OAK RIDGE National Laboratory

Advanced Combustion Concepts for High-Efficiency Gasoline Engines

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ORNL is managed by UT-Battelle, LLC
for the US Department of Energy

Project ID: ACE127

U.S. DEPARTMENT OF ENERGY

ACE127 Overview: Advanced Combustion Concepts for High-Efficiency Gasoline Engines

3 new projects reviewed together in FY 19 setting stage for DOE Combustion Consortium

Timeline

- FY 19-21 project plan from VTO Lab Call
- 3 projects will end in FY 19 in current form
- Set stage for DOE Combustion Consortium projects

Barriers*

- Goal: A 25% improvement in part-load engine efficiency compared to a 2010 baseline…
- Robust lean-burn and EGR-diluted combustion technology and controls…
- Determine the factors limiting range of LTC /develop methods for extending the limits

Budget

Task	FY19
High-dilution/lean overexpanded combustion systems - Splitter	$100k
LTC multimode and autoignition combustion fundamentals - Curran	$100K
Abnormal combustion and instability characterization and mitigation – Kaul	$50K

Partners / Interactions

Regular status reports to DOE

Industry technical teams, DOE working groups, and one-on-one interactions – AEC MOU, IEA combustion task

Industry: General motors, LSM

Universities: U. Wisconsin, MUST

DOE Labs: SNL, ANL

VTO: Other ACES projects, Fuel Lube Tech./Co-Optima projects

*https://www.energy.gov/sites/prod/files/2018/03/f49/ACEC_TT_Roadmap_2018.pdf

Relevance and Project Objectives

Overall objective

Improve the efficiency and robustness of advanced combustion engines under part-load and high-load operation to enable much higher fuel economy than is now possible

In-Cylinder Processes for Dilute Gasoline Combustion

- To assess the potential of an overexpanded cycle with a high stroke-to-bore ratio to improve part-load and high-load engine efficiency and emissions performance through increased dilution tolerance for SI and LTC operation
- To improve the fundamental understanding of autoignition for expanding the operational range of high-efficiency LTC while preserving boosted SI operation

Diagnostics for New Physical Understandings

- To develop and make use of new tools based on nonlinear dynamics to identify and characterize instability mechanisms and precursors to abnormal combustion and dynamical trends important for prediction and mitigation

Tasks provide foundational knowledge discovery required to eliminate or overcome long-standing barriers to meeting and surpassing the program fuel economy goal while meeting or outperforming emissions regulations

Milestones for FY 19 and FY 20

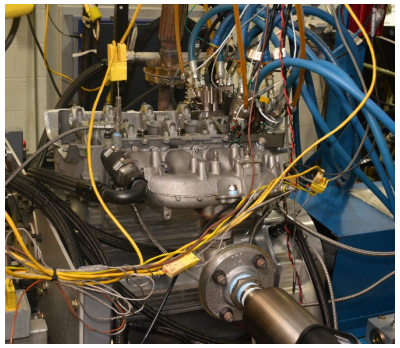
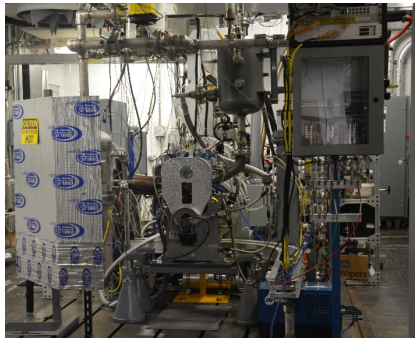
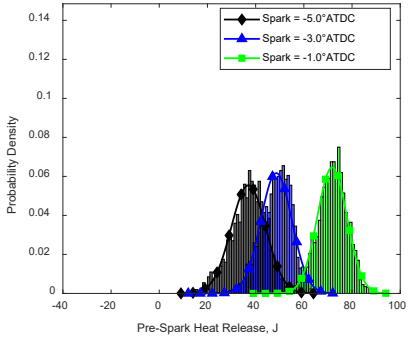
All current milestones met or- new milestones will be determined as part of combustion consortium planning

Month/Year	Description of Milestone	Status
Dec. 2018	Characterize cyclic variability of pre-spark heat release (PSHR) phenomenon and identify any observable dynamics in PSHR variations.	**Met**
March 2019	Identify limits of LTC operation for multimode ACI operation and critical factors based on pressure– temperature trajectory analysis	**Met**
FY 2020	TBD – Future Milestones will be part of Combustion Consortium	TBD

Overall Technical Approach:

Two unique metal engine experimental platforms and advanced analysis methods/tools that work to achieve the overall project objectives

Previous research has historically focused on peak engine efficiency, meeting the fuel economy program goal and beyond will require a **strong focus on part-load operation**, where

