STRETCH EFFICIENCY FOR COMBUSTION ENGINES: EXPLOITING NEW COMBUSTION REGIMES

PROJECT ID: ACE015

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June 10th, 2015

DOE Management Team
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Project Overview

Barriers (MYPP 2011-2015, Section 2.4, Challenges and Barriers C.)

Lack of fundamental knowledge of advanced engine combustion regimes.

…inadequate understanding of the fundamentals of thermodynamic combustion losses

…inadequate capability to accurately simulate these processes

Budget

- FY13: $350k
- FY14: $300k
- FY15: $300k

Project Timeline

- ***Stretch Efficiency research program started at ORNL in 2005***
  - ***Initiated current focus on thermochemical recuperation in 2011***
- ***Investigations have evolved based on comments from previous AMR reviews and will continue to evolve with emerging needs***

Industrial Partnerships and Collaboration

- ***AEC working group led by SNL***
  - ***Mechanism for industry feedback***
- ***SNL – Isaac Ekoto***
- ***Gas Technology Institute***

Universities

- ***University of Michigan - Galen Fisher***
- ***University of Minnesota – Will Northrop***

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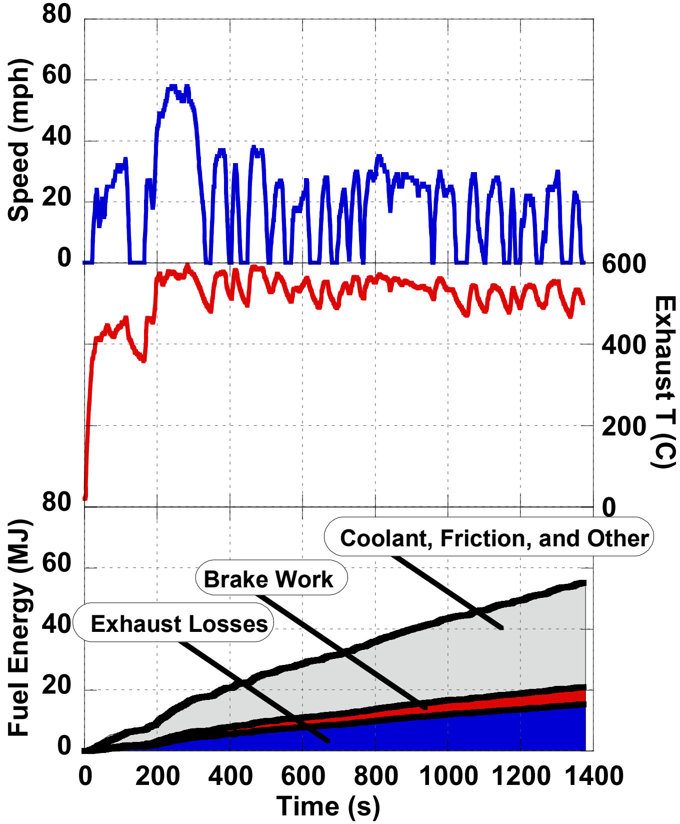
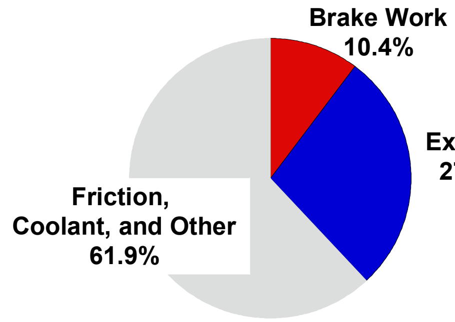
PURSUING THERMODYNAMIC STRATEGIES THAT COULD PROVIDE AN INCREASE IN EFFICIENCY THAT IS REVOLUTIONARY

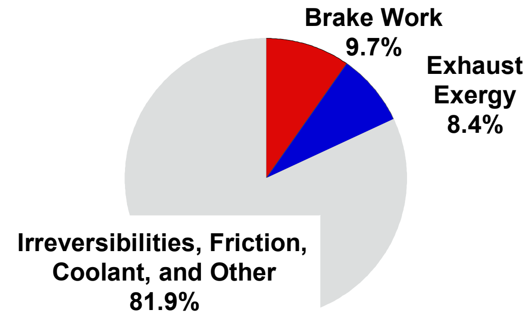


UDDS drive cycle for a 2007 Saab Biopower vehicle
Experimental data collected at the ORNL vehicle laboratory

1st Law Basis



2nd Law Basis

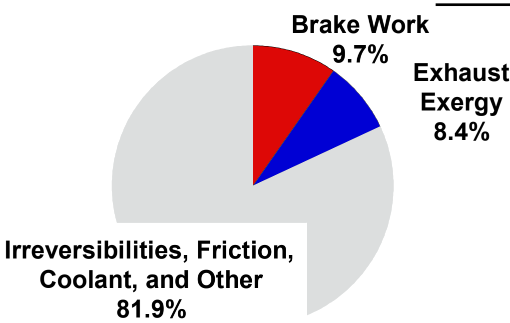


- In this light-duty example, about 10% of the fuel energy was converted to brake work
- Nearly as much usable work potential (exergy) was in the hot exhaust stream

Project Goals
1. **Increase brake work directly**
2. **Recover work from the exhaust**

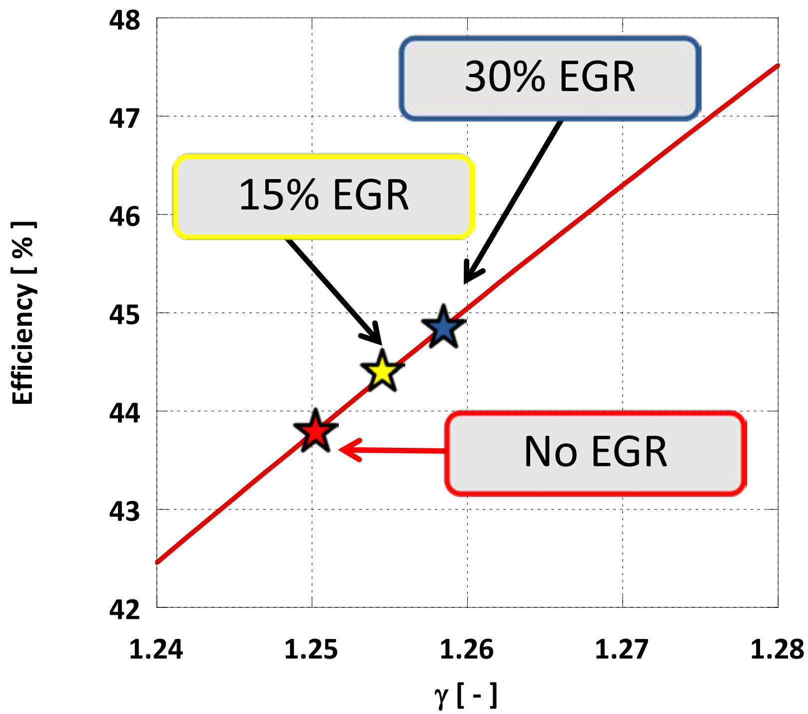
Pursuing Thermodynamic Strategies that could provide an increase in Efficiency that is Revolutionary

2nd Law Basis



Increasing Brake Work Directly Through Dilute Combustion

Higher Effective γ through Expansion Provides Real Efficiency Benefits



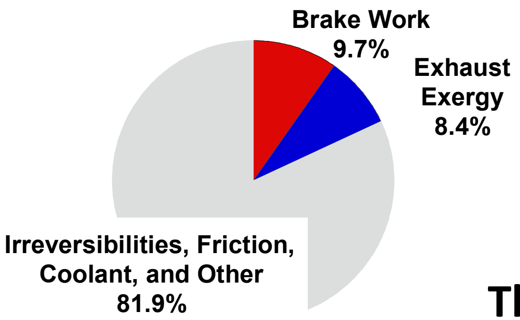
- Theoretical gross efficiency benefit of 30% EGR is approximately equivalent to raising compression ratio from 10:1 to 11:1
- Additional net efficiency benefits through reduced heat loss and pumping

Ideal Gross Otto Cycle Efficiency

$$\eta_{thermal} = 1 - \left(\frac{1}{r_c^{(\gamma-1)}}\right)$$

PURSUING THERMODYNAMIC STRATEGIES THAT COULD PROVIDE AN INCREASE IN EFFICIENCY THAT IS REVOLUTIONARY

2nd Law Basis



THERMOCHEMICAL RECUPERATION FOR EXHAUST HEAT RECOVERY

Thermochemical recuperation converts exhaust heat to usable chemical energy by providing heat for endothermic reactions

	Reforming Reaction	LHV Increase	Exergy Increase
Octane	$C_8H_{18} + 8H_2O \rightarrow 8CO + 17\ H_2$	25%	14%
Ethanol	$C_2H_5OH + H_2O \rightarrow 2\ CO + 4H_2$	24%	9%

- **Reforming supports dilute combustion because H_2 allows the dilution limit to be extended prior to combustion instability**
- **Goal is to achieve exhaust heat recovery with a single work conversion device!**

THIS PROJECT HAS A TRACKED MILESTONE FOR EACH QUARTER OF FY15

FIRST QUARTER, FY2014

Characterize the performance and sulfur tolerance of a rhodium-based reforming catalyst under steam reforming and partial oxidation conditions.

