Optical-Engine and Surrogate-Fuels Research for an Improved Understanding of Fuel Effects on Advanced-Combustion Strategies

Charles J. Mueller

Combustion Research Facility

Sandia National Laboratories

2011 DOE Vehicle Technologies Annual Merit Review
Crystal City Marriott, Washington, DC
May 10, 2010

Project ID#: FT004

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Overview

Timeline

- Project provides fundamental research to support DOE/ industry fuel-technologies projects
- Project directions and continuation are evaluated annually

Budget

- Project funded by DOE/VT:
  FY10 – $730K
  FY11 – $760K

Barriers *(from DOE/VT MYPP 2011-2015)*

- Inadequate data and predictive tools for understanding fuel-property effects on
  - Combustion
  - Engine efficiency optimization
  - Emissions

Partners

- Project lead: Sandia – C.J. Mueller (PI); B.T. Fisher, C.J. Polonowski (post-docs); N.D. Matthew, K.R. Hencken (part-time technologist assistance)
- 15 industry, 6 univ., and 6 nat'l lab partners in Advanced Engine Combustion MOU
- Coordinating Research Council (CRC)
- Caterpillar Inc.

Relevance – Objectives

Develop the science base to enable high-efficiency, clean-combustion (HECC) engines using fuels that improve US energy security

- Specific objectives of work since FY10 Annual Merit Review
  - Study mixing-controlled HECC strategies/barriers using baseline diesel
    - To achieve mixing-controlled in-cylinder combustion that does not form soot
  - Co-lead team to formulate and begin testing surrogate diesel fuels
    - To understand fuel-component effects, enable computational engine optimization
  - Understand injection-rate and heat-release effects on liquid length
    - To avoid wall impingement and resultant detrimental effects
  - Enhance critical experimental capabilities (high-pressure fuel injection)
    - To allow study of new combustion strategies with current and emerging fuels

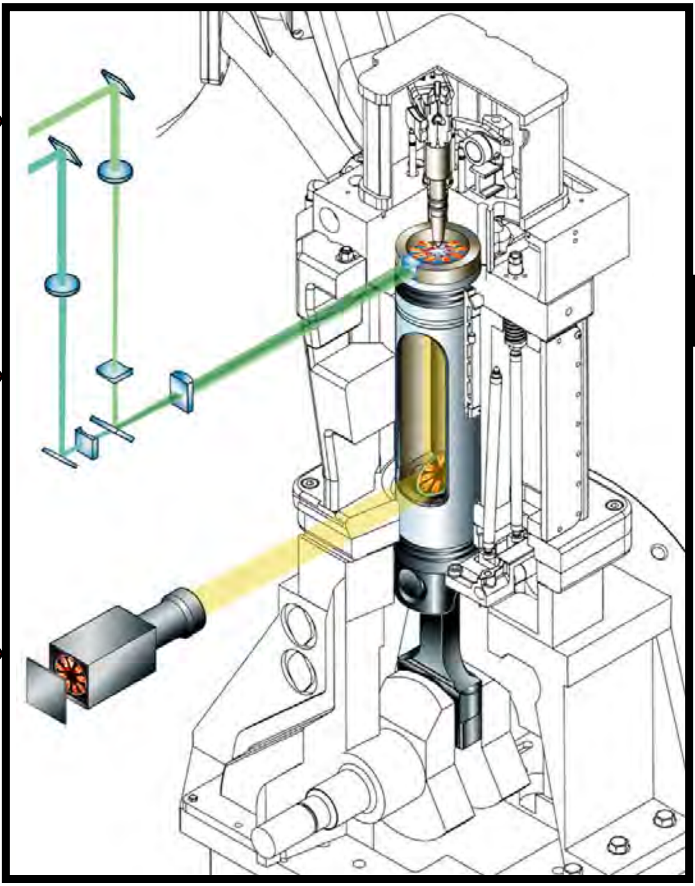
Approach – Experimental

Use optical engine and advanced diagnostics to understand fuel effects on in-cylinder processes

