A University Consortium on Efficient and Clean High-Pressure, Lean Burn (HPLB) Engines

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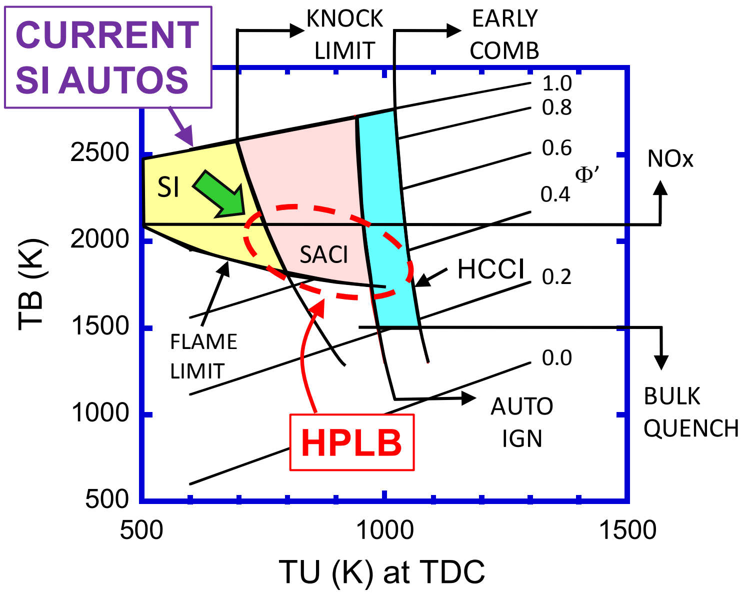
DOE Merit Review
Washington DC, May 13-17, 2013
DOE Project DE-EE0000203

Background

History:

- 2002 – 2005 Consortium on HCCI – Basic understanding
- 2006 – 2009 Consortium on LTC – Beyond HCCI: expanded to other combustion modes
- 2010 – 2013 High Pressure Lean/Dilute Burn – Focus on fuel economy



Lavoie, G., Martz, J., Wooldridge, M., and Assanis, D., (2010) "A Multi-Mode Combustion Diagram for Spark Assisted Compression Ignition," Combustion and Flame, 157, pp. 1106-1110.

Overview

- TIMELINE
  - Start - Oct 2009
  - Finish – June 2013
  - 90% completed

- BUDGET
  - Total Funding - $3,000k
  - Rec'd FY10 - $1,000k
  - Rec'd FY11 - $ 1,000k
  - Rec'd FY12 - $ 830k

- BARRIERS ADDRESSED
  - Improved fuel economy in light duty gasoline engines
  - Fundamental knowledge of advanced engine combustion

- PARTNERS
  - Universities – UCB, MIT
  - Collaborations – SNL, LLNL, ORNL, ANL
  - Industrial – GM, Conoco-Phillips, Ford

Objectives and Relevance

DOE VTP Technical Target:

- Demonstrate path to achieve 45% peak engine efficiency with 25 - 40% potential vehicle fuel economy (FE) gain

Project Objectives:

Explore advanced dilute, high pressure combustion modes and fuel properties as enablers to achieve FE targets

1. Develop analytical link between engine combustion results and potential in-vehicle FE gains
2. Investigate benefits of stratification
3. Explore multi-mode combustion: Spark Assisted Compression Ignition (SACI), and Microwave Assisted Spark Plug (MWASP)
4. Determine potential of novel fuel properties for improved FE

Approach

ANALYTICAL TOOLS

TASK 1.

Fuel Efficiency of Advanced HPLB Cycles (UM)

- Develop analytical link between combustion and fuel economy benefits
- Assess potential FE gains of advanced combustion cycles

TASK 2.

Investigate the benefits of stratification (UM, MIT)

- DNS and combustion subgrid scale modeling of mixing effects
- RCM and engine experiments

TASK 3.

Advanced multi-mode combustion (UM, UCB)

- Metal engine, optical engine, RCF Experiments
- SACI, MWASP
- CFD – flamelet+AI

TASK 4.

Fuel properties for optimal fuel economy (UM, MIT)

- Metal and optical engine and RCF experiments
- Explore Negative Temperature Coefficient (NTC) effects, ON, Gasoline/ethanol blends, alkanes, esters, etc.
- Chemical kinetic models

