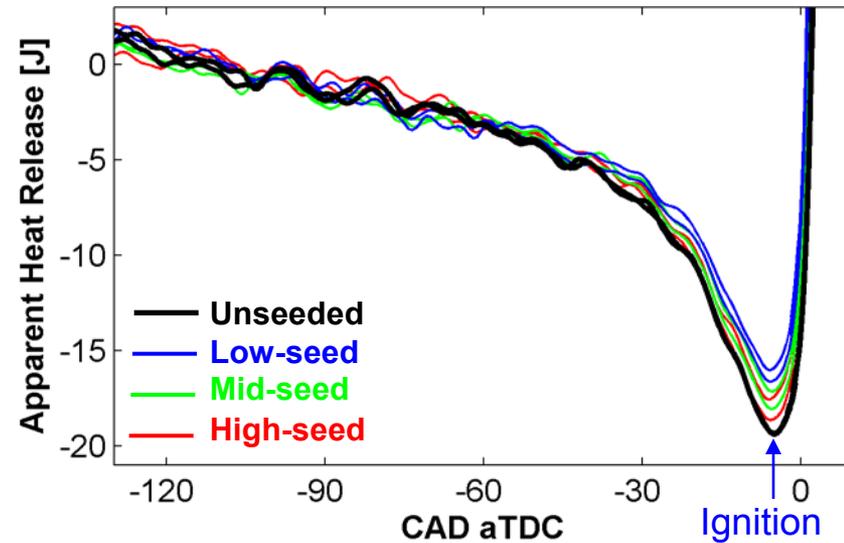
Effect of C₂H₂ on cycle temperatures.

- Plot shows intake temperatures required to maintain CA50 phasing.
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- As seeding level increases, we can achieve target phasing using significantly lower T_{INTAKE} .
 - At max seeding, intake temperatures are 25-30 K colder than the unseeded cases.
- But IVC temperatures are a better metric since they represent mixture of intake and residuals.
- At IVC, temperatures again show a steady decrease with seeding level.
 - Difference between two loads is diminished, but both still show that C₂H₂ seeding significantly reduces required charge temperatures.
 - This plot provides a good measure of C₂H₂ enhancement since T_{IVC} is a variable that can be conveniently estimated for an engine.



Effect of C₂H₂ on cumulative heat release.

- We are also interested in identifying any early heat release between IVC and main ignition.
- Graph shows cumulative apparent HR for this period: 2 curves for each seeding level.
 - All seeded curves are located at or above the unseeded cases during late compression.
 - Since heat transfer to the walls should be very similar in all cases, the results indicate enhanced early heat release associated with C₂H₂. Thus, some of the combustion enhancement attributed to C₂H₂ is due to reactions prior to ignition.
 - In previous slide, we saw T_{IVC} decrease monotonically with seeding amount. Here, noise obscures any such interrelationship of the seeded cases.
- Significance of C₂H₂ seeding experiments:
 - Hypothesis of C₂H₂ combustion enhancement is consistent with experimental measurements.
 - We are encouraged to identify other reformed species that could play a similar role.
 - To achieve a more detailed understanding of NVO reactions, we must rely on chemistry simulations...