Modern Engine Hardware

Advanced Fuels

Collaboration with Industry, Academia, National Labs



Science Base to Lower Fuel Consumption, Emissions, and System Cost

Approach – Milestones

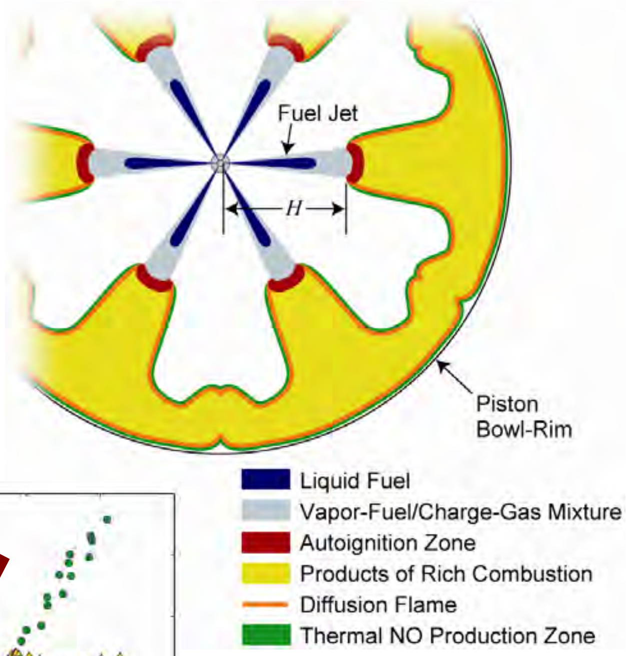
- ✓ **September 2010**
  Finish 10-factor parametric study of leaner lifted-flame combustion (LLFC) with baseline #2 ultra-low-sulfur diesel (ULSD) certification fuel
- ✓ **December 2010**
  Implement upgrades to 3000-bar fuel-flexible common-rail fuel pump to extend mean time between failures from < 2 hours to > 20 hours
- ✓ **March 2011**
  Create draft manuscript summarizing progress to date on diesel surrogate fuel formulation and testing
- **June 2011**
  Bring laser-induced incandescence diagnostic online to accurately measure exhaust soot levels below detection limit of AVL smoke meter
- **December 2011**
  Finish study of sooting tendencies of subset of FACE diesel fuels under mixing-controlled combustion conditions

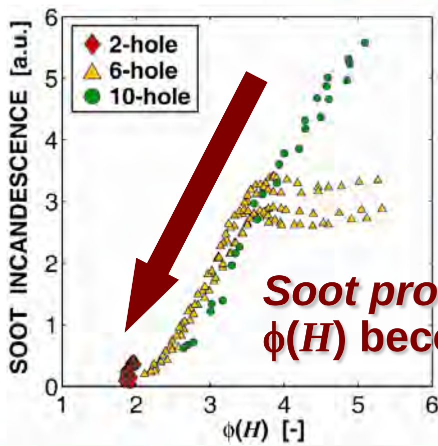
Technical Accomplishments Summary

1. **Completed 10-factor parametric study of leaner lifted-flame combustion (LLFC) with baseline #2 ULSD certification fuel**
   - Achieved and studied LLFC (*i.e.*, mixing-controlled combustion that does not form soot) in the optical engine
   - Identified key barriers to sustaining LLFC at higher-load conditions
2. **Co-led CRC Proj. AVFL-18: Development of surrogate diesel fuels**
   - Formulated and tested two surrogate fuels, drafted manuscript summarizing improved methodology and results
3. **Improved understanding of injection-pressure and heat-release effects on liquid length**
   - Inj. pressure: Increasing from 70 to 140 MPa affects liquid length by < 2%
   - Heat release: Observations consistent with hypothesis that liquid length is affected only through changes to ambient thermodynamic conditions
4. **Enhanced laboratory capabilities**
   - Modified fuel pump to enable fuel-flexible, robust 3000-bar rail pressure

TA#1: Evaluated LLFC Strategy in the Optical Engine to Establish Baseline Understanding

