Low-Temperature Gasoline Combustion (LTGC) Engine Research – Previously known as HCCI / SCCI –

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This presentation does not contain any proprietary, confidential, or otherwise restricted information.
### Overview

#### Timeline
- Project provides fundamental research to support DOE/Industry advanced engine projects.
- Project directions and continuation are evaluated annually.

#### Barriers
- Rapid control of LTGC / HCCI combustion timing
- Spark-Assisted LTGC / HCCI
- Improved stability / robustness of LTGC combustion
- Advanced fuel-injection strategies
- Improved understanding of LTGC fundamentals

#### Budget
- Project funded by DOE/VT:
  - FY15 – $680k
  - FY16 – $600k

#### Partners / Collaborators
- **Project Lead**: Sandia ⇒ John E. Dec
- Part of Advanced Engine Combustion working group – 15 industrial partners
- General Motors – in-depth collaboration
- Cummins – spark-plug cylinder heads
- LLNL – support kinetic modeling
- Co-Optima Fuels project
- Chevron – advanced fuels for LTGC
- Sandia LDRD – fuel injection
Objectives - Relevance

**Project objective:** to provide the fundamental understanding (science-base) required to overcome the technical barriers to the development of practical LTGC / HCCI engines by industry.

**FY16 Objectives** ⇒ address barriers, particularly Controls and Robustness

- Performance mapping with new low-swirl, spark-plug capable cylinder head: Compare thermal efficiency (TE) & load range with data from old head.

- Evaluate performance with RD5-87 (typical regular 87 AKI, E10 gasoline) compared to Tier-2 certification gasoline (CF-E0) for premixed (PM) fueling and with partial fuel stratification (PFS).

- CA50 control and improved robustness using Double-DI PFS (DDI-PFS) ⇒ Determine the potential for CA50 control and improved EGR tolerance.

- Initial studies of Spark Assist (SA): Determine CA50 control and intake-temperature ($T_{in}$) tolerance at selected conditions.

- Support Modeling: Chemical-kinetics at LLNL and related RCM experiments at ANL, and CFD modeling at GM.
Response to Reviewer Comments

- Reviewers made many positive comments. ⇒ We thank the reviewers
- Several comments indicated ⇒ focus less on high efficiency and high loads and more on ways control combustion timing and operation at lower boost.
  - We have accelerated plans to shift research in these directions, as reflected in the FY16 objectives (prev. slide) and explained in greater detail below.

Specific comments

1. Accelerate installation of spark-plug head and studies of spark assist (SA)
   - Several mechanical/technical problems were encountered that delayed installation of head.
   - Head was installed latter part of FY15, debugged. Initial studies of SA have been conducted.

2. Studies of DDI-PFS should include CA50 control methodologies.
   - DDI-PFS has strong potential for rapid CA50 control and for increased robustness. ⇒ We have shifted the focus of DDI-PFS studies to these objectives.

3. Concerns that high boost can be difficult with LTGC
   - PFS requires that fuel autoignition be $\phi$-sensitive ⇒ typically greater at higher boost.
   - Investigated $\phi$-sensitivity over a wide range of boost for CF-E0 and RD5-87
     ⇒ Found good potential that PFS can provide benefits down to $P_{in}=1.3$ bar, better for RD5-87
   - New studies have been conducted at lower boost ⇒ additional low-boost studies planned.

4. Need to show Combustion Noise Levels (CNL) as well as Ringing Intensity (RI)
   - CNL values are presented and discussed.
Overall Approach: Use a combination of metal- and optical-engine experiments, analysis & modeling to build a comprehensive understanding of LTGC processes.