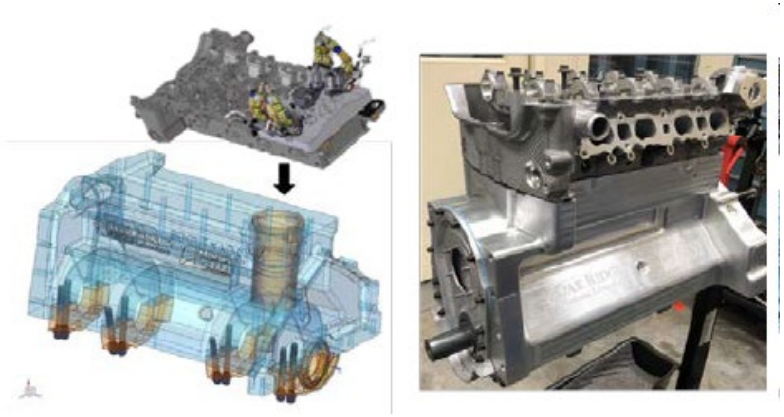
High-dilution/lean over-expanded combustion systems	LTC multimode and autoignition combustion fundamentals	Abnormal combustion and instability characterization and mitigation
		
Custom long-stroke SI **SCE** with hydraulic variable valve actuation allowing enhanced mixing	GM **SCE** (SG2 Head) well suited for SI/ multi-mode mode research	**Advanced tools** based on nonlinear dynamics to identify and characterize abnormal combustion

DOE Combustion Consortium Projects

Approach: High-dilution/lean over-expanded combustion systems

Objective: To assess the potential of an overexpanded cycle with a high stroke-to-bore rat to improve part-load and high-load engine efficiency and emissions performance through increased dilution tolerance for SI and LTC operation

End-of-Project Goal: Demonstrate dilution tolerance and performance improvements across the engine operational range as compared to the 2015 baseline program goal reference.



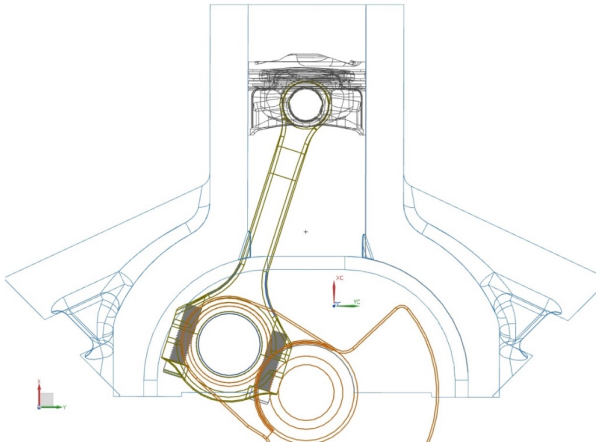
The high-compression-ratio, high-turbulence single-cylinder research engine has a stroke-to-bore ratio of 1.5:1 and an infinitely variable hydraulic valvetrain.

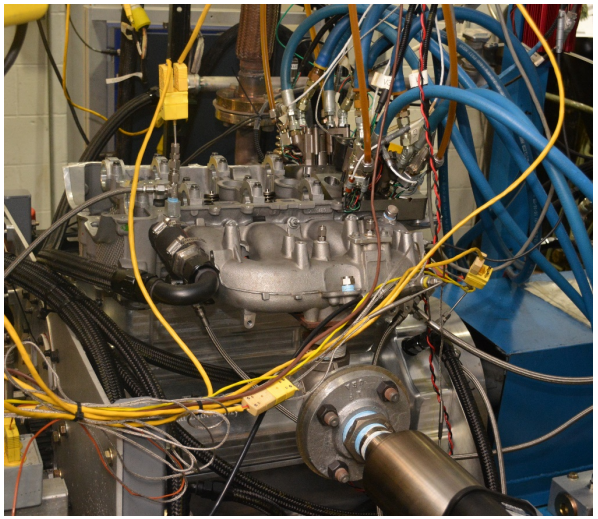
Expected Outcomes.

- Provide fundamental characterization of dilute combustion potential in the P-T domain to characterize the efficiency potential of overexpanded cycle and high stroke-to-bore ratio for SI and LTC operation to enable higher overall drive-cycle efficiency.

Accomplishment: Long-stroke research engine installed and operational

- Infinity variable valve timing and duration
  - Multiple valve events per cycle
- Full control of all pressures and temperatures
- Driven based engine controller
- Stock ignition system
- Cooled EGR
- Multiple compression ratios available
  - 13.3:1-20.5:1