MODELS, EXPERIMENTS

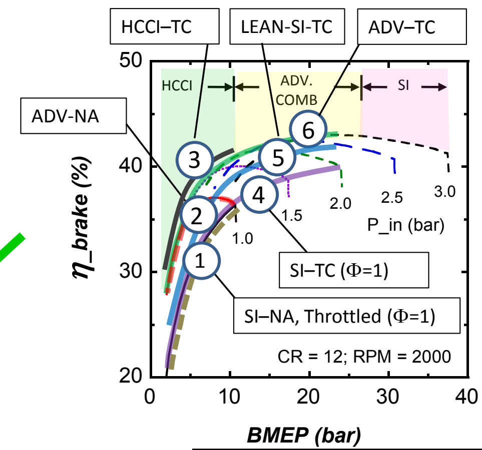
Path to in-vehicle FE improvement

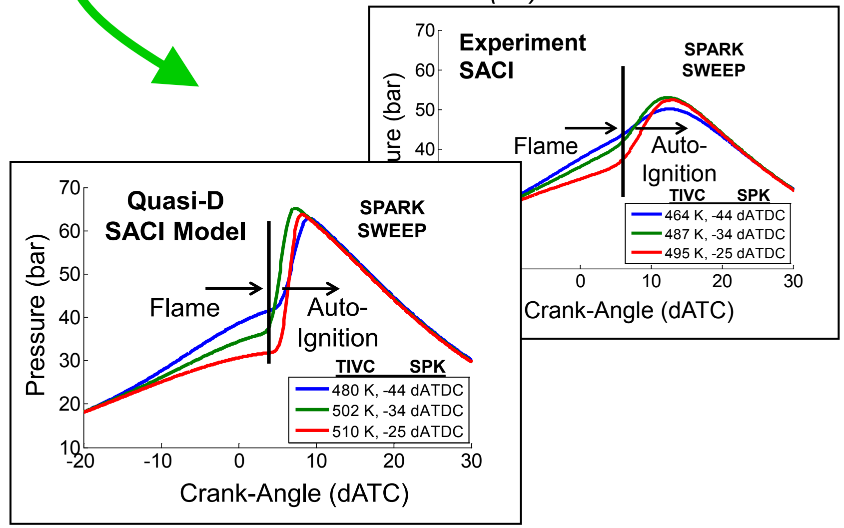
Technical Accomplishments and Progress

Task 1. Fuel Efficiency of Advanced HPLB Cycles (UM)

- <u>Goals</u>
  - Develop analytical link between combustion and fuel economy benefits
  - Refine previous ideal estimates of FE gains of advanced combustion cycles including combustion limitations
- <u>Approach</u>
  - Use GT Power simulation tool
  - Develop Quasi-D model of SACI, combining SI and HCCI submodels
  - Reevaluate vehicle fuel economy projections

PREVIOUS ESTIMATES OF IDEAL EFFICIENCY GAINS





Task 2. Investigate the benefits of stratification (UM, MIT)

High fidelity modeling: effects of small scale mixing on autoignition (UM)

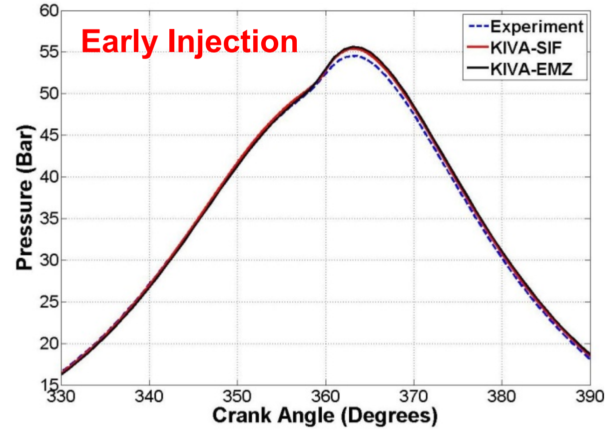
- Understand effects of stratification in Φ, EGR and T on autoignition
- Incorporate effects in engine modeling
- Guide interpretation of experimental observations in RCF, RCM, and optical and metal engines

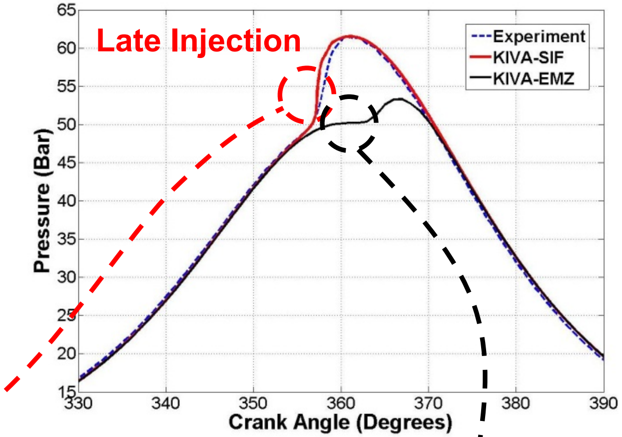
Experiments on large scale stratification (MIT)

- RCM ignition delay studies integrating heat transfer and using commercial fuels
- Experiments with gasoline in a small bore diesel engine under LTC conditions

Task 2. Flamelet Modeling of Small Scale Turbulence Effects on Autoignition in HCCI Engines (UM)

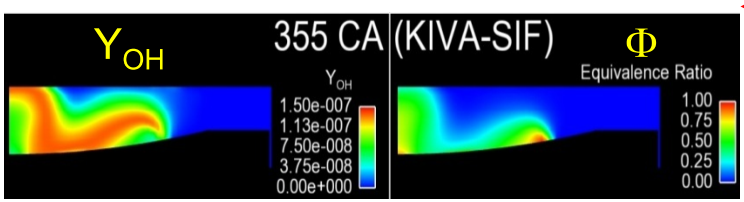
- **Goal:**
  - Develop improved combustion and mixing submodels for HCCI engine simulations
- **Accomplishments/Results:**
  - Integrated spray-interactive flamelet (SIF) model with a multi-dimensional CFD code KIVA-3V.
  - Validated the SIF model against DI HCCI experiments for early and late injection cases.
  - SIF model provides more accurate predictions of ignition timing and heat release rate over a wider stratification range than EMZ (simple RANS) model

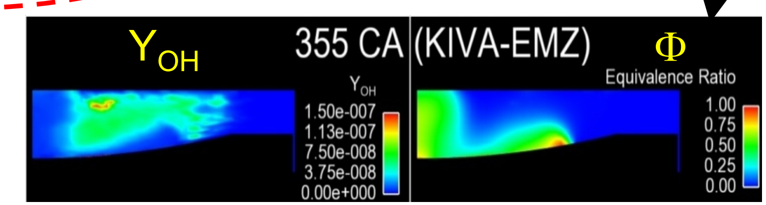




Impact:

