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

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Annual Merit Review and Peer Evaluation

Program Managers: Gurpreet Singh & Leo Breton
Project ID: ACE004

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
● Increase the efficiency of LTGC / HCCI.
● Extend LTGC / HCCI operating range to higher loads.
● Improve the understanding of in-cylinder processes.

Budget
● Project funded by DOE/VT:
  FY14 – $720k
  FY15 – $680k

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
● Univ. of Calif. Berkeley – CFD modeling
● Univ. of Melbourne – biofuels & analysis methods
● Chevron – advanced fuels for LTGC
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.

FY15 Objectives ⇒ Increased Efficiency, High Loads, Improved Understanding

- **Energy-Loss Distribution:** Determine magnitude of loss terms (heat transfer, combust. inefficiency, exhaust) & how they change with operating conditions. ⇒ Understand the Trade-offs to Improve the Thermal Efficiency
- **DI Partial Fuel Stratification (DI-PFS) for improved Thermal Efficiency (TE):** Systematically evaluate the TE gains possible with DI-PFS for both single and double direct injections ⇒ including various injection strategies for double DI (multi-year task).
- **Fuel-Distribution Imaging:** Apply PLIF imaging in optical eng. to understand how GDI strategies affect $\phi$-distribution, to help optimization (multi-year task)
- **Performance mapping with new low-swirl head:** Compare TE and load range for new cylinder head with data from old head at selected conditions.
- **Support Modeling:** Chemical-kinetics at LLNL & CFD at UC-Berkeley & GM.
Approach

● Use a combination of metal- and optical-engine experiments, analysis and modeling to build a comprehensive understanding of LTGC processes.

● **Metal Engine** ⇒ high-quality performance data ⇒ well-controlled experiments
  - **Energy-Loss Distribution**: Acquire data for several parameter sweeps & analyze.
  - **DI-PFS for increased TE**: Systematically evaluate TE vs. load for multiple fueling strategies ⇒ 1) well-premixed, 2) single-injection DI at two $T_{\text{in}}$s to separate out effect of initial charge $T$, 3) double-injection DI for a range of late DI timings & fuel fractions.

● **Optical Engine** ⇒ detailed investigations of in-cylinder processes.
  - **Fuel Distribution Imaging**: 1) PLIF imaging calibrated in-situ; 2) Vertical laser sheet to see all elevations, 3) Obtain $\phi$-map images for various fuel-injection strategies. ⇒ **Guide application of PFS in metal-engine for higher TE** ⇒ **Model validation**

● **Analytical Techniques** ⇒ Develop & apply 1) duplicate methods for computing energy lost to heat transfer and exhaust, 2) method to determine changes in TE attributable to changes in CA50 & $\gamma$ ⇒ **Guide further TE improvements**

● **Computational Modeling**: 1) Collaborate with UC-B and GM on CFD modeling for improved understanding of PFS. 2) Work with LLNL on kinetic mech. for Cert-fuel.

Combining techniques provides a better understanding & more-optimal solutions

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

- **September 2014**
  Complete installation and shakedown testing of new low-swirl cylinder head
  with spark-assist capability.

  ⇒ **Postponed Milestone until September 2015:** Needed to complete double-
  injection DI-PFS study with the same cylinder head used for previous work.
  ✓ ⇒ New head has now been installed and initial testing is underway.

- **December 2014**
  Prepare and submit a paper on recent results to the SAE International
  Congress.

- **March 2015**
  Determine the magnitude of the various energy losses for LTGC-engine
  operation (combustion inefficiency, heat transfer, and exhaust energy) and
  how they change with operating conditions.

- **June 2015**
  Present an overview of project accomplishments and directions at the DOE
  Annual Merit Review.

- **September 2015**
  Major Milestone - Determine the effectiveness of double-injection fueling
  strategies for reducing the heat-release rate in LTGC engines over a range of
  injection timings and fuel-fraction splits between the two injections.
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

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

* Indicates additional accomplishment not in original objectives.

● Determined magnitude of energy-loss terms (heat transfer, combustion inefficiency, exhaust) & evaluated changes for several parameter sweeps
  – Developed analysis techniques for heat-transfer loss and exhaust loss terms.
  * Developed analysis technique for change in TE attributed to changes in CA50 & $\gamma$.

* Extended heat-transfer analysis technique to developed a more objective & accurate method for determining the onset of knock in LTGC engines.