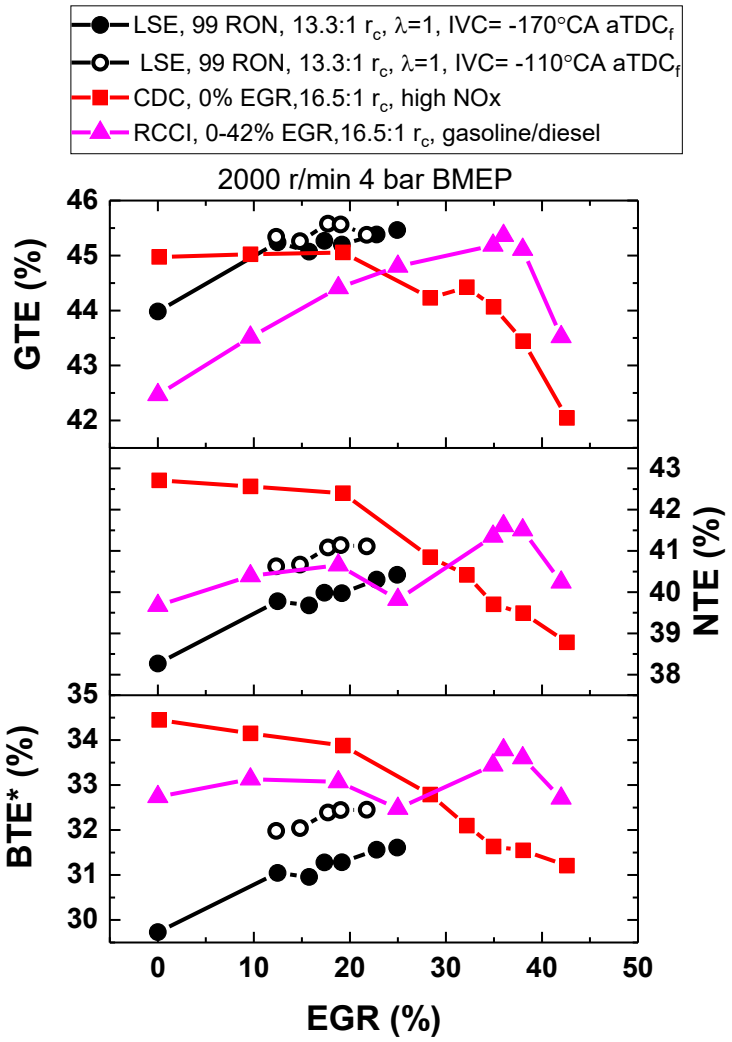


S/B ratio of 1.5 requires
- 129 mm (5.08”) stroke
- 86 mm bore (stock GM LNF)

TDC geometry is matched to stock engine
- Static r_c ~13.3:1 (stock 9.2:1)
- piston blanks available for later piston bowl and increased r_c work

Accomplishment: 4 bar BMEP 2000 r/min LSE data is BTE*/NTE/GTE Competitive to CDC and RCCI

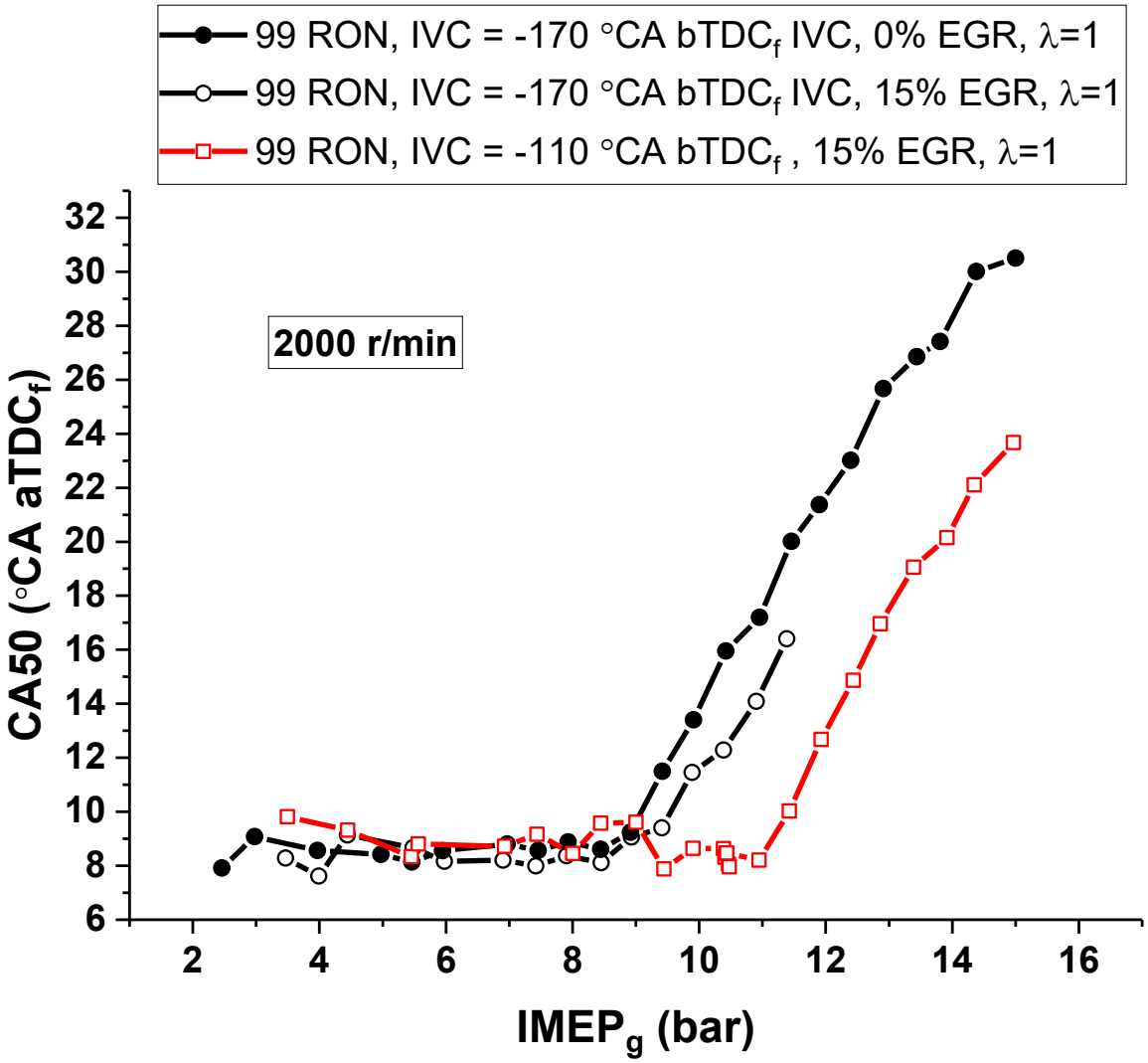
- ORNL efficiency projects on production engine
- 2000 r/min 4 bar BMEP point
  - 1.9L GM engine (European model)
  - CDC is high NOx maximum efficiency operation (not Euro V)
  - Dual fuel modified for RCCI
    - PFI gasoline, common rail DI ULSD
- LSE data exhibits very competitive results at this condition
  - Extent of late IVC and EGR not fully explored