- **Metal Engine**
  - Modify new cylinder heads to install spark-plug (SP) ports.
    - Work with Cummins on design, SP port installation, & new pressure transducer (PT) port
    - In-house modifications to SP-head for Bosch HDEV 5.1 GDI injector (300 bar capable).
  - Well-controlled experiments to 1) evaluate SP-head performance, and investigate:
    - 2) DDI-PFS: develop methods of varying fuel stratification to obtain injection-timing control of CA50, increased CA50 tolerance, and improved stability.
    - 3) Spark-Assist: systematically adjust spark time for CA50 ctrl. & T_{in} compensation.

- **Optical Engine** – adaptation of SP-head and installation will follow.

- **Fuels** – Worked with GM to specify a research-grade E10 regular gasoline, RD5-87, and compare performance with CF-E0. (Prior to recent E10 Tier 3 cert. gas.)

- **Analytical Techniques** – Apply our recently developed techniques to understand:
  - 1) changes in energy-loss distribution, and 2) noise levels, CNL

- **Computational Modeling**: 1) Collaborate with LLNL on kinetic mechanism for RD5-87, and 2) with GM on CFD modeling for improved understanding of PFS.

- Combining techniques provides a better understanding and more-optimal solutions.

- **Transfer results to industry**: 1) physical understanding, 2) improved models
Approach – Milestones

- **September 2015**
  Complete installation and initial testing of new low-swirl cylinder head with spark-assist capability.

- **December 2015**
  Map performance of SP-head (Head #2) over a range of operating conditions and compare with previous head (Head #1).

- **March 2015**
  Complete installation of spark ignition system and initial study of spark-assisted (SA) LTGC.

- **June 2016**
  Present an overview of project accomplishments and directions at the DOE Annual Merit Review.

- **September 2016**
  Map the operating range for effective DI-PFS with E10 regular gasoline at a compression ratio of 14:1 (plan to switch soon from current CR = 16:1 to 14:1).
Sandia LTGC Engine Laboratory

- Matching all-metal & optical LTGC research engines.
  - Single-cylinder conversion from Cummins B-series diesel.

- Bore x Stroke = 102 x 120 mm
- 0.98 liters, CR = 16:1, switch to 14:1

Unless noted: Ringing ≤ 5 MW/m² & spd = 1200 rpm
NOₓ & soot emiss. more than 10x below US-2010
Overview of Accomplishments

- Completed installation and shakedown testing of new spark-plug capable, low-swirl cylinder head (Head #2).
- Conducted performance mapping of Head #2 and comparisons with Head #1 for both premixed & Early-DI fueling ⇒ TE, high-load limits, CNL, etc.
  - Applied energy-loss analysis tools (developed in FY15) to understand differences.
- Evaluated performance of a research-grade regular 87-AKI, E10 gasoline (RD5-87) and compared to high-octane, E0 certification gasoline (CF-E0).
- Demonstrated CA50 control over a wide range by varying injection timing for a DDI-PFS fueling method:
  - Retard late-DI timing ⇒ incr. strat. ⇒ adv. CA50
- Showed that DDI-PFS can also substantially increase robustness (EGR & CA50 tolerance) and increase stability for an extended load range.
- Demonstrated Spark-Assisted (SA) LTGC for CA50 control and increased tolerance to variation in $T_{in}$ (compensate for $T_{in}$ variation).
- Collaborated with LLNL on development of a kinetic mechanism for RD5-87 and related RCM measurements at ANL, and with GM on CFD modeling.
Low-Swirl Spark-Plug Head ⇒ “Head #2”

- Worked with Cummins to design SP capability and fabricate.
  - SP port in location of original
    D = 10 mm PT (AVL QC34C)
- Install new PT port through fire-deck
  - Very small, D = 5 mm (AVL GH15D)
  - For CI studies, 2nd GH15D in SP port.
- Problems w/ small PT, not all are durable.
- Both heads are low-swirl, but:
  - Head #1, custom anti-swirl plate directs helical port flow against tangential port to create a **counter-swirling flow**.
  - Head #2, ports designed to give low swirl ⇒ thought to produce tumble flow.
- Central-mount Bosch HDEV 5.1 GDI injector ⇒ 300 bar capable.
- Same valves / camshaft / rocker assembly for both heads.
Thermal Eff. (PM) – Spark-Plug Head #2

- Initial testing of Head #2 used:
  - CF-E0 ⇒ large database for Head #1
  - Premixed (PM) fueling to eliminate differences due to fuel inject & mixing.