● Completed an in-depth study of DI-PFS for increased TE using both single and double direct injections.
  – Various GDI timing and fuel-fraction strategies evaluated.
  * Analyze energy-loss terms to explain changes in TE for double-DI strategies.

● On track with PLIF imaging study to understand how changes in GDI injection strategy affect the in-cylinder fuel distribution.
  – Resolved problem with optical engine.

● Facility upgrade ⇒ completed modifications to new cylinder head for low-swirl, 300-bar GDI injector and spark assist, and installed head on engine.
  – On track to complete shakedown tests & performance comparison this FY.

● Collaborated with UC-B and GM on CFD modeling and LLNL on kinetics.
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Energy-Distribution Analysis

- Understanding the reasons for changes in TE with operating conditions is critical for finding ways to improve efficiency.

- Analyze how Energy distribution varies with conditions.
  - Energy-loss terms: 1) combst. inefficiency, 2) heat transfer, 3) Exhaust Loss (EL)
  - Energy shift, Work \( \Rightarrow \) EL: 1) Effective Expansion Ratio (ER), CA50, 2) \( \gamma = \frac{c_p}{c_v} \)

- Heat Transfer computed by two methods:
  1) **Woschni HT correlation** with coeffs. adjusted to make HRR flat before and after combustion.
     \( \Rightarrow \) Also total HR equals energy of burned fuel.
  2) **Exhaust loss and energy closure** \( \Rightarrow \) Exh Loss based on \( T_{EVO} \), corrected for work after EVO.
     \( \Rightarrow \) HT similar for both \( \Rightarrow \) confidence in analysis

- Changes in CA50 and \( \gamma \) directly affect whether energy produces work or is lost to exhaust.
  - Compute changes in TE and EL using ideal Otto-cycle analysis using \( \gamma \) based on real-gas properties averaged over expansion stroke
    \( \Rightarrow \) with CR = Effective ER.

\[
TE = 1 - \frac{1}{CR^\gamma - 1}
\]
Changes in Energy Dist. for $\phi_m$ Sweep

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

For each $\phi_m$, advance CA50 until Ringing Intensity (RI) = 5 MW/m² for max TE w/o knock

- As $\phi_m$ increases, TE increases to a maximum of 49.3%, then decreases.

- Improved Combustion Eff. (CE) explains increase, but not decrease.

- Analysis of energy-loss terms with increasing $\phi_m$ shows:
  - Combustion inefficiency decreases
  - Heat transfer losses decrease
  - Exhaust losses increase significantly
    > Woschni & $T_{EVO}$ methods give similar trends ⇒ Woschni considered more accur.

- Decrease in TE is related to increase Exhaust Losses (EL).
  ⇒ What are the causes?
Contributions to Exhaust Loss for $\phi_m$ Sweep

- CA50 is retarded with increased $\phi_m$ to hold RI = 5 MW/m².
  ⇒ Eff. ER $\downarrow$, Decreases TE & incr. EL
- $\gamma$ decreases with higher $\phi_m$ (T, EGR, TA)
  ⇒ Decreases TE and increases EL
- Lower HT & better CE increase TE & EL
- $\gamma$-effect $>$ CA50-effect on the TE reduction.
- Sum of individually computed terms closely matches EL based on Woschni.
Shift of Energy Distribution over $\phi_m$ Sweep

- “Stacked” plot more clearly shows the shift and reasons for changes in TE.

- Decreased TE for $\phi_m < \phi_m \text{-Max-TE}$ due to:
  - Reduced CE for CA50 after TDC.
  - Increased HT for CA50 before TDC.

- Decreased TE for $\phi_m > \phi_m \text{-Max-TE}$ due to:
  - Lower gamma ($\gamma$) $\Rightarrow \phi_m$, $T_{\text{combustio}}$, and EGR all higher.
  - Lower Exp-Ratio $\Rightarrow$ more retarded CA50 to prevent knock.

- Effect of $\gamma$ dominates over CA50 retard.
- Improved CE and reduced HT mitigate $\gamma$ and CA50 effects.

- Energy distribution analyses also conducted for:
  1) Two CA50 sweeps
  2) $T_{\text{in}}$ sweep
  3) Speed sweep
As load ($\phi_m$) increases, or CA50 advanced, PPRR & RI increase ⇒ RI ~ PPRR$^2$/P$_{max}$.
- Excites acoustic modes of chamber.
- Weak ripples even for low PPRR, but no detrimental consequences.