Status: Complete

SECOND QUARTER, FY2014

Speciate the composition of in-cylinder reformate on the flexible ORNL TCR research engine using an FTIR and a mass spectrometer.

Status: Complete

THIRD QUARTER, FY2014

Measure the best brake thermal efficiency from the in-cylinder reforming strategy and compare to conventional SI combustion.

Status: Complete

FOURTH QUARTER, FY2014

Integrate EGR-loop catalyst onto engine and collect baseline data.

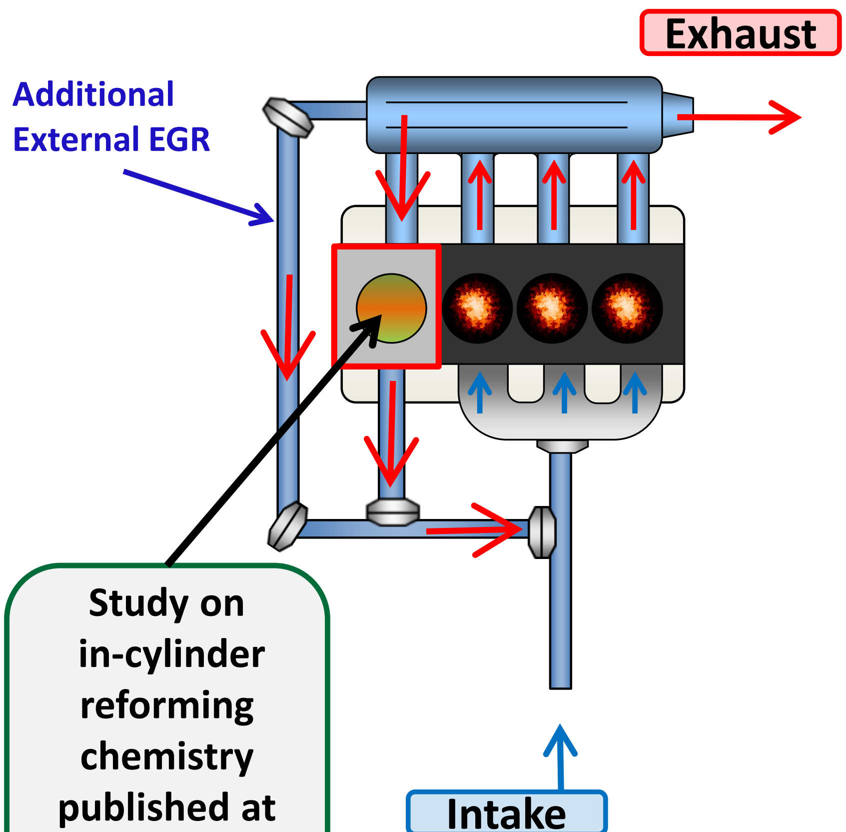
Status: On-track

PURSUING REFORMATE-ASSISTED DILUTE SI COMBUSTION THROUGH TWO PARALLEL STRATEGIES

APPROACH (1/2)

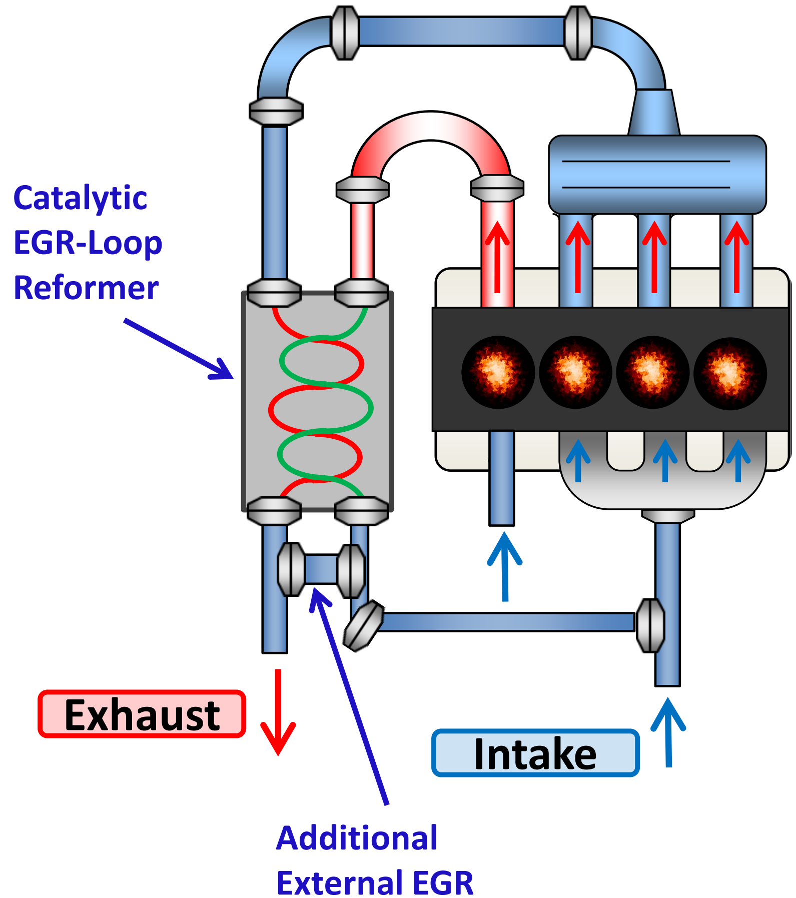
Flexible Hydraulic Valve Actuation for Cylinder 4 Enables Both Strategies to be Investigated on the same Experimental Engine Platform

In-Cylinder Reforming



Study on in-cylinder reforming chemistry published at 2014 SAE

EGR-Loop Reforming

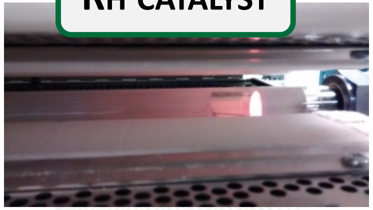


Flow Reactor Used to Evaluate Catalyst Performance and Durability Prior to Engine Experiments

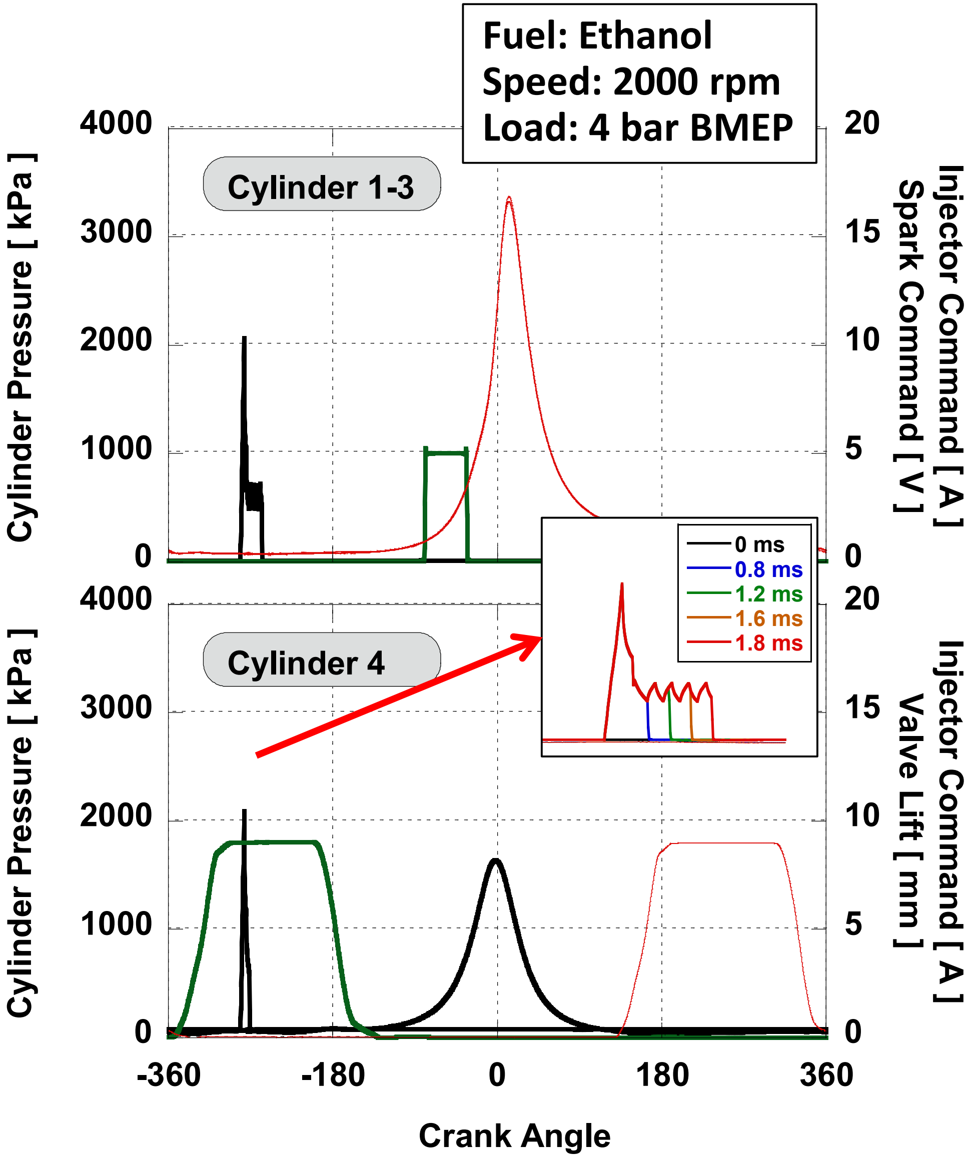
- EGR operating environment varies significantly from typical industrial steam reforming applications
  - water concentration fixed by engine stoichiometry, dilution
  - lower operating temperatures and pressures
  - sulfur from fuels and lubricants
- Currently focused on a pre-commercial Rh-based catalyst
  - previously showed Ni/Rh catalyst extremely sensitive to sulfur
  - Galen Fisher (University of Michigan) advising on catalyst formulation and operating conditions through subcontract
- Modified flow reactor experiments to more closely resemble anticipated engine operation
  - moved catalyst outside furnace heated zone
  - using liquid fuels: iso-octane, ethanol, gasoline
  - holding flows of H_2O, CO_2, N_2 fixed
    - adjusting steam/carbon ratio by changing fuel dosing
    - adjust oxygen/carbon ratio by adding air

