Natural Gas Vehicle Technology Forum 2021

Virtual

May 11–12, 2021

The National Renewable Energy Laboratory (NREL) hosted the forum in partnership with the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy's Vehicle Technologies Office, the California Energy Commission, South Coast Air Quality Management District, and Natural Gas Vehicles for America.

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U.S. DEPARTMENT OF
ENERGY

Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

Natural Gas Funding Opportunities from DOE’s Vehicle Technologies Office

NGV Technology Forum

May 2021

DOE VTO has many FOA projects underway in natural gas…

Prime	Project Title (Category)
Clean Fuels Ohio	NGV U.P.-T.I.M.E. Analysis: Updated Performance Tracking Integrating Maintenance Expenses (NG Maintenance Cost)
E4 Carolinas (University of NC)	Carolina Alt-Fuel Infrastructure for Storm Resilience Planning (Resiliency)
Florida Division of Energy Mgmt.	Florida Statewide Alternative Fuel Resiliency Plan (Resiliency)
Gas Technology Institute	Smart CNG Station Deployment (Smart CNG Infrastructure)
Gas Technology Institute	Next-Generation NGV Driver Information System (Next Generation Information)
Gas Technology Institute	Field Demonstration of a Near-Zero, Tier 5 Compliant, Natural Gas Hybrid Line Haul Locomotive
Montana State University	Heteroatom-Modified and Compacted Zeolite-Templated Carbons for Gas Storage (Advanced Storage)

Prime	Project Title (Category)
Northwestern University	Theory-Guided Design and Discovery of Materials for Reversible Methane and Hydrogen Storage (Advanced Storage)
Pennsylvania State University	Developing New NG Super-Absorbent Polymer (NG-SAP) for a Practical NG Storage System with Low Pressure, Ambient Temperature, and High Energy Density (Advanced Storage)
University of Delaware	Methane Storage with Porous Cage-Based Composite Materials (Advanced Storage)
University of Michigan	Optimal Adsorbents for Low-Cost Storage of Natural Gas: Computational Identification, Experimental Demonstration, and System-Level Projection (Advanced Storage)
University of South Florida	Metal-Organic Frameworks Containing Frustrated Lewis Pairs for H2 Storage at Ambient Temperature (Advanced Storage)
University of South Florida	Uniting Theory and Experiment to Deliver Flexible MOFs for Superior Methane (NG) Storage (Advanced Storage)
Washington State University	Develop an Efficient and Cost-effective Novel Anaerobic Digestion System Producing High Purity Methane from Diverse Waste Biomass (Waste to Energy)

FY2021 Vehicle Technologies Office FOAs

1 Vehicle Technologies Office Fiscal Year 2021 Research Funding Opportunity Announcement

DE-FOA-0002420

Topics for R&D/deployment on batteries, electric motors, EEMS, analysis (NG not included in this FOA)

Released December 2020

Applications were due April 7

Announcements on awards to come

2 Low Greenhouse Gas (GHG) Vehicle Technologies Research, Development, Demonstration, and Deployment

DE-FOA-0002475

Topics for R&D/deployment on electrification, off-road vehicles, natural gas, DME, propane, opposed piston

Released April 2020

Concept papers due May 13

Two NG-related topics (see next slide)

Find these at https://eere-exchange.energy.gov

Please direct questions on the FOA to DE-FOA-0002475@netl.doe.gov

FOA2475 Area of Interest 5

Natural Gas Engine Enabling Technologies

TOTAL FUNDING $6.25 million
ESTIMATED # AWARDS 1 to 3
PROJECT DURATION 3 years
COST SHARE 20%

- Research, develop, validate natural gas engine component technologies that improve efficiency of engines (MD/HD)
- Potential technology approaches could include
  - Advanced ignition systems – e.g., prechamber, plasma, etc.
  - Improved injectors for direct injection engines.
  - Systems enabling multi-mode SI/advanced compression ignition combustion
  - Enabling low temperature NG combustion using novel technologies such as plasma assist and/or SACI (high dilution, advanced spark, end-gas controlled combustion)
  - Reduced-cost, in-cylinder pressure sensors
  - Real time methane number sensing and compensation systems
  - Technologies enabling improved air-fuel mixing
  - Dynamic cylinder deactivation
  - Development of predictive simulation tools (data- & physics-driven) for NG direct injection, combustion, and emission modeling
  - Application of thermal barrier coatings to improve efficiency
  - Improvements to catalyst manufacturing which improve utilization of platinum group metals (PGMs) or technologies to reduce the need for PGMs in three-way catalysts
  - Low temperature methane oxidation
  - Lean-NOx emission control

Please direct questions on the FOA to DE-FOA-0002475@netl.doe.gov

FOA2475 Area of Interest 8

Natural Gas Vehicle Technology Proof of Concept

- Spur adoption of on-road natural gas vehicles (medium or heavy-duty) in a specific fleet or community where low emissions from natural gas can provide unique and immediate health benefits
- Proof of concept demonstration
    - 5 or fewer vehicles
    - Supporting infrastructure
- Validate energy, environmental, economic, operational benefits – reduce burden from truck usage in these communities

TOTAL FUNDING	$2.5 million
ESTIMATED # AWARDS	2 to 5
PROJECT DURATION	3 years
COST SHARE	50%

Please direct questions on the FOA to DE-FOA-0002475@netl.doe.gov

VTO Request for Information – MD/HD Truck Research

Released: October 2020

Topic: research needs and opportunities related to medium and heavy-duty freight trucking

Inputs sought from: industry, academia, research laboratories, government agencies, other stakeholders

Responses: over 800

Webinar to summarize results: December 2020

Selected feedback (from webinar slides) related to natural gas

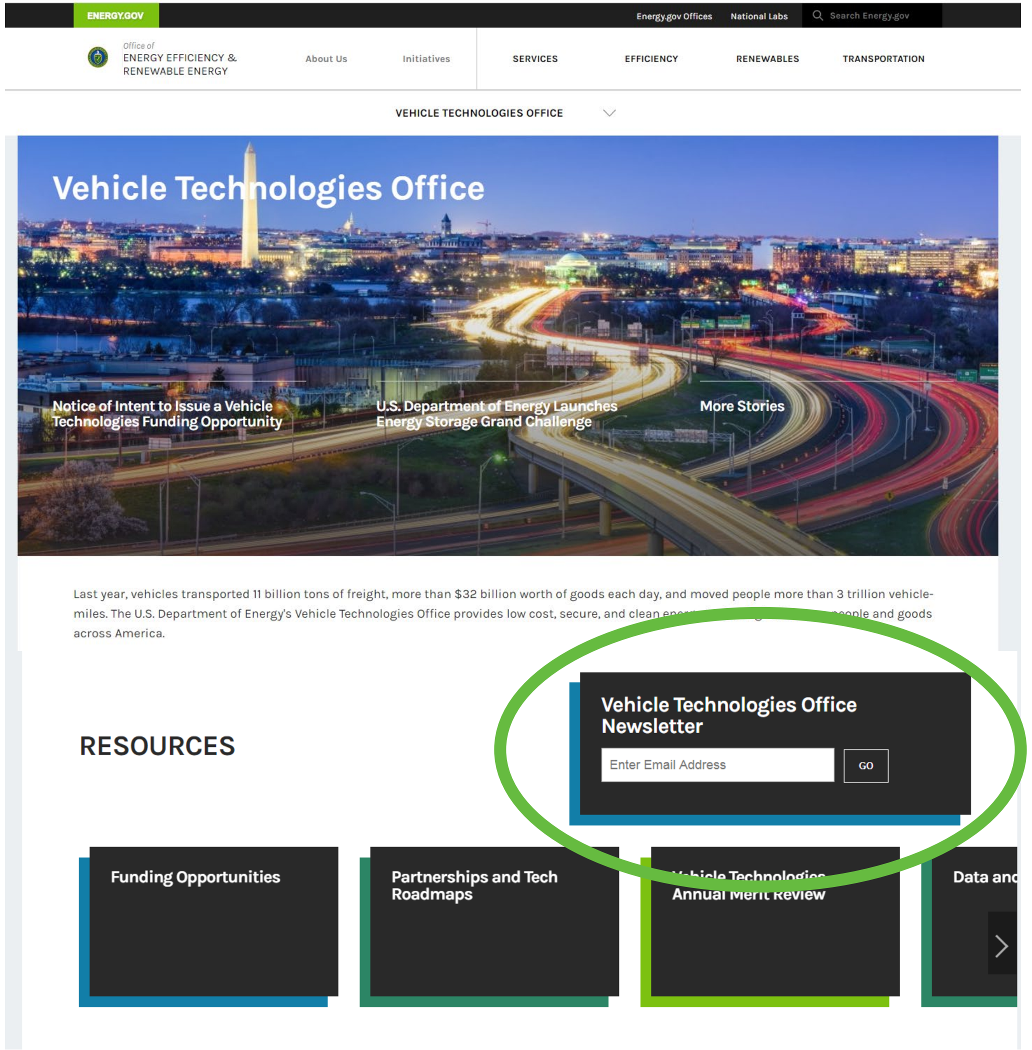
Gaseous fuels of interest due to expected lower cost and simpler emissions controls to reach low NOx levels

Small/niche market at present, cost of fuel storage, lack of engines available in some sizes

Biofuels/RNG interest – carbon reduction as corporate or social goal

OEMs have CO2 metric at or near top of corporate priorities, but dominance of TCO among customers makes independent action difficult, despite customers also claiming CO2 is priority

How to stay informed about VTO activities



Visit vehicles.energy.gov...

...and sign up for the newsletter

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Natural Gas R&D Program Update

2021 Natural Gas Vehicle Technology Forum

Peter Chen
Energy Research and Development Division
Transportation Research Unit

Program Background

- Research and development specific to natural gas done in the public interest to support the transition to clean energy, greater reliability, lower costs, and increased safety for Californians.
- "Directed towards developing science or technology, and 1) the benefits of which accrue to California citizens, and 2) are not adequately addressed by competitive or regulated entities."
- **$24 million annually**, funded by a surcharge on natural gas consumption in CA. Funding is split between five major research areas:
  - Energy Efficiency
  - Natural Gas Infrastructure Safety and Integrity
  - Renewable Energy and Advanced Generation
  - Energy-related Environmental Research
  - **Transportation**

General Approach

- Identify research gaps to address and propose initiatives through:
  - Discussion with utilities, public stakeholders, state and federal governmental agencies, other CEC programs;
  - Roadmaps;
  - Public meetings with industry and trade associations; and
  - Research ideas submitted by the public
- Energy research priorities are guided by policy directives and equity considerations
- Need clearly identified natural gas ratepayer benefits
- Research projects are selected through competitive solicitations

Transportation Research Area Goals

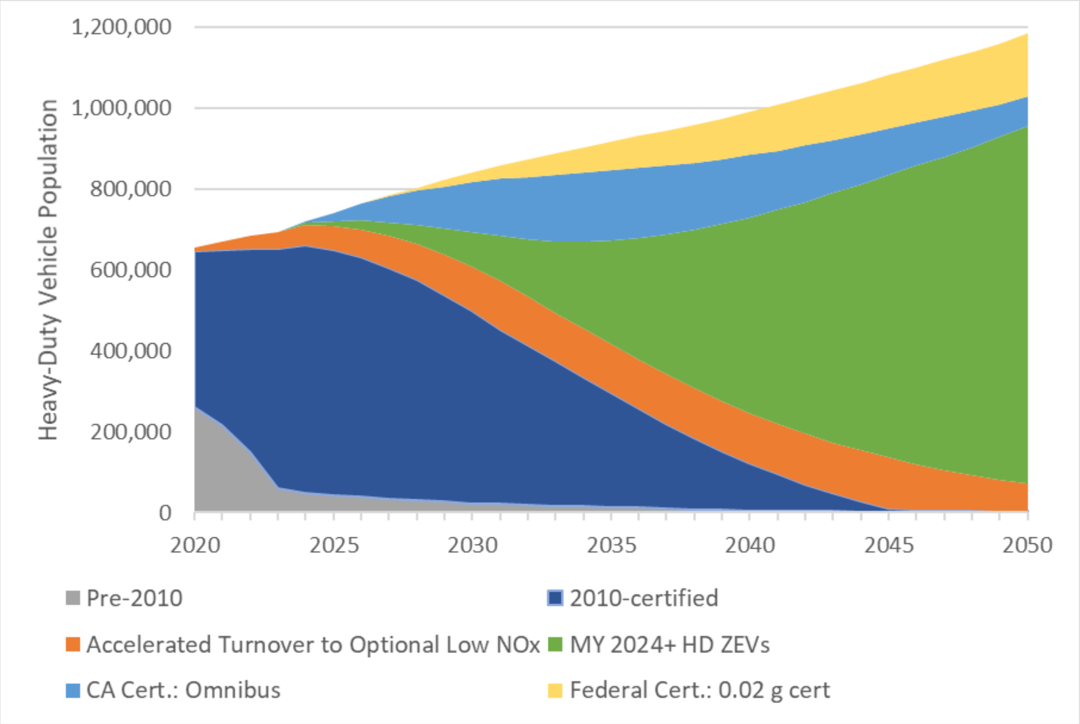
- Improve the energy efficiency and performance of gaseous fueled vehicles to reduce emissions and improve competitiveness.

- Increase the use of renewable gas to reduce GHG emissions from the transportation sector.

- Improve fueling infrastructure technology capabilities to promote the further adoption of low-carbon gaseous fueled vehicles.

California's Transportation Sector

- Executive Order N-79-20 sets a goal to transition all heavy-duty vehicles to zero-emission by 2045, where feasible.
- To enable this transition, technology advancement is needed to:
  - Ensure that combustion vehicles are as clean as possible.
  - Accelerate market acceptance and adoption of emerging zero-emission technologies.



CARB 2020 Mobile Source Strategy:
Statewide Heavy-Duty Population by Technology Type

Ongoing NGV Research Highlights

In-Use Emissions and Fuel Usage Assessment

- In partnership with SCAQMD, SoCalGas, and CARB, CEC is contributing $2M to collect in-use activity and emissions data from over 200 HDVs.
  - Inform development of CNG emissions factors for EMFAC2021.
  - Inform infrastructure projection models for zero-emission HDVs.
  - Identify technology benefits, shortfalls, and opportunities for improvement.

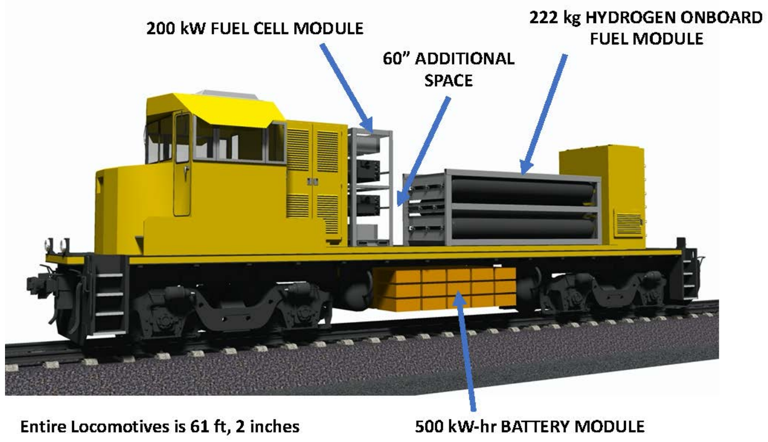
Ongoing NGV Research Highlights

Natural Gas Vehicle Research Consortium

- In partnership with DOE, SCAQMD, and NREL, CEC is contributing $3.7M across four projects:
  - **Cummins:** high efficiency natural gas engine development
  - **Transient Plasma Systems:** advanced ignition
  - **US Hybrid:** CNG hybrid-electric truck demonstration
  - **Gas Technology Institute:** cost effective CNG full fills

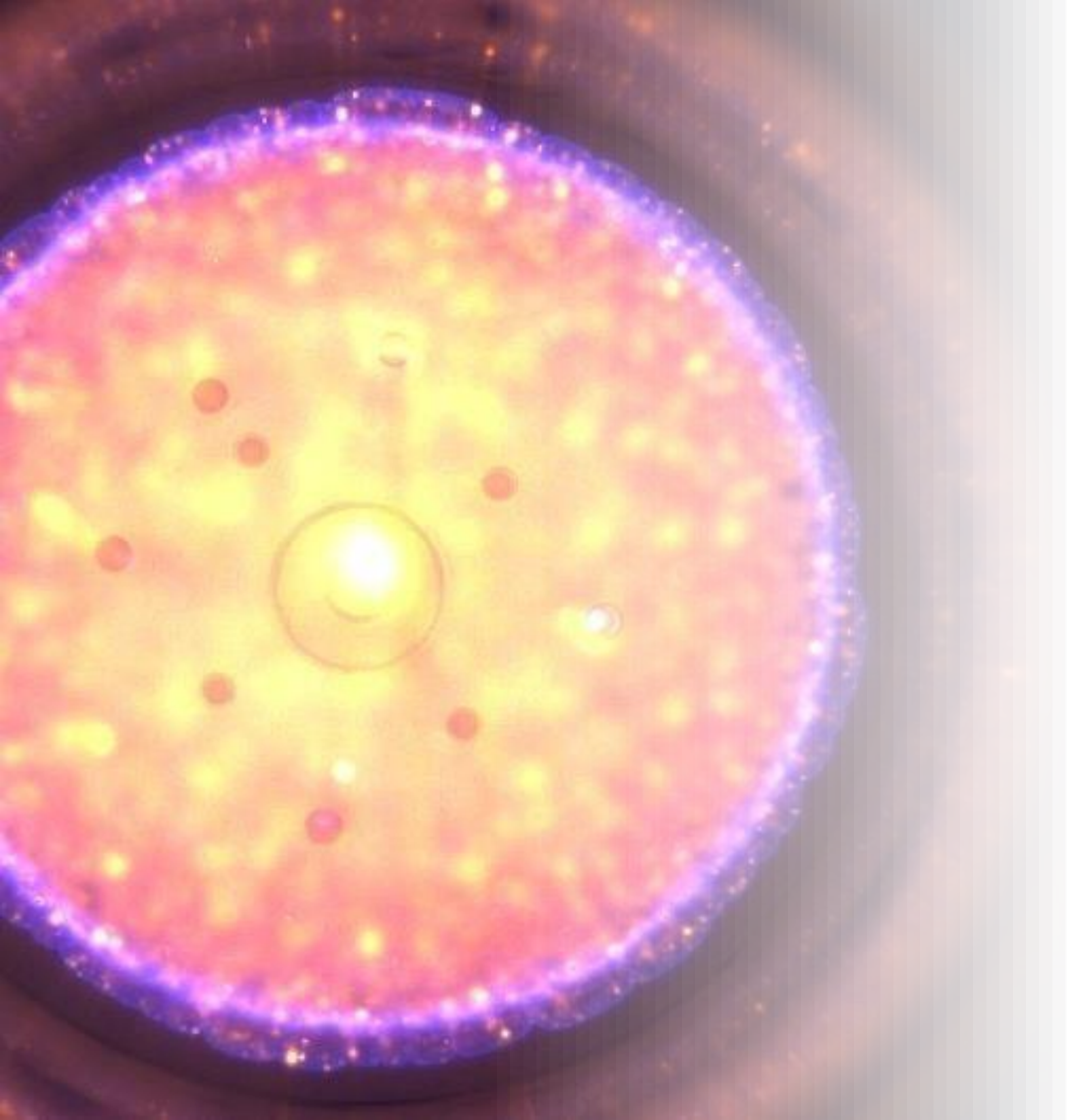
Hydrogen Fuel Cell Demonstrations in Rail and Marine Applications at Ports (H2RAM)

- Solicitation released in July 2020. Projects kicked off in April 2021.
- $10.5M awarded through four projects:
  - **Golden Gate Zero Emission Marine:** Small Fast Multi-Use Hydrogen Fuel Cell Harbor Craft
  - **Gas Technology Institute:** Sierra Northern Hydrogen Locomotive Project
  - **Shell:** Multi-Modal Hydrogen Refueling Station (pending approval)
  - **CALSTART:** HyZET: A Design and Feasibility Study of a Fuel Cell-Powered Commercial Harbor Craft



Future Research Priorities

- Accelerate the commercialization of hydrogen fuel cell trucks and buses for applications with challenging duty cycles.
- Reduce the costs of distributing and dispensing hydrogen for heavy transport applications.
- Build on ongoing R&D projects to support a rapid transition to cleaner technologies.



TRANSIENT PLASMA SYSTEMS

A Multi-cylinder Transient Plasma Ignition System for Increased Efficiency and Reduced Emissions in Natural Gas Engines

Natural Gas Vehicle Technology Forum

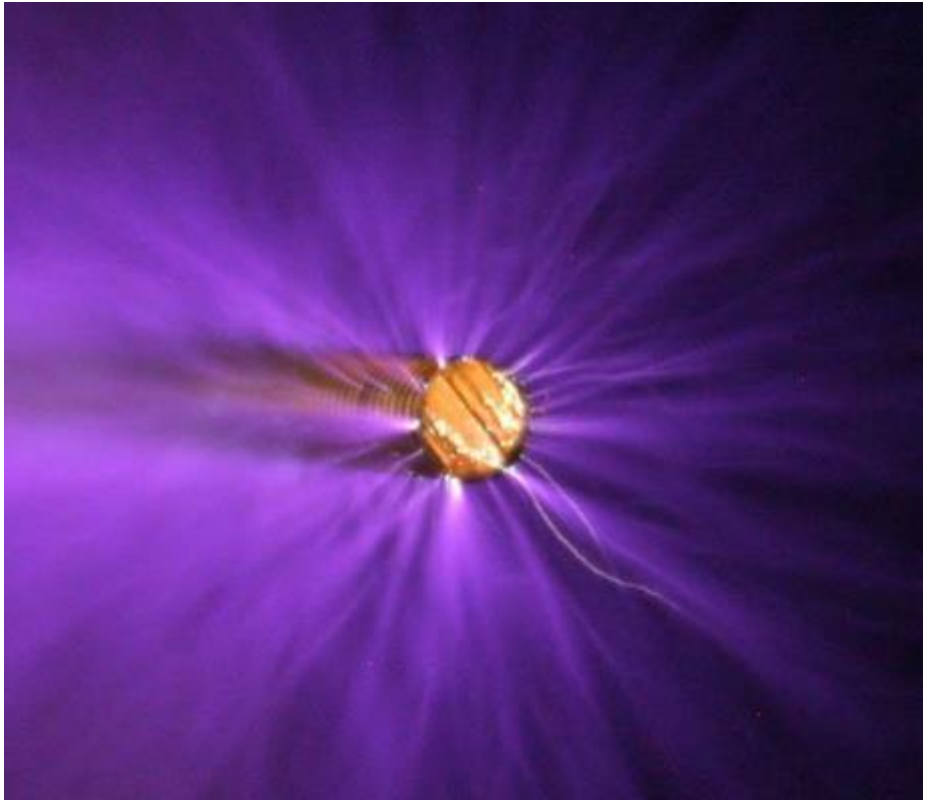
Dr. Jason Sanders, CTO

May 11, 2021

With support from the Natural Gas Vehicles Consortium

Overview

- The Big Picture
- Project Goals & Objectives
- Approach & Accomplishments
- Remaining Work, Future Plans



TPS

Advanced Ignition Systems

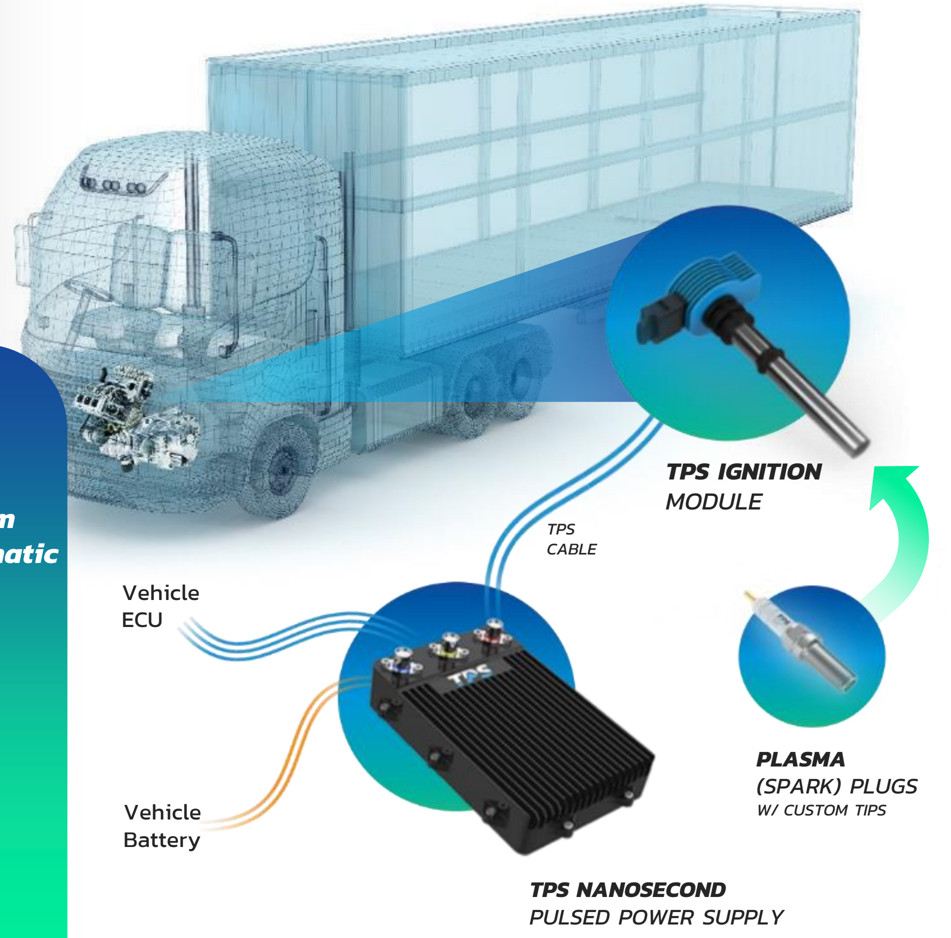
can unlock more than 2X reduction in CO_2

compared to other available engine technologies

What's needed for mass adoption?

- *Extend current dilution limits*
- *Compact size with cost that matches benefit*
- *Durable*
- *Transient performance*
- *Nominal load on battery power*
- *Seamless fit with engine architecture*

System Schematic



Ignition System Path to Market

Understand Industry Fuel Efficiency Challenges & Needs

Develop Ignition Solutions to meet OEM Needs

Path to Market

TPS Update

Investment: Series A

Active Grants:

1. $1.5M NREL grant focused on ignition system packaging (matched with $1.5M from Series A)
Collaborators: Argonne National Laboratory, Cummins Westport

2. $1.1M DOE Phase IIB grant focused on energy efficiency and durability
Collaborators: Sandia National Laboratories

Commercial: Test campaigns with multiple passenger car OEMs, CNG OEMs, and Tier 1 suppliers

Award: Automotive News PACE Pilot Honoree

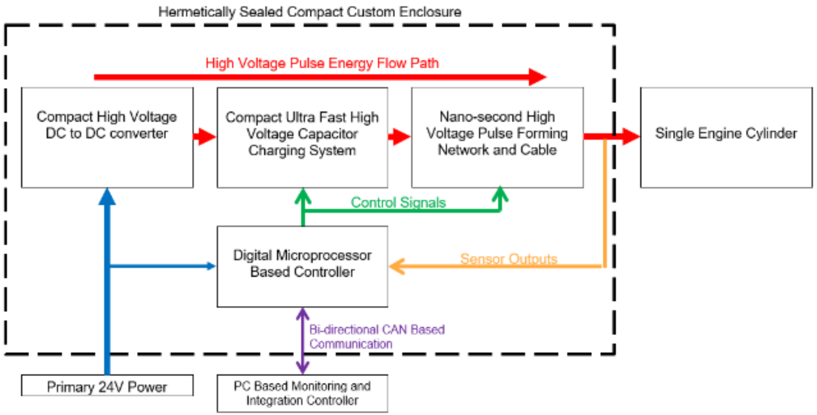
Automotive News PACE pilot EXCLUSIVE LEAD SPONSOR Deloitte. 2020 HONOREE

Press (links in logos):

WIRED Forbes MOTORTREND AUTOLINE FUTURRIDE

Project Goals

- Down-select electrical parameters based on prior six-cylinder engine testing
- Develop pulse tracking feedback system to enable intelligent, adaptive pulse trains
- Explore approaches to finding best fit for packaging
- Redesign thermal management to enable hermetically sealed enclosure
- Investigate 12 VDC compatibility
- Validate performance with our test partners at Argonne National Laboratory



Block diagram of initial concept for the updated transient plasma ignition system being built and demonstrated during this effort.

Quantifying Performance Metrics

Pulse Generator Metrics (Bench-marked at TPS)

Maximum Voltage	15 kV	20 kV	Peak output voltage that the system can drive onto a 50 Ω cable
Pulse Duration	-	< 15 ns	The full-width-half-maximum duration of the voltage pulse switched into 50 Ω

Engine Test Metrics (Measured at Argonne National Laboratory)

Engine Performance Metric	Threshold	Objective	Description
Indicated Thermal Efficiency	TBD	TBD	Ratio of the power developed in cylinder relative to the power in the fuel
Brake Thermal Efficiency	TBD	TBD	Ratio of the power available in the crankshaft relative to the power in the fuel
Exhaust Emissions	TBD	TBD	Exhaust gas will be monitored to identify the concentration of NO_x, CO, HC, and CH_4)

Project Accomplishments – Ignition Module

- Diagram at right shows TPS design for independent pulse compression modules for each igniter / cylinder
- Charging and control is shared / common for this multi-cylinder system
- This block diagram was initial concept at the outset of this effort

Project Accomplishments – Ignition Module

- Diagram at right now integrates the subsystems in order to perform ignition for an entire multi-cylinder engine
- User control and DC input power are shared / common
- This block diagram was initial concept at the outset of this effort

Initial Transient Ignition Module **Prototypes**

- Six prototype modules were built and tested at TPS
- Target specifications:
    - Adjustable amplitude, up to 30 kV at the igniter
    - Multi pulse ignition capable with burst rates up to 100 kHz
    - Pulse duration of approximately 10 ns
    - CAN communication protocol compatible
- Initial prototypes were capable of all target specifications except peak voltage of 30 kV. EMI internal to the enclosure limited peak operating voltage to approximately 20 kV at the igniter.
- TPS conducted extensive testing of these six prototypes in house and demonstrated the capability of these ignition modules to extend lean burn limit.
- Lessons learned from testing these modules will be incorporated into the modules that are currently in development for this effort.

These prototypes are "open loop". The user enters the pulse parameters (voltage amplitude, pulse repetition rate, and pulses per burst), and these parameters are delivered for every ignition event.

TPS has since developed control capabilities coupled with revised high-power charging to enable real-time pulse-to-pulse amplitude control to enable dynamic pulse trains.

Closed-Loop Control

- Why used closed-loop control for ignition? Potential for:
  - Extending spark plug lifetime
  - Reducing prime power consumption
  - Improving performance in dilute conditions

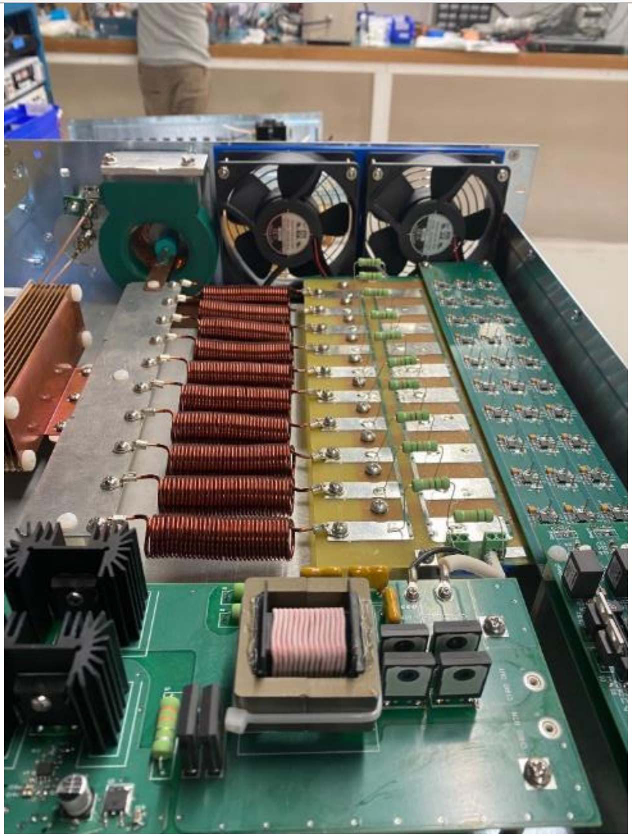
- Our approach to a more automated, adaptive pulse train for ignition requires the integration of three main components:

  - Hardware and algorithm for sensing the discharge mode (i.e., no discharge, corona/glow plasma, or spark)

  - Hardware and algorithm for rapidly adjusting the output voltage of our pulser

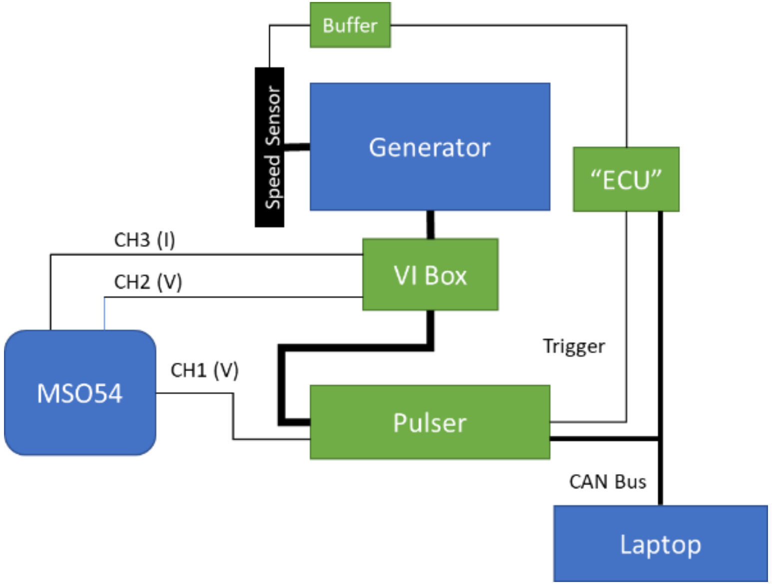
  - Microcontroller for storing / executing the process

Ignition Module Architecture Control and Feedback



- Left: Full scale pulse generator was designed and built and implemented in a large rack mount enclosure for ease of experimentation (lots of space, easy to test new sense techniques)
- Above: Instrumented testing was conducted on a Honda EM 6500 generator, enabling us to record voltage, current traces for different discharge modes

Ignition Module Architecture **Control and Feedback**



- Measurement setup for generator testing shown above
- "ECU" is a custom MCU developed by TPS to eliminate the wasted spark in the generator
- TPS has successfully implemented the sense and control circuitry and demonstrated its efficacy in static cell and engine tests

Key Considerations

- The Transient Ignition Module architecture that was matured at the beginning of this effort has been shown to perform well and to extend stable lean burn operation, but there are challenges with achieving size and cost targets required for commercial adoption

- Interconnect and cabling between the output of the nanosecond ignition module and the igniter is critical for achieving efficient operation

- Appropriate gap distance between the igniter electrodes is critical for each application

Remaining Work / Future Plans

- Further investigation and maturation of new ignition architecture
  - Motivation: realize a more cost-effective and compact circuit to generate high-power nanosecond pulses

- Optimizing igniter design for increased durability and performance
  - Testing conducted during this effort in static cells and engines has indicated that igniter design must be carefully considered in conjunction with sense and control (smart pulse train) to achieve durability requirements for a commercial ignition system

- Late 2021 / early 2022: Engine testing with closed-loop nanosecond ignition module at Argonne National Laboratory
  - Sense and control circuit for smart pulse train delivery has been implemented in multiple systems built at TPS
  - Testing at Argonne will focus on demonstrating this capability with the intent of further optimizing the relationship between stable lean-burn extension and energy delivery / durability

TRANSIENT
PLASMA
SYSTEMS

1751 Torrance Blvd, Torrance, CA 90501 USA

transientplasmasystems.com

DOE Contract: DE-AC36-08GO28308
NREL Subcontract: NHQ-9-82305-06

A Compression-Ignition Mono-Fueled NG High-Efficiency, High-Output Engine for Medium and Heavy-Duty Applications

NGVTF 2021

May 11th

Dr. Jeffrey D. Naber *MTU PI / Director* *APS LABS* jnaber@mtu.edu	***Dr. Brian Eggart*** ***MTU Project Manager / Research Engineer*** **bjeggart@mtu.edu**	*Dr. Sandeep Munshi,* *Senior Director, Advanced Engineering* smunshi@westport.com

Michigan Tech   Westport   APS LABS

Presentation Outline

Motivation & Overview

Michigan Technological University and Westport are addressing natural gas engine emissions and efficiency improvements by demonstrating the feasibility of *compression ignition of directly injected natural gas*. This research will ultimately enable the development of commercialized *mono-fuel natural gas internal combustion engine* technology.

36mo project, will take concept from TRL 2 to TRL 4

Benefits Include:

- 100% NG operation – simplicity of mono-fuel system
- Diesel-like or better efficiency – target 48%
- Maintain high power density: 24 bar BMEP
- 22-25% lower CO_2/GHG emissions compared to diesel, 12-15% lower compared to SI NG
- Payback (long haul) ~1 year

Performance Targets

Displacement	*2.5L/Cyl*
Peak Brake Eff.	*48%*
BMEP	*24 bar*
Eng.Out NOx	*1.0 g/bhp-hr*
TP NOx via SCR	*0.016 g/bhp-hr*

Current best-in-class North American diesel & SI NG engines, emerging technologies (RCCI) in comparison to CIDI

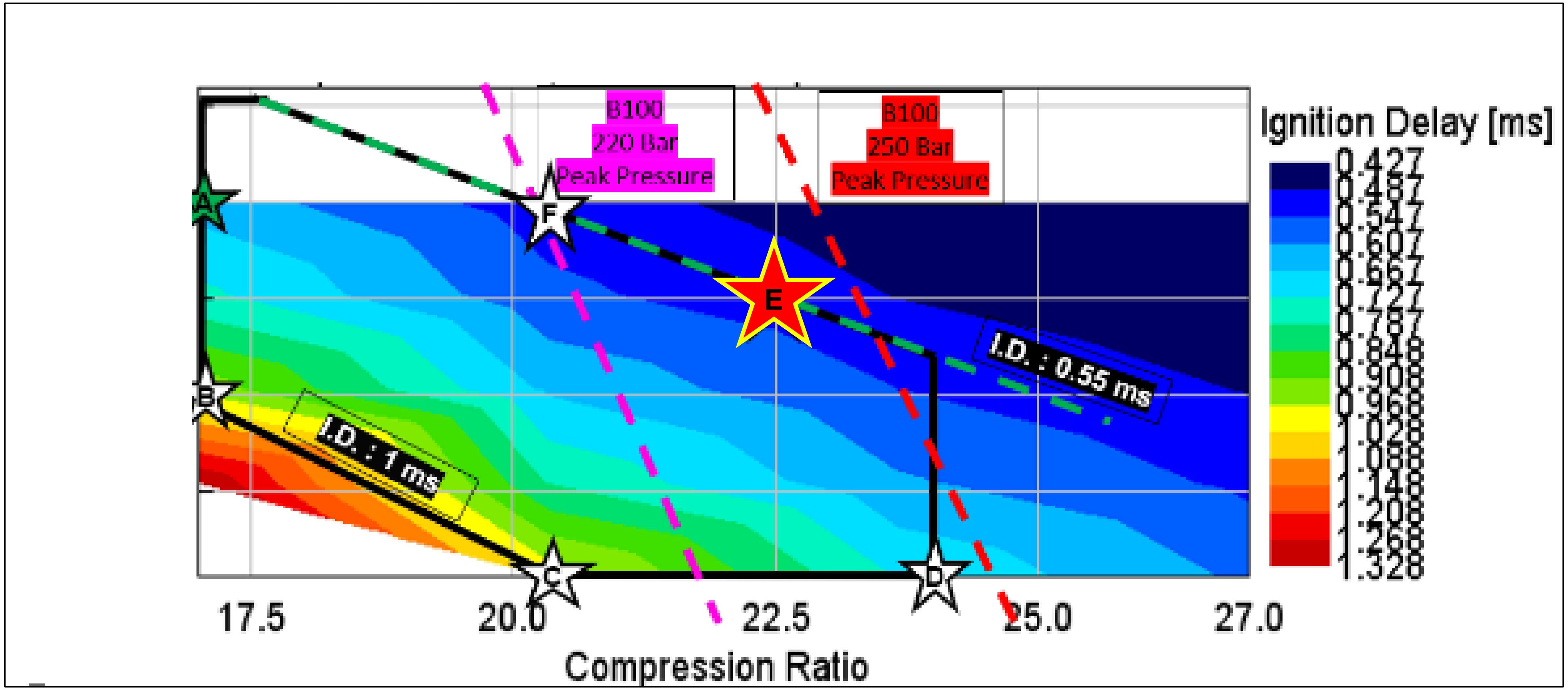
	Diesel BL 2018	SI NG 2018	RCCI[19]	CIDI	CIDI vs. SI NG
Displ (L)	12-15	12	13	12-15	-
BMEP (bar)	24.0	20.0	12	24	+20%
Brake Eff (%)	46%	37%	42%	48%	+30%

Single Cylinder Research Engine (SCRE)

- Cummins ISX15
  - 6 Cylinder (2.5L/cylinder)
  - Bore: 137 mm
  - Stroke: 169 mm
- Cylinder 1 through 5 deactivated (single)
- CR increased to 23.5:1 (17:1 stock)
- Stand-alone development controller
- Selected Instrumentation:
  - A&D CAS Redline II – Cylinder pressure (Kistler 6125C), MAP, Injector current, Optical Crank position, Heat flux (Medtherm), Fuel pressure
  - Temperatures, Pressures, Fuel flow (Coriolis)
  - Horiba emissions analyzer, AVL Smoke Meter
- Intake air heating
- Shop air boost system

SCRE Compression Ratio: Selection

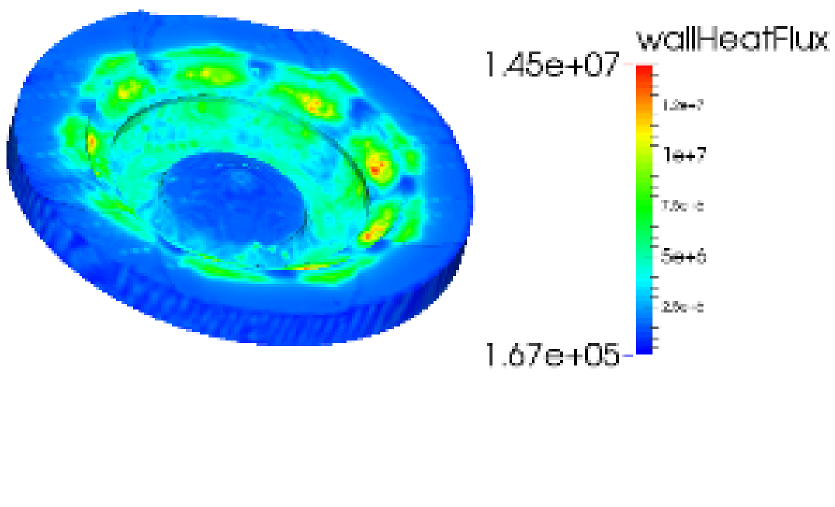
1D simulation utilized to examine the trade-off between increased CR and intake air heating for robust ignition

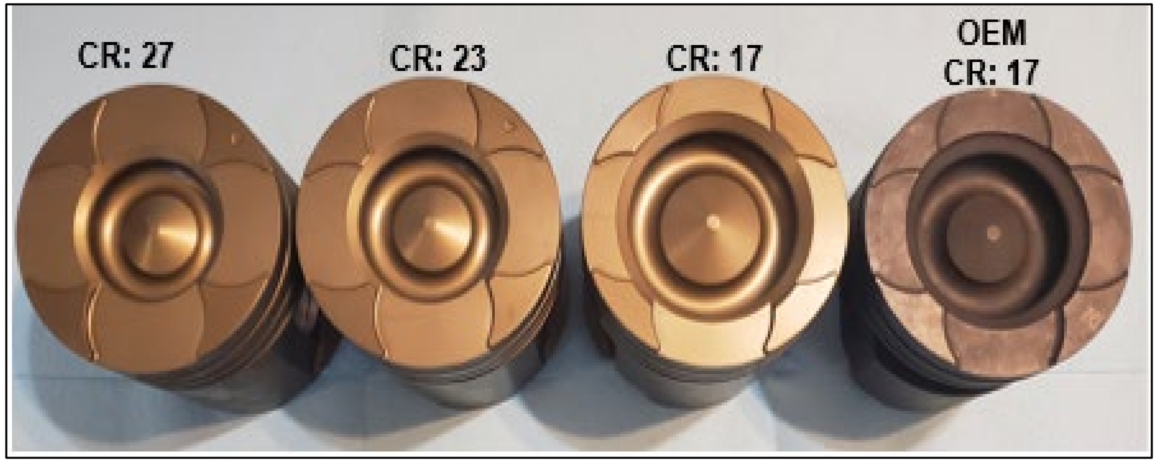


SCRE Compression Ratio: Piston Design

- FEA on higher compression piston designs
  - 23:1 selected as conservative starting point
    - Balance trade-off between CR and intake heating
    - Reduced jet impingement

Peak heat flux 7-14MW/m^2 near the impingement point from thermal model





SCRE: Key Capabilities

Increased Compression Ratio

- Increased CR piston (currently 23.5:1) to achieve required TDC temperature for reliable combustion with low COV of IMEP and relatively low IAT (90°C to 150°C)

Intake Air Temperature Heating (Ambient to 250°C)

- Ability to vary IAT to control TDC temperatures and tune ignition delay

Injection Control (SOI, Duration, Pilot)

- Ability to vary injection timing and implement split injection using injector driver and ECU
- Ability to control combustion phasing via SOI
- Ability to tune split injection timing to improve ignitability and decrease peak ROHR

Injection Pressure (130 to 330 bar)

- Ability to vary injection pressure with Westport's prototype injector and tune burn rates, peak heat release, and ignition delay

Boosted Operation (MAP: ambient to 8 bar)

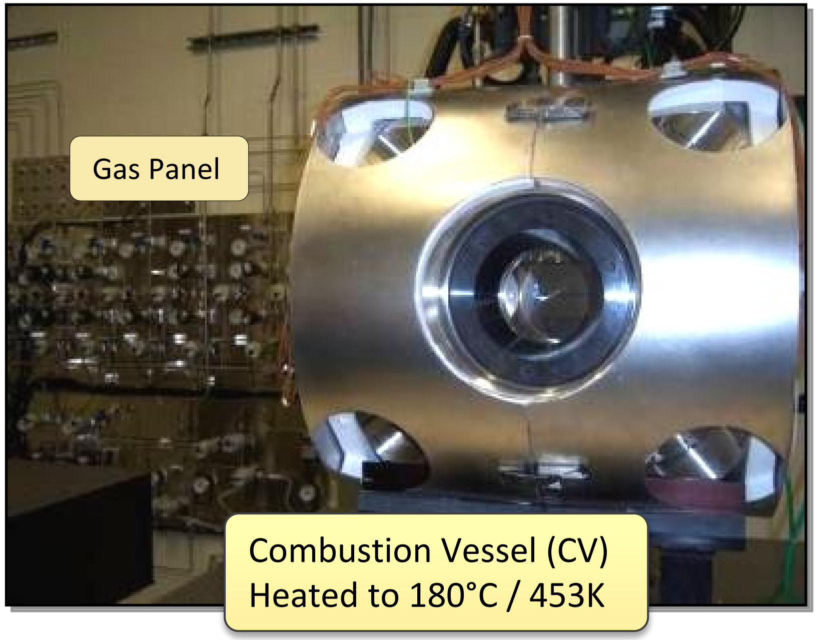
- Ability to operate the engine with test cell boosted air controlled from ambient conditions up to 8 bar absolute with EGR

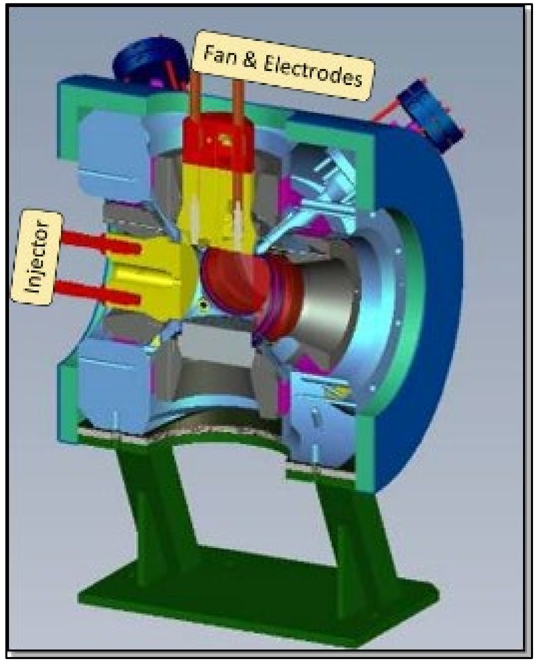
Westport CIDI Injector

- Based on a production Westport HPDI 2.0™ injector
  - Dual-fuel concentric needle configuration
  - Hydraulically actuated by high pressure diesel system
  - Sized for 2.5L / cylinder engine
- Mono-fueled NG Injector Prototype
  - Utilizes hydraulic actuation, but no liquid is injected
  - Internal parts customized for additional sealing against liquid entering the high pressure gas side
  - Operating pressure up to 330 bar

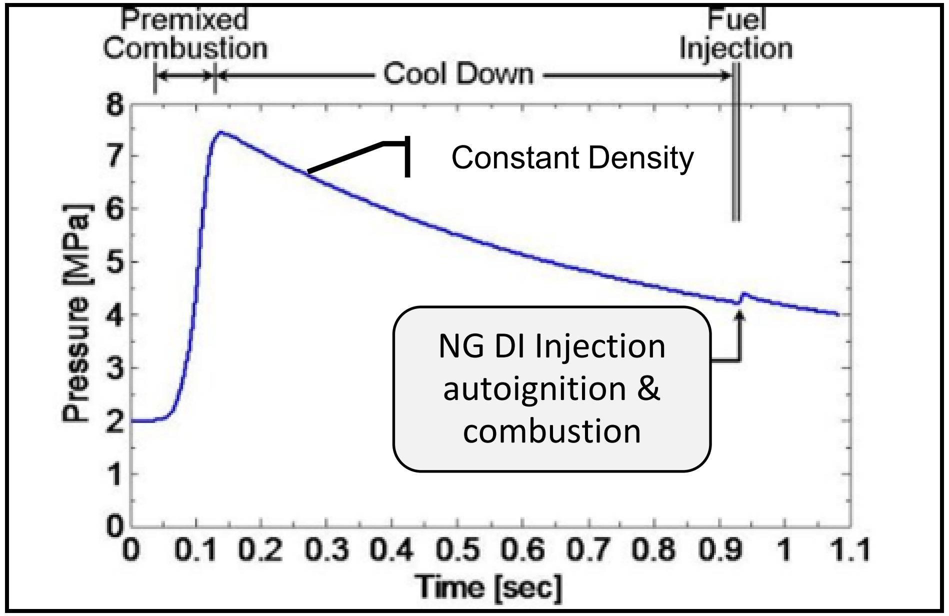
Constant Volume Combustion Chamber (CVCC): Overview

- 1.1 Liter vessel with orthogonal optical windows
- Pre-burn process utilized to achieve CI engine thermodynamic conditions up to 2000K & 350bar with varying dilution

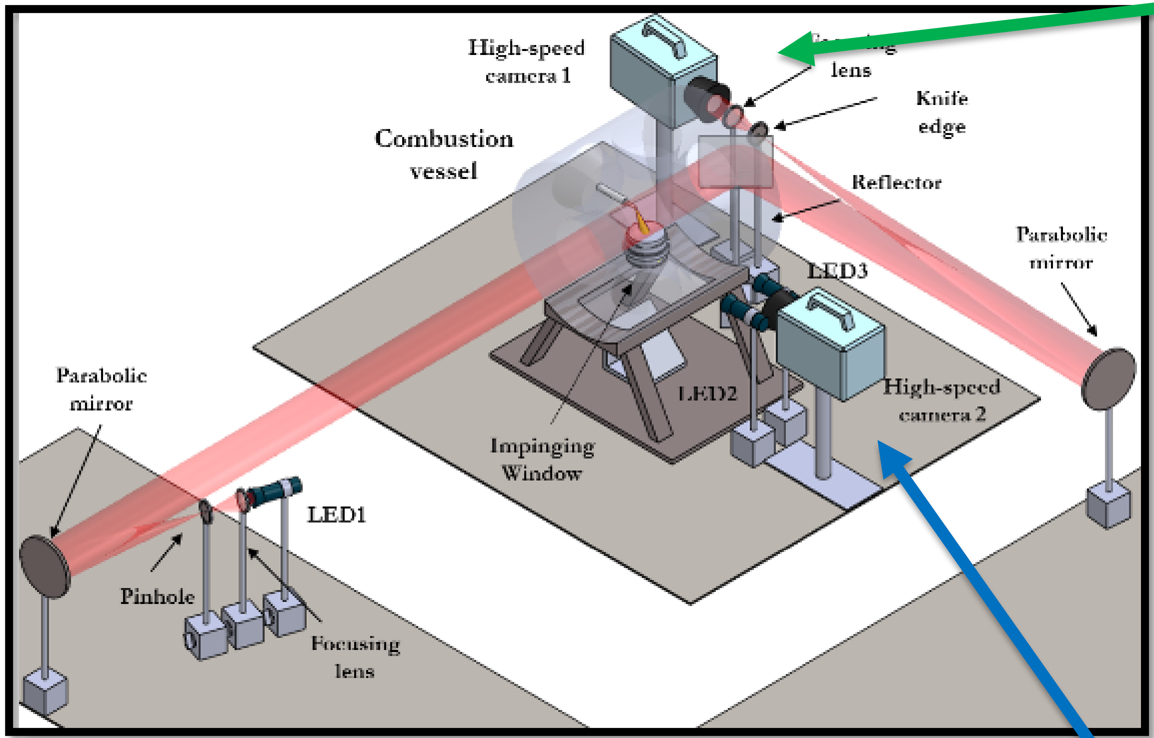


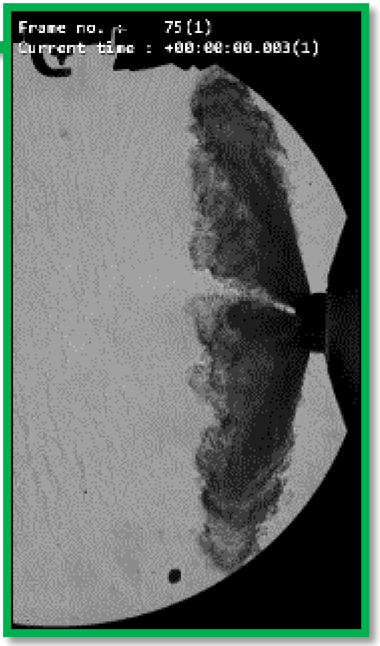


Pre-burn Process



CVCC: Optical Setup





Z-Type Schlieren Photography

- Due to different refractive index of gases, visualize NG Plumes
- Start/End of injection
- Penetration
- 25k fps @ 320x576 pixel

Pressure Data

- Recorded at 100kHz from a Kistler 6001 piezoelectric pressure transducer
- Heat release and ignition delay, …

Natural Luminosity

- CH* and broadband soot oxidation
- ignition delay (temporal) & ignition sites (spatial)
- 10k fps @ 768x768 pixel

CVCC: Testing

Work to date has focused on:

- Ignition delay
  - Charge temperature, density, and oxygen concentration
  - Injection pressure
- Pilot injection vs no pilot injection
- Fuel composition

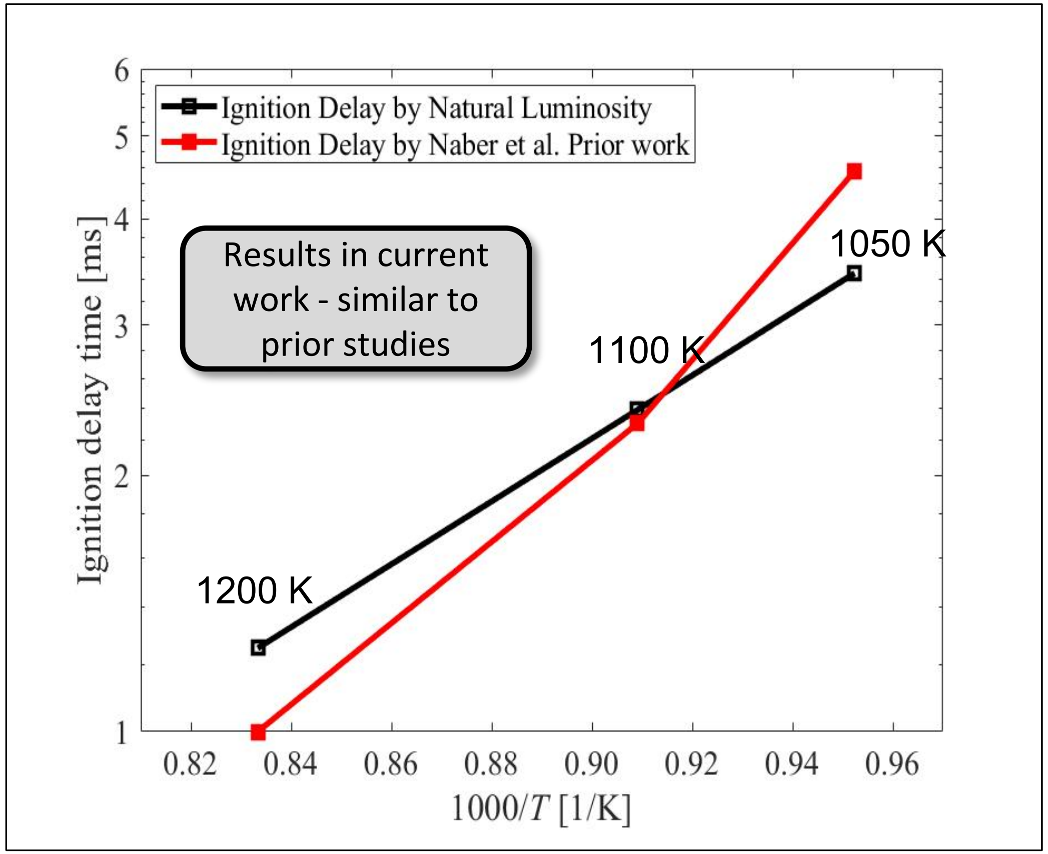
Variable	Test Conditions
Temperature (K)	1050, 1100, 1200
Injection Pressure (bar)	150, 300
EGR	21% O_2, 16% O_2
Fuel	Low Ethane, High Ethane
Injection Strategy	Single Injection, Split Injection (Pilot+Main)

NG Test Fuels

		Methane	*Low Ethane*	*High Ethane*
CH_4	**Methane**	100	95	84.945
C_2H_6	**Ethane**	0	3	12
C_3H_8	**Propane**	0	0.5	1.5
C_4H_{10}	**N-Butane**	0	0	0.035
C_4H_{10}	**i-Butane**	0	0	0.02
CO_2	**CO2**	0	0.5	0.5
N_2	**N2**	0	1	1
Methane Number		100	90	75
	LHV (MJ/kg)	50	48	48
	MW	16.04	16.86	18.43

CVCC: Summary of Findings

- Autoignition and Combustion is observed for $T \geq 1050$ K
- Ignition and combustion is repeatable
- Increase in charge temperature, charge pressure, and injection pressure all reduce ignition delay



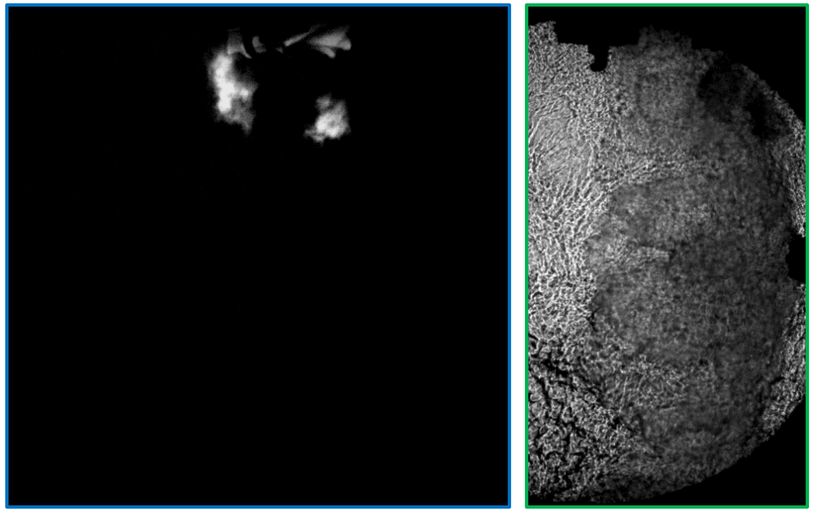
<u>Differences on plot attributed to:</u>

- Different injectors: nozzle diameter, opening rate, single vs multi-hole
- Injection pressure (150 bar vs 207 bar)
- Density (24.4 kg/m^3 vs 20.4 kg/m^3)

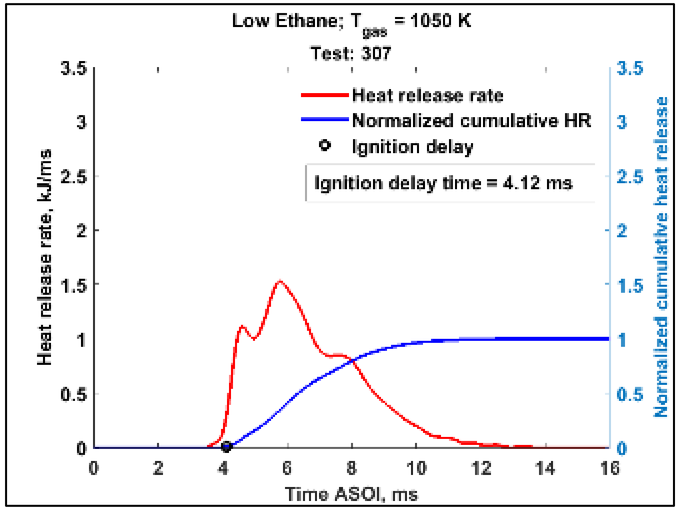
CVCC: Charge Temperature Effect on Ignition Delay of NG

Charge Cond:
1050K
24.5 kg/m^3
21% O_2

Inj Pressure:
150 bar



3.4 ms ASOI

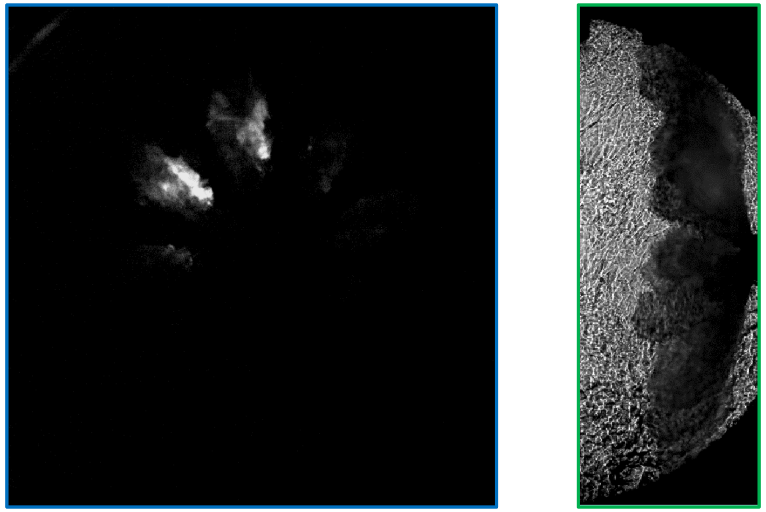


Test 309

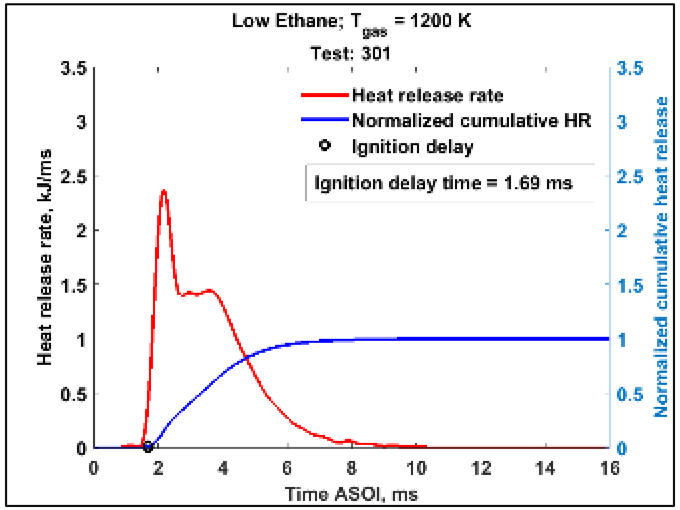
Charge temperature has the strongest dependence