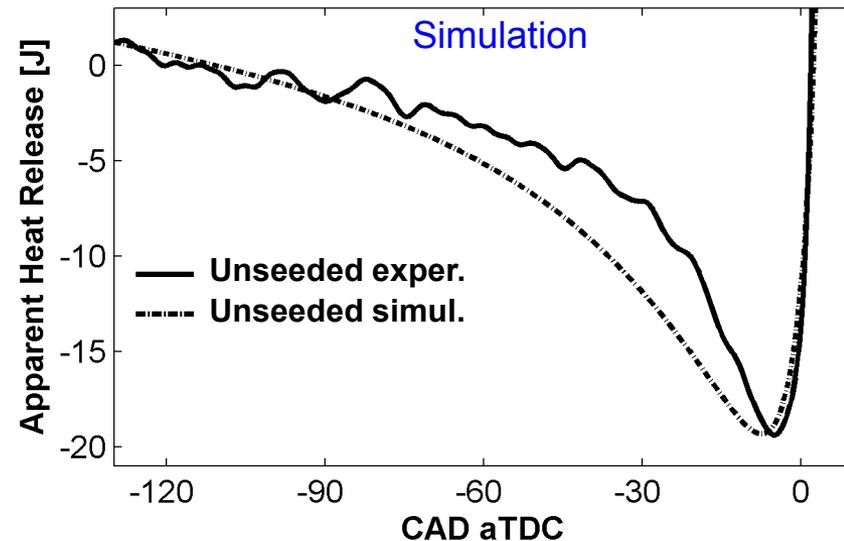
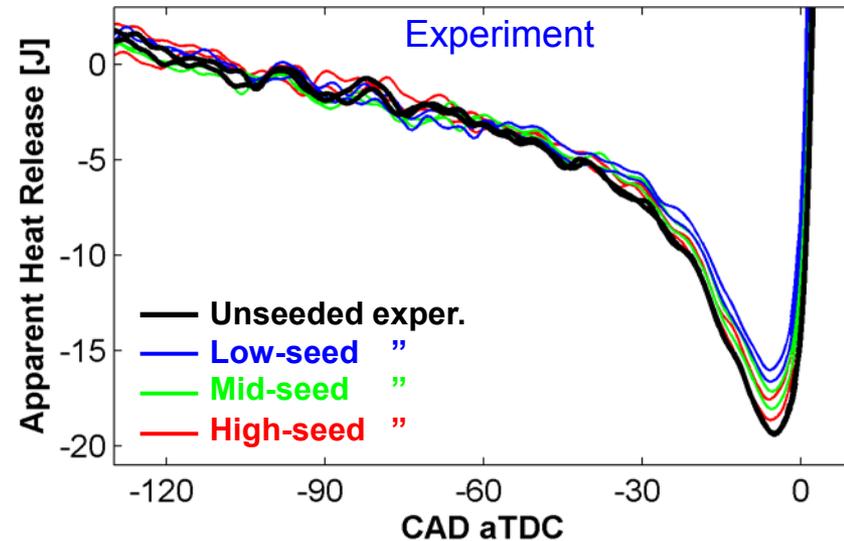


FY12 Accomplishments: Model development and application

- We employ multiple engine models to guide and interpret experiments.
 - In-house cycle-temperature analysis program.
 - Chemkin Pro piston/cylinder reactor model.
 - GT Power engine system simulation.
 - LLNL/UW collaborative CFD/kinetics 3-D optical engine model.
- Progress this year includes:
 - Applying cycle-temperature analysis to quantify effects of C_2H_2 seeding (T_{IVC} , etc.).
 - Simulating the combustion kinetics of C_2H_2 in engine cycle using Chemkin Pro.
 - Employing CFD model to guide tuning of heat transfer for Chemkin simulations.
- The following section summarizes our Chemkin modeling work...

