NREL Transforming ENERGY

Natural Gas Vehicle Technology Forum 2020

Downey, California

February 4–5, 2020

The National Renewable Energy Laboratory (NREL) hosted the forum in partnership with the U.S. Department of Energy's Vehicle Technologies Office within the Office of Energy Efficiency and Renewable Energy, the California Energy Commission, South Coast Air Quality Management District, and Agility Fuel Solutions.

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Overview of the Natural Gas R&D Program

2020 Natural Gas Vehicle Technology Forum

Peter Chen
February 4th, 2020
California Energy Commission

Introduction

- In 2004, pursuant to AB 1002, the CPUC established the Natural Gas R&D Program with CEC as the administrator.
- The program has an annual budget of $24M to invest in technologies and strategies that can benefit California’s natural gas IOU ratepayers and support our clean energy policies.
- The program has five primary research areas:
  - Energy Efficiency
  - Renewable Energy and Advanced Generation
  - Natural Gas Infrastructure Safety and Integrity
  - Energy-Related Environmental Research
  - Transportation Research

General Approach

- Identify research gaps for research initiatives through:
  - Discussion with utilities, public stakeholders, state and federal agencies, other CEC programs;
  - Roadmaps;
  - Public meetings with industry and trade associations; and
  - Research ideas submitted by the public
- Research projects are selected through competitive solicitations.
- Energy research priorities are guided by policy directives.
- Investments require clearly identified benefits.

Transportation Research Area

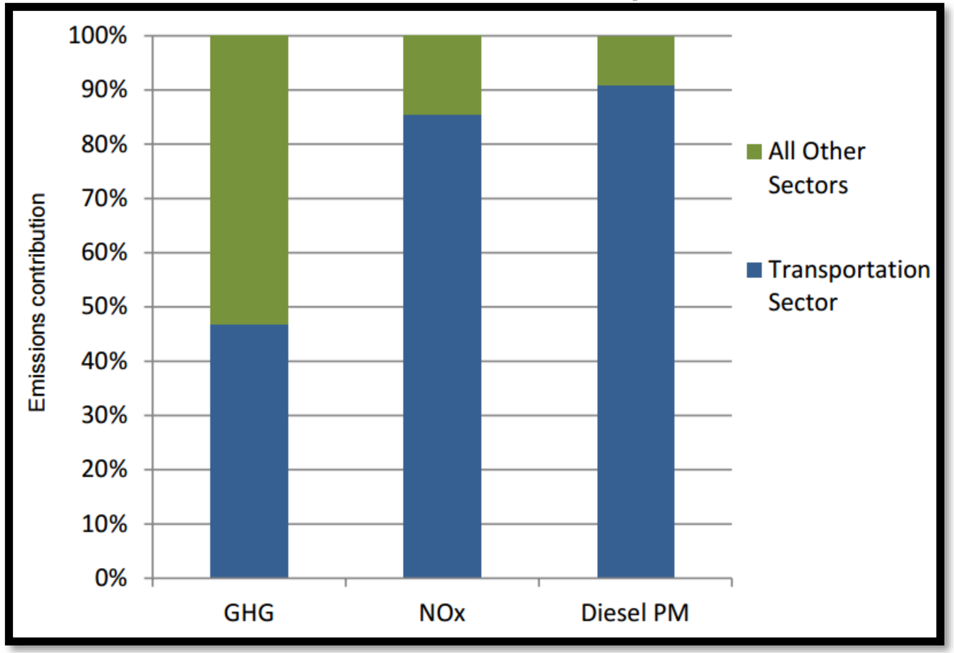
Primary Goals:

- Accelerate the beneficial commercial adoption of near-zero and zero emission gaseous fueled vehicles to improve air quality.
- Improve the energy efficiency and performance of gaseous fueled vehicles to reduce carbon emissions and improve competitiveness with conventional fuel vehicles.
- Increase the use of renewable gas to reduce the GHG emissions of the transportation sector.
- Improve fueling infrastructure technology capabilities to promote the further adoption of low-carbon gaseous fueled vehicles.

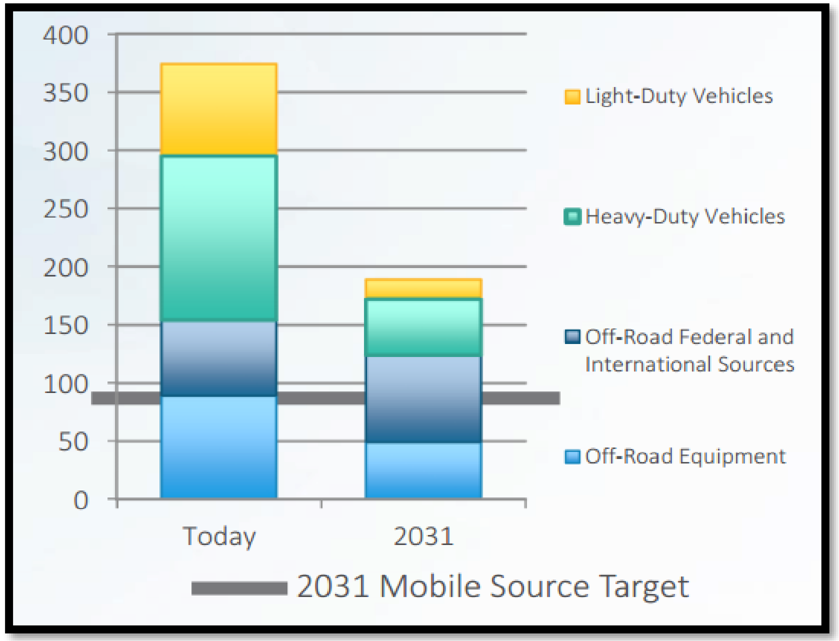
Emissions from California's Transportation Sector

- Heavy-duty trucks and buses emit 20% of GHG emissions from the transportation sector, 28% of statewide NOx emissions, and 23% of statewide PM emissions.
- The South Coast needs an additional ~70% reduction in NOx emissions from heavy-duty vehicles to attain to federal ambient air quality standards by 2031.

Emission Contributions from the Transportation Sector

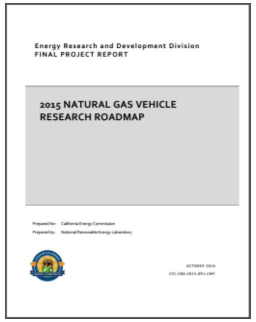


NOx Emission Reductions Needed in the South Coast



NG R&D Program Portfolio Timeline

2016: Published updated Natural Gas Vehicle Research Roadmap


Energy Research and Development Division
FINAL PROJECT REPORT

2015 NATURAL GAS VEHICLE RESEARCH ROADMAP

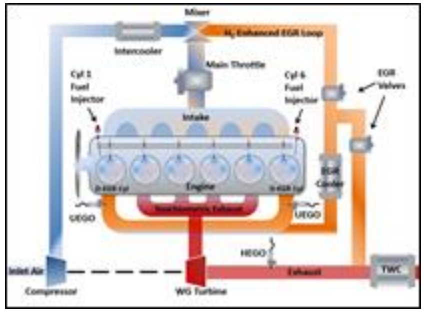
Prepared for: California Energy Commission
Prepared by: National Renewable Energy Laboratory

OCTOBER 2016

2016: In-use emissions assessment

2017: Off-road vehicle integration for yard hostlers and agricultural vehicles

2017: NG engine efficiency research with advanced ignition and D-EGR



2018: NG-hybrid electric truck optimization and demonstration

2019: NGV Research Consortium with NREL, DOE, SCAQMD

2016: ISL G Near Zero certified to 0.02 g/bhp-hr NOx (transit bus, refuse truck, <66,000 lbs truck)

2018: ISX12N certified to 0.02 g/bhp-hr NOx (heavy-duty truck)

2018: B6.7N certified to 0.10 g/bhp-hr NOx (school bus, shuttle bus, MD truck)

Natural Gas Vehicle Research Consortium

- Funded a consortium of projects with ~$18M, including co-funding from DOE Vehicle Technologies Office and SCAQMD.
- CEC is contributing $3.7M across 4 projects that include:
  - High efficiency heavy-duty engine development
  - Advanced ignition
  - Hybridization
  - Enabling cost effective CNG full fills

Expansion to Include Fuel Cell Technologies

- California gas utilities are interested in hydrogen as a pathway for decarbonizing the natural gas system.
- The transportation sector is an important early market for renewable hydrogen due to existing policies like LCFS.
- CEC is planning to pursue research in integrating and demonstrating hydrogen fuel cells for rail, marine, and heavy-duty vehicle applications.
- Moving forward, the CEC will continue pursuing various technologies that can help meet California's decarbonization goals.