Flow Reactor

Rh catalyst

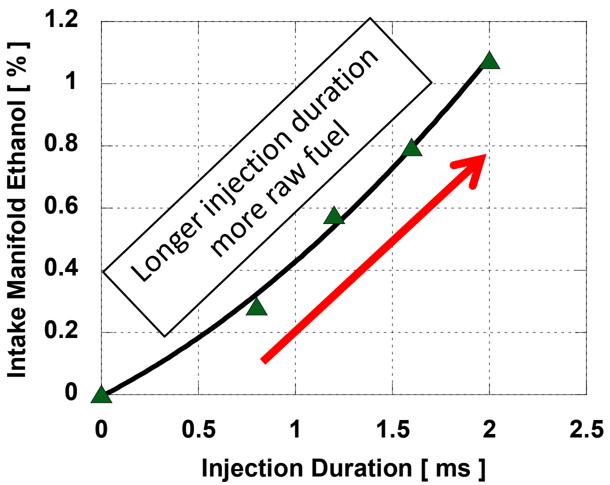


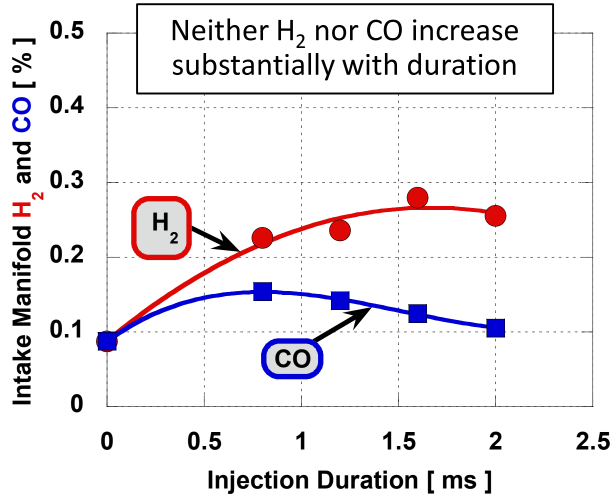
Fuel Injection Duration Sweep Demonstrates the Functionality of the Flexible Engine System

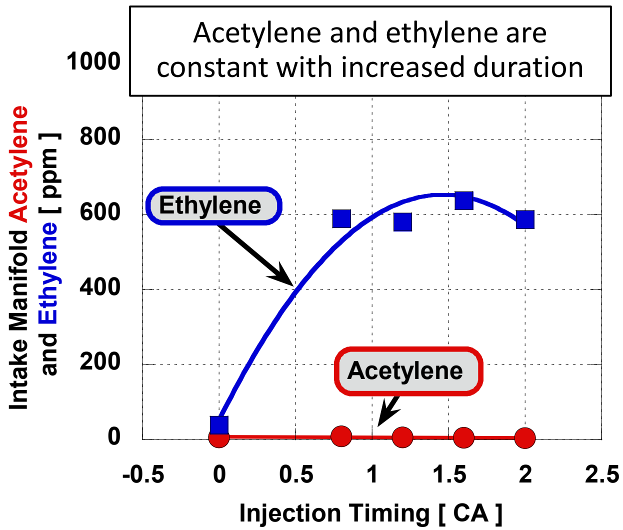


- Complete experimental details available (backup slide)
- Sweep of cylinder 4 fuel injection duration
  - 0, 0.8 ms, 1.2 ms, 1.6 ms, and 2.0 ms
  - Injection in cylinders 1-3 adjusted to maintain load and stoichiometry
- Fuel injection timing and valve settings held constant
  - Mass flow through cylinder 4 increased with injection quantity due to charge cooling
  - Higher fuel injection resulted in higher EGR
- CA50 in cylinders 1-3 held constant at 8 CA aTDC$_f$

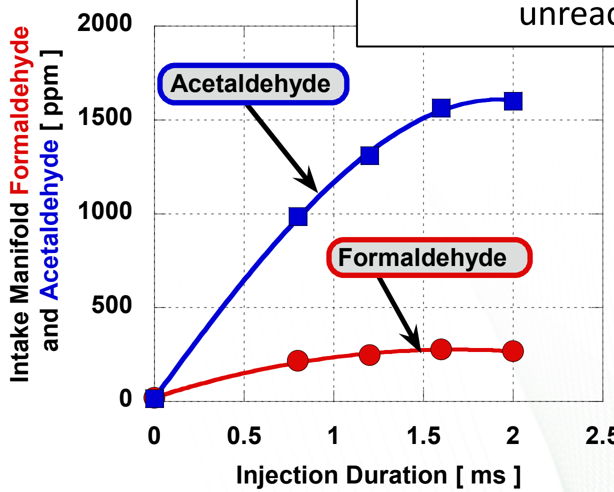
Increased Injection Duration Results in Raw Fuel in Intake Manifold, Little effect on Reformate



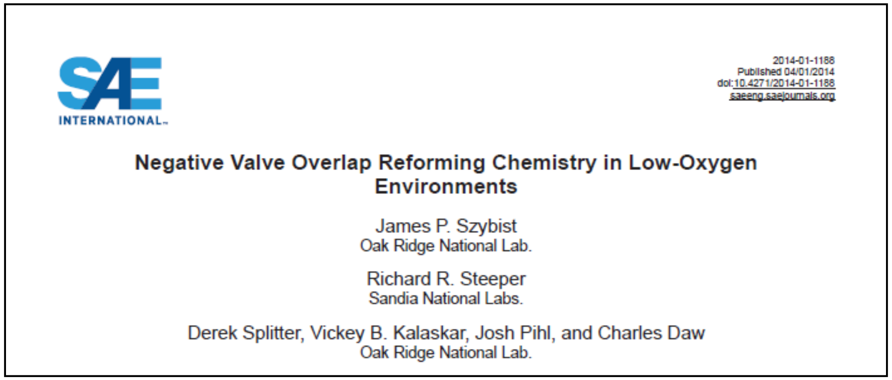




Acetaldehyde increases with injection duration, but concentrations are nearly an order of magnitude below unreacted fuel



Recent Effort by ORNL, SNL, and University of Minnesota Provide Insight into the Conditions Required for Reforming



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SAE INTERNATIONAL

Negative Valve Overlap Reforming Chemistry in Low-Oxygen Environments

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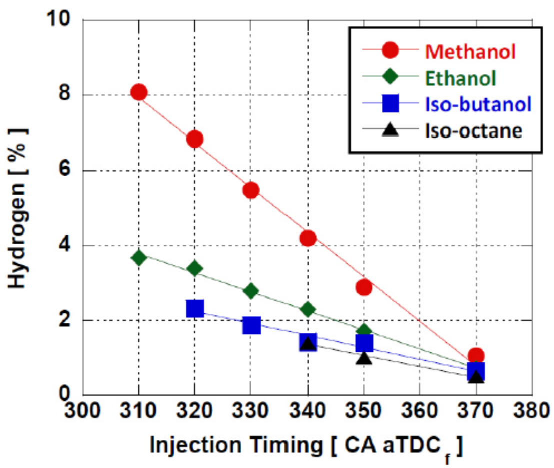
Sandia National Labs.