*BTE estimated for SCE

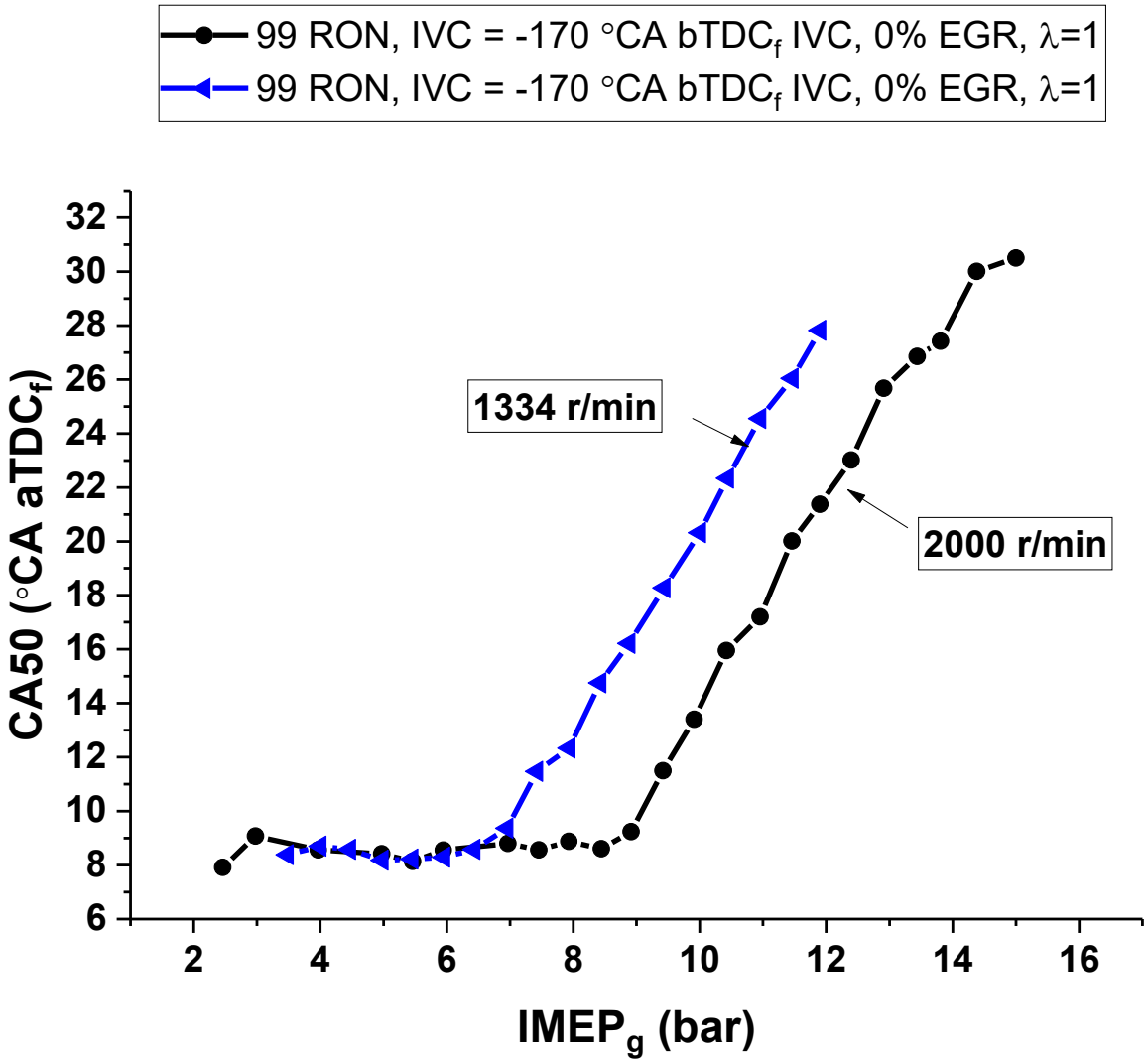
Accomplishment: EGR Offers Minimal Knock Improvement at this r_c, Late IVC+EGR Offers More Benefit

- At boosted conditions EGR offers no significant advantage in knock mitigation
- Late IVC offers much more knock mitigation advantage
  - Pressure-Temperature effect on ignition improved with IVC