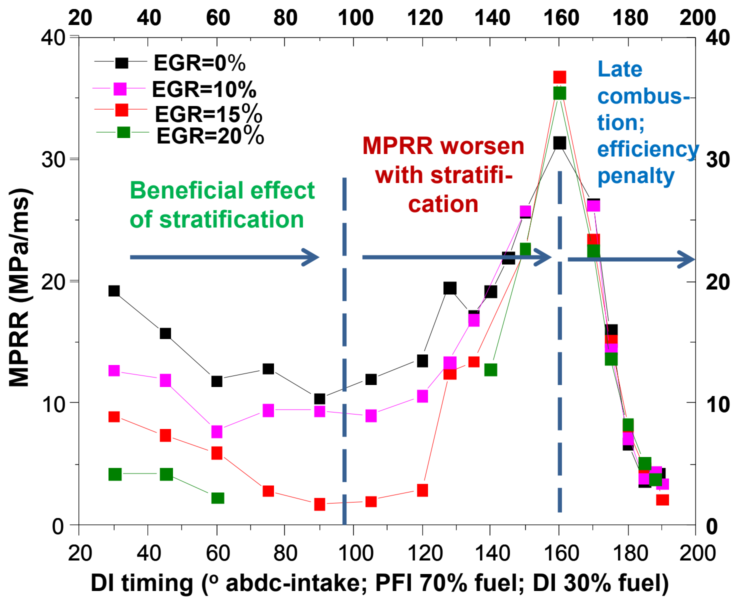
- Small scale bulk gas turbulent fluctuations affect heat release predictions under stratified conditions

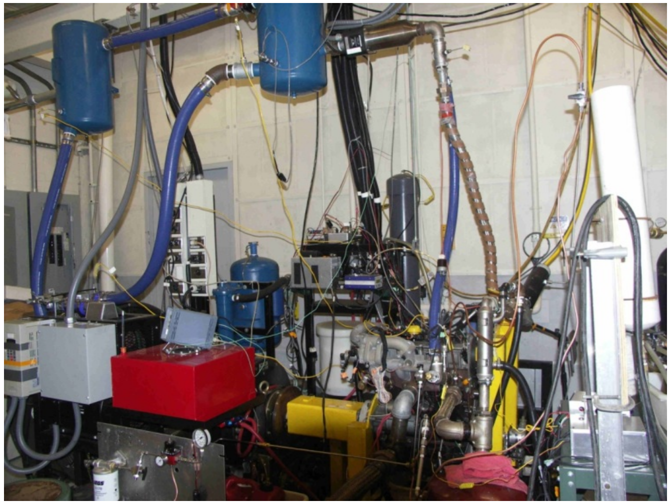




Task 2. Experimental studies of the benefits of stratification in LTC engine(MIT)

- <u>Goals:</u>
  - To understand the role of stratification in mitigating high pressure rise rate
- <u>Engine experiments</u>
  - Small bore, boosted engine operated with certification gasoline
  - PFI provides background homogeneous charge
  - DI provides stratification by changing injection timing
- <u>Results</u>
  - Stratification can be beneficial or detrimental, depending on the interplay between local fuel concentration, temperature and ignition delay





<u>Impact</u>:

- Managed stratification can allow access to advanced combustion regime

Task 3. Advanced multi-mode ignition and combustion (UM, UCB)

SACI/HCCI in FFVA engine (UM)

- Study multi-mode combustion spark assisted compression ignition (SACI) in well controlled metal engine

Modeling of SACI (UM)

- Laminar flame speed correlations (submodel)
- Coherent flamelet + AI multi-zone (CFMZ) CFD model
- System level model development

Microwave Assisted Spark Plug (MWASP) experiments (UCB)

- Feasibility testing in combustion bomb
- Tests in CFR engine
- Modeling of plasma/spark behavior

Imaging studies of SACI (UM)

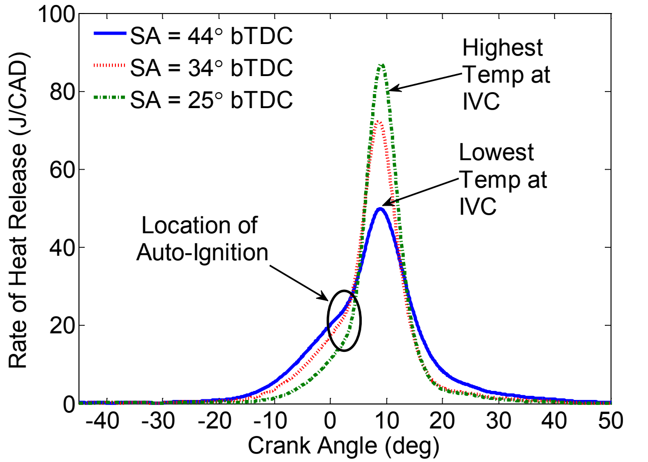
- Optical engine imaging and quantification
- RCF studies of spark + autoignition interactions

Task 3: Reduced Heat Release Rate with SACI (UM)

Accomplishments/Results

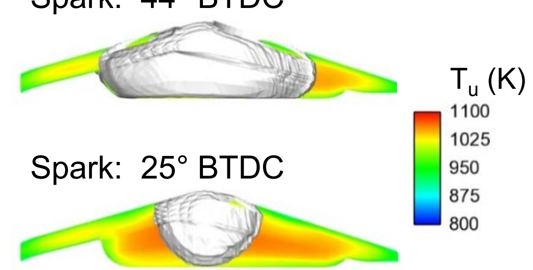
- FFVA engine and KIVA-3V studies have shown that the use of Spark Assisted Compression Ignition (SACI) can moderate HCCI heat release and increase maximum load