- $\phi_m \geq 0.34$: TE with Head #2 is just slightly lower (~0.2 %-units).
- $\phi_m < 0.34$: greater TE loss w/ Head #2

- Cause is not well understood:
  - Combst. Eff (CE) and CA50 are similar
  - EGR requirement & $\gamma$ also similar

- Analysis shows increased HT with Head #2 is the most likely explanation.
  - Possibly high-tumble flow breaks down near TDC and increases HT.
  - Greater at low $\phi_m$ since CA50 is closer to TDC.

- Is counter-swirl better for low HT?

PreMixed, CF-E0, $P_{in} = 2.4$ bar, $RI = 5$ MW/m$^2$

$\phi_m = \frac{(F/C)}{(F/A)_{stoich}}$

Oxygen limited
Thermal Eff. (Early-DI) – Spark-Plug Head #2

- Compare heads, Early-DI @ 60° CA
  - $T_{in} = 40°C$ vs. $60°C$ for Premixed
  - Injection Press = 120 bar, both heads
- Overall TE higher than PM mainly due to lower $T_{charge} \Rightarrow$ higher $\gamma$ & lower HT.
- $\phi_m \leq 0.4$: Trends similar to PM, but
  - For $\phi_m \leq 0.35$: TE reduction with Head #2 slightly larger for E-DI due to lower CE with Head #2 $\Rightarrow$ higher CO.
- $\phi_m > 0.4$: TE of Head #2 falls below Head #1, rapid drop in CE $\Rightarrow$ higher CO
- Increased CO at low and high $\phi_m$ indicate a less well-mixed charge with Head #2.
  - Low $\phi_m$ overly lean zones make CO
  - High $\phi_m$ rich zones make CO – high EGR
- Counter-swirl improves mixing for Early-DI fueling with Head #1.
High Load Limit as a Function of Boost

- Max. load for PM fueling with CF-E0 nearly identical for two heads, all $P_{in}$.
  - Oxygen limited $P_{in} > 2.4$ bar (CF-E0).
- RD5-87, PM is similar to CF-E0.
  - Max. load slightly greater, $P_{in} \leq 2.0$ bar.$\Rightarrow$ Higher $\phi_m$ for RI = 5 MW/m$^2$
  - Max. load is less at $P_{in}=2.4$ bar.$\Rightarrow$ More reactive, requires more EGR, becomes $O_2$-limited at $P_{in} < 2.4$ bar.
- Early-DI fueling: Max. load quite similar for two heads, all $P_{in}$.
  - Highest load at $P_{in} = 3.0$ bar.$\Rightarrow$ 17.2 bar IMEP$_g$ for Head #2 vs. $\Rightarrow$ 17.7 bar IMEP$_g$ for Head #1
- Combustion Noise (CNL) is similar for all max. load curves, for RI = 5MW/m$^2$
  - Close to high end of diesel CNL range.
  - Could reduce CNL by small CA50 retard 5 dBA reduction for 0.8 %-units less TE
Injection-Timing/PFS to Control LTGC

- If the fuel’s autoignition timing varies with the local in-cyl. $\phi_m$, said to be $\phi$-sensitive $\Rightarrow$ richer regions autoignite faster.

- Partial fuel stratification (PFS) can be used to provide several benefits.
  - Reduced HRR for higher loads & higher TE. $\Rightarrow$ Shown in previous years.
  - Combustion-timing control
  - Increased robustness, i.e. tolerance to variation in EGR and CA50

- **Std-PFS** = most Premixed + late DI
  **Double-DI PFS** = most Early-DI + late DI
  $\Rightarrow$ late-DI timing & fraction adjusts strat.