Charge Cond:
1200K
24.5 kg/m^3
21% O_2

Inj Pressure:
150 bar



1.5 ms ASOI



Test 302

CVCC: Injection Pressure Effect on Ignition Delay of NG

Test 302

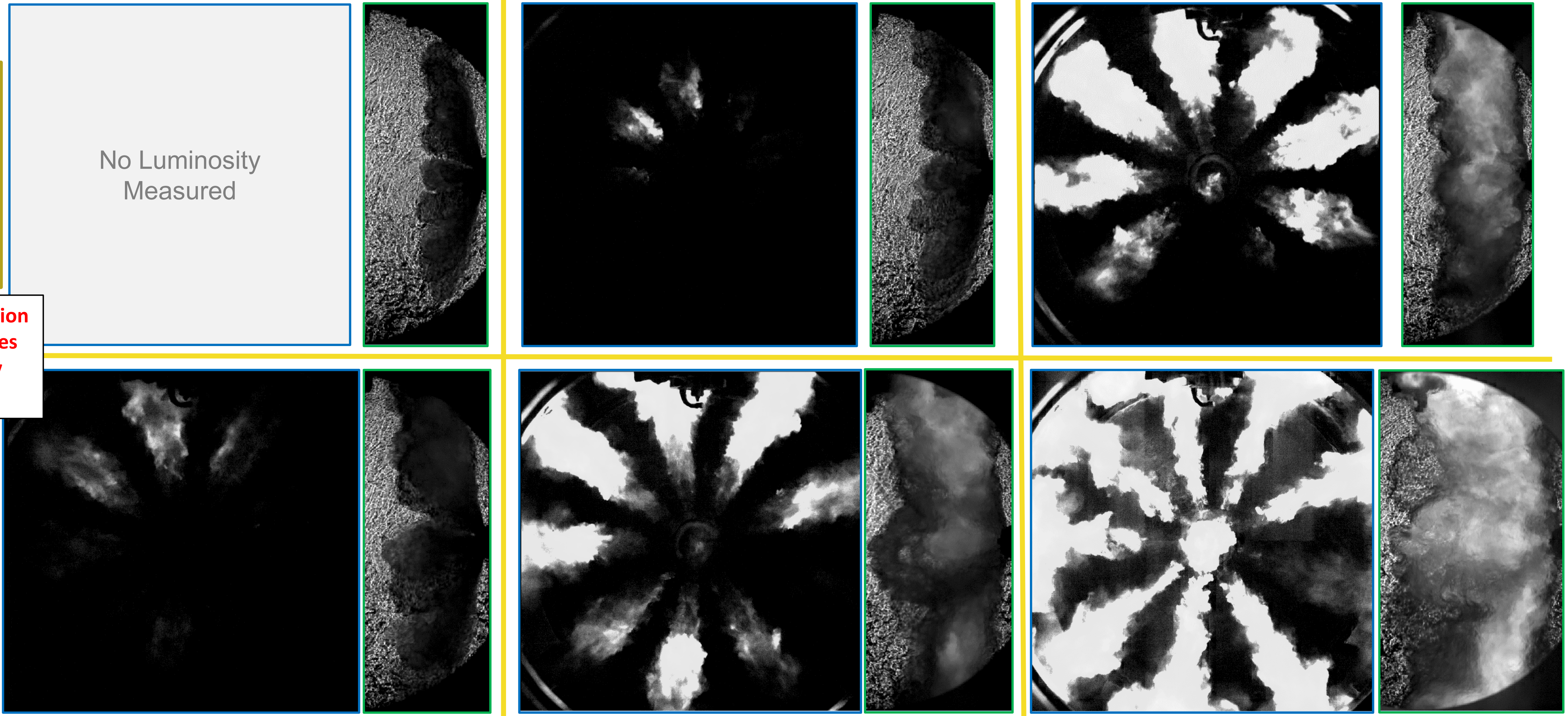
Charge Cond:
1200K
24.5 kg/m^3
21% O_2

Inj Pressure:
150 bar

Increasing injection pressure reduces ignition delay by 25%

Charge Cond:
1200K
24.5 kg/m^3
21% O_2

Inj Pressure:
300 bar



1.2ms ASOI

1.5ms ASOI

2.0ms ASOI

Test 310

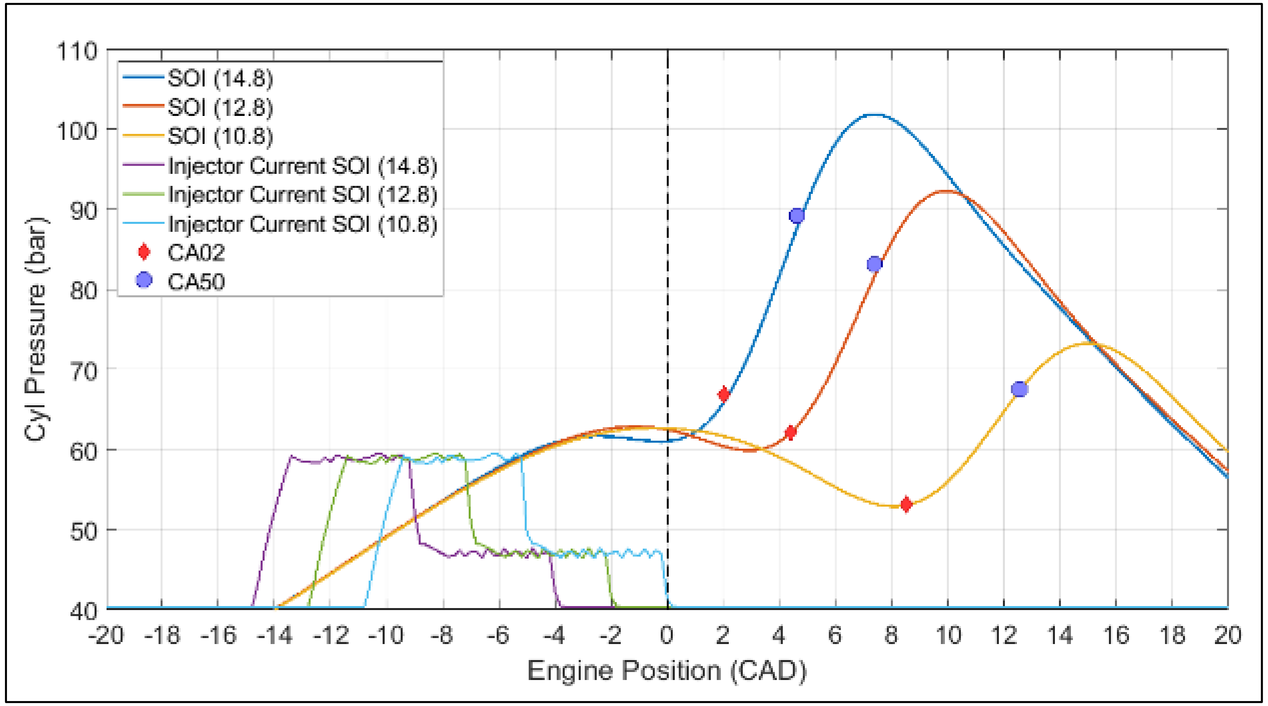
SCRE Testing

- Successful CI of DI NG has been consistently achieved with stable ignition and low COV of IMEP
    - Testing conducted with standard line gas supplied to the building (sales gas)
- Tested effects of:
    - Injection timing (SOI) at a fixed IAT
    - IAT sweep at a fixed SOI
    - NG injection pressure (2 pressures)
    - Pilot injection

Engine operates similar to a diesel CI engine with respect to response to injection and other controls

SCRE Testing: ***SOI SWEEP***

Test	IAT	TDC Temp Calc.	Eng. Speed	Inj. Dur	SOI	lambda	Diesel Press	CNG Press	IMEP (G)	COV IMEP	CA02	CA10	CA50	CA90	CA10-90	Ignition Delay	Peak RoHR
#	(°C)	K	(rpm)	(ms)	°BTDC	(-)	(bar)	(bar)	(bar)	(%)	°ATDC	°ATDC	°ATDC	°ATDC	CA°	ms	J/CAD
9	124	1211	1300		14.8	1.21			6.7	2.4	2.0	3.3	4.7	9.2	5.9	1.47	753
10	124	1215	1300	1.40	12.8	1.21	145	137	6.8	2.2	4.4	5.7	7.5	12.1	6.4	1.53	614
11	124	1216	1300		10.8	1.22			6.9	2.2	8.5	10.1	12.7	17.1	7.0	1.79	410



SOI Sweep Completed at IAT: 124C

- **Combustion phasing controlled by SOI timing**
- **Reasonable combustion stability (will improve with improved fuel system pressure control)**
- Ignition delay increased from 1.47ms to 1.79ms (0.32 ms) as SOI was retarded from 14.8 to 10.8 °BTDC
- Gross IMEP peaked at SOI = 10.8° (CA50 12.7°ATDC)

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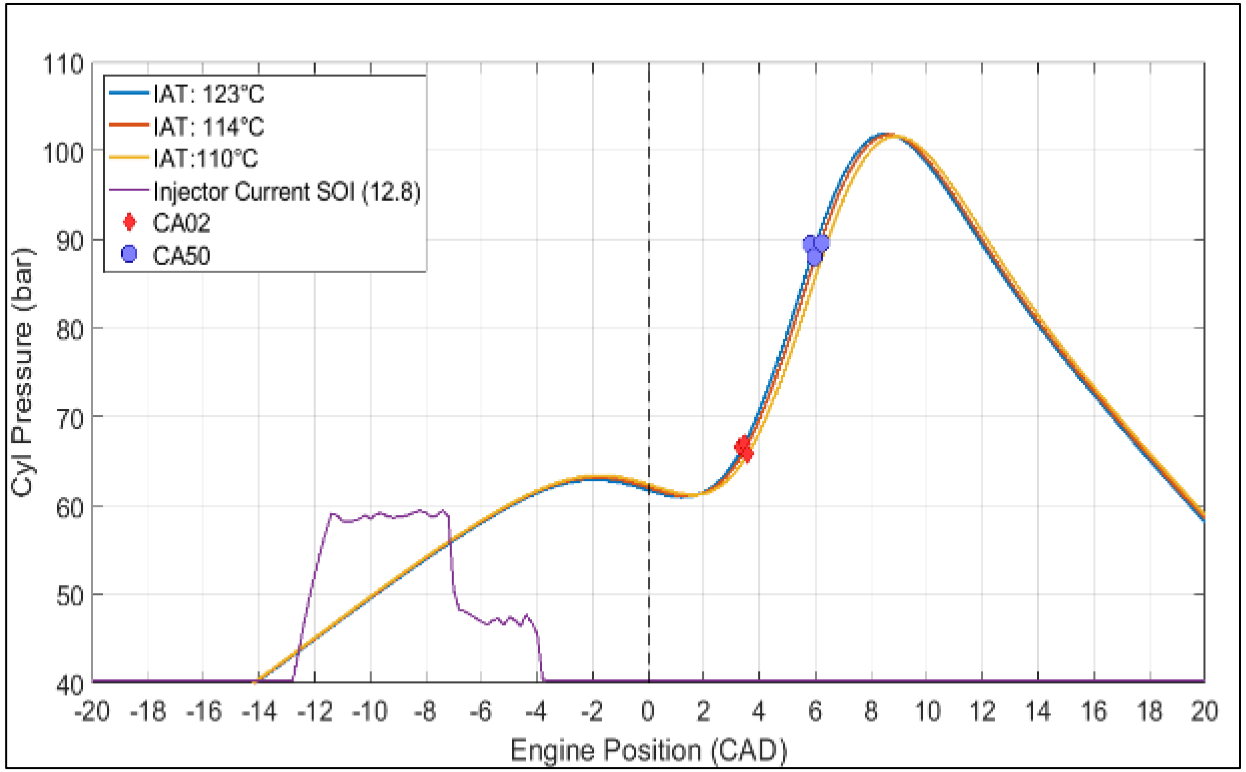
SCRE Testing: ***IAT SWEEP***

Test #	IAT (°C)	TDC Temp K	Eng. Speed (rpm)	Injection Duration (ms)	SOI °BTDC	lambda (-)	diesel PRES (bar)	CNG PRES. (bar)	IMEPG (bar)	COV (%)	CA02 °ATDC	CA10 °ATDC	CA50 °ATDC	CA90 °ATDC	CA10-90 CA°	Ign Delay ms	Peak RoHR J/CAD
18	123	1213	1300	1.15	12.8	1.16	193	186	7.0	1.8	3.3	4.4	5.8	9.5	5.1	1.38	746
20	114	1189	1300		12.8	1.19			7.0	1.7	3.4	4.5	6.0	9.7	5.2	1.40	729
21	110	1179	1300		12.8	1.17			7.1	2.3	3.6	4.7	6.2	9.7	5.0	1.42	698



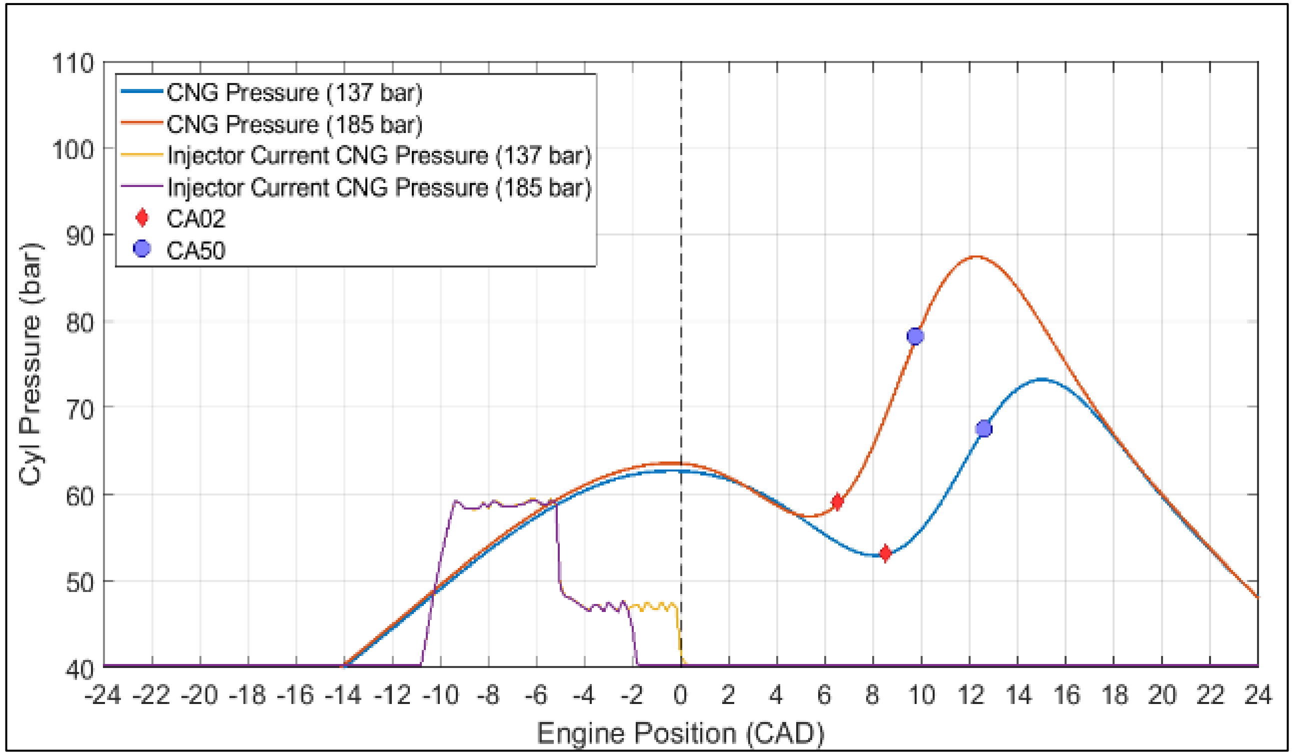
IAT Sweep Completed With SOI at 12.8°BTDC

- **TDC temperatures for all cases were adequate for ignition with good combustion stability**
- **Only a small decrease in ignition delay with increasing temperatures – near the limit – lower IAT's possible**
- Ignition delay decreased as IAT was increased, 1.42 ms to 1.38ms (0.04 ms) as IAT changed 110°C to 123°C
- COV of IMEP increases slightly as IAT was decreased (1.8 to 2.3%)

Michigan Tech Westport APS LABS

SCRE Testing: ***NG INJECTION PRESSURE***

Test #	IAT (°C)	TDC Temp K	Eng Speed (rpm)	Injection Duration (ms)	SOI °BTDC	Lambda (-)	diesel pres. (bar)	CNG pres. (bar)	IMEP (G) (bar)	COV IMEP (%)	CA02 °ATDC	CA10 °ATDC	CA50 °ATDC	CA90 °ATDC	CA10-90 CA°	Ign Delay ms	Peak RoHR J/CAD
11	124	1216	1300	1.40	10.8	1.22	146	137	6.9	2.2	8.5	10.1	12.7	17.1	7	1.79	410
19	120	1200	1300	1.15	10.8	1.19	194	185	7.1	1.8	6.5	7.8	9.8	13.4	5.6	1.54	547

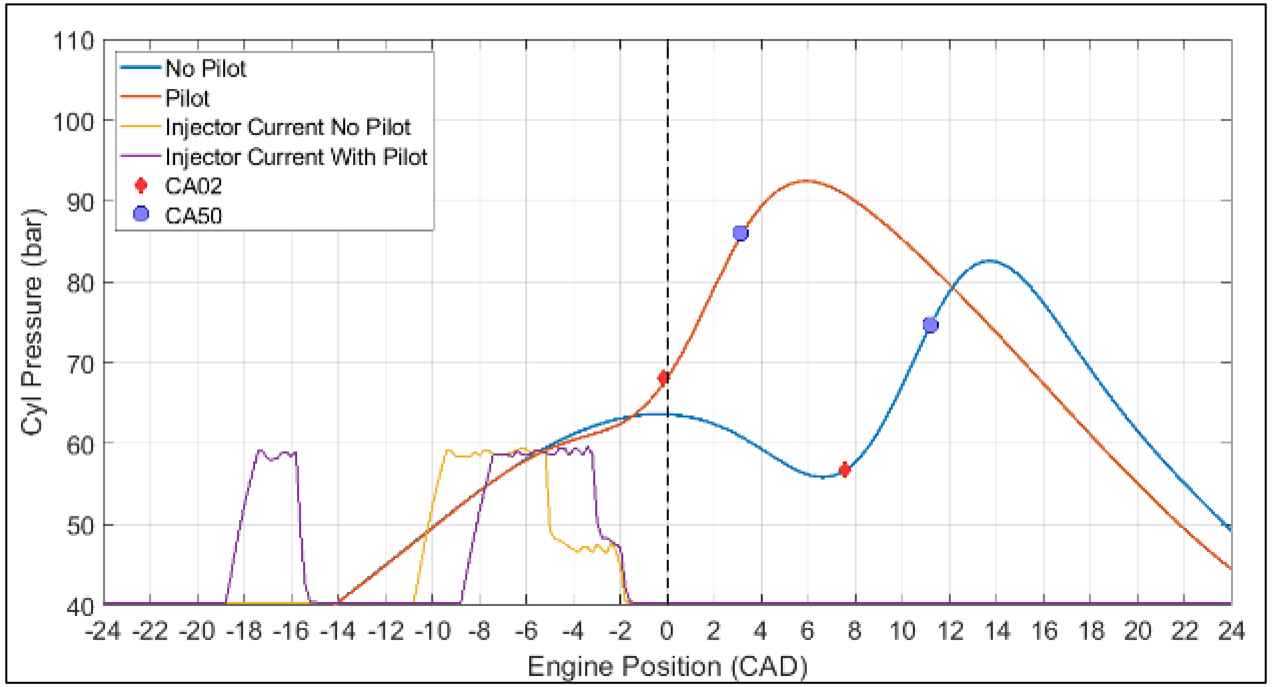


<u>CNG Pressure Sweep (137 bar → 186 bar)</u>

- **Injection pressure reduced ignition delay (15%).**
- **Additional increase in injection pressure is expect to further reduce ignition delay (Based on CVCC findings)**
- Peak Rate of Heat Release increased with injection pressure – Potential to reduce by adding EGR and refining injector design

SCRE Testing: ***Pilot vs. No Pilot***

Test #	IAT (°C)	TDC Temp K	Eng Speed (rpm)	Injection Duration (ms)	SOI °BTDC	CNG PRES (bar)	pilot dur (ms) (ms)	pilot SOI °BTDC	Lambda (-)	diesel Pres. (bar)	IMEP (G) (bar)	COV IMEP (%)	CA02 °ATDC	CA10 °ATDC	CA50 °ATDC	CA90 °ATDC	CA10-90 CA°	Ign Delay ms	Peak RoHR J/CAD
22	107	1177	1300	1.15	10.8	185	N/A	N/A	1.17	194	7.2	1.6	7.6	8.9	11.2	14.5	5.6	1.68	447
24	100	1143	1300	0.90	8.8		0.40	18.8	1.22	192	6.5	2.1	-0.2	0.9	3.1	9.8	8.9	0.42	343



Addition of Pilot Injection

- **Pilot injection decreased the peak ROHR (25%) and increased burn duration by reducing the pre-mixing time**
- Reduced ignition delay (1.68ms to 0.42ms) to below our target of 0.5ms

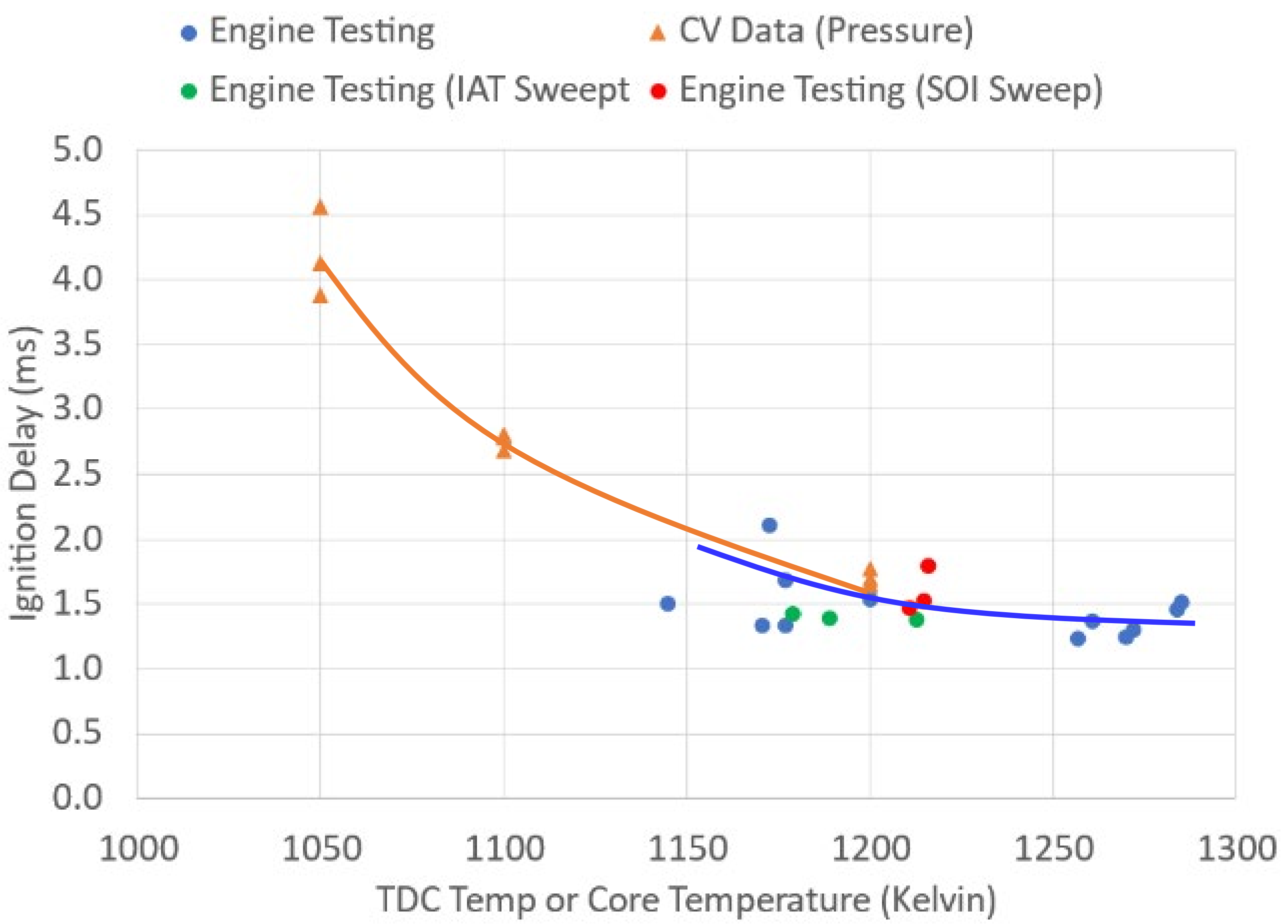
Ignition Delay: CV & SCRE Comparison

SCRE Testing:

- Trend over the range of 1140-1270K exhibits ignition delays similar to CVCC ignition delay
- Ignition delay variation for the engine data includes changes in SOI, Injection Pressure, and IAT
- 1150K TDC temperature is sufficient for reliable NG ignition and combustion ***(COV IMEP < 3% All Cases)***

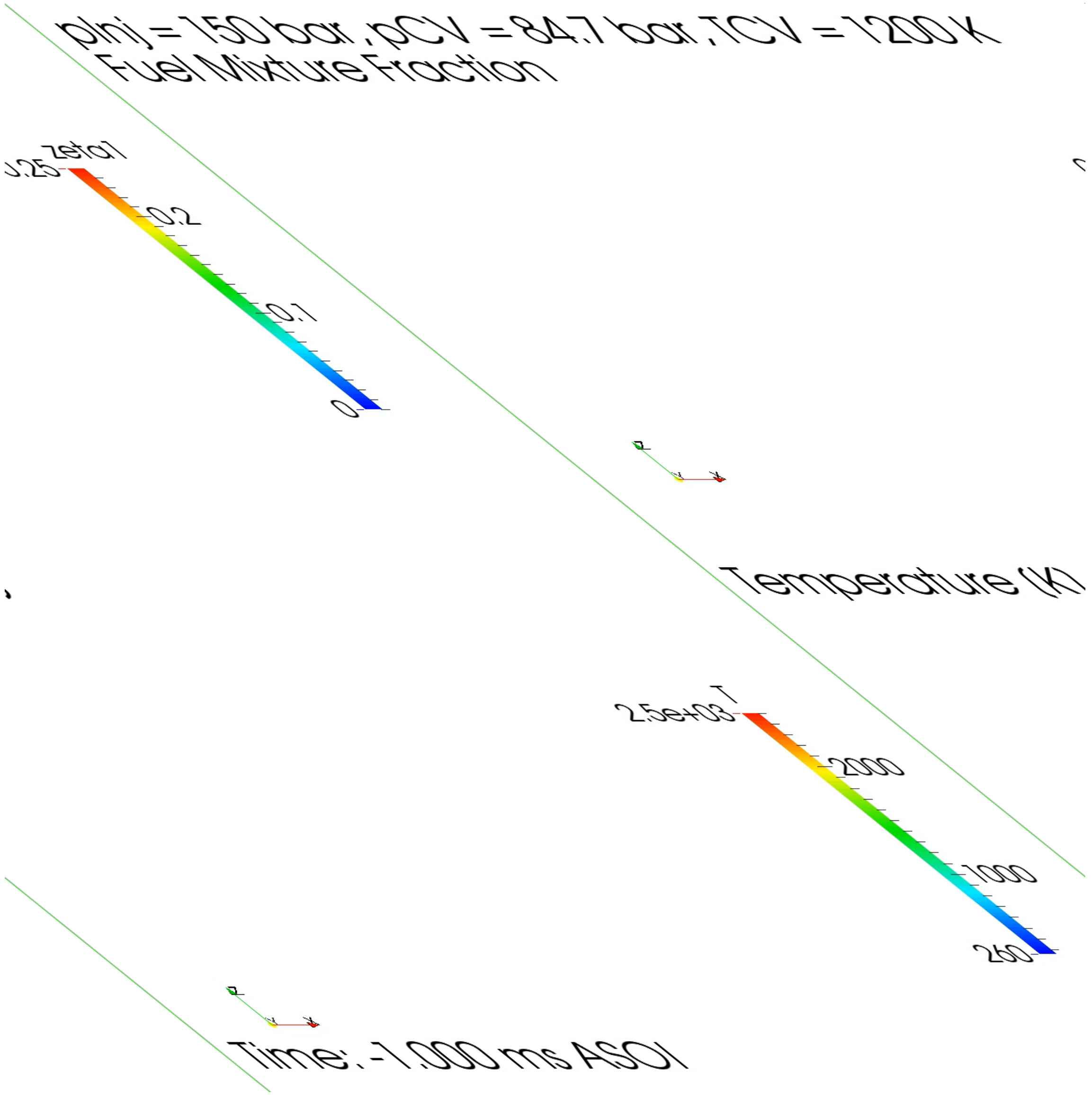
CVCC Testing

- Provides a well controlled environment to investigate the injector performance, ignition and combustion
  - Quantitative jet & combustion data for CFD model validation
- Independently change charge pressure, temperature, and composition as a tool to investigate combustion regimes an limits and impact of injector design



Modeling & Simulation: CV Ignition Visualization

- Jet penetration and combustion model tuning
- Ignition timing matches CVCC at about 1.55 ms
- Further validation underway with additional fuel compositions
- Tool to investigate potential design and operating trade-offs and improvements



CI of DI NG – Methods for Achieving Robust Ignition

Current Approach:

- Intake air heating – sufficient to meet compression temperature requirements for reliable ignition (23:1 & 100°C)
- Increased compression ratio – works in tandem with intake heating
- Pilot injection, injection pressure, …

Additional methods being explored:

- Thermal barrier coatings – have test piston/valves available
- Cetane booster – under investigation (chemical kinetics)
- CAM phasing – increase hot residuals

Summary of Future Work

CVCC:

- Testing of expanded boundary conditions and extended injection pressure range

SCRE:

- Near term testing includes: Low & Mid Load Sweeps (4 to 12 bar), Expanded range SOI Sweep, Injection Pressure Sweep, and IAT Sweep
- DOE matrix to map out the operational space for CI DI NG (speed, load, IAT, boost (MAP), injection pressure, EGR)
- Mapping and optimization of: Fuel consumption, Peak pressure, and NOx emissions

Simulation & Modeling:

- Utilize Engine and CVCC data for further validation of 1D and CFD models
- Combustion optimization studies
- Piston heat transfer simulation
- Fuel consumption modeling

Summary

- Boundary conditions, trends, operating limits, and performance predictions established based on CFD and 1D engine simulations $\rightarrow$ selection of initial compression ratio & intake heating
- Prototype mono-fuel injectors developed and available for experimental testing
- Injection and ignition characteristics have been quantified at engine relevant conditions in the CVCC
- Engine test platform (SCRE) developed and demonstrated reliable compression ignition of direct injected natural gas
- Testing and simulation under way to further investigate and refine CI of DI NG combustion technology

Acknowledgements

This NGVTF presentation was developed based upon funding from the Alliance for Sustainable Energy, LLC, Managing and Operating Contractor for the National Renewable Energy Laboratory for the U.S. Department of Energy. Subcontract No. NHQ-9-82305-06, in Partnership with Westport Fuel Systems Inc.

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Tyler White
Sahil Bakde
Dr. Sandeep Munshi
Ashish Singh
Dr. Jim Huang
Marco Turcios

Discussion and Wrap-up

Supporting Slides

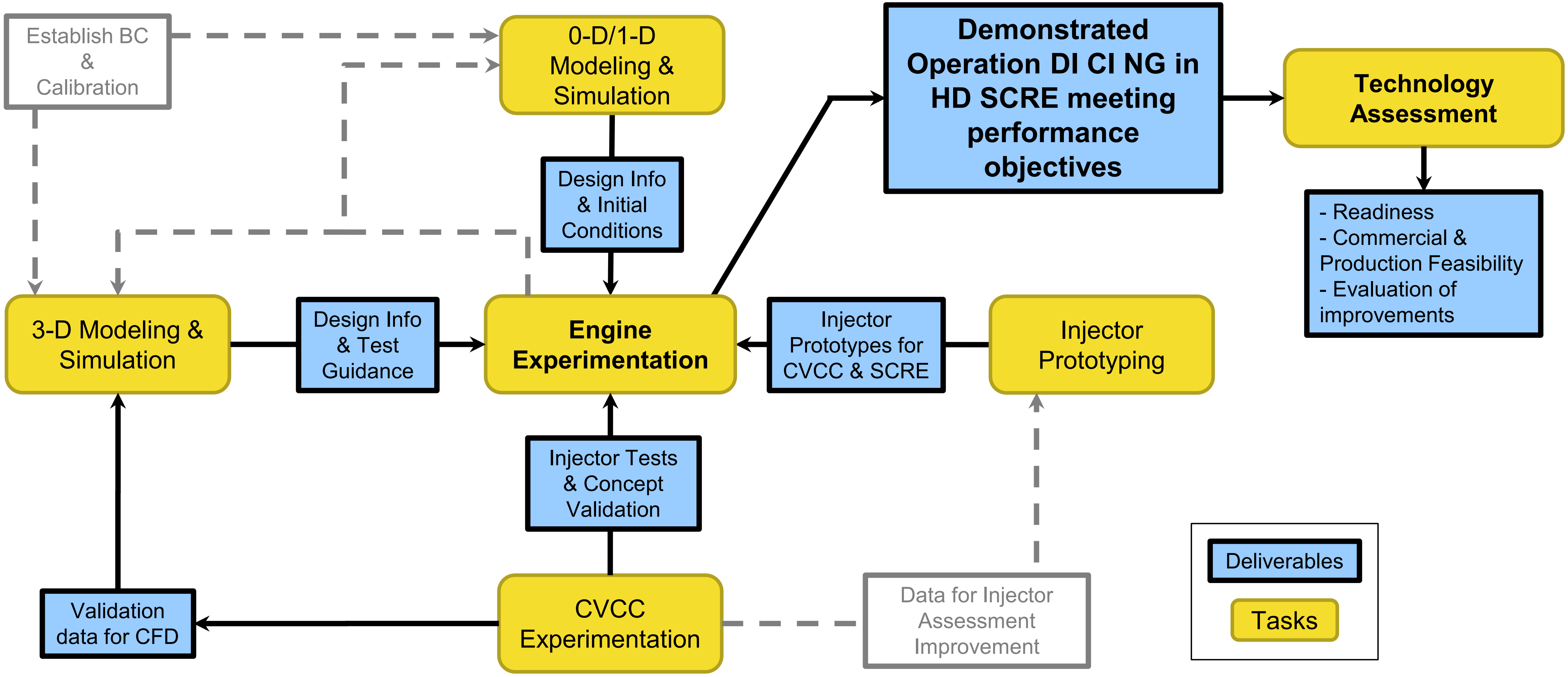
Motivation & Overview

	Current NG products		This project
	Late cycle, direct injection (HPDI 2.0)	Premixed, stoich. with spark ignition	Compression Ignition Direct Injection (CIDI)
	Diesel-like		Diesel-like or better
	~24 bar		~24 bar
	20% below diesel		22-25% below diesel
NOx emissions		0.02 g/bhph in service	
Fuel	~95% NG, 5% diesel	100% NG	100% NG
			~1 year

- CIDI of NG retains high efficiency, and power of non-premixed combustion
  - Significant fuel system complexity / cost reduction vs. HPDI
- Combining diesel-like efficiency with the lower up-front costs of a simplified, mono-fuel injection system offers CIDI as a compelling commercial proposition while addressing key market barriers

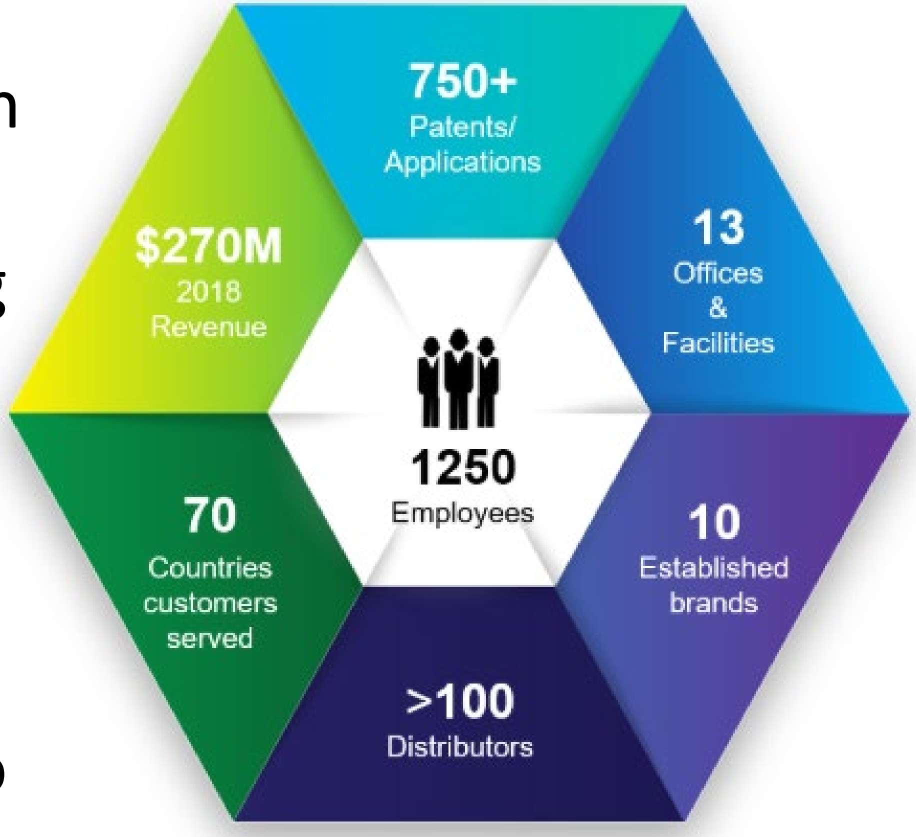
Subcontract:
NHQ-9-82305-06

Overview of Project Structure



Westport Background

- Westport Fuel Systems is a clean transportation technology company focusing primarily on natural gas vehicle/engine technologies serving the LD, MD and HD sectors.
- We Have customers in more than 70 countries with leading global transportation brands. Customers that demand new, economic, sustainable, and efficient transport solutions to meet increasingly stringent emission standards to address the challenges of urban air quality and climate change.

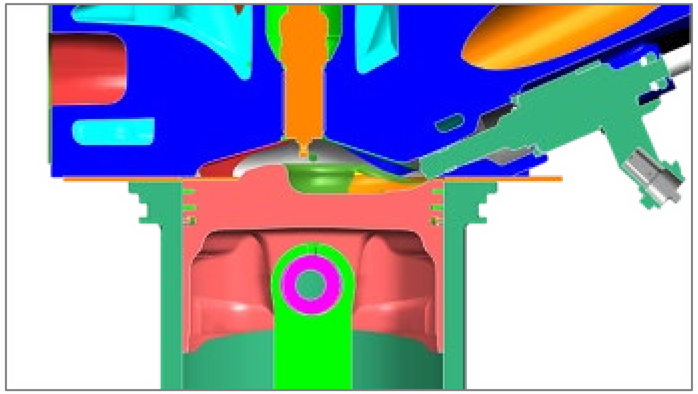


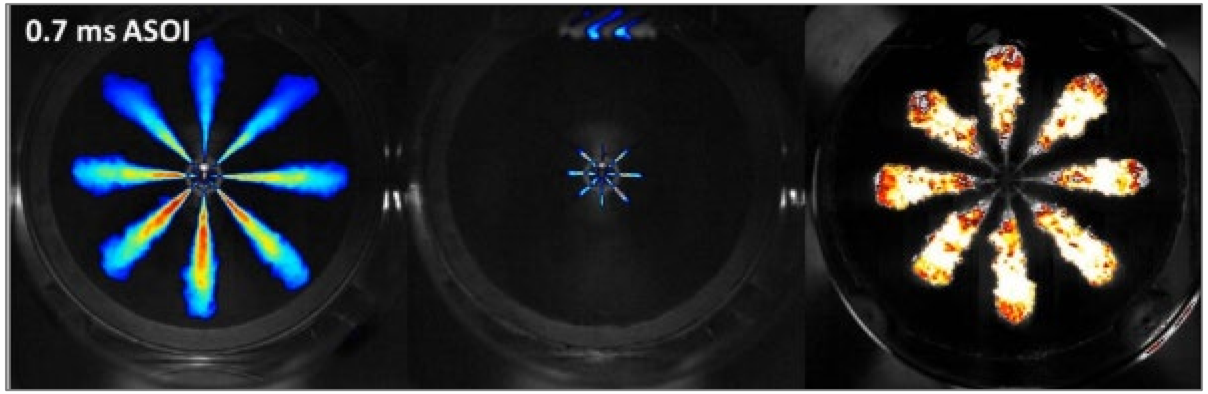
Subcontract:
NHQ-9-82305-06

APS LABS (Advanced Power Systems Research Center)

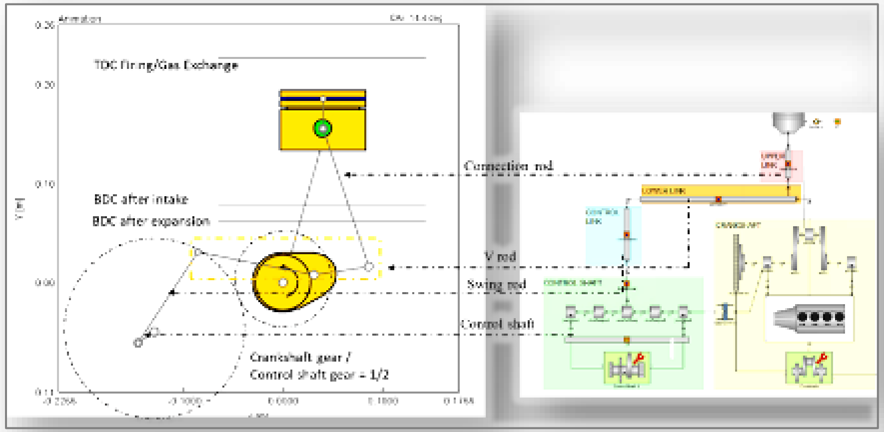
Michigan Tech Westport™ APS LABS

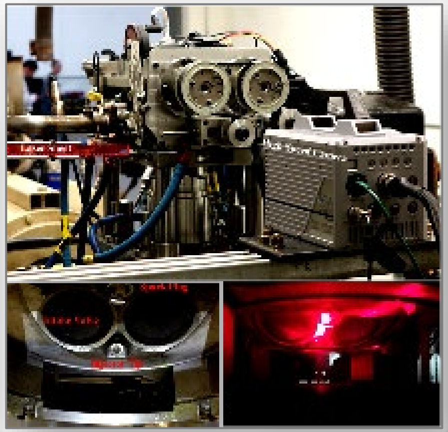
APS LABS IC Engine Research



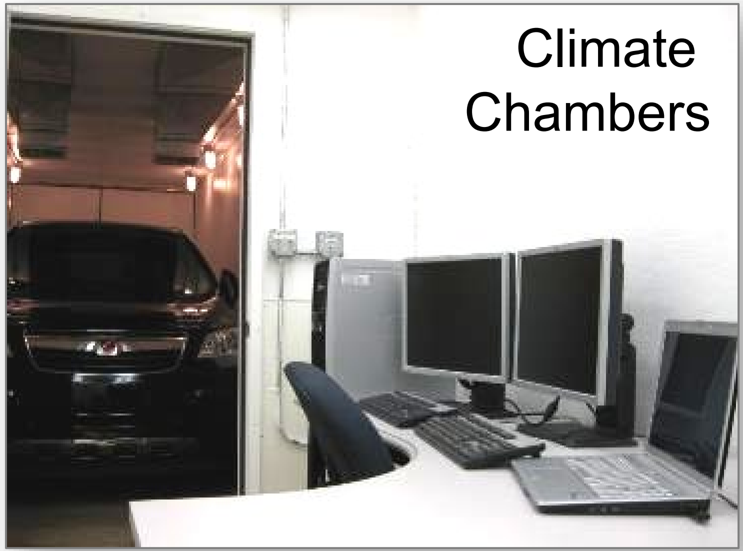


Fundamental and Applied Research & Development



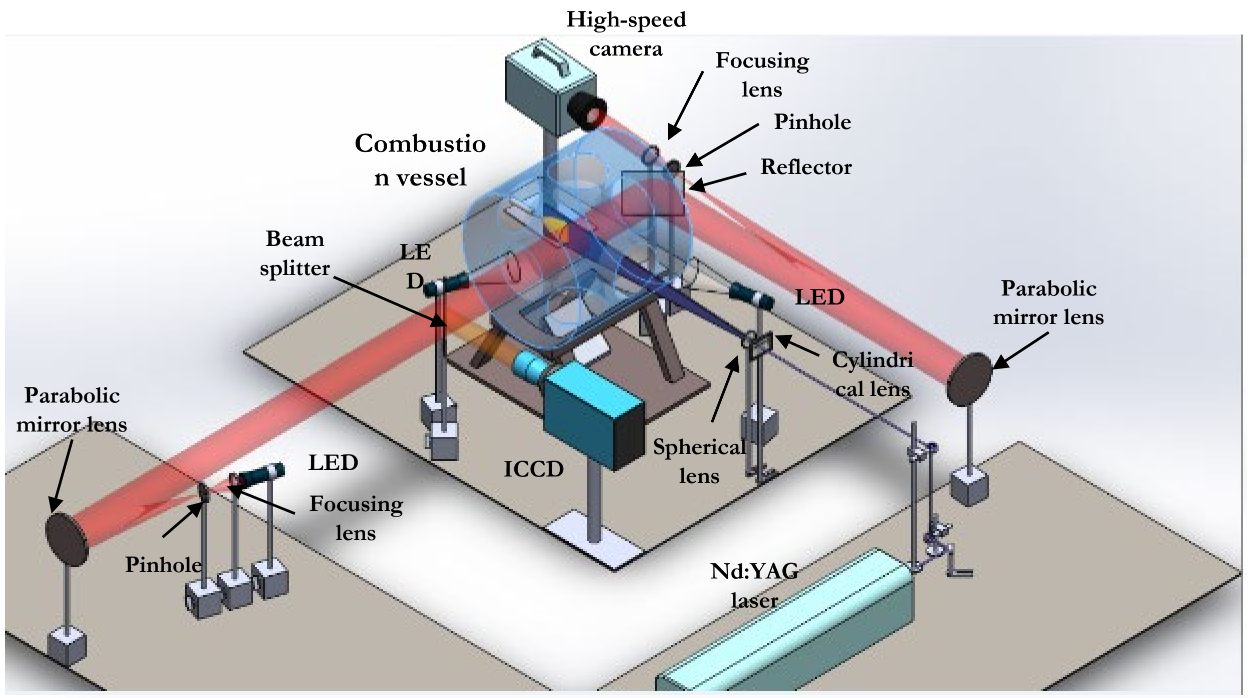


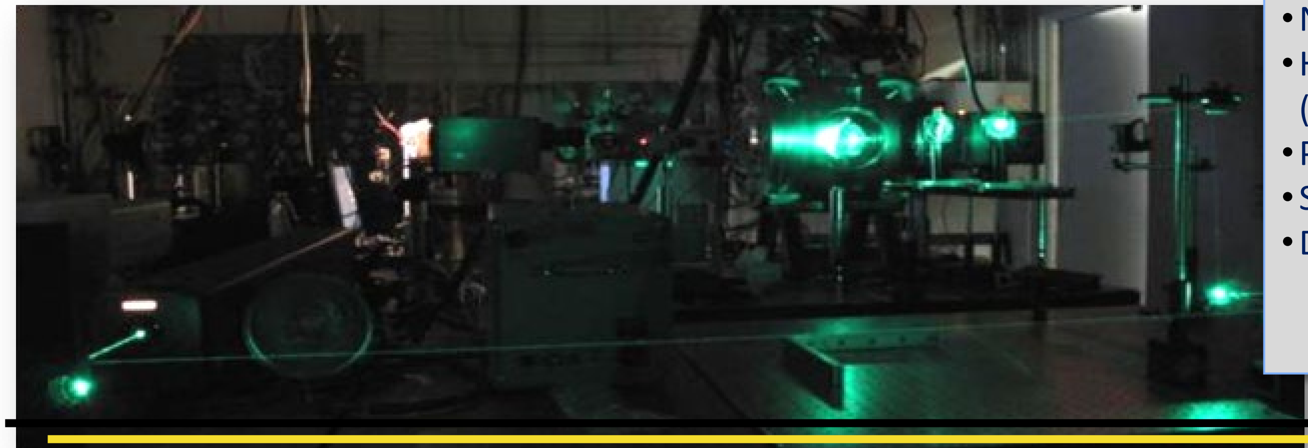
Powertrain Facilities



- Fourteen IC engine dynamometer test ends
  - Single cylinder research engines to 500 hp HD diesel
  - 1200 hp available upon special request
  - CI, SI, 2-stroke, alt fuels, gaseous, liquid
  - Specialized fuels including HPNG – 3600 psi
- Optical Fuel, Spray & Combustion Lab
  - Gasoline/Diesel/NG/Biogas/Syngas
- Transmission/Torque Test Cell
- Vehicle & Component Scale Cold chambers
- Two Vehicle Chassis Cells
- Mobile Lab
- Related facilities
  - Electronics / Mechatronics
  - Controls & Embedded Sys.
  - Fuel Cell Labs
  - NVH, CFD
  - Tire Testers

CVCC Diagnostics





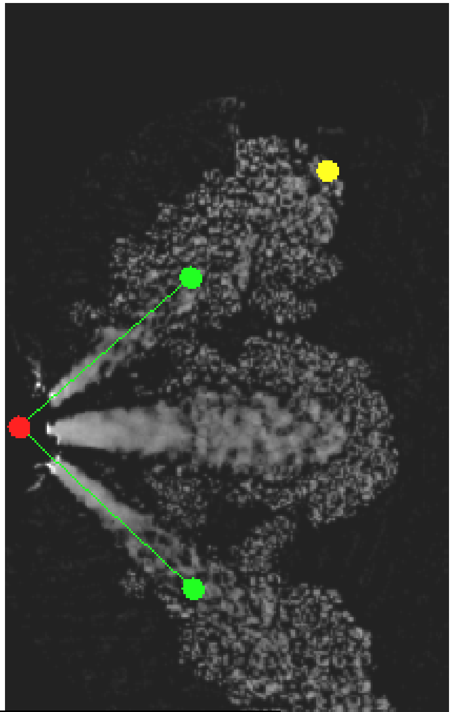
Spray Measurements
- Massing & ROI
- Droplet Sizing
- Cavitation
- Surface impingement and heat flux

Combustion Measurements
- Ignition Delay
- Heat Release Rate
- Radiant heat flux
- Surface
- Cavitation

Diagnostics
- Shadow/Schlieren: Spray & Ignition
- Mie Scattering: Spray
- PLII/PLIF/PLIEF: Species
- Natural luminosity: Soot
- High Speed Chemiluminescence: (OH*, CH*)
- Particle Image Velocimetry
- Spectroscopy
- Droplet sizing – Malvern Spraytec

Cameras
- PCO DiCam Pro ICCD Camera
- PI IMAX 4 ICCD Camera
- Photron SAx high speed camera
- PCO SensiCam CCD Camera

Laser and Light Sources
- High power Nd:Yag laser
- 5 W Argon-Ion Laser
- Pulse flashlamp
- Pulse LED's



HP NG DI

CNG Full Fills with a Complete Smart Fueling System

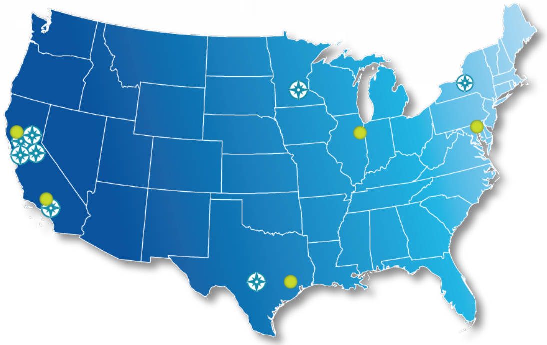
May 2021

Jason Stair, Senior Engineer
GTI

75-year History of Turning Raw Technology into Practical Energy Solutions

FOR A BETTER ECONOMY AND A BETTER ENVIRONMENT

SUPPLY	CONVERSION	DELIVERY	UTILIZATION



World-class piloting facilities headquartered in Chicago area

- RESEARCH & DEVELOPMENT
- PROGRAM MANAGEMENT
- TECHNICAL/ ANALYTICAL
- CONSULTING
- TRAINING
- COMMERCIALIZATION

400+ EMPLOYEES

U.S. Office Locations

GTI Office Locations

- Des Plaines, IL (Headquarters)
- Capitol Hill
- Woodland Hills, CA
- Davis, CA
- Houston, TX

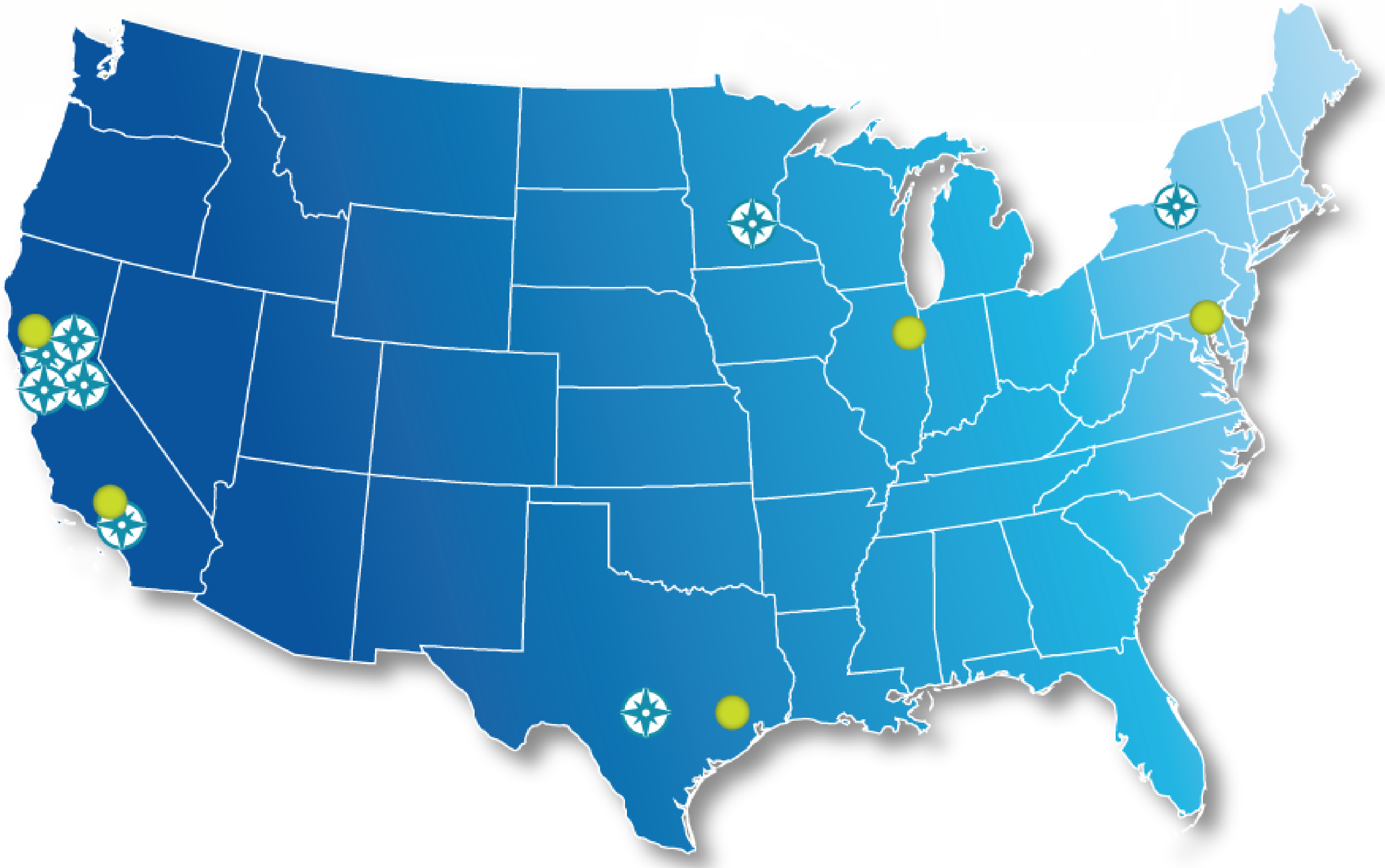
GTI Subsidiaries

FRONTIER energy

- Oakland, CA
- West Sacramento, CA
- Davis, CA
- San Ramon, CA
- Los Angeles, CA
- Cazenovia, NY
- Austin, TX

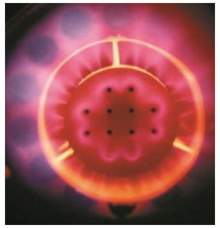
Energy Insight, a division of Frontier Energy

- Chanhassen, MN



GTI Technology Expertise

Unconventional Oil & Gas
- Fracturing optimization
- Water management
- Methane monitoring and mitigation



Combustion Systems
- Advanced design and modeling
- Industrialburner development
- Oxy combustion
- Low NO_x equipment

Infrastructure Asset Management
- Data analytics and AI
- Pipeline GIS location, inspection, and maintenance
- Methane emissions

Gasification & Partial Oxidation
- Raw hydrocarbons to syngas
- Entrained flow and fluidized bed processes

Clean Fuels and Chemicals
- Biomass-to-hydrocarbon fuels
- Gas to Liquids
- Direct conversion of methane

Pipeline Integrity
- Advanced risk models
- Testing/analysis
- Materials research

Gas Processing
- Advanced separations
- Gas reforming and synthesis
- Carbon capture

Power Generation
- Combined heat and power
- sCO_2 power cycles
- Oxy-PFBC process

Biological and Chemical Analyses
- Methanotrophic microbes
- qPCR genotyping
- Microbial influenced corrosion

Hydrogen (H_2)
- Sorbent enhanced reforming
- Dispensing
- Electrochemical conversion

Alternative Transportation
- Vehicle and station demonstrations
- Advanced fueling station component development
- Renewable Natural Gas

Energy Efficiency (EE)
- Design and oversee EE programs
- Industrial equipment
- Commercial/residential appliances
- Building envelopes

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NGV Infrastructure Sponsors - Thank you!!!

U.S. DEPARTMENT OF ENERGY

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

CALIFORNIA ENERGY COMMISSION

South Coast AQMD

SoCalGas
A Sempra Energy utility

UTD
Utilization Technology Development

The Flame of Innovation
SMP

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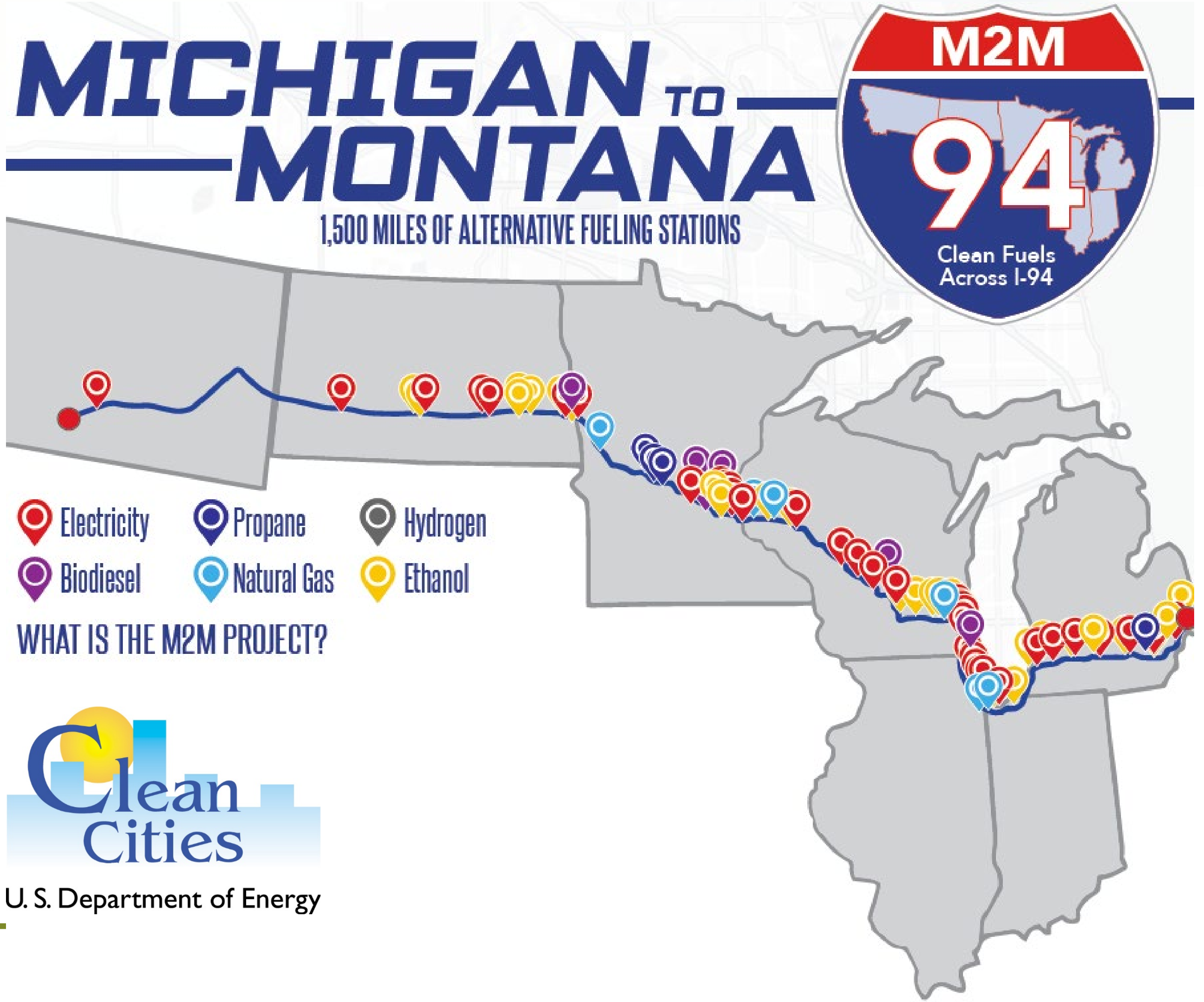
U.S. Fuels Across America's Highways
Michigan to Montana I-94 Corridor Project (M2M)

- GTI was awarded M2M Corridor deployment and planning project
- M2M corridor covers full length of I-94; Billings, MT to Port Huron, MI Over 1,500 Miles
- **Deployment:** 60 trucks,15 alternative fueling stations
- **Planning:** Sustainable alternative fuel corridor model;
  7 Clean Cities Coalitions providing outreach, training, community-based partnerships



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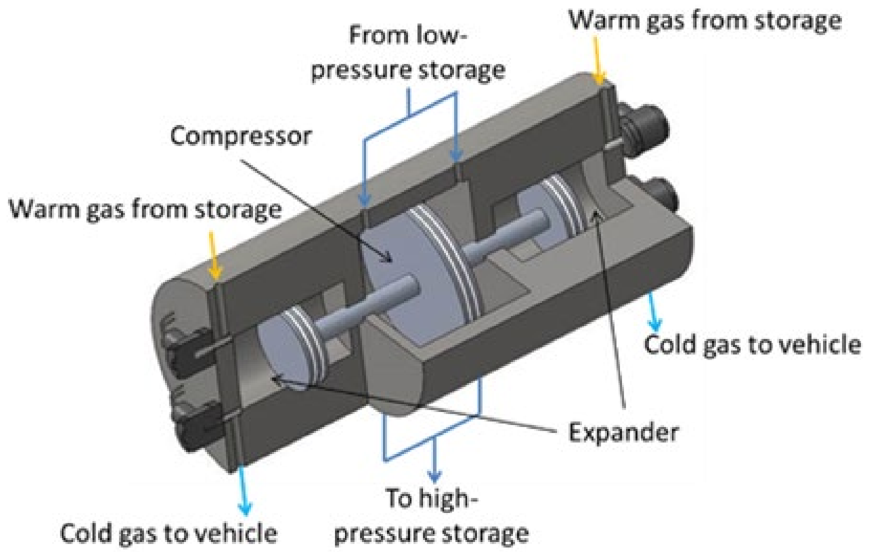
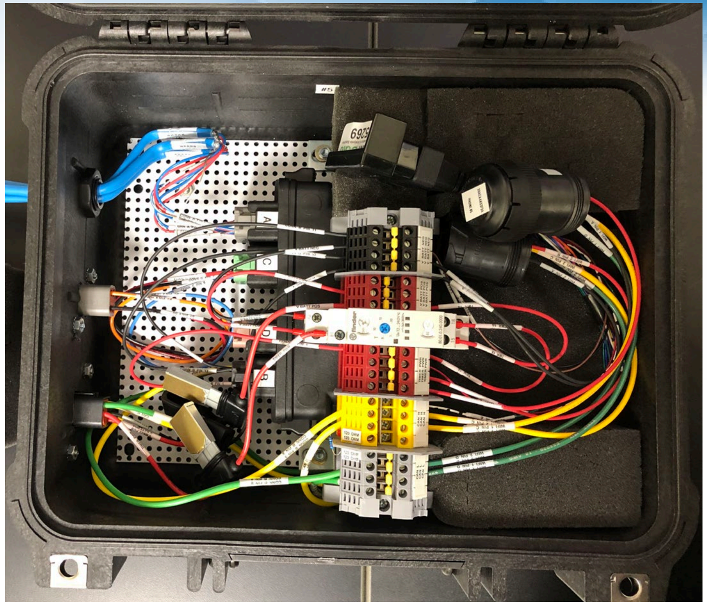
Smart Station and Expander Development

- Award: Alliance for Sustainable Energy – NREL, US DOE, CEC, SCAQMD
- Development for CNG **full fills** using:
  - **Smart** vehicles and dispensers
  - Advanced full fill **algorithm**
  - Cost effective **pre-cooling**
- Build and test lab-based dispenser and vehicle
- Design and build CNG reciprocating free-piston expander
- Test and demonstrate full fills using expander to pre-cool gas



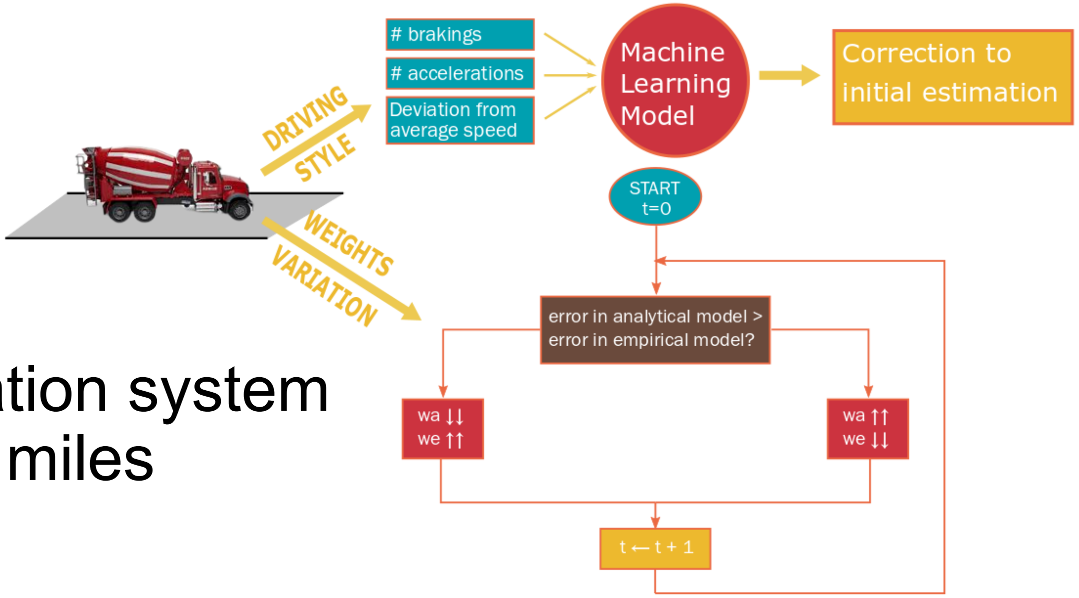
Smart Station Demonstration



- Award: US DOE -- DE-EE0008799
- Period of Performance: 10/2019 – 12/2022
- Objective:
  - Collect baseline data to quantify underfilling and transient thermodynamics during a CNG fill
  - Integrate smart vehicle and dispenser hardware into commercial vehicles and dispensers
  - Deploy smart CNG dispensers and vehicles at 5 sites
  - Demonstrate improved full fills using smart vehicles and dispensers

Next-Generation NGV Driver Information System

- Award: US DOE -- DE-EE0008802
- Period of Performance: 10/2019 – 12/2022



- Main Objective: Develop NGV driver information system that predicts miles-to-empty within 5% or 25 miles
  - Reduced range anxiety by NGV drivers
  - Increased range per fill and/or fewer fills
  - Enable optimization of fleet resources by linking 'miles-to-empty' prediction back to fleet dispatch center to aid in route selection
- Addresses final stage of the fueling solution – the driver

U.S. DEPARTMENT OF ENERGY

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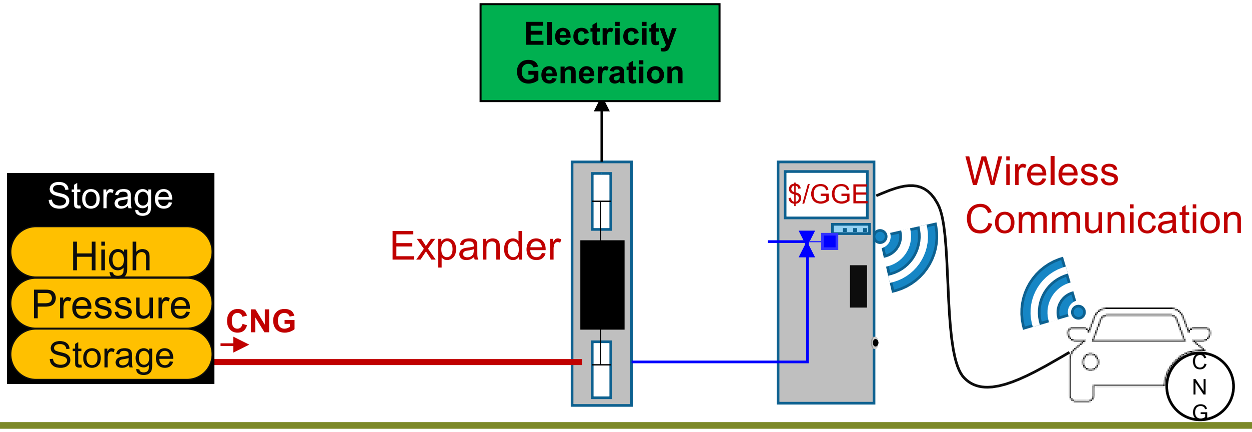
Technology Focus – CNG Full Fills with a Complete Smart Fueling System