Accomplishment: INITIAL ORNL Data Suggests that Minimal Speed Effect on KLSA

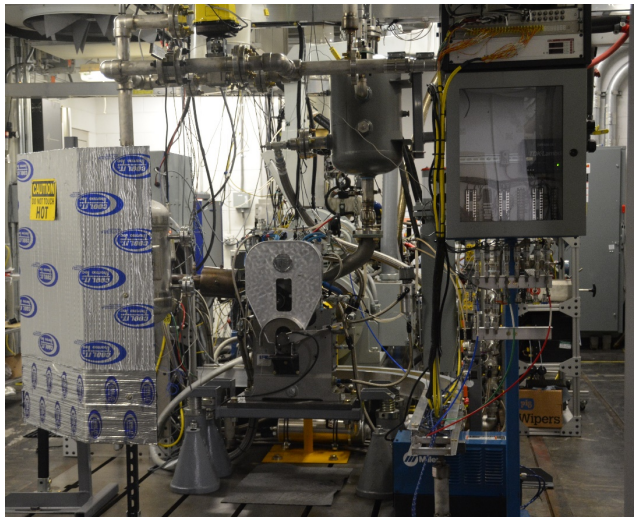
- 0% EGR used
  - EGR effects are part of ongoing work
  - Critical effect of EGR at reducing ignition delay in unbooted/low boost conditions are of critical interested to project, next steps of this work



Approach: LTC multi-mode and autoignition combustion fundamentals

Objective: To improve the fundamental understanding of autoignition for expanding the operational range of high-efficiency LTC while preserving boosted SI operation.

End-of-Project Goal: Demonstrate improvements in part-load engine efficiency with LTC operation while maintaining or improving the high-load engine efficiency advantages of boosted SI operation and provide fundamental knowledge discovery of autoignition fundamentals critical to expanding LTC operation.

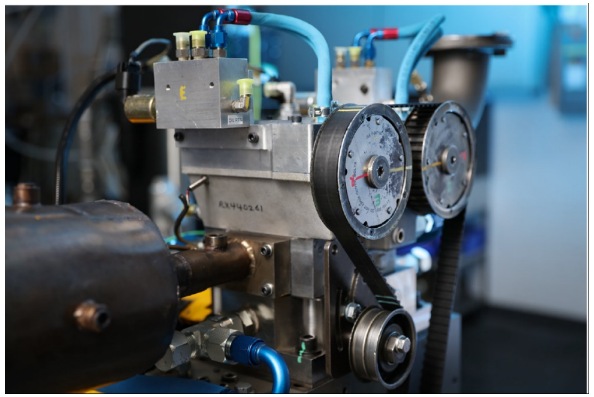


GM SG2 MM SCE

Expected Outcomes:

- Provide fundamental knowledge discovery of autoignition fundamentals and demonstrate improved part-load engine efficiency improvements with LTC operation while maintaining the high-load engine efficiency advantages of boosted SI operation.

Accomplishments/ Progress: Multi-mode engine installed and operational



CR (-) - base	12.1:1
Disp. (L)	0.55
Bore x Stroke (mm x mm)	86 x 94.6
Injection	DI (central)

- Metal GM SCE (SG2 head) well suited for multi-mode operation
- Advanced cam authority, adv. ignition system
  - trapped residuals, partial fuel stratification+
- ACEC cold-start protocol ready

Engine experiments underway

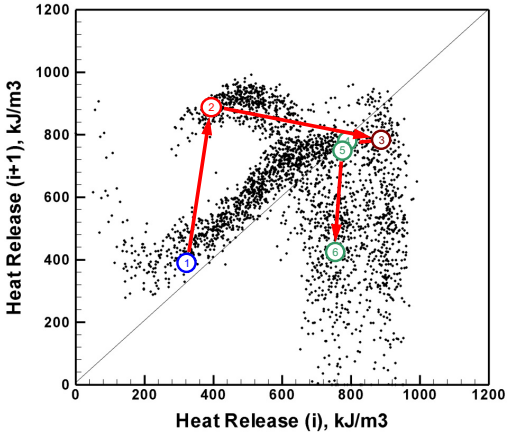
- Exploring trapped residual authority, beyond MON operation capabilities, stability limits and

Approach: Abnormal combustion and instability characterization and mitigation

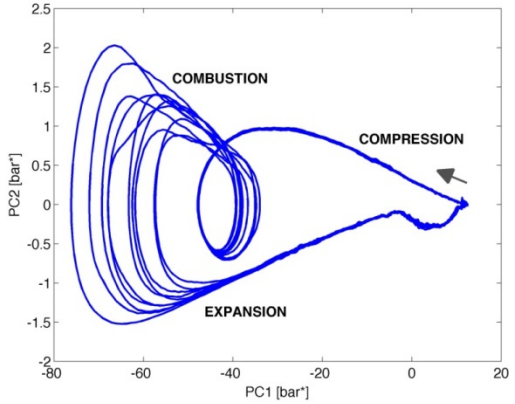
Objective: To develop and make use of new tools based on nonlinear dynamics to identify and characterize instability mechanisms and precursors to abnormal combustion and dynamical trends important for prediction and mitigation.

End-of-Project Goal: Demonstrate potential of new understanding of abnormal combustion and cyclic variability to enable the development and implementation of mitigation strategies for expanding the operational range of part-load high-efficiency combustion.