- **LLFC ≡ mixing-controlled combustion that does not produce soot because equivalence ratio at lift-off length, $\phi(H)$, is < 2**
- **Potentially attractive alternative to HCCI**
  - Ignition timing easily controlled by injection timing (rather than by kinetics)
  - Lower heat-release rates (quieter combustion), especially at higher loads
  - Well-suited for use with biodiesel, oxygenates
  - Potentially improved peak-load capability
  - Potentially lower emissions and fuel consumption at light loads
- **High injection pressures and small orifices help (> 2000 bar, < 120 μm)**





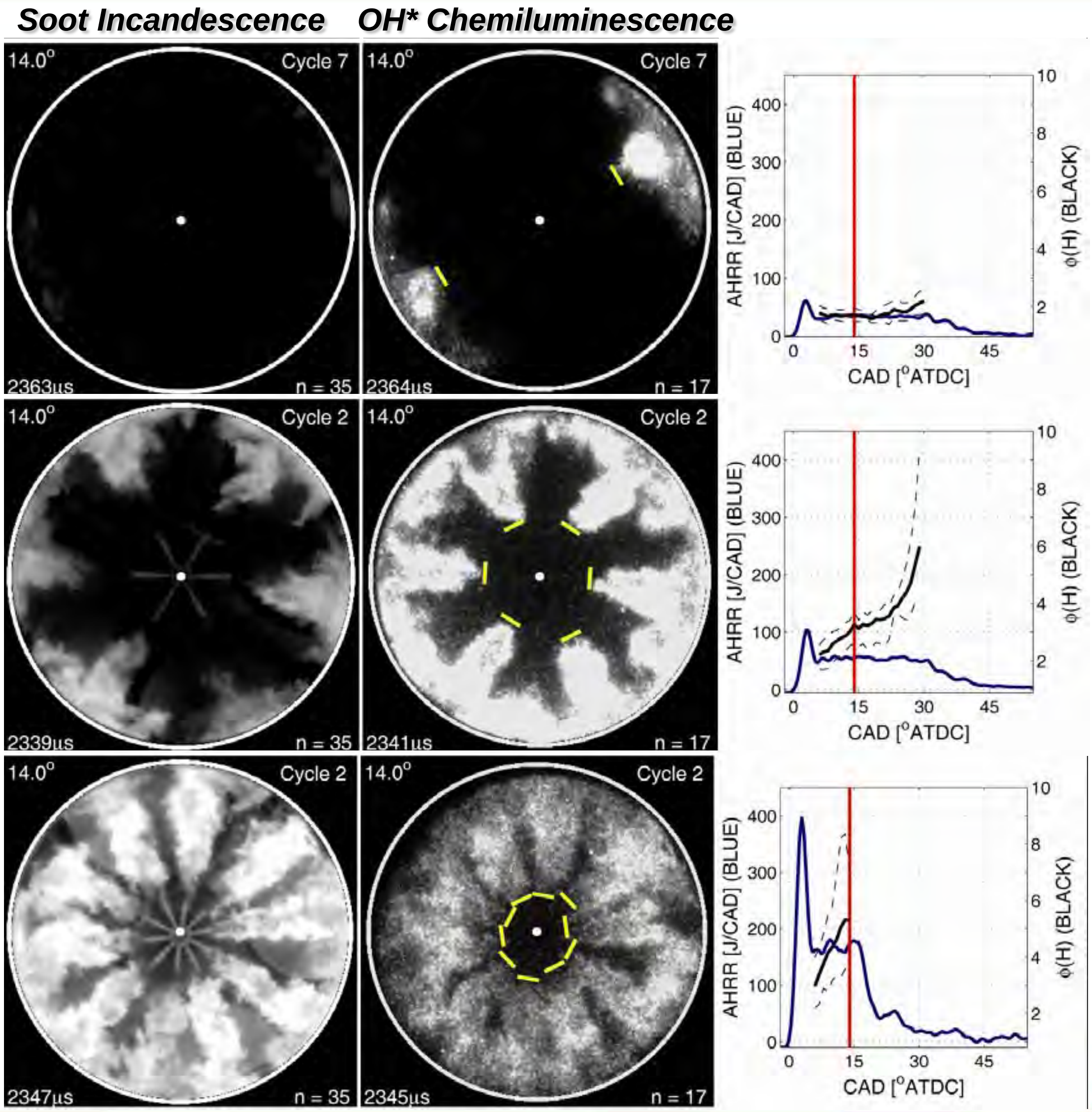
Soot production ↓ as $\phi(H)$ becomes leaner