- For what $P_{in}$ range are fuels $\phi$-sensitive? $\Rightarrow$ Direct measurement very tedious.

- Use CA50 adv. for $RI = 5 \text{ MW/m}^2$ with std-PFS vs. PM as a measure of $\phi$-sensitivity.
  - Here std-PFS = 90% PM + 10% at 310° CA.
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- Both fuels $\phi$-sensitive from $P_{in} = 2.4$–1.3 bar ⇒ RD5-87 more $\phi$-sensitive, all $\phi_m$ s & $P_{in}$ s.
CA50 Control with Injection-Timing

- Apply Double-DI (DDI) PFS to control CA50.

- Procedure:
  1. Set initial conditions ⇒ adjust CA50 to give RI=2.5 MW/m² for single, Early-DI injection.
  2. Switch to DDI with 70% Early-DI at 60°CA & 30% late-DI with variable timing (70/30%).
  3. Hold EGR and Tin constant while sweeping late-DI timing.

- Late-DIs from 200 – 280° CA retards CA50 compared to Single-DI at 60°CA (S-DI-60).
  - Indicates better mixing than S-DI, which already gives some PFS. ⇒ RI < 2.5 MW/m²

- Late-DIs from 280 – 300° CA advance CA50 significantly due to greater stratification.
  ⇒ RI = 2.3 – 6.1 MW/m²

- **CA50 was adjusted 6.7° CA** with 70/30% (4.5° COV-IMEP₉ = 1.9% to RI = 5 MW/m²)

- With DDI-80/20%, **CA50 ctrl. range 8.6° CA**

- CNL trend is similar to RI ⇒ below upper range for diesels for most of the sweep, RI ≤ 3.5 MW/m².
Increasing Robustness with DDI-PFS

- Our general range of acceptable operation from “knock” to “poor stability” is from $R_I = 5 \text{ MW/m}^2$ to $\text{COV-IMEP}_g = 2\%$.
- Sweep EGR at constant $T_{in}$ to shift CA50 across a wide range for S-DI and DDI. ⇒ Use intake $O_2$ as a metric for EGR.
- **S-DI-60**: CA50 tolerance = 1.8° CA ⇒ EGR must vary ≤ 0.08 O₂%-units.
- **DDI, 30% at 305°CA**: CA50 tol. = 4.3°CA ⇒ EGR can vary ≤ 0.28 O₂%-units
- DDI-PFS greatly increases tolerance to non-ideal CA50 and EGR levels.

![Graph showing the variation of CA50 and Intake O₂]
Increasing Stability with DDI-PFS, $P_{in} = 1.6$ bar

- Both Head #1 and Head #2 show reduced stability for Early-DI (S-DI-60) at $P_{in}=1.6$ bar ⇒ Cause is not understood.

- Maximum fueling rate ($\phi_m$) is significantly reduced compared to PM or S-DI-60 at other $P_{in}$s.
  - Becomes unstable if $\phi_m$ is increases, and quickly runs away to knock or misfire.

- With RD5-87, max. $\phi_m$ with S-DI-60 is even lower than with CF-E0.

- Apply DDI-PFS with an relatively early “late-DI” timing ⇒ 80% at 60° + 20% at 200°CA

- DDI-80/20%-200 greatly increases stability, allowing a substantial load increase. ⇒ $\phi_m$ increased from 0.34 to 0.42

- Moreover, still stable at $\phi_m = 0.42$, so further increases are possible.