Overview of the Natural Gas R&D Program

Questions or comments?

Peter Chen
February 4th, 2020
California Energy Commission

Evaluation of NGV Fuel System and Fuel Container Integrity Requirements

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Natural Gas Vehicle Technology Forum
Tuesday, February 4th
10:40-11:40 am
SoCalGas Energy Resource Center, Downey, CA

Agenda

- Introduction
- Project Background
- Project Objective
  - Scope
  - Key Deliverables
- Interactive Discussion
  - Literature Review Comparison
  - Stakeholder Feedback Comparison
- Next Steps

Introduction

Lou Browning

- Principal Engineering Consultant @ ICF
- D. Eng, Mechanical Engineering, Stanford University
- Worked on implementing Alternative Fuel Vehicles for over 40 years
- Consulted with California Energy Commission and NREL on alternative fuels for over 20 years

ICF is supporting NREL on the evaluation of NGV fuel system and fuel container integrity requirements

Project Background

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"
  - CNG vehicle focused:
    - "Passenger cars, multipurpose passenger vehicles, trucks, and buses up to 10,000 lbs GVWR"
    - "School buses regardless of weight that use CNG as a motor fuel"
- FMVSS 304 "Compressed Natural Gas Fuel Container Integrity"
  - 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
- **Both Standards are compliance standards not design standards but tend to focus on light-duty vehicles**

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 vehicles.

Project Objective

- **NHTSA is considering fuel system integrity requirements for medium-duty and heavy-duty CNG & LNG vehicles to update FMVSS No. 303.**
- **NHTSA is also considering updates to FMVSS No. 304 to address safety issues and to better reflect current best practices and existing standards for high pressure fuel tanks in motor vehicles.**

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

Project Objective

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.

***Not new-design and manufacture**

CNG Fuel System Integrity

Standards and References

- **CNG Fuel System Integrity**
  - FMVSS No. 303
  - Canadian Motor Vehicle Safety Regulations (CMVSS): Test Method 301.2 CNG Fuel System Integrity
  - National Fire Protection Association (NFPA) 52: Vehicular Natural Gas Fuel Systems Code
  - SAE J2343: Recommended Practice for LNG Medium and Heavy-Duty Powered Vehicles
  - SAE J2406: Recommended Practices for CNG Powered Medium and Heavy-Duty Trucks
  - Railroad Commission of Texas (RRC): Regulations for CNG and LNG

Today's Federal Standard

- No. 303 – CNG Fuel System Integrity
  - Labeling:
    - "Service pressure ________________ kPa (______ psig)."
    - "See instructions on fuel container for inspection and service life."
  - Pressure drop from barrier crashes over 60 minutes after motion stops shall not exceed 154 psi (1062 kPa) at the high pressure portion of the fuel system or 895 (T/V_{FS})

Labeling
Key Commonalities and Gaps

- **NFPA 52 and RRC**
  - Identification as a CNG/LNG-fueled vehicle
  - CNG: Service pressure; LNG: MAWP
  - Installer/converter's name or company and contact information
    - *NFPA 52 only*: System designed and installed in conformance with NFPA 52-XXXX (code edition year)
- **SAE J2343**
  - LNG Symbol (Blue and White Diamond)
  - Design code, service pressure, serial number, gross capacity in water liters (gallons), date of manufacture (MM/YY)
  - Name of company
  - "This container meets or exceeds the drop test requirements of SAE J2343 in effect on the date of manufacture."

Fuel System Testing
Key Commonalities and Gaps

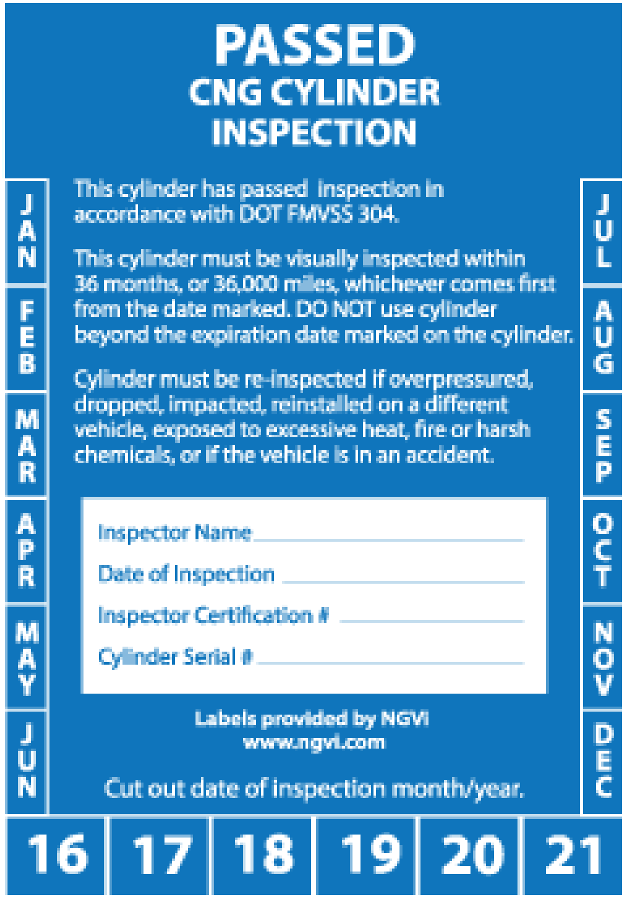
- **NFPA 52 requires bubble testing of connections**
  - No bubbles in 3 minutes
- **SAE J2343 requires cryogenic piping to be protected against blockage between valve sections by relief valve**
- **NPFA 52 and SAE J2406 require qualified personnel to service vehicles**
- **FMVSS 303 requires Nitrogen to be used for testing while other codes allow other inert gases to be used**

Vehicle Inspections

- **NGVAmerica provides guidance for inspections**
  - Various fleets have defined their own inspection protocol
- **Inspections include**
  - Cursory visual inspections (pre- and post-trip)
  - General visual inspections (during routine maintenance)
  - Detailed visual inspections (once a year by qualified CNG fuel system inspector) – FMCSA label issued

FMCSA Inspection Label

Other Inspection Labels



CNG Fuel System Integrity: Recommendations

- All CNG and LNG vehicles should be covered
- Clear and standardized labeling should be used
- Standardized inspections should be specified

CNG Fuel Container Integrity

Standards and References

- **CNG Fuel Container Integrity**
  - FMVSS No. 304
  - CSA Group/ANSI NGV 2: Compressed natural gas vehicle fuel containers
  - International Organization for Standardization (ISO) 11119-3: Gas cylinders - Refillable composite gas cylinders and tubes
  - National Fire Protection Association (NFPA) 52: Vehicular Natural Gas Fuel Systems Code
  - UN GTR 13: Global Technical Regulation concerning the hydrogen and fuel cell vehicles
  - CSA/ANSI PRD 1: Pressure Relief Devices For Natural Gas Vehicle (NGV) Fuel Container
  - CGA S-1.3: Pressure Relief Device Standards-Part 3-Stationary Storage Containers for Compressed Gases
  - SAE J2343: Recommended Practice for LNG Medium and Heavy-Duty Powered Vehicles
  - SAE J2406: Recommended Practices for CNG Powered Medium and Heavy-Duty Trucks

Today’s Federal Standard

- **No. 304 – CNG Fuel Container Integrity**
  - Barrier crashes:
    - Frontal
    - Rear moving
    - Lateral moving
    - Moving contoured

Today's Federal Standard

- **No. 304 – CNG Fuel Container Integrity**
  - Does not include (Part of NGV2)
    - Chemical exposure testing
    - Impact testing
    - Drop testing
    - Accelerated stress rupture testing
    - Leak testing
    - Permeation testing
    - Penetration testing
    - Extreme temperature cycling tests
    - Composite flaw tolerance tests
    - Natural gas cycling tests
    - Non destructive vibration testing

These tests are considered part of design and manufacturing testing by manufacturer. DOT label assumes compliance with those tests. If visual inspection determines problems, the tank is sent back to the manufacturer for retesting.