TA#1: LLFC Could Be Sustained in Engine but Required 2-Hole Injector Tip

2-hole tip: soot-free combustion achieved and sustained

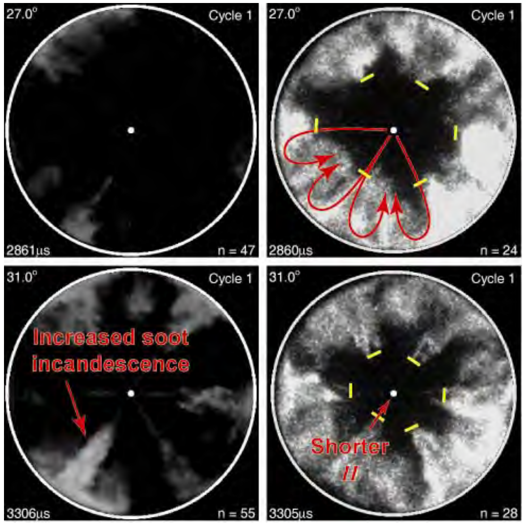
6-hole tip: soot-free combustion achieved but not sustained

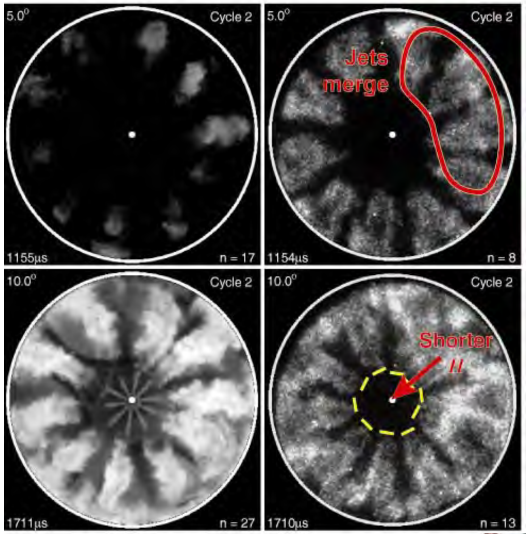
10-hole tip: soot-free combustion not achieved



TA#1: Identified 2 Previously Unknown Barriers to LLFC: Re-Entrainment and Proximity Coupling

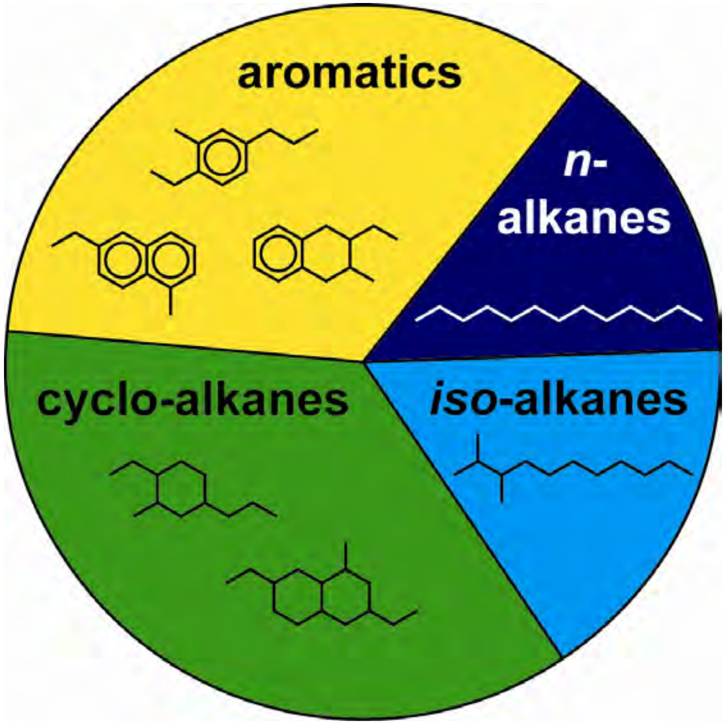
- **Re-entrainment**
  - Hot, reactive, oxygen-depleted combustion products are entrained into fuel jet upstream of lift-off length, H
- **Proximity coupling**
  - Close inter-jet spacing affects the species, temperature, and velocity fields between jets in a manner that tends to reduce H
- **These phenomena impose limitations on injection duration and end**
- **Higher injection pressure can help**
  - Shorter injection duration for same load
  - Advanced end of inj. → more time for oxidation
  - Jet momentum↑ → better late-cycle mixing
  - Less time spent at richest $\phi(H)$ late in cycle