If acoustic oscillations (Ringing) become too intense ⇒ Distinctive irritating sound ⇒ Commonly known as engine knock.

Criterion required to define knock onset.

Magnitude of ripples ⇒ energy content of 1$^{\text{st}}$ acoustic mode, Knock Integral (KI)

Not always consistent ⇒ sensitive to location of pressure transducer relative to direction of acoustic wave.

A better metric is needed.
Improved Metric for the Onset of Knock

- Previously, selected $RI = 5 \text{ MW/m}^2$ as the maximum RI w/o knock.
  - Based on knocking sound and strong ripples on P-trace $\Rightarrow$ somewhat subject.

**Example:** CA50 sweep at constant $\phi_m$

- As CA50 advanced, RI increases $\Rightarrow$ TE $\uparrow$ due to greater Exp Ratio.
- Also, RI $\uparrow$ due to increased PPRR. $\Rightarrow$ Strong knock at more adv. CA50s.
- KI increases, but no distinct indicator of knock $\Rightarrow$ sensitive to direction of P-osc.
- HT $\uparrow$ at a greater rate for RI > 5
  - P-osc. have associated Vel-osc., HT $\uparrow$
  - Woschni 2nd coeff. indicates combust-induced velocities & captures this effect.

- $C_2$ is a consistent, objective indicator of knock $\Rightarrow$ a spatially integrated measure
- Verified for several param. sweeps $\Rightarrow$ most match RI = 5 MW/m$^2$. 
DI-PFS with Single Injection

- PFS with DI fueling can significantly improve TE and/or max. load.
  - Single DI at 60° CA (DI-60) $\Rightarrow$ mixing is incomplete $\Rightarrow$ gives PFS.
  - PFS reduces HRR if fuel is $\phi$-sensitive.
    $\Rightarrow$ More adv. CA50 or incr. load w/o knock.
  - DI fueling allows lower $T_{in}$ w/o fuel conden.
- Baseline: PreMixed (PM) fueling, $T_{in} = 60^\circ$C
- Single DI-60, $T_{in} = 73^\circ$C to match $T_{BDC}$ of PM with $T_{in} = 60^\circ$C (fuel-vap. cooling).
  - TE $\sim$0.5% $\Rightarrow$ CA50 adv, but not sufficient.
    Perhaps HT $\Rightarrow$ further analysis required.
- Single DI-60, $T_{in} = 40^\circ$C $\Rightarrow$ Lower $T_{in}$ means:
  - PFS more effective $\Rightarrow$ greater CA50 adv.
  - $T_{\text{combust}} \downarrow$, EGR $\downarrow$, $\phi_m \downarrow$ ($\rho \downarrow$) $\Rightarrow$ higher $\gamma$
  - $T_{in} \downarrow$ and $T_{\text{combust}} \downarrow$ $\Rightarrow$ less HT
- Peak TE increases by 1.0 %-units $\Rightarrow$ TE at 13 bar IMEP$_g$ increases 2.5 %-units.
- Substantial TE benefit to Single-DI-PFS w/ lower $T_{in}$ $\Rightarrow$ particularly at high loads.
Double-Injection DI-PFS at $\phi_m = 0.4$

- Can further gains in TE be made by increasing the fuel stratification?

- Double-DI PFS = Early + Late DI injections (DDI-PFS)
  - Hold Early-DI timing constant at 60° CA.
  - Varying timing and fuel fraction of the late-DI injection.

- Although single-DI PFS already reduces Peak PRR & HRR significantly vs. PreMixed ⇒ DDI-PFS gives a much greater reduction.
  - Better optimizes stratification to further slow HR.

- Peak HRR \( \downarrow \) and burn duration \( \uparrow \) progressively with increasing late-DI fraction.
  - Late-DI fraction increased from 8% \( \Rightarrow \) 35% of total fuel \( \Rightarrow \) holding late-DI timing = 305° CA.