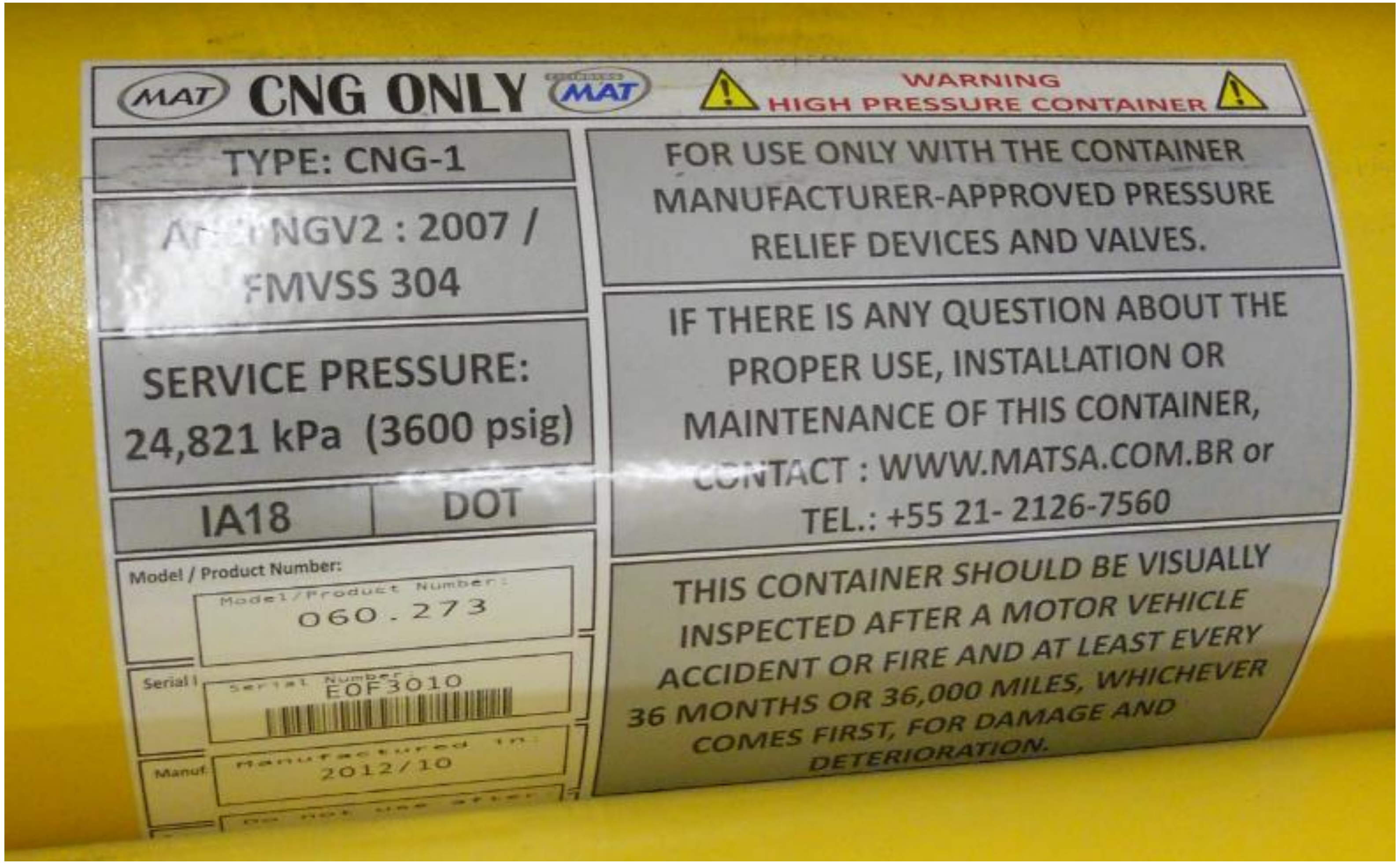
Today's Federal Standard

- No. 304 – CNG Fuel Container Integrity
  - Labeling:
    - "If there is a question about the proper use, installation, or maintenance of this container, contact___________," inserting the CNG fuel container manufacturer's name, address, and telephone number.
    - "Manufactured in ______," inserting the month and year of manufacture of the CNG fuel container.
    - "Service pressure ______ kPa, (______ psig)."
    - The symbol DOT, constituting a certification by the CNG container manufacturer that the container complies with all requirements of this standard.
    - The container designation (e.g., Type 1, 2, 3, 4)
    - "CNG Only."
    - "This container should be visually inspected after a motor vehicle accident or fire and at least every 36 months or 36,000 miles, whichever comes first, for damage and deterioration."
    - "Do Not Use After ______," inserting the month and year that mark the end of the manufacturer's recommended service life for the container.

DOT Label

NGV2-07
DOT
Type 4 Container
CNG ONLY
Part Number: 112206 — 001
Serial Number: C13042741DB170
Manufactured: 2013/04
DO NOT USE AFTER: 2033/04
Service Pressure: 24,821 kPa (3,600 psi)
@ 21°C (70°F)
QUANTUM
Printed in USA
This container should be visually inspected after a motor vehicle accident or fire and at least every 36 months or 36,000 miles, whichever comes first, for damage and deterioration.
If there is a question about the proper use, installation, or maintenance of this container, contact:
Quantum Technologies Inc.
25242 Arctic Ocean Dr.
Lake Forest, CA 92630 USA
949-399-4500
For more information go to:
WWW.QTWW.COM/QUALITY
QUANTUM
TECHNOLOGIES
FIRE
For use only with the container manufacturer's approved pressure relief devices and valves.
113446
QUANTUM
DANGER
Installation of a valve and or Pressure Relief Device (PRD) not approved for use in this cylinder can result in a cylinder rupture. Contact Quantum regarding the valves and PRD's approved for use in your cylinder.
Failure to follow these instructions will result in death or serious injury.
WARNING
Cylinder must be purged prior to use or after any cylinder service.
Installation of this cylinder must be performed by competent personnel in accordance with all Federal, State and Local regulations applicable to the application.
Refer to the Cylinder Installation and Maintenance Guide applicable to your cylinder for additional information. The manual is available at www.QTWW.COM/QUALITY.
This cylinder must only be used for storing the media defined by the cylinder certification label. Use of this cylinder for storing media other than what is defined on the cylinder certification label or exceeding the cylinder rated pressure, may damage the cylinder. Contact Quantum Technologies regarding questions about the proper installation or use of this cylinder.
A damaged cylinder must not be installed. Inspect the cylinder for shipping or handling damage before installation.
Failure to follow these instructions may result in death or serious injury.
Printed in U.S.A.