Derek Splitter, Vickey B. Kalaskar, Josh Pihl, and Charles Daw
Oak Ridge National Lab.

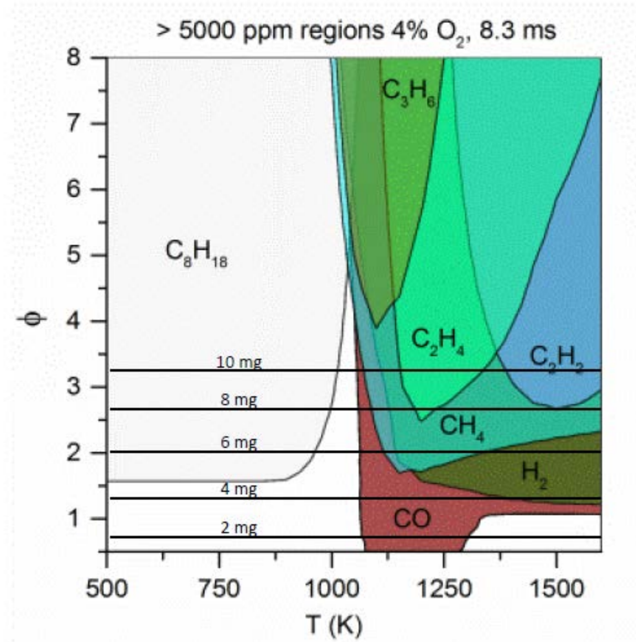


- Nearly 4% H_2 formed with ethanol in single-cylinder experiments
- EVC temperature was nominally 600°C
- Compression ratio was 11.85:1
- Estimated peak temperature: 1120-1200K

Investigation of NVO partial products utilizing gas sampling and single-zone chemistry modeling

Brian Peterson and Isaac Ekoto, Sandia National Labs
Will Northrop, University of Minnesota

2015-01-0818, 2015 SAE World Congress



- Temperatures above 1050K are required to form H_2 under fuel rich conditions with iso-octane

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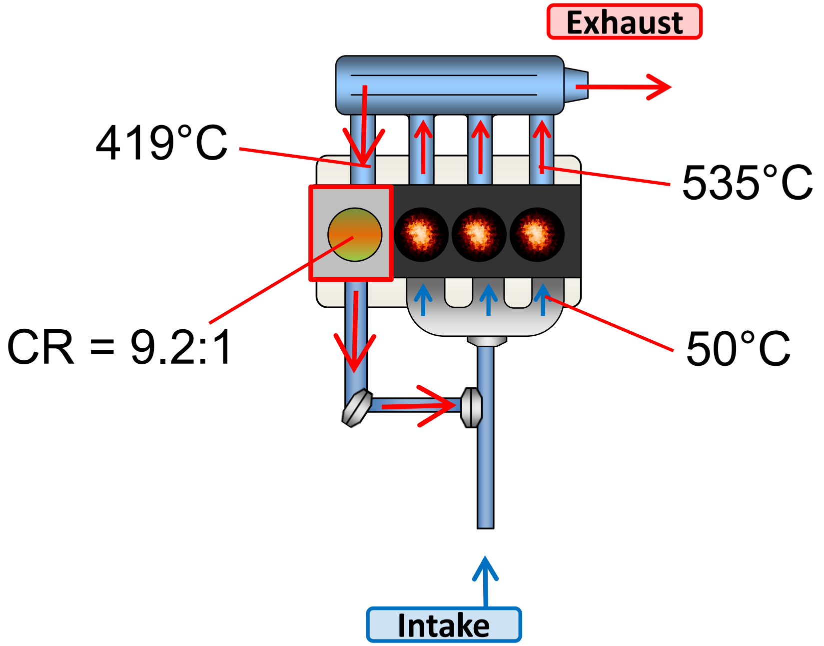
Current Thermal Conditions are Insufficient for Reforming, Several Paths Forward Being Pursued to Enhance Reforming

Stock exhaust manifold designed to provide divided flow to the turbo.

Very long flow path and high heat losses in current application.



Estimated peak temperature: < 950 K

- Possible solutions to low reforming temperature
  1. Redesigned exhaust manifold with additional insulation
  2. Higher compression ratio
  3. **Exothermic reactions to drive reforming**

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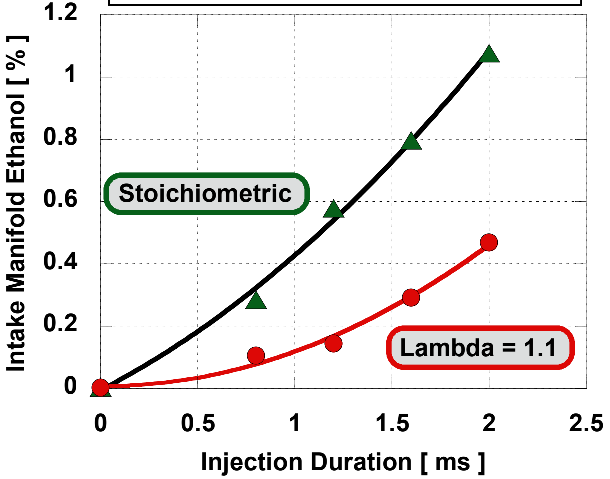
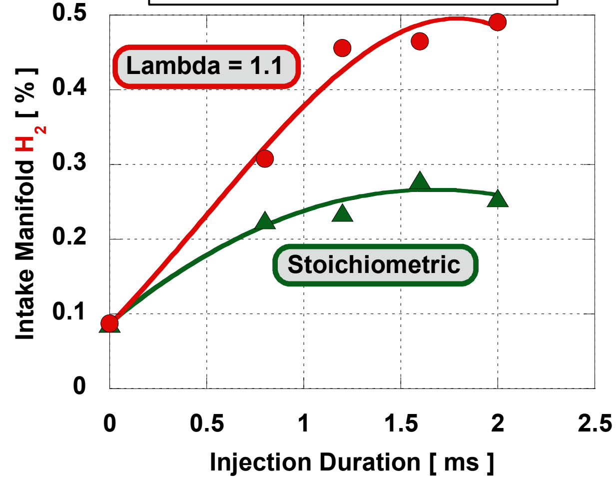
IF ENGINE IS OPERATED UNDER GLOBALLY LEAN CONDITIONS, FUEL CONVERSION AND REFORMATE YIELD INCREASES SUBSTANTIALLY

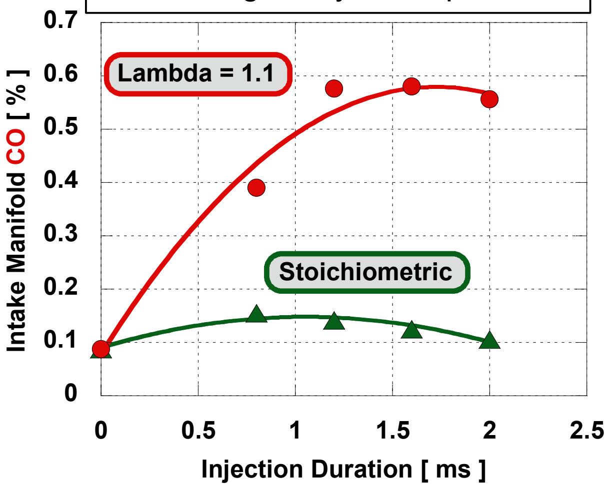
Unconverted ethanol in intake manifold decreases by > 50%



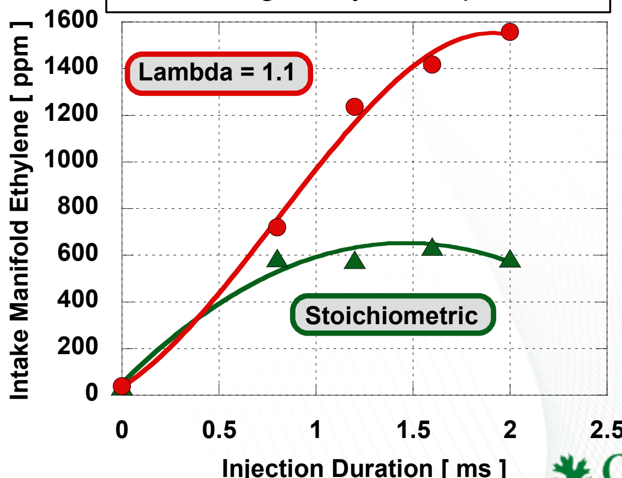
H_2 nearly doubles with globally lean operation