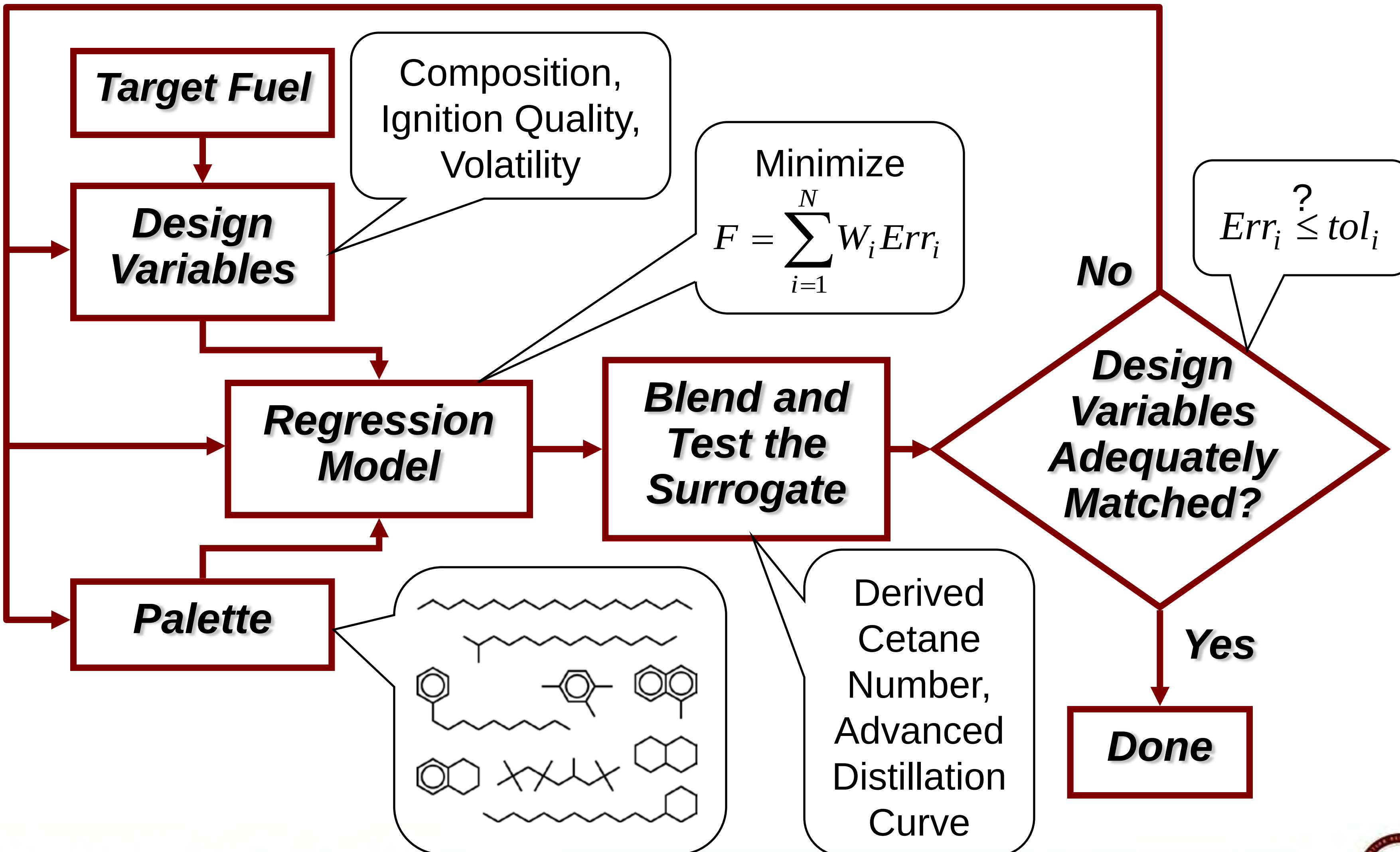


TA#2: Co-Led CRC Project AVFL-18 on Development of Surrogate Diesel Fuels

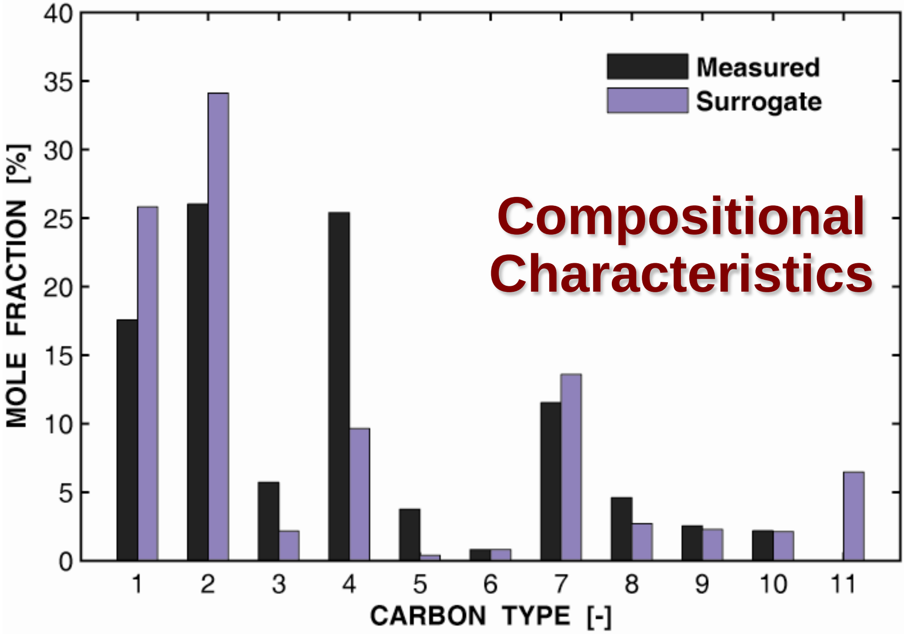
- **A market diesel fuel (target fuel) may contain hundreds or thousands of compounds in a number of chemical classes**
  - "Drop-in replacement" biofuels have same types of compounds
  - Biodiesel esters and other oxygenates can be added easily
- **A surrogate fuel may contain only ~10 compounds, yet it reproduces selected key characteristics of the target fuel**
- **Surrogate fuels**
  - Enable improved understanding of individual fuel-component effects on combustion and emissions
  - In conjunction with accurate kinetic models and CFD, enable computa-tional engine optimization for current and emerging fuels