- Use **information theory** to **identify and characterize deterministic structure** in cyclic variability and precursors to abnormal combustion events
- **Collaborate with experimental combustion researc**h tasks to define mitigation strategies to push stable boundaries of advanced combustion
- **Assess mitigation strategies** in context of multi-mode combustion strategies



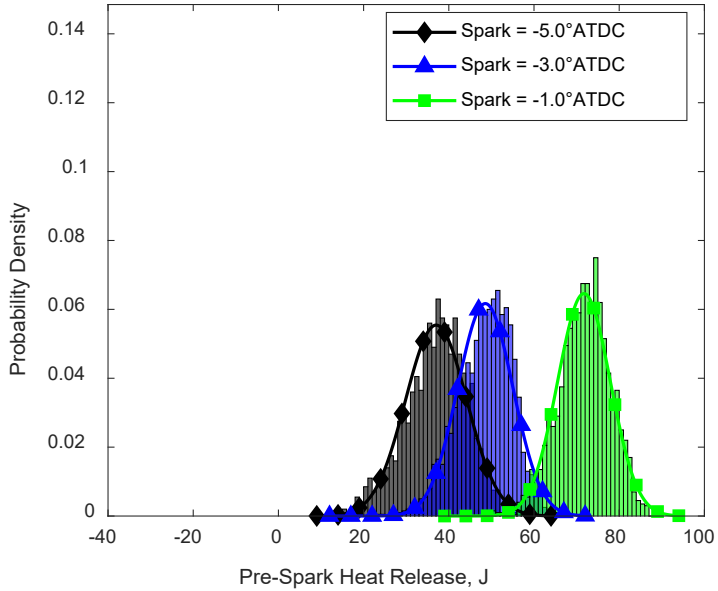
*Example of complex but **short-term predictable** patterns in spark assisted HCCI combustion*

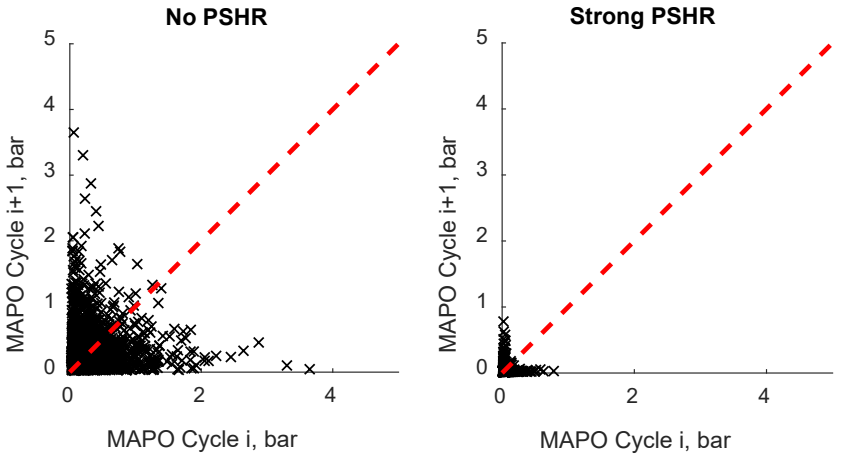


*Example phase-space reconstruction which is one method that has potential for **prediction and avoidance** of abnormal combustion events*

Accomplishments/progress: Abnormal combustion and instability characterization and mitigation

- Prior work[1] indicates impact of pre-spark heat release (PSHR) on knock limit: cycle-resolved dynamics investigated here
- Variations in magnitude of PSHR are stochastic and normally distributed at all operating conditions where PSHR was observed
- No correlation was found between magnitude of PSHR and knock onset timing or Maximum Amplitude of Pressure Oscillations (MAPO)
- Cyclic variations in knock do not exhibit apparent dynamical structure with or without PSHR





1. Splitter DA, Gilliam A, Szybist J, Ghandhi J. Effects of pre-spark heat release on engine knock limit. Proceedings of the Combustion Institute (37)4:4893-4900, 2018. doi:10.1016/j.proci.2018.05.145

Reviewer Comments

New projects – not previously reviewed in FY 18

Collaboration and Coordination

Leveraging Collaborations:

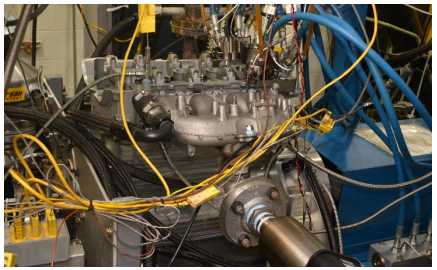
- **Unique research engine platforms and tools being used across DOE and Strategic Partnership Projects**

15 Industry partners in the AEC MOU

- **Meet two times a year to share information with industry partners**
- **Other national labs and University partners as well**

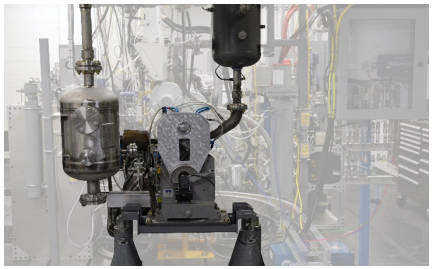
High-dilution/lean over-expanded combustion systems