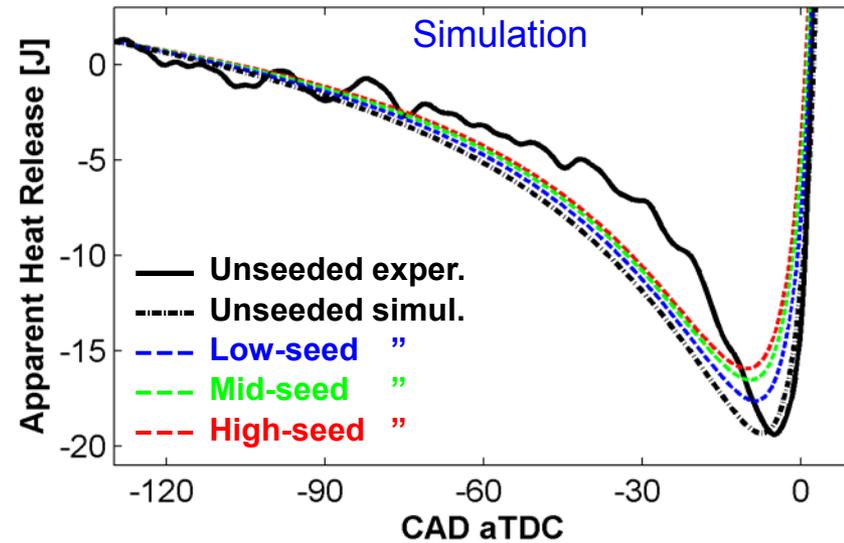
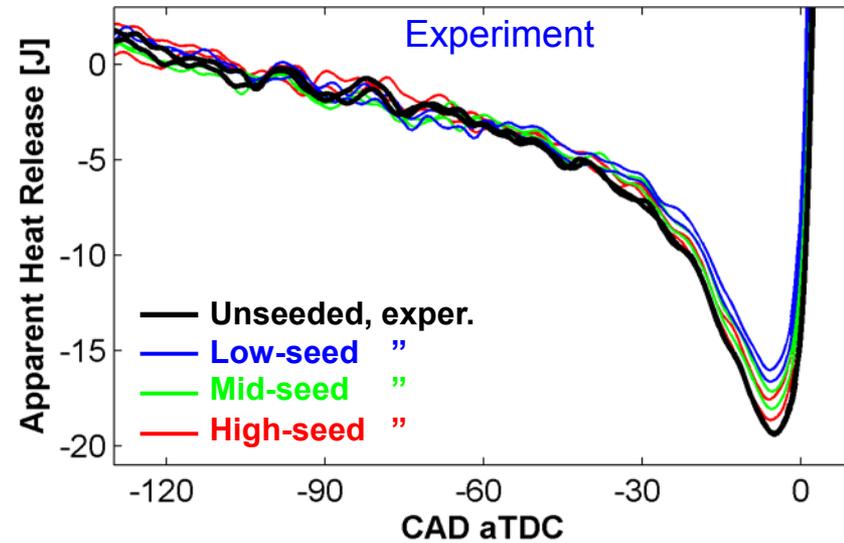
Chemkin simulation of C_2H_2 seeding experiments.

- Chemkin simulation setup:
 - Single-zone piston/cylinder model of IVC to EVO.
 - LLNL iso-octane mechanism: 874 species and 3796 reactions.
- Simulation mimics seeding experiments.
 - Boundary/initial conditions taken from experiment.
 - Heat-transfer correlation is scaled to match apparent HR of unseeded experiment at ignition. This scaling parameter remains constant for all simulations.
 - Finally, just as in the experiments, input temperature is adjusted until CA50 phasing matches target value.



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 - Heat-transfer correlation is scaled to match apparent HR of unseeded experiment at ignition. This scaling parameter remains constant for all simulations.
 - Finally, just as in the experiments, input temperature is adjusted until CA50 phasing matches target value.
- Comparison of simulation and experiment:
 - Seeded simulation curves lie above unseeded case, supporting the experimental observation of early heat release.
 - Also as in experiments, seeding reduces the T_{IVC} (not shown) that are required to match target CA50.
 - However, the reaction mechanism overpredicts the magnitude of C_2H_2 enhancement: the simulated high-seed T_{IVC} is 39 K cooler than unseeded case (versus 12 K for the experiments).



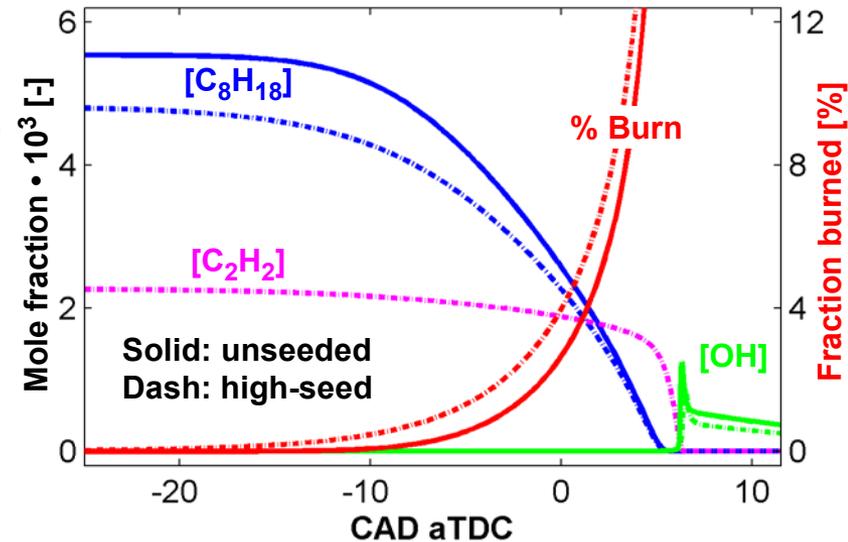
Chemkin simulation of C_2H_2 seeding experiments.