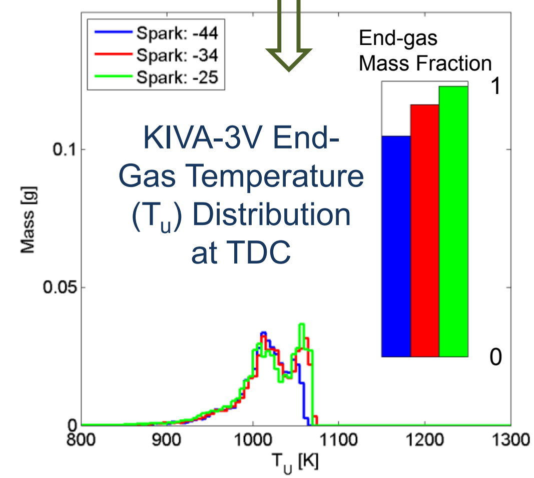
FFVA SACI spark timing sweep at 2000 RPM, ~ 6.5 bar $IMEP_n$, Φ = 1.0, Φ' ~ 0.59



Explain experimental behavior with models

KIVA-3V T_u predictions at TDC, just prior to onset of end-gas auto-ignition





Impact:

- The factors influencing the peak rate of heat release with spark advance have been identified with KIVA-3V

With more spark advance there is

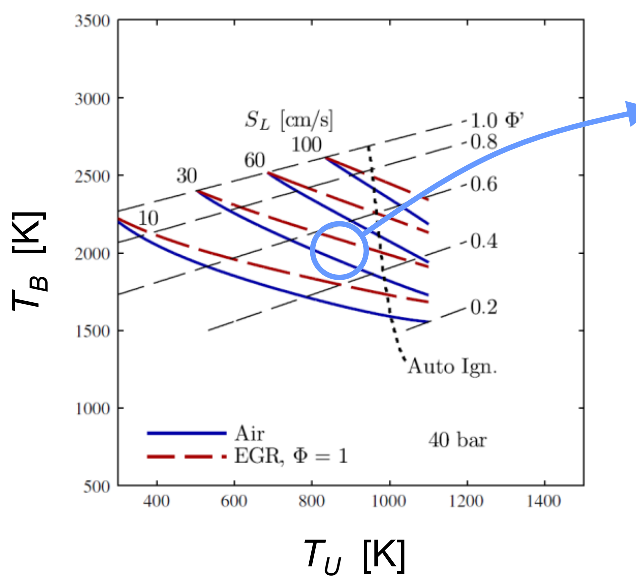
- less mass in end gas when it ignites
- smoother end gas temperature distribution
- reduced peak heat release rate

Task 3: Air vs. EGR Effect on Flame Heat Release (UM)

Accomplishments/Results

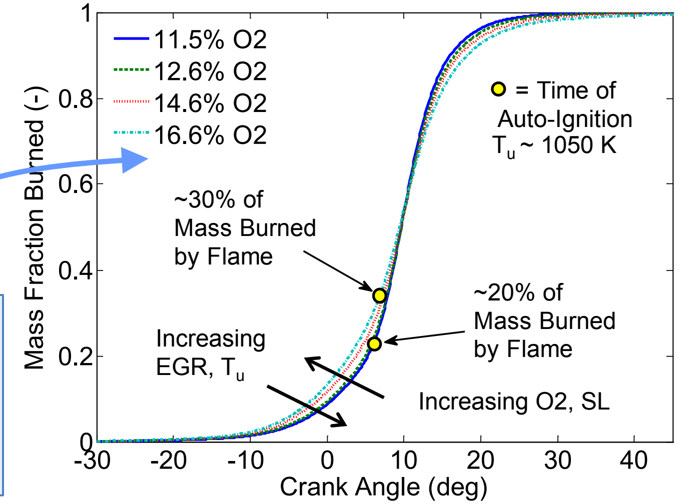
- Models and the FFVA engine demonstrate the sensitivity of flame propagation in Spark Assisted Compression Ignition (SACI) to dilution method

LAMINAR FLAME SPEED SIMULATIONS FOR HIGH PREHEAT AND HIGH DILUTION



Air dilute flames are faster than EGR dilute for a given T_U, T_B (~same load)

Constant SPARK; Constant NVO



- Hold Spark (25 BTC), NVO, and fueling constant
- Increase O2 by replacing e-EGR with air
- Reduce Tin to keep CA50 constant
- Result: Increased flame speed consumes more charge before ignition, and peak heat release is reduced

Impact:

- Dilution method affects the tradeoff between flame heat release and ignition delay time factors, and can be used to manage heat release

Task 3: Enabling advanced combustion with MWASP (UCB)

Goal:

Explore the use of a Microwave Assisted Spark Plug (MWASP) with application to SACI combustion

Methods:

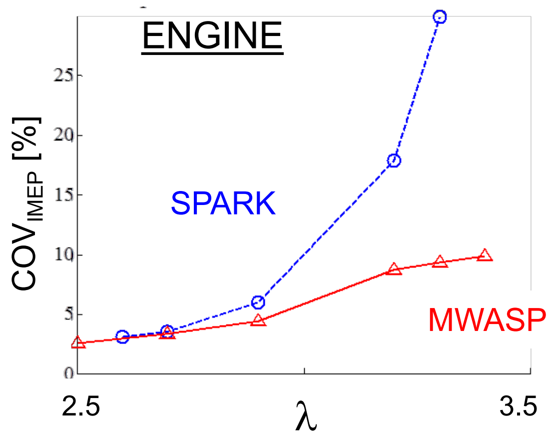
Engine testing, optical chamber experiments, chemical kinetic modeling

Results:

Engine Testing	Optical Chamber	Num. Model
Reduced COV_{IMEP} Extended stab. limits	Faster flame kernel Extended ign. limits	Reduced comb. time with electric fields
MW less effective at high pressure and faster burning conditions		
Identified optimum MW pulse duration	Microwave enhances flame after spark	MW most effective at higher electron conc.