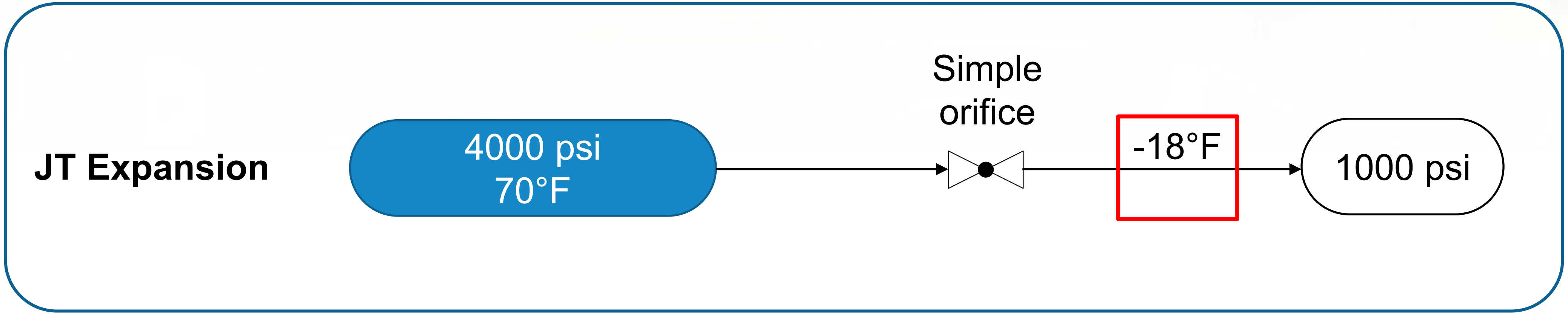
- Problem: Heat of compression
  - Solution: Novel CNG expander will provide additional cooling during fueling
- Problem: Filling algorithm uncertainty
  - Solution: Vehicle/Dispenser wireless communication system
  - Solution: Advanced filling algorithm

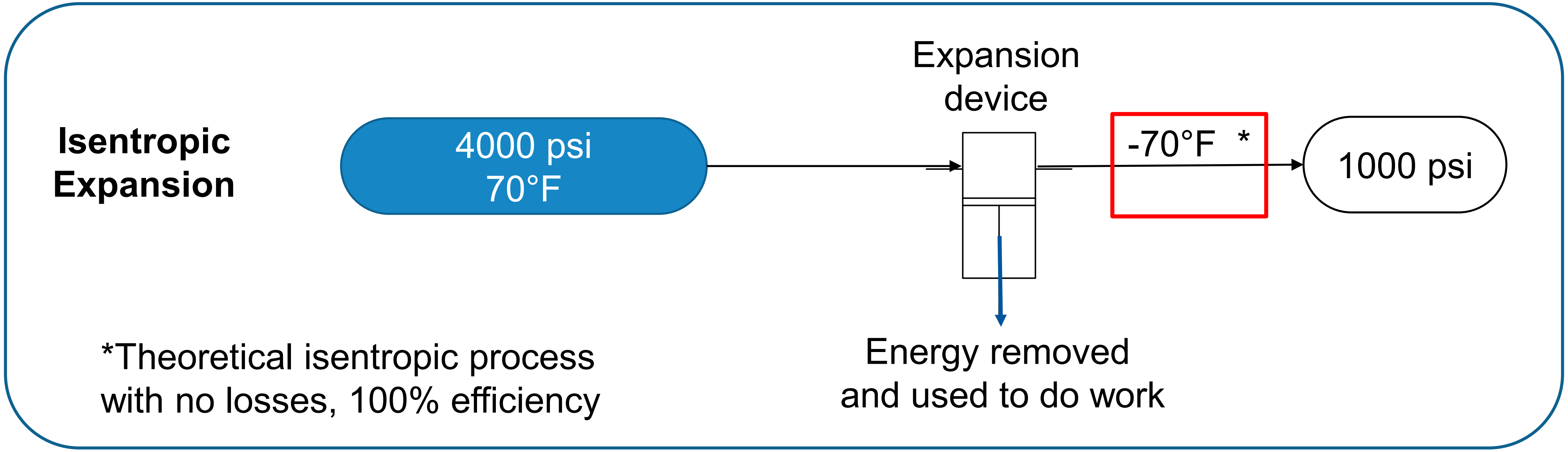


Expander Background

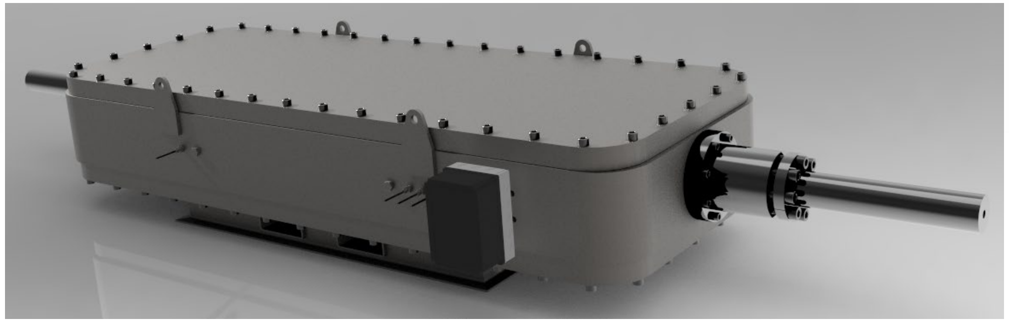
- Expanders remove energy from a gas as it drops from a high to low pressure
- Removing energy causes the gas to get colder than JT expansion
- Energy can be used to produce electricity or offset compression energy
- Expansion is widely used in many industries
  - NGL separation
  - Air separation
- Commercial expanders have limitations
  - Narrow operating range
  - No commercial designs suitable for CNG

Joule-Thomson vs. Isentropic Expansion Example





GTI Linear Motor, Free-Piston Expander Concept



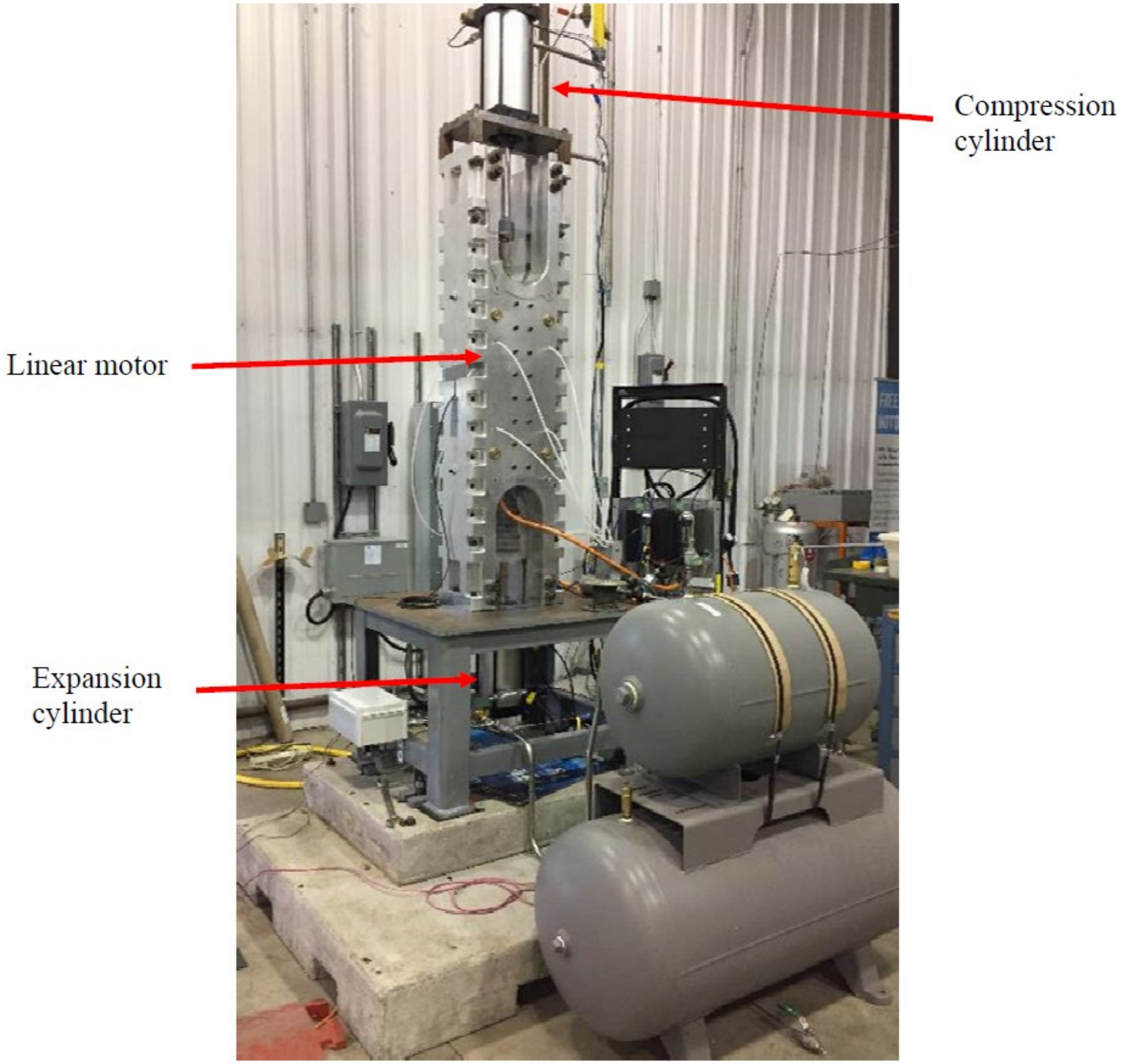
- Piston expanders are proven
  - High efficiencies
  - Can use commercial valves and seals
- Novel linear motor drive
  - Enables fast, dynamic control of system
  - Single moving part simplifies design
- Linear motor expander is best option for CNG fueling
  - Variable expansion ratio
  - Work can be utilized for creating electricity or compressing gas

Advantages of a Linear Free-Piston Expander

- Flexible inlet and discharge pressures
  - Expansion ratio adjusts automatically
  - Adjusted throughout fill as vehicle and station pressures change
- High expansion efficiency
  - Simulation predicts 80-90% expansion efficiency
- Programmable to act as flow controller
- Generates electricity when expanding gas
  - Use electricity to offset station operating costs
- Can potentially operate as booster to ensure tanks reach max pressure at end of fill

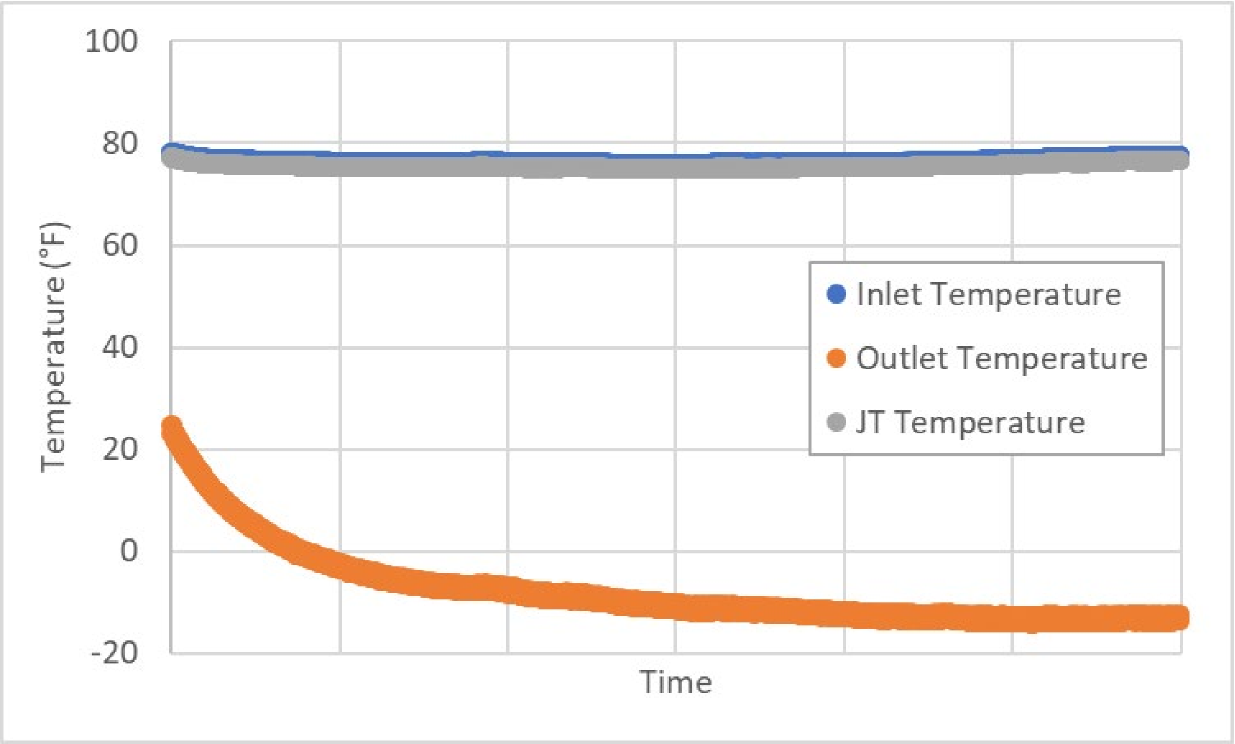
Preliminary Testing

- Preliminary test system
  - Controlled using linear motors
  - Includes compression and expansion ends
  - Tested with nitrogen
- Tested at steady state
  - 50-60% efficient using off-the-shelf parts
- Filled a test cylinder
  - Verified variable expansion ratio operation



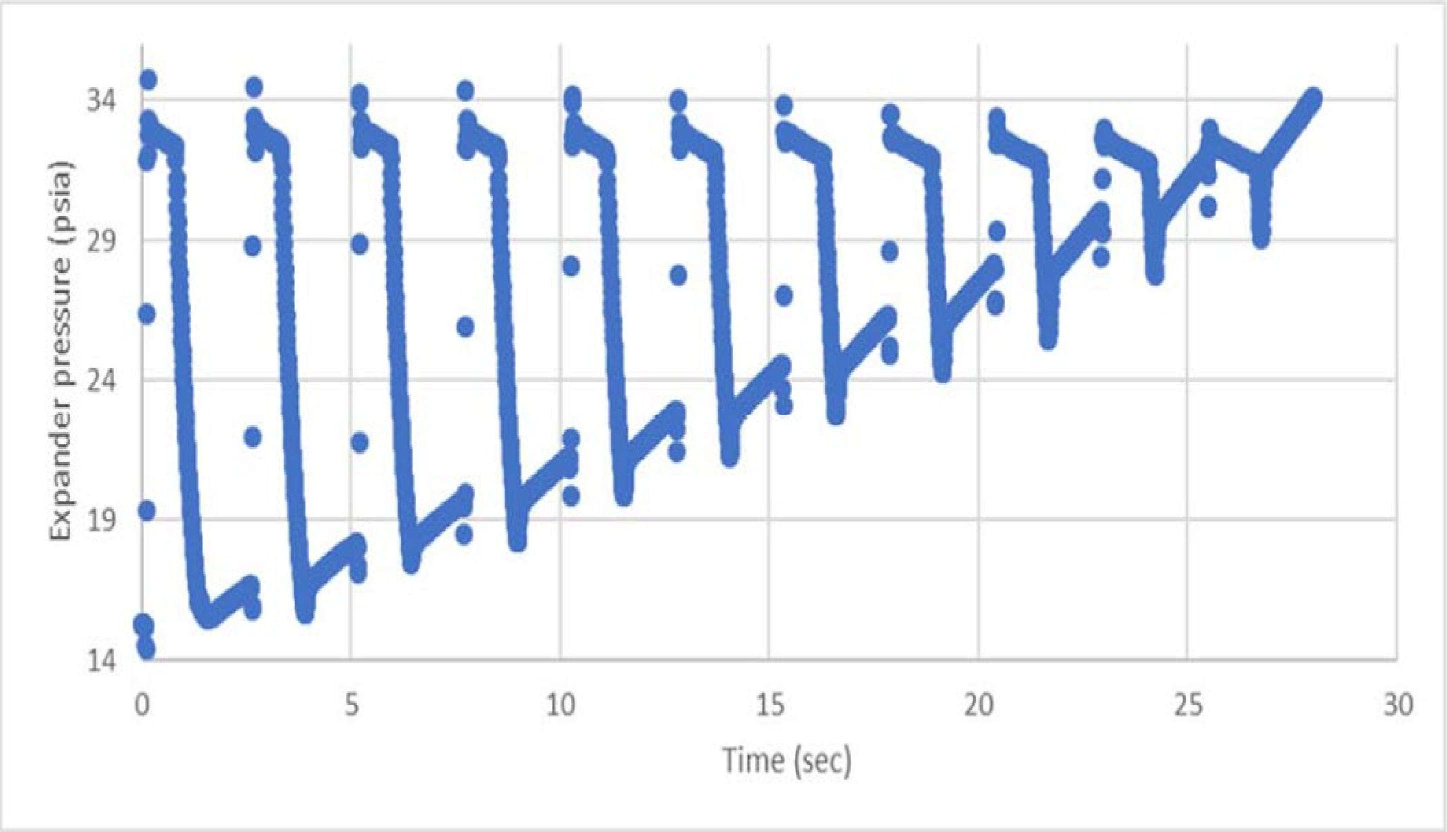
Testing with Low Pressure Nitrogen

- Low pressure nitrogen tests
  - 55 psi pressure drop
  - JT temperature drop ~2F
  - Expander temperature drop ~90F



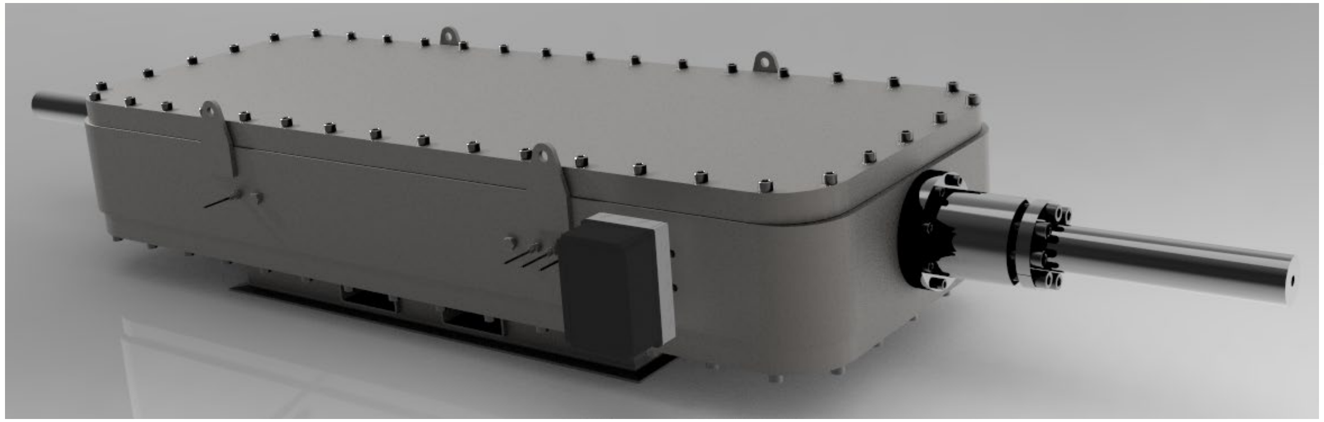
Testing with Low Pressure Nitrogen

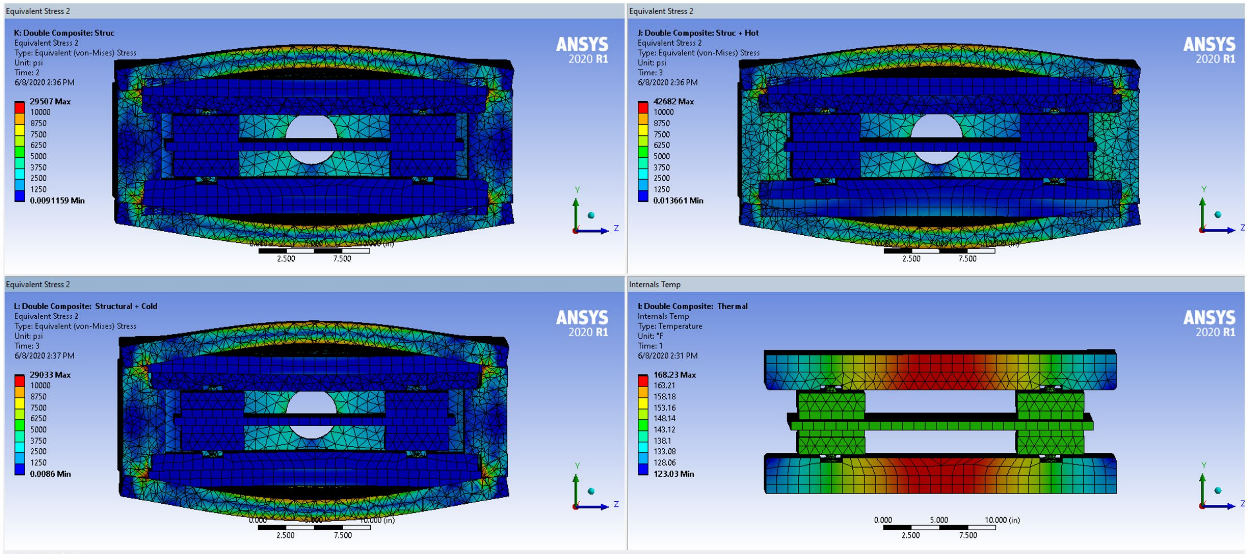
- Low pressure nitrogen tests
  - Filled a low-pressure test cylinder



Expander Prototype Status

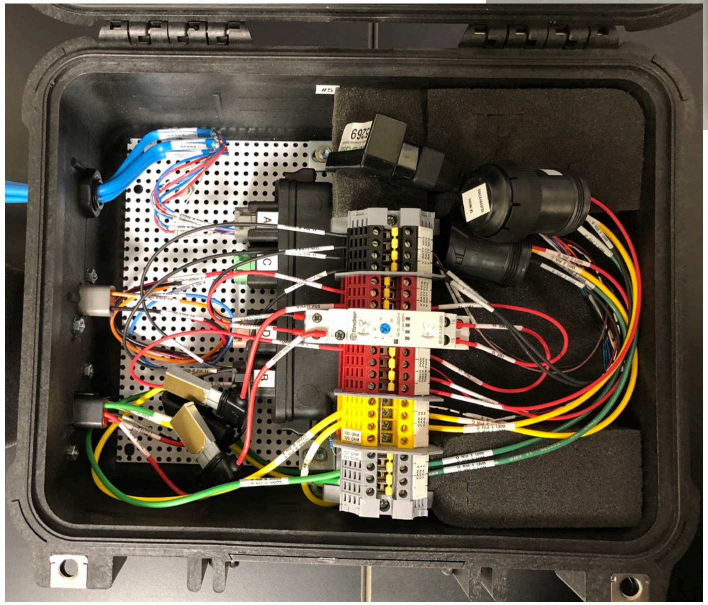
- Solid model complete
- Custom components ordered and being fabricated
  - Motor frame
  - Expansion cylinders
- Commercial components ordered
  - Motor, bearings, and controls
  - Seals and valve
- Next steps: Assembly, commissioning, and testing





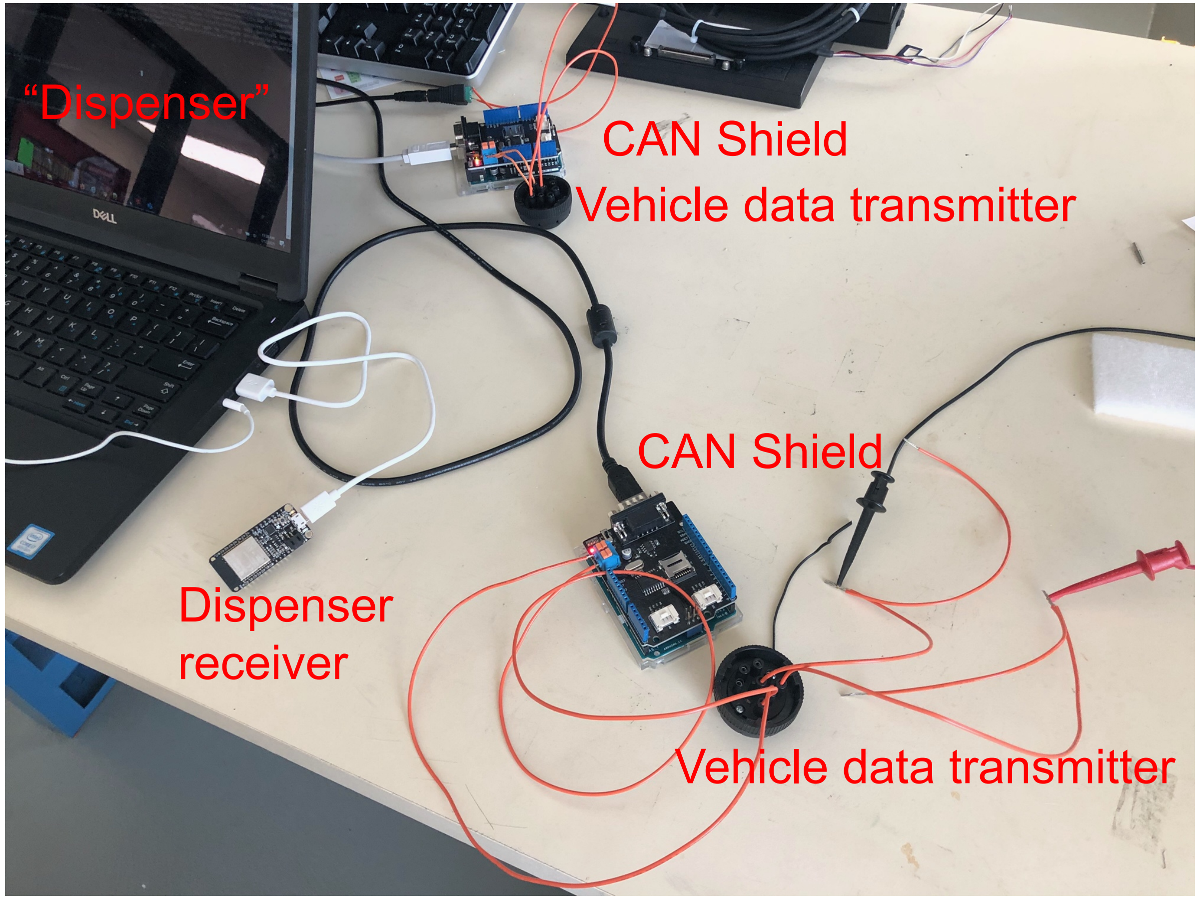
Vehicle Data Collection

- Multiple data collection systems being prepared for deployment on CNG vehicles
  - Collect CAN bus and fuel system data
  - Transmit via cellular and Wi-Fi
- Monitoring fuel consumption
- Monitoring fast fills and slow fills
- Capable of connecting to smart dispenser



Smart Dispenser Development

- Vehicle CAN traffic and fuel system data generated using CAN shield
- Data is broadcast using commercial transmitters
- GTI is developing receiver to manage vehicle to dispenser connection
  - Identify smart vehicles
  - Establish secure connection
  - Supply vehicle data and CNG fill status to dispenser



Testing and Deployment

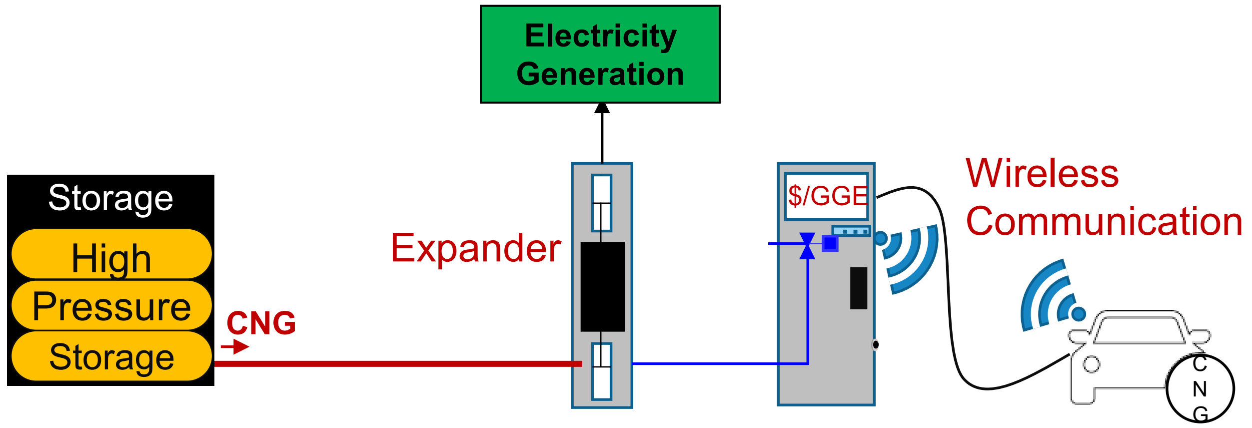
- Expander and smart vehicle/dispenser components will be installed in GTI test facility
- Facility capabilities
  - High-pressure H2 and CNG testing
  - Gas and environmental conditioning
- Expander performance will be tested steady state to determine efficiency
- Expander and smart station components will be used together to fill CNG cylinders to test improved full fill performance

gti

Smart Dispenser Deployment

- GTI is planning to field test smart vehicle and station components
- Following lab demonstration:
  - GTI will work with dispenser manufacturers to integrate dispenser receiver into the commercial dispenser cabinet
  - Complete smart dispenser and vehicle system will be tested to verify proper operation and safety
  - Smart vehicle and dispensers will be deployed to multiple CNG stations to demonstrate fuller fills
- No field demonstration of expander planned at this time

Questions


Electricity Generation
Storage
High Pressure Storage
CNG
Expander
$/GGE
Wireless Communication
C N G

CNG Codes & Standards Considerations and EOL Tank Testing

Lauren Lynch
Senior Mechanical Engineer
National Renewable Energy Laboratory

NGVTF 2021

May 11, 2021

AGENDA

- CNG Codes & Standards Considerations
  - Project Background & Objectives
  - Proposed Considerations to DOT
  - Discussion
- CNG Fuel Tank End of Life Testing
  - Project Background & Objectives
  - Testing Results
  - Recommendations
  - Discussion

ICF supported NREL on the study. Lou Browning presented during NGVTF 2020.

Aaron Williams presented during NGVTF 2020.
Test results from subcontractor Hexagon (previously Digital Wave) were presented by Brian Burks.

CNG Codes & Standards Considerations

NREL's Evaluation of Alternative Fuel Systems & Alternative Fuel Container Safety Standards

Federal Motor Vehicle Safety Standards (FMVSS) specify requirements for integrity of the fuel system and fuel container on CNG fueled vehicles.

- FMVSS 303 "Fuel System Integrity of Compressed Natural Gas Vehicles"
  - Light-duty CNG vehicle focused:
    - "Passenger cars, multipurpose passenger vehicles, trucks, and buses < 10,001 lbs GVWR"
    - "School buses regardless of weight that use CNG as a motor fuel"
- FMVSS 304 "Compressed Natural Gas Fuel Container Integrity"
  - Light-duty CNG vehicle focused:
    - "Passenger cars, multipurpose passenger vehicles, trucks, and buses (regardless of weight) that use CNG as a motor fuel"
  - CNG Fuel Systems Only

Despite the increasing number of CNG heavy-duty vehicles on the road, there are no Federal fuel system integrity requirements for CNG (and LNG) heavy-duty vehicles.

CNG Codes & Standards Considerations

Objective

- NREL conducted a study to provide applicable and accurate recommendations to ensure the standards address relevant safety issues, are practical, and do not produce future barriers.

Scope

- Fuel system and fuel container integrity requirements for CNG & LNG vehicles.
  - Light-, medium-, and heavy-duty.

Key Deliverable

- Recommendations of **performance requirements and specifications** for CNG & LNG fuel systems and fuel containers.
  - Justified by literature review, relevant research and technical forum's feedback.
  - Provide relevant research/test data where available.
  - Recommend test procedures to evaluate compliance with the recommended performance requirements.

Proposed Considerations to DOT NHTSA

- In Summary, the considerations presented to DOT were to:
  - Update FMVSS to include fuel system integrity assessment of medium- and heavy-duty vehicles
  - Update FMVSS to include fuel system integrity requirements for propane vehicles and tanks
  - Add additional CNG fuel tank integrity tests
  - Incorporate more repeatable fire test procedure for fuel tank integrity.

Proposed Considerations to DOT NHTSA

- Considerations for Minimum Safety Standards:
  - Consider expanding the applicability of FMVSS No. 303 to medium- and heavy-duty CNG fuel vehicles to address.
  - Consider modifying FMVSS No. 304 test requirements to include chemical test specifications that subject CNG containers to various chemical agents, as described in NGV 2, to better represent the external container environment of real-world applications.
  - Consider modifying FMVSS No. 304 to effectively represent container failures experienced in field CNG vehicle fires and to improve repeatability and reproducibility of the fire test for efficient compliance verification.

- Link to the full report: www.nrel.gov/docs/fy21osti/77455.pdf

Proposed Considerations to DOT NHTSA

- Considerations to Reflect Industry Best Practices:
  - Consider modifying FMVSS No. 303 to define acceleration tests, instead of barrier crash tests, to evaluate the integrity of tank mounts to ensure applicability and ease of verification across the large variety of medium- and heavy-duty vehicle configurations.
  - Consider modifying FMVSS to include PRD venting requirements for medium- and heavy-duty vehicles that align with NGV 6.1 and NFPA codes that require venting of the PRD and manifold upwards, above the vehicle to prevent injuries from PRD venting.
  - Consider modifying FMVSS No. 304 test requirements to include a drop test, notch test, and impact test, as defined in NGV 2, to better represent the external container environment of real-world applications, harmonize with North American standards, and ensure compliance with tank manufacturer design requirements.
  - Consider modifying FMVSS No. 304 test to harmonize with a newly developed test procedure in Phase 2 of UN GTR No. 13.

- Link to the full report: www.nrel.gov/docs/fy21osti/77455.pdf

CNG Codes & Standards Considerations

Questions and Discussion

CNG Fuel Tank End of Life Testing

Evaluating safety concerns of CNG fuel tanks at the end of their defined useful life.

Fuel Tanks that have reached their labeled expiration date/end of life (EOL) or have been condemned by inspection shall be removed from service (and destroyed).

- Natural Gas Vehicles tend to last longer than their fuel tanks
- Not economical to replace tanks
- Vehicle have been known to continue operation with expired tanks
  - No consistent method to track expired tanks
- Replacing tanks has potential to introduce acute hazards
  - Improper installation of fittings and mounting components compared to original
- Safety challenges of visual inspection
  - Human error
  - Qualitative and subjective measure
  - Non-visible damage
  - Non-conservative

CNG Fuel Tank End of Life Testing

Objective

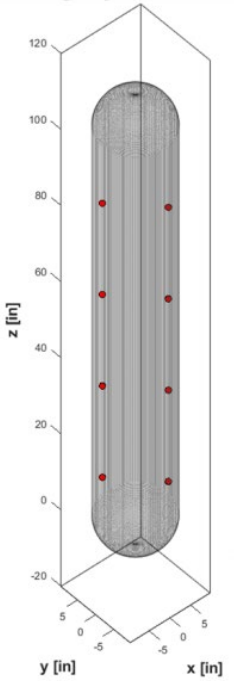
- Characterize tank conditions at the end of their defined useful life
- Characterize the remaining functional life of expired tanks
- Determine how fuel tanks might fail under routine operating conditions
- Understand alternative methods for inspecting tanks

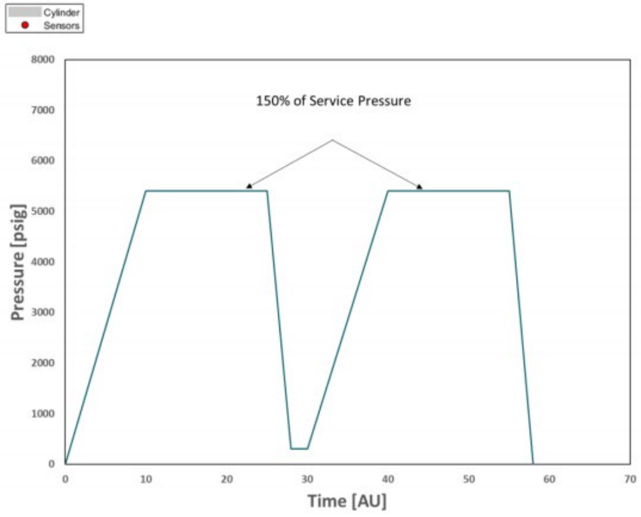
Project History

- Started 2016
- Paused 2017-2018
- Concluded Testing 2019
- Final Report 2020

CNG Fuel Tank End of Life Testing

- High-level Test Outline:
  - 101 Tanks sourced from LA Metro
  - Visual Inspection and Modal Acoustic Emission (MAE) Evaluation
  - Burst Pressure Testing
  - Artificial Damage
    - Notching or Impact
  - Fatigue Cycle
  - Burst Pressure Testing
  - MAE Evaluation





(Left) MAE sensor placement
(Right) MAE inspection pressure schedule

Testing Results & Recommendations

- Potential opportunity of continued use of tanks
- Additional research and development with an expanded CNG fuel tank sample size to characterize tank integrity after experiencing a full service
- Life in a variety of applications could further verify such potential
- Visual inspection was not sufficient in identifying damage inflicted by a localized impact test on Type III and Type IV CNG fuel tanks
- A nondestructive evaluation method successfully assessed the structural integrity of the tanks and would not have compromised the original installation

60 of 101 Tanks Initial Visual and MAE Inspection
60 Passed

20 of 60 Tanks Burst Pressurized as Received
20 Passed

Number of Tanks Tested	Minimum Burst Pressure Test Pass/Fail	
20 of 20 Tanks as Received from LA County Metro Transportation Authority	20 Tested 20 Passed	10 Type III 10 Type IV

20 of 60 Tanks Artificially Damaged and Burst Pressurized
14 Passed, 6 Failed

Number of Tanks Tested	Hydraulic Fatigue Tested to 15,000 Cycles Pass/Fail		Minimum Burst Pressure Test Pass/Fail	
8 of 20 Tanks Notch Damaged	4 Tested 4 Passed	2 Type III 2 Type IV	8 Tested 8 Passed	4 Type III 4 Type IV
4 of 20 Tanks Impact Damaged	2 Tested 2 Passed	1 Type III 1 Type IV	4 Tested 4 Passed	2 Type III 2 Type IV
4 of 8 Tanks Local Impact Damaged at Standard Height	2 Tested 2 Passed	1 Type III 1 Type IV	4 Tested 2 Passed 2 Failed	2 Type III 2 Type IV
4 of 8 Tanks Local Impact Damaged at Double Height	2 Tested 2 Passed	1 Type III 1 Type IV	4 Tested 4 Failed	2 Type III 2 Type IV

20 of 60 Tanks Hydraulically Fatigued to 18,000 Cycles
20 Passed

Number of Tanks Tested	Hydraulic Fatigue Tested to 18,000 Cycles Pass/Fail		Minimum Burst Pressure Test Pass/Fail	
2 of 20 Tanks Leak-Tested	2 Tested 2 Passed	1 Type III 1 Type IV	None Tested	
20 of 20 Tanks Burst Pressurized	20 Tested 20 Passed	10 Type III 10 Type IV	20 Tested 20 Passed	10 Type III 10 Type IV

CNG Fuel Tank End of Life Testing

Questions and Discussion

High Efficiency, Ultra Low Emissions Heavy-Duty Natural Gas Engine Research and Development

Task# 1.13 – Mid-Project Presentation

Saradhi Rengarajan

Principal Investigator

May 12th, 2021

Overview

Timeline

- Begin: 08/15/2019
- End: 07/30/2023 (10/13/2022)
- 35% Complete

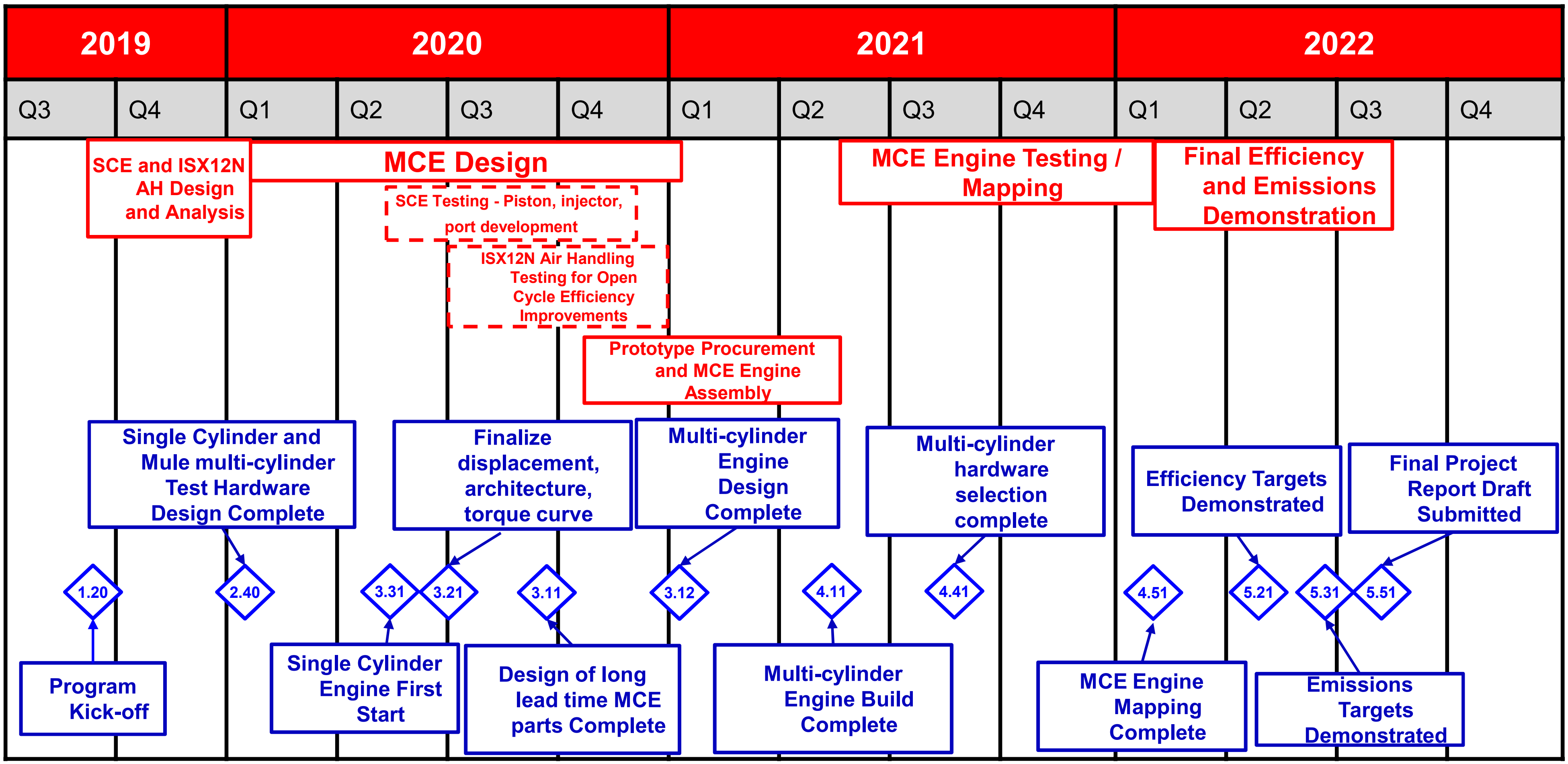
Budget

- Total Project: $10.996M
  - NGV Consortium: $4M
  - Cummins: $6.996M
- Total Spent: $4.07M
  - NGV Consortium: $1.31M
  - Cummins: $2.76M

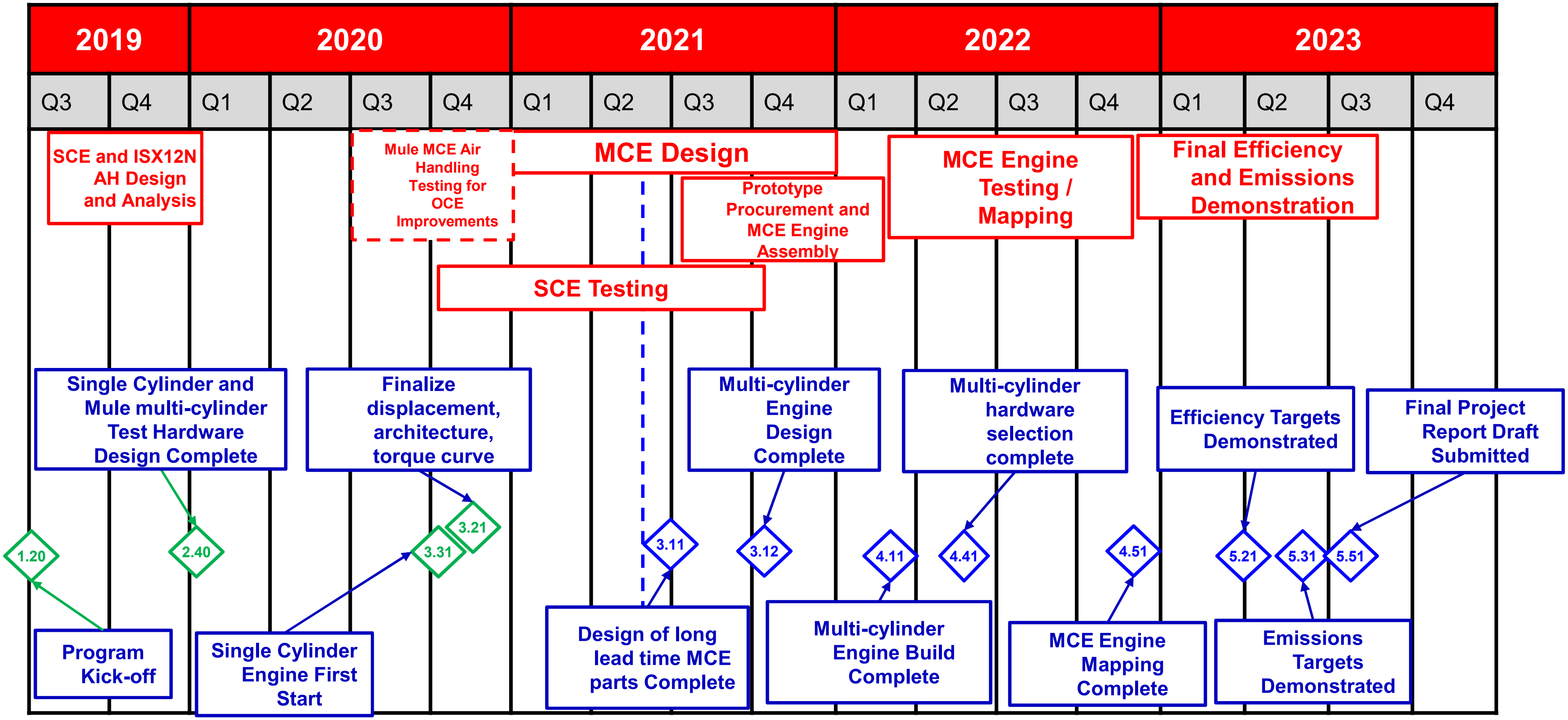
Project Objectives

- 12-15 liter engine with a natural gas specific combustion system utilizing tumble charge motion and cooled EGR
- Peak Engine Brake Thermal Efficiency (BTE) of 41-43%
- RMCSET cycle average BTE of 38-40%
  - 10-16% Fuel Economy and CO_2 improvement compared to ISX12N
- Diesel like torque curve rating of 450-500 hp and 1550-1800 lb-ft
- Up to 20% system cost reduction relative to current production ISX12N engine and aftertreatment

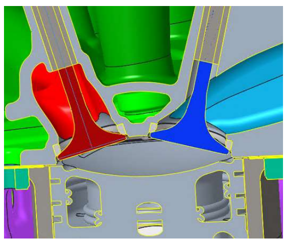
Original Project Schedule



Amended Project Schedule



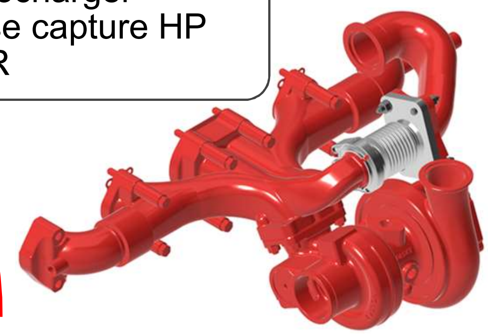
Technical Approach



- Tumble Ports and Pent roof head
- Piston bowl shape and compression ratio
- M18 Spark Plugs
- PFI

Combustion System Development (SCE)

- Divided Exhaust Manifold
- Twin scroll turbocharger
- Pulse capture HP EGR

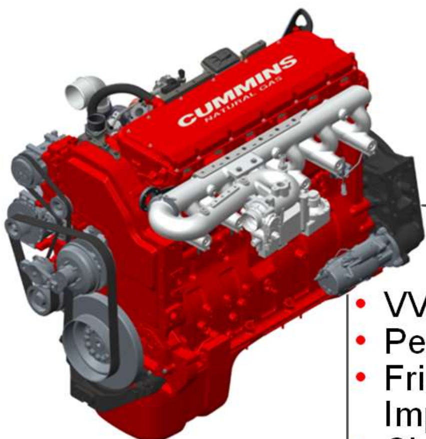


Air Handling Development (ISX12N Mule Engine)

Multi-Cylinder Simulation (GT-Power / Coupled CFD)

- Valve profile
- Intake Manifold Optimization
- Turbo match
- Pulse capture EGR

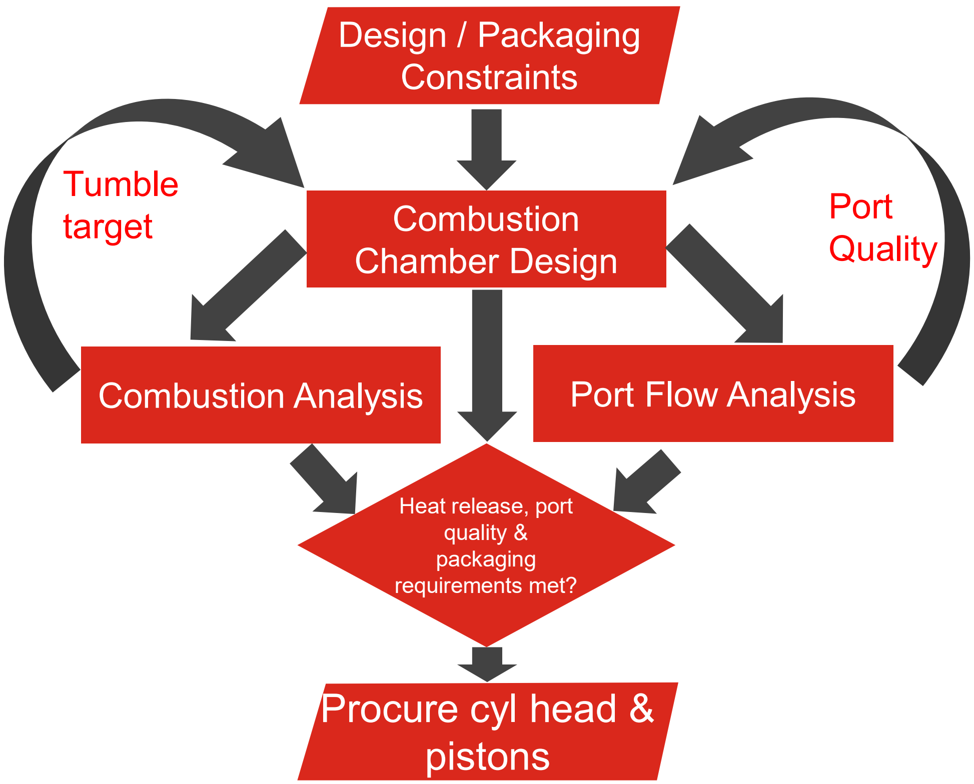
Final Multi-Cylinder Demonstration



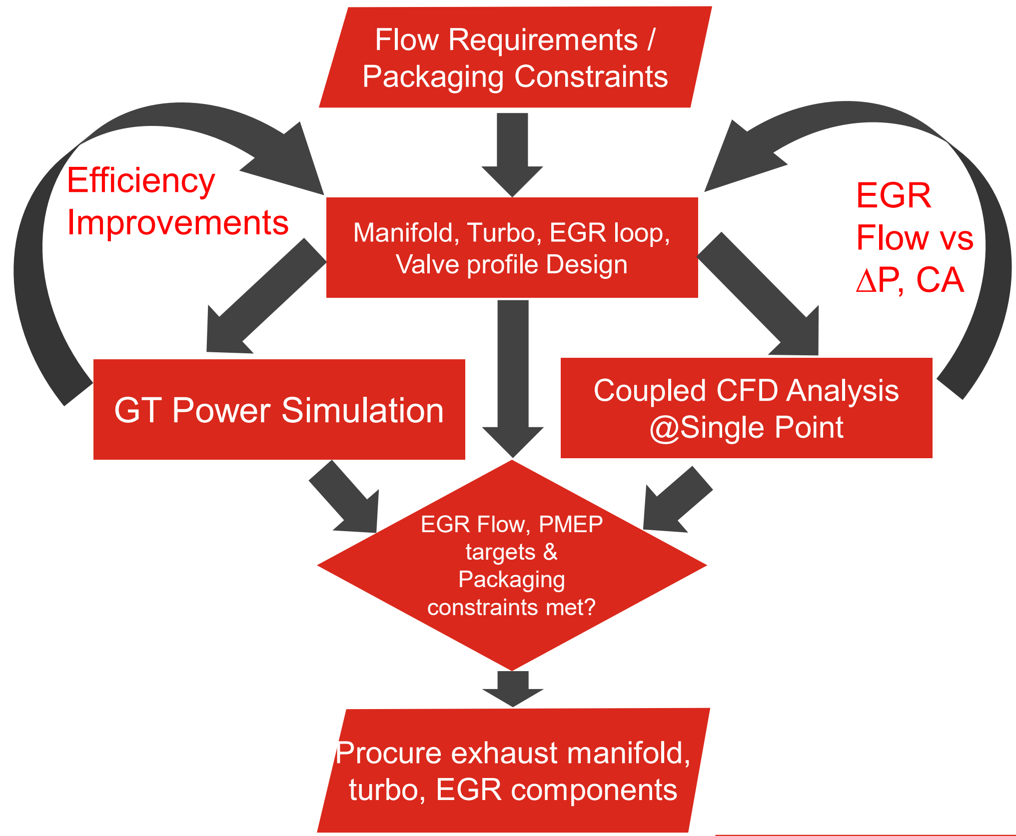
- VVT (DOHC)
- Pent roof head
- Friction Improvements
- Close coupled + Underfloor Catalyst

Technical Approach

Combustion System Development



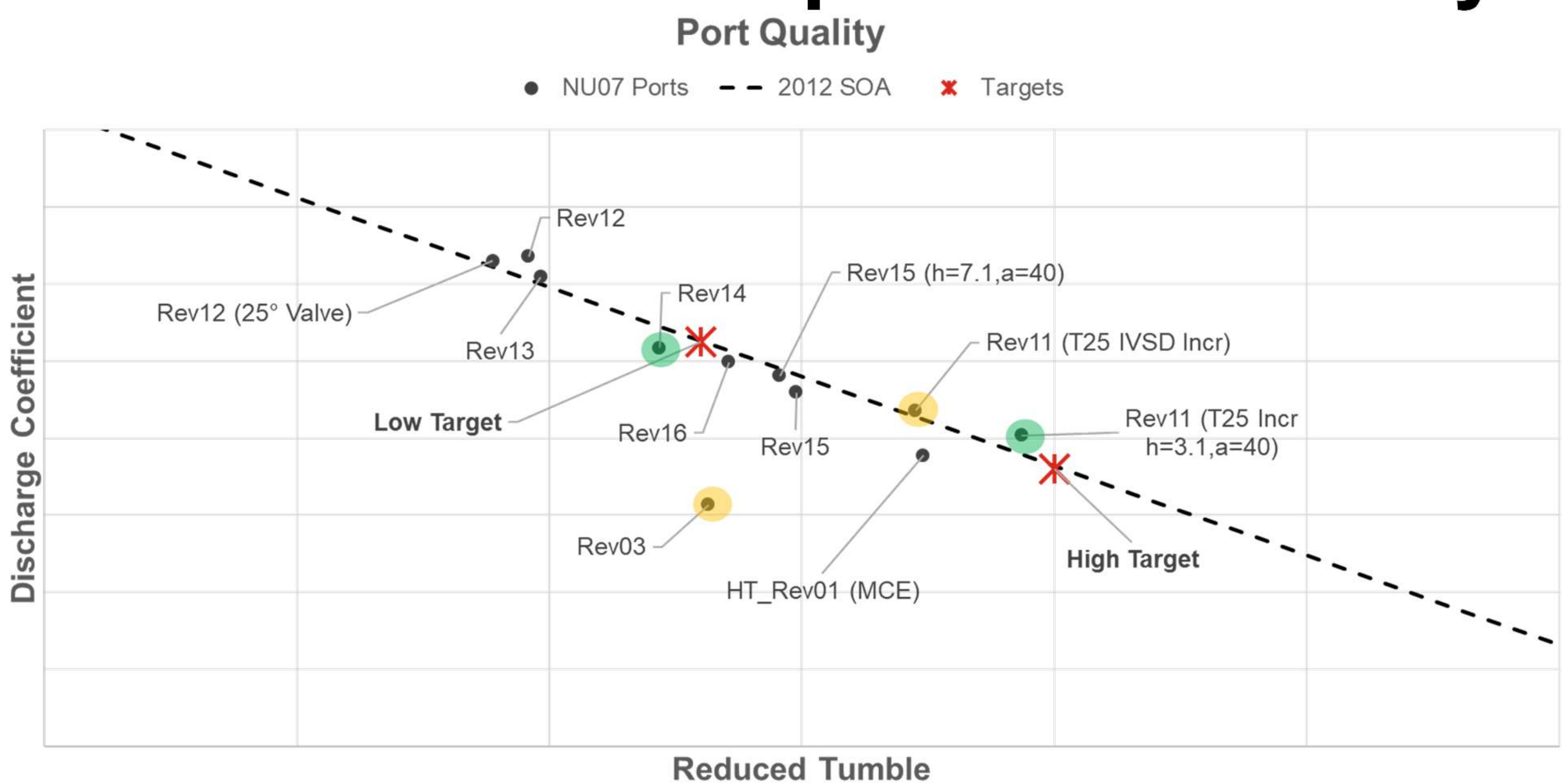
Air Handling Development



Combustion System Status

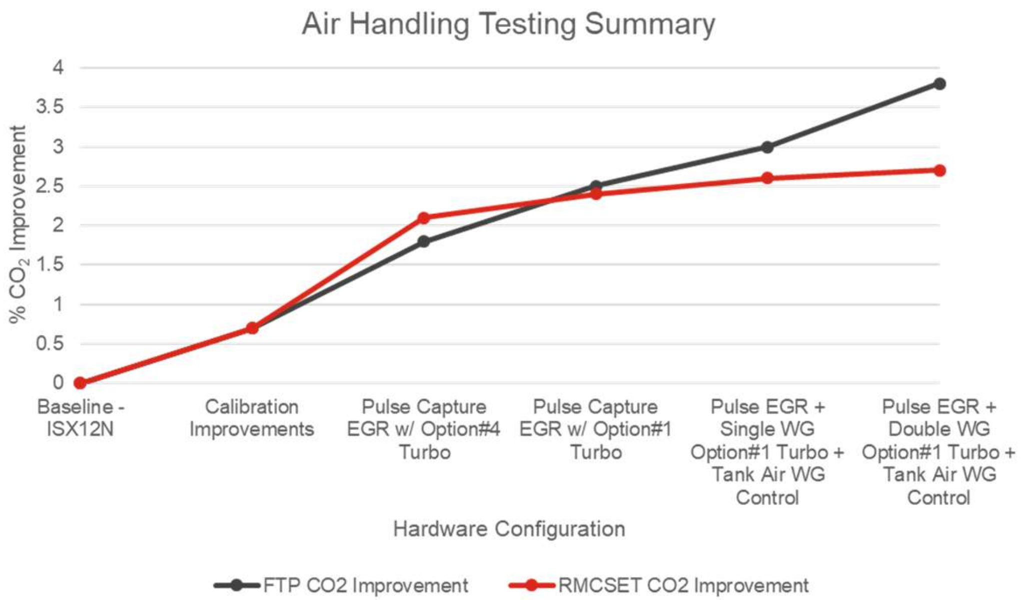
- 15 unique intake port designs developed and analyzed
  - Several DOE's completed to understand sensitivity of port flow quality to port and valve seat geometry
  - 4 ports with different tumble levels selected for procurement and testing on single cylinder engine (SCE)
- Combustion CFD analysis completed for several port and piston combinations
  - CFD models calibrated with initial dataset from SCE
- SCE suffered a catastrophic cylinder head and power cylinder failure suspected to be caused by a valve seat drop
  - SCE has been rebuilt again
  - Starting to collect data with a moderate tumble head

Tumble Port Development Summary



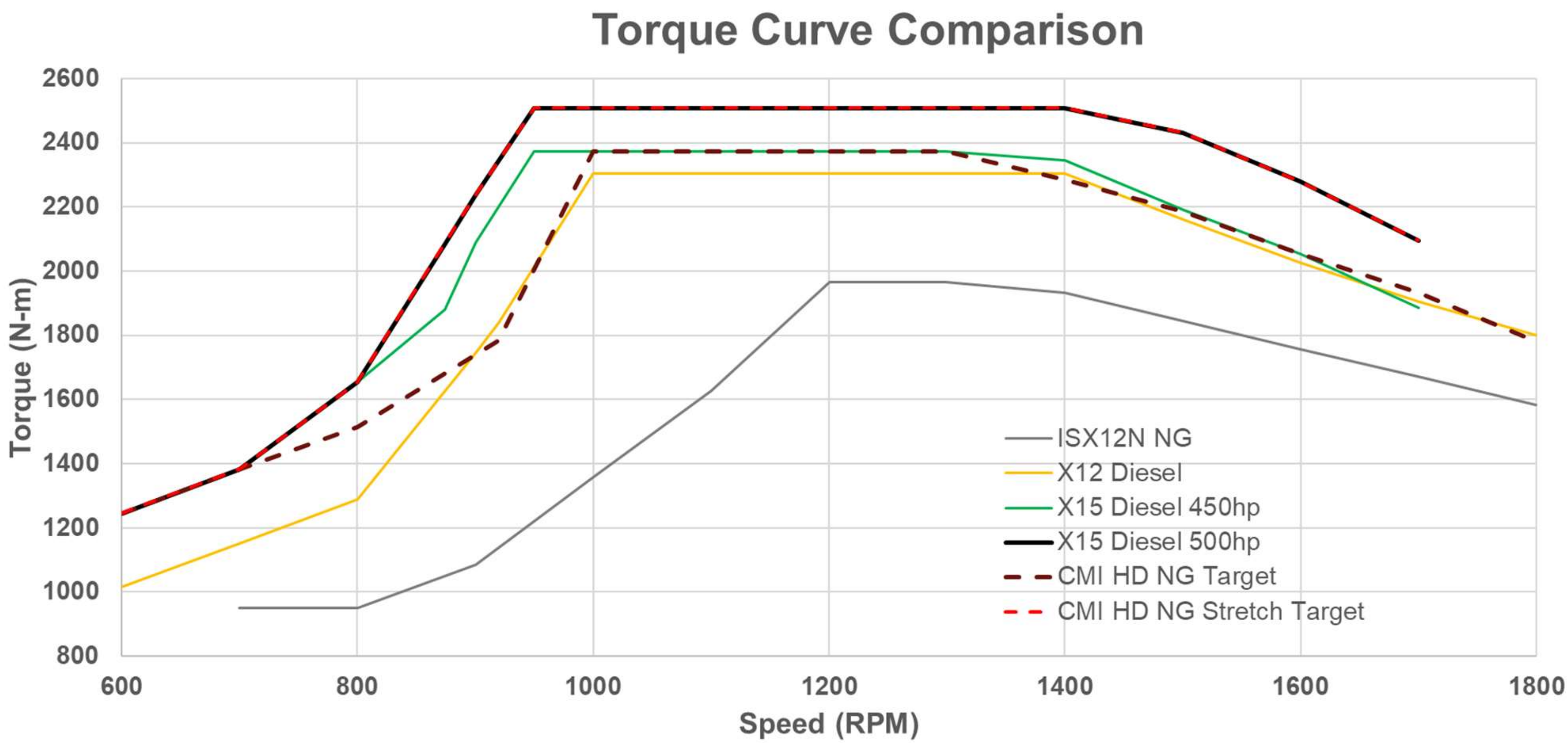
- Port revisions previously procured
- Port designs planned for procurement

Air Handling Development Summary



- ISX12N engine used as mule engine for air handling development
- Divided exhaust manifold with a twin entry turbocharger
- High pressure loop EGR system that utilizes a pulse capture design
- Two different turbocharger options selected for testing
- ~50 kPa reduction in PMEP achieved at peak torque for similar or slightly lower EGR flows
- Lower exhaust pressure results in a reduction in trapped residuals

Torque Curve Targets



- Minimum target of 1750 lb-ft / 450 hp
- Stretch target of 1850 lb-ft / 500 hp

Multi-Cylinder Engine Design Progress

- Base engine platform for MCE demonstration selected
  - 14.5 liter global platform – compact and lighter weight
- MCE Cylinder head and initial overhead layout completed
  - Structural analysis initiated
  - Design protected for multiple intake port options to achieve different tumble levels – design to be finalized based on SCE recommendations
- Pulse capture EGR system and exhaust manifold design initiated based on mule engine designs that were tested
- Initial turbocharger match identified to initiate turbine housing design
- Friction improvement technologies identified for implementation on MCE
- Charge distribution analysis initiated to identify changes to intake manifold

Q+A


Cummins

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Development of Zeolite-Based Catalysts with Improved Low-Temperature CH_4 Conversion

Tala Mon[1], Junjie Chen[1], Judy Liu[1], Jingzhi Liu[2], Viktor J. Cybulskis[2], Eleni A. Kyriakidou[1]

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May 12, 2021

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Acknowledgments

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U.S. DEPARTMENT OF ENERGY

Materials Technology R&D
Technology Manager:
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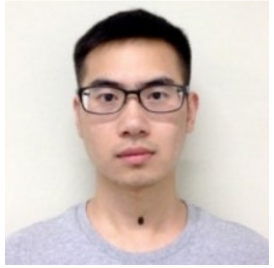
PhD students



Junjie Chen
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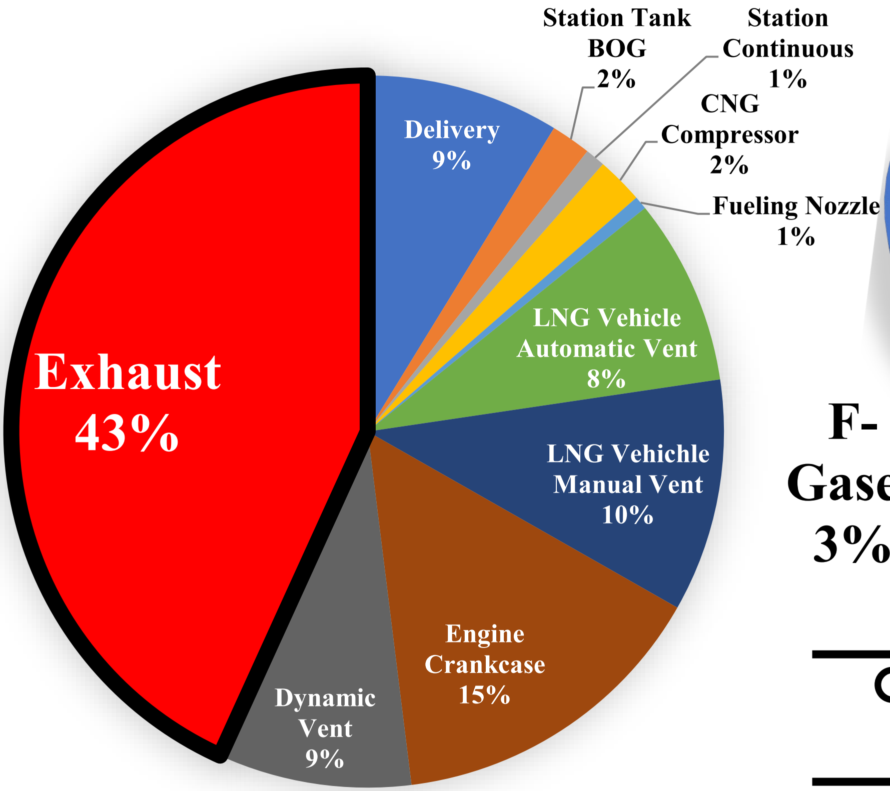
NATIONAL RENEWABLE ENERGY LABORATORY

Abby Brown
John Gonzales
Margo Melendez
Aaron Williams

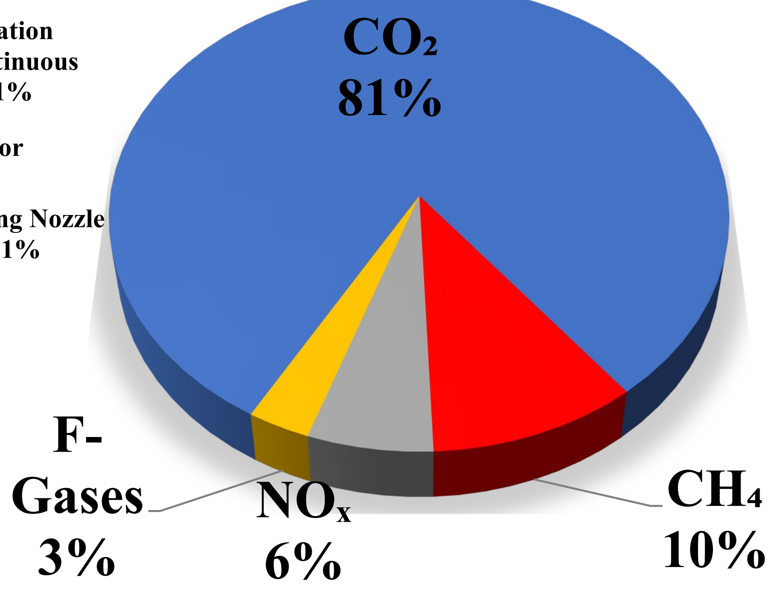
Vehicle exhaust is the greatest contribution to NGV CH_4 emissions with more stringent regulations due to outsized effect of CH_4 on global warming

Projected CH_4 Emissions for Heavy Duty NGVs (2035)



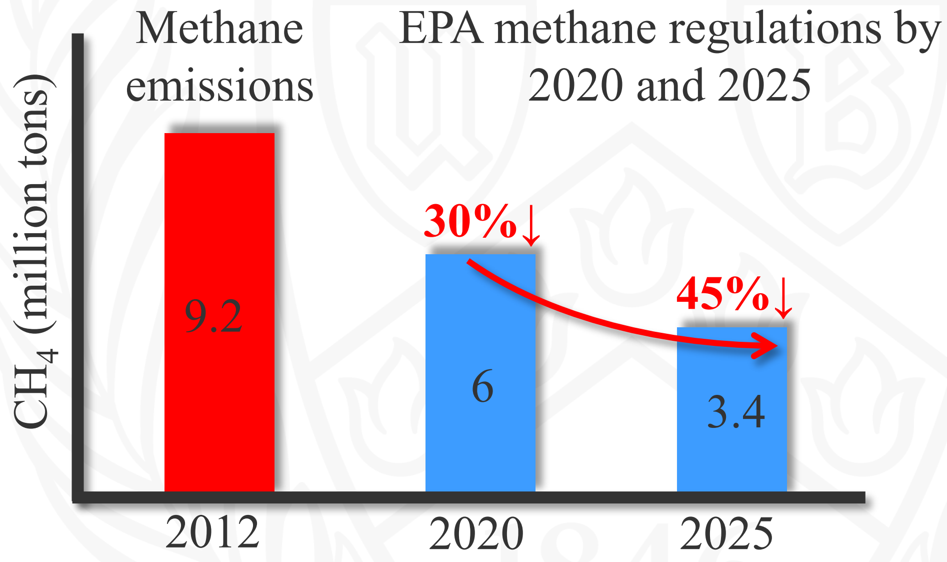
$$CH_4 + 2O_2 \Rightarrow CO_2 + 2H_2O$$

U.S. Greenhouse Gas Emissions



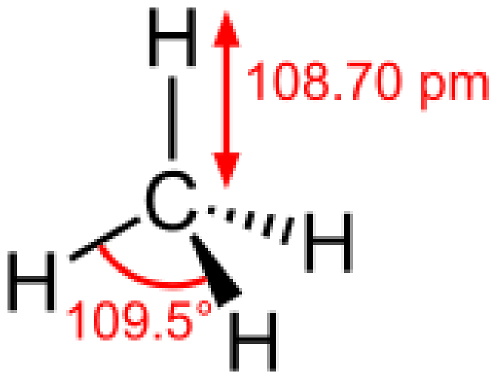
Gas	100-year global warming potential (GWP)
CO_2	1
CH_4	>23

- 43% of NGV CH_4 emissions come from vehicle **exhaust** due to unburnt CH_4 (slip).
- CH_4 is a more **potent greenhouse gas** than CO_2.
- **Reduction of 45%** in CH_4 emissions expected in **2025** compared to 2012.