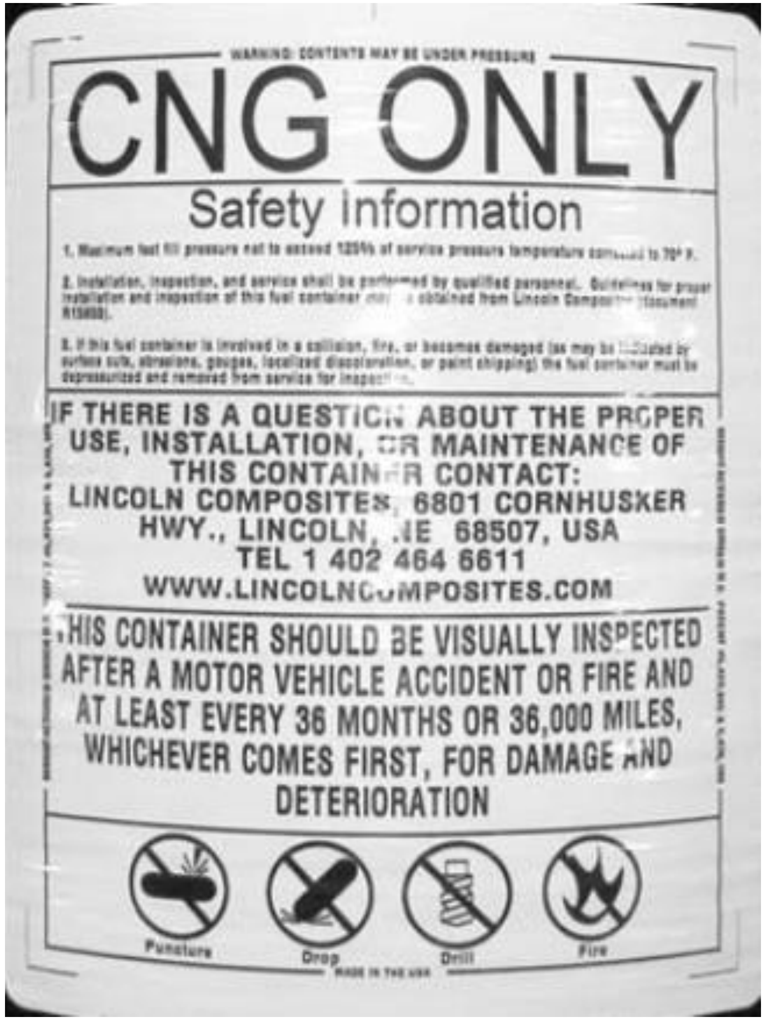
DOT Label



MAT
CNG ONLY
MAT
WARNING
HIGH PRESSURE CONTAINER
TYPE: CNG-1
NGV2 : 2007 /
FMVSS 304
SERVICE PRESSURE:
24,821 kPa (3600 psig)
IA18
DOT
Model / Product Number:
060.273
EOF3010
2012/10
FOR USE ONLY WITH THE CONTAINER MANUFACTURER-APPROVED PRESSURE RELIEF DEVICES AND VALVES.
IF THERE IS ANY QUESTION ABOUT THE PROPER USE, INSTALLATION OR MAINTENANCE OF THIS CONTAINER, CONTACT : WWW.MATSA.COM.BR or TEL.: +55 21- 2126-7560
THIS CONTAINER SHOULD BE VISUALLY INSPECTED AFTER A MOTOR VEHICLE ACCIDENT OR FIRE AND AT LEAST EVERY 36 MONTHS OR 36,000 MILES, WHICHEVER COMES FIRST, FOR DAMAGE AND DETERIORATION.

DOT Label

EL6020
BigIron AUCTIONS
LINCOLN COMPOSITES
A Member of Hexagon Composites Group
CNG ONLY
DO NOT USE AFTER 06-2030
SN 1264-029 MODEL No. RH36A21-06011
SERVICE PRESSURE
24800 kPa (3600 psig) / 21°C (70°F)
TUFFSHELL
ANSI NGV2 – 2007
DOT TYPE 4
US
MANUFACTURED IN 06-2010
FOR USE ONLY WITH THE CONTAINER MANUFACTURER'S APPROVED PRESSURE RELIEF DEVICE AND VALVES.



CNG ONLY
Safety Information
IF THERE IS A QUESTION ABOUT THE PROPER USE, INSTALLATION, OR MAINTENANCE OF THIS CONTAINER CONTACT:
LINCOLN COMPOSITES, 6801 CORNHUSKER HWY., LINCOLN, NE 68507, USA
TEL 1 402 464 6611
WWW.LINCOLNCOMPOSITES.COM
THIS CONTAINER SHOULD BE VISUALLY INSPECTED AFTER A MOTOR VEHICLE ACCIDENT OR FIRE AND AT LEAST EVERY 36 MONTHS OR 36,000 MILES, WHICHEVER COMES FIRST, FOR DAMAGE AND DETERIORATION
Puncture
Drop
Drill
Fire

Today's Federal Standard

- No. 304 – CNG Fuel Container Integrity
  - Burst pressure:
    - Type 1 non-welded containers, Type 2-4: 2.25 x service pressure
    - Type 1 welded containers: 3.5 x service pressure
  - Hydrostatic pressure:
    - Testing of 13,000 cycles from service pressure to <10% of service pressure at ambient temperature
    - Then 5,000 cycles from 125% of the service pressure to <10% of service pressure at ambient temperature

Burst Pressure:
Key Commonalities and Gaps

- **NGV2**
  - Three containers shall be pressurized to failure
  - Pressurization rate not exceed 1400 kPa/s (200 psi/s) at pressures above 80% of calculated burst pressure
  - For Type 1-4 containers: Minimum burst pressure must exceed 125% of service pressure
  - For Type 2 containers: Minimum burst pressure must not be less than 2.25 x the service pressure
- **ISO 11119-3**
  - The burst pressure must exceed the minimum design burst pressure specified by the cylinder manufacturer.
  - Different burst pressure requirements depending on fiber reinforcement
  - For cylinders without liners manufactured from two parts joined together, the burst shall not result in failure at the joint below a pressure 1.2 x the burst pressure for the appropriate fiber.

Hydrostatic Pressure
Key Commonalities and Gaps

- **NGV2**
  - Varied between ≤10% of service pressure and 125% of service pressure for a total of 3000 cycles.
  - The maximum pressurization rate shall be 27.5 bar (400 psi) per s.
  - After pressure cycling, containers shall be pressurized to 125% of service pressure and held at that pressure for a minimum of 24 h and until the elapsed exposure time (pressure cycling and pressure hold) to the environmental fluids equals 48 h.
- **ISO 11119-3**
  - Pressure in the cylinder be increased gradually and regularly until the test pressure is reached.
  - The cylinder test pressure shall be held for at least 30 s with the cylinder isolated from the pressure source, during which time there shall be no decrease in the recorded pressure or evidence of any leakage.
  - Adequate safety precautions shall be taken during the test.
  - If leakage occurs in the piping or fittings, the cylinders shall be re-tested after repairing such leakages.
  - The limit deviation on attaining test pressure shall be test pressure +3 % / -0 or +10 bar whichever is the lower. Pressure gauges with the appropriate accuracy shall be used.
  - All internal surfaces of cylinders shall be dried (to ensure no free water) immediately after testing.

CNG Fuel Container Integrity Testing

Test	FMVSS No. 304	CSA/ANSI NGV 2	ISO 11119-3	UN GTR
Burst pressure	X	X	X	X
Hydrostatic pressure	X	X	X	X
Chemical exposure		X		X
Impact		X		X
Drop		X	X	X
Accelerated stress rupture		X	X	
Leak		X	X	
Permeation		X	X	
Penetration		X		
Extreme temperature cycling		X		X
Composite flaw tolerance		X		
Natural gas cycling		X		
Non destructive		X		

CNG Fuel Container Integrity: Recommendations

- **Labeling:**
  - No further updates or changes to FMVSS label requirements
  - HDVs should be inspected once a year instead of every 36,000 miles
- **Burst Ratio:**
  - Concerns that FMVSS doesn’t define the requirement per tank material/type and doesn’t address the concern of stress rupture.
  - Recommendation: **NGV 2**

CNG Fuel Container Integrity: Recommendations

- **Cycling Test:**
  - NGV2 seems to be more representative of real-world applications and conditions
- **Container Inspections:**
  - Proposed standard for container inspection intervals for heavy-duty vehicles does not provide guidance on what is entailed in the inspection
  - Standardization of inspections
- **Leak Testing:**
  - NGV2, NFPA and CSA B109 are all harmonized – recommend the same
  - Leak test w/bubble solution criteria listed as zero leak rate is not possible due to permeation, based on multiple studies of the bubble requirements