- Informal discussions with Toyota
- Potential to leverage platform for other projects



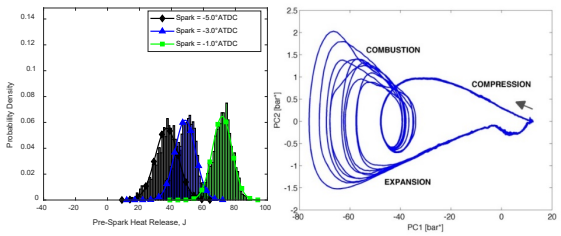
LTC multimode and autoignition combustion fundamentals

- **General motors** – provided engine
- Co-Optima and ACES projects – platform being leveraged across other DOE projects
- SNL – Coordination with similar head
- U. Wisc – Coordination
- LLNL - Russell Whitesides, Scott Wagnon, Bill Pitz – kinetics modeling



Abnormal combustion and instability characterization and mitigation

- Missouri University of Science & Technology – research collaboration including planning of joint papers
- Other national labs in Combustion Consortium (planned)



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Remaining Challenges and Barriers

Remaining challenges and barriers being addressed in remainder of FY 19 and will be addressed in Combustion Consortium project plans

- **Barriers that require improvements in physical understanding**
  - Autoignition processes, high-dilution combustion, reduction in cyclic variability,
  - Formation of combustion emissions and minimization of carbon monoxide and unburned hydrocarbon emissions, and
  - New approaches to higher engine efficiency for part-load operation while maintaining or improving high-load operation
- **Barriers that require new diagnostics for new physical understanding**
  - Developing new physical understandings to guide design and to inform predictive modeling.
  - Diagnostics with the longer-term potential to be done under real boundary conditions in a firing metal engine.
  - Fundamental research on abnormal combustion and cyclic variability, which are both barriers to the development of modern high-dilution engines

Proposed Future Work*

*Any proposed future work is subject to change based on funding levels.

Task Specific Future Work Remainder of FY 19

High-dilution/lean over-expanded combustion systems

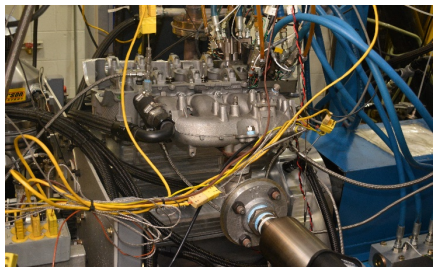
- Leveraging propane project
- detailed particulate study
- Efficiency comparison to CDC, RCCI, SI reforming, and SI.
- Increased compression ratio to come later in FY.C
- Complete papers on initial scope of work

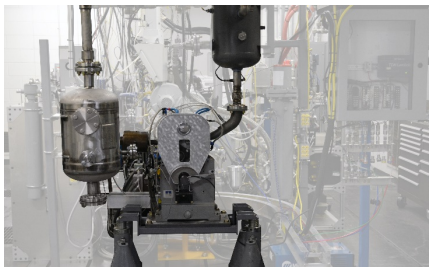
LTC multimode and autoignition combustion fundamentals

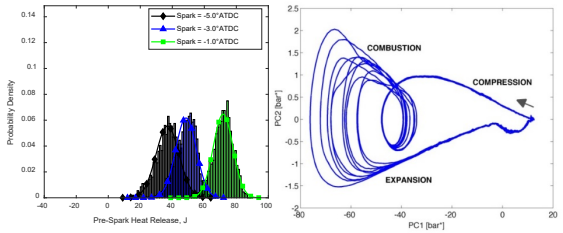
- Multi-mode experiments are on going
- Complete pressure-temperature trajectory paper

Abnormal combustion and instability characterization and mitigation

- Details on next slide



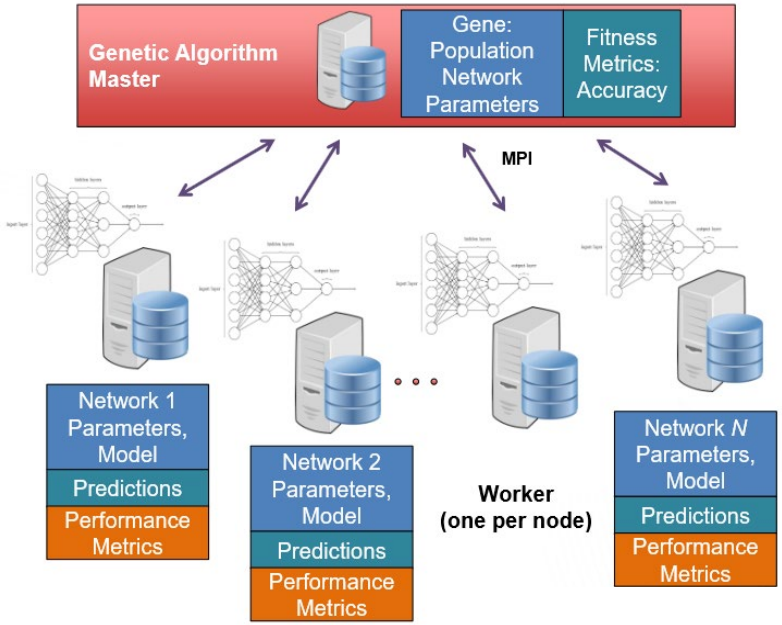




Proposed future work (in Combustion Consortium)