- Even greater increases may be possible with optimization of DDI fueling strategy.
Spark-Assist for LTGC Control, $P_{in} = 1$ bar

- Spark-assist (SA) is a promising control method, $P_{in}=1$ bar & lower boost (limit=?)
- Complements injection-timing/PFS control at higher $P_{in}$ ⇒ fuel is $\phi$-sensitive

**Robustness:** $\phi = 0.42$, PM fueling

- For CI only (no SA), $\Delta T_{in} = 3.7^\circ$C from $RI = 5\text{ MW/m}^2$ to COV-IMEP$_g = 2\%$
  - $\Delta T_{in} = 3.7^\circ$C gives a $\Delta CA50 = 7^\circ$ CA
- For SA + CI, can reduce $T_{in}$ & maintain $CA50$ and $RI$ by advancing spark-timing.
  - Limited by large cycle-to-cycle variations; COV suddenly becomes $>> 2\%$.
    - Variability in early-flame propagation
  - $\Delta T_{in} = 21^\circ$C

- Spark assist greatly increases tolerance to $T_{in}$ variation, from 3.7 to 21°C.
- No significant change in $CA50$, $RI$, or $CE$. Slight decrease in NOx ⇒ lower $T_{in}$
Flame Propagation Effect on HRR, $\phi = 0.42$

- First part of HR associated with flame propagation contributes a significant fraction of the total HR.
  - Up to about 15%
- Compression heating caused by the flame combustion appears to compensate for decrease in $T_{in}$
  - Effect is similar to the ITHR for boosted operation with CI.

- Can the flame propagation allow CA50 to be retarded further while maintaining robust combustion (COV-IMEPg < 2%)?
- How much control over CA50 does SA provide?
CA50 Control with Spark Assist

- Spark timing swept at two $T_{in}$s:
  - 117°C ⇒ if no spark, COV-IMEP$_g$ > 5%
  - 107°C ⇒ if no spark, no combustion
- Retard CA50 by retarding spark timing, from RI = 5 MW/m$^2$ to COV-IMEP$_g$ = 2%.

- $T_{in} = 117°C$: CA50 range = 6.5°CA
  - 0.8° ΔCA50 / 1.0° Δspark-timing
- $T_{in} = 107°C$: CA50 range = 2.4°CA

- CA50 range for acceptable SA combustion is smaller for lower $T_{in}$.
- At these conditions: Flame propagation with SA does not allow CA50 to be more retarded than for CI-mode w/o SA (374° CA).
  - Pure CI-mode, has virtually the same CA50 range = 6.4°CA.
- But Spark-Assist gives rapid control.

Reminder:
- $T_{in} = 123°C$ for no spark, RI = 5
- Lowest $T_{in}$ with spark = 102°C
- Max. CA50 retard w/o spark = 374° CA (limited by COV-IMEP$_g$ = 2%)

PM, CF-E0, $P_{in} = 1$ bar, $\phi_m = 0.42$
Collaborations

- Project is conducted in close cooperation with U.S. Industry through the Advanced Engine Combustion (AEC) / HCCI Working Group, under a memorandum of understanding (MOU).
  - Twelve OEMs, Three energy companies, Six national labs, & Several universities.

- General Motors: Bimonthly internet meetings ⇒ in-depth discussions.
  - GM provided 300-bar Bosch HDEV5.1 GDI injector and spark-ignition system.
  - Provide data to GM on boosted LTGC and for modeling PFS-LTGC.

- Cummins, Inc.: Discussions and guidance on working with new low-swirl, spark-plug cylinder heads (Head #2), potential acquisition of Head #3.

- LLNL: Support development and validation of chemical-kinetic mechanism for RD5-87 (87-AKI, E10 gasoline) and related RCM measurements at ANL.

**DOE-OVT project is also leveraged through three related research efforts**

- Co-Optima Fuels Project: Funds-in project of advanced fuels containing a significant renewable fraction for boosted SI and low-T combustion engines.

- Chevron: Funds-in project on advanced petroleum-based fuels for LTGC.

- Sandia LDRD: Funds-in project on fuel injection.
Future Work

● Continue to focus efforts on combustion-timing control & improved robustness, with an emphasis on lower boost (1.0 ≤ $P_{\text{in}}$ ≤ 2.0 bar).