Fuel Container Integrity
Fire Test

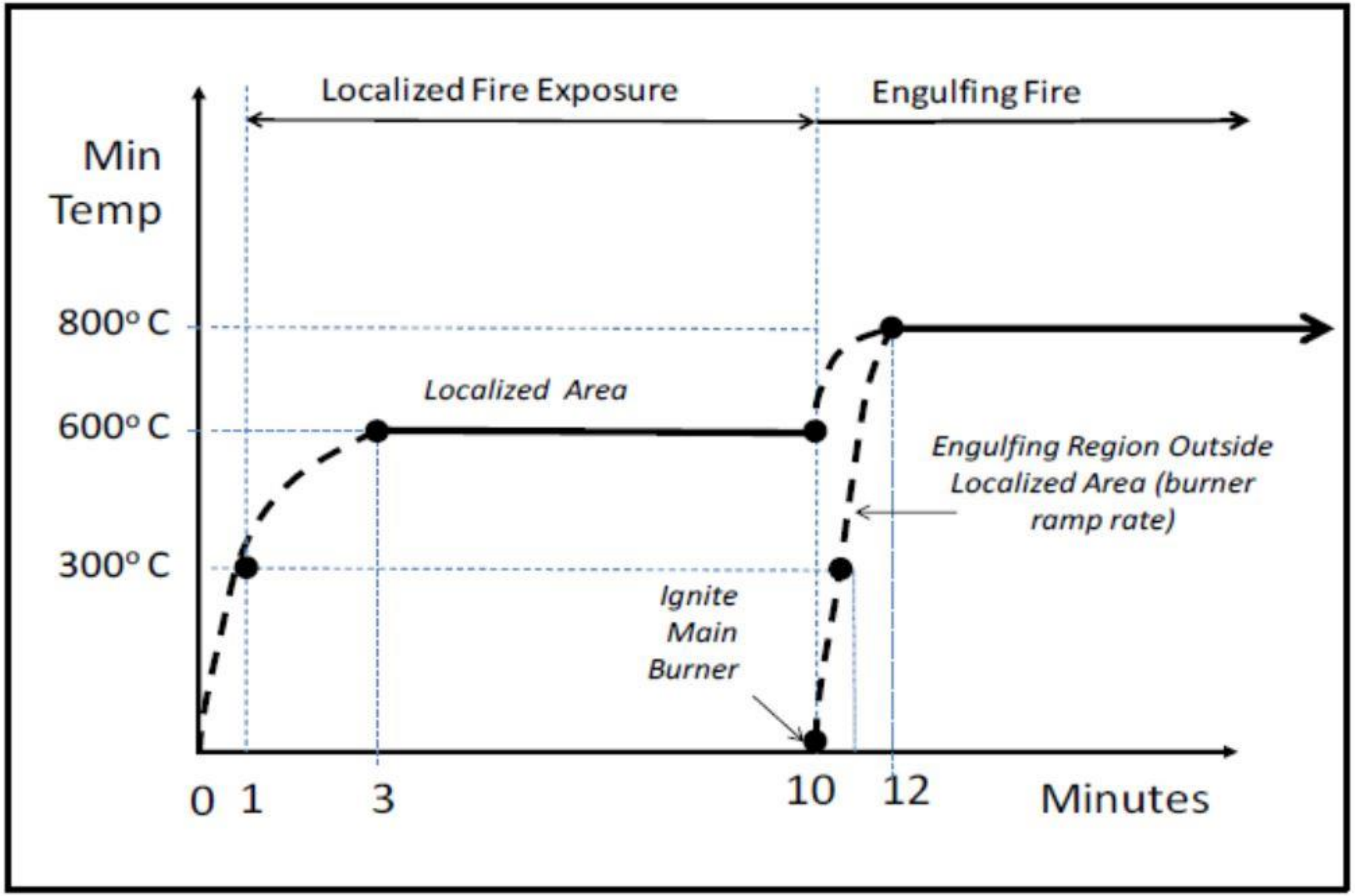
Standards and References

- **CNG Fuel Container Integrity Fire Test**
  - FMVSS No. 304
  - CSA Group/ANSI NGV 2: Compressed natural gas vehicle fuel containers
  - National Fire Protection Association (NFPA) 52: Vehicular Natural Gas Fuel Systems Code
  - SAE J2343: Recommended Practice for LNG Medium and Heavy-Duty Powered Vehicles

Today’s Federal Standard

- **CNG Fuel Container Integrity Fire Test**
  - Each fuel container shall be equipped with a PRD
  - When subject to the bonfire test, each CNG fuel container shall completely vent its contents or it shall not burst while retaining its contents
  - Fire Source: 1.65 meter long uniform fire source with an average temperature of 800 deg F.
  - Location of fire source: Locate further away from PRDs
  - Duration of fire exposure: 20 minutes or until pressure relief device releases
  - Shielding to prevent the flame directly contacting the PRD, valves, and fitting
  - Wind velocity of not more than 5 mph.

Temperature Profile of Localized & Engulfing Fire Test



CNG Fuel Container Integrity Fire Test: Recommendations

- Industry hasn’t seen a PRD system operate to save system from localized fire
- Most HD systems are mostly enclosed
  - Most test facilities are considering getting out of the bonfire testing because they wouldn’t be able to control temps and remain consistent
  - Don’t want to define tests that can’t be performed/repeated
- 20 mins of fire doesn’t seem sufficient based on industry feedback to firefighters to not put the fire out until all of the gas has been emitted without rupture

Next Steps

- ICF will send feedback to NREL
- NREL will summarize the discussion
- Post summary to NGVTF website
- Share summary with NHTSA
- Follow-up on open questions

Final Questions

Lou Browning
Office: 831-662-3683
Email: louis.browning@icf.com

Appendix - CNG Fuel System Integrity Comparison

	FMVSS No. 303	CMVSS 301.2
Applies to:	CNG GVWR≤10k lbs. & School buses	All CNG vehicle types
Front:	30 mph	N/A
Rear:	30 mph	30 mph
Lateral:	20 mph	20 mph
Moving contoured:	40 mph	40 mph
Max spillage allowed:	1062 kPa (154 psi) or 895 (T/V_{FS}) 60-min period	20640 kPa or maximum operating pressure
Test agent:	Nitrogen	Nitrogen

Appendix - CNG Fuel Container Integrity

Test	NGV2
Chemical exposure	Each marked area is to be exposed to one of five solutions. 1) sulfuric acid — 19% solution by volume in water; 2) sodium hydroxide — 25% solution by weight in water; 3) methanol/gasoline — 5/95% concentration of M5 fuel meeting the requirements of ASTM D4814; 4) ammonium nitrate — 28% by weight in water; and 5) e) windshield washer fluid — 50% by volume solution of methyl alcohol Cylinder should cycled between ≤10% of service pressure and 125% of service pressure for a total of 3000 cycles.
Impact	Cylinder shall be impacted by steel pyramid at an impact of not less than 30 nM (22.1 ft-lbs)
Drop	Types 2,3,4 dropped from greater than 1.83 m (72 in) vertically on each end
Accelerated stress rupture	Types 2,3,4 hydrostatically pressured to 125% of service pressure and held for 1000 hrs then tested as above in hydrostatic pressure testing
Leak	Types 1,2 varied between ≤10% of service pressure and 125% of service pressure not to exceed 10 cycles per minute until they leak or exceed 2250 times the service life
Permeation	Type 4 only with boss torqued 2x installation torque and pressurized with NG to service pressure. Cylinder placed in enclosed sealed container and monitored for 500 hrs to measure permeation rate
Penetration	Pressurized to service pressure with NG or N2 and penetrated by armor piercing bullet of at least 0.3 in. Must pass through at least one side of the container. Container should not rupture.
Extreme temperature cycling	Cylinder at over 85°C (185°F) cycled between ≤10% of service pressure and 125% of service pressure for 4000 cycles then cooled to below -40°C (-40°F) and cycled between ≤10% of service pressure and 80% of service pressure for 4000 cycles.
Composite flaw tolerance	Type 2,3,4 with two flaws cut into sidewall cycled between ≤10% of service pressure and 125% of service pressure for 3000 cycles
Natural gas cycling	Type 4 cycled with NG between 10% of service pressure and service pressure holding 2 hrs at each pressure. Two more cycles holding 72 hrs at high pressure and 4 hrs at low pressure. Repeat 750 times.
Non destructive	Subject to vibration and mechanical shock testing

Appendix - Fuel Container Fire Test

	FMVSS No. 304	NGV 2: 2019
Test conditions:	Fill fuel container and test at 100% service pressure and 25% service pressure	N/A
Container positioning:	Center of the container is over the center of the fire source	N/A
Height:	Approximately 100 mm (4 in) above the fire source	Approximately 100 mm (4 in) above the fire source
Fire source:	Use a uniform fire source that is 1.65 meters long (65 in)	1.65 m (65 in) length shall provide direct flame impingement on the container surface across its entire diameter
Thermocouples	• Place three thermocouples that are suspended 25 mm (1 in) below the bottom of the CNG fuel container • Equally space over the length of the fire source or length of the container, whichever is shorter	N/A
Location of fire source:	Locate further away from PRDs	The localized fire exposure area shall be located on the test article furthest from the PRD(s)
External temperature	Five minutes after the fire is ignited, maintain an average flame temperature of not less than 430 degrees C (800 degrees F)	N/A
Data recording:	Record time, temperature, and pressure readings at 30 second intervals, beginning when the fire is ignited and continuing until the pressure release device releases	N/A