CO increases by nearly a factor of 4 with globally lean operation



Ethylene increases by a factor of 2-3 with globally lean operation



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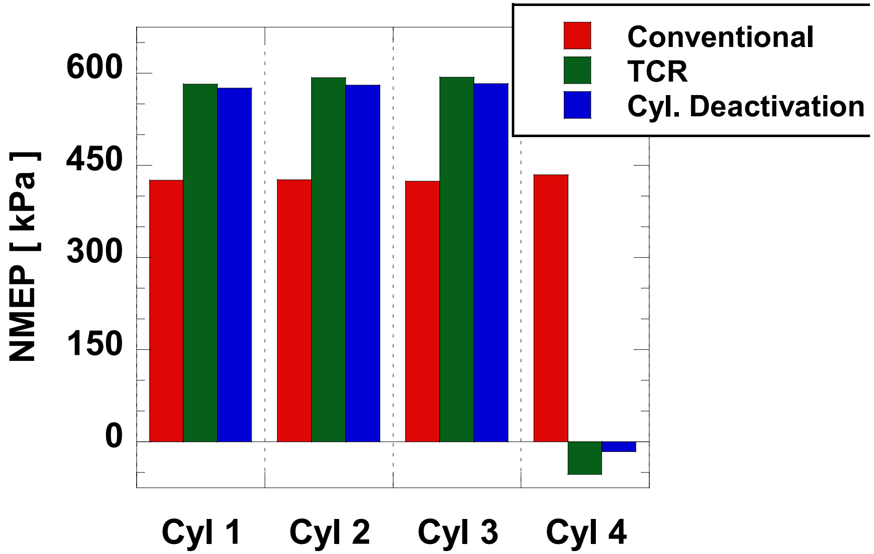
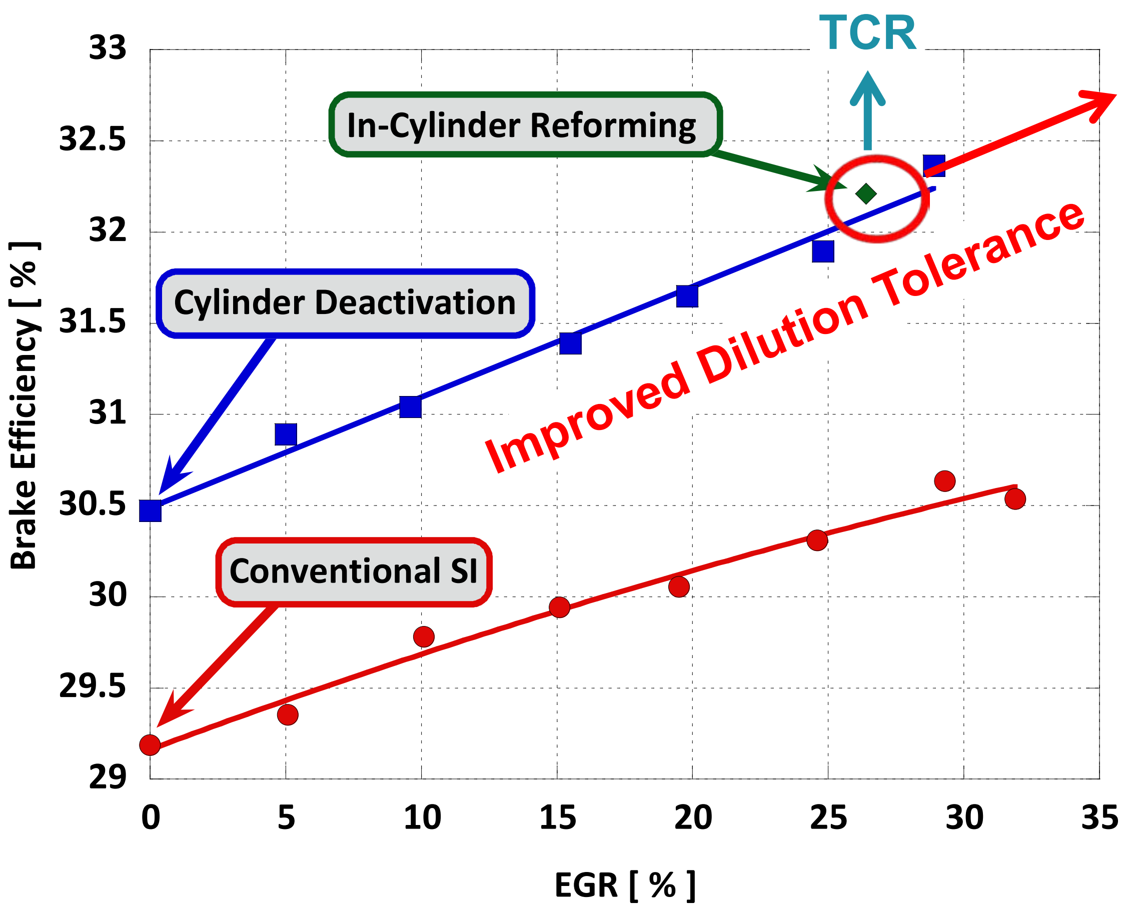
How should Efficiency for the TCR Strategy be Compared?



- All 4 cylinders nominally produce the same power during conventional SI operation
- Only 3 cylinders produce power for the TCR strategy using in-cylinder reforming
  - Because brake torque is held constant, these cylinders operate at a higher mean effective pressure
  - Increasing load from this part-load condition increases efficiency (higher gross efficiency, reduced pumping)
- Additional point of comparison: operate conventional SI with cylinder 4 deactivated
  - Cylinder deactivation is a technology in the marketplace, provides substantial system efficiency benefit
- Investigate effect of external cooled EGR with both the conventional and valve deactivation methodologies

Efficiency Increase can be Primarily Attributed to Cylinder Deactivation and EGR Dilution rather than In-Cylinder Reforming

Stoichiometric Combustion with CR = 9.2:1
2000 rpm, 4 bar BMEP, CA50 = 8 CA aTDC$_f$



*Efficiency comparison to other engines installed at ORNL is available on backup slide 3

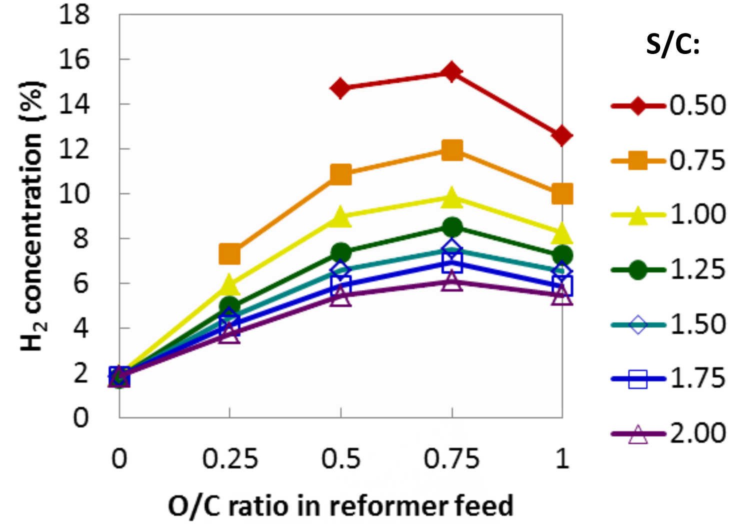
- BTE improvement with valve deactivation is substantial
  - Fuel consumption decrease of 4.2%
- BTE improvement with in-cylinder reforming is higher
  - Fuel consumption decrease of 9.4%
- EGR increases efficiency for both valve deactivation and conventional SI
- Valve deactivation with EGR matches efficiency from in-cylinder reforming
- Future work will focus on maintaining improving reforming so that dilution limit can be extended

EGR Operation Presents Challenging Parameter Space for Reforming

Accomplishments (8/9)

- At 600 °C, steam reforming of iso-octane without air addition using the current catalyst is not a viable path for significant H_2 production
  - Endothermic steam reforming drops catalyst T
  - <2% H_2 generated from steam reforming (O/C = 0) of C_8H_{18} for all HC doses at 600 °C
  - Increasing steam-to-carbon ratio (S/C) improves C_8H_{18} conversion, but...
  - Fixed exhaust H_2O concentration requires drop in C_8H_{18} concentration to increase S/C
- Partial oxidation reforming (air addition) increases H_2 production
  - Increases catalyst T and C_8H_{18} conversion
  - max H_2 production at O/C = 0.75 for all HC doses
  - O/C >= 1 results reduces H_2 concentration due to oxidation of reformate