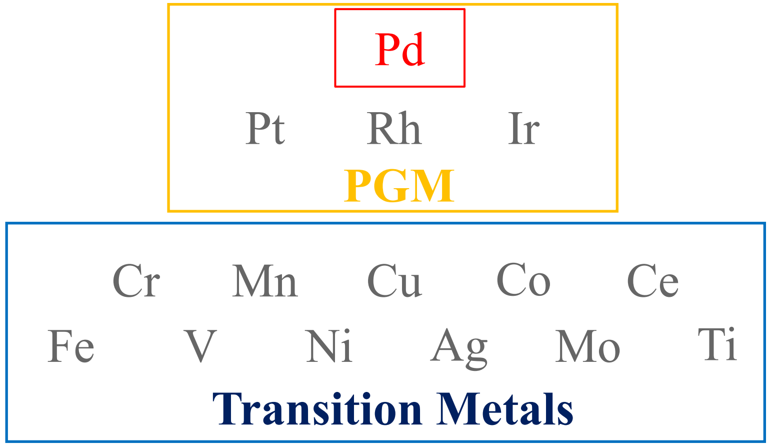


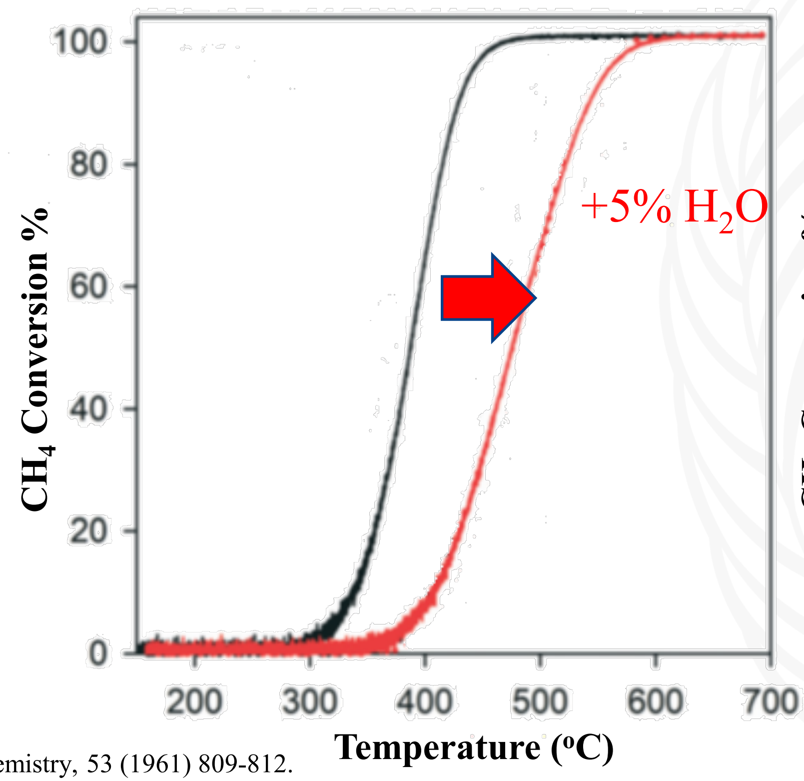
U.S. Energy Information Administration
N.N. Clark, D.R. Johnson, D.L. McKain, W.S. Wayne, H. Li, J. Rudek, R.A. Mongold, C. Sandoval, A.N. Covington, J.T. Hailer, Journal of the Air & Waste Management Association, 67 (2017) 1328-1341.

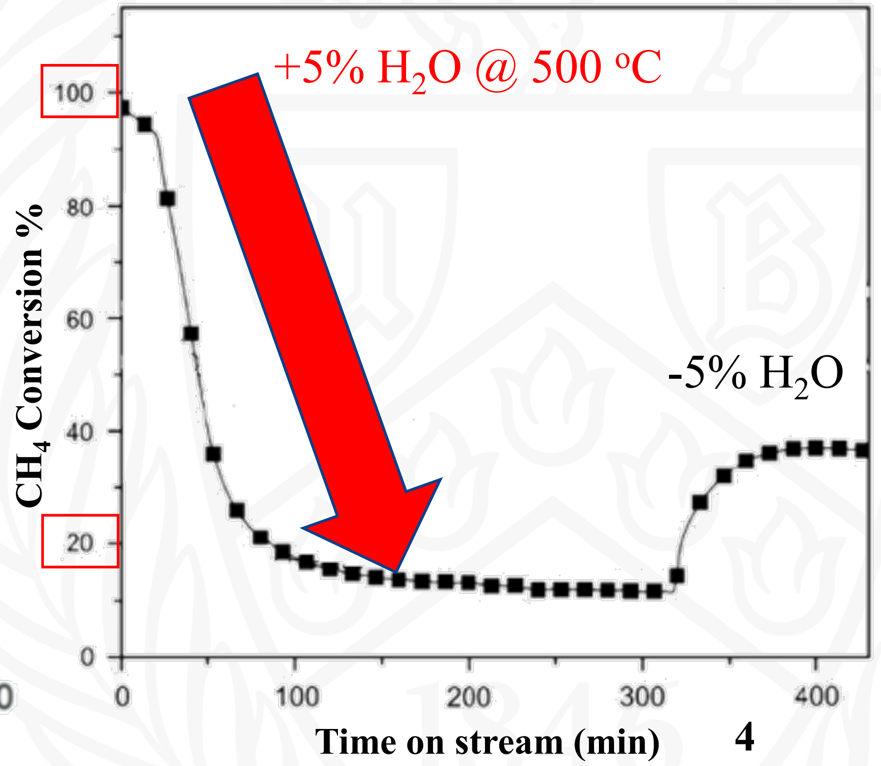
Water inhibits low-temperature CH_4 oxidation over Pd/Al_2O_3



- CH_4 is difficult to activate compared to other HCs due to stable C-H bonds.
- **Pd** is the most **active** CH_4 oxidation metal compared to other PGMs and transition metals with PdO as the active sites.
- Conventional catalyst, **Pd/Al_2O_3**, suffers from **deactivation** in the presence of H_2O with minimal conversion at **low temperatures (< 500 ^oC)**.



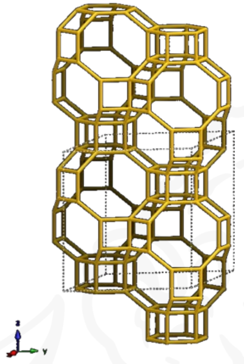




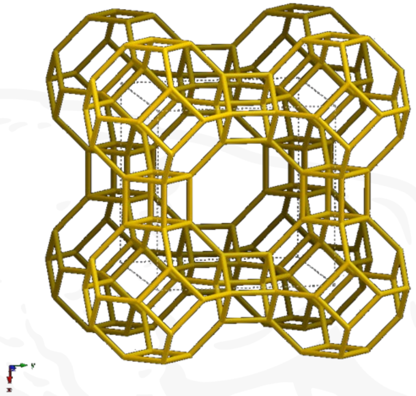
H. Davy, Philos. Trans. Roy. Soc. London, 1 (1817) 45.
R. Gholami, M. Alyani, K. Smith, Catalysts, 5 (2015) 561-594.
R.B. Anderson, K.C. Stein, J.J. Feenan, L.J.E. Hofer, Industrial & Engineering Chemistry, 53 (1961) 809-812.
O. Mihai, G. Smedler, U. Nylén, M. Olofsson, L. Olsson, Catalysis Science & Technology. 7 (2017) 3084–3096.

Small-pore zeolites (SSZ-13 and LTA) are hydrothermally stable

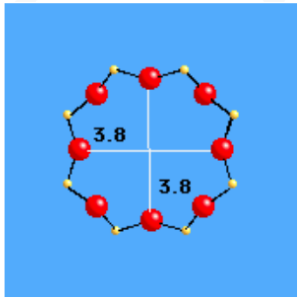
- Zeolites are microporous aluminosilicates defined by unique 3-dimensional frameworks with size-limiting pores and act as molecular sieves.
- SSZ-13 and LTA are small-pore zeolites known for high surface area and high **hydrothermal stability**.
- **Ion-exchange capacity** for active metals and second metals due to unbalanced charge from Al in the framework along with tunable **hydrophobicity** through **Si/Al** molar ratio.



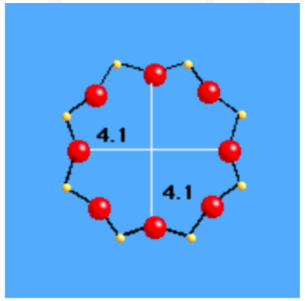
SSZ-13



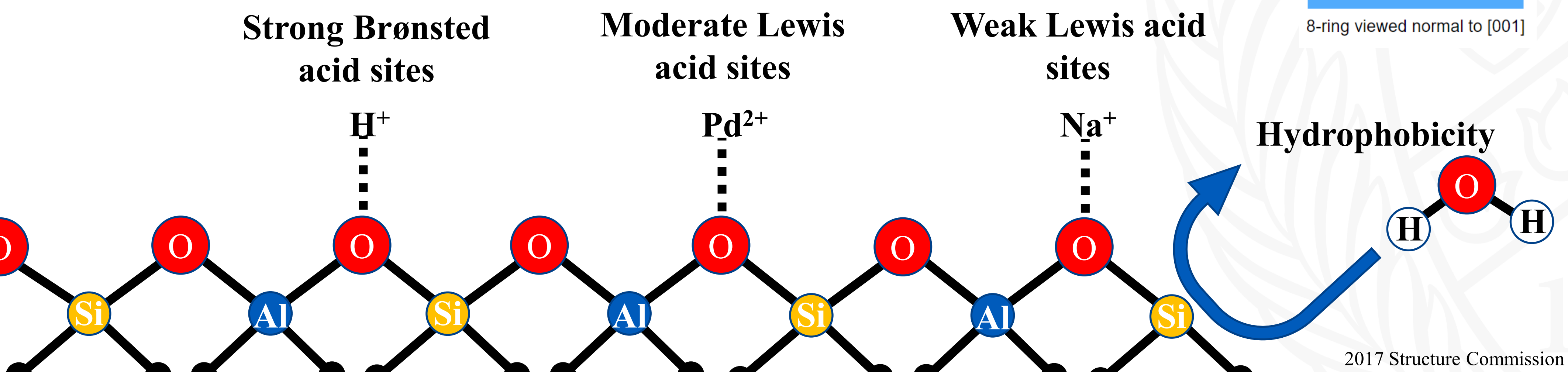
LTA



8-ring viewed normal to [001]



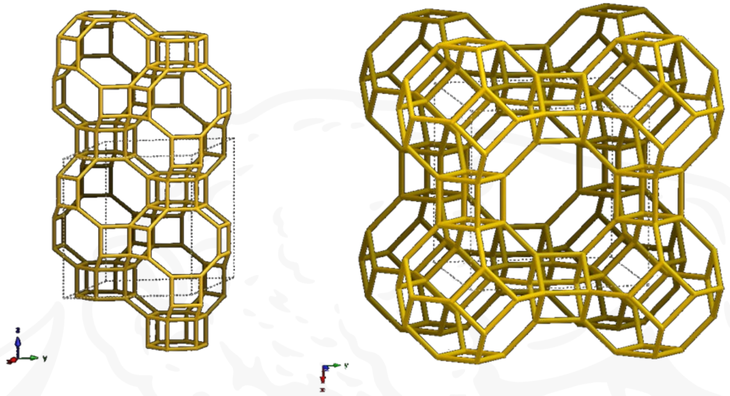
8-ring viewed along <100>

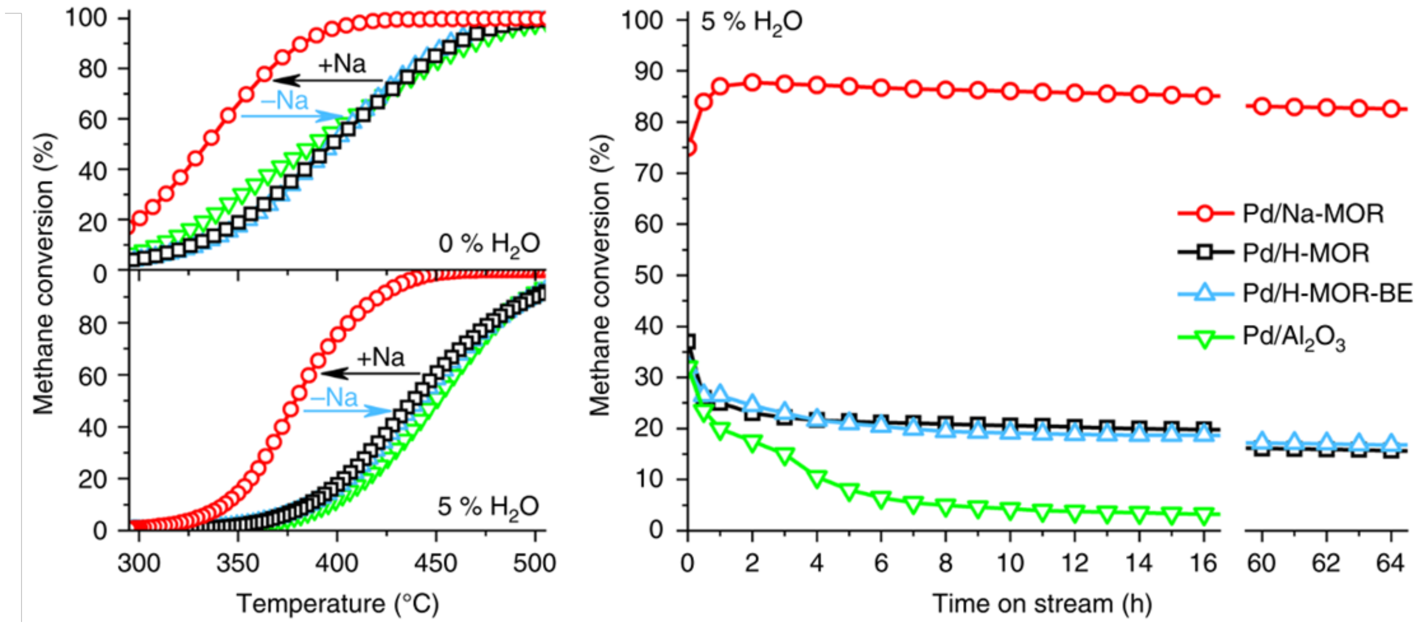


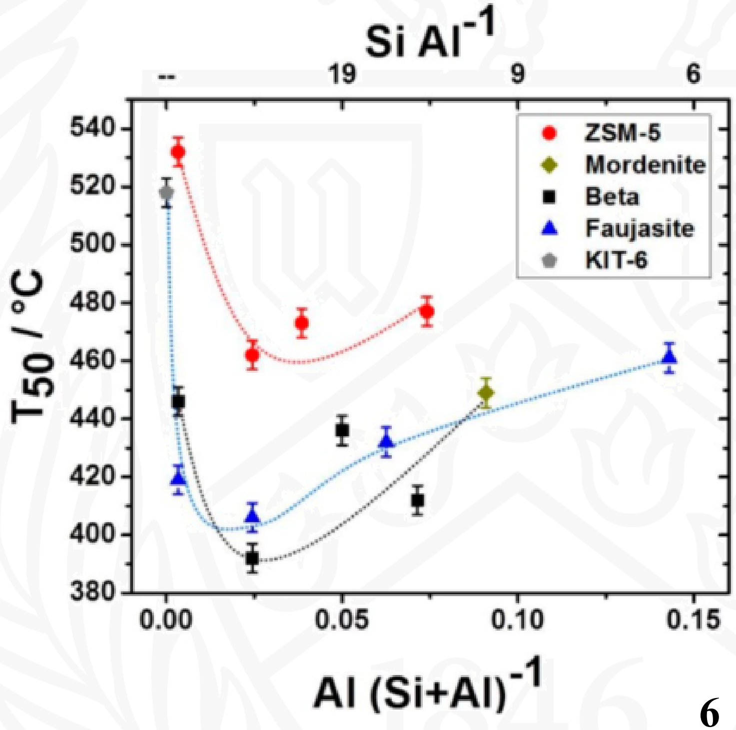
2017 Structure Commission of the International Zeolite Association

Improving low-temperature CH_4 oxidation using Na and increasing Si/Al molar ratios with SSZ-13 and LTA

- Studies on the effect of Na as a second metal for CH_4 oxidation are limited and relegated to large-pore zeolite, MOR.
- The effect of increasing Si/Al molar ratio on CH_4 oxidation were done using destructive techniques such as dealumination, leading to large mesopores from the destruction of the zeolite framework and are limited to large-pore zeolites.
- Improve CH_4 conversion with small-pore zeolites at low-temperatures through **Na loading** and **increasing Si/Al** molar ratio from synthesis with **target goal of 90% CH_4 conversion (T_{90}) < 400 °C**.





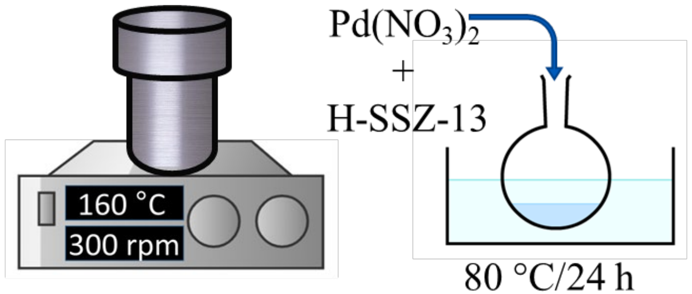


2017 Structure Commission of the International Zeolite Association
P. Losch, W. Huang, O. Vozniuk, E.D. Goodman, W. Schmidt, M. Cargnello, Acs Catal, (2019) 4742-4753.
A.W. Petrov, D. Ferri, F. Krumeich, M. Nachtegaal, J.A. van Bokhoven, O. Krocher, Nat Commun, 9 (2018) 2545.

Development of catalyst for low-temperature CH_4 oxidation

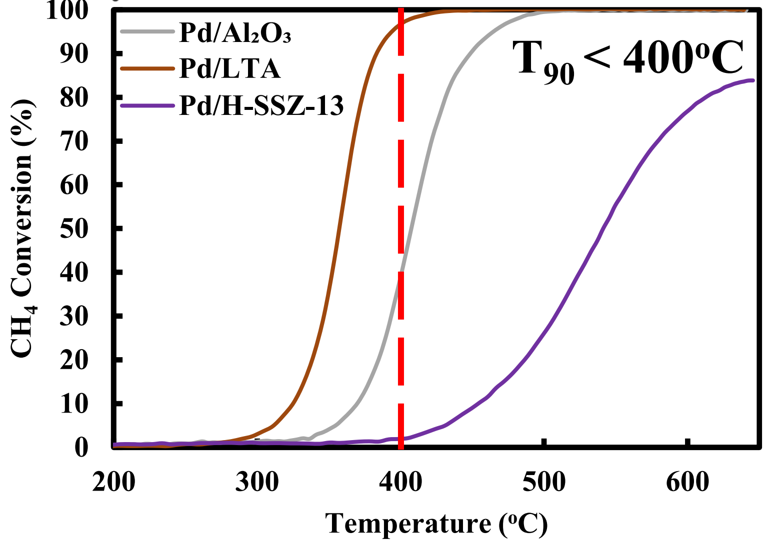
Phase 1

Development of Catalysts for Low-temperature CH_4-oxidation



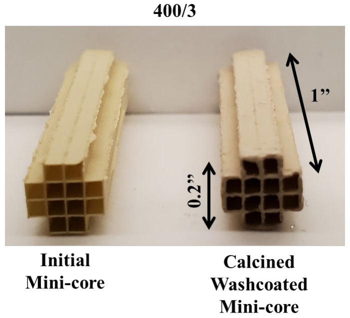
Hydrothermal Synthesis Dry Gel Conversion

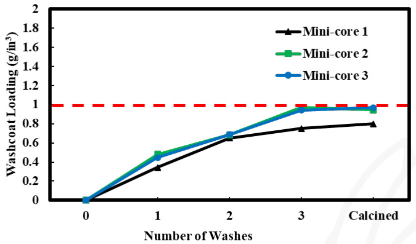
Pd ion-exchange

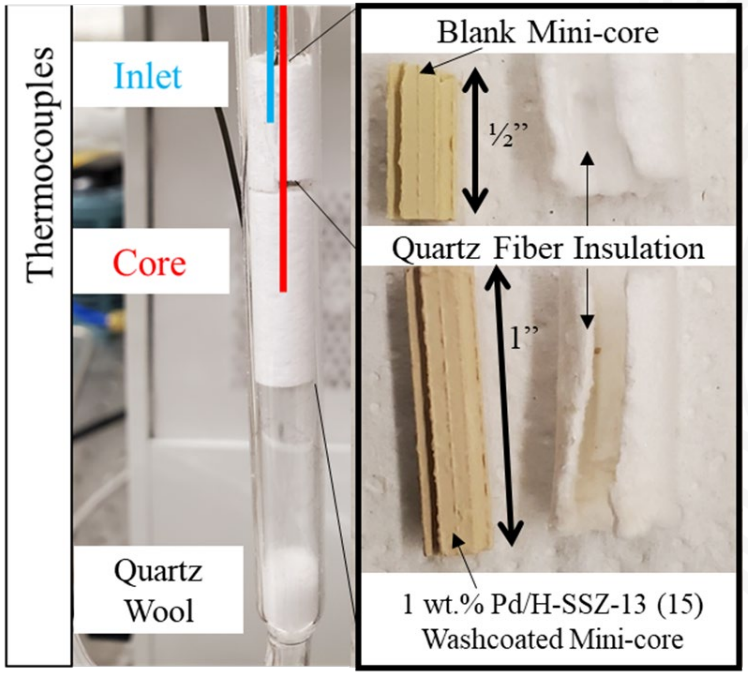


Phase 2

Washcoat Study of Zeolite-based Catalysts

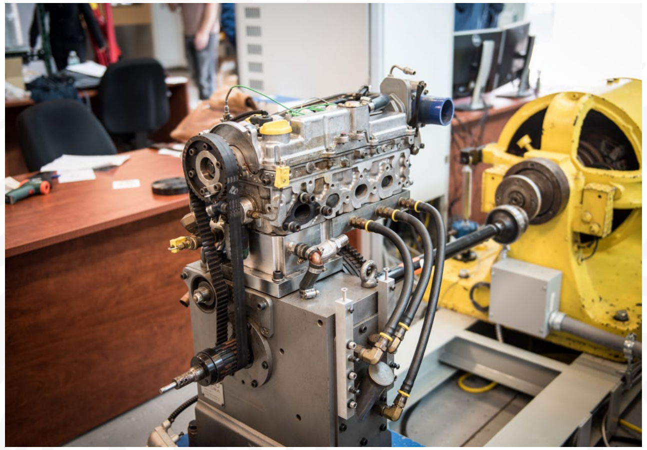




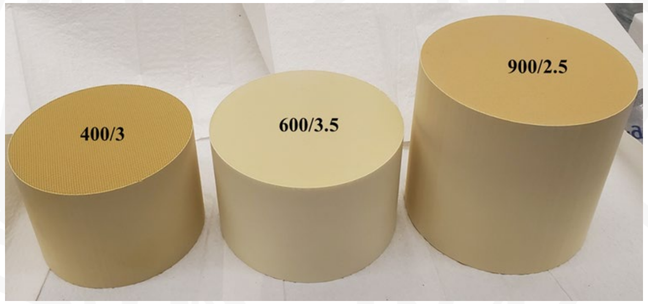


Phase 3

Catalysts Experimental Testing using Single-cylinder Research Engine

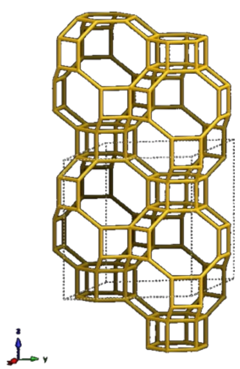


Ricardo Hydra Engine at Stony Brook University

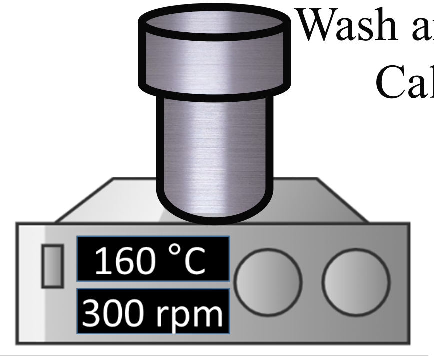


Full Monoliths

Successful synthesis of SSZ-13 confirmed by XRD



SSZ-13

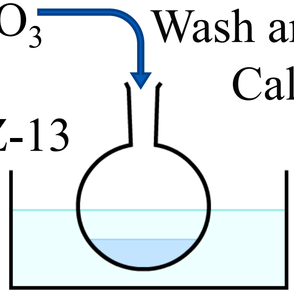


Hydrothermal Synthesis

Wash and dry (110 °C overnight)
Calcination (550 °C/8 h)

Na-SSZ-13 (15)
Na-SZZ-13 (33)

NH_4NO_3
+
Na-SSZ-13

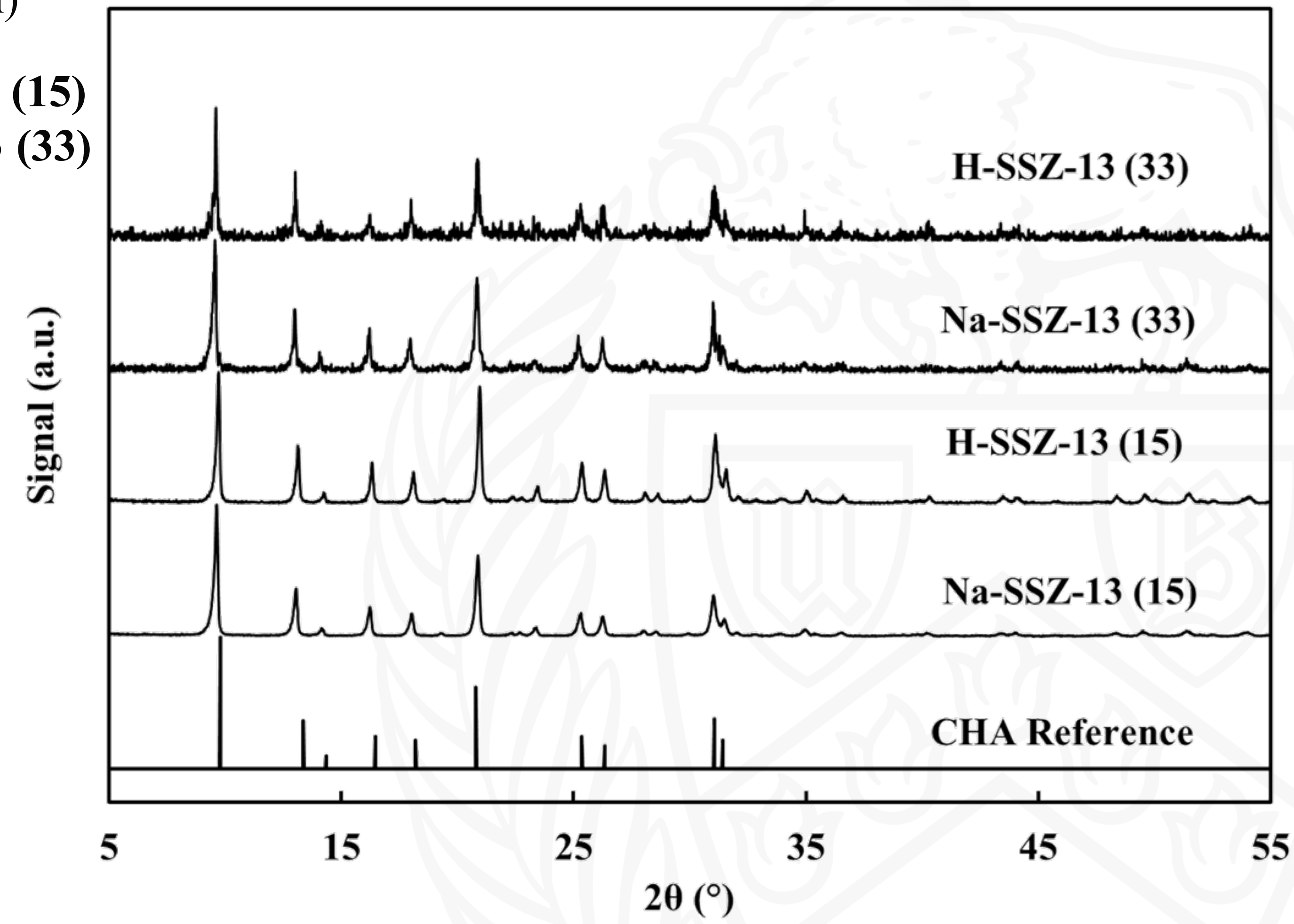


80 °C/24 h
NH_4 ion-exchange

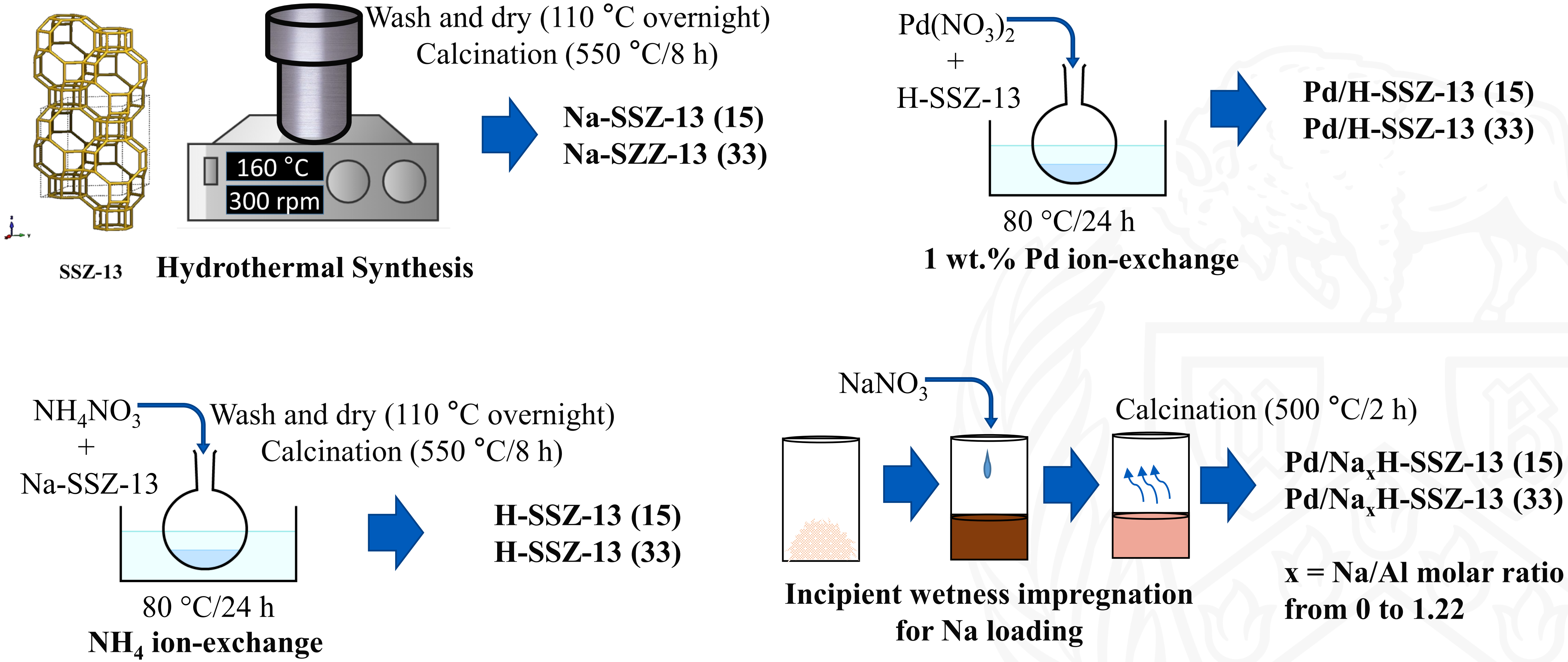
Wash and dry (110 °C overnight)
Calcination (550 °C/8 h)

H-SSZ-13 (15)
H-SSZ-13 (33)

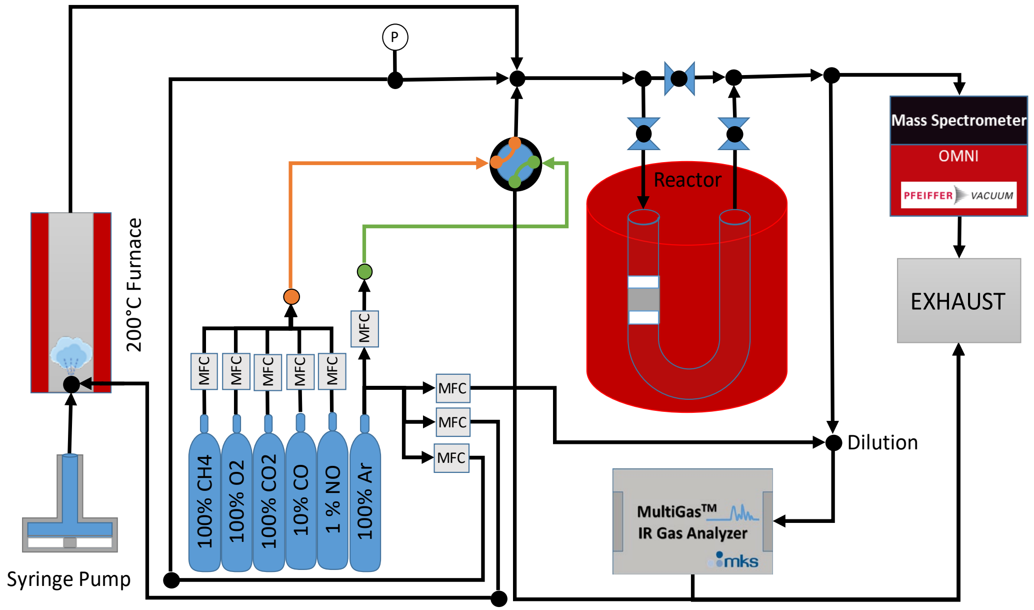
X-ray Diffraction (XRD)



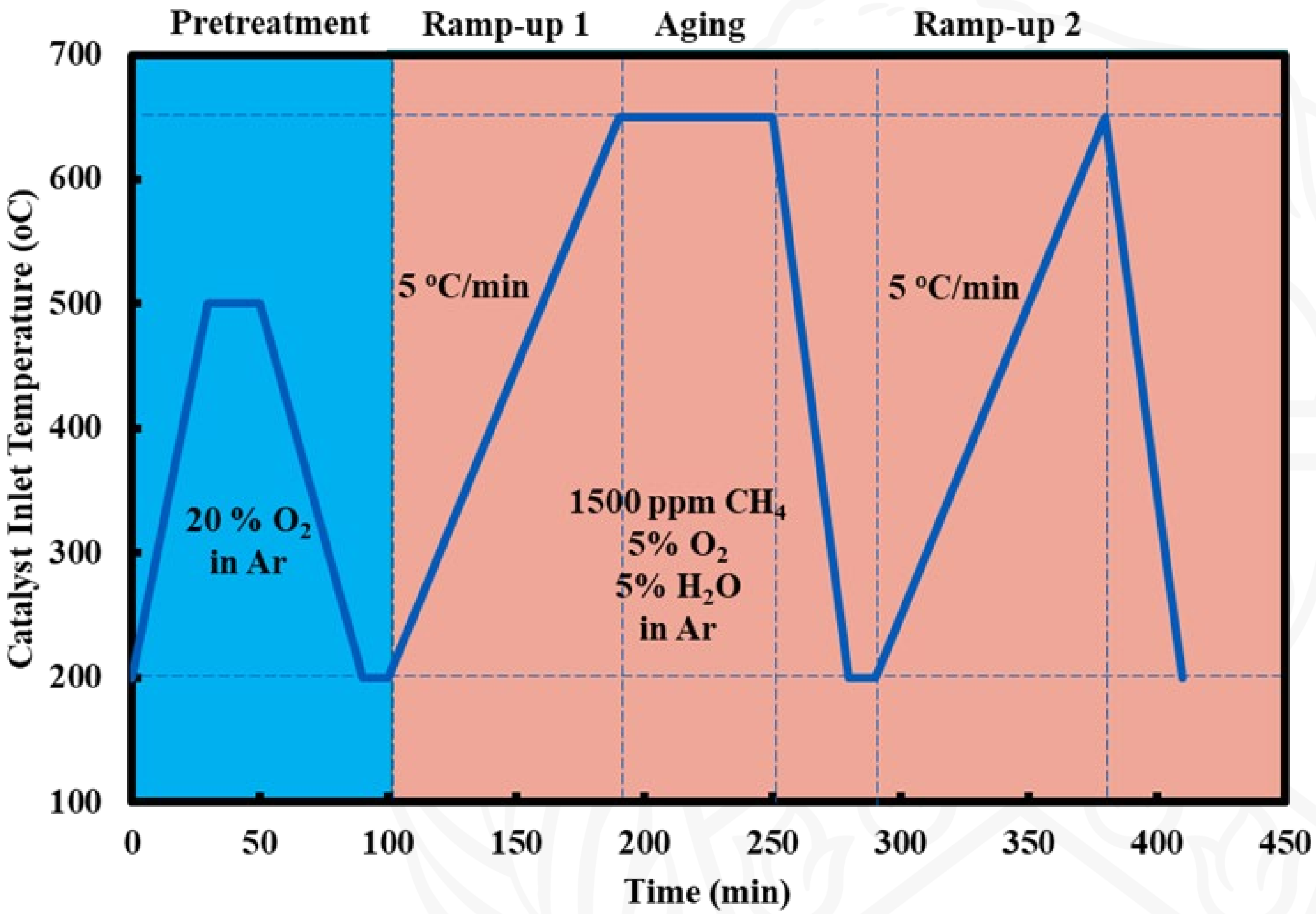
Pd ion-exchange and Na impregnation on H-SSZ-13 (15, 33)



Microreactor evaluation for CH_4 oxidation

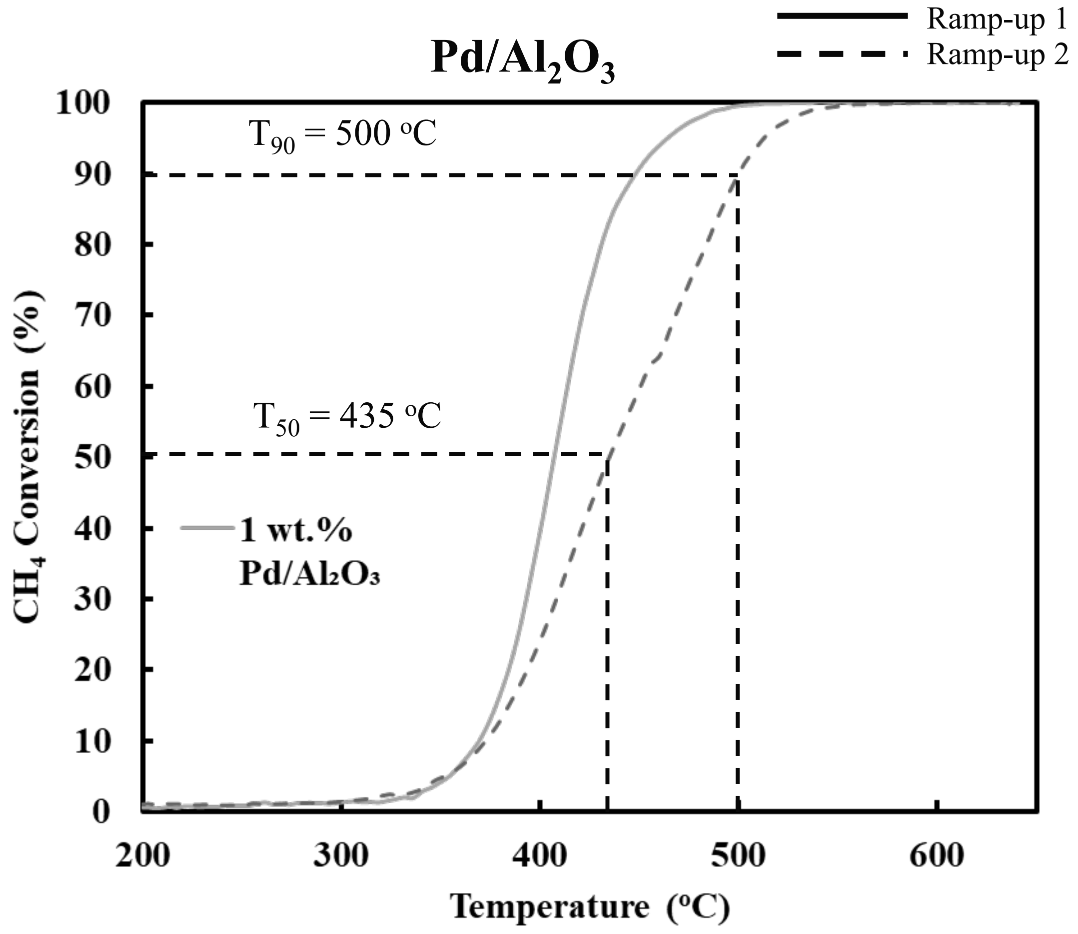


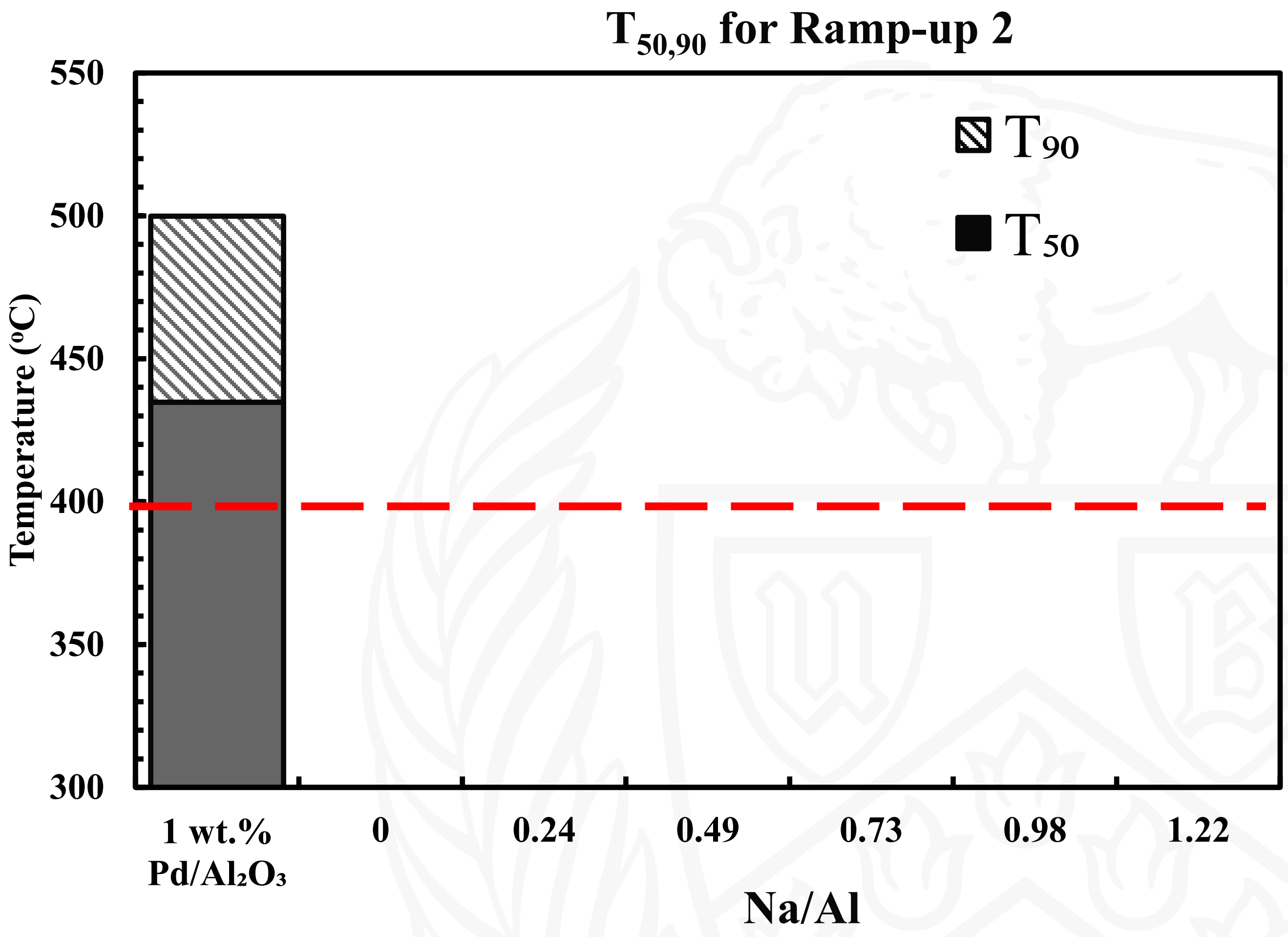
Micro-reactor Setup



Catalyst loading: 100 mg (250-500 μm)
Feed: 1500 ppm CH_4, 5% O_2, 5% H_2O in Ar
Flow rate: 333 sccm
WHSV: 199.8 L g_{cat}^{-1} h^{-1}
GHSV: 19874 h^{-1}

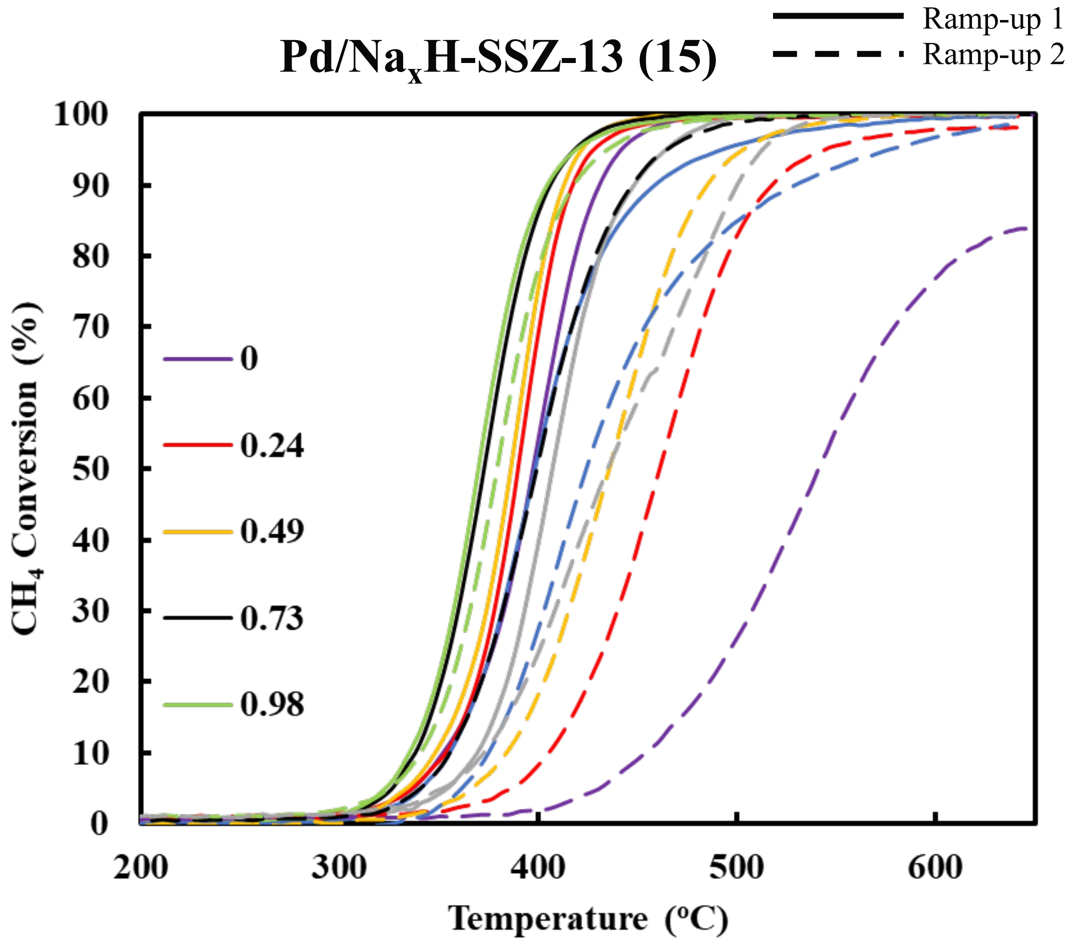
Pd/Al_2O_3 does not meet the target goal of T_{90} < 400 °C

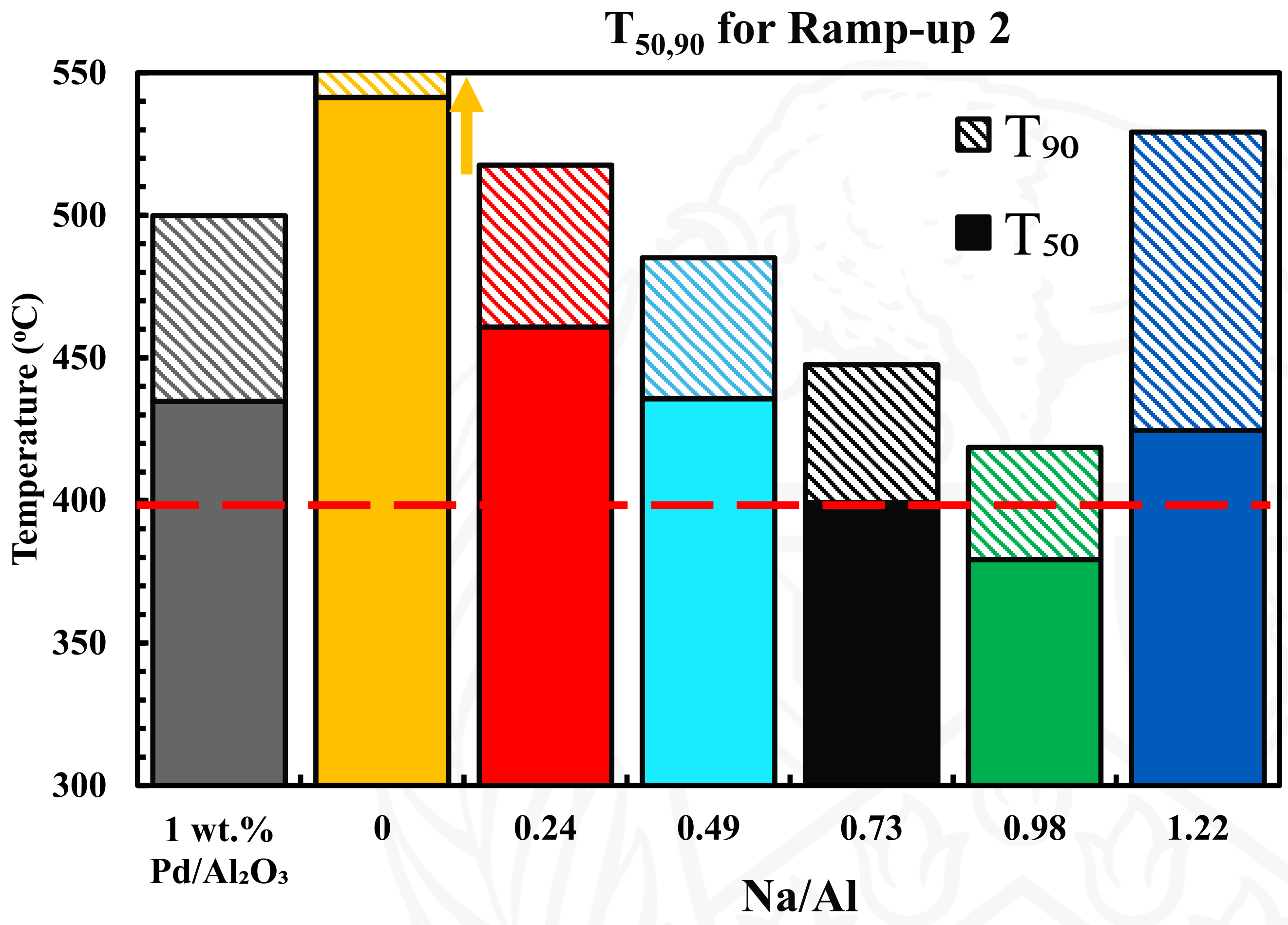




❖ Goal is to outperform Pd/Al_2O_3 and achieve target of T_{90} <400 °C (red dashed line).

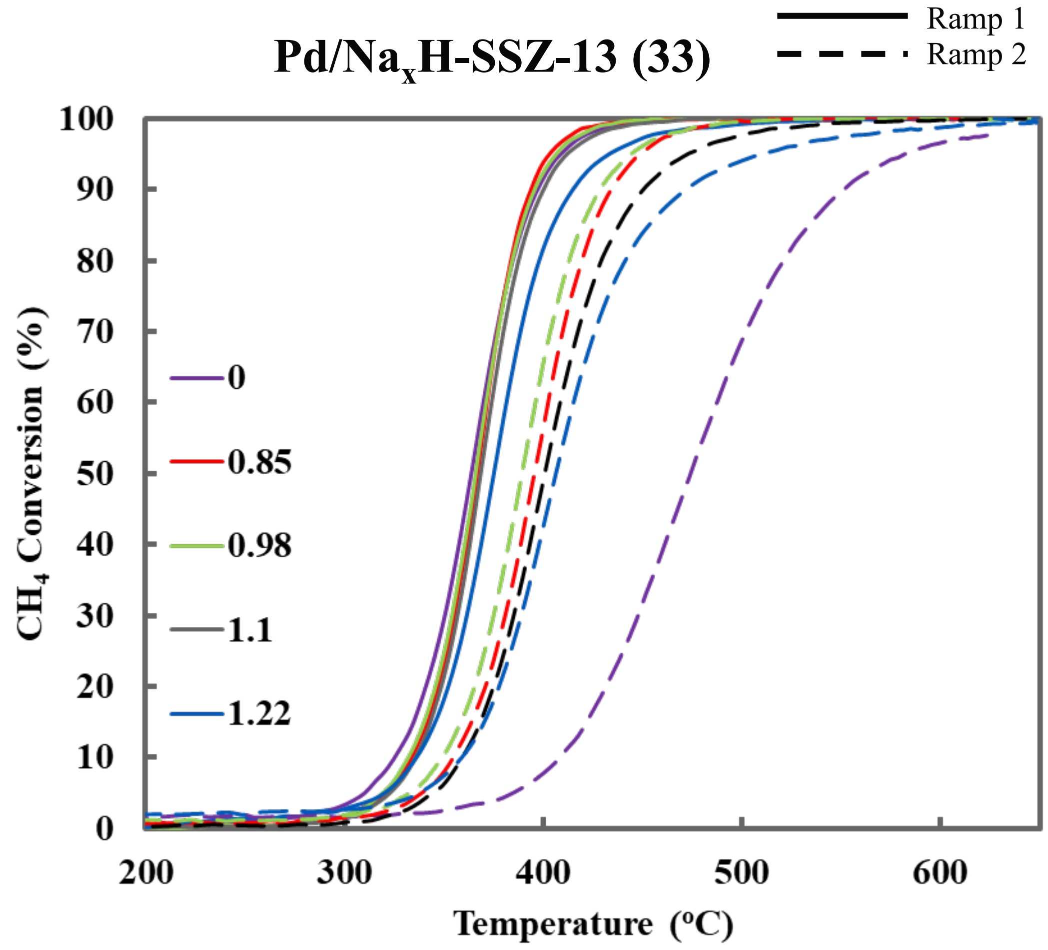
Na/Al molar ratio of 0.98 with Pd/H-SSZ-13 (15) approaches target goal of T_{90} < 400 °C

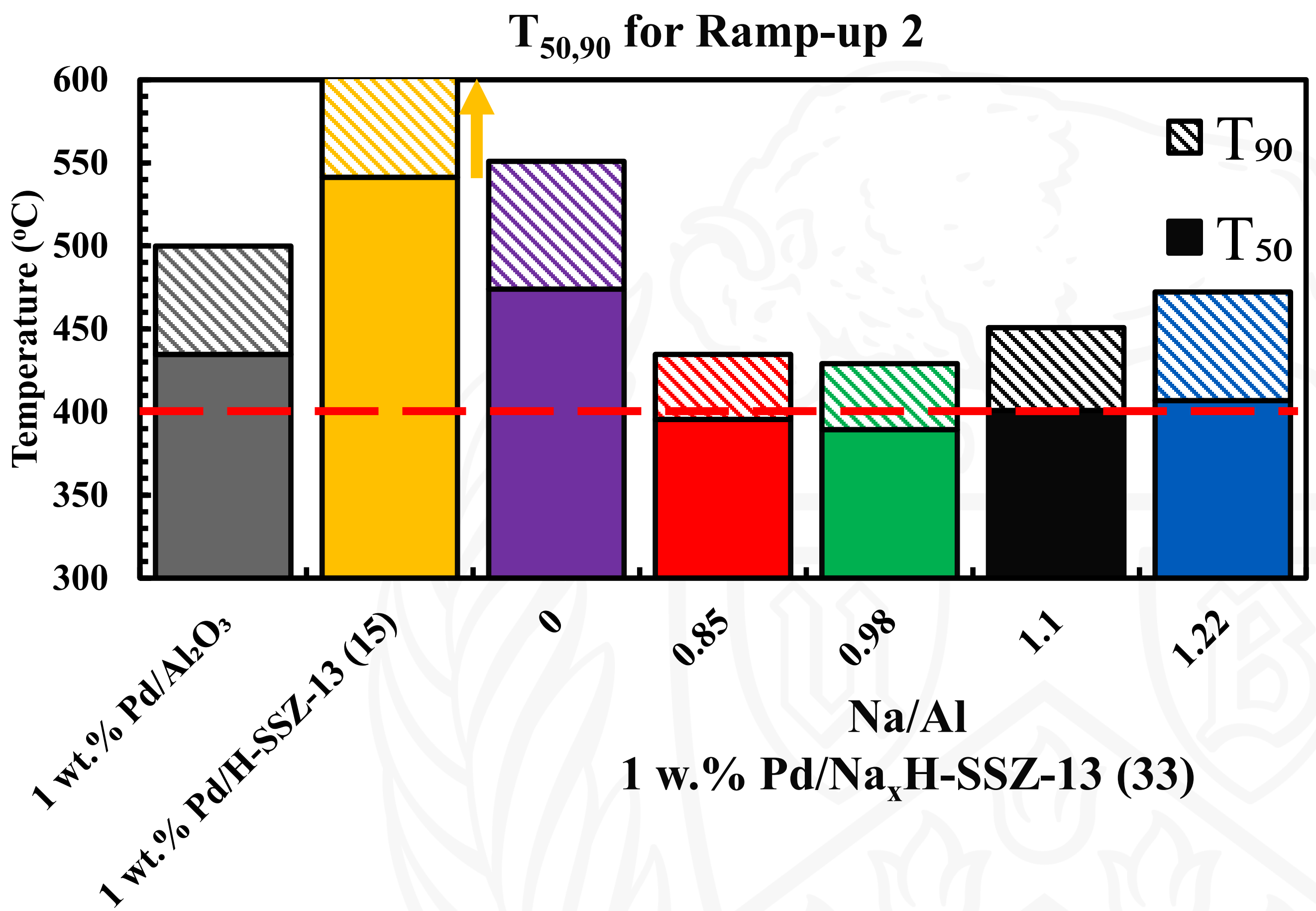




- Pd/$Na_{0.98}$H-SSZ-13 (15) showed the lowest T_{50} and T_{90} out of all the studied Pd/Na_xH-SSZ-13 (15) catalysts at 379 and 419 °C, respectively.
- Underloading (Na/Al<0.98) and overloading (Na/Al>0.98) of Na results in deactivation in ramp-up 2.