TA#2: Surrogate Diesel Fuel Formulation Methodology Established

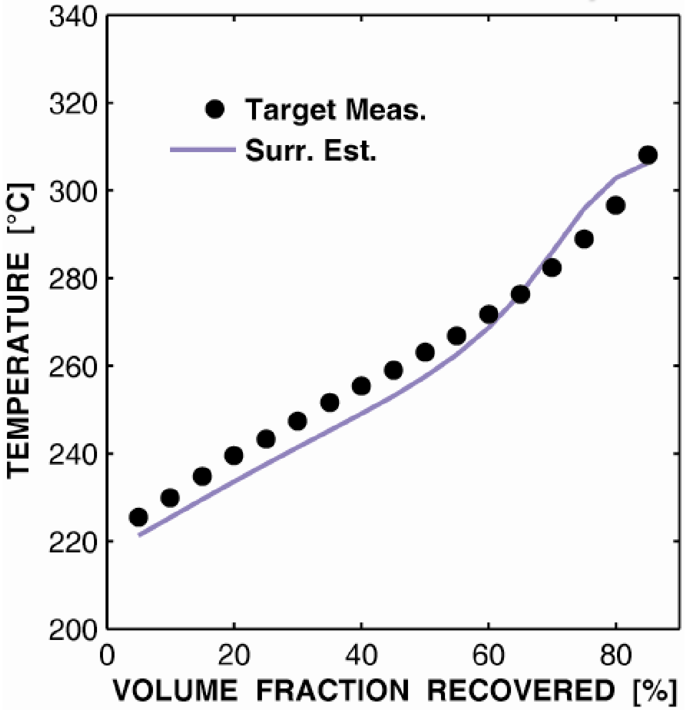


TA#2: Surrogate Diesel Fuels Blended, Analysis of Results is Underway

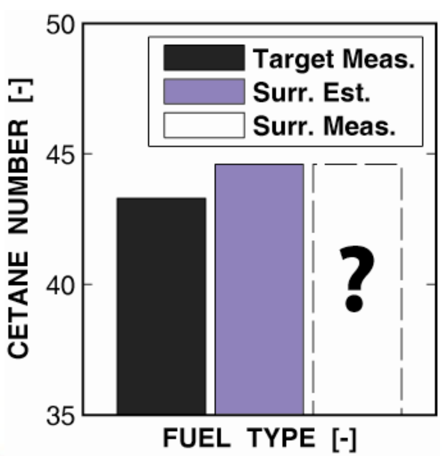


Compositional Characteristics

Volatility (Advanced Distillation Curve)



Ignition Quality



Manuscript describing results has been drafted, submission anticipated in coming months.

Collaborations and Coordination with Other Institutions

- **Mixing-controlled combustion research conducted with guidance from Advanced Engine Combustion Memorandum of Understanding (MOU)**
  - 10 engine OEMs, 5 energy companies, 6 national labs, 6 universities
  - Semi-annual meetings and presentations
- **Surrogate diesel fuel research conducted under auspices of CRC; AVFL-18 includes participants from**
  - 3 energy companies, 1 Canadian + 7 US national labs, 1 auto OEM
  - Tri-weekly teleconferences, quarterly presentations
  - Co-authored diesel surrogates literature review with Bill Pitz (LLNL)
- **Work-for-others contract**
  - Funds in from Caterpillar Inc.
  - Bi-weekly teleconferences, semi-annual meetings

Proposed Future Work (through FY12)

- **Quantify fuel and injection-strategy effects on mixing-controlled combustion**
  - Measure lift-off lengths, liquid lengths, emissions (esp. soot), efficiency
  - Use subset of FACE diesels
  - Other potential fuels: biodiesel esters, heavy ethers, oil-sands diesel
- **Complete current phase of diesel surrogate fuel development efforts (AVFL-18), propose / conduct follow-on research**
  - Explore effects of new palette compounds and/or formulation strategies
  - Includes surrogate- and target-fuel testing in optical engine
- **Continue other active collaborations**
  - Advanced Engine Combustion MOU
  - CRC Advanced Vehicles, Fuels and Lubricants activities
  - Work-for-Others agreement with Caterpillar
- **Continue to enhance experimental capabilities**
  - Increase fuel-pump flow-rate capacity, implement stronger optical piston

Summary

- **This research is dedicated to an improved understanding of fuel effects on advanced combustion strategies**
  - Efforts focused on DOE objectives of achieving HECC with current and emerging fuels, to enhance energy security and environmental quality
  - Includes close collaboration and guidance from engine manufacturers, energy companies, academia, and other national laboratories
- **Significant technical accomplishments have been made during this reporting period, including:**
  - Completed large parametric study of leaner lifted-flame combustion (LLFC) with baseline #2 ULSD; identified opportunities and challenges
  - Co-led CRC team of experts in developing surrogate diesel fuels to enhance understanding of fuel effects on advanced combustion and to support computational engine design / optimization
  - Improved understanding of injection-pressure and heat-release effects on liquid length over a wide range of injection timings
  - Enhanced critical experimental capabilities (high-pressure fuel injection)