H_2 Concentration



reforming conditions:
2 wt% Rh/Al_2O_3
GHSV: 50000 h^{-1}
inlet T: 600 °C
0.65 - 2.28% C_8H_{18}
0 - 7.5% O_2
12% H_2O, 14% CO_2

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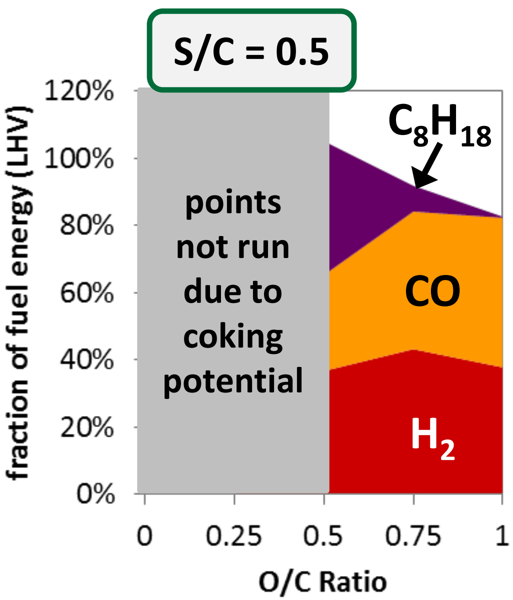
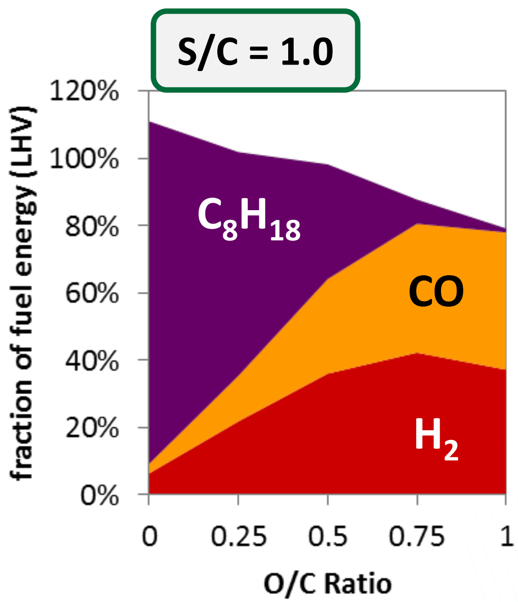
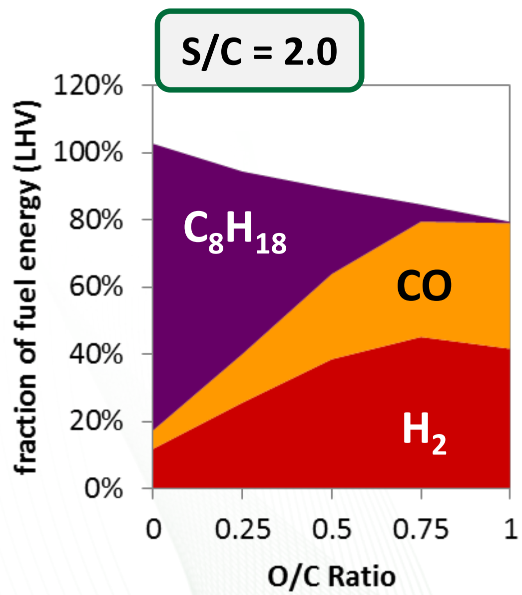
Partial Oxidation Reforming Creates a Tradeoff:
H_2 Generation vs. Fuel Energy Consumption

- S/C ratio (fuel dosing) has minimal impact on C_8H_{18} conversion
  - Beneficial for turndown ratio, load following
- Higher O/C ratios increase C_8H_{18} conversion to H_2 and CO, but consumes fuel energy
  - Need better HC speciation to confirm energy balance
- Tradeoff between H_2 production, efficiency of reforming, and ultimately engine efficiency







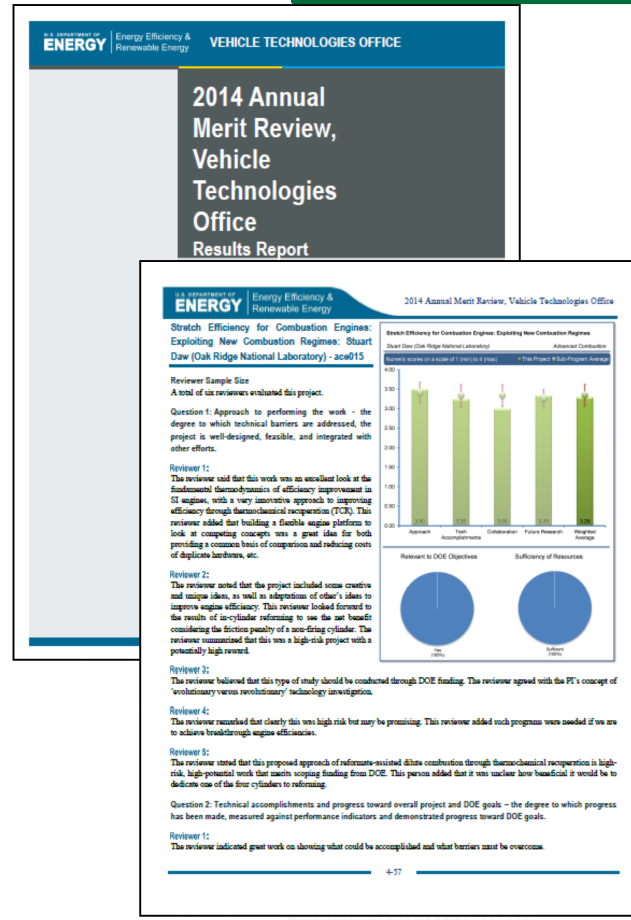
Six Reviewers Evaluated This Project (ACE015) at the 2014 AMR – Comments Overall were Very Positive

Positive Comments (paraphrasing)

- Excellent to look at the fundamental thermodynamics with an innovative approach to thermochemical recuperation for improved engine efficiency.
- Good progress on assembling the engine system and starting to evaluate the two approaches.
- Flexible engine platform is a good approach to provide a common platform and to keep down costs compared to duplicating hardware setups.

Areas for Improvement (paraphrasing)

- Looking forward to seeing the net benefits considering the friction penalty of the non-firing cylinder. ***Results showed improved efficiency due to cylinder deactivation-like conditions with non-firing cylinder at a part-load condition.***
- Are there plans to incorporate any CFD modeling? ***Modeling efforts to-date are through our collaboration with U Minn and SNL. We will be looking to expand the modeling as budgets allow.***
- There could be more collaboration opportunities, especially with industry. ***We would like to establish a mechanism for incorporating more industry input for this project. We would like to setup meetings with the OEMs to come and discuss our dilute combustion portfolio as a whole.***



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2014 Annual Merit Review, Vehicle Technologies Office Results Report

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy — 2014 Annual Merit Review, Vehicle Technologies Office

Stretch Efficiency for Combustion Engines: Exploiting New Combustion Regimes: Stuart Daw (Oak Ridge National Laboratory) - ace015

Reviewer Sample Size
A total of six reviewers evaluated this project.

Question 1: Approach to performing the work - the degree to which technical barriers are addressed, the project is well-designed, feasible, and integrated with other efforts.

Reviewer 1:
The reviewer said that this work was an excellent look at the fundamental thermodynamics of efficiency improvement in SI engines, with a very innovative approach to improving efficiency through thermochemical recuperation (TCR). This reviewer added that building a flexible engine platform to look at competing concepts was a great idea for both providing a common basis of comparison and reducing costs of duplicate hardware, etc.

Reviewer 2:
The reviewer noted that the project included some creative and unique ideas, as well as adaptations of other's ideas to improve engine efficiency. This reviewer looked forward to the results of in-cylinder reforming to see the net benefit considering the friction penalty of a non-firing cylinder. The reviewer summarized that this was a high-risk project with a potentially high reward.

Reviewer 3:
The reviewer believed that this type of study should be conducted through DOE funding. The reviewer agreed with the PI's concept of 'evolutionary versus revolutionary' technology investigation.

Reviewer 4:
The reviewer remarked that clearly this was high risk but may be promising. This reviewer added such programs were needed if we are to achieve breakthrough engine efficiencies.

Reviewer 5:
The reviewer stated that this proposed approach of reformate-assisted dilute combustion through thermochemical recuperation is high-risk, high-potential work that merits scoping funding from DOE. This person added that it was unclear how beneficial it would be to dedicate one of the four cylinders to reforming.

Question 2: Technical accomplishments and progress toward overall project and DOE goals – the degree to which progress has been made, measured against performance indicators and demonstrated progress toward DOE goals.