NGV Consortium Program Status Update

Margo Melendez
February 4, 2020

Program Overview

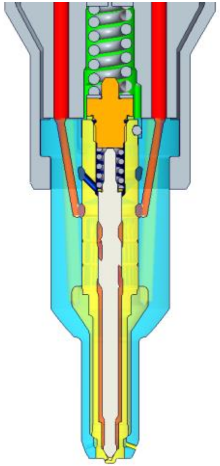
- Eight projects
- $36M total investment
  - $17M in agency funding
    - DOE – $12M
    - CEC - $3.7M
    - SCAQMD - $1.5M
  - $14M in matched funding
- 30-36 month projects, kicking off in 2019/2020

Partner Participation by Award

Offeror	DOE	CEC	AQMD
Alabama			
Buffalo			
Cummins			
GTI – Fuel			
Michigan Tech			
SwRI			
Transient Plasma			
US Hybrid			

Projects include engine development, vehicle demonstration, hybridization, smart fueling, combustion research and emissions control research

Michigan Tech University & University of Alabama



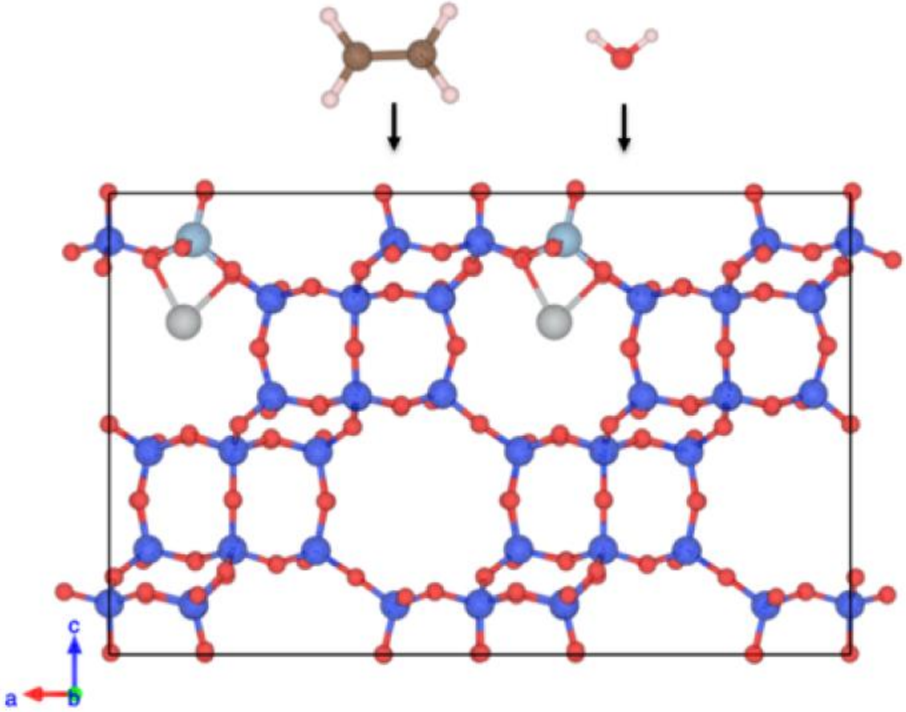
Compression ignition of Natural gas – with and without pilot fuel

- DME pilot fuel being examined
- Injector designs, valve control, test engines/equipment

University of Buffalo

Developing Zeolite-based catalyst for low temp methane oxidation

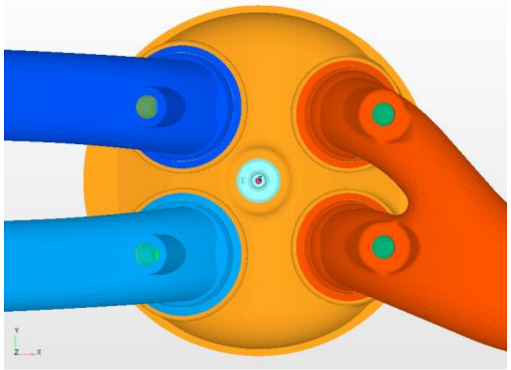
- Exploring different formulations (Na, K, Ca) to stabilize against low-temp catalyst deactivation – at molecular level

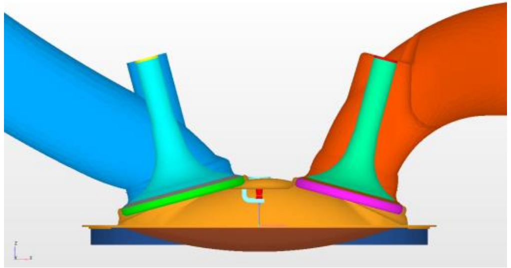


Cummins, Inc.

Developing a natural gas specific combustion engine

- Evaluating in-cylinder charge motion/cooled EGR
- Significant re-design of air handling system





Transient Plasma Systems

Developing a plasma ignition system for NG combustion

- Ignition modules designed and built
  - Miniaturizing components
  - Thermal management
- Developing strategy for measure of real-time combustion

GTI Fuel

Development of a smart vehicle and dispenser, an advanced full fill algorithm and cost-effective gas pre-cooling

- Developing simulations
- Thermal management strategies
- Free piston expander/compressor design

US Hybrid

Developing and demonstrating a fully integrated and optimized natural gas, plug-in hybrid class 8 vehicle for port drayage. Includes a GPS-based predictive geofencing hybrid control architectures to ensure zero emission operation at the port

- Powertrain specifications complete
- Simulation work complete
- Procuring components

Southwest Research Institute

Developing and demonstrating a hybrid medium-duty truck using advanced natural gas spark-ignited engine.

- Pent-roof cylinder head version
- Elevated levels of EGR dilution

Multi-Laboratory Natural Gas Research

Brad Zigler

Natural Gas Vehicle Technology Forum

5 February 2020

Fundamental Advancements in Pre-Chamber Spark Ignition and Emissions Control for Natural Gas Engines

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Fundamental Advancements in Pre-Chamber Spark Ignition and Emissions Control for Natural Gas Engines

Argonne NATIONAL LABORATORY — Doug Longman

NREL NATIONAL RENEWABLE ENERGY LABORATORY — Brad Zigler

OAK RIDGE National Laboratory — Scott Curran

Sandia National Laboratories — Mark Musculus

Relevance

- DOE Vehicle Technologies Office (VTO) has **specific input regarding natural gas (NG) engine research needs** for efficiency and emissions
  - Annual Natural Gas Vehicle Technology Forum
  - Natural Gas Vehicle Research Workshop (July 2017), which fed VTO's funding opportunity announcement (FOA) and the Lab Call that resulted in this multi-lab project

- **Key high-level NG engine research needs:**
  - Research needed to address ***barriers for achieving diesel like efficiency*** for NG engines
  - Ignition technology to enable ultra-lean operation (***pre-chamber***, volumetric ignition)
  - Fundamentals for improving NG combustion efficiency (***physics, thermodynamics and chemistry***)
  - ***Low temperature combustion*** (LTC) concepts conceivable for NG engines, ensure real-world mode switching and emissions control compatibility
  - Advances in computational fluid dynamics ***(CFD) and modeling for NG engines***
  - Avoiding knock and ***abnormal combustion*** (i.e. low speed pre-ignition)
  - Fundamental catalysis research for methane conversion is needed due to ***challenge of methane activation***
  - Research needed for both stoichiometric and ***lean engine (LTC and conventional) emission control***

Relevance

This project focuses on early stage research focusing on pre-chamber spark-ignition (PCSI) to achieve diesel-like efficiency in medium duty (MD) and heavy duty (HD) NG gas engines by extending the lean dilution limit and/or exhaust gas recirculation (EGR) dilution limit, as well as shortening burn duration, with integrated aftertreatment

Impact:

This project integrates experimental and simulation-based tasks to address four key barriers to market penetration of PCSI for MD/HD NG engines:

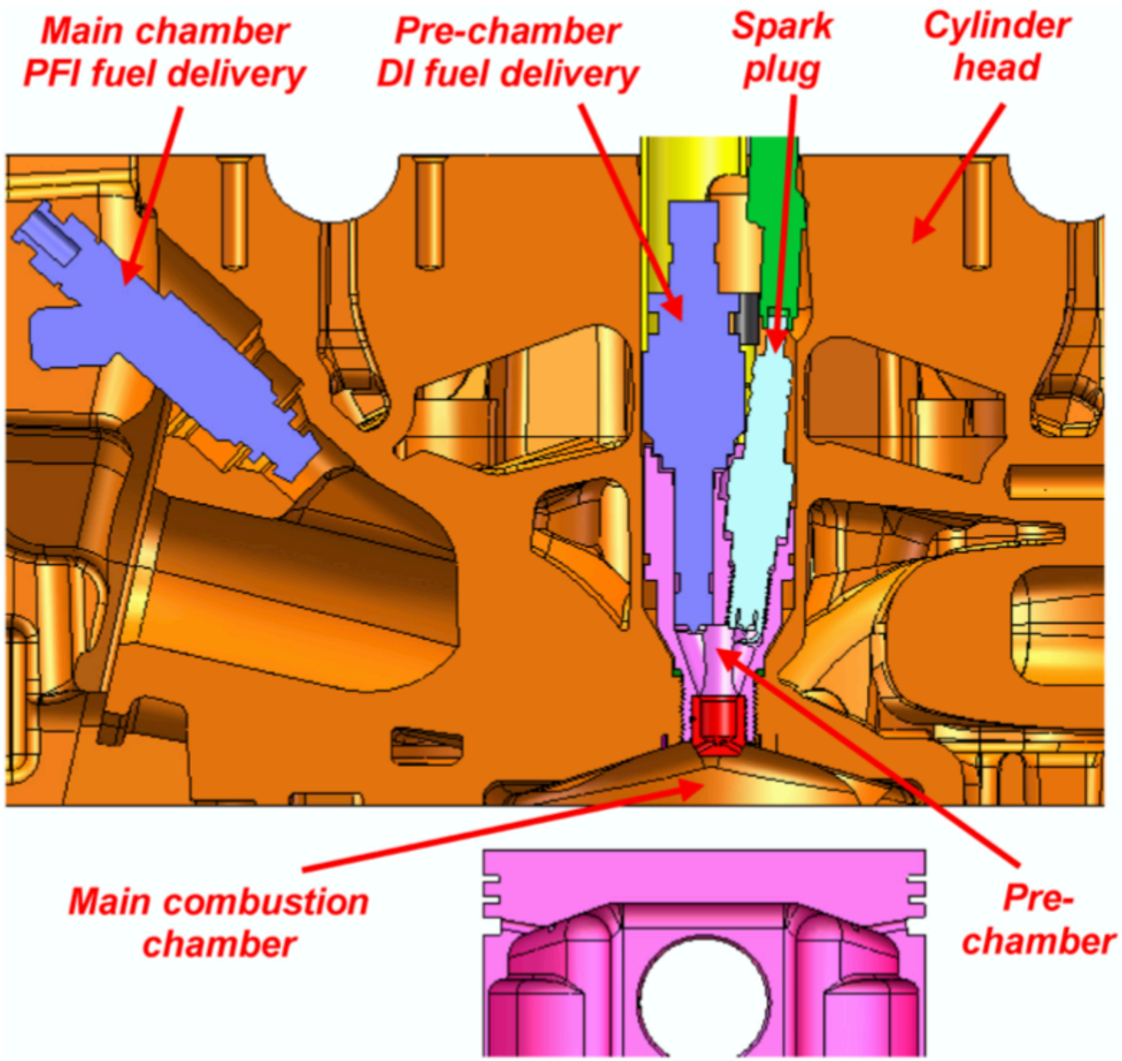
Barrier 1 – ***Inadequate science base and simulation tools to describe/predict the fluid-mechanical and chemical-kinetic processes governing PCSI*** to enable engineers in industry to optimize designs for efficiency, noise, reliability, pollutant formation, emissions control integration, and drivability

Barrier 2 – Limited ability to ***extend EGR and/or lean dilution limits*** at higher loads

Barrier 3 – Increased propensity for PCSI ***hot-spot pre-ignition*** at high loads relative to spark ignition

Barrier 4 – ***Ineffective methane catalysts*** for the high engine-out unburned fuel concentrations coupled with low exhaust temperatures (<<400 °C) of high efficiency engines

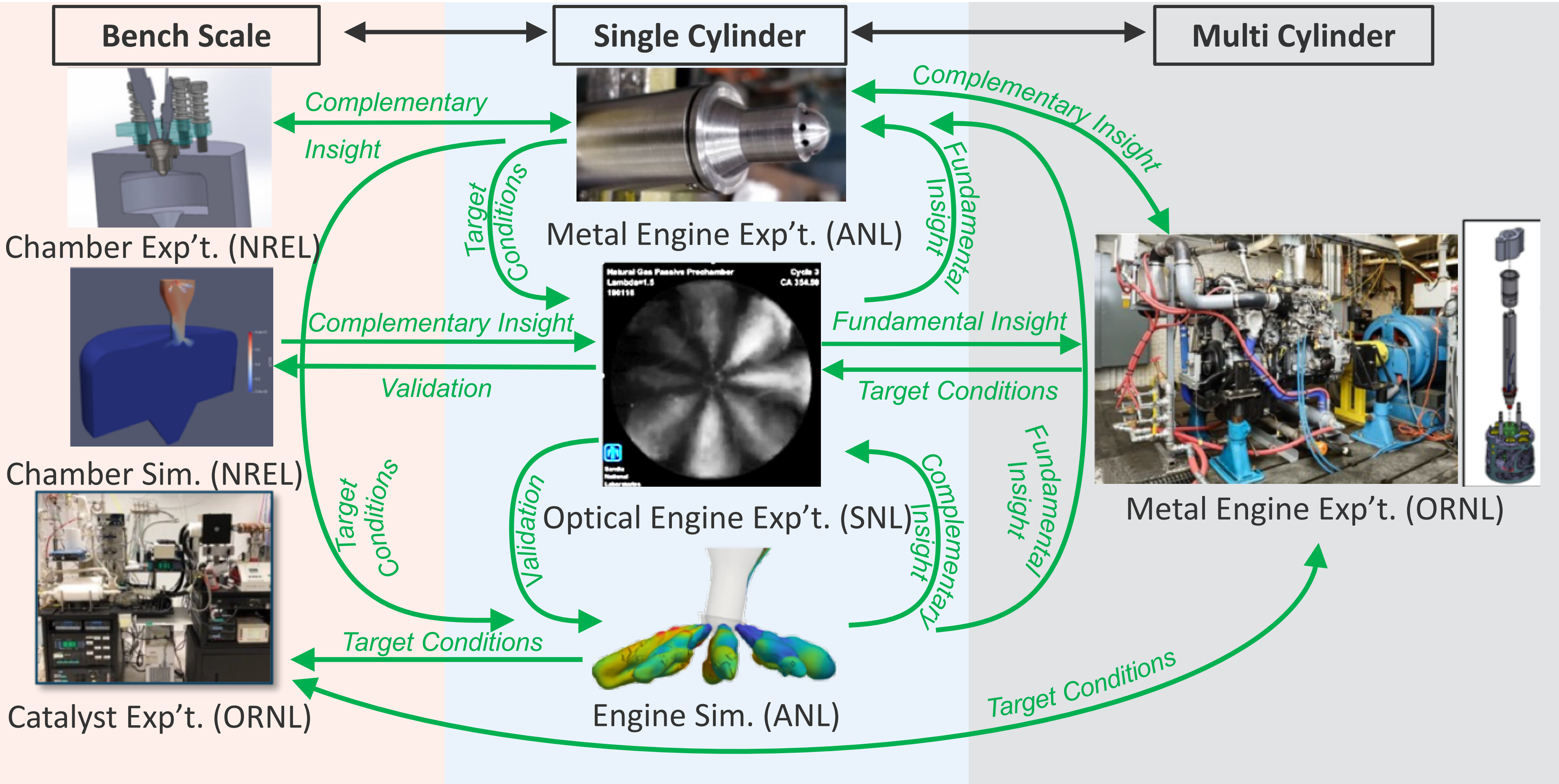
Pre-Chamber Spark Ignition



Attard, W. and Blaxill, H., "A Gasoline Fueled Pre-Chamber Jet Ignition Combustion System at Unthrottled Conditions," SAE Int. J. Engines 5(2):315-329, 2012, https://doi.org/10.4271/2012-01-0386.