- DDI-PFS should allow significant CA50 advancement w/o knock (RI \( \leq \) 5 MW/m²).
  - CA50 advancement will act to improve TE.
CA50 and TE for Double-DI PFS at $\phi_m = 0.4$

- Systematically vary both DI timing and DI fraction.
- CA50 for RI = 5 MW/m² advances progressively as stratification is increased by both:
  - Later late-DI timing
  - Greater late-DI fraction
  - Should increase TE.
- However, max. TE is about the same for all late-DI fractions ≥ 14%.
  - Optimal late-DI timing for each DI%.
- CA50 continues to advance for later DI-timings, acting to improve TE.
- Therefore, other factors must act to reduce TE for these later late-DI timings down to the measured values.
**CE & HT Losses for Double-DI PFS at \( \phi_m = 0.4 \)**

- Combustion Efficiency (CE) for DDI-PFS ⇒ Decreases with greater stratification.
  - Later Late-DI timing & greater Late-DI%
- Due to increased CO from overly rich regions. HC emissions are slightly lower.
  - Smoke is near zero at peak TE points, but rises rapidly for later late-DI timings.
  - NOx increases slightly, but remains more than a factor of 20 below US-2010 stds.
- CE acts opposite CA50 advancement
  - Accounts for about half of discrepancy.
- Apply HT analysis ⇒ found that HT loss increases with increased stratification.
  - Due to adv. CA50 or to injection velocities?
  - Additional studies needed to understand.
- Sum of expct’d TE gain for CA50 + losses from CE & HT closely match expr. TE.
- Explains the limit of the TE improvement.
DI-PFS with Single and Double Injections

- Have shown that Single-DI PFS, $T_{in} = 40^\circ$C substantially increases TE vs. PreMixed.
- D-DI PFS further incr’s TE at higher loads.
  - Later CA50 ⇒ advance w/ PFS ⇒ TE↑.
- No TE gain with D-DI at lower loads where CA50 close to TDC (< ~368°CA).
  - Also, HT↑ mitigates TE gain w/ CA50 adv.
- D-DI PFS acts to further flatten TE vs. load curve ⇒ TE at 13 bar IMEP$_g$ close to TE$_{Peak}$
- Noteworthy that CA50 advancement w/ D-DI PFS could give even greater TE gains if increase in HT & CE loss could be mitigated.
  - More-optimized strat. ⇒ likely reduce CE loss.
- D-DI PFS could also incr. max load if not O$_2$ ltd.
- Further gains likely at other oper. conditions and with regular gasoline, AKI 88 (RON 91).
  - Current data for E0-Cert fuel, AKI 93 (RON 97)
Response to Reviewer Comments

1. Reviewers made many positive comments. ⇒ We thank the reviewers.

2. Several comments supported the CFD modeling work, requested more details, mentioned model validation, and use of the models to guide PFS optimization.
   - CFD modeling can provide an important complement to expr. work. However, the models currently show limited agreement w/ experiment ⇒ See Backup Slides for FY14 & FY15.
   - Does not seem valuable to provide more-detailed results until models are improved for better agreement. ⇒ Currently, kinetic submodels appear to be a key problem.
   - We plan to compare fuel-distribution images w/ model as become available. ⇒ Will help model validation. Unclear if models will be accurate enough to guide expr. as hoped.
   - A difficulty is that the modeling effort has limited resources and is not directly linked with our expr. program. ⇒ Progress could likely be improved with in-house modeling effort.

3. Will future work investigate more than two injections? - Yes
   - The best PFS performance requires a high level of stratification w/o overly rich regions that produce CO & reduce CE, as can occur with only two injections ⇒ see previous slides.
   - Three or more injections offer the potential to better tune the mixture distribution. We plan to investigate this in combination with PLIF imaging, and multi-zone kinetic modeling to help determine desired distribution. CFD may also be used to guide if results can be improved.

4. Practical considerations – est. brake TE, required turbo eff, transient controls.
   - Current work is on fundamentals of PFS mixture ⇒ As we move to new studies of high-load and TE limits with regular E10, we will apply turbo and friction models for est. brake TE.
   - Combust. ctrl. systems can require substantial resources ⇒ OEMs? However, we do have plans to study potential of Spark Assist for ctrl. & use of small late fuel injection as a trigger.
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.
  - Provide data to GM on boosted LTGC and for modeling PFS-LTGC.

- **Cummins, Inc.**: Design & fabrication of low-swirl, spark-plug cylinder heads.

- **LLNL**: Support the development and validation of a chemical-kinetic mechanism for Certification Gasoline (CF-E0), Pitz *et al*.

- **U. of California - Berkeley**: Collaborate on CFD modeling of PFS-LTGC.

- **U. of Melbourne, Australia**: Collaborate on analysis methods. Patent application filed on new biofuels.