Reviewer 1:
The reviewer indicated great work on showing what could be accomplished and what barriers must be overcome.

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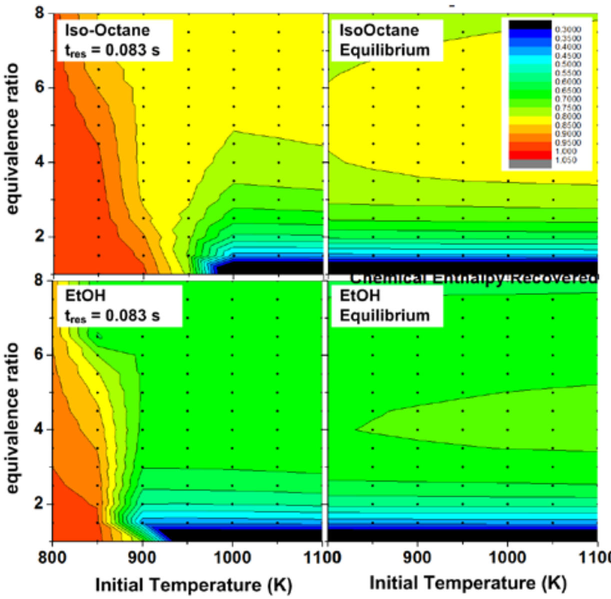
COLLABORATIONS

- 2010 USCAR Colloquium (overall direction)
  - 29 invited experts from industry, universities, labs and government to identify long-term research priorities regarding the theoretical and practical efficiency limits of internal combustion engines

http://feerc.ornl.gov/pdfs/Stretch_Report_ORNL-TM2010-265_final.pdf

- AEC Working Group bi-annual meetings
  - Mechanism for industry feedback
- Joint effort with SNL on in-cylinder chemistry (ACE 006)
  - 2014 SAE paper (ORNL lead, Dick Steeper)
  - 2015 SAE paper is in manuscript form (SNL lead, Isaac Ekoto)



- University of Minnesota: Will Northrop is collaborating with SNL and ORNL, performing kinetic and thermodynamic simulations of in-cylinder reforming
- University of Michigan: Galen Fisher advising on catalyst formulation and operating conditions through subcontract
- Collaboration with Gas Technology Institute (GTI): 2015 NDA with GTI on relevant recuperative technologies for syngas production

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Future Work will Continue on Dilute Combustion Combined with TCR Reforming for High Efficiency

In-Cylinder Reforming Work will Continue Past the 2016 Timeframe

- 2015 data illustrates need to change experimental configuration to produce conditions conducive to in-cylinder reforming
- Parametric investigations of in-cylinder reforming will expand to encompass additional fuels and engine operating conditions
  - Continue with 2000 rpm, 4 bar BMEP point (ACEC Tech Team light-duty point for downsized-boosted) to investigate hardware configurations (CR, exhaust manifold, air injection)
  - Investigations in 2017 will be based on data, but if successful at 4 bar BMEP, further investigations will likely expand the operating envelope from near-idle to boosted operation

Catalytic EGR-loop Reforming will Move to On-Engine Experiments in 2016

- Currently procuring a full-size Rh-based catalyst for on-engine experiments beginning in late FY2015
  - Catalytic reforming experiments on-engine in FY2016 will be guided by knowledge from the previous and on-going bench-flow reactor studies (operating regimes, fuel compositions)
  - Assuming pathway is continued, additional experiments will be informed by on-engine campaigns and focused on improving performance

Data-based Evaluation of Current Course by End of FY17

Summary

Relevance

Investigate high risk revolutionary combustion strategies with potential for large efficiency increases

Approach: Dilute Combustion and Thermochemical Recuperation (TCR) to Increase Efficiency

- Strategy 1- In-cylinder reforming in a low oxygen environment
- Strategy 2- Catalytic EGR-loop reforming

Accomplishments

- Flexible research engine and accompanying analytical equipment is fully operational
- Showed that the friction associated with the TCR reforming strategy is not a barrier to improved brake efficiency under part-load condition
- Barrier to reforming in the first campaign was that the temperature was too low, subsequently changed engine configuration to increase temperature in reforming cylinder
- Bench flow reactor configured to replicate engine-conditions, developing an understanding of how to operate the catalyst for on-engine experiments

Collaborations

- Collaborative investigation with SNL, University of Minnesota, subcontract to University of Michigan, and a non-disclosure agreement with GTI

Future Work

- Experimental parametric studies on in-cylinder reforming, changing engine configuration as-necessary to produce required conditions for in-cylinder reforming and TCR
- Continue durability and performance investigations of Rh-based catalyst conditions with bench-flow reactor, move to on-engine studies

TECHNICAL BACKUP SLIDES

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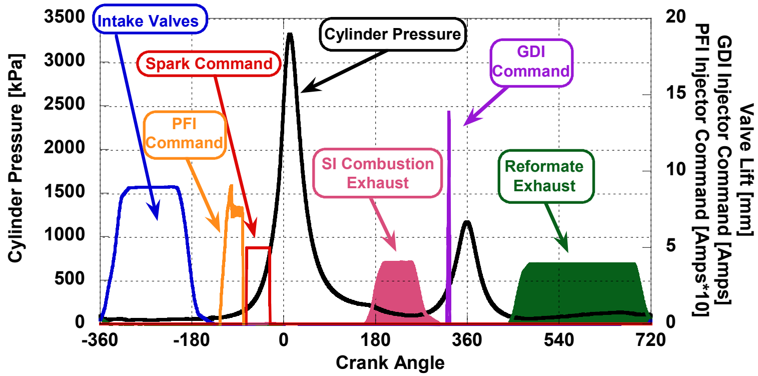
Work in 2015 Follows the Data-Based Path Laid Out by Prior Efforts

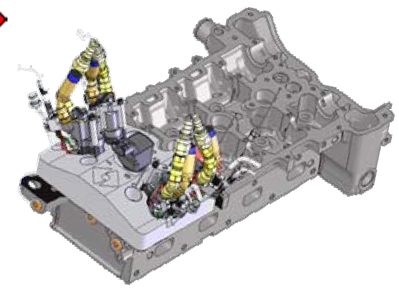
In-Cylinder Reforming Pathway

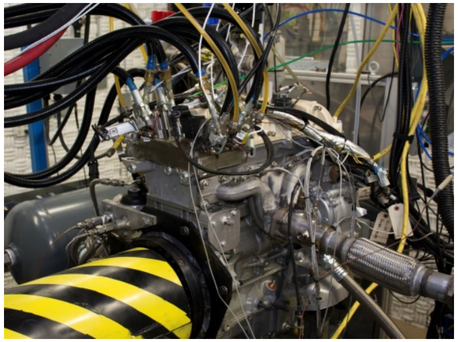
Backup 1

2013: Experiments using Unique 6-Stroke Engine Cycle to Investigate NVO Reforming

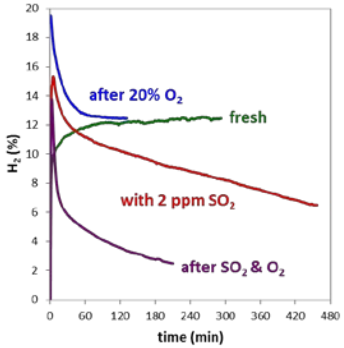


2014: Design, Construction, and Commissioning of a Uniquely Flexible Research Engine

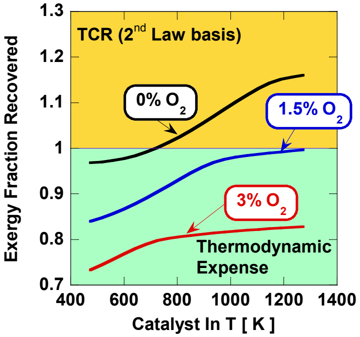


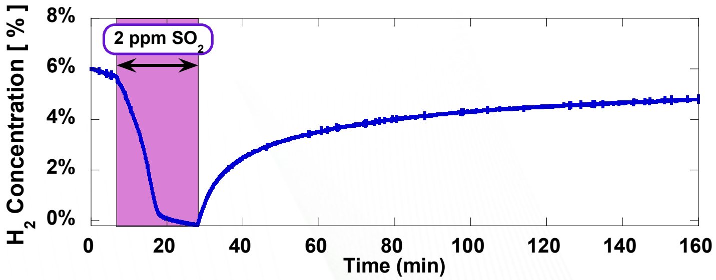


Catalytic Reforming Pathway



2013: S poising (2ppm) is the cause of Ni-based catalyst deactivation (GTI/Cummins)





2014: Moved to Rh-based catalyst
Modeling, performance mapping, S tolerance investigations