Impact:

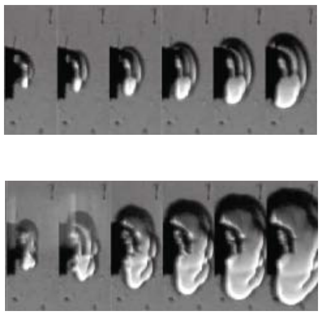
Characterizing processes governing microwave-assisted ignition informs design and implementation of future ignition systems for HPLB applications



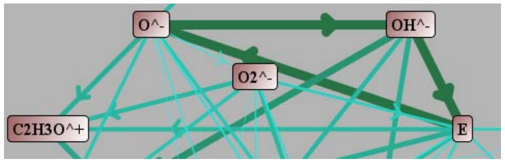
OPTICAL CHAMBER

SPARK

MWASP



MODELING

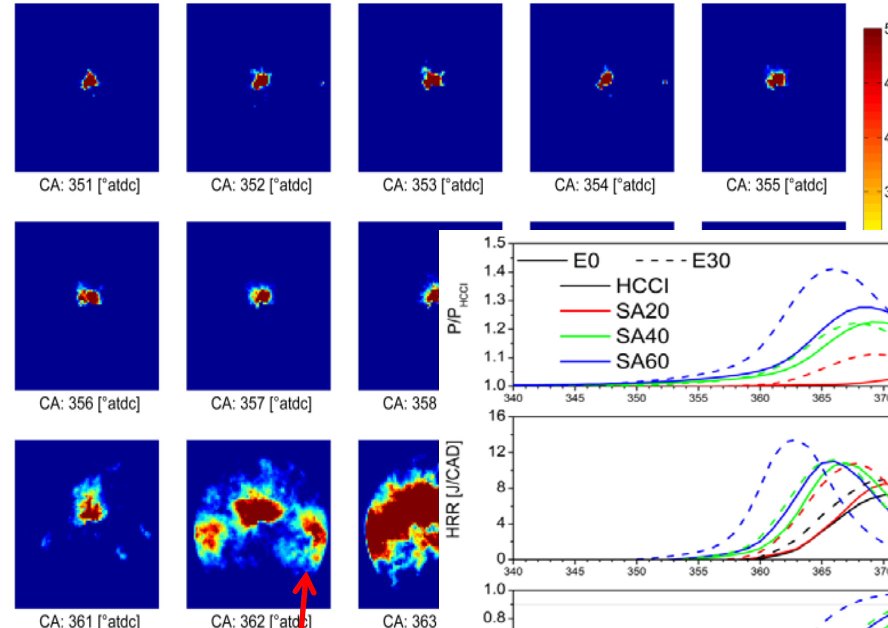


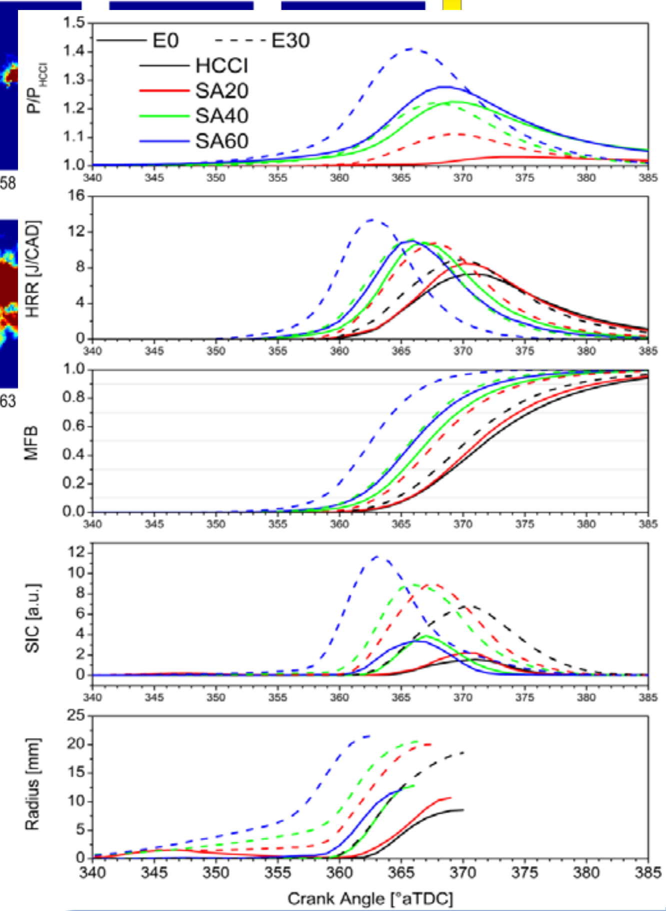
Tasks 3 and 4: SACI measurements of E0 and E30 ignition and combustion in an optical engine (UM)