Higher Si/Al at 33 and Na loading improves CH_4 conversion with Pd/H-SSZ-13 (33)

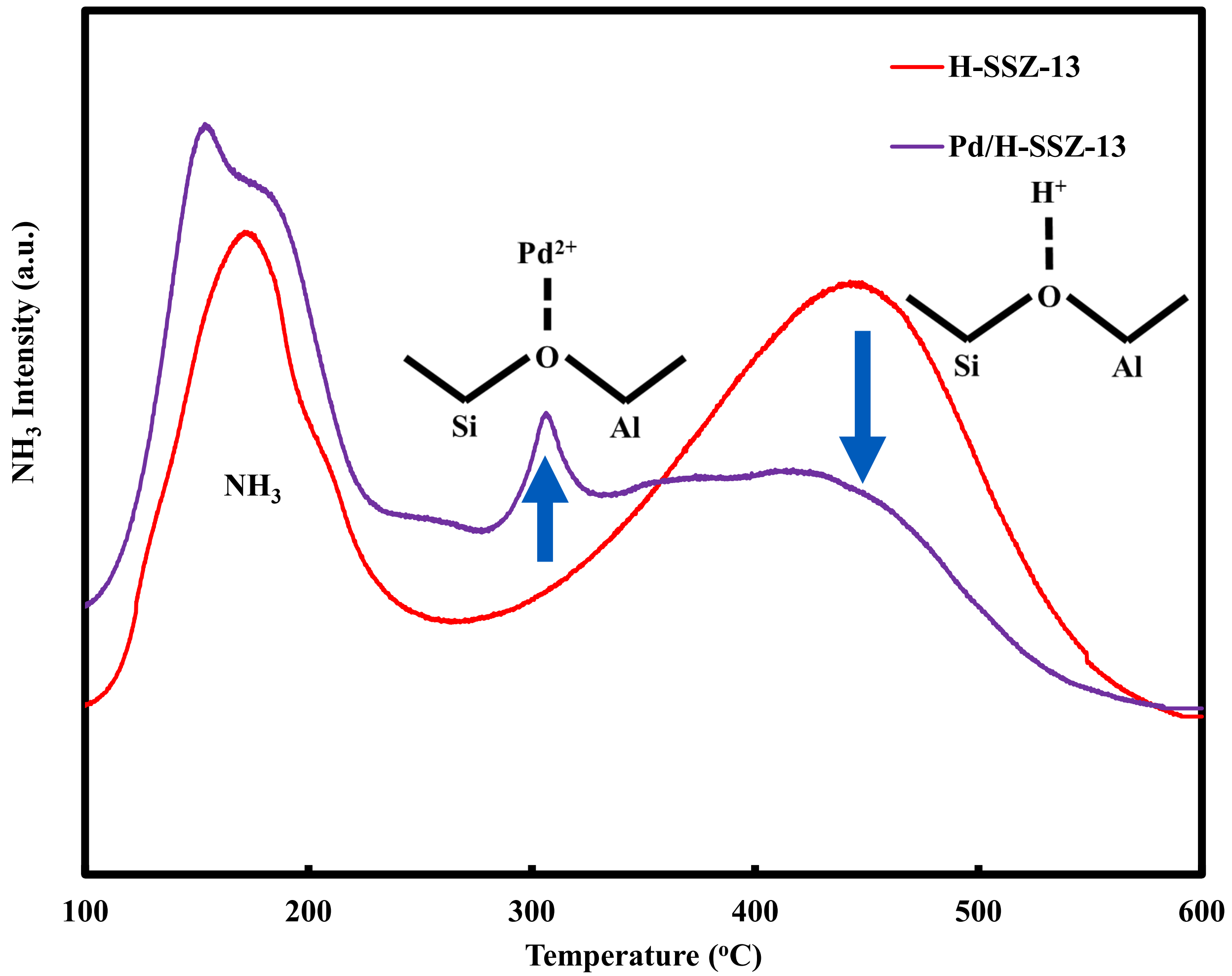




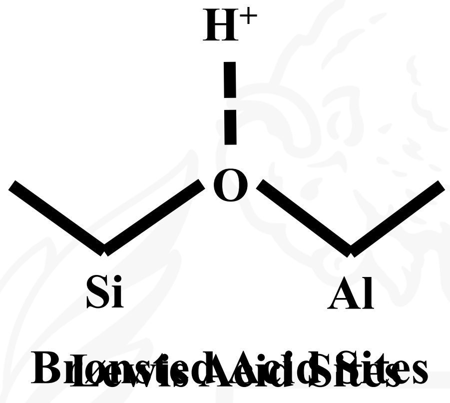
❖ Na/Al = 0.98 for Si/Al of 33 is also the optimum Na/Al molar ratio with T_{50} and T_{90} of 389 and 429 °C, respectively.

Ion-exchanged Pd converts Brønsted acid sites to moderate Lewis acid sites

NH_3-TPD: Effect of Pd ion-exchange on H-SSZ-13 (15)



Pd^{2+}

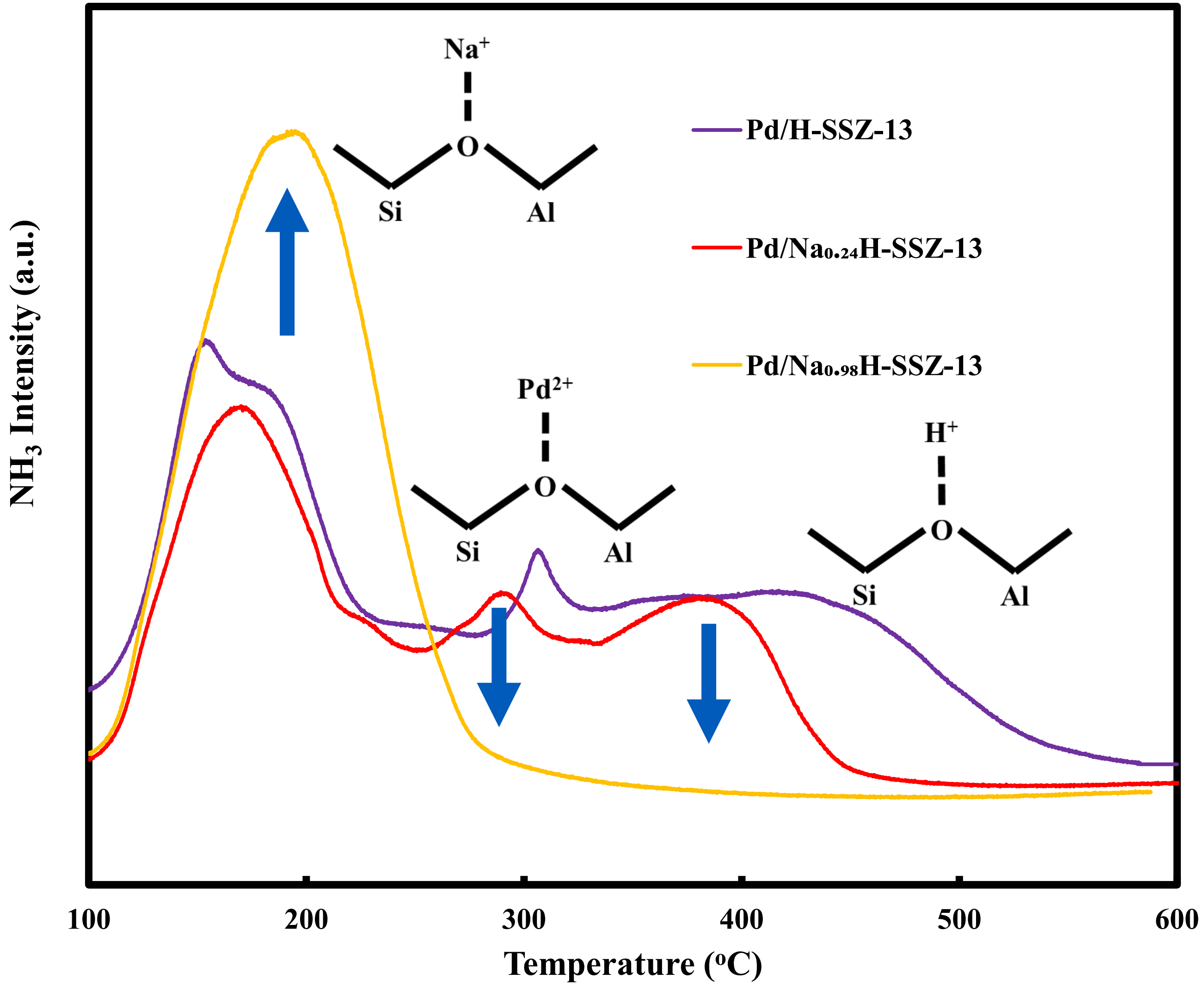


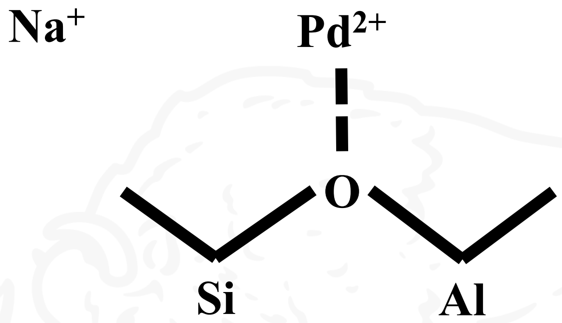
❖ Ion-exchange of Pd at 1 wt.% results in the exchange of the H^+ for Pd^{2+}, leading to moderate Lewis acid sites as evident by the increase in the moderate temperature peak and decrease in high temperature peak.

D. Wang, F. Gao, C.H.F. Peden, J. Li, K. Kamasamudram, W.S. Epling, Chemcatchem, 6 (2014) 1579-1583.

Na removes ion-exchanged Pd and prevents Pd migration through acid sites

NH_3-TPD: Effect of Na loading on Pd/Na_xH-SSZ-13 (15) where x is Na/Al molar ratio





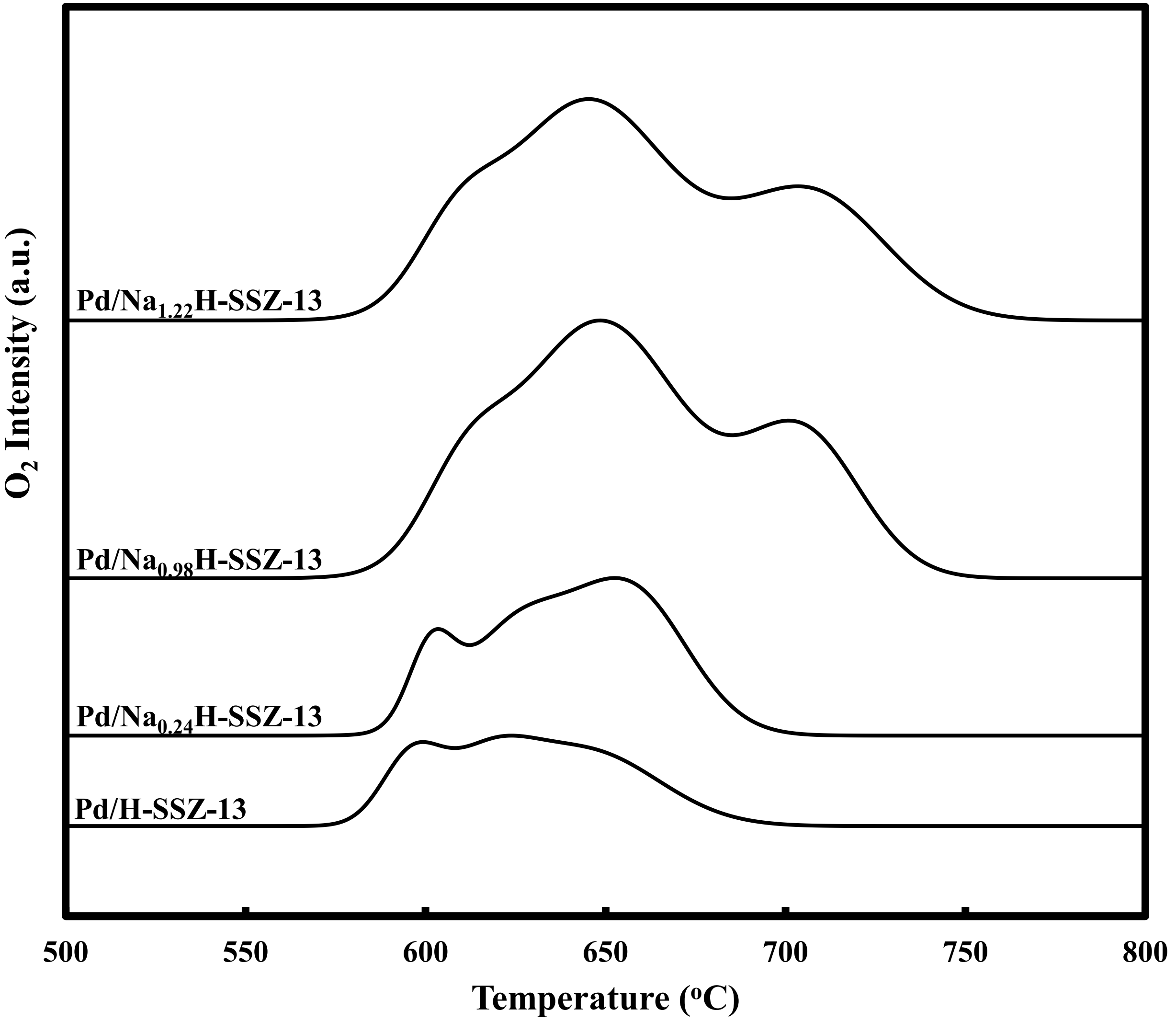
Increasing the amount of Na from Na/Al molar ratio of 0.24 to 0.98 resulted in:

- ❖ Increase in intensity of the low temperature desorption peak (100-250 ^{o}C) -> weak Lewis acid sites through ion-exchanged Na^+.
- ❖ Decrease in intensity of moderate temperature desorption peak (250-350 ^{o}C) -> moderate Lewis acid sites from Pd^{2+} prevented by ion-exchanged Na^+.
- ❖ Decrease in intensity of the high temperature desorption peak (350-550 ^{o}C) -> Brønsted acidity is decreased by ion-exchange of H^+ by Na^+.

A.W. Petrov, D. Ferri, F. Krumeich, M. Nachtegaal, J.A. van Bokhoven, O. Krocher, Stable complete methane oxidation over palladium based zeolite catalysts, Nat Commun, 9 (2018) 2545.

Na loading favors formation of active PdO

O_2-TPD: Effect of loading Na on Pd/Na_xH-SSZ-13 (15)



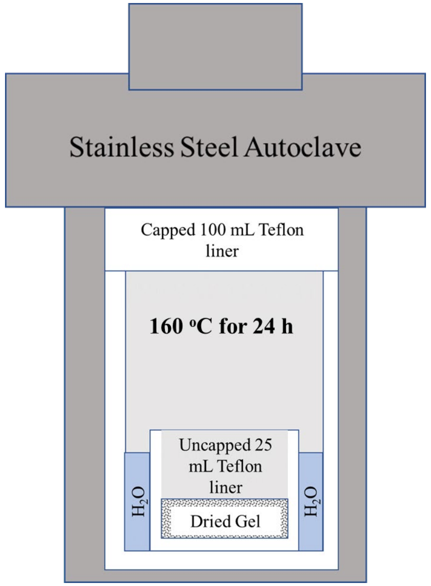
Catalysts	PdO (μmoles/$g_{catalyst}$)	PdO/Total Pd (molar ratio)
Pd/H-SSZ-13	32.5	0.35
Pd/$Na_{0.24}$H-SSZ-13	51.6	0.55
Pd/$Na_{0.98}$H-SSZ-13	94	1
Pd/$Na_{1.22}$H-SSZ-13	94	1

- ❖ Addition of Na increases the formation of PdO.
- ❖ Adding Na at Na/Al = 1.22 results in a similar O_2 desorption as Na/Al = 0.98 suggesting the limit has been reached for PdO to form.

Successful synthesis of high silica (Si/Al ≥50) with dry gel conversion

Dried gel molar ratio

Si/Al	x Al_2O_3
50	1
100	0.5
200	0.25

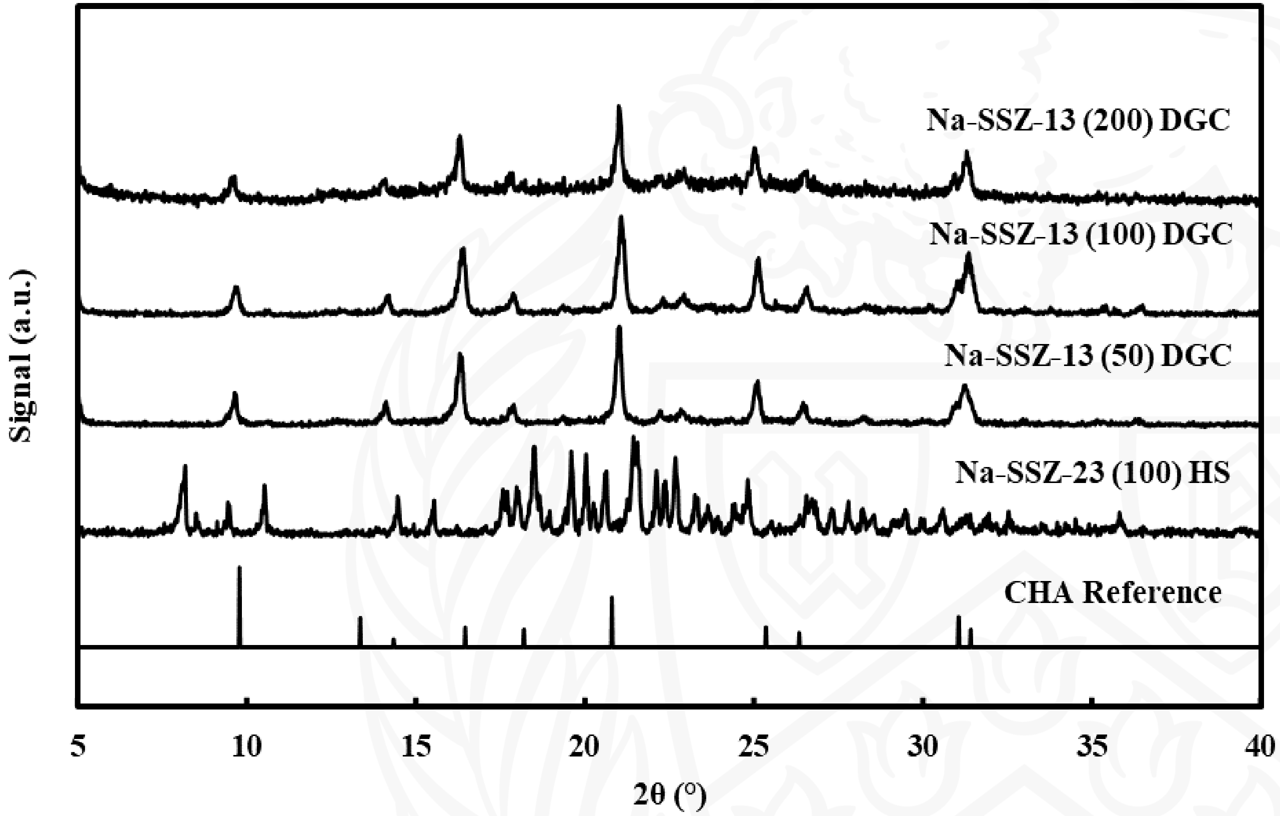


Dry gel conversion (DGC)

Elemental analysis (ICP)

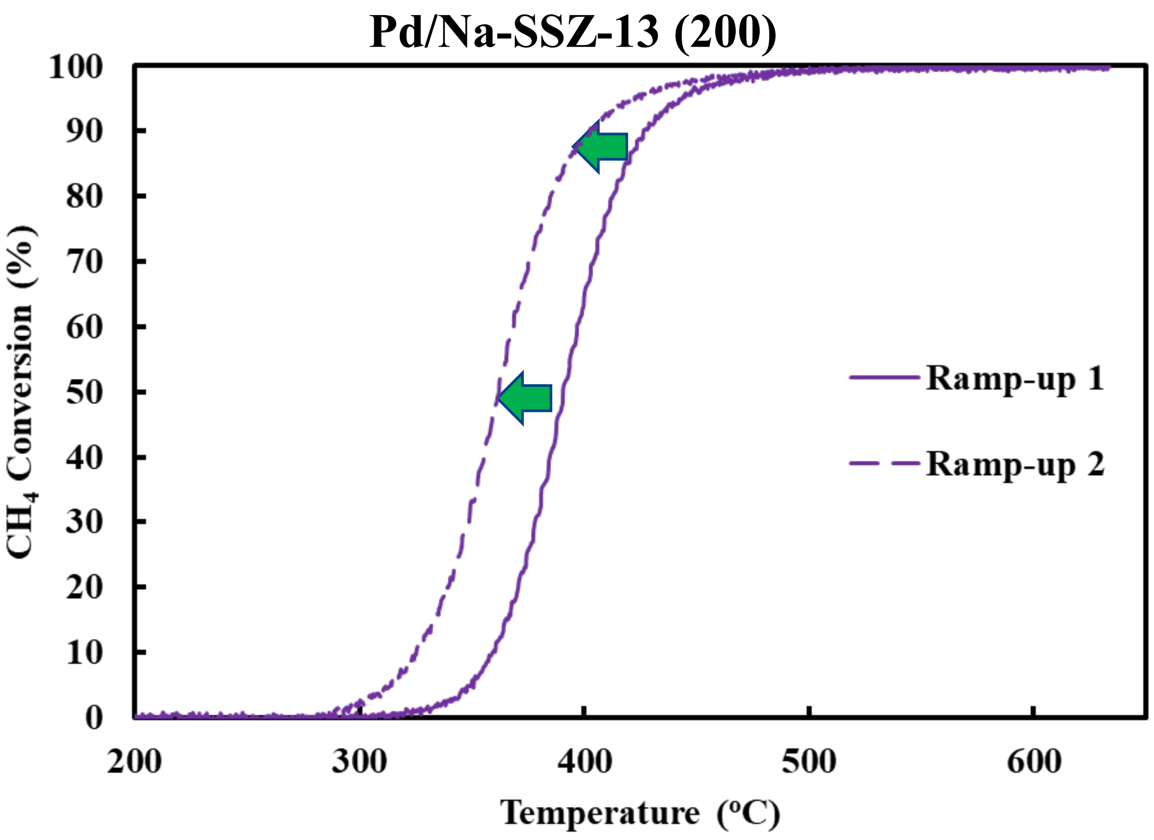
Catalysts	Si/Al	Pd (wt.%)
Pd/Na-SSZ-13 (50)	47	0.8
Pd/Na-SSZ-13 (100)	99	1
Pd/Na-SSZ-13 (200)	191	1

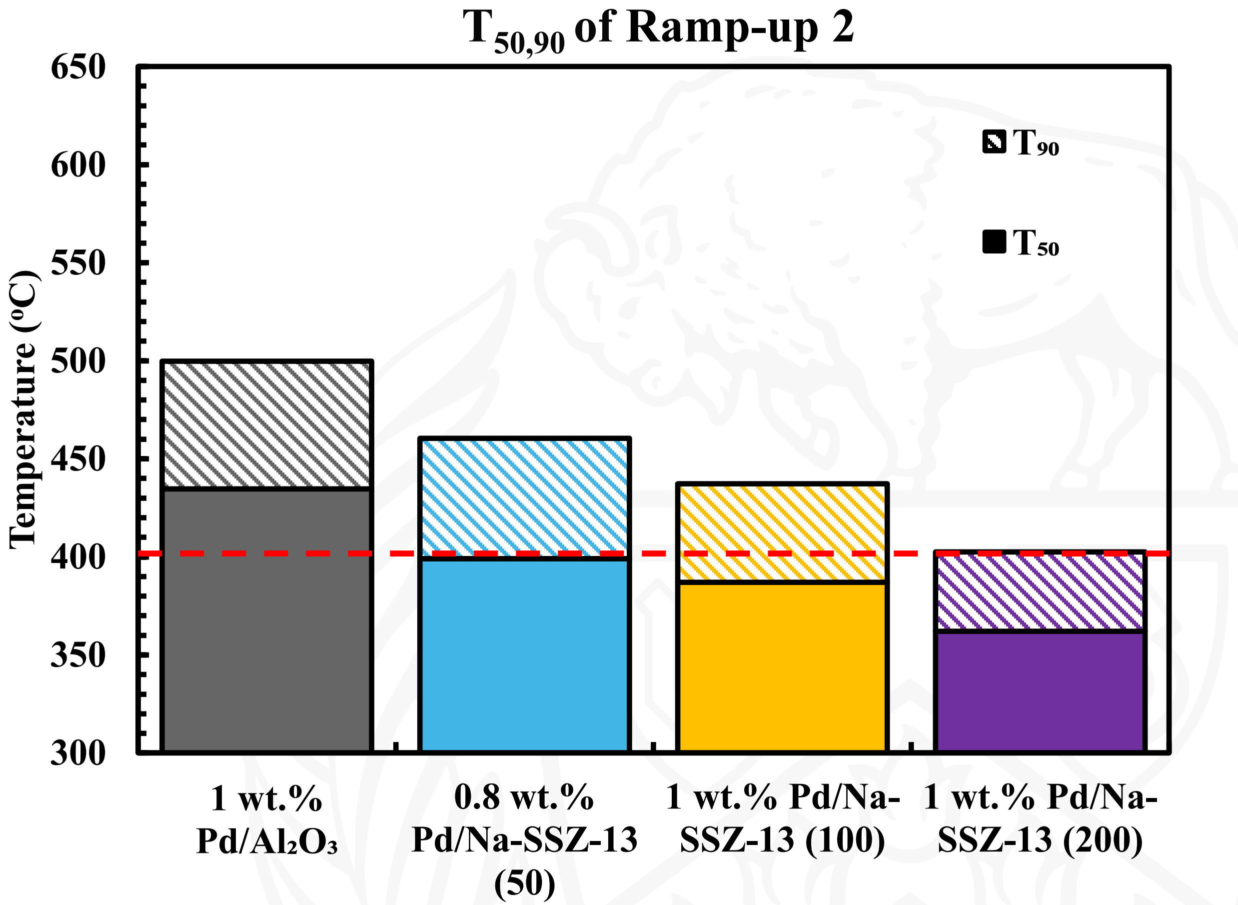
XRD of Na-SSZ-13 (50, 100, 200)



❖ SSZ-23 is preferred at higher Si/Al molar ratio with hydrothermal synthesis and does not have the CHA framework structure!

Pd/Na-SSZ-13 (200) improves after aging and meets the target goal of T_{90} < 400 °C





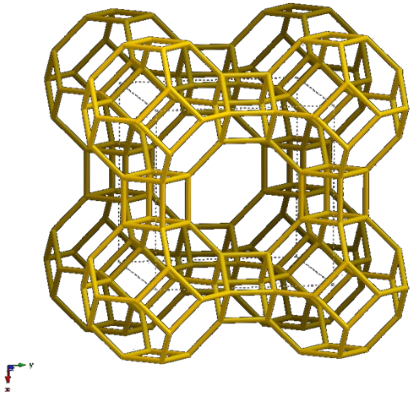
- T_{50} decreased from 390 to 362 °C.
- T_{90} decreased from 426 to 402 °C.
- The prevention of hydroxyl accumulation due to high hydrophobicity and water-created edge sites on PdO nanoparticle surface may lead to higher CH_4 oxidation activity.

P. Losch, et al, Acs Catal, (2019) 4742-4753.
A.C. Yang, et al, Proc Natl Acad Sci U S A, 117 (2020) 14721-14729.

Successful synthesis of H-LTA confirmed by XRD

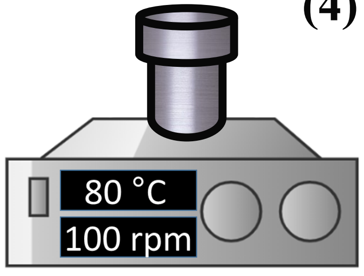

Viktor J. Cybulskis Jingzhi Liu

Syracuse University



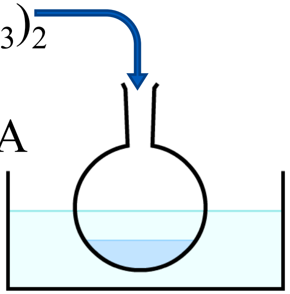
(1) SDA(OH)
TMA

(2) Al_2O_3
(3) TEOS
(4) HF



- ❖ Stir 24 h at RT
- ❖ Evaporate hydrolyzed water and ethanol
- ❖ 160 °C/14 days

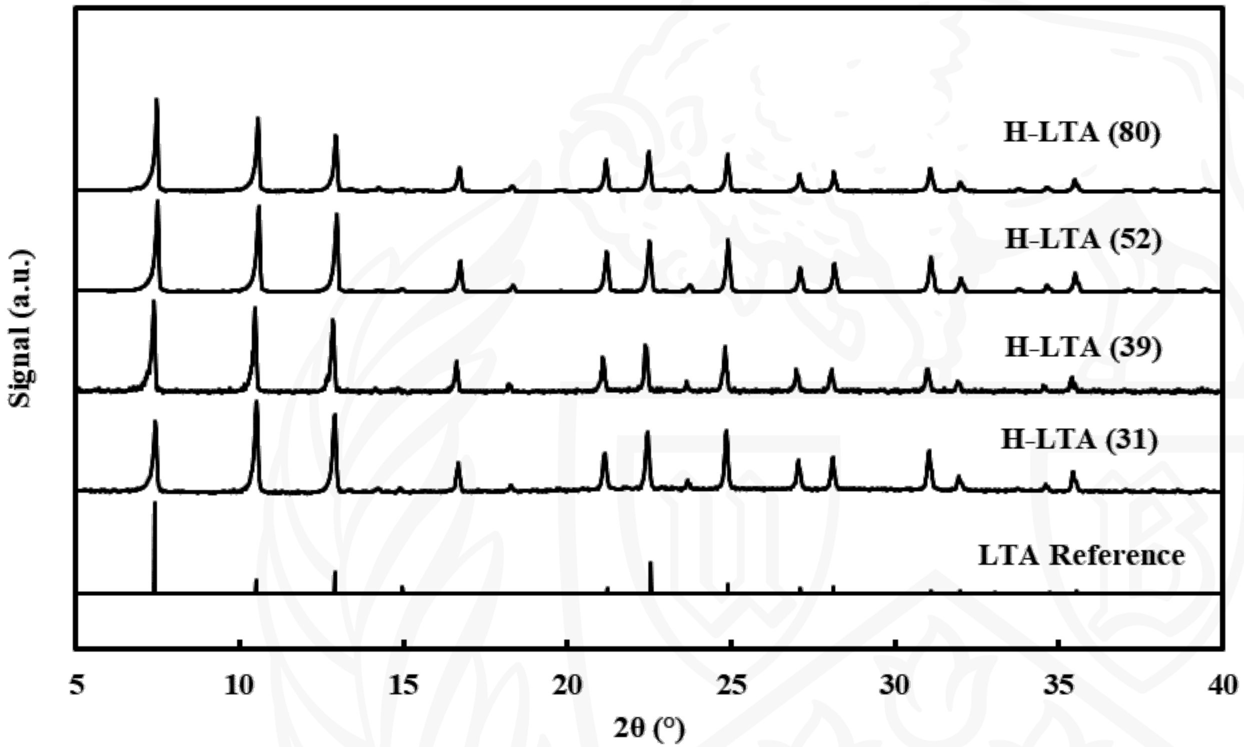
$Pd(NO_3)_2$
+
H-LTA



80 °C/24 h

1 wt.% Pd ion-exchange

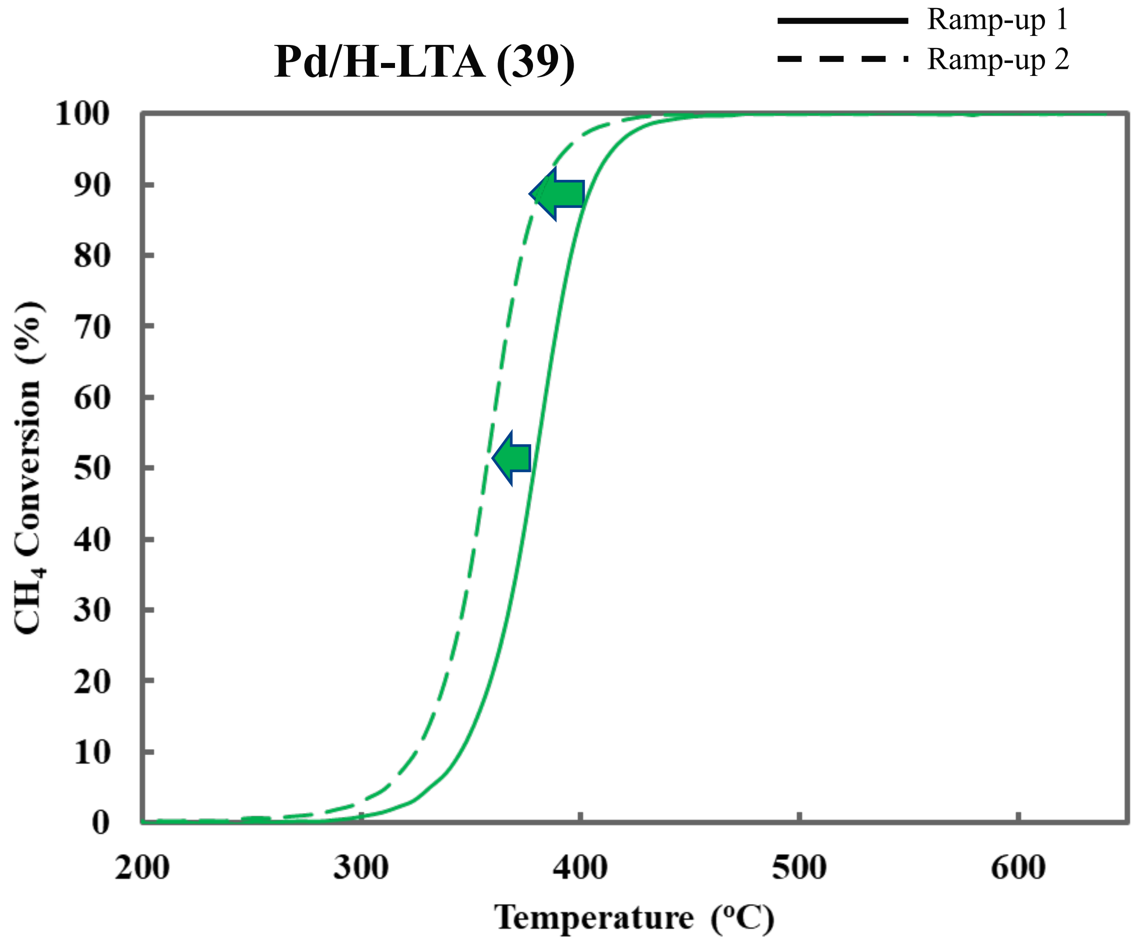
XRD of H-LTA (31, 39, 52, 80)

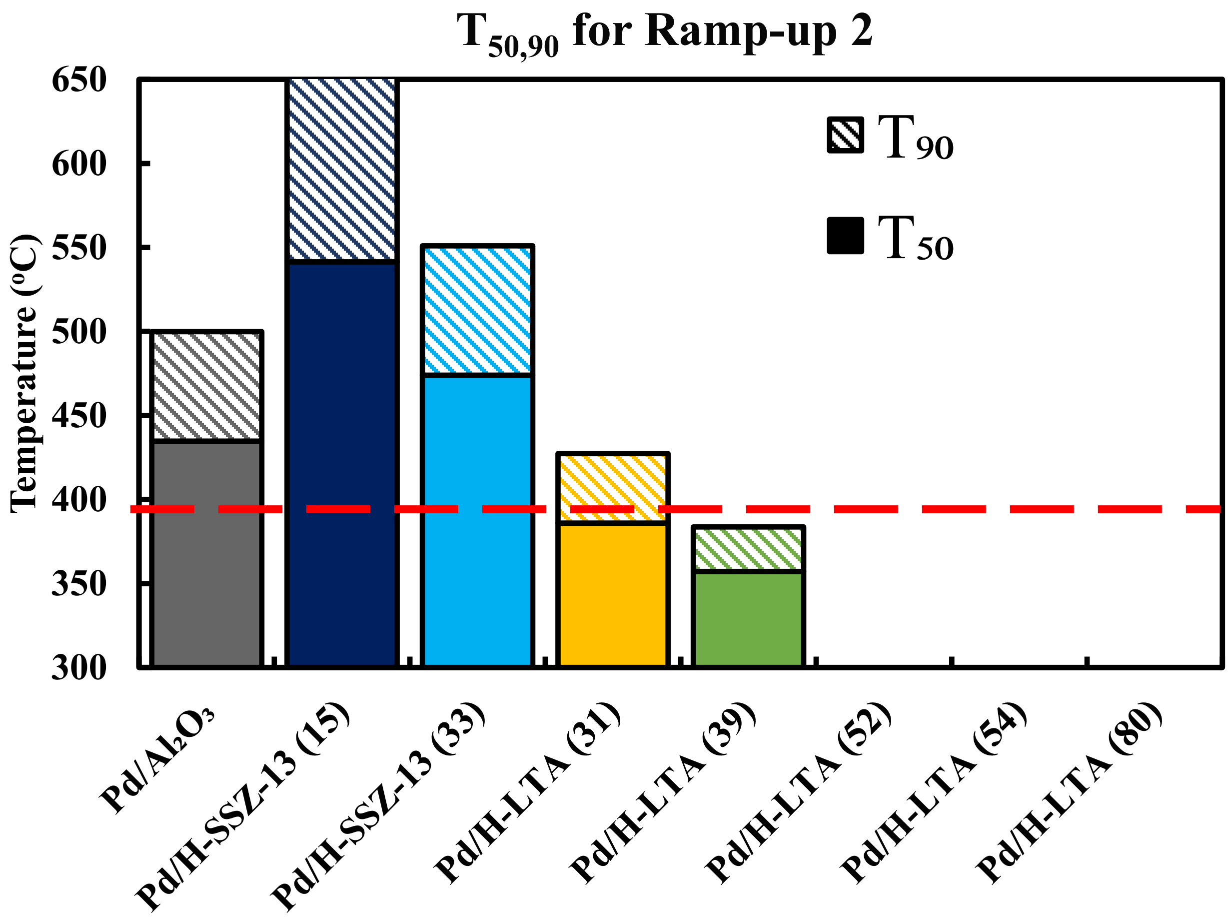


- ❖ Synthesizing LTA is challenging as it requires the synthesis of a structure directing agent and usage of HF to dissolve the silica precursors.

B.W. Boal, J.E. Schmidt, M.A. Deimund, M.W. Deem, L.M. Henling, S.K. Brand, S.I. Zones, M.E. Davis, Facile Synthesis and Catalysis of Pure-Silica and Heteroatom LTA, Chem Mater, 27 (2015) 7774-7779.

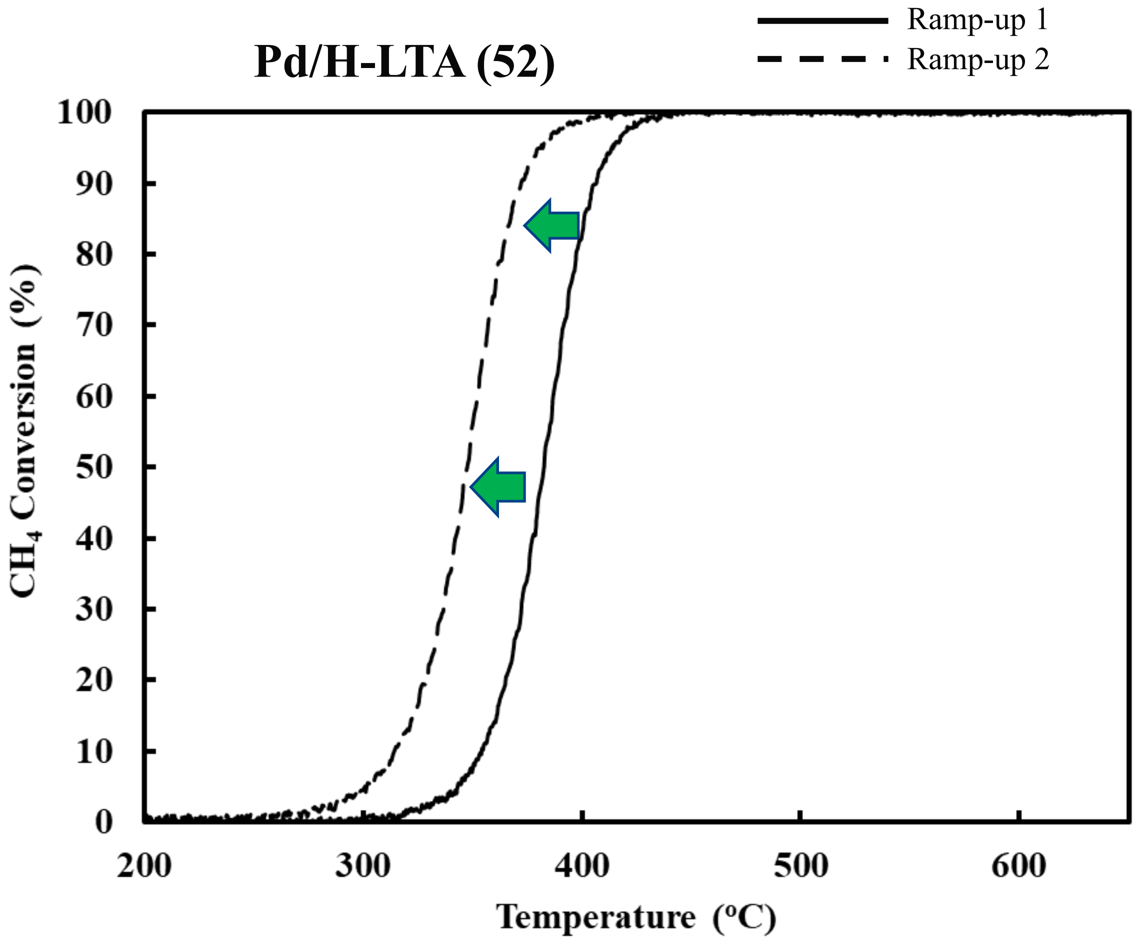
Pd/H-LTA (39) shows lower $T_{50, 90}$ after aging

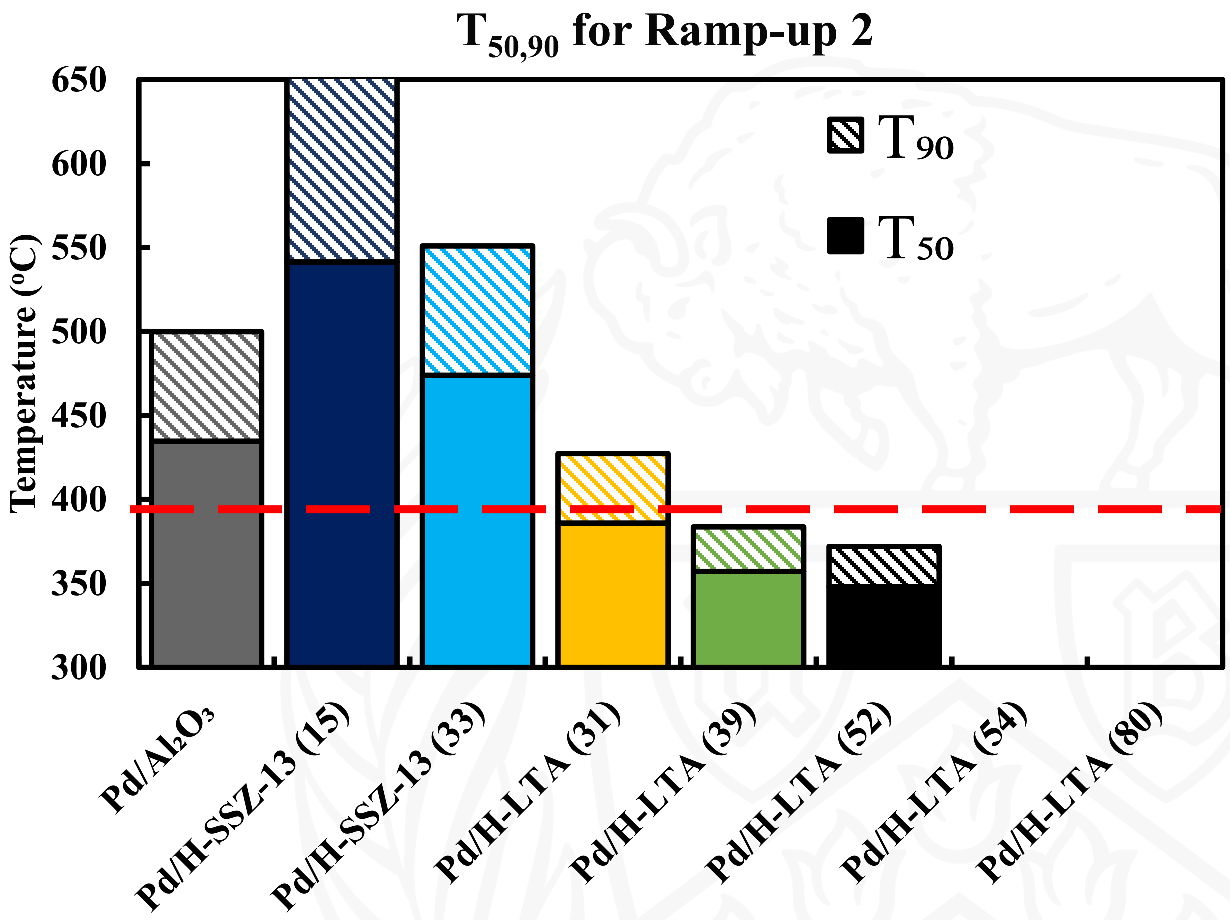




- Ramp-up 1 already matches the T_{50} of Pd/$Na_{0.98}$H-SSZ-13 (15) at 379 °C with an even lower T_{90} at 406 °C.
- Ramp-up 2 showed an improvement in CH_4 oxidation performance compared to ramp-up 1 with T_{50} of 357 °C and T_{90} of 384 °C.

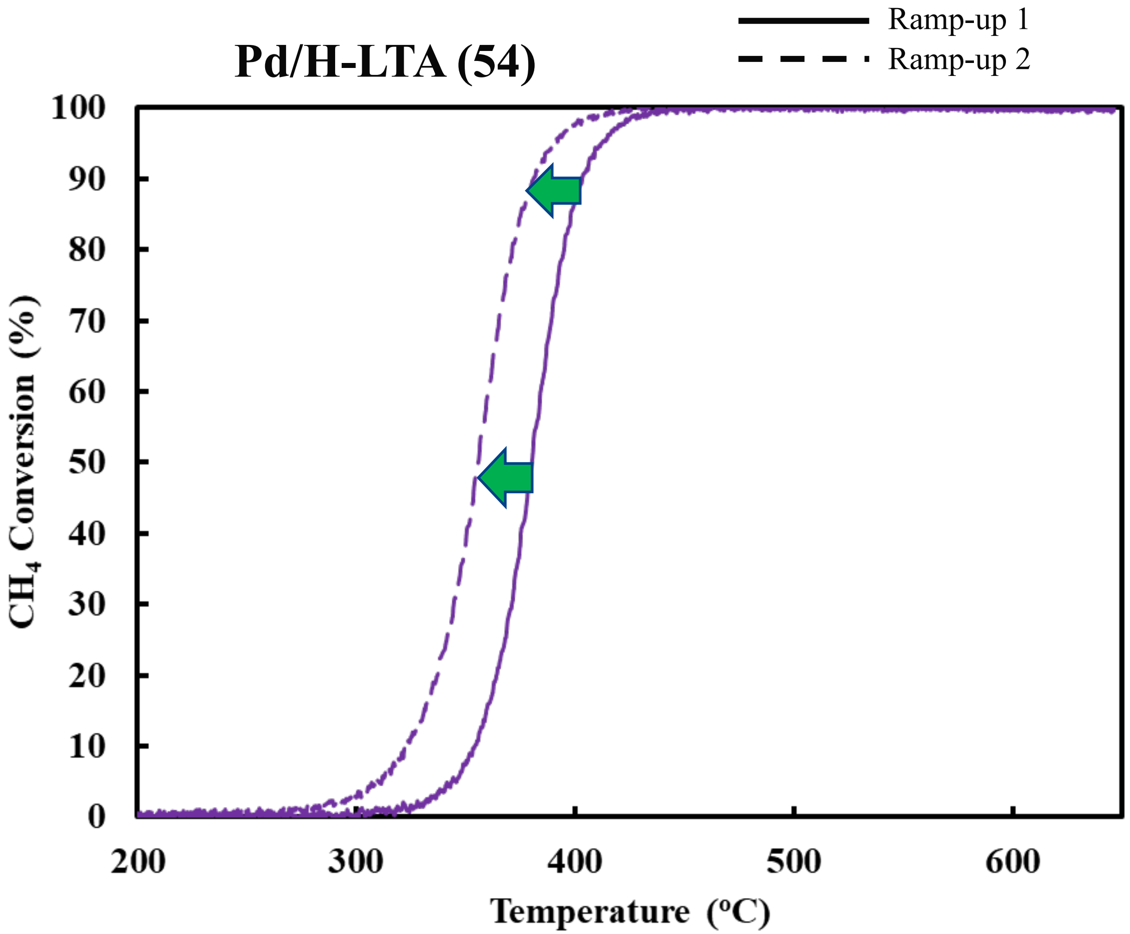
Maximum improvement in $T_{50, 90}$ with Pd/H-LTA (52)

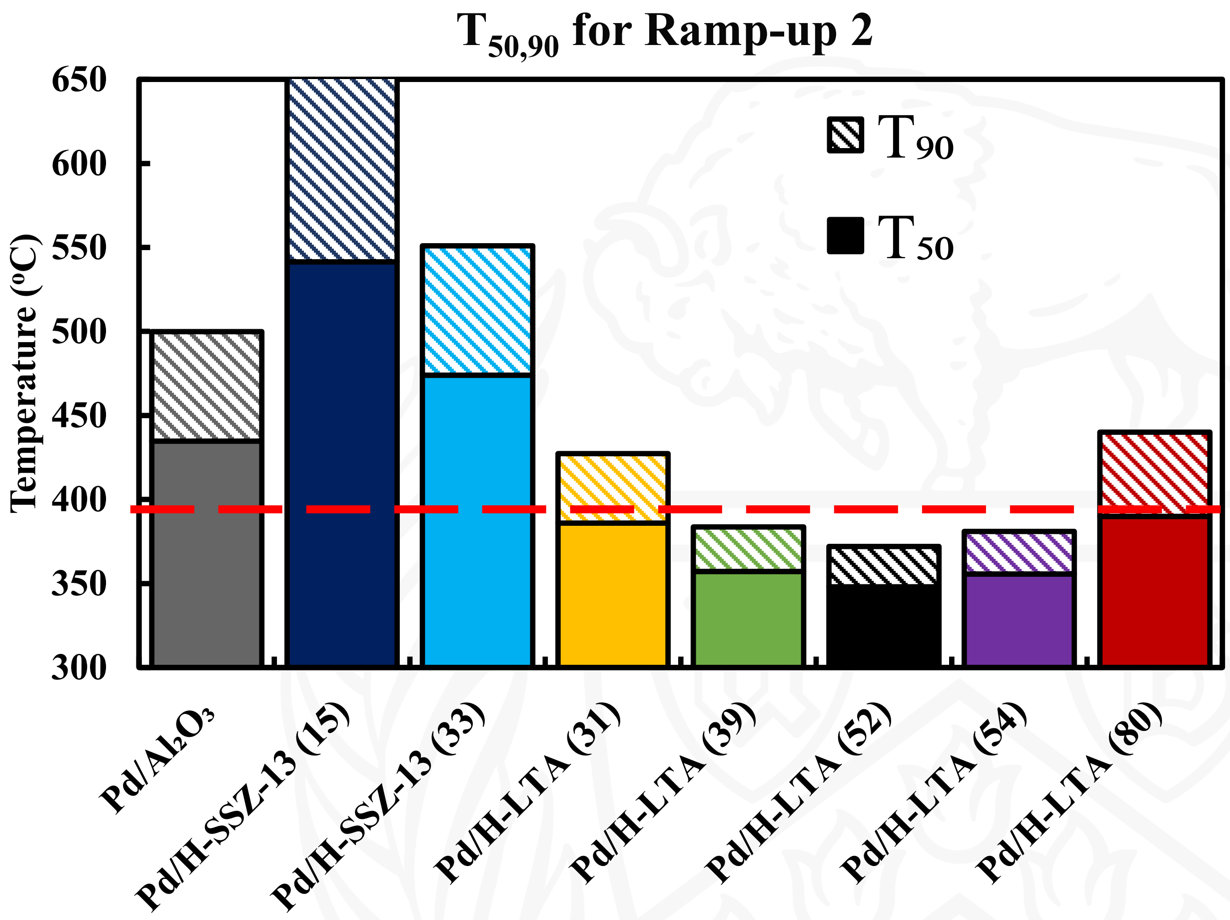




- Ramp-up 2 showed an improvement in CH_4 oxidation performance compared to ramp-up 1 with T_{50} of 348 °C and T_{90} of 372 °C.

Increasing Si/Al molar further reduces improvement in $T_{50, 90}$ with Pd/H-LTA (54, 80)





❖ Ramp-up 2 showed an improvement in CH_4 oxidation performance compared to ramp-up 1 with T_{50} of 356 ^oC and T_{90} of 381 ^oC.

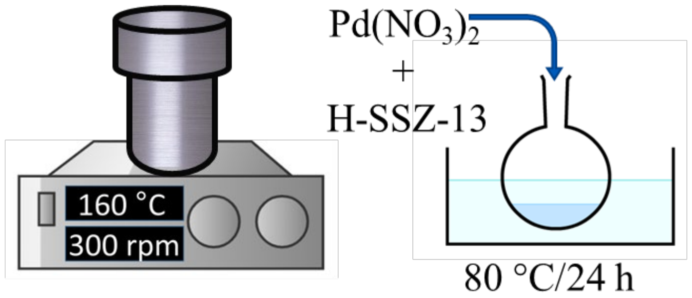
Summary

- To improve low-temperature CH_4 oxidation performance for small-pore zeolite catalysts (Pd/H-SSZ-13 and Pd/H-LTA):
  - Load Na as a second metal at a Na/Al molar ratio of ~1 for low Si/Al molar ratios.
  - Synthesize zeolites with less Al and optimize Si/Al molar ratios.
- Both techniques work by reducing Brønsted acid sites and prevent Pd sintering from occurring by blocking Pd migration using ion-exchanged Na and reducing available sites for migration by increasing Si/Al molar ratios.
- 1 wt.% Pd/H-LTA with Si/Al molar ratio of 39, 52, and 54 are able to reach and surpass the target goal of $T_{90} < 400\ ^{o}C$.

Development of catalyst for low-temperature CH_4 oxidation

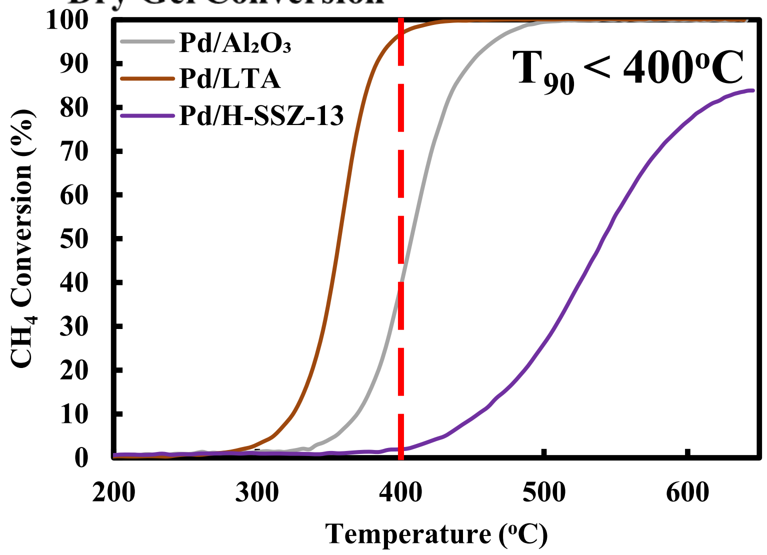
Phase 1

Development of Catalysts for Low-temperature CH_4-oxidation



Hydrothermal Synthesis Dry Gel Conversion

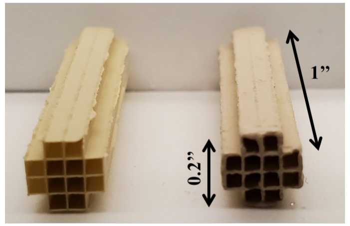
Pd ion-exchange



Phase 2

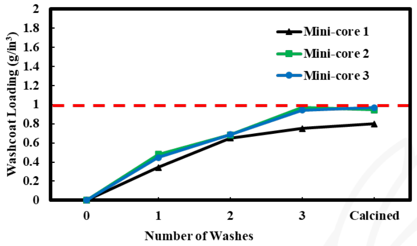
Washcoat Study of Zeolite-based Catalysts

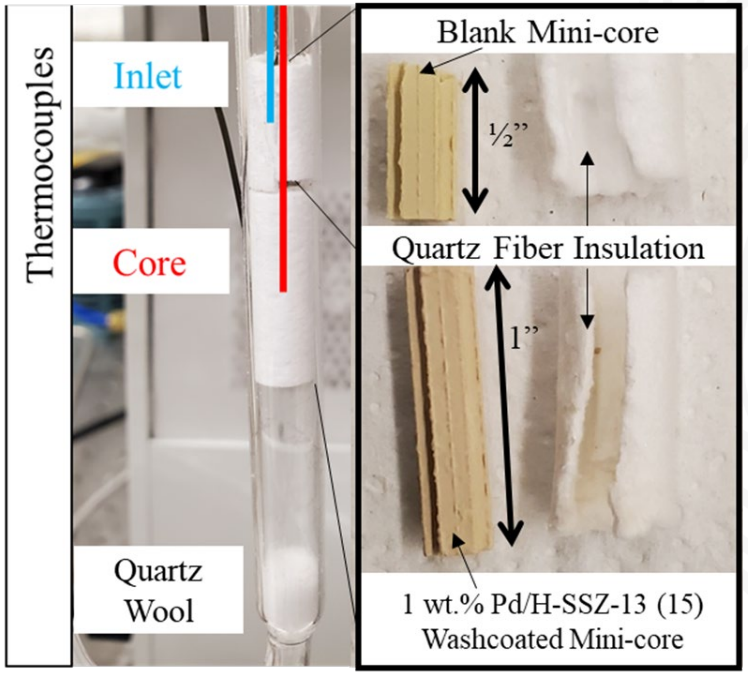
400/3



Initial Mini-core

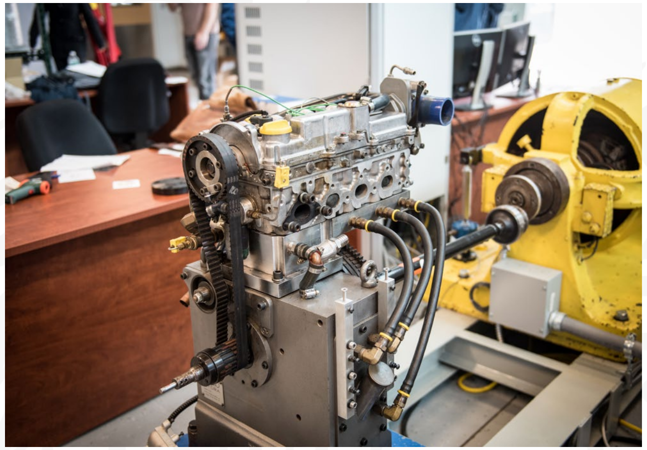
Calcined Washcoated Mini-core



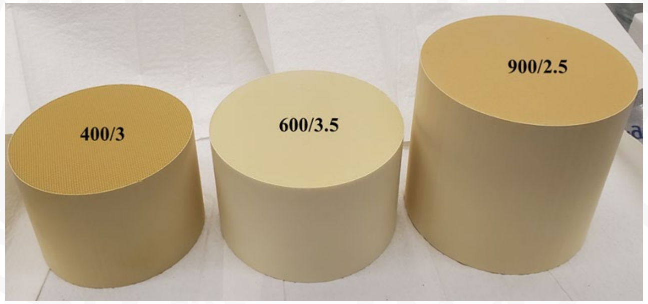


Phase 3

Catalysts Experimental Testing using Single-cylinder Research Engine



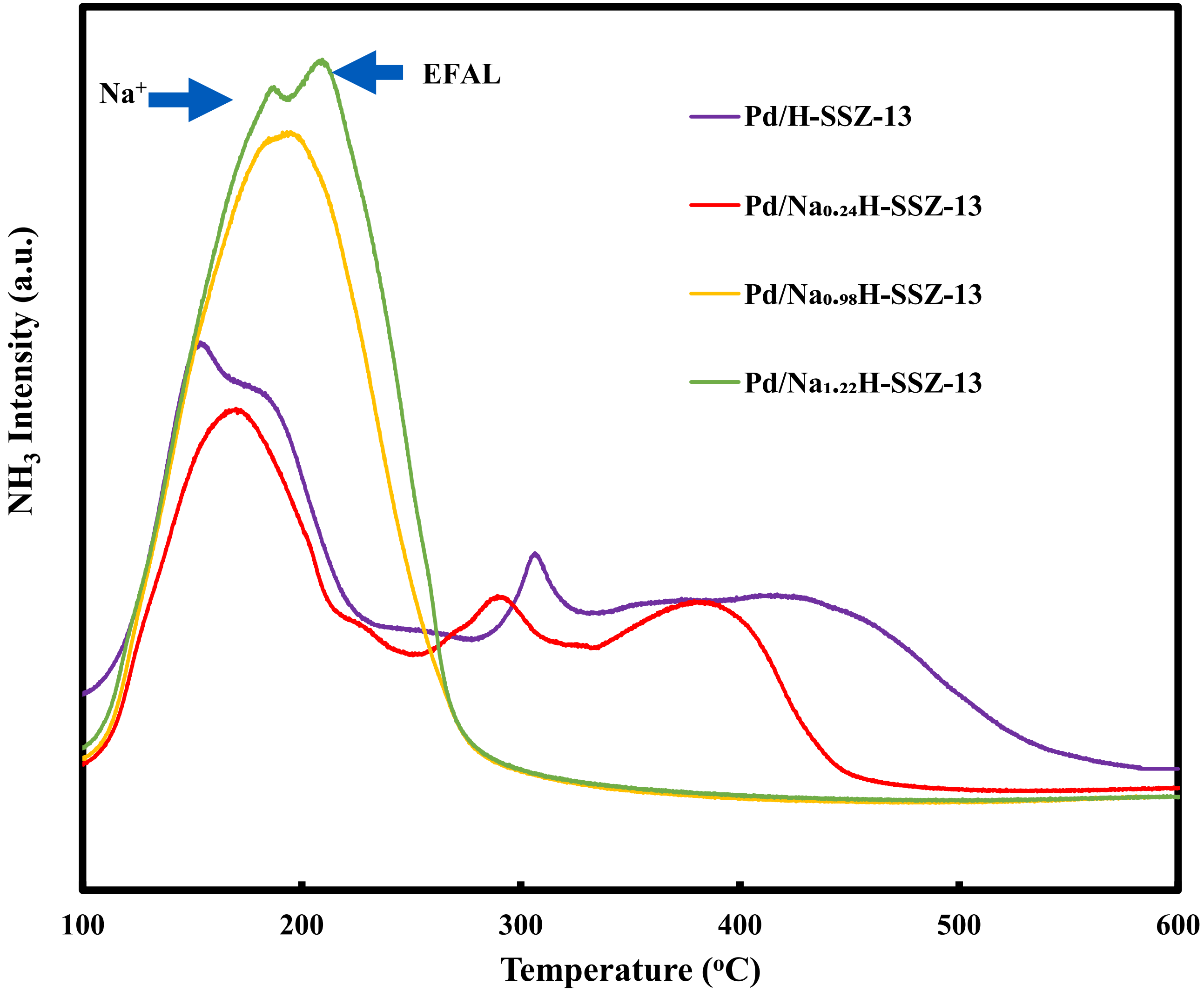
Ricardo Hydra Engine at Stony Brook University



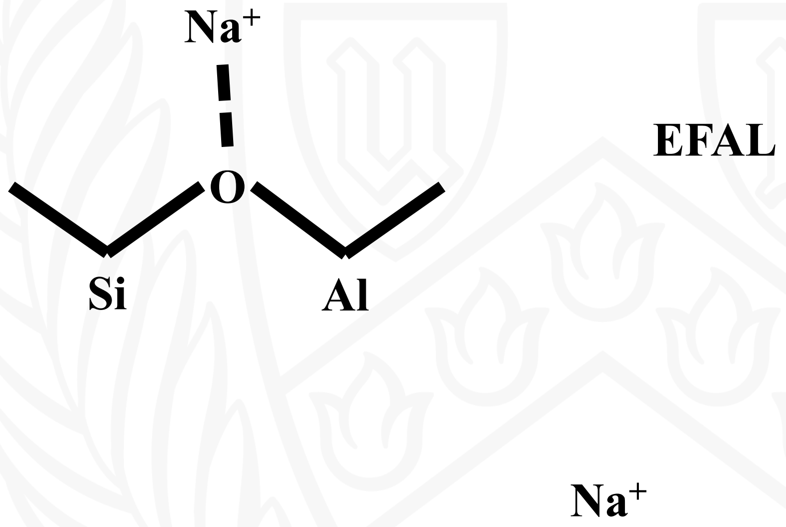
Full Monoliths

Excess Na leads to EFAL and deactivation

Effect of Na loading on Pd/Na_xH-SSZ-13 where x is Na/Al molar ratio



- The addition of Na at a Na/Al molar ratio of 1.22, two additional peaks can be seen that may be the result of mobile Na ions that may destroy the zeolite framework (194 °C) and caused extra-framework Al (212°C) (EFAL) to occur that poison the catalysts.