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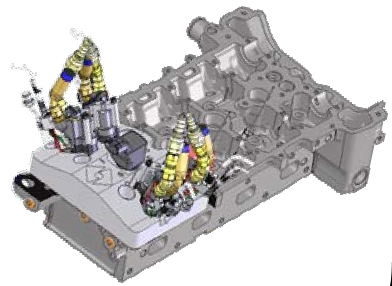
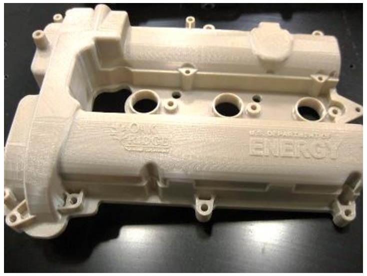
Effort to Build a Flexible Multi-cylinder Engine Platform at ORNL Capable of TCR Operating Strategy

Backup 2

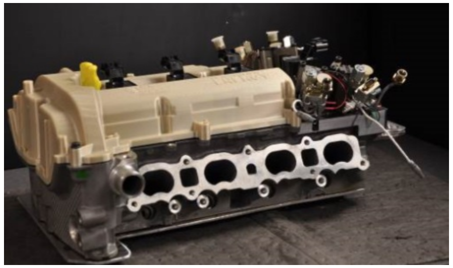
Cylinder head design for 3 cam-based cylinders and 1 HVA cylinder

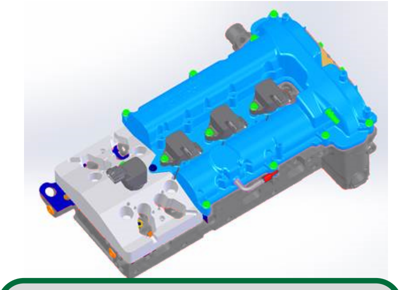


Custom valve cover fabricated with 3D printing at ORNL's MDF

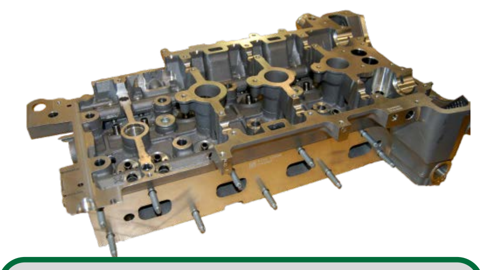


Major hardware modifications complete



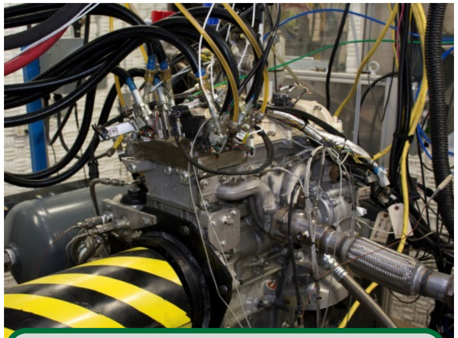


Design of custom valve cover complete



Machining of cylinder head and HVA transfer plate

High pressure fuel cart completed and tested

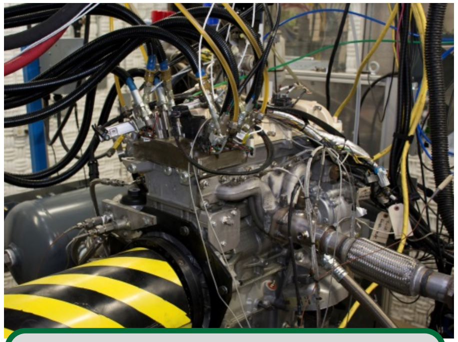


Engine assembly and installation complete

EXPERIMENTAL DETAILS

BACKUP 3

- Highly modified 2007 GM LNF engine
  - 2.0 L Displacement (bore x stroke: 86 mm x 86 mm)
  - Direct injection (constant rail pressure of 85 bar for this study)
  - Stock pistons and compression ratio (9.2:1)
  - Cylinders 1-3 operate on the stock cam
  - Cylinder 4 is operated with a Sturman hydraulic valve actuation system
- Single operating point study: 2000 rpm, 4 bar BMEP
  - Brake torque of 47 ft-lbs maintained even when cylinders are operating differently
- All data collected at a CA50 combustion phasing of 8 CA $aTDC_f$
- Engine-out emissions measured with a 5-gas emissions bench
- Additional analyzers used to speciate reformate and exhaust
  - FTIR to speciate hydrocarbons
  - Magnetic sector mass spectrometer used to measure H_2
- Chemically pure ethanol used based on prior results
  - Low sooting tendency and high propensity for reforming



Engine assembly and installation complete

50 gallons of 200 proof ethanol delivered to my office!

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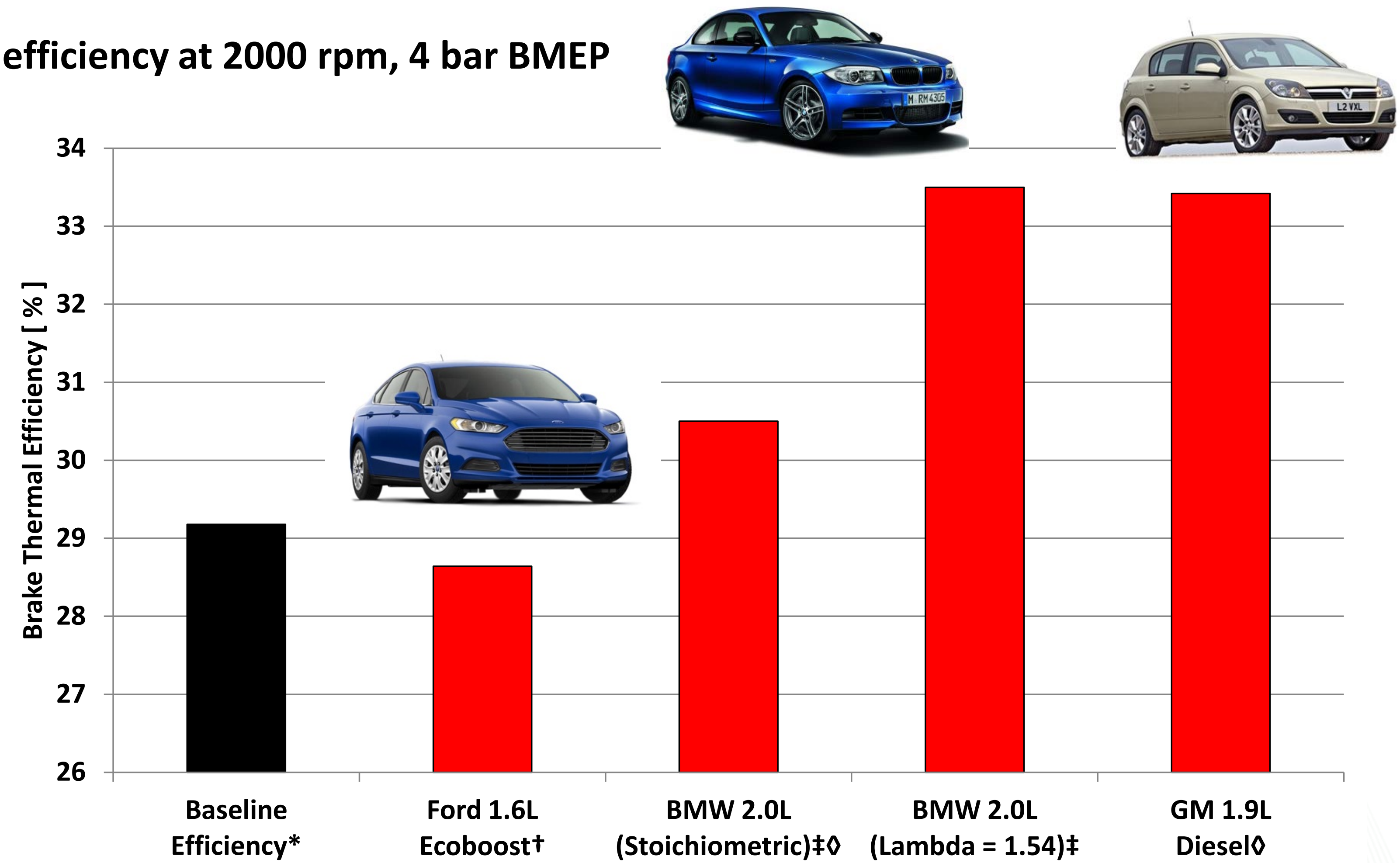
Baseline Engine Efficiency after Modifications is Reasonable Compared to Other Engines Installed at ORNL

Backup 4

Brake efficiency at 2000 rpm, 4 bar BMEP



* TCR engine has no belt drive or fuel pump
† Dyno ECU with production calibration
‡ Laboratory ECU with reproduced operating maps
◊ Laboratory ECU with reproduced Euro IV operating maps

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