- **FY19**: Evaluate existing LSPI data sets to improve understanding of dynamics and develop methods for improved detection and potential precursor identification

- **FY20**: Leverage results from ORNL LDRD project which is **developing machine learning algorithms for next-cycle prediction** of dilute limit cyclic variability
  - **Implement algorithms for combustion instability prediction**
  - Evaluate efficacy for enabling next-cycle control for combustion stability improvement at the dilute limit

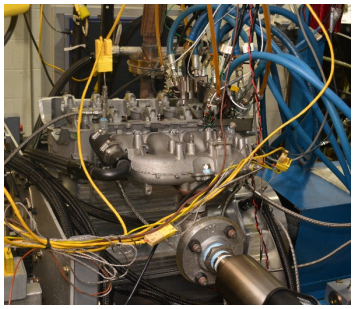


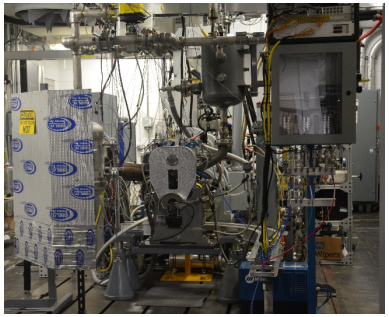
- **Future:** evaluate experimental data generated within **Combustion Consortium** using **machine learning, statistical model, and nonlinear dynamics approaches** to enable advanced combustion control strategies which mitigate abnormal combustion and/or control CA50 in ACI modes

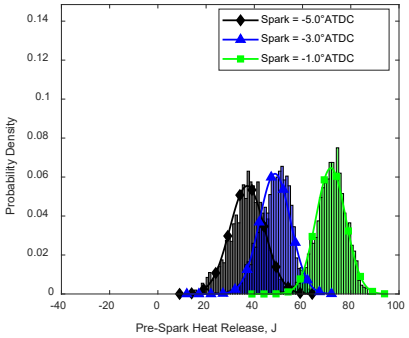
*Any proposed future work is subject to change based on funding levels.

ACE127 Summary

- Relevance
  - Improve the efficiency and robustness of advanced combustion engines under part-load and high-load operation to enable much higher fuel economy than is now possible.
- Approach/Strategy
  - Two unique metal engine experimental platforms and advanced analysis methods/tools that work to achieve the overall project objectives
- Technical Accomplishments
  - Longstroke engine running + experimental results
  - Multi-mode engine running + pressure temperature trajectory analysis
  - Machine learning approach from prior work in abnormal combustion and instability characterization and mitigation
- Collaboration and Coordination
  - Industry and Tech Teams
  - University and National lab partners
- Proposed future work
  - Completion of FY 19 work
  - Transition machine learning to combustion consortium







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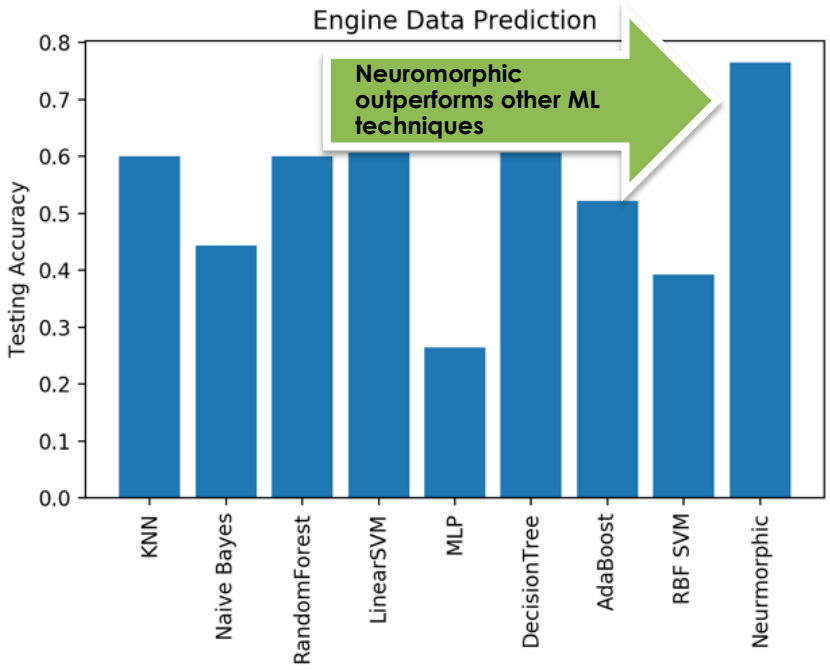
Technical Backup Slides

1. ML – 1
2. ML – 2

Neuromorphic computing for engine data analysis

- Our goal is to predict next-cycle instabilities in order to improve fuel efficiency
- Preliminary results indicate that neuromorphic systems are well-suited to process the engine time series data for prediction
- We are optimizing neuromorphic systems to achieve high accuracy, small size, and low power



Goal: use model or ML-based prediction to enable combustion stability control for dilute-limit SI combustion