Y. Du, C.A. Wang, Q. Lv, L. Deng, D. Che, Asia-Pacific Journal of Chemical Engineering, 11 (2016) 973-980.

Development of a Pent-Roof MD Spark-Ignited Natural Gas Engine in an Optimized Hybrid Vehicle System:

SOUTHWEST RESEARCH INSTITUTE®

Mid Project Review, May 12, 2021
Scott Sjovall

SwRI Project # 25912 / NREL Subcontract number NHQ-9-82305-07

Agenda

- Executive Summary
- Team
- Schedule
- Task updates
  - Task 1: Project Management
  - Task 2: Vehicle Study
  - Task 3: Engine Development
  - Task 4: Hybrid System Development
  - Task 5: Vehicle Integration, Evaluation and Demonstration
  - Remaining milestones

SwRI Project Team

Project Manager

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SwRI Project Oversight

Terry Alger – Director, APS R&D

Chris Hennessy – Director, D&D R&D

Chris Chadwell – Assistant Director, APS R&D

Michael Kocsis – Manager, Engine Certification and Emissions Development

Executive Summary

Mission

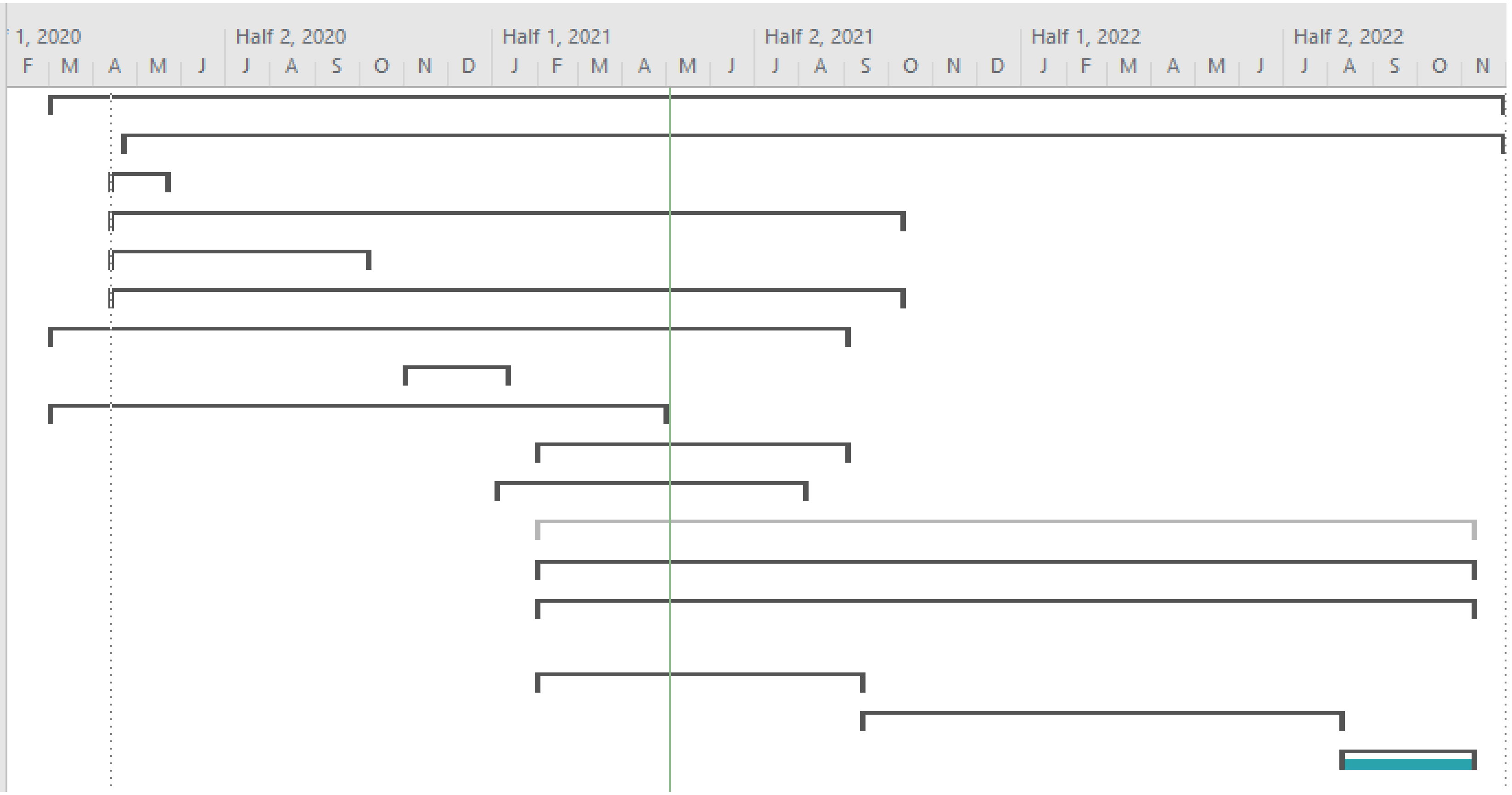
Improve NG Engine and Vehicle Emissions and Efficiency – The objective is to reach an efficiency level similar to that of conventionally fueled vehicles and reduce emissions to near-zero levels with improvements to the natural gas engine as part of a hybrid powertrain, capable of being commercially saleable into a medium- or heavy-duty vehicle

Key program deliverables

- Medium Duty Natural Gas Hybrid Demonstration Vehicle
- 25% reduction in GHG compared to diesel baseline
- 0.02 g/bhp-hr NO_X

Schedule Overview

Task Name	Start	Finish
NREL Project Plan	Mon 3/2/20	Wed 11/30/22
Task 1: Project Management	Wed 4/22/20	Wed 11/30/22
Task 2: Vehicle Study	Mon 4/13/20	Fri 5/22/20
Task 3: Engine Development	Mon 4/13/20	Mon 10/11/21
Single Cylinder Combustion Development	Mon 4/13/20	Wed 10/7/20
Multi-Cylinder Engine Development	Mon 4/13/20	Mon 10/11/21
Task 4: Hybrid System Development	Mon 3/2/20	Fri 9/3/21
4.2 Vehicle Simulation	Mon 11/2/20	Mon 1/11/21
4.3 Selection of Hybrid Components	Mon 3/2/20	Fri 4/30/21
Hybrid Component Procurement	Tue 2/2/21	Fri 9/3/21
4.6 Supervisory Controller Development	Mon 1/4/21	Wed 8/4/21
NREL Schedule D&D 20210401	Mon 2/1/21	Wed 11/9/22
NREL Project Plan	Mon 2/1/21	Wed 11/9/22
Task 5: Vehicle Integration, Evaluation and Demonstration	Mon 2/1/21	Wed 11/9/22
Vehicle Integration - Design	Mon 2/1/21	Tue 9/14/21
Vehicle Integration - Build	Tue 9/14/21	Wed 8/10/22
Vehicle Demonstration	Thu 8/11/22	Wed 11/9/22



Project is on schedule at mid point

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Task 2: Vehicle Study

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Vehicle Study Overview

The objective was to determine which hybrid architecture offered the best balance of fuel consumption savings, air quality improvement, and total cost of ownership.

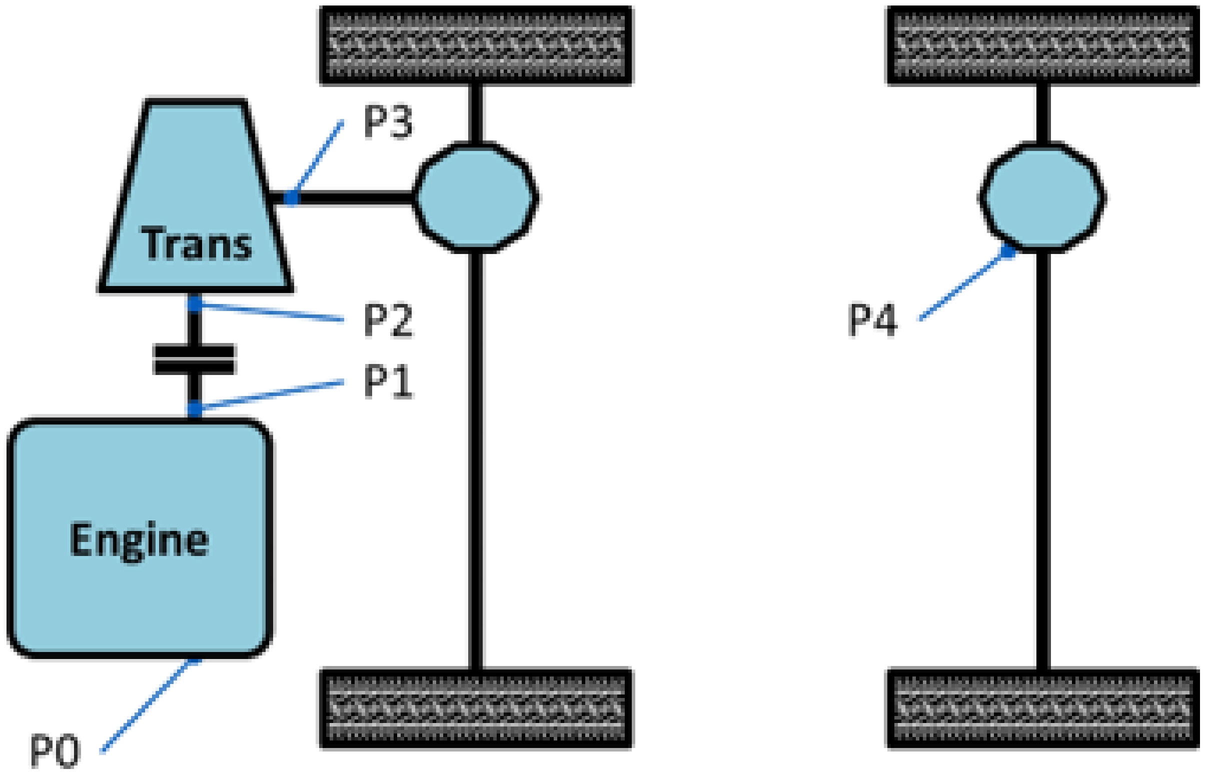
SwRI followed a three-step process:

1. A performance study was conducted to evaluate hybrid architectures on fuel economy, using an Isuzu 4H-F-series-VF76 Class 6 medium-duty truck as the baseline. Several drive cycles and payloads were considered to represent real world usage
2. Next the initial cost and fuel economy benefits were combined them into total cost of ownership (TCO) and evaluated against CO2 emission production to determine the hybrid architecture that showed the largest benefit
3. Finally, a vehicle packaging study was undertaken to evaluate the potential for integration of the hybrid system previously identified with minimal disruption to the existing truck hardware

Vehicle Study - Results

The vehicle study identified a P2 hybrid architecture with a 100 kW electric machine and 40 kWh battery pack as the architecture with the best balance of fuel consumption savings, air quality improvement, and total cost of ownership for this vehicle platform

P2 = Motor located behind engine, after clutch to allow disengagement and EV operation



HYBRIDIZATION ARCHITECTURES

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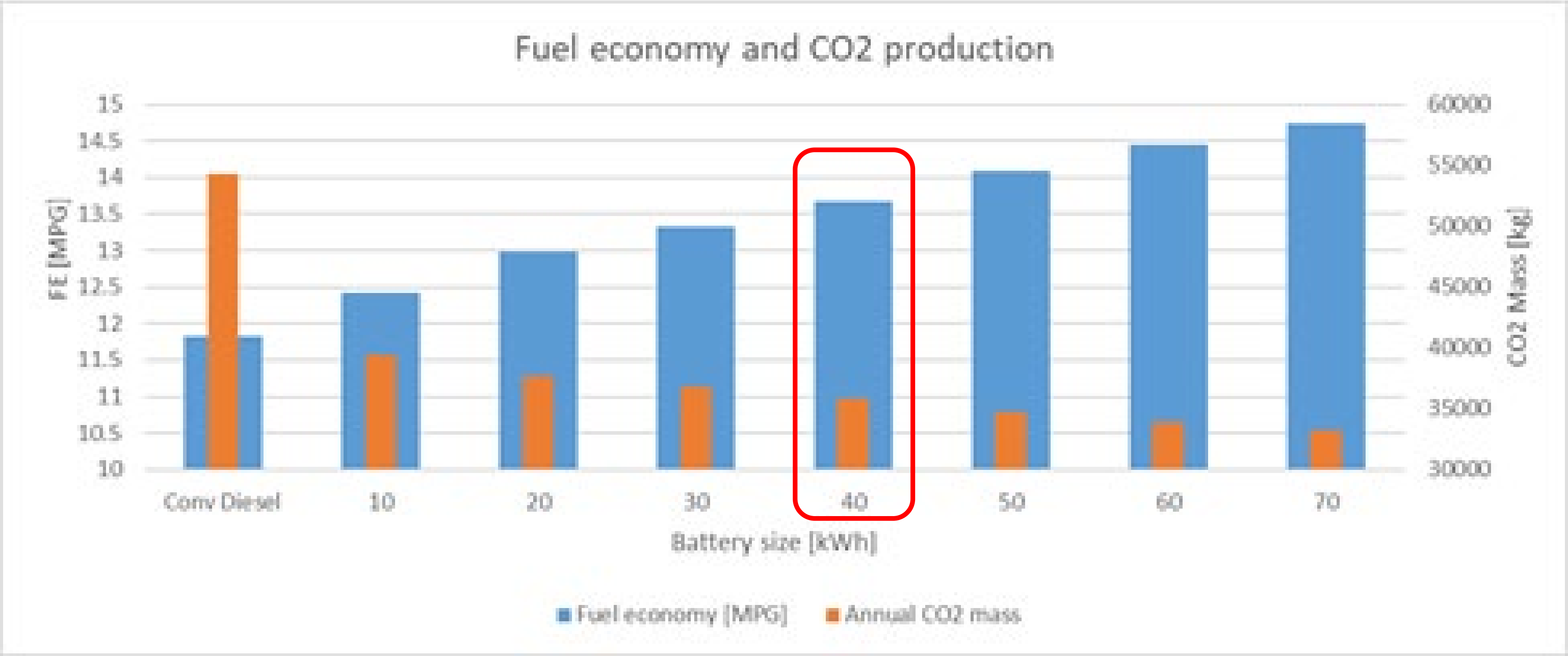
Vehicle Study - Results



Preliminary results indicated the potential of this hybrid powertrain to net:

- 15% improvement on fuel economy and a 34% reduction in CO_2 on a combination of Isuzu real world cycles
- 25% to 80% fuel economy improvement compared to the conventional diesel engine vehicle on the standard cycles (HD-UDDS, HHDDT transient and CSC)

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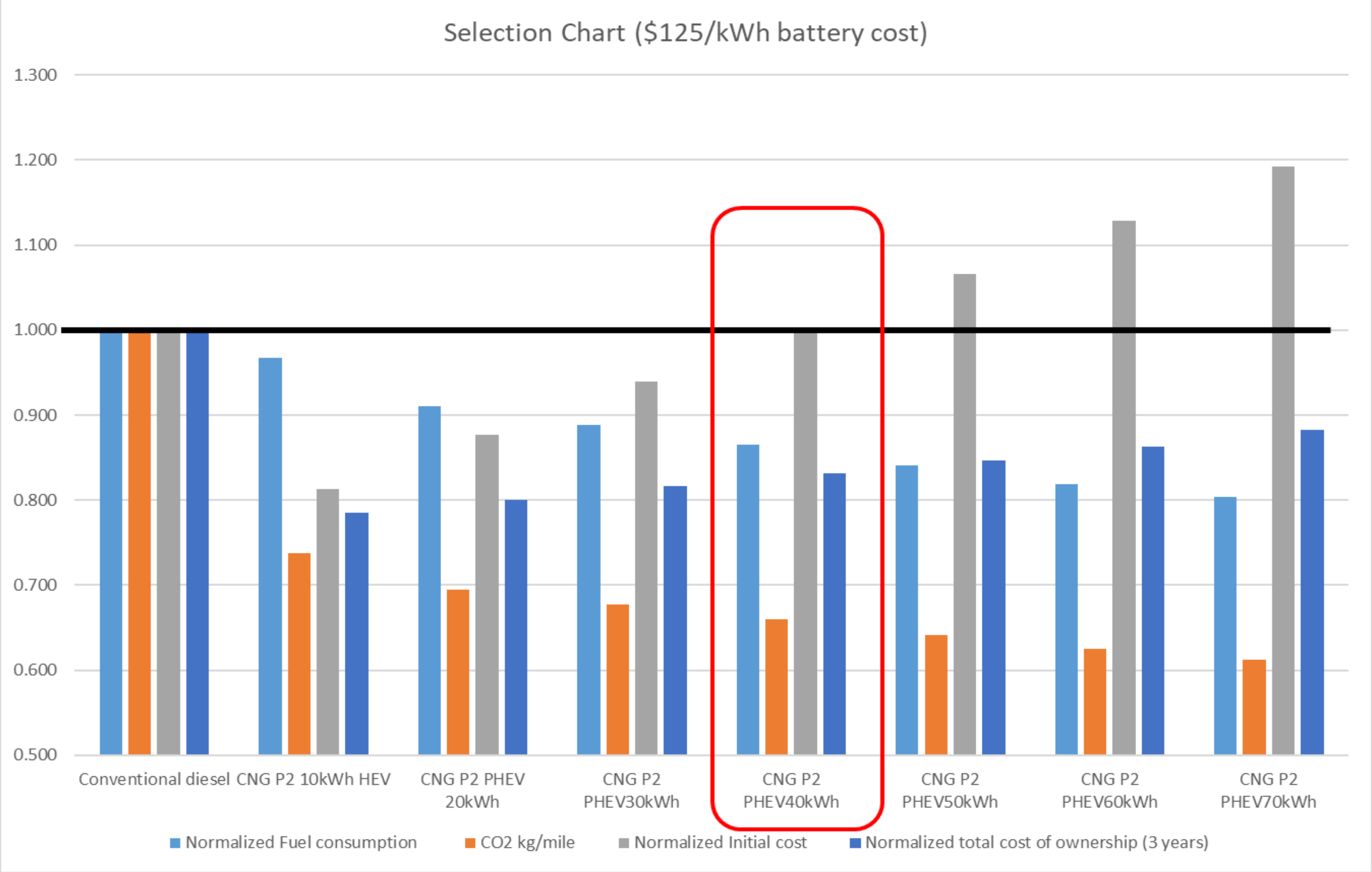
Vehicle Study - Conclusion

Based on this study a P2 hybrid architecture with a 100 kW machine and 40k Wh battery pack was selected based on:

- CO2 reduction/fuel efficiency
- Three-year cost of ownership
- Initial cost vs benchmark



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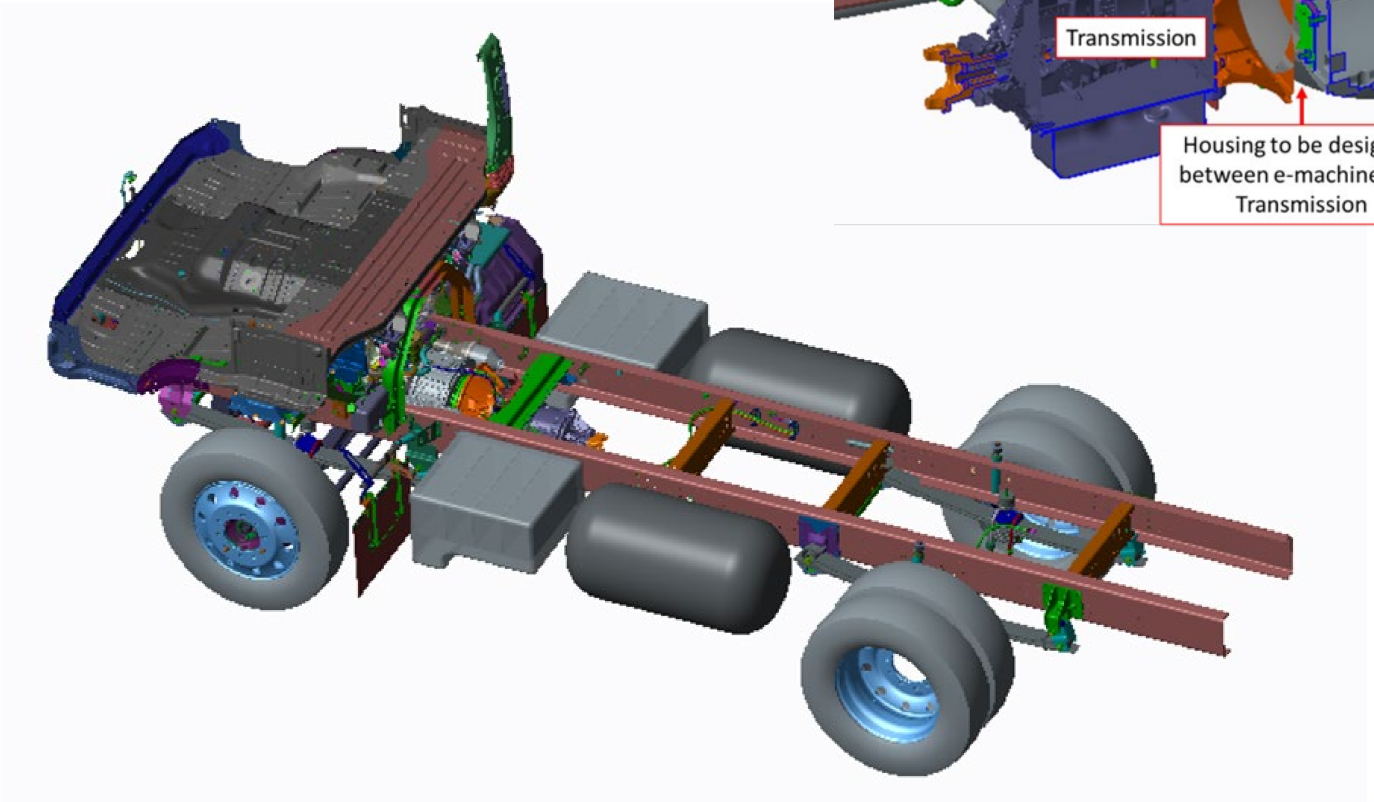
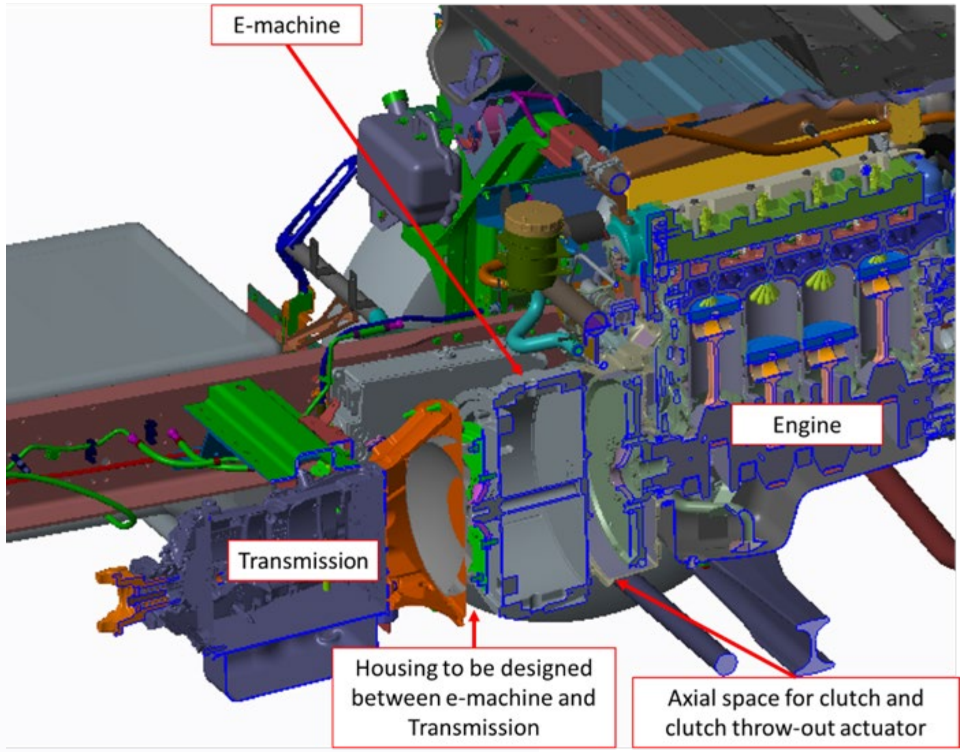
Vehicle Study - Packaging

Typical e-machine and battery pack geometries were then utilized to verify if hybrid components could be integrated into the Isuzu F-series truck





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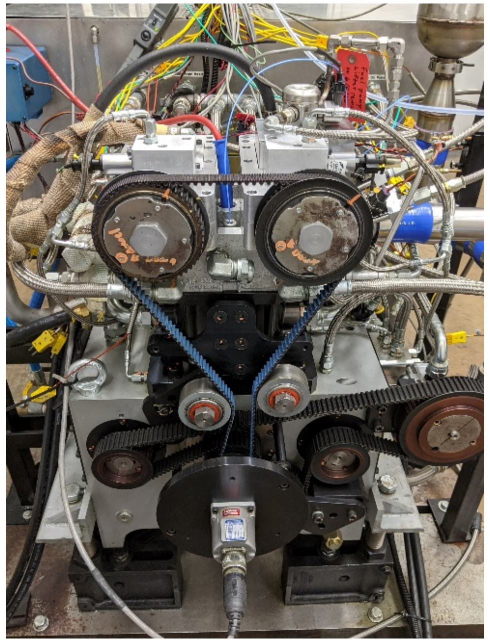
Task 3: Engine Development

3.1: Single Cylinder Engine (SCE)

SCE Research

To determine if the requirements of the project could be met, a single-cylinder research engine based on the Isuzu 4HK diesel platform was configured with a bespoke high-tumble, pent-roof cylinder head and converted to run on natural gas.



Key features included on SCE to support test program

- High Tumble Pent Roof Cylinder Head
- Variable valve timing
- Fumigated injection and port injection
- Cooled EGR

Displacement (cc)	1300
Bore (mm)	115
Stroke (mm)	125
Compression Ratio	12.2:1
MAT (°C)	40
Oil temp (°C)	100
Coolant temp (°C)	100
Boost	Electric SC
Exhaust BP	Manual, match to Intake
Valve Timing Control	Intake & Exhaust VVT
Ignition System	High-energy, single strike

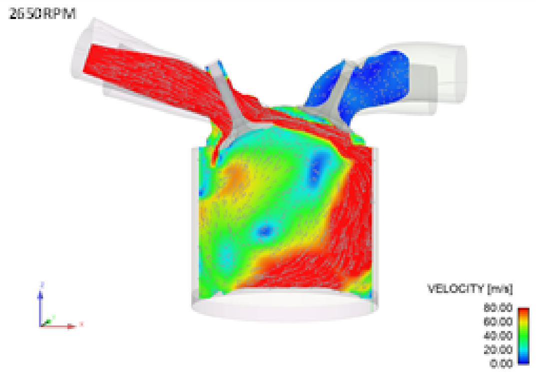
SCE Test Results

The results indicated that the Gen 2 combustion system would meet the vehicle demonstration requirements

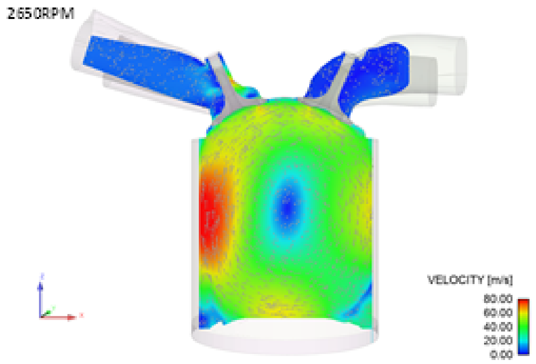
These improvements included:

- Reduction in pumping work of up to 0.1 bar PMEP
- Lower lumped efficiency losses
- Up to 10% higher EGR tolerance

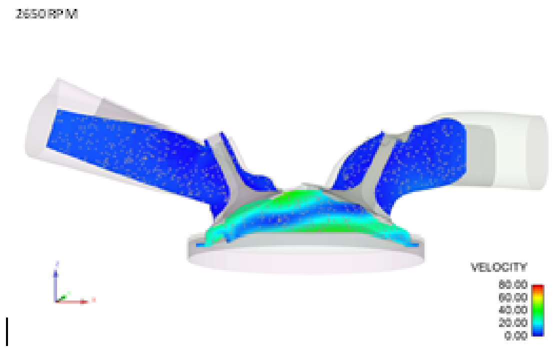
Analysis results were also used to refine modeling efforts for the multi cylinder engine program



VELOCITY CONTOUR AT MAXIMUM VALVE LIFT



VELOCITY CONTOUR AT INTAKE VALVE CLOSING



VELOCITY CONTOUR AT SPARK TIMING

Task 3: Engine Development

3.2: Multi Cylinder Engine (MCE)

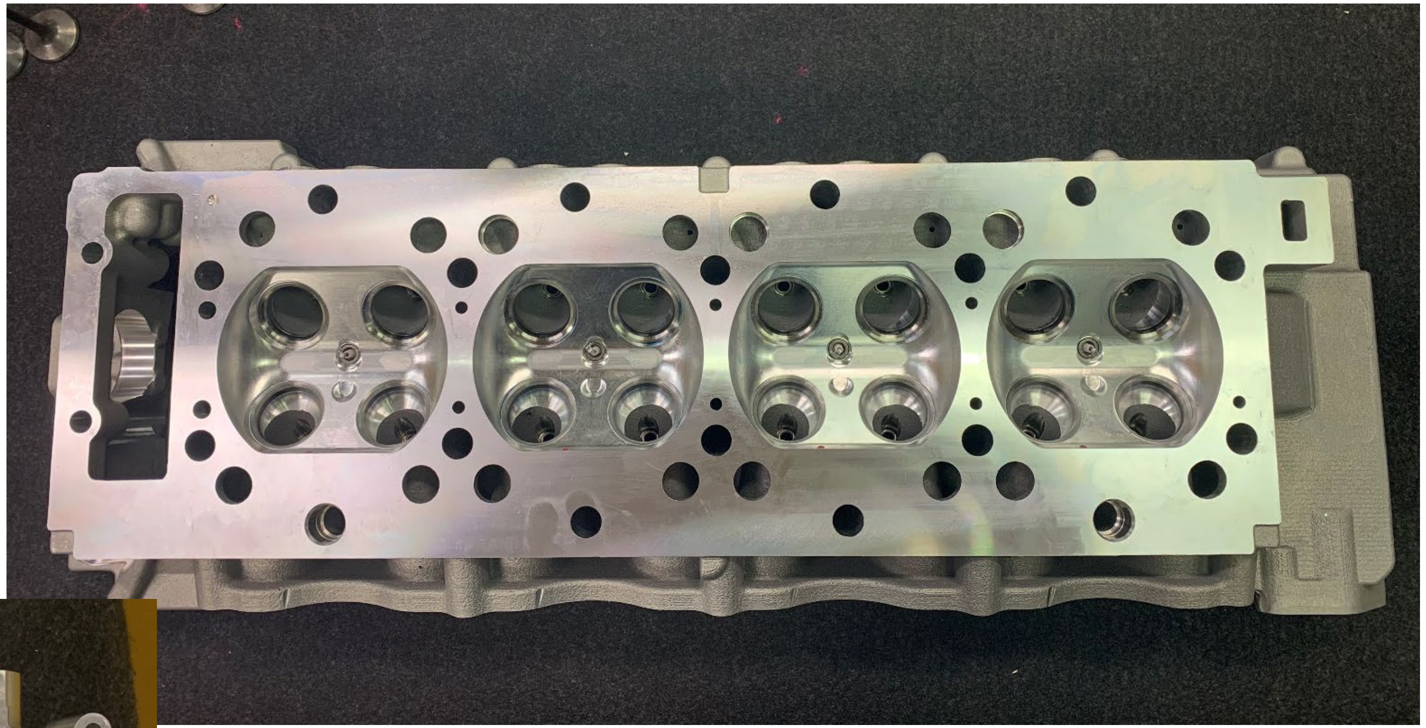
MCE – Design & Build

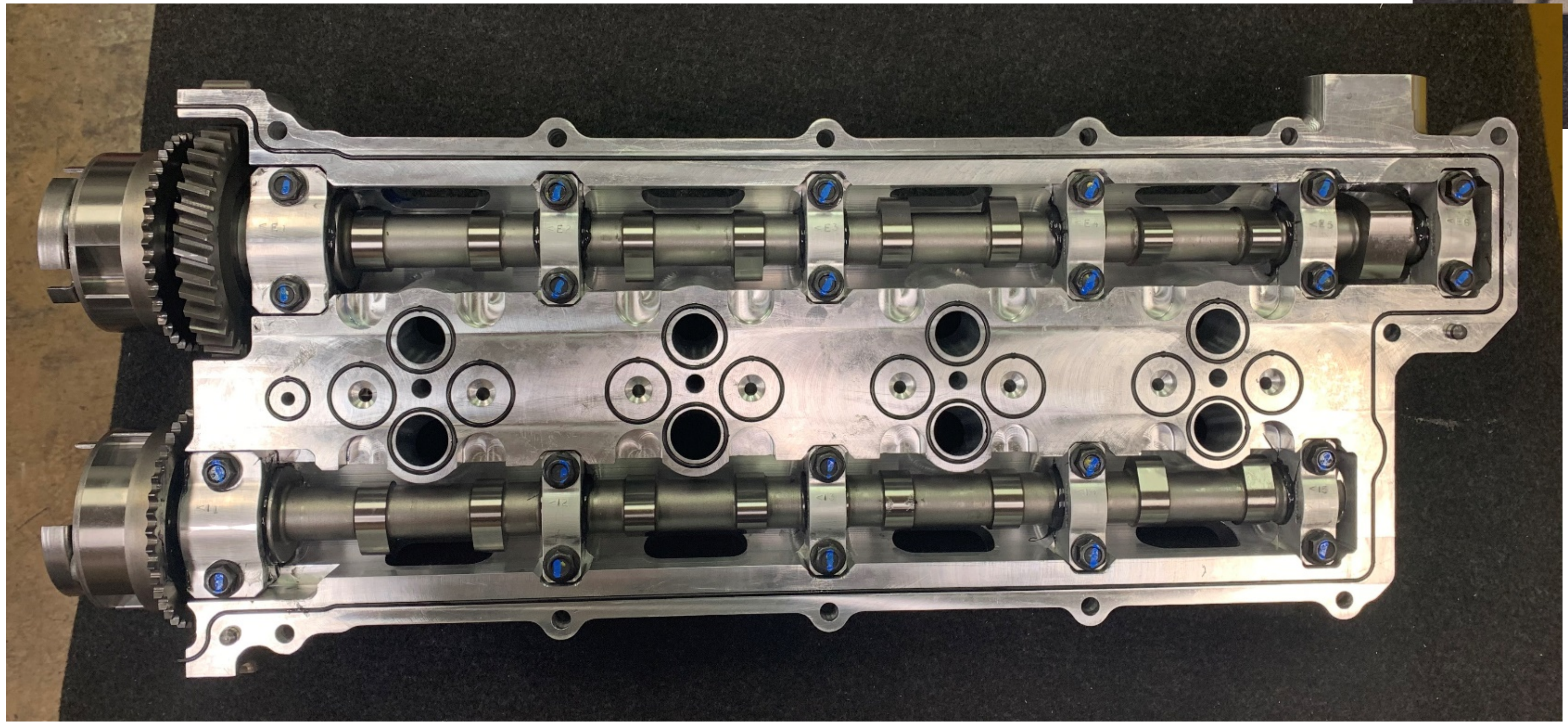
- MCE build utilized an Isuzu 4HK1 long block assembly
  - Removed Isuzu cylinder head, valvetrain, injectors, connecting rods and pistons
  - Remainder of 4HK1 assembly utilized for MCE build
- 12:1 compression ratio pistons with custom designed connecting rods
- New high tumble pent roof cylinder head and cam carrier assembly
- New intake and exhaust manifolds
- Woodward ECU (OH6), EGR and fuel system

- Engine assembly completed 10/28/20
- Engine started 12/14/20

MCE - High Tumble Cylinder Head

- Pent roof
- Four valve
- Dual cam





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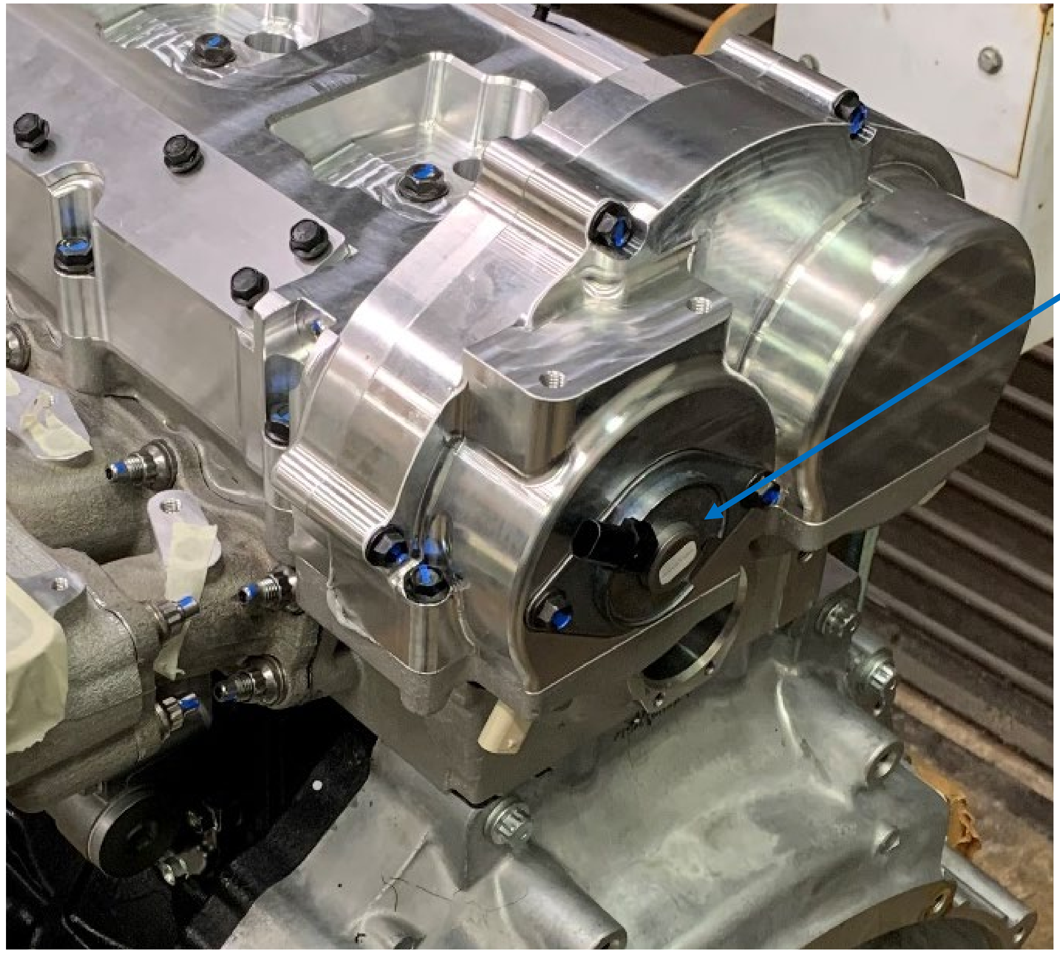
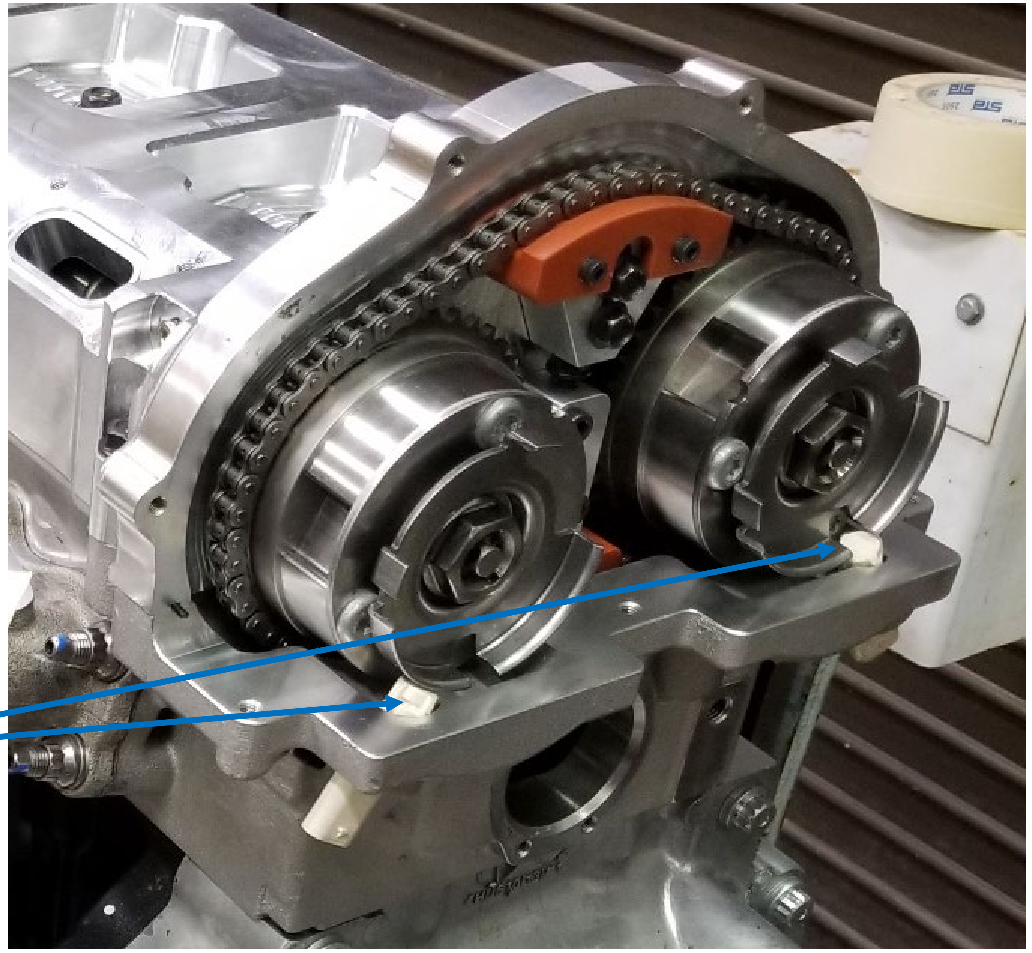
MCE - Variable Intake Timing



Intake Cam Phaser Control Solenoid

Cam Position Sensors



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MCE - Fully Assembled Engine

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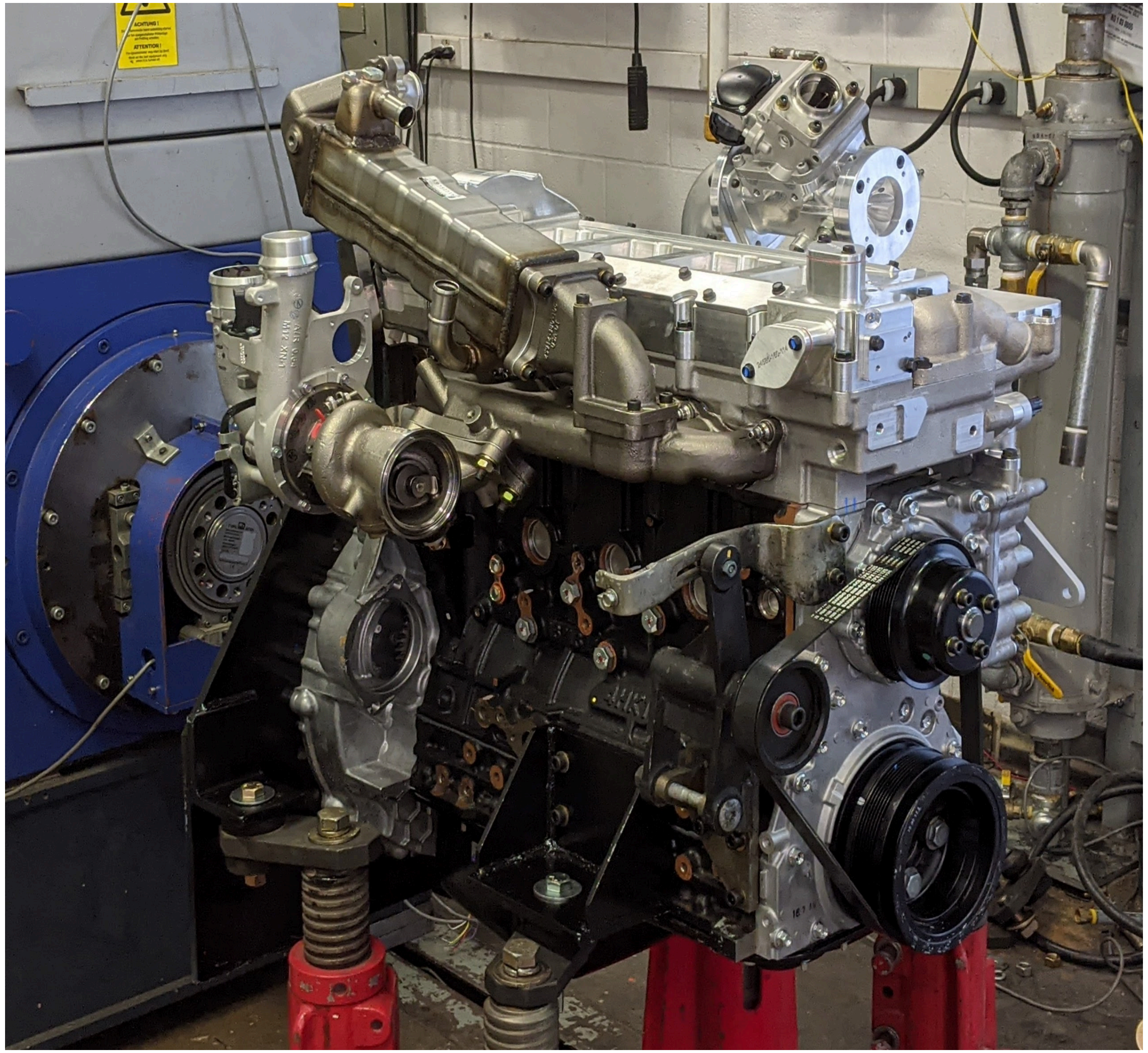
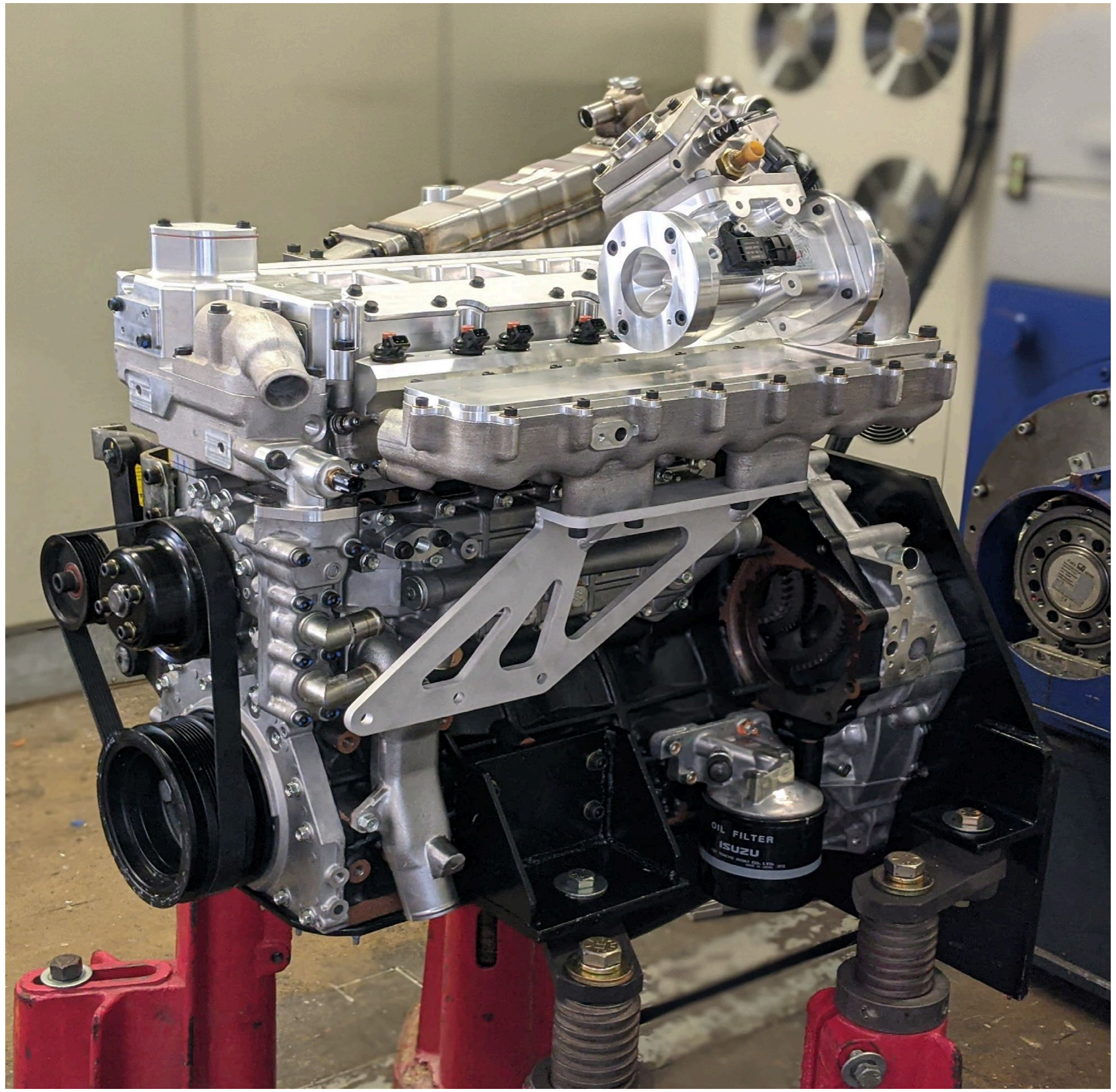
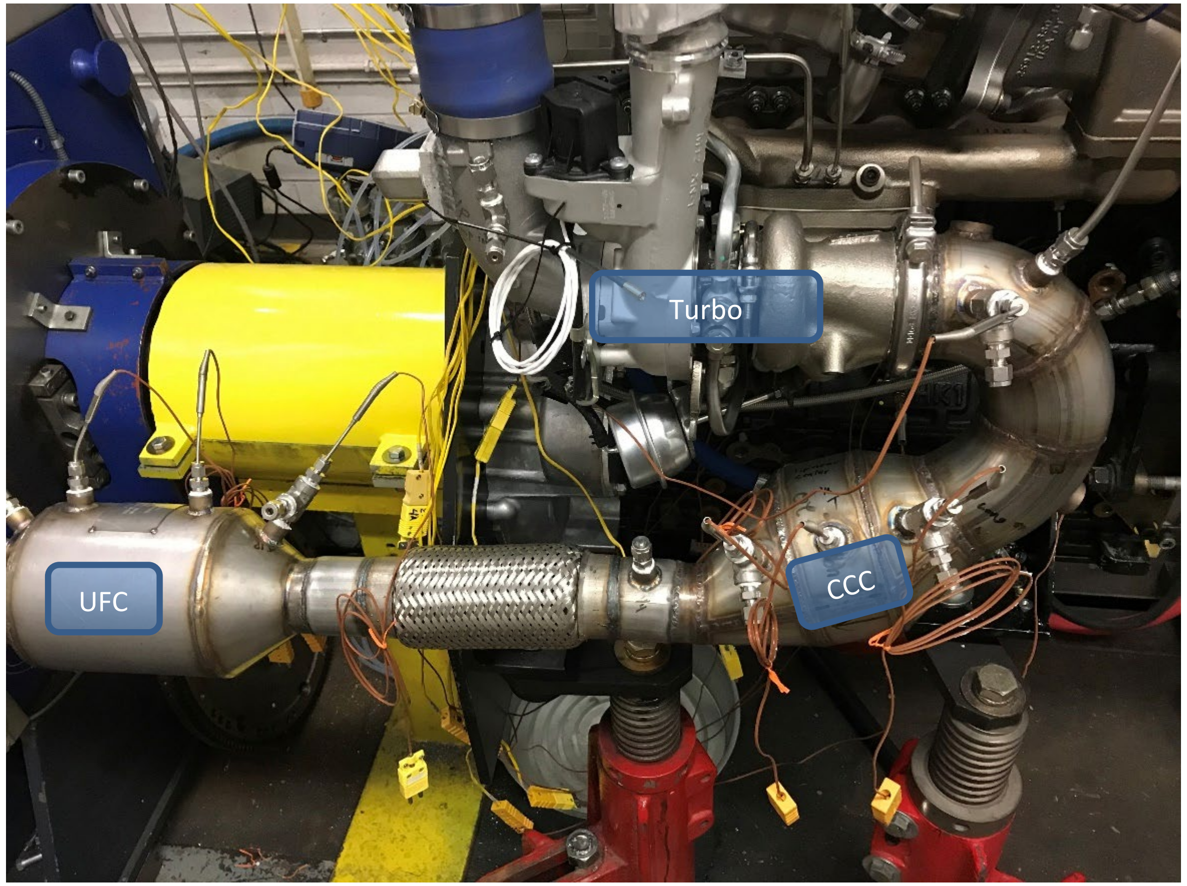
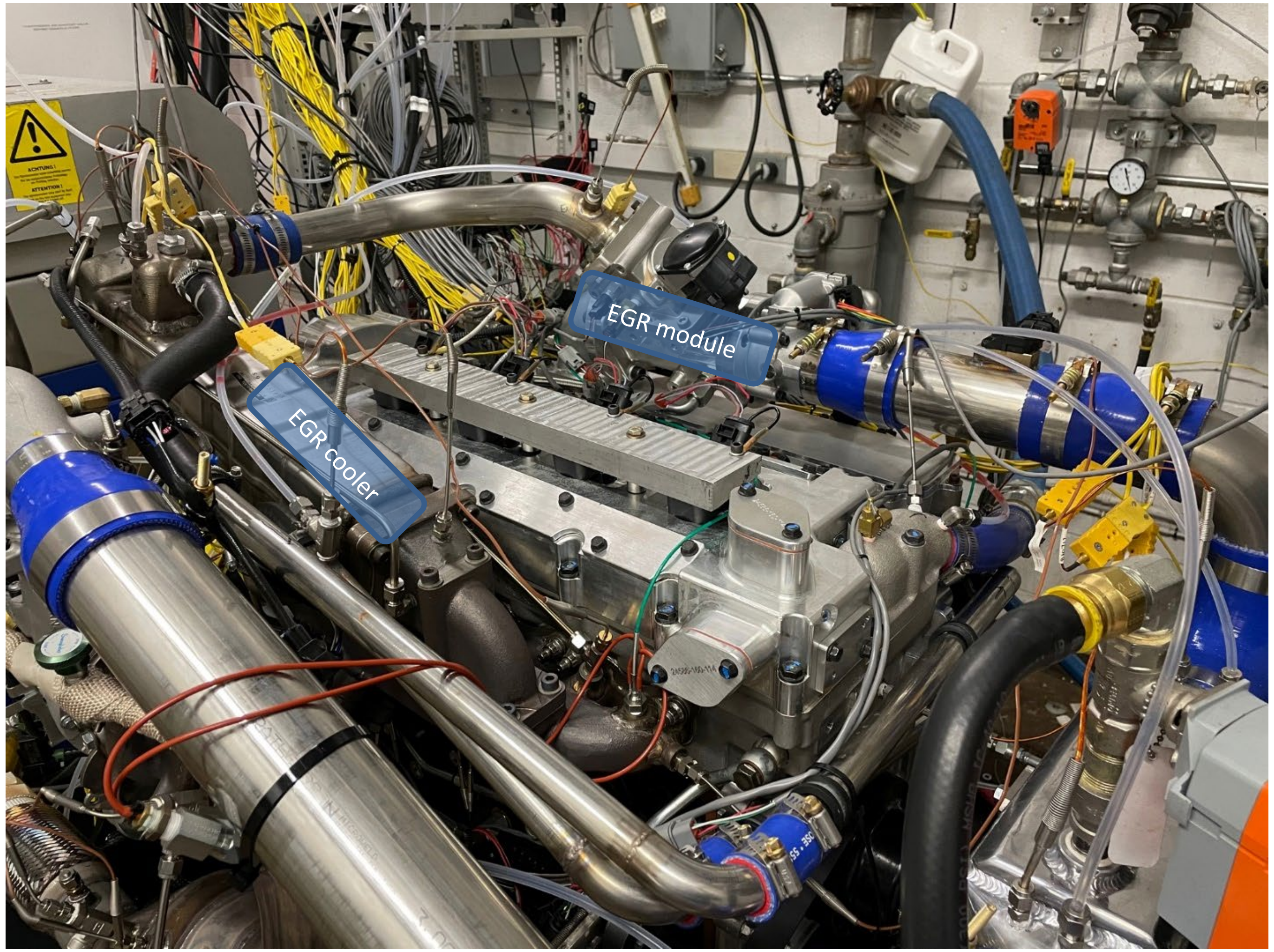




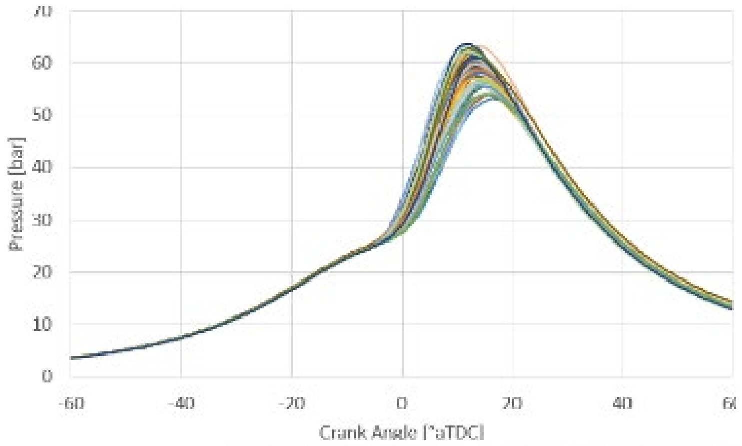
MCE – Operational

Engine first start: 12/14/20





Multiple cycle cylinder pressure traces



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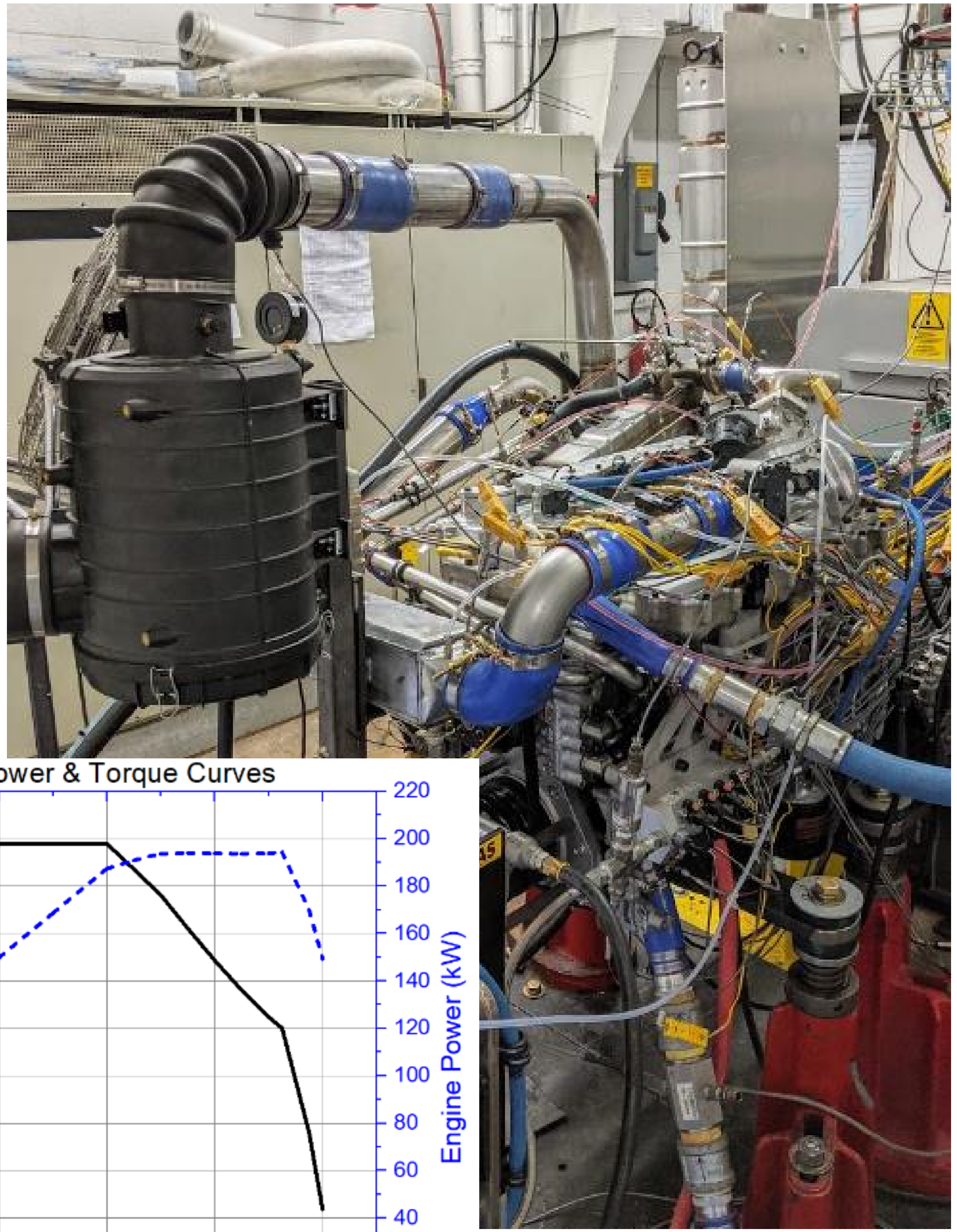
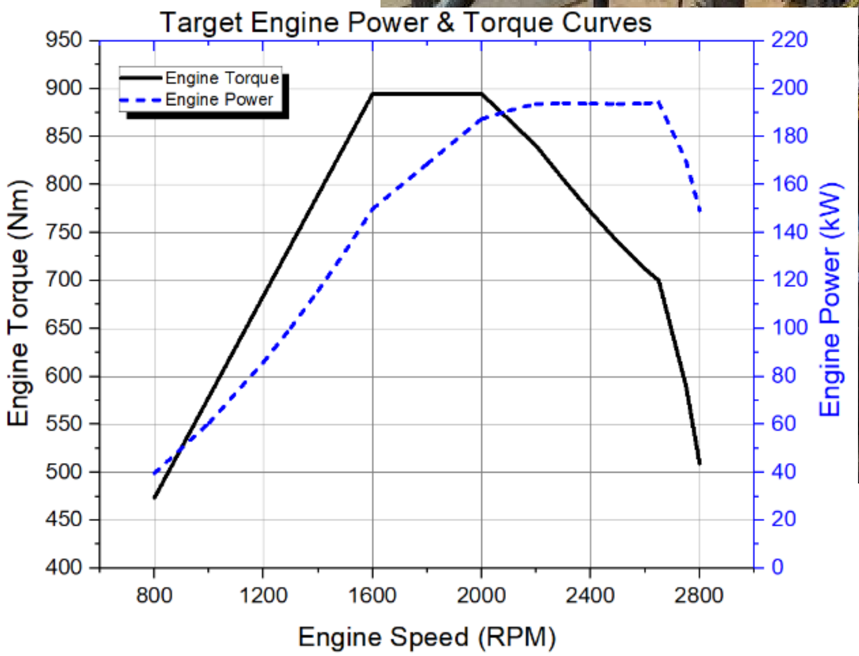
MCE - Status

- Initial engine performance validation
  - Break in completed
  - Target engine torque curve achieved (260/660)
  - Peak thermal efficiency (BTE) of 40% achieved
- Turbocharger selection validated
- 140+ hours of cumulative engine run time
- Baseline calibration completed
- In Process
  - Steady state calibration
- Next
  - Transient calibration July - October 2021





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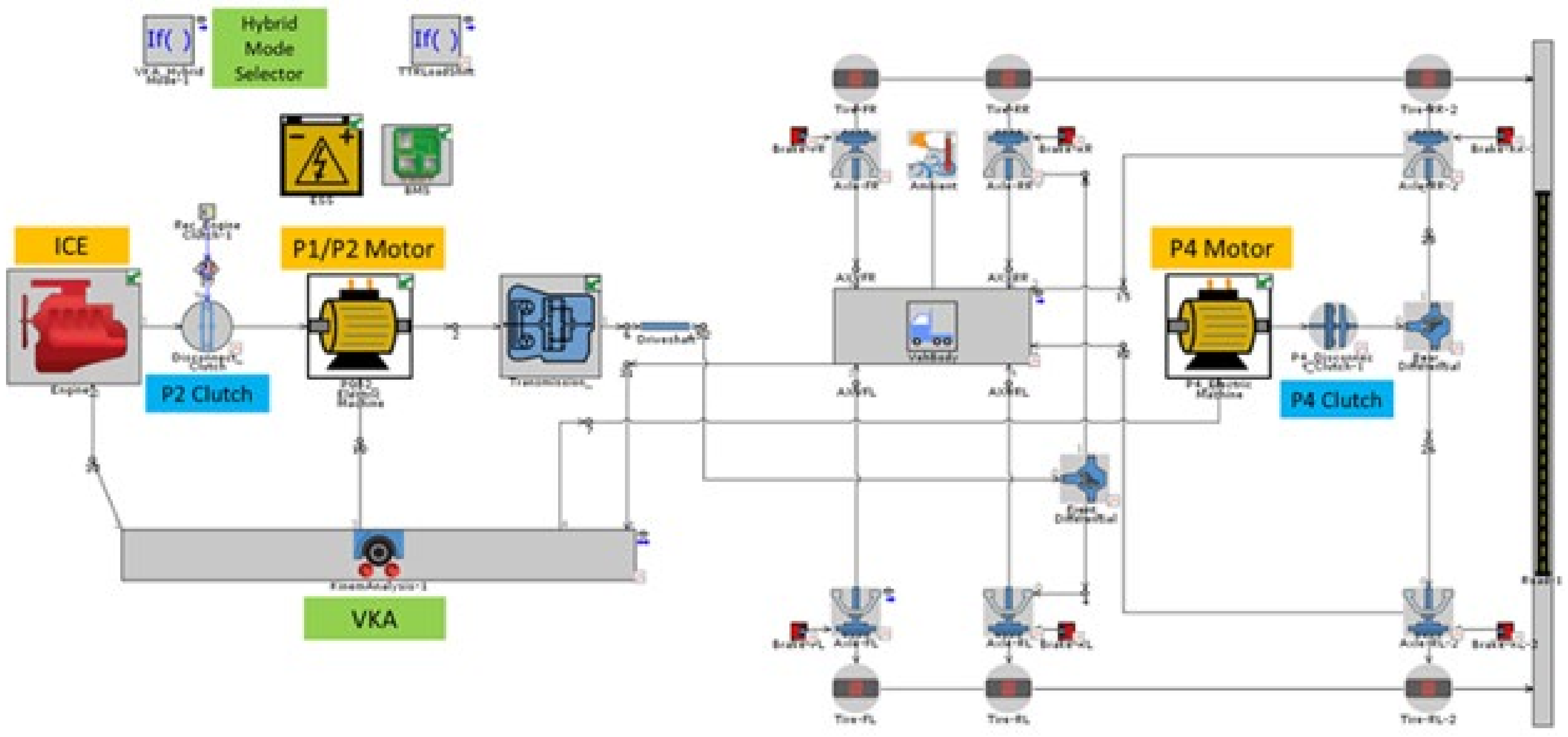
Task 4: Hybrid System Development

Drive Cycle Performance Modeling

- The Isuzu 4H-Fseries-VF76 Class 6 medium-duty truck was modeled in GT-DRIVE
- The same hybrid vehicle model captures P2 and P4 hybrid architectures using clutch arrangements to select either configuration

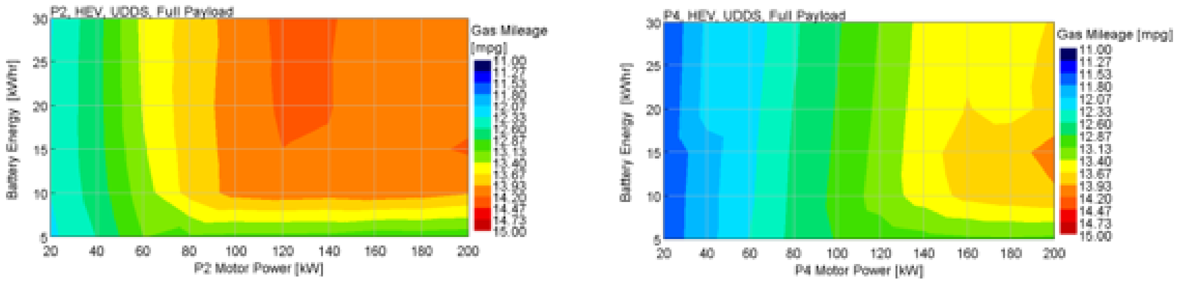


GT-DRIVE VEHICLE AND POWERTRAIN VKA MODEL

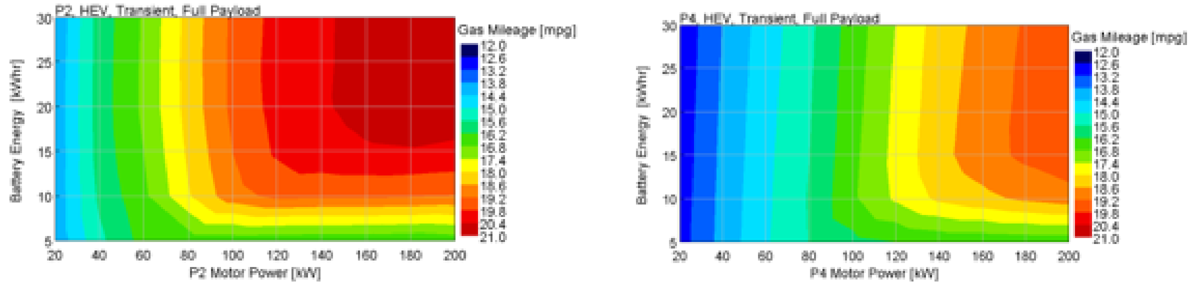
SwRI Project # 25912 / NREL Subcontract number NHQ-9-82305-07