● Use RD5-87 gasoline (regular E10) for now, and reduce CR to 14:1 ⇒ should increase operating range with RD5-87 and more in-line with OEM targets.
  — Map engine performance for CR = 14:1 w/ RD5-87 (will reduce TE 1.0 – 1.5 %-units)

**DDI-PFS with Variable Inj. Timing:** ⇒ CA50 control & multiple other benefits

● Determine the range of conditions for which DDI-PFS can be applied effectively ⇒ range of $P_{\text{in}}$ (down to 1.3 bar?), fueling rates ($\phi_m$), and speed effects.

● Investigate various fueling strategies to improve PFS performance and extend range of application ⇒ vary late-DI timing & fraction, multiple injections, etc.
  — Image fuel distributions in optical engine to guide strategies.
  — Potential of 300 bar GDI injector to improve PFS and its operating range.

**Spark-Assisted (SA) LTGC:** ⇒ CA50 control, etc.

● Map out range of conditions for effective SA-LTGC with CR = 14:1.
  — Determine benefits at $P_{\text{in}}$ = 1.0 bar, and find max. $P_{\text{in}}$ for effective SA.
  — Investigate effect of DI fueling and PFS, speed effects, potential to extend load.

**Continue to support of LTGC/HCCI modeling:** Provide data, analysis, and discussions to support kinetic modeling at LLNL, and CFD modeling at GM.
Summary

- A new spark-plug capable, low-swirl cylinder head has been installed, and it’s combustion performance characterized.
  - Overall performance is similar to previous head, with two exceptions:
    1) For PM fueling, TE is lower by 0.2 – 1.0%-units, due to increased heat transfer.
    2) For early-DI fueling, TE is also reduced at low and high fueling rates due to reduced combustion efficiency caused by less complete fuel/air mixing.
  - High-load limits and CNL are similar for both heads, both PM & DI fueling, all $P_{in}$s.

- Both CF-E0 & RD5-87 are $\phi$-sensitive for $P_{in}$s down to at least 1.3 bar, indicating that the benefits of PFS can be obtained ⇒ RD5-87 better at lower $P_{in}$s.

- Showed injection timing can control CA50 up to 8.6°CA, from strong knock to near misfire, as part of DDI-PFS fueling strategy ⇒ ultra-low NOx & soot.
  - Retard the late-DI timing ⇒ increases stratification ⇒ advances CA50

- Showed that DDI-PFS substantially increases the allowable CA50 range from knock to near misfire. ⇒ It can also increase stability for a significant extension of the load range.

- Spark-Assist was found to be effective for CA50 control & increased $T_{in}$ tolerance for $\phi > 0.36$ at $P_{in} = 1$ bar. ⇒ Complements DDI-PFS, which works $P_{in} \geq 1.3$ bar.

- Collaborated with LLNL on development of a kinetic mechanism for RD5-87 and supported related RCM measurements at ANL, and with GM on CFD modeling.
Technical Backup Slides
Collaboration: Kinetic Mechanism for RD5-87

- RD5-87 is a research-grade 87-AKI, E10 regular gasoline with tightly controlled specifications. ⇒ Representative of market fuels.
- Accurate chemical-kinetic mech. will be valuable for research groups & industry.
- Collaborate with LLNL (W. Pitz & M. Mehl) to support their development of a kinetic mech. for RD5-87, and support related RCM measurements at ANL.
- **SNL**: Engine data recently acquired for RD5-87 for fully premixed operation over a wide range of $P_{in}$ and fueling rates ($\phi_m$).
  - Data to be provided to LLNL for mechanism tuning and validation.
  - Provided fuel to ANL for RCM studies.
  - Discussions with LLNL and feedback on mechanism performance for further improvement.
- **LLNL**: Proposed a chemical-kinetic mechanism based on a 5-component surrogate, matching compositional & octane properties. ⇒ will tune and validate based on SNL engine data and ANL’s RCM data as available.
- **ANL**: RCM data on RD5-87 autoignition.