Accomplishments/Results

SACI images show flame propagation and autoignition at lean conditions ϕ = 0.4 for ethanol blend, but not for indolene (the local mixture may be below the flammability limit)

SACI images synchronized with in-cylinder pressure data yield insight into the mechanisms affecting phasing and heat release rate (HRR)

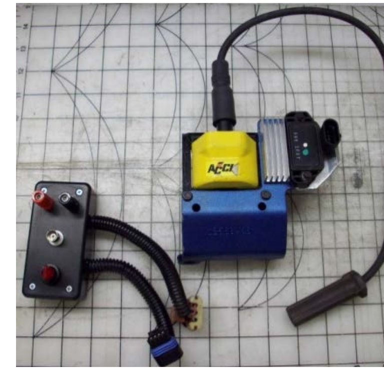




Impact:

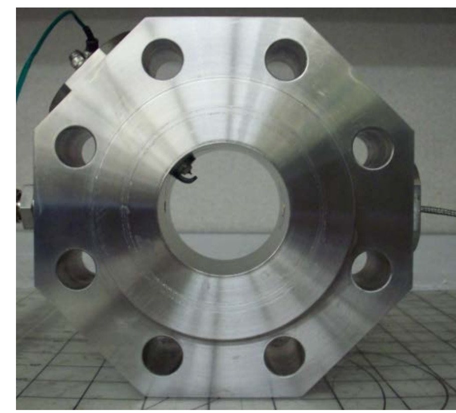
- HRR not always a good indicator of flame initiation or propagation
- Increase in HRR immediately prior to volumetric autoignition is due to local autoignition sites

Task 3: Understanding simultaneous flame + autoignition interactions



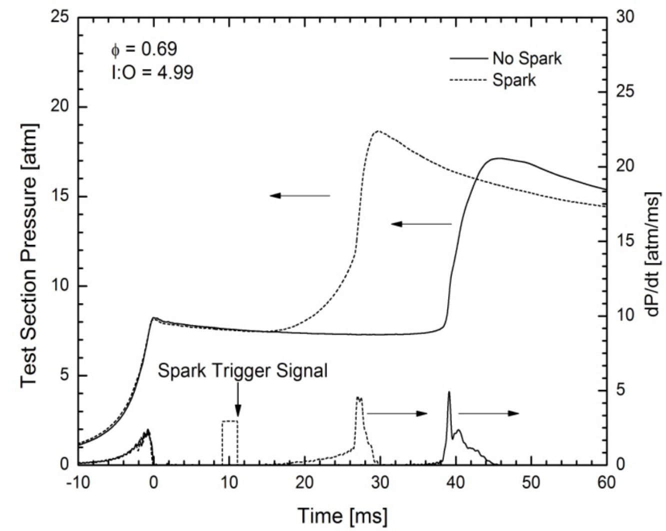
Fundamental need to better understand flame propagation in low temperature (700-1100 K), high pressure (~10 atm), lean (Φ = 0.3 – 0.7) and dilute mixtures

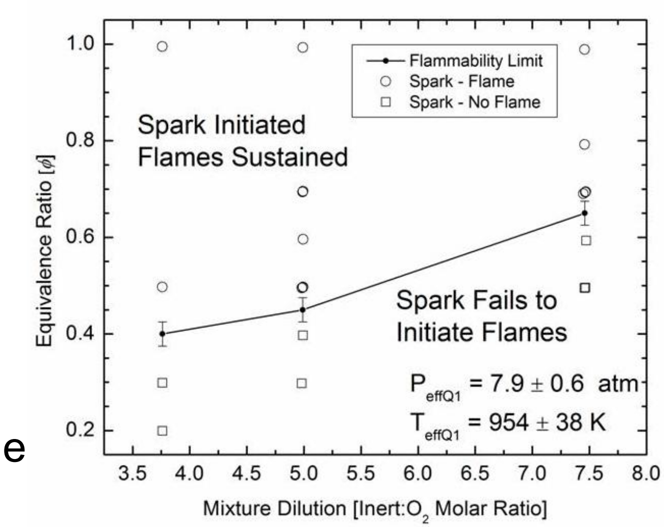
- <u>Goal:</u>
  - Quantify flame + autoignition interactions
- <u>Approach:</u>
  - RCF experiments varying Φ and dilution in premixed iso-octane/O_2/N_2 mixtures
  - Spark to ignite flames
  - High speed imaging to measure flame speeds and autoignition time



Task 3: Understanding simultaneous flame + autoignition interactions

- <u>Accomplishments/Results</u>
  - Quantified the effects of spark on iso-octane ignition at controlled, nominally uniform temperature and pressure conditions
  - measured flame characteristics including flame speeds for high temperature, high pressure, premixed iso-octane and air
  - Identified flammability limits for SACI in range of:
    - Φ = 0.4 – 0.6
    - T = 954 K; P = 7.9 atm
    - Inert :O_2 dilution = 3.6 to 7.5:1 (mole basis)





<u>Impact</u>:

- Vital missing link for theory and modeling
- Fundamental limiting conditions for SACI identified for the time, including flame propagation rates
- Developed metric for quantifying the effect of SACI on ignition

Task 4. Fuel properties for optimal fuel economy (UM)

Fuel testing in FFVA engines (UM)

- Establish range of combustion with fuels of varying octane number

Optical engine (UM)

- Investigate effects of alcohol blends,
- PRF blends

Rapid Compression Facility (UM)