Drive Cycle Performance HEV Modeling

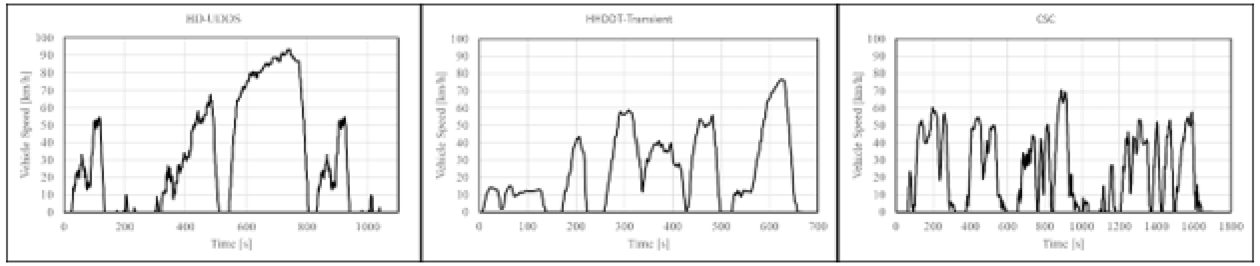
- The best fuel economy across all three cycles in HEV mode was achieved with a P2 configuration integrating an electric machine of 100 to 150 kW peak power



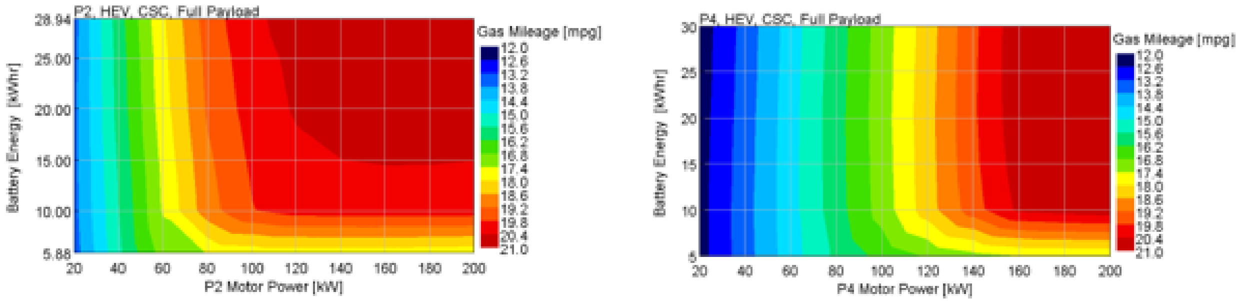
HYBRID ARCHITECTURES FUEL ECONOMY ON HD-UDDS CYCLE



HYBRID ARCHITECTURES FUEL ECONOMY ON HHDDT-TRANSIENT CYCLE



STANDARD DRIVE CYCLES



HYBRID ARCHITECTURES FUEL ECONOMY ON CSC CYCLE

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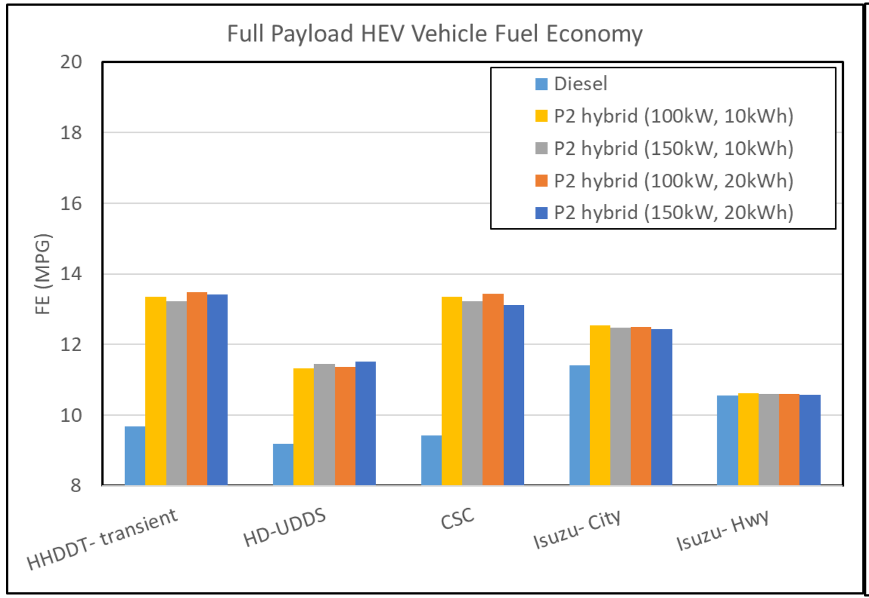
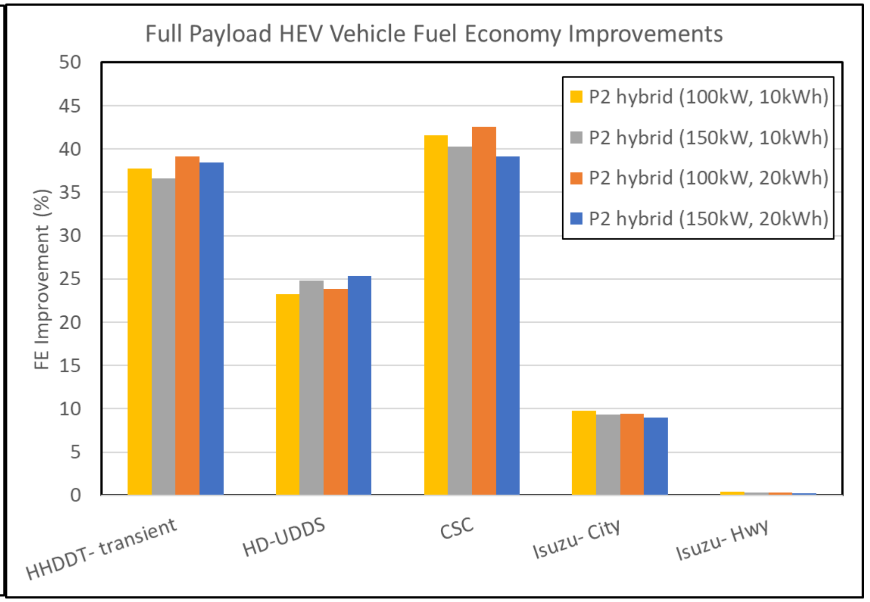
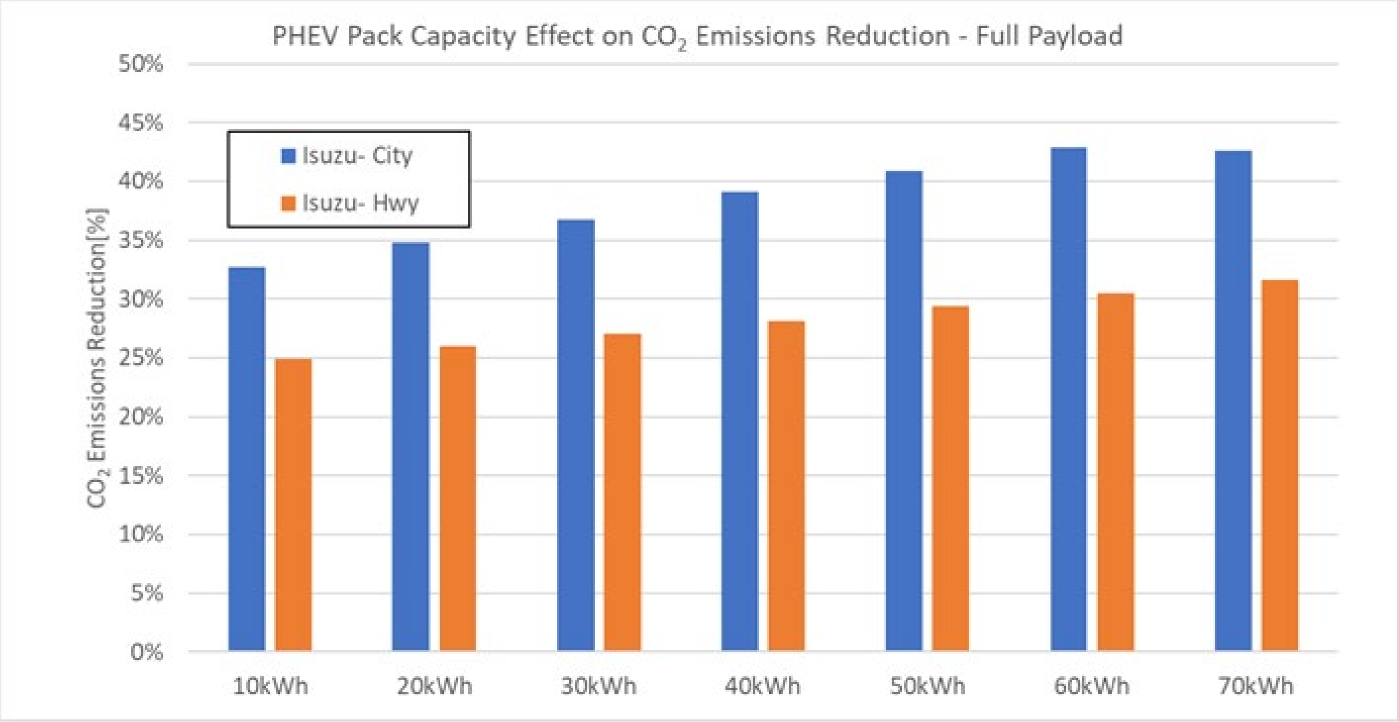
Drive Cycle Performance PHEV Results

To improve performance further PHEV operation was modeled

- Best architecture:
  - P2
  - 100 kW e-motor
  - 40kWh battery
- PHEV Fuel economy improvements
  - Standard cycles: 24% to 48%
  - Isuzu-City cycle: 10%
  - Isuzu-Highway cycle: less than 1%







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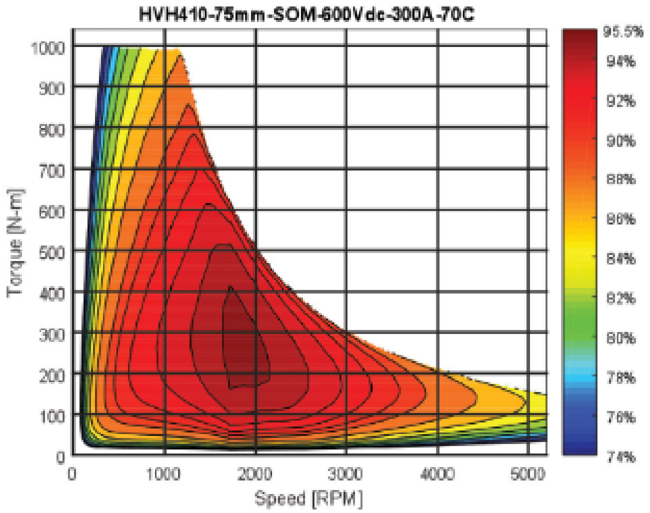
Hybrid Component Selection

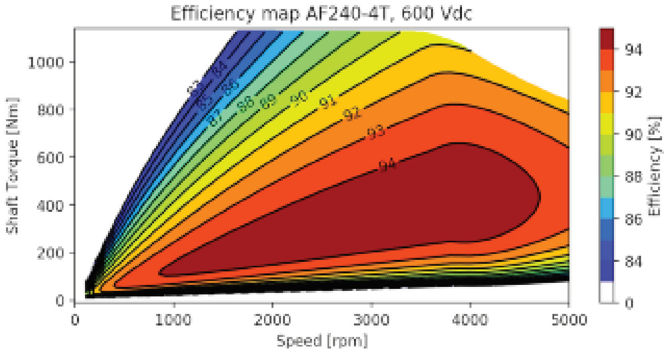
Motor options:

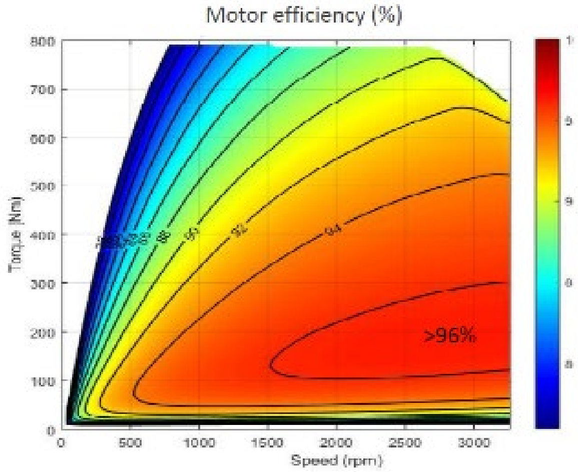
- Borg Warner HVH410–75
- AVID 240 4T
- YASA 750R

Battery options:

- Cell suppliers
  - CATL (LFP)
  - CALB (LFP)
  - Leclanche (NMC)
  - Kokam (NMC)
  - Haidi (LFP, NCM)
  - A123 (LFP, NCM)
- One suitable COTS pack supplier: Leclanche







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Hybrid Component Procurement

Components selected and POs placed for:

- Leclanche for INTEG-39 Energy HV battery
- Borg Warner HVH410-75-DOM motor
- Cascadia PM250DZ inverter:
- EDN EVO11KLR4 On-Board Charger:
- Sevcon SEV-GEN5-DCDC-001 DC-DC converters (2)

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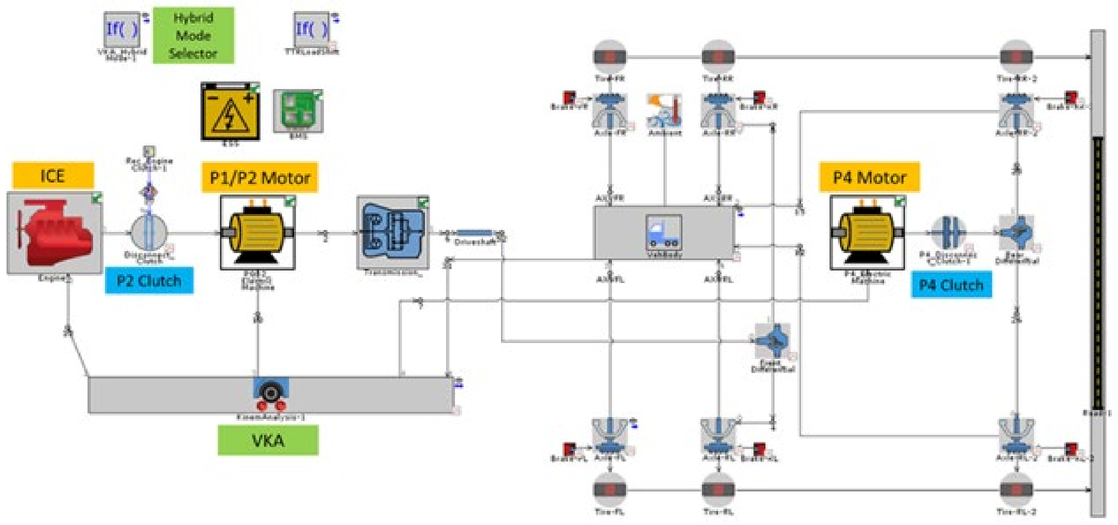
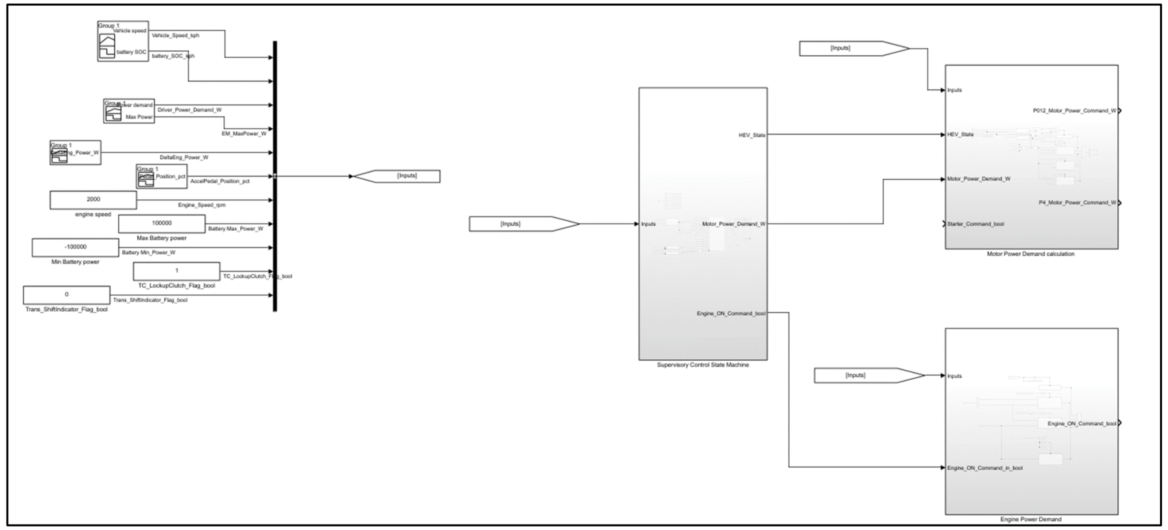
Hybrid Control Development

Transition from simulation to vehicle implementation

- Control strategies converted from GT-Drive to Simulink
- Co-simulation of Simulink strategies with GT plant model
- Benefits:
  - More detailed control strategies in Simulink
  - Allows auto-coding of Simulink strategies straight to vehicle controller
  - Faster implementation and iteration when testing in vehicle



GT-DRIVE VEHICLE AND POWERTRAIN VKA MODEL

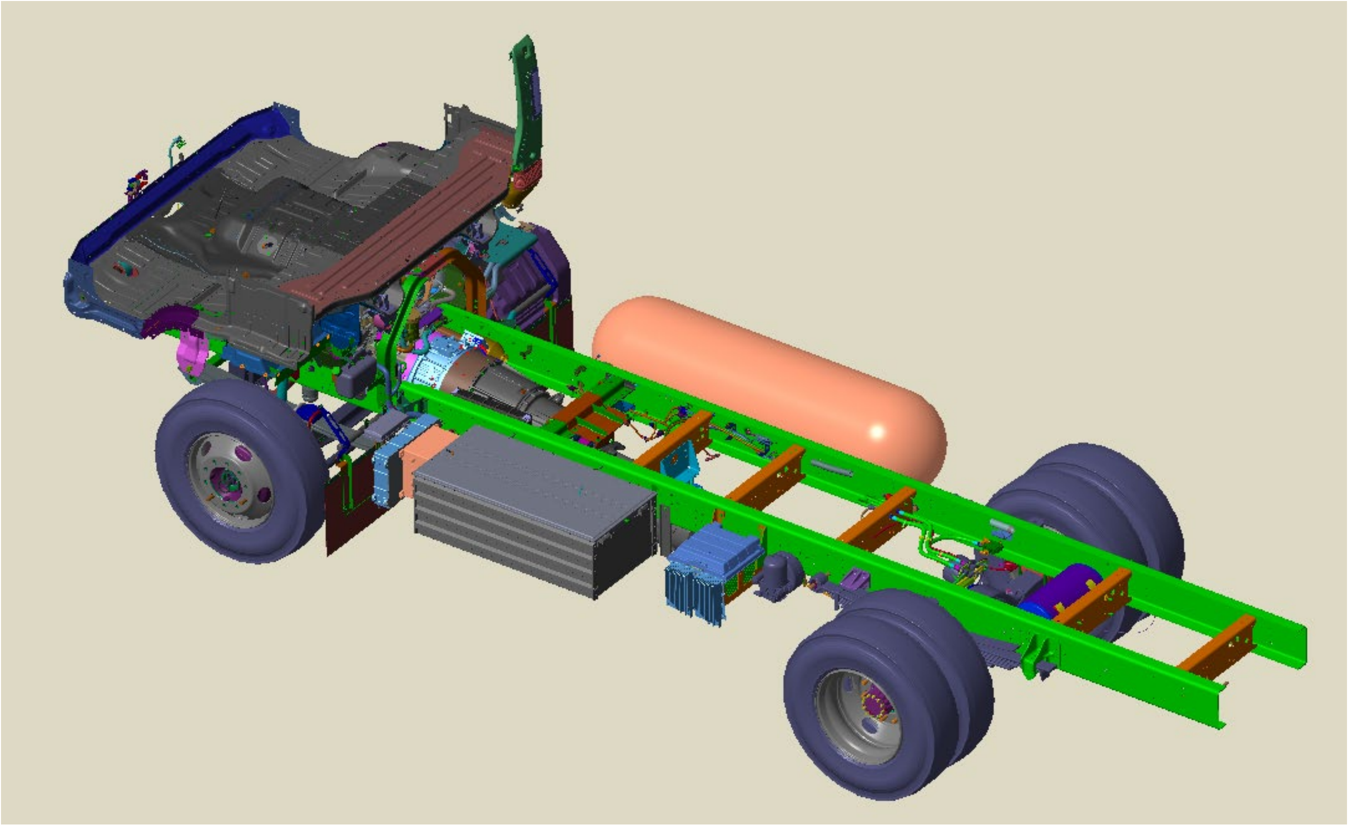


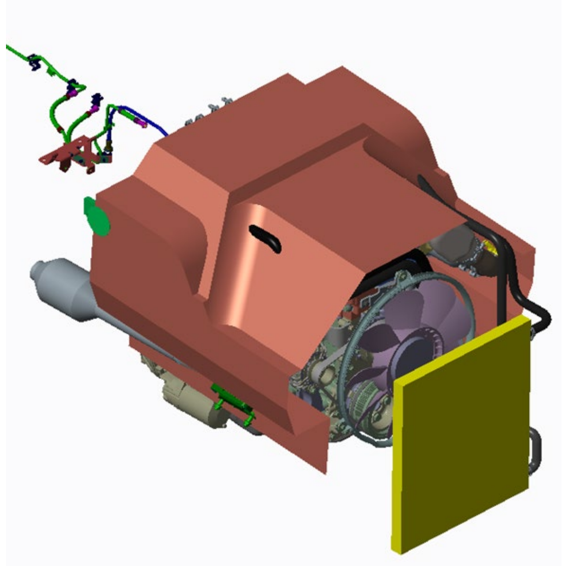
SwRI Project # 25912 / NREL Subcontract number NHQ-9-82305-07

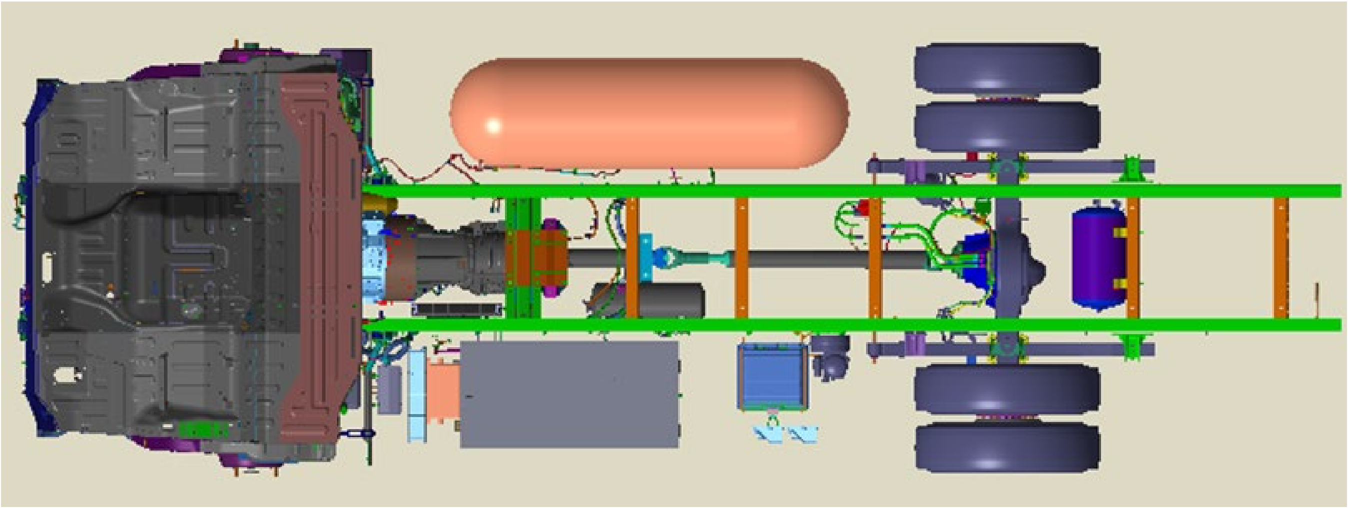
Task 5: Vehicle Integration, Evaluation and Demonstration

Vehicle Integration – NG Conversion

- 4HK based pent roof engine fits under existing cab floor of Isuzu class 8 F-Series truck
- 46.5 DGE fuel tank along passenger side frame rail combined with FE improvements results in slightly increased range over stock vehicle with 60-gallon diesel tank

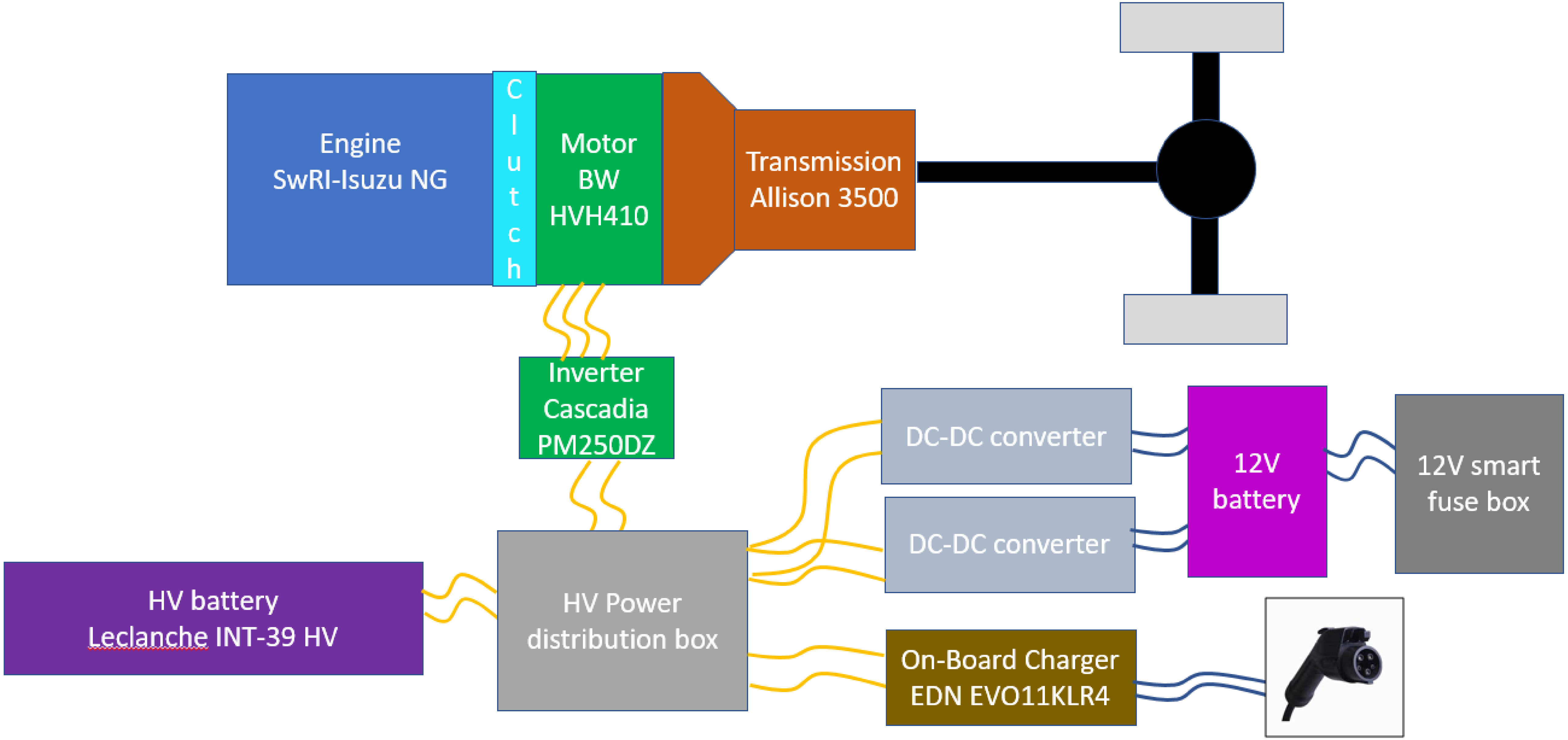






SwRI Project # 25912 / NREL Subcontract number NHQ-9-82305-07

Vehicle Integration – Hybrid Mechanization

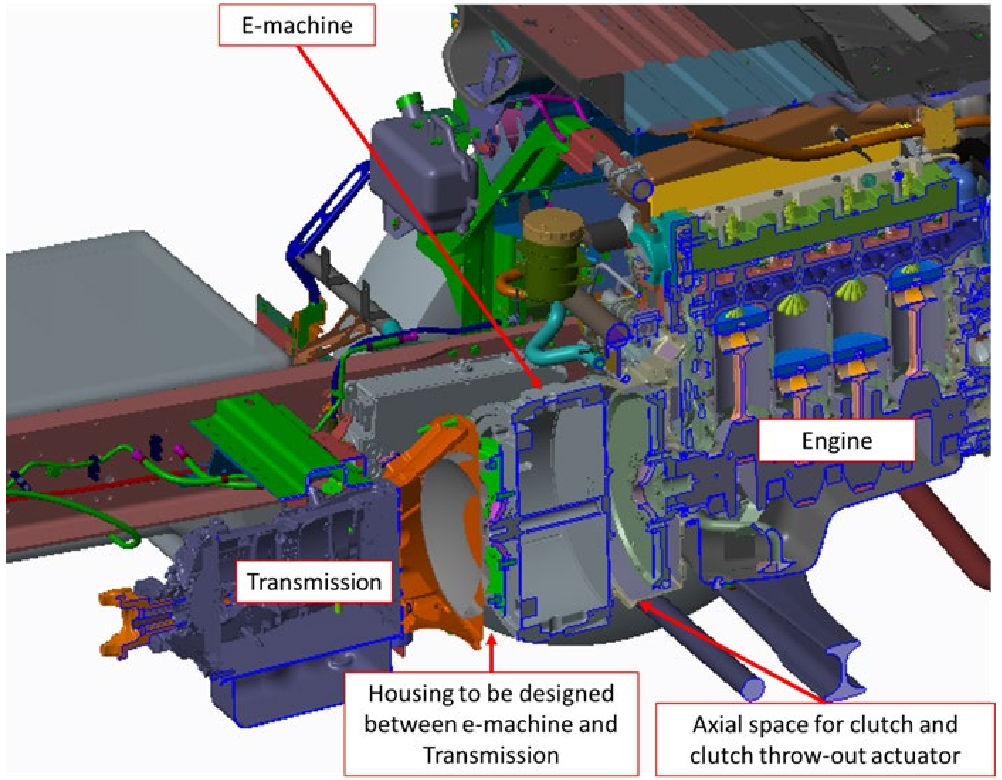


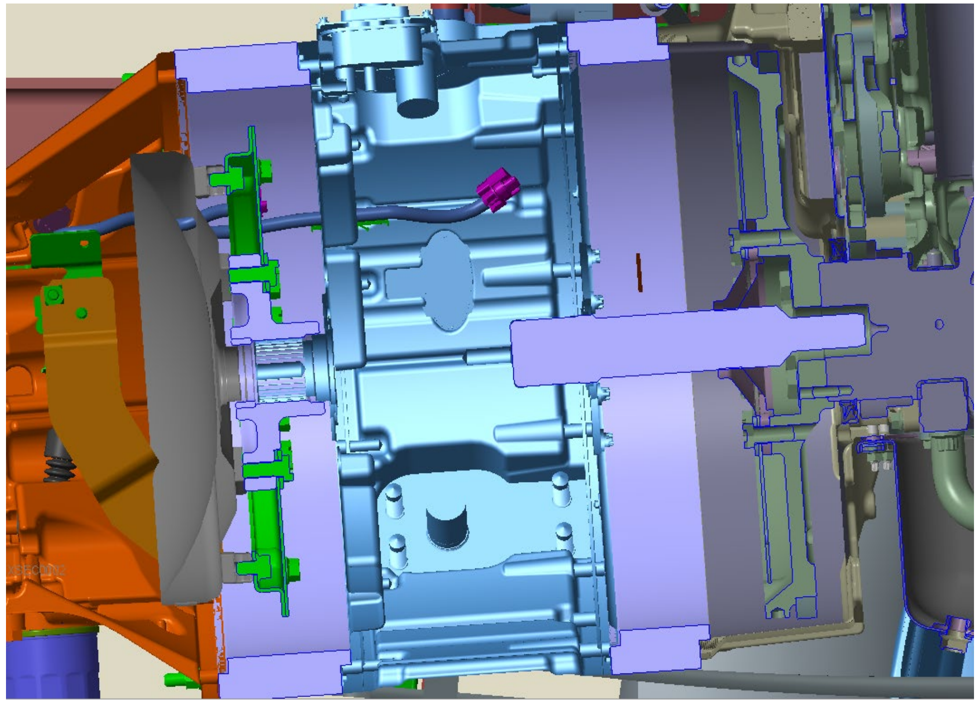
SwRI Project # 25912 / NREL Subcontract number NHQ-9-82305-07

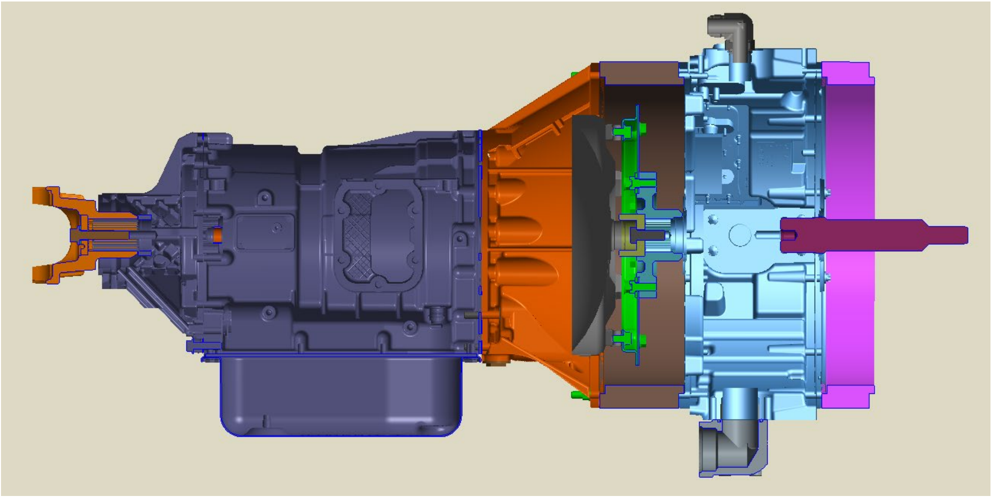
Vehicle Integration – Electric Motor

Electric motor integration

- Natural Gas 4HK engine with pent roof cylinder head
- Engine to motor spacer and clutch assembly
- Borg Warner HVH410-75-DOM motor
- Motor to transmission spacer and torque converter adaptor
- Torsional Vibration Analysis (TVA) in process







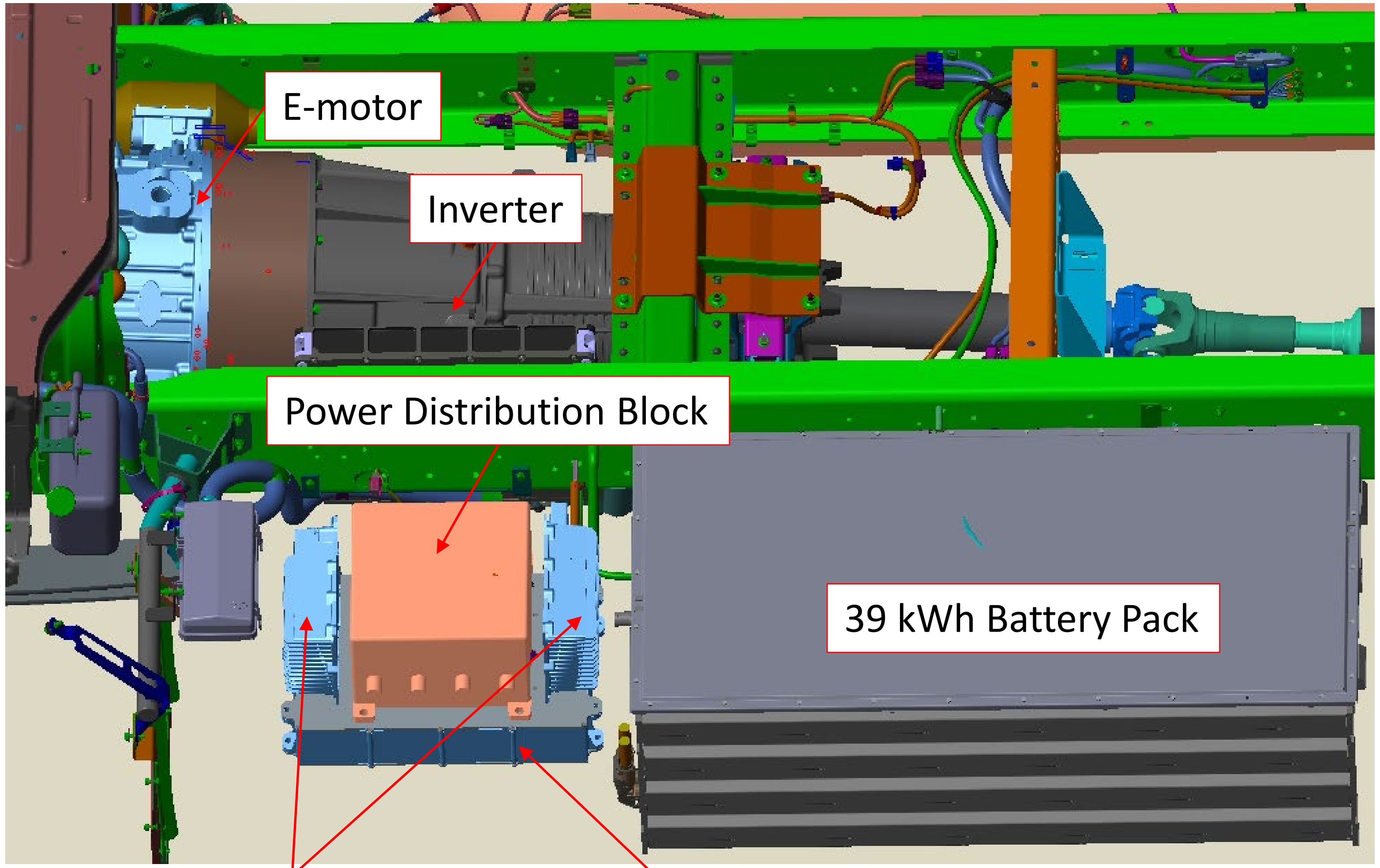
SwRI Project # 25912 / NREL Subcontract number NHQ-9-82305-07

Vehicle Integration – Hybrid Electronics

Component packaging:

- 39 kWh battery pack
- Inverter
- Power distribution block
- DC-DC converters

Locations in flux as concept design matures and high voltage component locations are optimized to minimize cabling length and associated EMI



Schedule Wrap-Up

Completion dates for future milestones:

- July 2021 Hybrid component procurement
- September 2021 Vehicle integration detailed design
- September 2021 Supervisory controller development
- October 2021 MCE transient calibration
- January 2022 Remaining procurement
- July 2022 Vehicle build
- October 2022 Vehicle calibration and performance testing
- November 2022 Vehicle Demonstration and final report

SwRI Project # 25912 / NREL Subcontract number NHQ-9-82305-07

Integrated Electric, Fuel Cell and Hybrid Powertrain Components Powering Clean Mobility

Plug-In Hybrid CNG Drayage Truck "CNG-PHET"

Near Zero NOx emission and cost of CNG
Higher Torque, Power and fuel economy of Diesel Engine

Daycab M2-112, Drayage

2 Trucks, 1000 Miles range

650 hp

Cascadia, Regional

1000 Miles range

650 hp

Abas Goodarzi, Ph.D., PE.

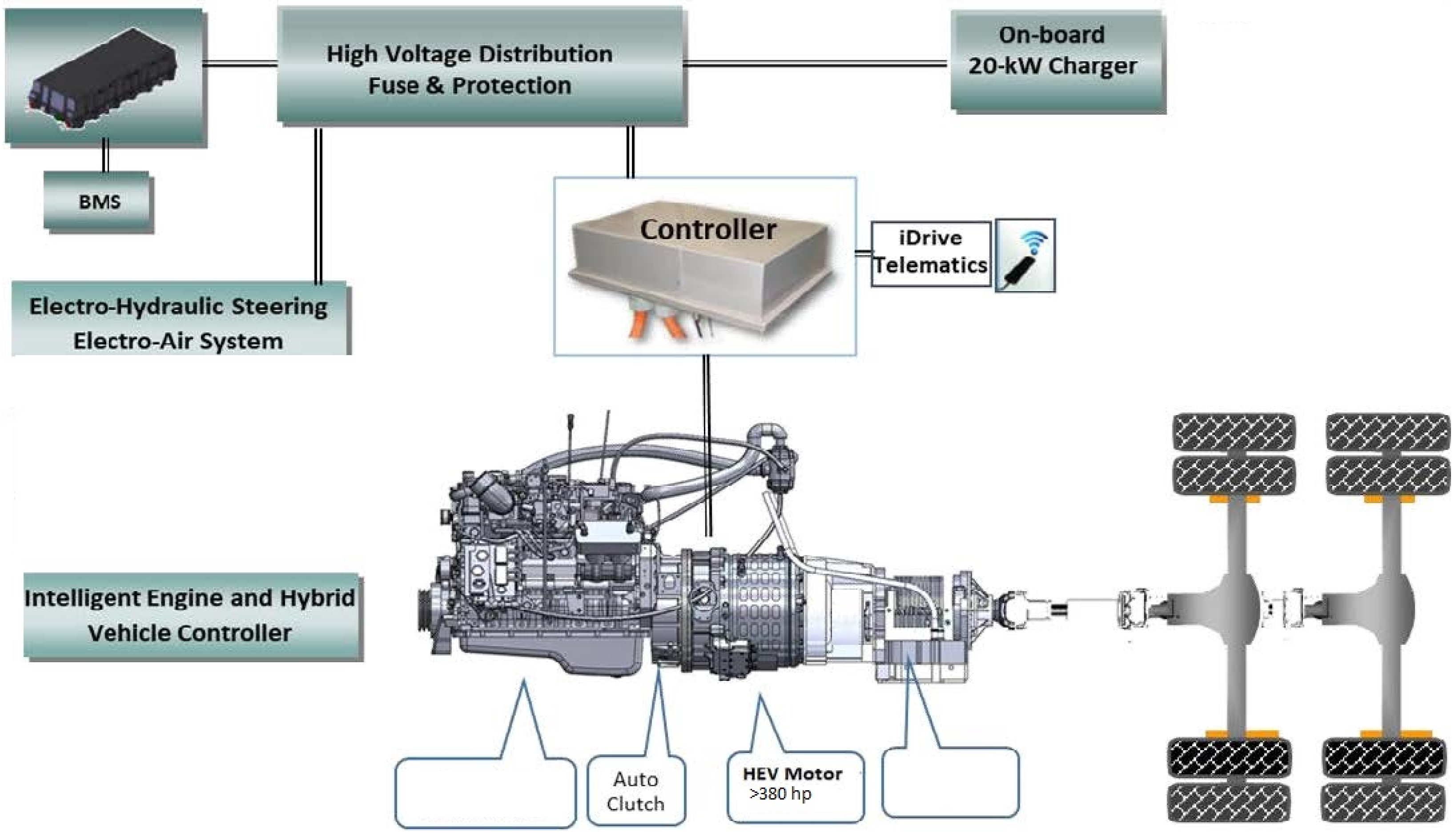
May 12, 2021

Plug-In Hybrid Benefit Chart

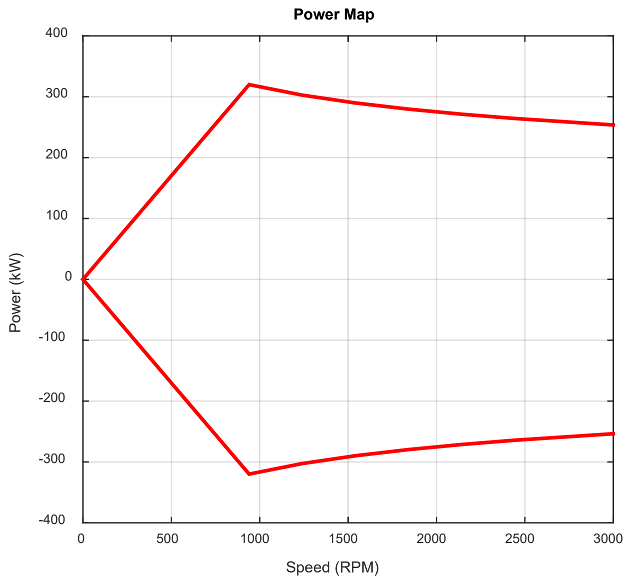
	Performance Goals				
Performance Metric	Metric Unit	Benchmark	Current Project	Minimum Target	Target
US Hybrid - 1.5 to 2X efficiency improvement	Mpg (gge)	**3**	**5**	**5.5**	**6** Comparable to Diesel >2X of LNG
Zero emissions Range iZeo™ system	Miles	**5**	**20**	**30**	**35**
US Hybrid - Reduce NOx emissions	NOx (g/mile)*	**0.36**	**0.24**	**0.18**	**0.15**
Power (HP)	hp	**400**	**550 hp**	**600**	**650**

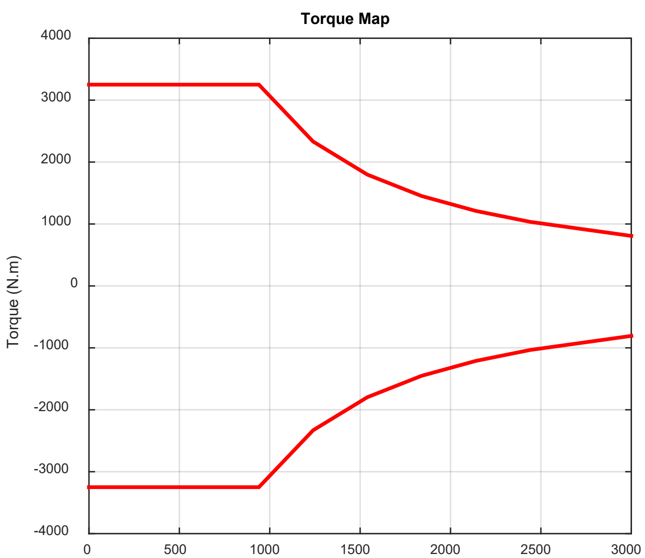
(*) Using 0.02g NOx/bhp-hr, (Cummins L9N, near Zero CNG engine) driving 65,000 lbs. GVWR and ~20 Tonne payload (44,000 lbs.), Operating the Simulated Port Cycle and estimated BSFC of the CNG engine and 4hp-h (3kWh)/mile fuel efficiency and Av. BSFC

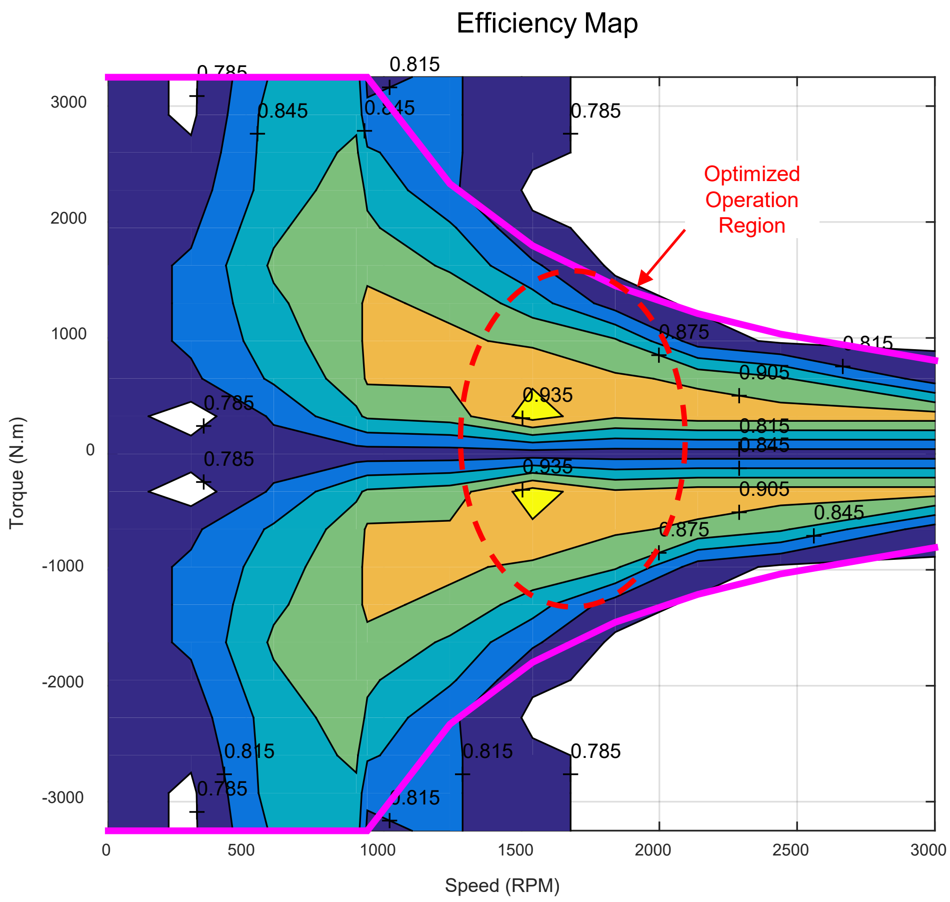
PHET Powertrain Architecture



Optimized Hybrid Electric Motor Characteristics (for L9N)

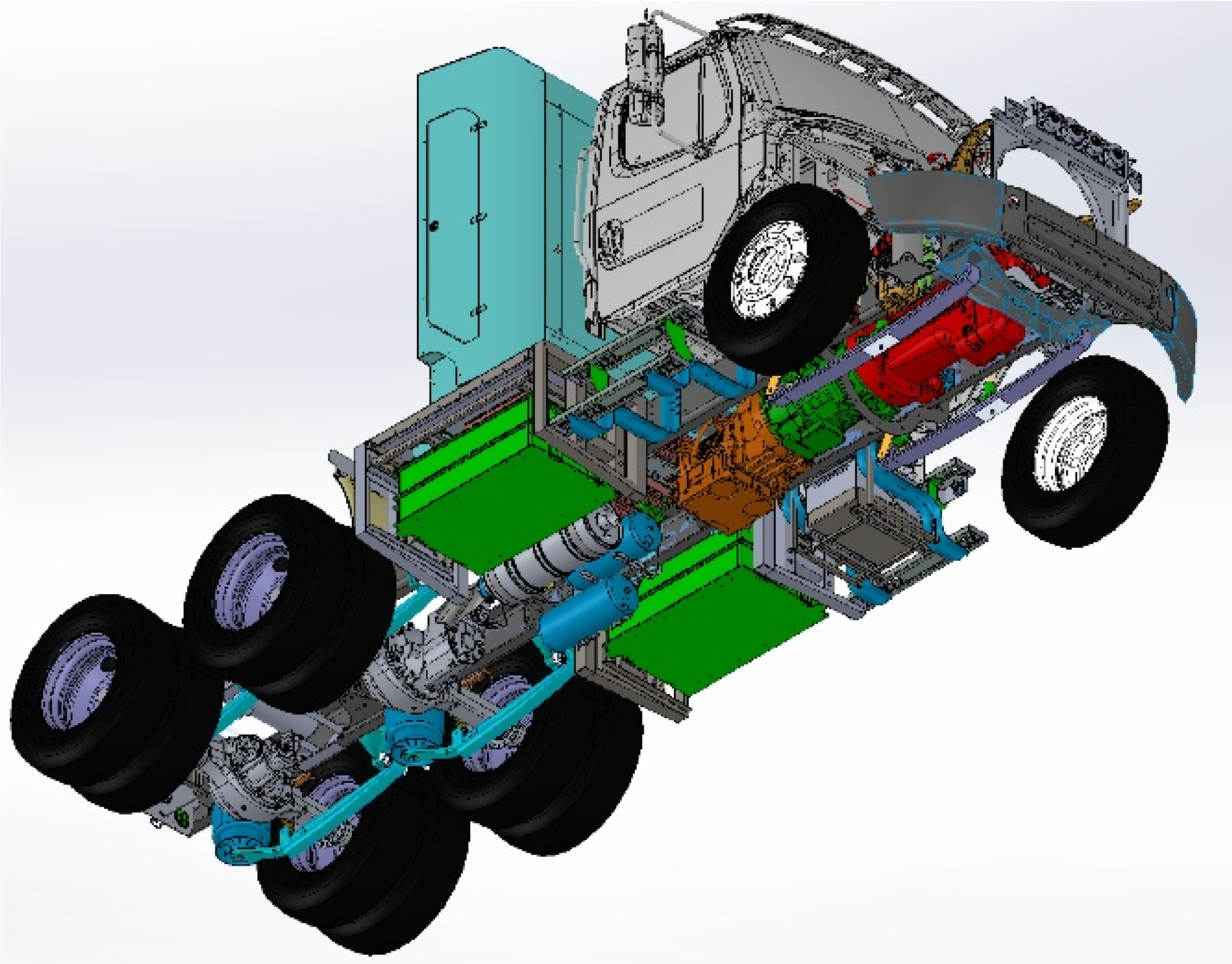


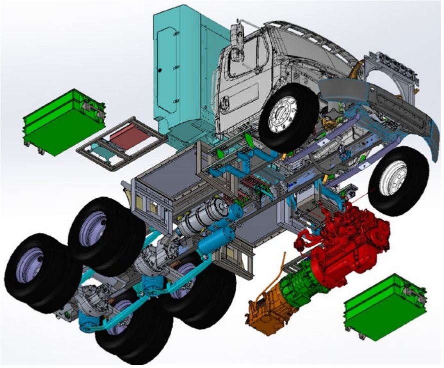




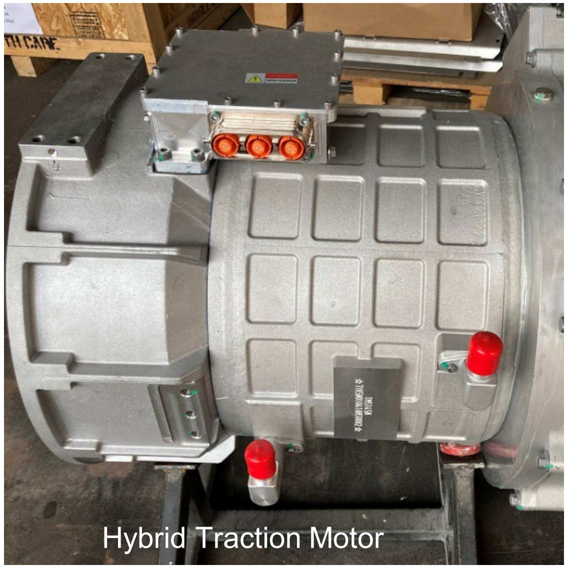
Vehicle Packaging

No compromised Cargo load capacity, Minimized Curb weight





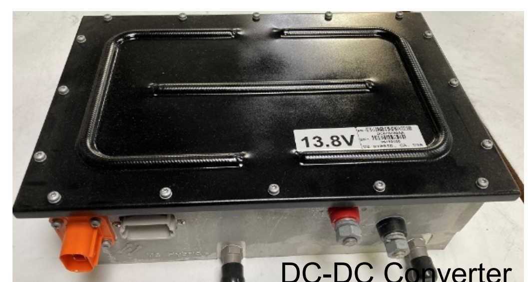
Minor Hardware & Lots of Software



Hybrid Traction Motor

Auxiliaries Controllers

Air system & Aux Battery

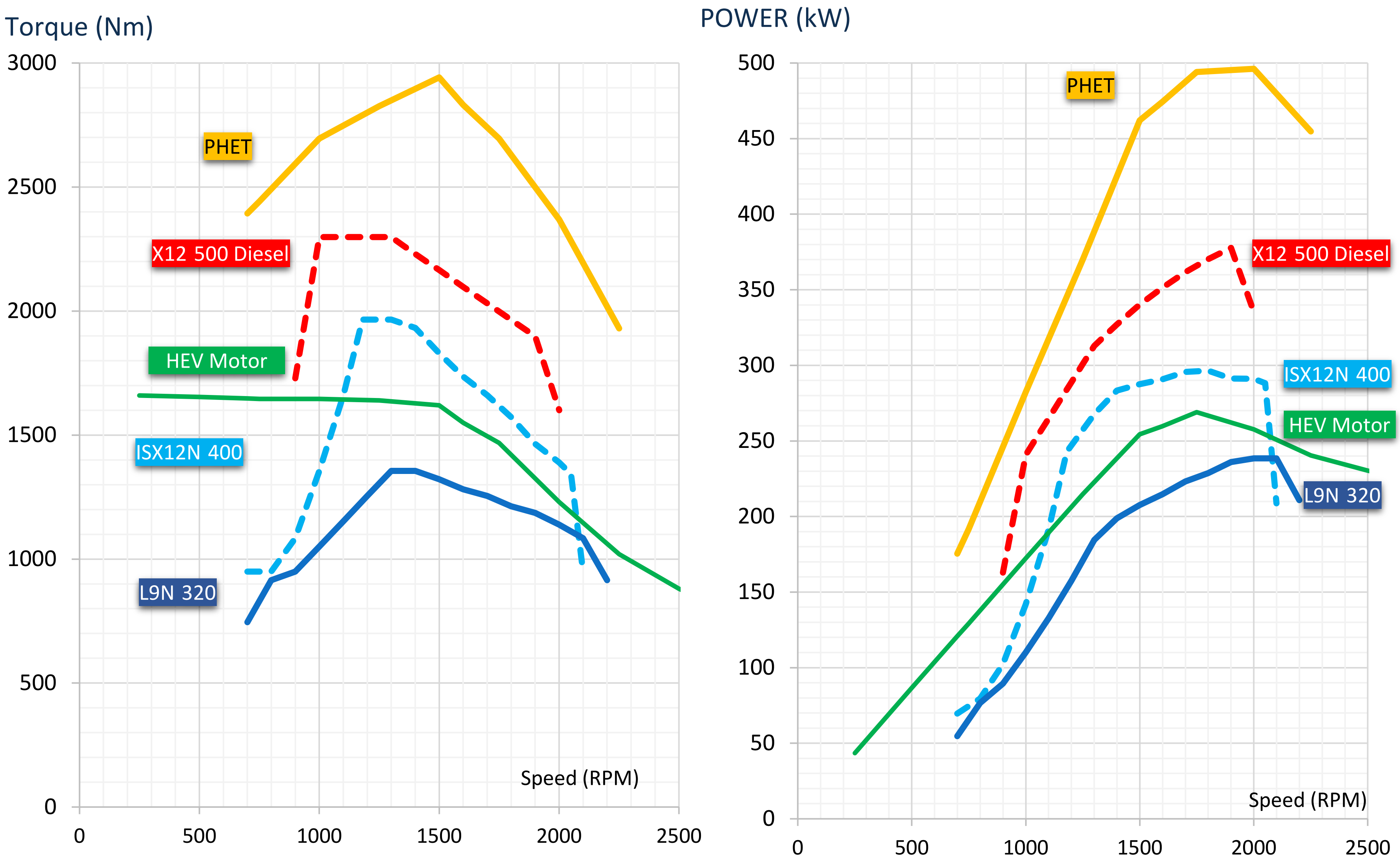


DC-DC Converter

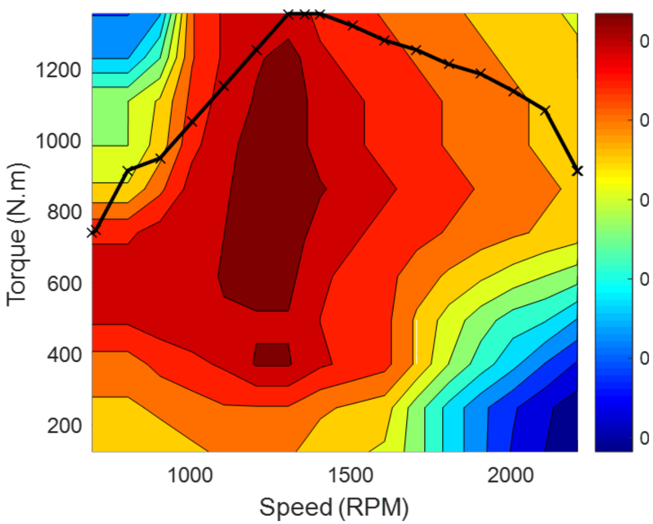
Project Teaming

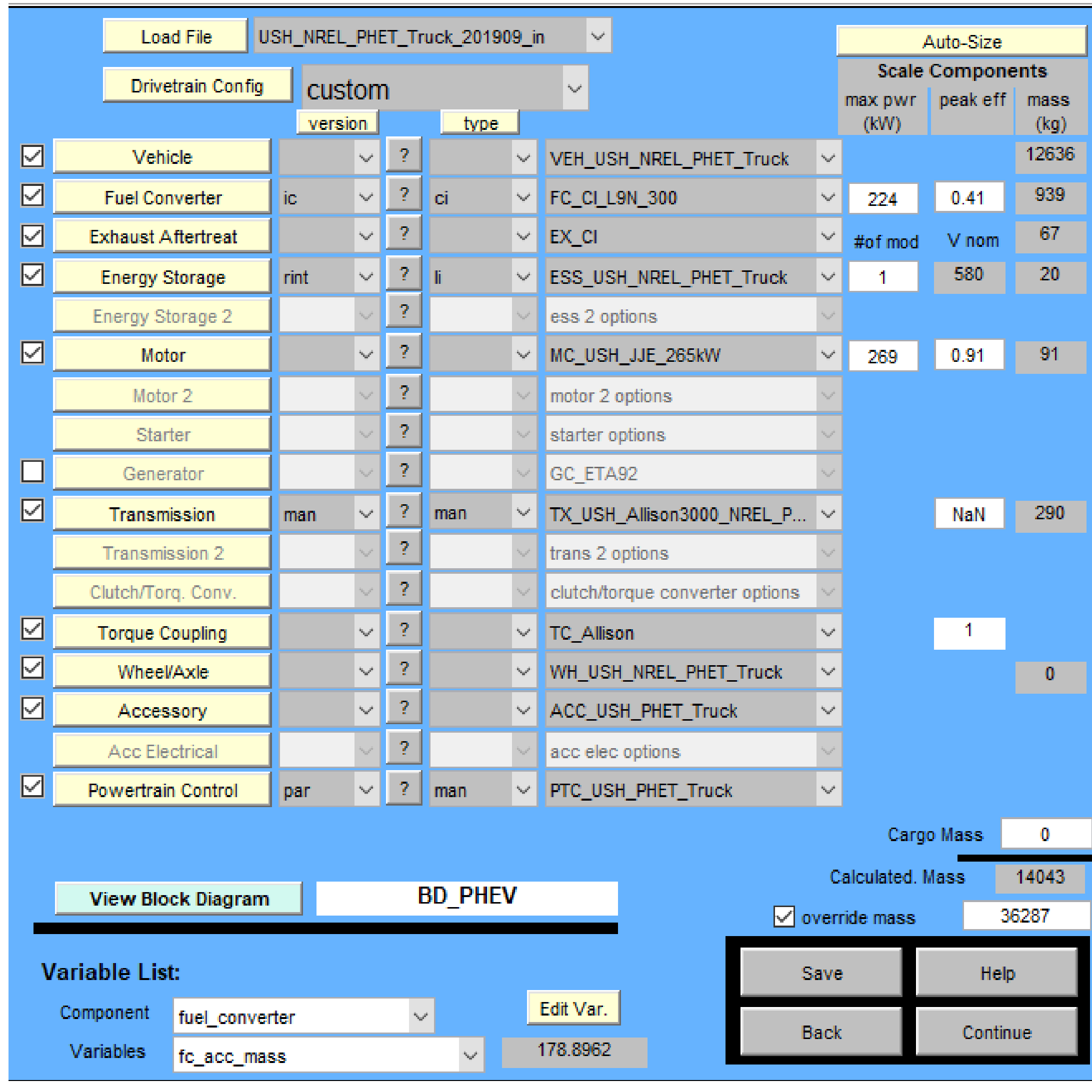
Item	Description	Company
1	M2-112 Drayage truck 4x6	Freightliner/Velocity
2		Freightliner/Velocity
3		Cummins
4		Allison
5		US Hybrid
6		A123
7		

NET CNG-PHET Torque and Power Maps (Gen 1)

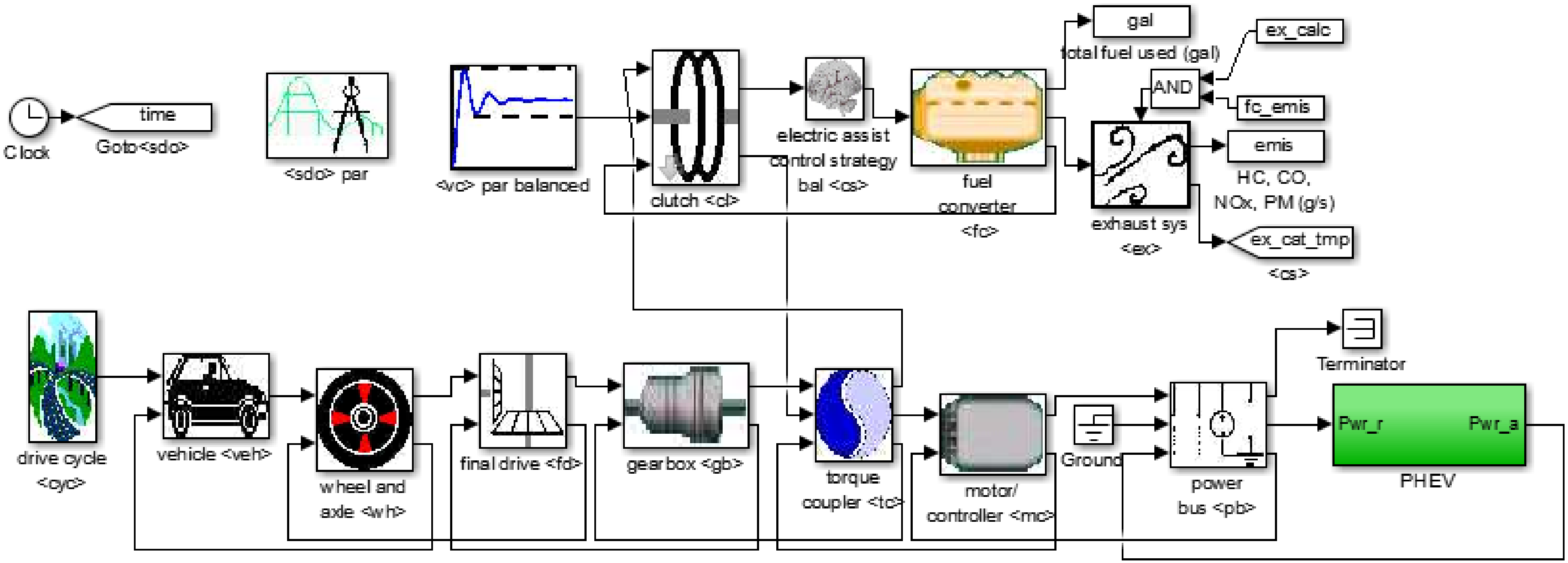


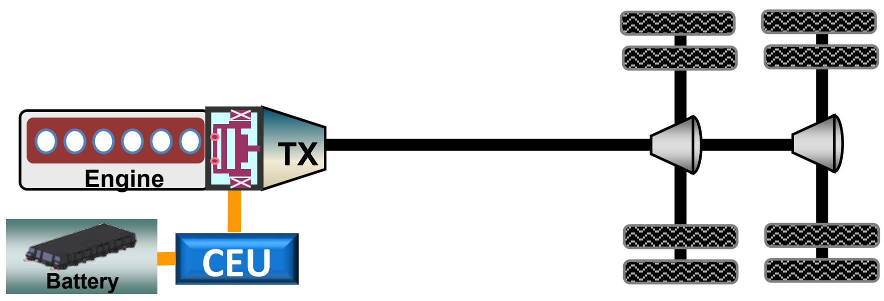
Customized Advanced Vehicle Simulator Toolbox