- **Chevron**: **Funds-In project** on advanced petroleum-based fuels for LTGC.
Future Work

Extend Operating Range of PFS-LTGC (multi-year task)
- Evaluate potential for extending the benefits of PFS over a wider load & speed range by using E10 regular gasoline and reducing the CR to 14:1.
  - Research-grade regular E10 reactivity > current Cert-Fuel (AKI = 88 vs. 93)
  - Analysis indicates that these changes will increase load range for PFS
  - Changes more in-line with OEM targets, but will reduce TE ~1.0 to 1.5 %-units.
- Investigate multiple-injection strategies to better optimize PFS for this config.
- Image fuel distributions in optical engine to guide fuel-injection strategies.
- Guidance from multi-zone kinetic models on desired fuel dist., & CFD if practical

Apply New Capabilities and Analysis Techniques
- Potential of 300 bar GDI injector to improve PFS, & late injection for control.
- Parameter sweeps to study range of conditions w/ potential for spark-assist ctrl.
- Heat-transfer analysis to understand cause of tradeoffs with fueling strategies.
- Apply turbo-charger and friction models from GM to evaluate these effects.

Support of LTGC/HCCI Modeling
- Continue to provide data, analysis, and discussions to support: 1) kinetic modeling at LLNL, and 2) CFD modeling at UC-Berkeley and GM.
Summary

- Developed analysis techniques to compute the heat transfer and exhaust losses independently. ⇒ Used energy-closure to show they agreed well.
  - Also developed technique to compute the energy shift between TE & Exh-Loss for changes in CA50 and $\gamma$. ⇒ Showed that it gives a very good energy closure.

- Applied these techniques to determine the shift in energy distribution over a fueling rate ($\phi_m$) sweep, and sweeps of CA50, $T_{in}$, & engine speed. ⇒ Understanding the tradeoffs helps guide further TE improvements.

- Discovered that changes in Woschni 2nd HT coefficient give a consistent, objective indicator of knock onset. ⇒ Verified for several parameter sweeps.

- Investigation of Single-DI PFS with injection early in intake stroke showed:
  - TE ~0.5 %-units above Premixed, even with higher $T_{in}$ to match $T_{BDC}$ of Premix
  - Much larger TE improvement w/ $T_{in} = 40^\circ C$ ⇒ higher $\gamma$, less HT, more adv CA50

- Conducted an in-depth study of Double-DI PFS ⇒ Early + Late DI inj.
  - Can greatly increase strat. for a large reduction in HRR and large CA50 adv.
  - Lower CE & increased HT can mitigate the large TE gain from CA50 advance ⇒ but Double-DI PFS still significantly improves TE at higher loads.

- Collaborated with CFD modelers at UC-B & GM on PFS, & chemical-kinetic modelers at LLNL on certification gasoline ⇒ see Technical B-up Slides
Technical Backup Slides
Collaborators: Pitz and Mehl ⇒ Worked on the development of a mechanism for zero-ethanol Certification Gasoline (CF-E0) from Haltermann (97 RON, 93 AKI).
- CF-E0 is widely used by industry for certifying performance and emissions of gasoline spark-ignition automobiles.

CF-E0 used for Sandia LTGC experiments, FY13 – FY15. ⇒ Data for model validation.

LLNL developed a chemical-kinetic mechanism based on a 5-component surrogate.
- Toluene + branched & straight-chain alkanes.

Mechanism transferred to UC-Berkeley for CFD modeling of PFS with CF-E0.
- UC-B reduced mechanism to 250 species for CFD.

Provided experimental LTGC-PFS data using CF-E0 to UC-B for CFD modeling. ⇒ See next slide for UC-B collaboration.
UC-Berkeley Collaboration – CFD Model of PFS

- Collaborators: Dr. Ben Wolk & Prof. J-Y Chen (funding DOE-NSF grant).
  - Supplied and explained expr. PFS data and engine geometry for grid development.
  - Guide interpretation of modeling results and give feedback for improvement.

- FY15 work focused on standard PFS (premixed + late DI): DI timing sweep w/ 13% DI fueling.
  - Model captures comb. timing, but not HRR shape.
    - too much early HR even for Premixed (PM).
  - Analysis shows this is from kinetic mech., not CFD.

- Kinetic mechanism does correctly capture sequential autoig. from richest to leanest zones.

- Efforts underway to determine if problem is in basic mech., or the result of reducing mech. for CFD.

- Also working on another dataset for PFS with CF-E0 (Cert. Fuel).