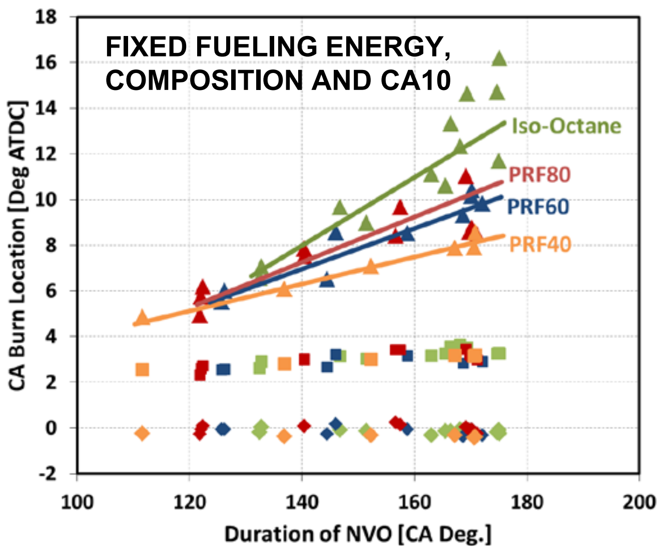
- Ignition delay measurements
- Detailed speciation
- Fuels: (isooctane, esters, alcohols and blends)

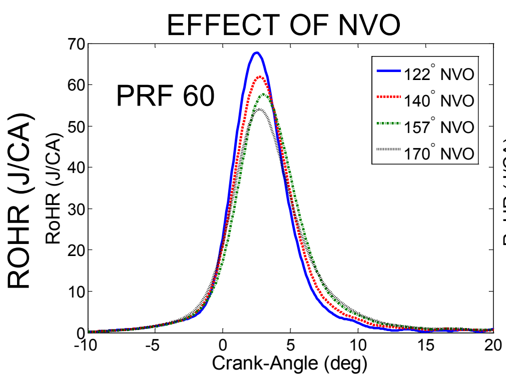
Correlations and Modeling

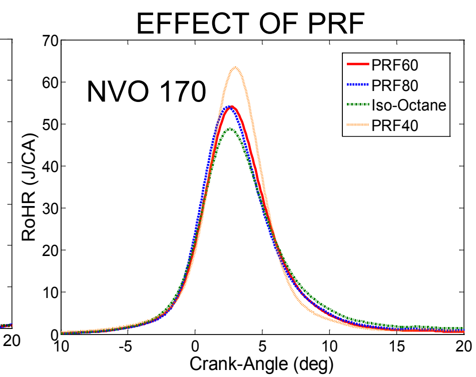
- RCF data used to develop ignition delay correlations for system level models
- Speciation assists development of improved detailed kinetic models

Task 4. Fuel properties for optimum fuel economy (UM)

- Goal:
  - Explore burn characteristics for different fuels in FFVA engine
- Accomplishments/Results
  - Separated fuel effect from NVO, composition and phasing
  - At fixed composition and CA10 phasing, increased NVO decreases heat release rates
  - At fixed NVO (~const. i-EGR) burn and heat release rates are faster for lower PRF fuels





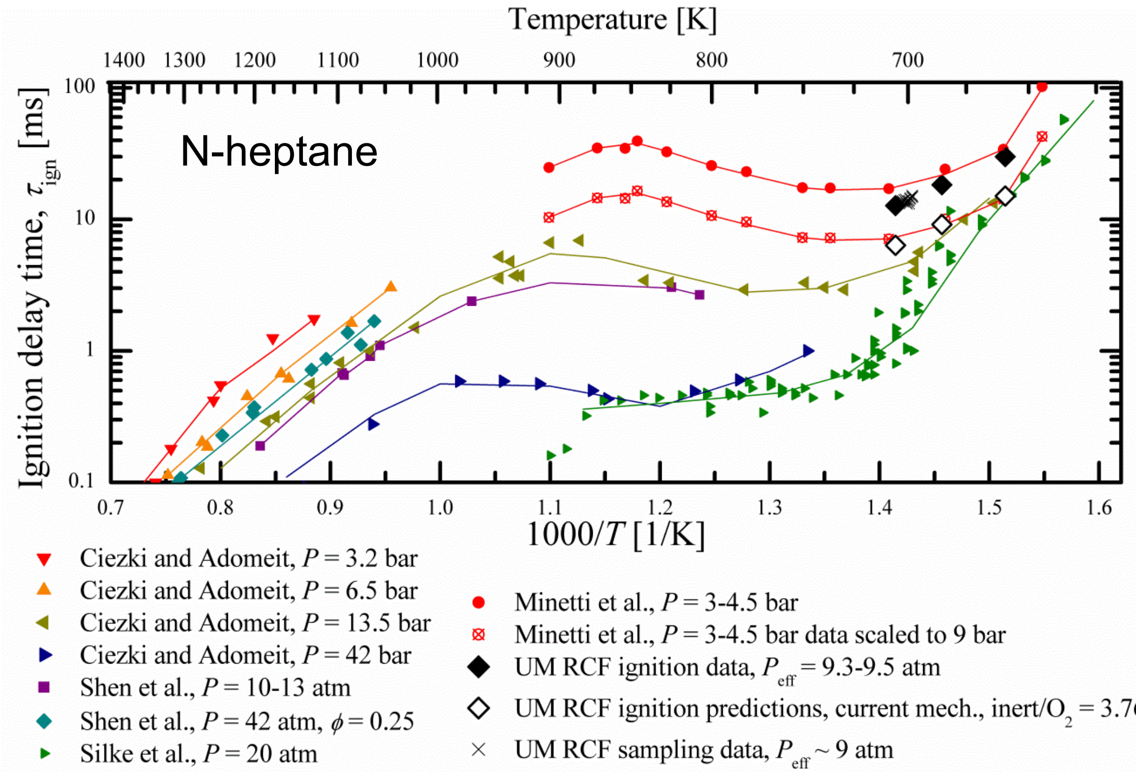


Impact:

- Results identify a direct fuel related heat release effect
- Explain high load extension previously shown with lower PRF fuels

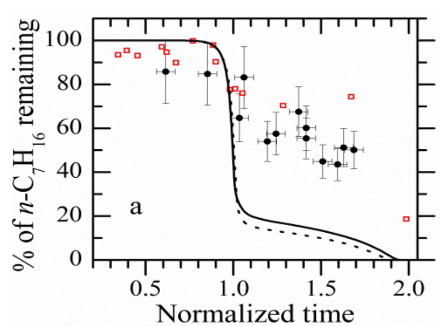
Task 4. Ignition studies in RCF (UM)

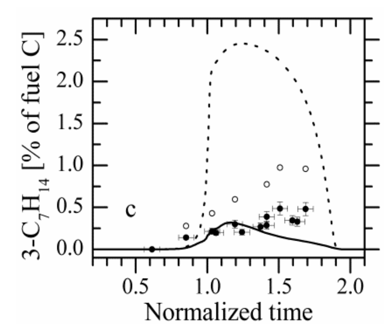
- Goal:
  - Quantify autoignition of key reference fuels
- Rapid Compression Facility
  - Ignition delay data obtained for several reference species, including now n-heptane
  - Correlations integrated into engine models
  - Speciation results used to improve kinetic mechanisms (with LLNL)



Impact:

- Identified areas of strengths and weaknesses in rules of reaction chemistry
- Created new and improved n-heptane reaction mechanism





Collaborations and Coordination

- Working on boosted single cylinder HCCI studies with GM
- Working with Microwave Enhanced Ignition device supplied by Yuji Ikeda, Imagineering, Inc., Japan
- Collaborated on SACI and combustion stability with Robert Wagner (ORNL)
- Currently working with Ford to adapt our optical engine to direct injection.
- Working with Jacqueline Chen (Sandia National Laboratories), Ramanan Sankaran (ORNL), Mauro Valorani (University of Rome, La Sapienza), Chris Rutland (UWisc) on mixing effects on HCCI combustion.
- Collaborated with Charles K. Westbrook on reaction mechanism for n-heptane
- Worked with William Pitz and Marco Mehl (LLNL) to apply new surrogate fuel kinetics to engine models

Future Work FY13

- Task 1: System and FE analysis tools
  - Complete analysis with realistic combustion constraints for stratification, stratification and fuel effects as determined in Tasks 2, 3, and 4.
  - Complete system level model of SACI for transient and controls work.
- Task 2: Stratification as a means to control combustion
  - Refine experimental data analysis and document findings
  - Complete assessment of new combustion and mixing submodels of stratification effects and mixed mode turbulent combustion.
- Task 3: Multi-mode combustion
  - Complete validation of CFMZ model of SACI by comparison to metal engine data.
  - Document study of partition of flame vs. autoignition heat release with SACI in FFVA engine
  - Implement a higher-energy microwave system for MWASP testing
  - Complete direct injection optical engine study of fuel effects on LTC
- Task 4: Fuel properties for optimum FE
  - Complete PRF studies of heat release, and load limit in HCCI mode. Conduct limited SACI studies with PRF fuels
  - Complete studies of buffer gas composition effects on ignition

Summary (1)

- Task 1: System and FE analysis tools
  - System level model combining HCCI-SACI-SI combustion modes is nearing completion and will be used for refined FE assessment of advanced combustion opportunities.
- Task 2: Stratification as a means to control combustion
  - Experiments with combined PFI/DI show that stratification can be beneficial or detrimental, depending on the interplay between local fuel concentration, and the regime of temperature and ignition delay.
  - Spray-Interactive Flamelet (SIF) model provides improved predictions of ignition timing and heat release rate relative to simple RANS models. Results show that small scale bulk gas turbulent fluctuations affect heat release predictions under highly stratified conditions.
  - Results to be utilized to set combustion regime constraints in FE estimates in Task 1.

Summary (2)

- Task 3: Multi-mode combustion
  - Coordinated engine experiments and new KIVA SACI modeling work have improved fundamental understanding of the dual (flame/auto-ignition) characteristics of SACI and add insight on the role of thermal gradients in modulating the heat release rate.
  - Provided the basis for further exploration of this combustion mode and integration into Task 1 FE estimates.
  - Determined that MWASP ignition extends lean limit in engine and combustion bomb. Developed chemical kinetic model of MW effect on combustion.
  - SACI engine and RCF data aid interpretation of metal engine modeling and experimental data from Tasks 2 and 3, and inform how spark assist can be used to control HRR (e.g. flammability limits, optimal and suboptimal spark plug location, etc.) (Tasks 2 and 3)
- Task 4: Fuel properties for optimum FE
  - Detailed studies of PRF fuels in NVO enabled HCCI operation have confirmed a chemical effect of octane number on heat release rate which leads to higher load limit for low octane fuels identified last year. This information will be incorporated into the KIVA modeling in Task 3, and the FE simulations in Task 1.
  - Ignition delay time correlations developed and integrated into (Tasks 2 and 3)
  - Fuel specific effects identified during HCCI and SACI. Best fuel features integrated into LTC strategies of Tasks 2 and 3.