Simulink Customized system Block Diagram





Pre-transmission Parallel Hybrid with Auto Clutch

Actual field Operation data Fuel Efficiency (Ge1 LNG-PHET)

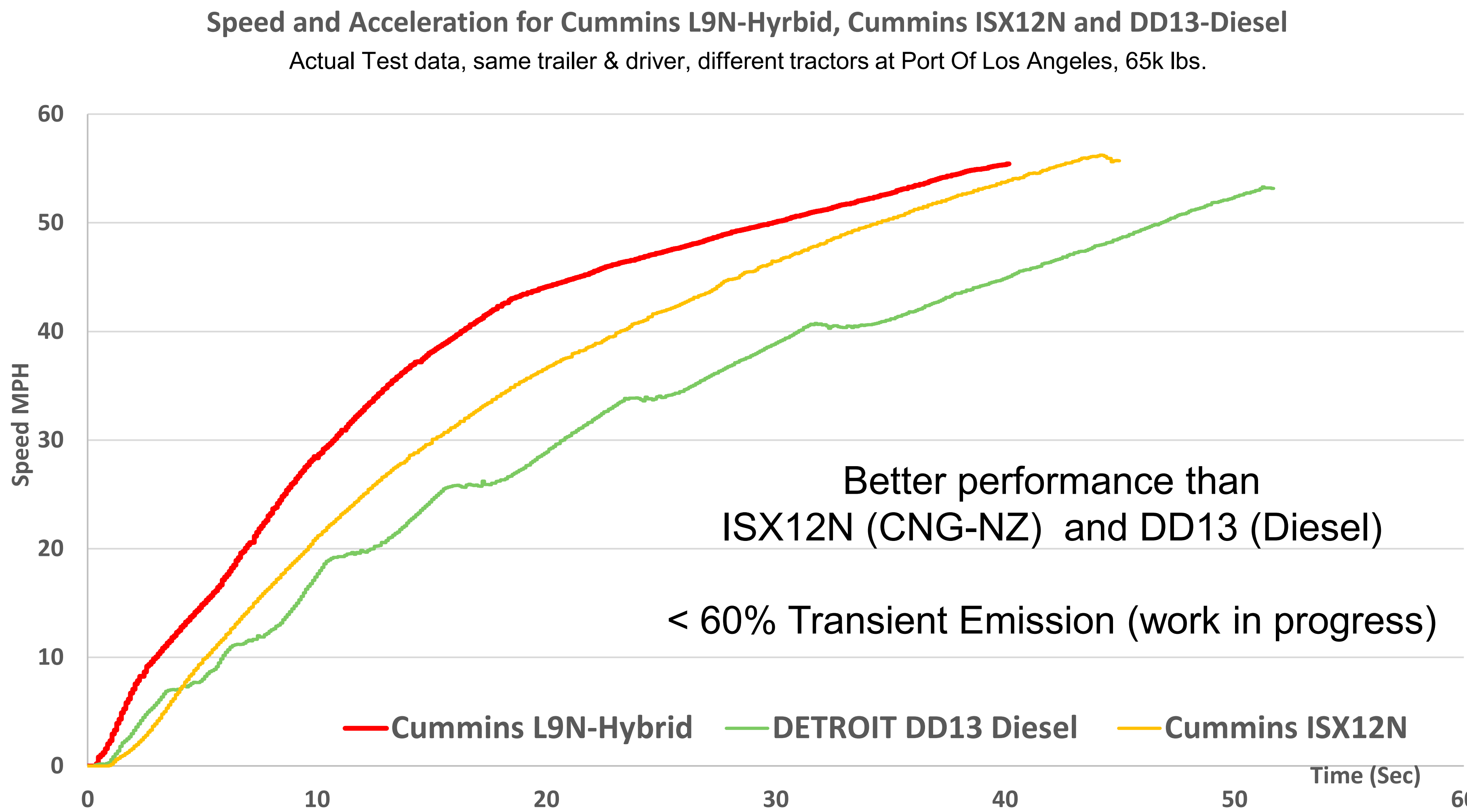
2020 Mileage Report

Trucks	# Trucks	Totals/Averages			%
		Total Mileage	Total DGE Consumed	MPG (DGE)	
Diesel	28	265,129	41,223	6.3	Bench Mark 100%
CNG	36	1,615,956	408,783	3.95	61% of Diesel
LNG	5	37,316.0	16,625	2.24	35% of Diesel
LL054 PHET, Jan 2021	1	3,662.0	762	4.81	**214%** wrt LNG
LL056 PHET, Jan 2021	1	689.7	159	4.33	**193%** wrt LNG

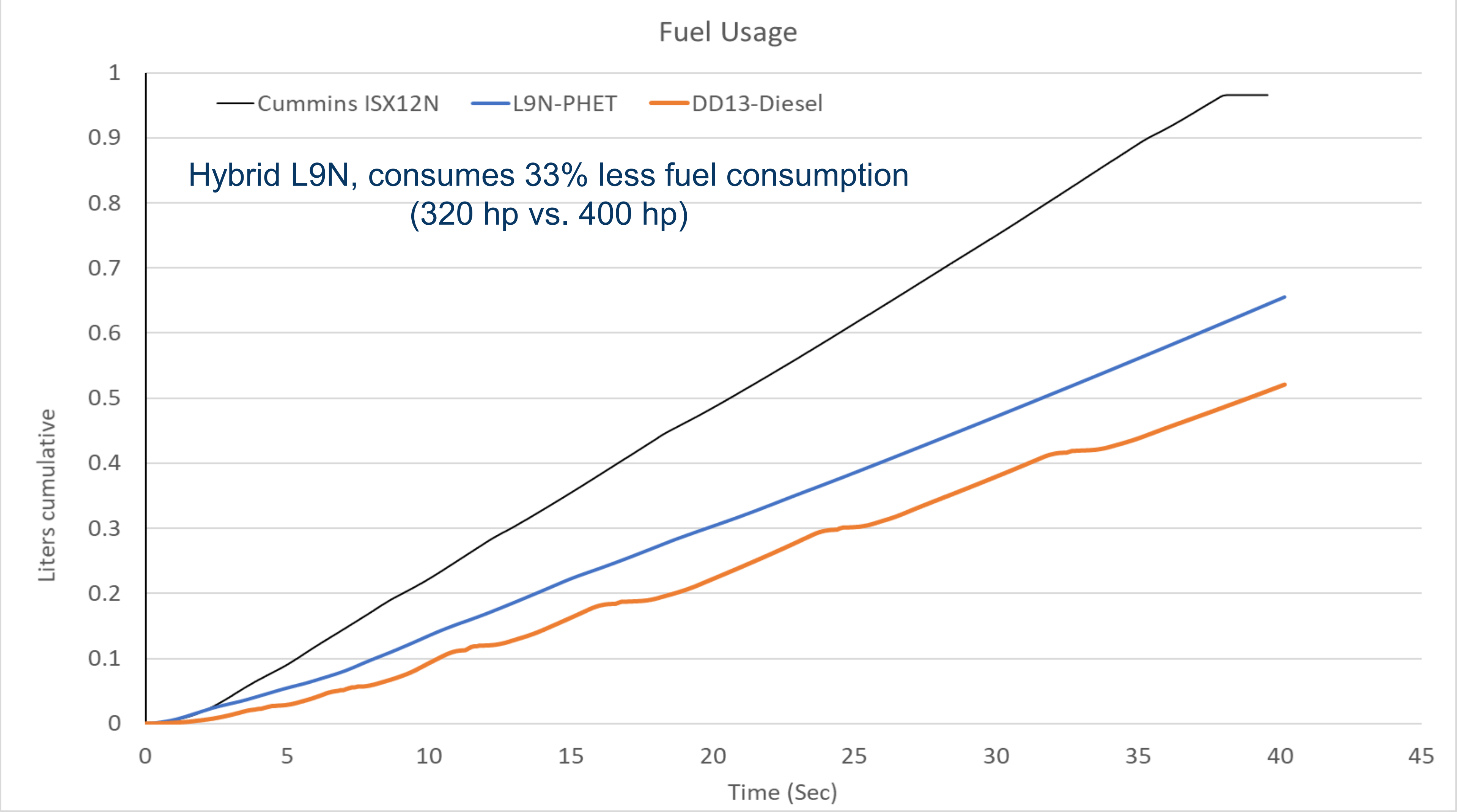
LNG PHET Fuel economy

is >200% that of conventional LNG trucks with 12L engines

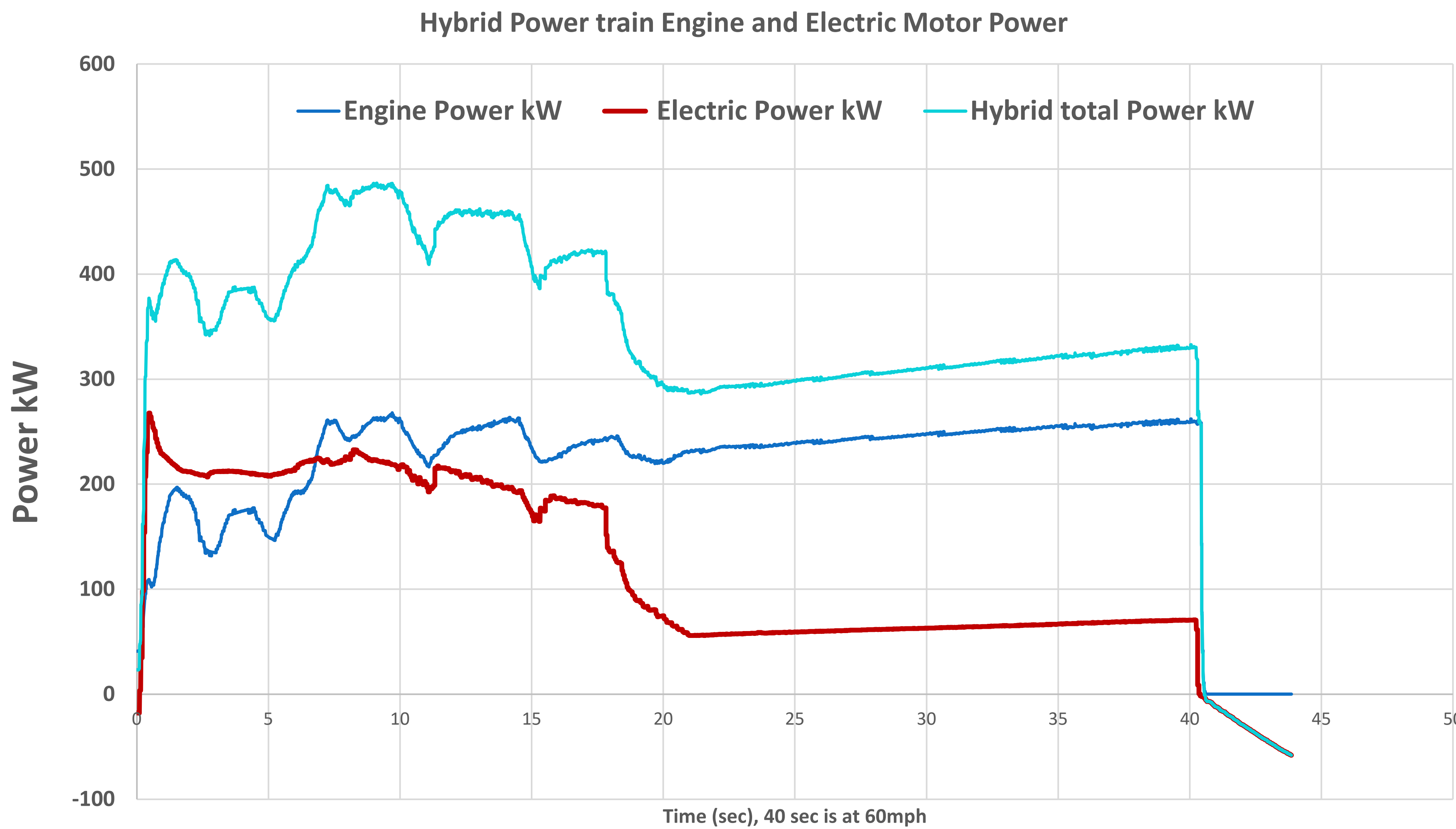
Actual field Operation data Performance (Ge1 LNG-PHET)



Actual field Operation data Fuel Efficiency (Ge1 LNG-PHET)



Hybrid Electric Motor is doing a lot of work (Gen 1 data)



iZeo™ Intelligent Zero Emission Operation, Enabling Technology

- **iZeo™ is the technology that enables repetitive Zero Emission Operation at targeted areas.**
- US Hybrid Proprietary firmware with Integrated Predictive, GPS, Fuzzy logic and cognitive/adaptive self-learning Energy system and Hybrid Vehicle Control
- CAN based Communications and diagnostics with Driver performance indicator.
- Integrated Service and diagnostic & Reporting
- Stand-alone and Wi-Fi operation
- Minimizes driver dependency variations.
- **Adaptable to all trucks and buses platforms**

Thank You & Welcome your questions

Abas@ushybrid.com

310-212-1200

High-Efficiency Natural Gas Dual Fuel Combustion Strategies for Heavy-Duty Engines

Subcontract#: NREL NHQ-9-82305-01

– *Mid-Project Presentation*

Prepared for NREL/Alliance for Sustainable Energy, LLC, by:

The University of Alabama

Technical Contacts:

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May 12, 2021

THE UNIVERSITY OF ALABAMA | College of Engineering

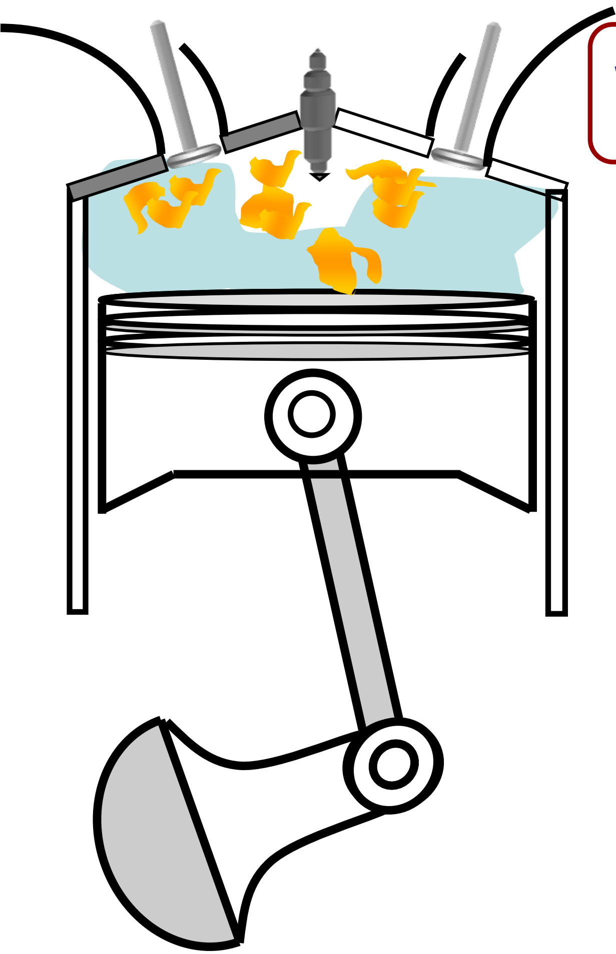
Outline

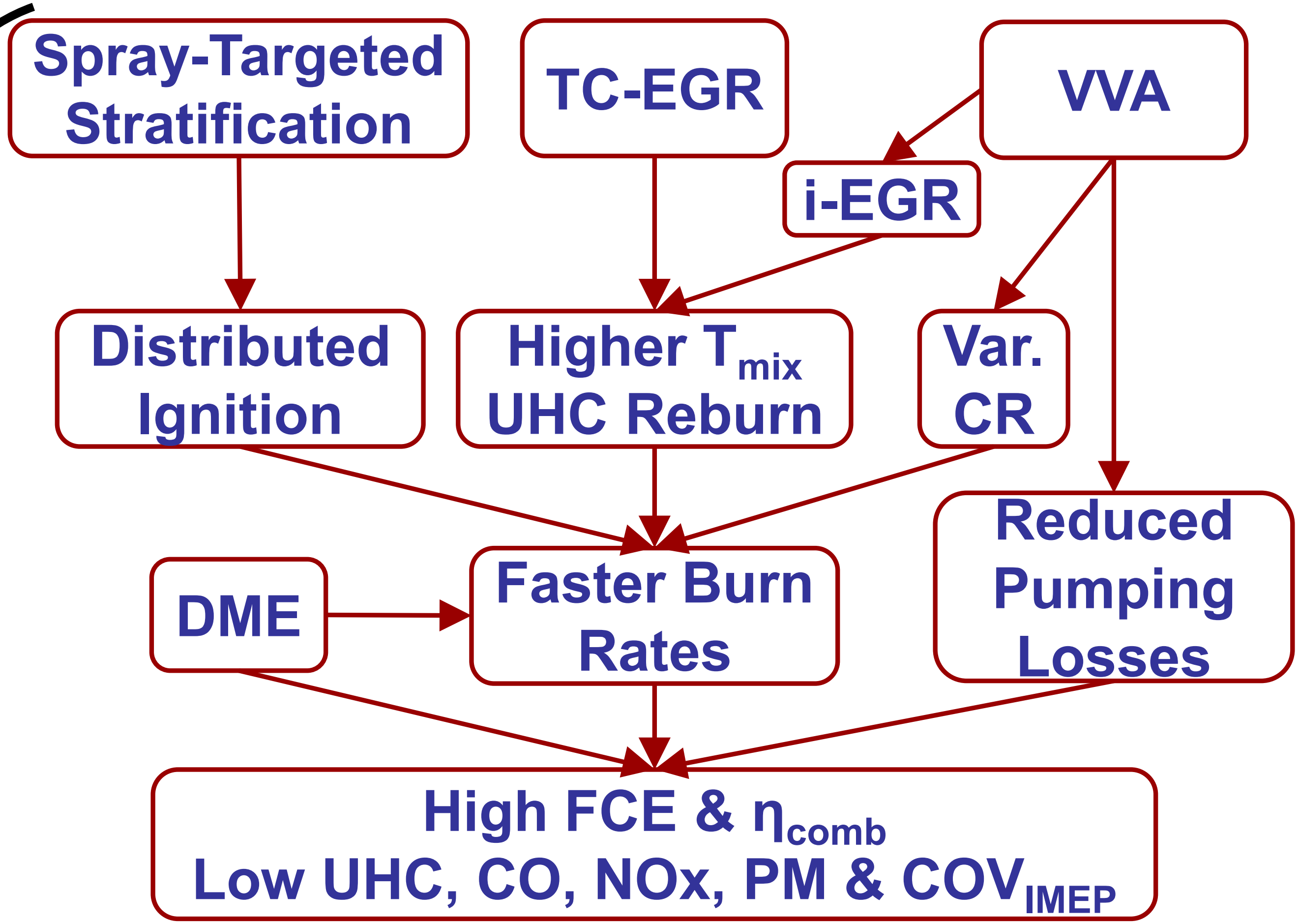
- Introduction
- System-Level Simulations - GT-SUITE
- CFD Simulations – CONVERGE
- Experimental work – UA SCRE
- Summary and Conclusions
- Publications and Students

Overall Project Approach – Analysis-Led Experiments

- System-level (1D) GT-SUITE simulations
- CFD simulations of diesel-NG & PODE-NG dual fuel low-temperature combustion (LTC)
- Single-cylinder research engine (SCRE) experiments for characterizing efficiency and emissions benefits of dual-fuel LTC with:
  - Poly-Oxymethyl-Dimethyl-Ether (PODE) as pilot fuel
  - Spray-TArgeted Reactivity Stratification (STARS)
  - Variable Valve Actuation (VVA)
  - Temperature-Controlled Exhaust Gas Recirculation (TC-EGR)

Conceptual Pathways for High Efficiency





GT SUITE Simulations

Outcomes of GT Tasks

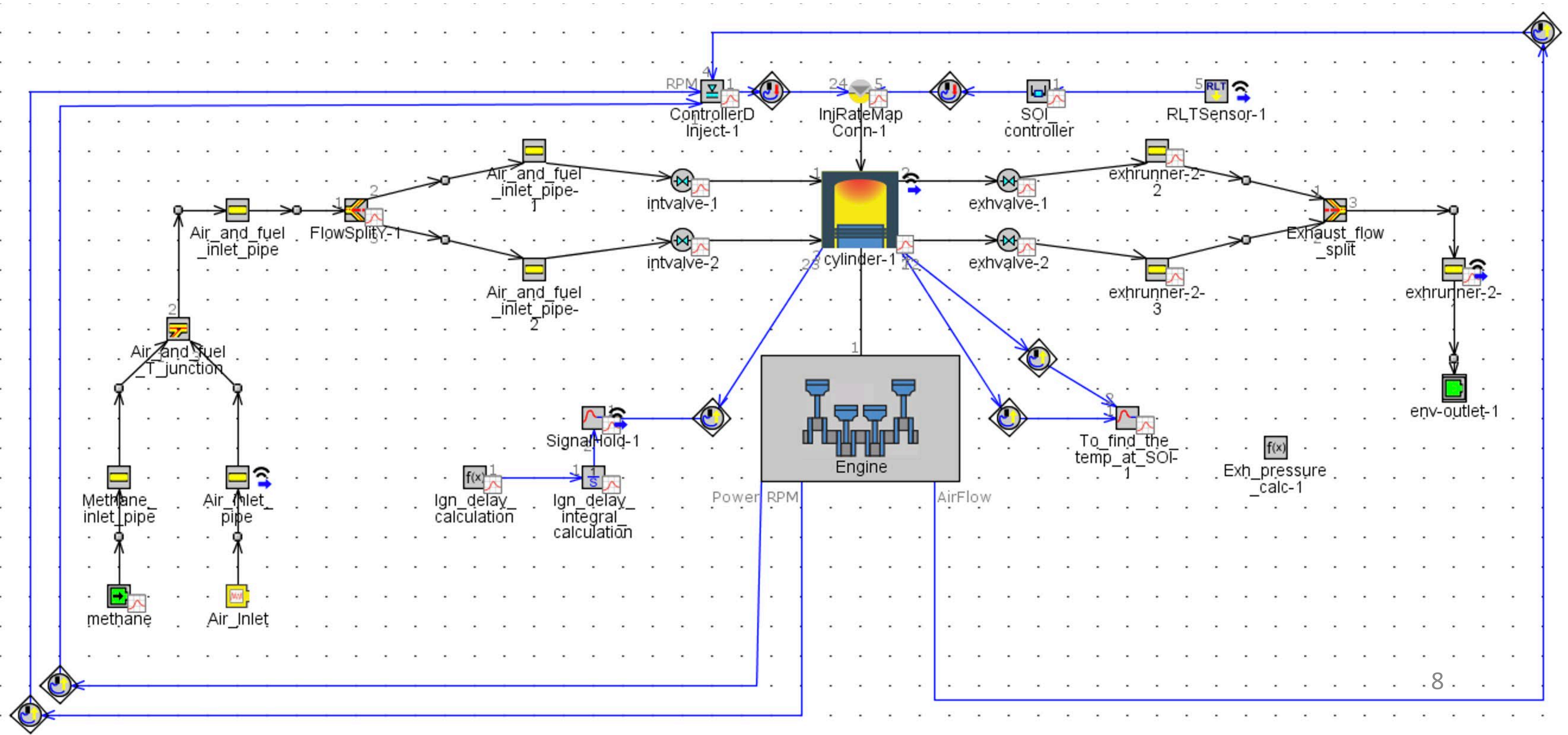
- The GT-SUITE tasks provided the baseline input parameters for the CFD model and also served as the main platform for performing exploratory VVA studies
- Major outcomes include the following:
  - **GT-SUITE results were crucial in specifying the VVA system parameters for the UA SCRE**
  - Provided an efficient platform for performing quick consistency checks with experimental results (e.g., compression ratio check) and for providing initial/boundary conditions for CFD
  - Provided results for ensuring internal consistency with CFD simulations before experimental data were available
  - Provided general roadmap and initial/boundary conditions for the experimental campaign

GT-SUITE Accomplishments

Quarter 1	GT model development
Quarter 2	Analysis-led VVA design
Quarter 3	Completed VVA design with two new valve lift profiles each for intake and exhaust
Quarter 4	Internal consistency ensured between CFD and GT
Quarter 5	Preliminary comparison with experiments

UA SCRE : GT-SUITE model

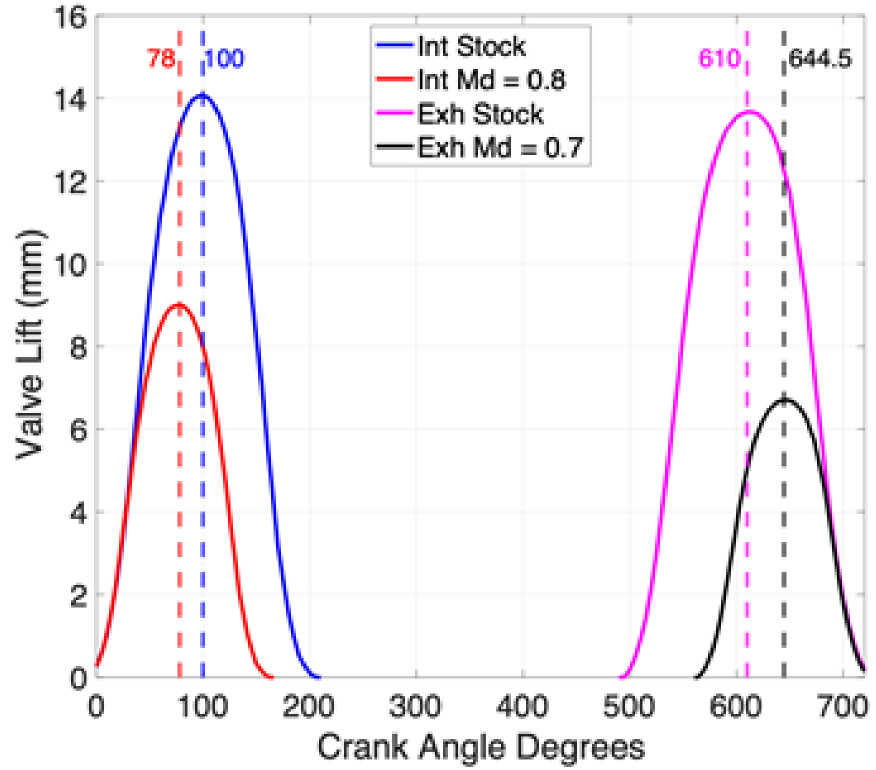
- Predictive 1D model built to simulate UA SCRE using GT-SUITE
- Internal consistency established with CONVERGE CFD model
- Separate controls for DI fuel mass and start of injection (SOI)
- Model is currently being validated with experimental results



VVA System (Cam Phaser-Based)

- GT model used to find best valve lift profiles for VVA
- Two different intake and exhaust profiles considered, in addition to stock profiles
- High-lift profiles were not as beneficial as expected
  - *For intake:* They hurt both dynamic compression ratio (r_d) and volumetric efficiency (η_{vol})
  - *For exhaust:* They hurt residual gas fraction (RGF)

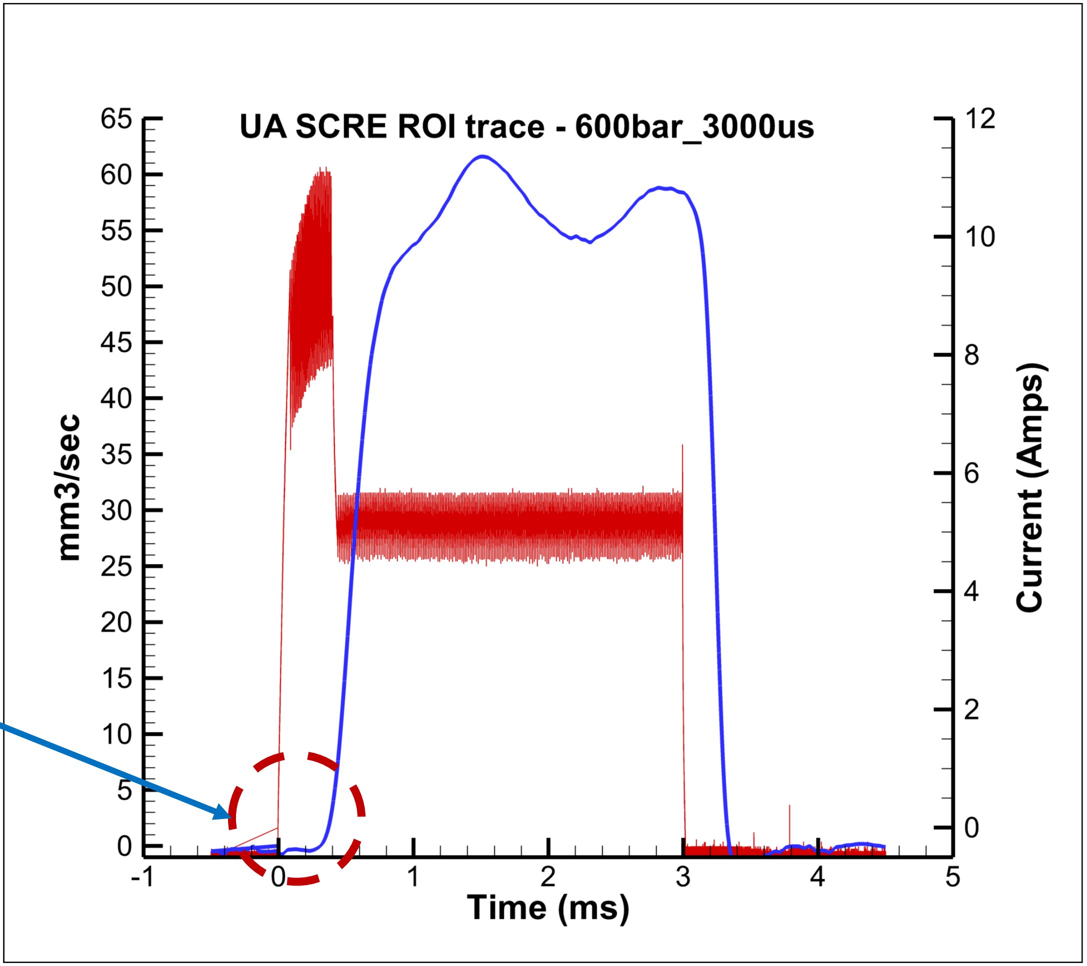
Desired intake and exhaust valve lift profiles



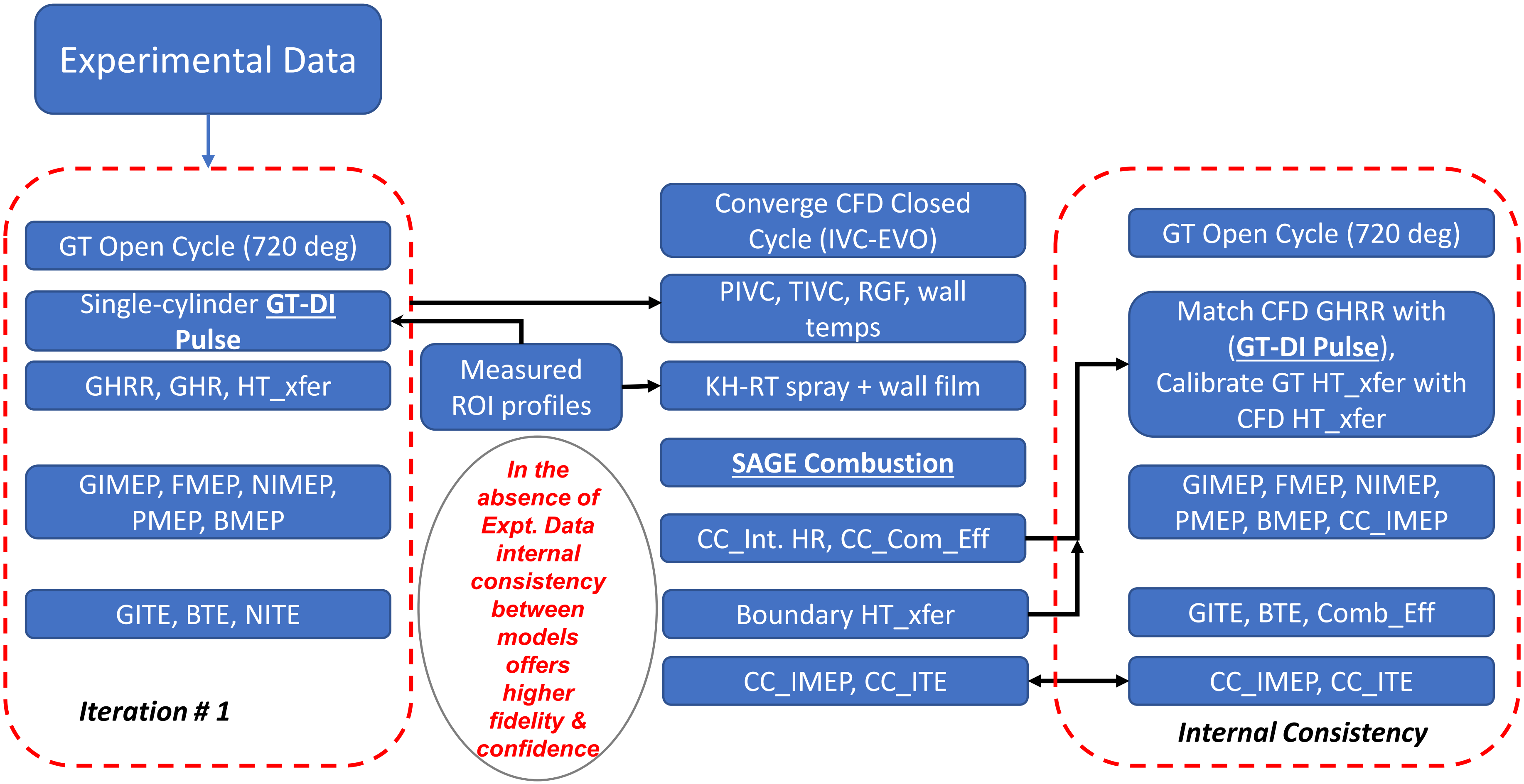
- So only one extra set of profiles were chosen for intake and exhaust
  - *For intake:* Md = 0.8, it can maintain a constant η_{vol} and r_d
  - *For exhaust:* Md = 0.7, it has the widest possible range for the RGF.

Measured ROI Profiles Input for Models

- Rate of injection (ROI) profiles for UA SCRE fuel injector characterized by Exergy
- A sample ROI trace is shown at 600 bar injection pressure and 3 ms injection duration
  - Note injection delay between current signal and ROI trace
- ROI profiles were critical inputs for our CFD and predictive GT-SUITE simulations

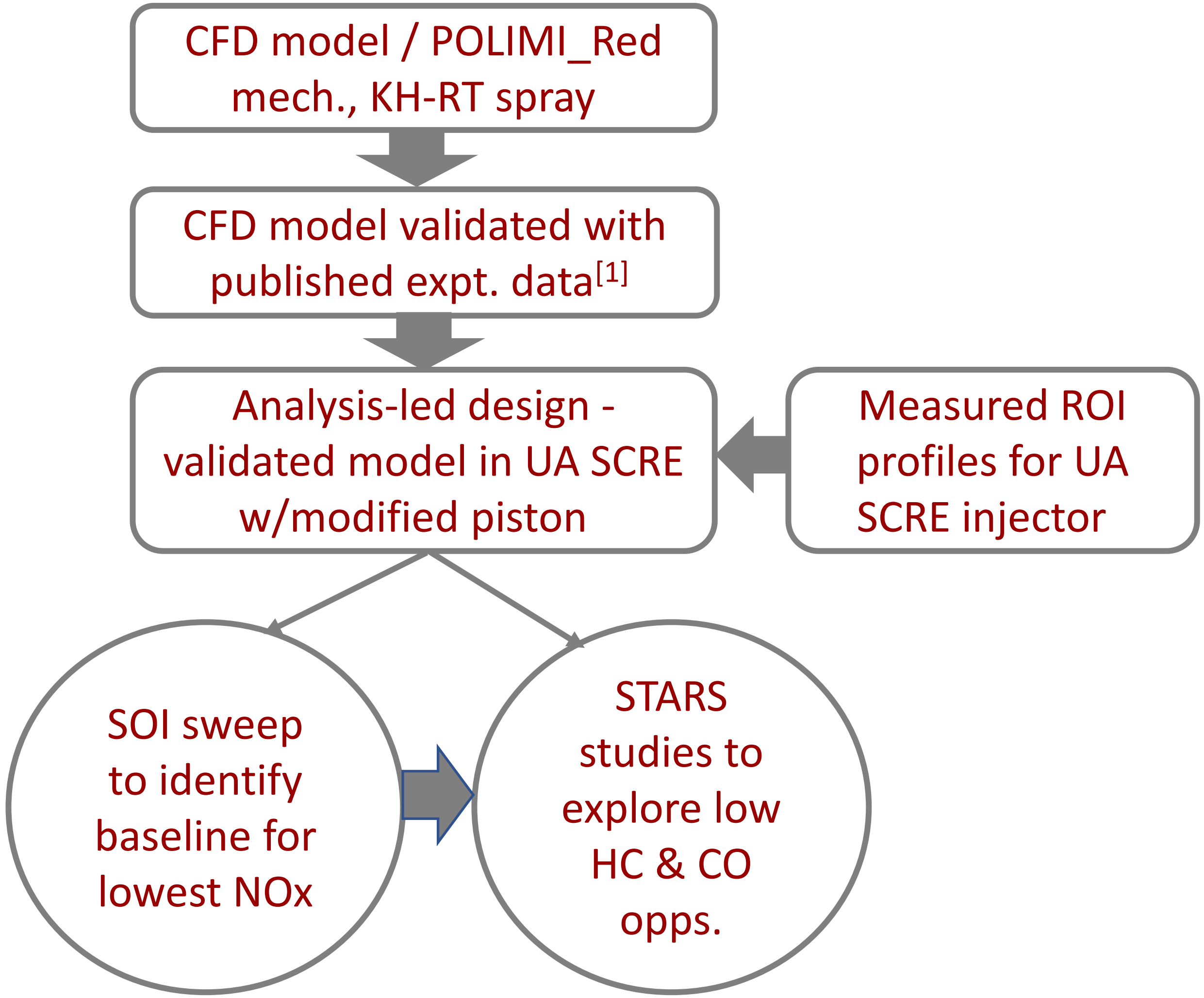


Workflow & Internal Consistency: GT-Suite ← → Converge CFD



CFD Simulations

CFD Simulations Workflow

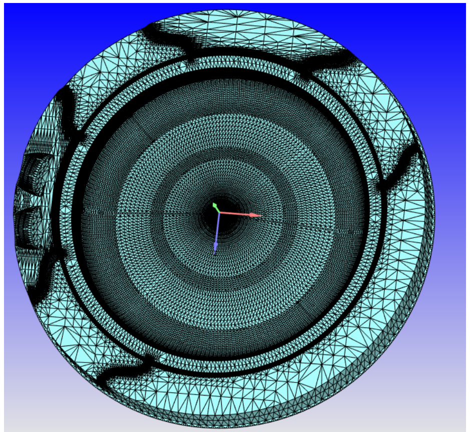


[1] Srinivasan, K.K., Krishnan, S.R., Jha, P.R., Mahabadipour, H. (2019). Cyclic Combustion Variations in Diesel-Natural Gas Dual Fuel Engines. Chapter 12 in Srinivasan, K.K., Agarwal, A.K., Krishnan, S.R., Mulone, V. (Eds.) (2019). Natural Gas Engines For Transportation and Power Generation. pp. 329-358. Springer Singapore. ISBN: 978-981-13-3306-4; https://doi.org/10.1007/978-981-13-3307-1_12

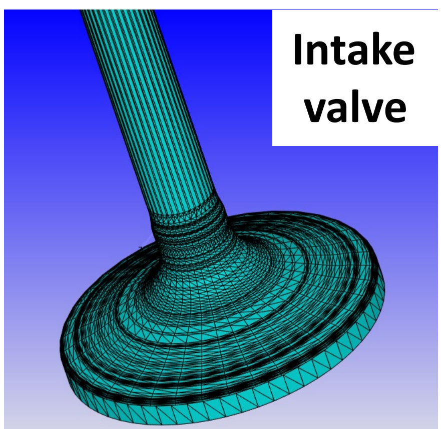
CFD Accomplishments

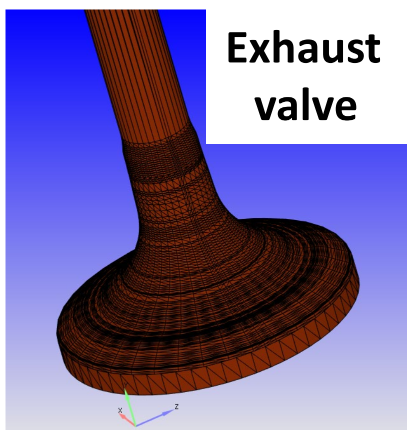
Quarter 1	Developed UA SCRE CFD model geometry and identified appropriate chemistry mechanisms
Quarter 2	Validated CFD simulations with our previously published SCRE data
Quarter 3	Validated model used to investigate SOI effects on dual fuel (DF) LTC on UA SCRE
Quarter 4	Used measured ROI profiles to perform DF LTC STARS and impact of CH_4 on diesel autoignition
Quarter 5	Preliminary comparisons of DME-NG and diesel-NG LTC

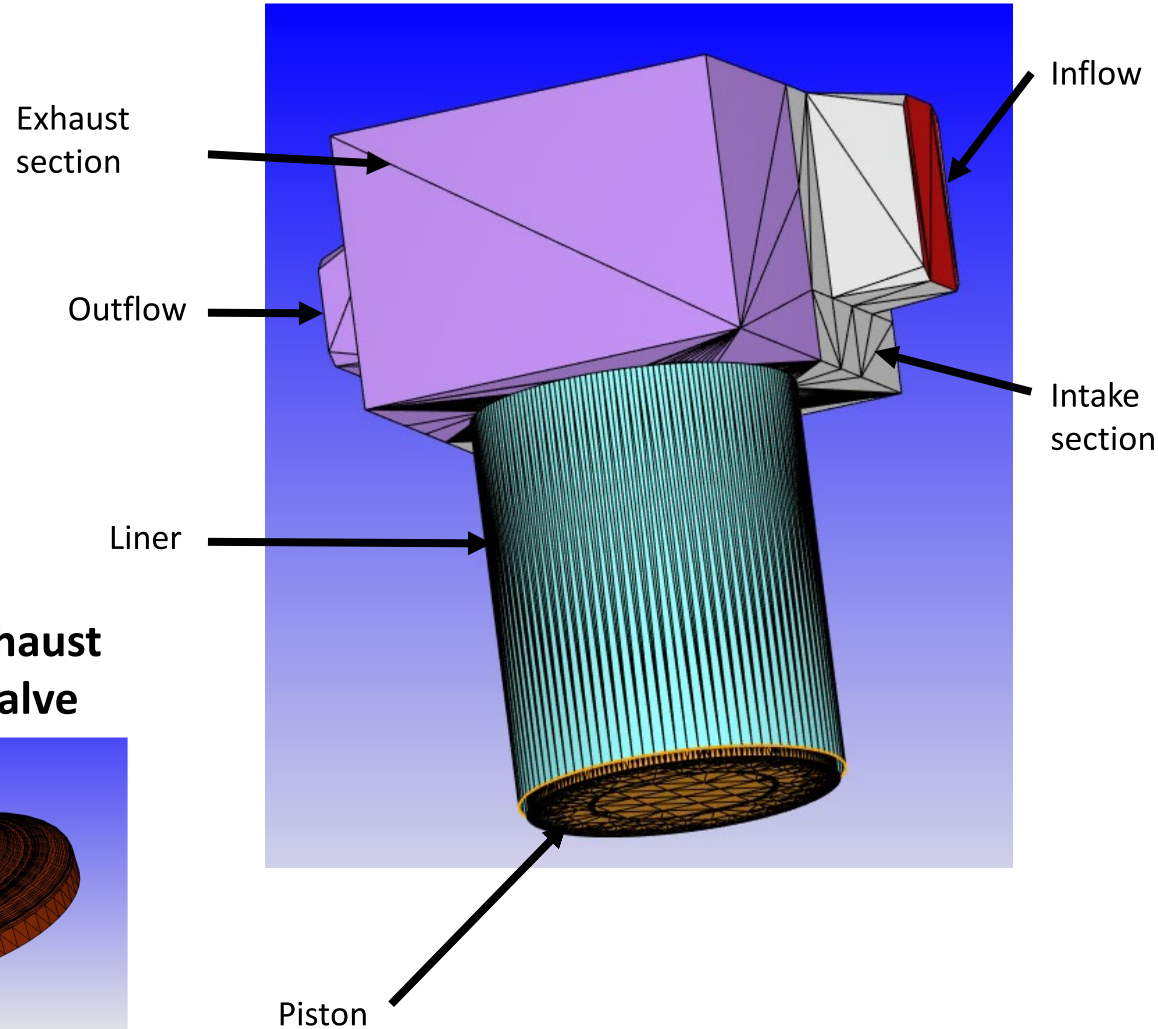
UA SCRE Geometry (1.8L Disp. Vol.)



SCRE piston scan with valve reliefs and endoscope access reliefs



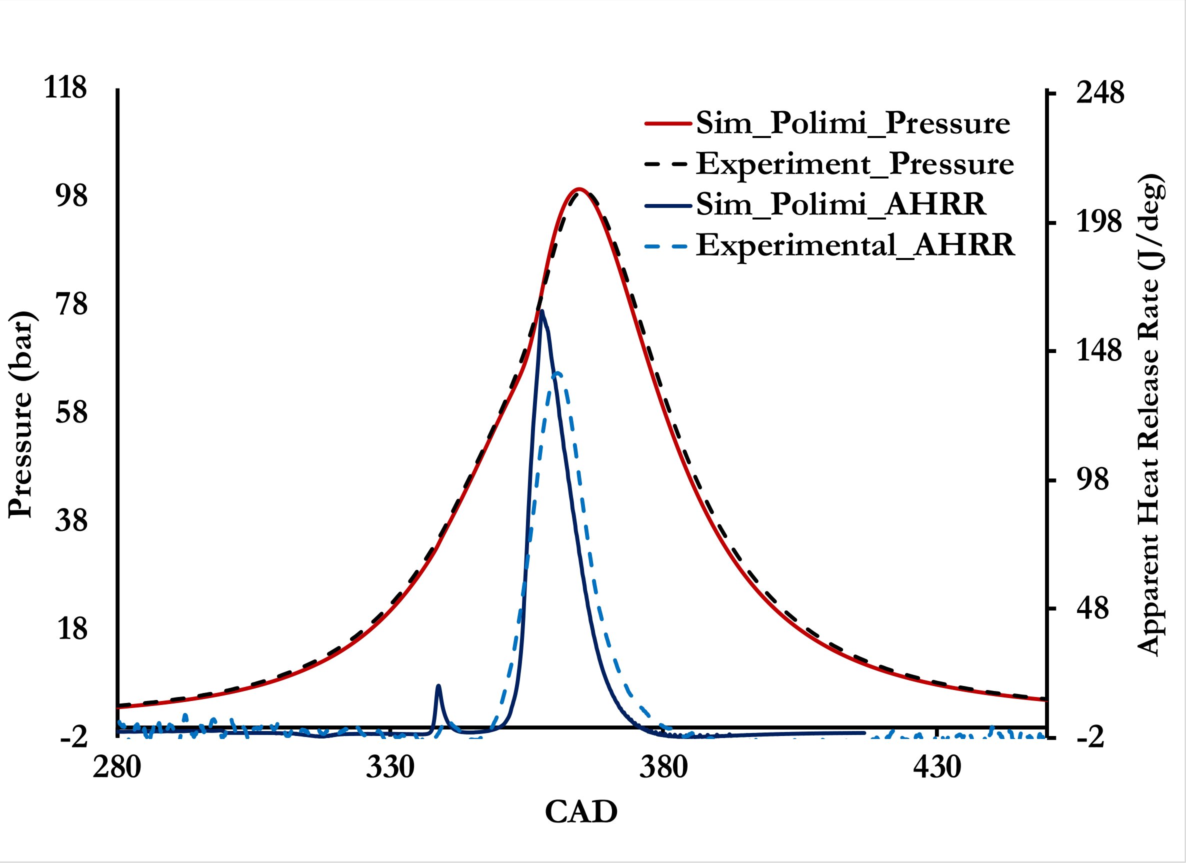




CFD Model Validation

Single Injection (310 CAD) – Ensembled Pressure and AHRR Comparisons – POLIMI Mechanism*

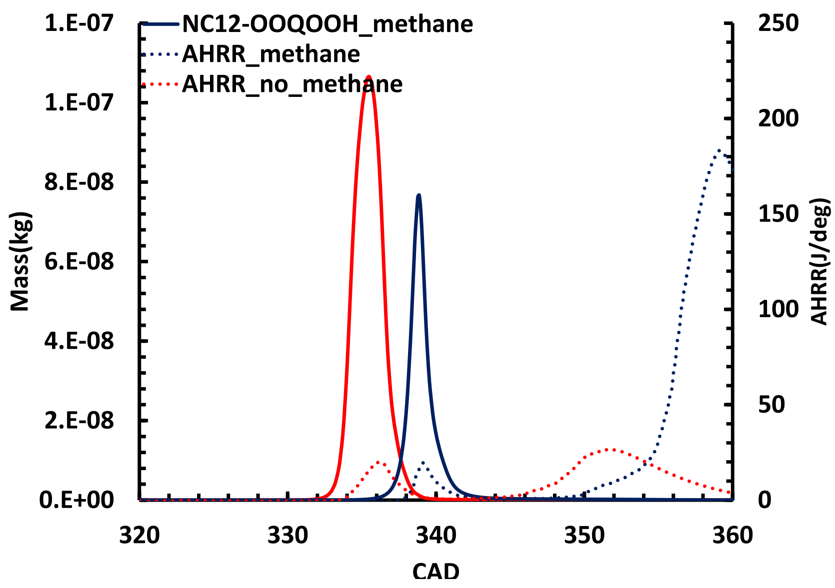
- Low temperature heat release is predicted correctly for dual fuel LTC
- Start of high temperature heat release is also predicted correctly
- Good agreement between experiments and model prediction



*Frassoldati A, D'Errico G, Lucchini T, Stagni A, CuociA, Faravelli T, et al. Reduced kinetic mechanisms of diesel fuel surrogate for engine CFD simulations. *Combust Flame* 2015; 162(10): 3991–4007

Effects of methane on n-dodecane (diesel) autoignition

- Methane delays n-dodecane low temperature chemistry[1]
- Methane also decreases magnitude of low temperature heat release
- Almost all n-dodecane takes part in low temperature heat release
- Initial high temperature heat release comes from n-dodecane followed by methane
- Similar to low temperature heat release, high temperature heat release is also delayed with methane addition



Physical Property Comparison: Diesel#2, DME, PODE

Property	Diesel 2*	DME (OME1)*	PODE (OME1-6)‡
Density (kg/m^3)	830	670	1066
CN	45	55	70
LHV (MJ/kg)	42.7	28.8	19.204
Normal boiling point (deg C)	180-370	-25.1	157 (IBP)
OME1/2/3/4/5/6 (%)	-	100	0.0/0.1/47.8/29.6/16.4/5.4
Oxygen Content (% w/w)	-	35	47

*https://ww3.arb.ca.gov/fuels/multimedia/meetings/dmetierireport_feb2015.pdf
‡Report received with PODE fuel from ASG Analytik-Service, GmbH, Germany

Temperature Evolution & Spray Penetration at SOI=300 CAD for UA SCRE

- <u>Observation:</u> Spray penetration of DME spray under similar conditions is significantly shorter than for Diesel 2 fuel.
- <u>Cause:</u> Likely due to DME's higher volatility.
- <u>Effect:</u> No spray-wall impingement. All of the DME is utilized to ignite CH_4. Clear LTC observed → potential for very low NOx
- <u>Outlook for PODE:</u> PODE shares similar high CN as that of DME, so early injection must be accompanied by EGR or should split fuel quantity into multiple injections to avoid HCCI-like sharp heat release rate peaks

Experimental Results

Outcomes of Experimental Tasks

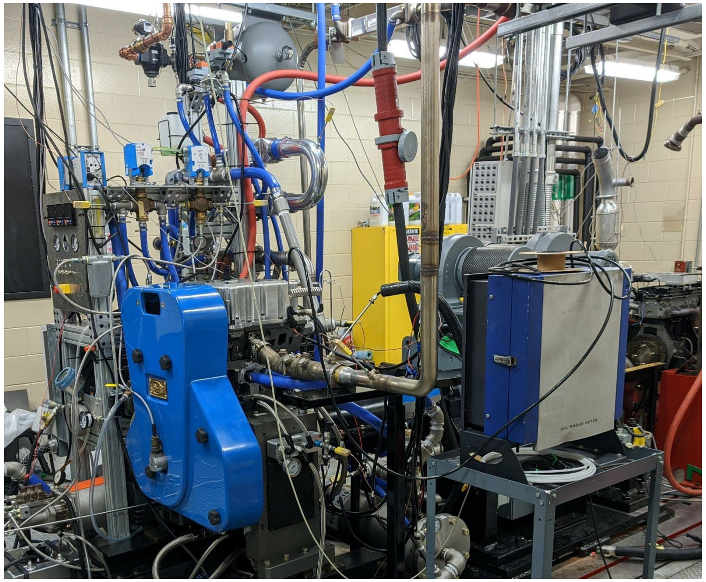
- Conventional dual fuel and dual fuel LTC combustion strategies investigated and compared to baseline diesel operation
- Experiments also helped assess the preliminary impact of the STARS strategy on dual fuel LTC
- ***Achieved engine-out NOx emissions < 0.1 g/kWh and engine-out smoke emissions < 0.1 FSN with dual fuel LTC***
- Specifically, the following results were obtained and discussed:
  - Combustion pressure and AHRR histories at different SOIs
  - Engine-out exhaust emissions, engine stability, and maximum pressure rise rates (MPRR)
  - Tradeoffs observed between engine efficiency, emissions, and combustion stability

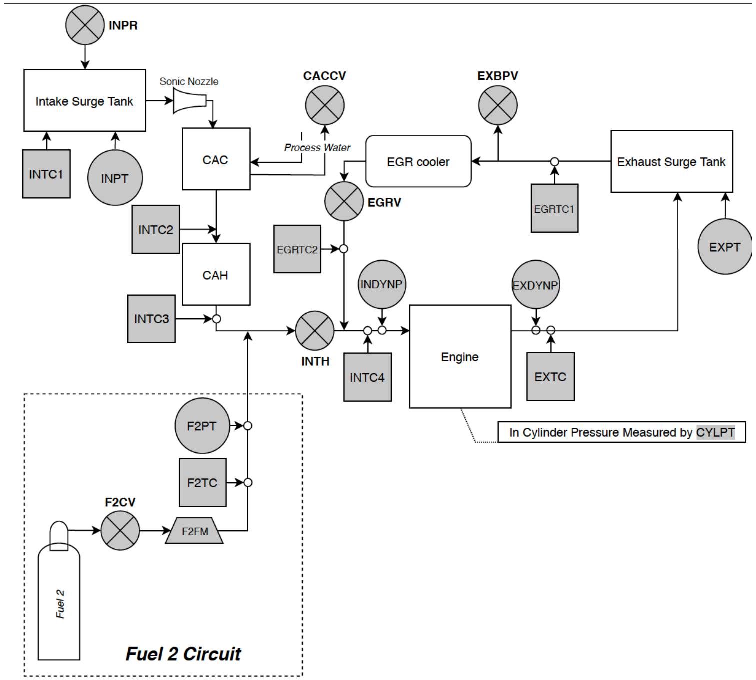
Experimental Accomplishments

Quarter 1	UA SCRE installed and subsystems designed
Quarter 2	Built fuel, coolant, and lubrication subsystems
Quarter 3	All subsystems were completed along with wiring harness for controller
Quarter 4	Successfully motored UA SCRE after ascertaining functionality of DAQ and control
Quarter 5	Baseline dual fuel LTC experiments with STARS were completed on UA SCRE

Experimental Setup

- UA SCRE setup consists of:
  - Air sub-system
  - High cetane (liquid) fuel sub-system
  - Low cetane (gaseous) fuel sub-system
  - Coolant sub-system
  - Lubricant oil sub-system
  - Engine controller
  - Instrumentation, DAQ, and control
- Each sub-system was tested individually before overall system was made functional



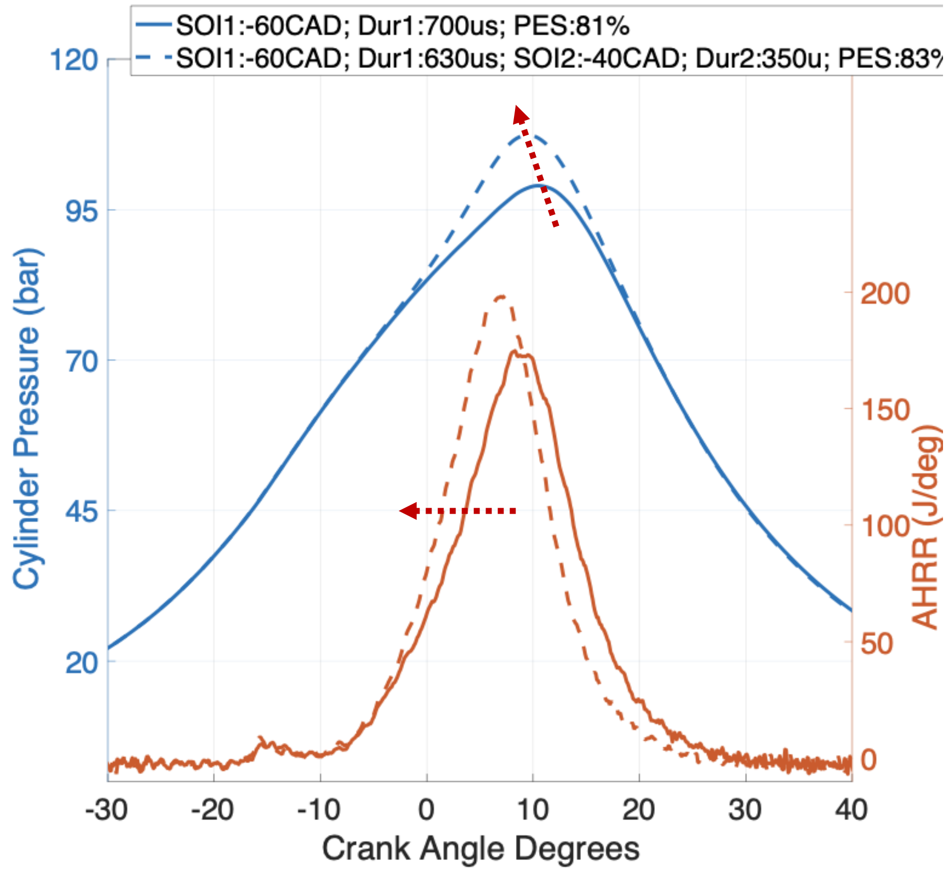


Pertinent Measurement Accuracies

Measured parameter	Unit	Measured Accuracy
Cylinder Pressure	bar	± 0.3% of reading
Diesel Flow Rate (Coriolis Meter)	kg/h	± 0.1% of reading
Methane Flow Rate (Coriolis Meter)	kg/h	± 0.25% of reading
Air Flow Rate	kg/h	± 0.25% of reading
Temperatures	°C	± 2.2°C or 0.75% of reading
Pressures (Intake, Exhaust)	psig	± 0.13% of reading
Pressures (Lubricant, Coolant, Fuels)	psig	± 0.5% of reading
Smoke Number (AVL 415S)	FSN	± 0.4% of reading
THC Emissions	ppm	±1% of the full scale
NOx Emissions	ppm	±2% of the full scale
CO Emissions	ppm	±1% of the full scale
CO_2 Emissions	%	±1% of the full scale
O_2 Emissions	%	±1% of the full scale

Experimental Results – LTC with STARS

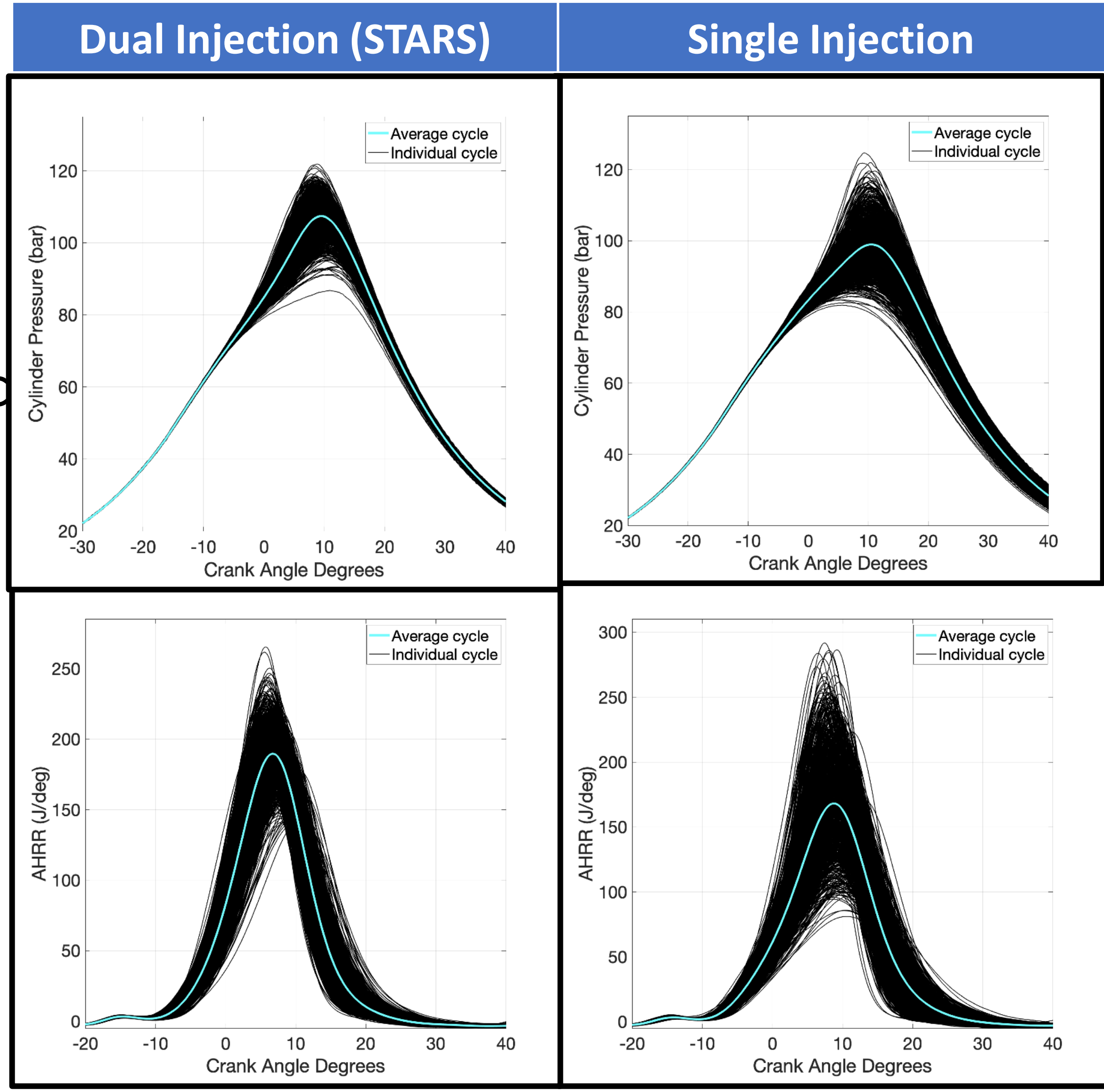
- Comparing single-injection LTC to LTC with STARS (two pilot injections) at 8 bar IMEPg, 1200 rpm, we note:
  - Significantly lower cyclic variability (much lower COV of IMEP)
  - A 2% point increase in IFCE
  - Higher combustion efficiency
  - A slight increase in peak cylinder pressure due to faster AHRR
  - A slight increase in MPRR



Mode	IMEPg	IFCE (%)	MPRR	COV_IMEPn (%)	Comb eff (%)	Ign delay (deg)
LTC	7.8	54.8	2.6	9.8	86.9	58.7
LTC with STARS	7.9	56.3	3.1	3.2	89.6	58.2

Experimental Results – LTC with STARS

- With LTC STARS, when two pilot injections are employed, we get a much more stable combustion process
- But we can still see cyclic variability with STARS (dual injection)
- ***These results are preliminary; there is scope for further optimization***
- With temperature-controlled EGR and VVA, results will be better



Experimental Results – LTC with STARS

- For -60 CAD ATDC SOI, when single pilot injection is compared to preliminary dual injection (STARS) results, we see:
  - A slight decrease in ISNOx emissions
  - Significantly better ISNOx-IFCE tradeoffs
  - Much lower ISCO emissions
  - Engine-out smoke < 0.1 FSN for all SOIs

Mode	ISNOx (g/kwh)	ISHC (g/kwh)	ISCO (g/kwh)	IFCE (%)
LTC	0.13	3.68	43.07	54.8
LTC with STARS	0.07	3.91	30.58	56.3

Summary and Conclusions

- Our approach utilizes multiple strategies (STARS, VVA, PODE, TC-EGR) to achieve high-efficiency dual fuel LTC
- GT-SUITE simulation results provided crucial inputs for the VVA system design and specifications
- CFD simulations predicted combustion evolution, fuel impingement, local UHC and CO sources, and showed opportunities for efficiency optimization in dual fuel LTC
- STARS strategy improved combustion efficiency and IFCE along with minimizing the COV of IMEPg by 67%
- Experimentally achieved engine-out NOx < 0.1 g/kWh and engine-out smoke < 0.1 FSN

Publications (Experimental and Computational) and Students

- List of journal papers published
  - Bartolucci et al. (2021), A Computational Investigation of the Impact of Multiple Injection Strategies on Combustion Efficiency in Diesel–Natural Gas Dual-Fuel Low-Temperature Combustion Engines, ASME J. Energy. Res. Technol.,JERT-20-1374,v 143 (2), Feb. 2021
  - Jha et al., (2019), Impact of methane energy fraction on emissions, performance and cyclic variability in low-load dual fuel combustion at early injection timings, Intl. J. Engine Res. v 122 (5), pp. 1255-1272
- List of conference papers published
  - Bartolucci et al. (2019), A Computational Investigation of the Impact of Multiple Injection Strategies on Combustion Efficiency in Diesel–Natural Gas Dual-Fuel Low-Temperature Combustion Engines, ICEF2019-7197, ASME ICEF2019, Chicago, IL, Oct 20-23
- List of papers submitted/in review
  - PR Jha et al. (2021) – "Impact of Low Reactivity Fuel Type on Low Load Combustion, Emissions and Cyclic Variations of Diesel –Ignited Dual Fuel Combustion" (*in review, Intl. J. Engine Res.*)
  - D. Hariharan et al. (2021) – "Multiple Injection Strategies for Reducing UHC and CO Emissions in Diesel-Methane Dual-Fuel Low Temperature Combustion" (*in review, Fuel*)
  - PR Jha et al. (2021) – "Numerical Investigation of Dual Fuel Combustion at Early Injection Timings" (*under internal review*)
  - KR Partridge et al. (2021) – "An investigation of the change in shape of apparent heat release rates across different injection timings for diesel-methane dual fuel combustion" *(under internal review)*
- Three different papers accepted to the 12th US National Combustion Meeting
- ***1 Ph.D. student graduated in December 2020, 3 current Ph.D. students and 1 postdoc working on this project***

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- Our Ph.D. students who are engaged in completing the experiments and performing the CFD simulations
- Our postdoc, funded internally with UA funds, who has been performing the GT-SUITE simulations and is also working on the experiments

Discussion/Questions?

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Thank You

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