- Final graph compares species profiles from the simulation: unseeded vs. high-seed.
- Solid lines represent the unseeded base case.
 - Shown are the consumption of iso-octane and the spike of OH marking the end of combustion.
 - Cum. fraction burned is also shown on right axis.
- High-seed case (dashed lines) are compared to base case:

- Initial iso-octane fraction is lower in seeded case due to our constant total fuel constraint. Otherwise the curves are similar.
- The C_2H_2 profile is distinct:
 - Profile declines gradually until an abrupt drop off near the end of combustion.
 - This is consistent with the higher experimental peak HR rates shown earlier.
- The high-seed fraction-burned curve shows advanced early HR, again consistent with experiment.

- **Significance of Chemkin modeling:**

- Model predicts the combustion enhancement trends of C_2H_2 .
- This encourages using the model to identify other NVO species of interest.
- Using simplified seeding experiments to further tune the reaction mechanism will improve performance when modeling the more complex NVO fueling experiments.



Collaborations

- **University partners:**

- University of Wisconsin and Lawrence Livermore National Lab: Joint development and application of a KIVA model of the Sandia automotive HCCI optical engine.
- Stanford University and University of Michigan: Invaluable assistance during diagnostic and model development.

- **Automotive OEM partners:**

- GM Research is actively engaged in our automotive HCCI research program: interactions include teleconferences, exchange of results, and hardware support.
- Ford Research has defined topics of mutual interest that are the basis of new collaborations.

- **DOE Working Group partners:**

- Research results are shared with DOE's Advanced Engine Combustion and University HCCI working groups at semi-annual meetings.

Future Work

- **Engine experiments:**

- Investigate cyclic variability of NVO heat release to understand cycle-to-cycle interaction.
- Quantify mass and duration of piston-top fuel films associated with late NVO fueling.
- Incorporate fuel sensitivity into the investigation of NVO fueling effects on main combustion.

- **Engine modeling:**

- Tune KIVA and CHEMKIN chemistry models using our HCCI engine data.
- Apply chemistry models to identify reactive products of NVO fueling.

- **Diagnostic development**

- Extend TDL CO-absorption diagnostic to detect additional species such as C_2H_2 , CO_2 , H_2O .

- **Engine hardware upgrade (contingent on funding availability):**

- Implement previous plans to install a new optical engine head:
 - An advanced design, direct-injection head has been provided by GM to be mounted on an existing base engine.
 - Upgrade will be implemented in a currently idle engine lab so that research progress in current lab will not be interrupted.
 - Project will benefit from the recent installation of the same head in the Lean-Burn DI Spark-Ignition Fuels Lab (Sjöberg).



Summary

- The Automotive HCCI Engine project contributes to the development of low-temperature combustion strategies to help meet DOE emission and efficiency goals.
- The project approach combines:
 - Optical engine experiments,
 - Diagnostic development and application,
 - Engine and combustion modeling.
- Current work focuses on the NVO combustion strategy. Accomplishments include:
 - Optical characterization of NVO piston fuel films and associated rich flames.
 - Quantification of effects of acetylene on main combustion phasing.
 - Application of a reaction kinetics model to interpret acetylene experiment results.
- Multiple collaborations leverage the impact of our research:
 - DOE's Advanced Engine Combustion group reviews research results and contributes feedback;
 - OEMs provide intensive technical and material support;
 - National lab and university partners collaborate on model and diagnostic development.