Approach

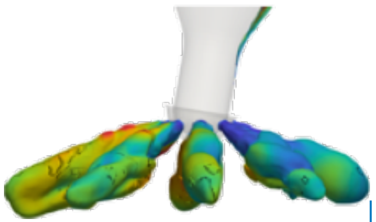
Collaboration and integration across four national labs connect fundamental experiments and modeling to practical hardware

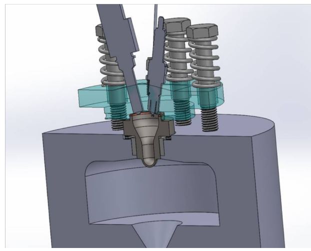


DOE laboratory expertise and capabilities focus on early-stage research to address key barriers for NATURAL GAS engines

Approach

Modular PCSI designs with as much commonality as possible are used across all platforms





Simulation

Engine Sim. (ANL)
High fidelity CFD focusing on PCSI output mixing, with ignition and flame propagation models.

Chamber Sim. (NREL)
Zero dimensional (0D) and CFD map PCSI composition output to explore main chamber ignition sensitivity.

Bench Scale ↔ Single Cylinder ↔ Multi Cylinder

Bench Scale

Chamber Exp't. (NREL)
PCSI added to constant volume chamber to study pre-chamber variable effects on main chamber ignition over lean / dilute conditions.

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Collaboration and Coordination

- **ANL / NREL / ORNL / SNL** collaboration
  - Integrated team of leading experts
  - Hold semi-monthly research coordination and data exchange meetings

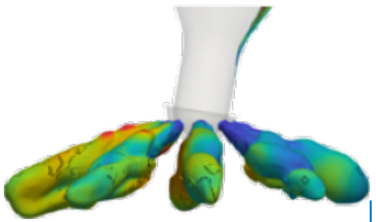
- ANL
  - Doug Longman (PI)
  - Riccardo Scarcelli
  - Sibendu Som
  - Ashish Shah
  - Joohan Kim
  - Munidhar Biruduganti
  - Prasanna Chinnathambi
- ORNL
  - Scott Curran (PI)
  - Josh Pihl
  - Jim Szybist
  - Melanie DeBusk
  - Sreshtha Sinha Majumdar
  - Chloe Lerin
- NREL
  - Brad Zigler (PI)
  - Matt Ratcliff
  - Mohammad Rahimi
  - Shashank Yellapantula
  - Whitney Collins
  - Jon Luecke
  - Ray Grout
- SNL
  - Mark Musculus (PI)
  - Zheming Li (post-doc)
  - Rajavasanth Rajasegar (post-doc)
  - Yoichi Niki (visiting scientist)
  - Dalton Carpenter (2018 intern)
  - José Maria Garcia Oliver (visiting scientist)

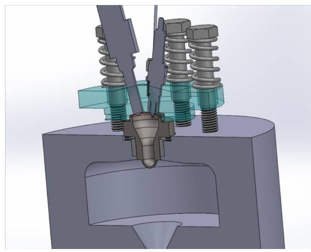
Collaboration and Coordination

- **Altronic**
  - Supplied NGI-1000 flexible natural gas engine spark ignition system to all four DOE labs to support experiments
- **ASG Analytik-Service Gesellschaft mbH**
  - Integrated revised controls and data acquisition for PCSI module in NREL's Advanced Fuel Ignition Delay Analyzer (AFIDA)
- **MAHLE**
  - Collaborated with ORNL to integrate MAHLE Turbulent Jet Ignition (TJI) PCSI system for DD13 multi-cylinder engine experiments
- **Daimler Trucks North America (Detroit Diesel)**
  - Collaborated with ORNL to provide details for modification and support for DD13 for multi-cylinder engine experiments

Approach

Modular PCSI designs with as much commonality as possible are used across all platforms





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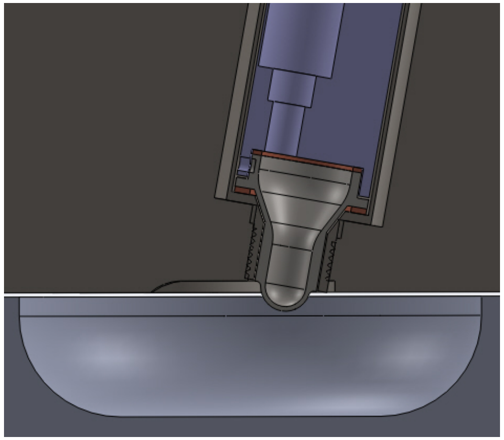
EXPERIMENTAL FACILITY AT ARGONNE (1/2)

Engine Test Facility

- Single Cylinder Engine setup (Hyundai based)
- Port fuel injected gaseous fuel
- Compression ratio variation possible (two-part piston)
- AVL VisioScope possible with cylinder head modification
- Altronics CD-200 spark ignition system
- Full exhaust emission analysis capability
- Possibility of using NG or pure gaseous fuels
- In-house modular pre-chamber design
  - M8 spark plug
  - Auxiliary fueling using check valve
  - Pressure measurement capability

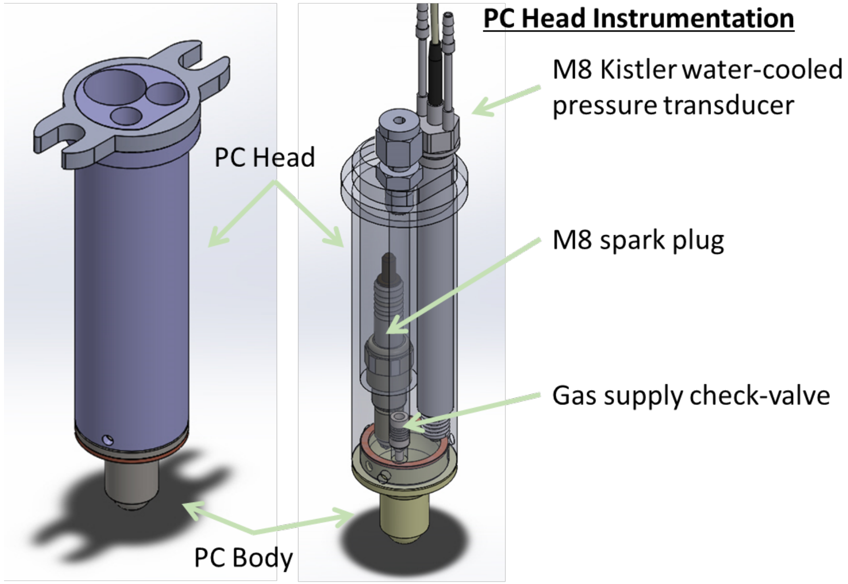
Bore [mm]	130
Stroke [mm]	140
Compression ratio	11:1
Valve timing IVO IVC EVO EVC	 10 bTDC 50 aBDC 50 bBDC 14 aTDC

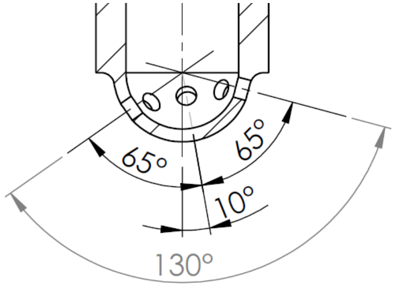


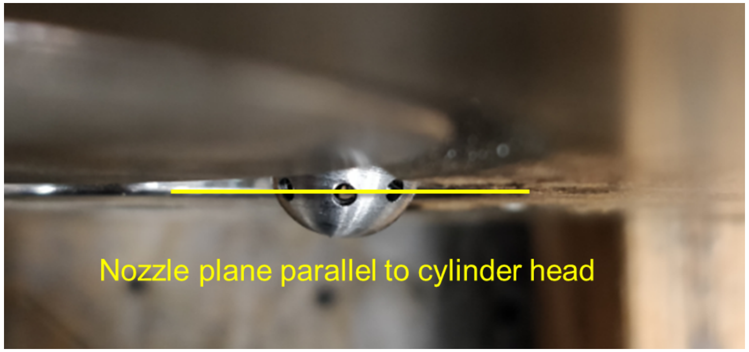
EXPERIMENTAL FACILITY AT ARGONNE (2/2)

Pre-chamber Igniter with unfueled and fueling capability

- In-house, modular pre-chamber design for flexibility needed for fundamental studies
- Relatively simple to change PC volume, nozzle geometry, number, and orientation
- Close collaboration with SNL and NREL to achieve "common PC design"

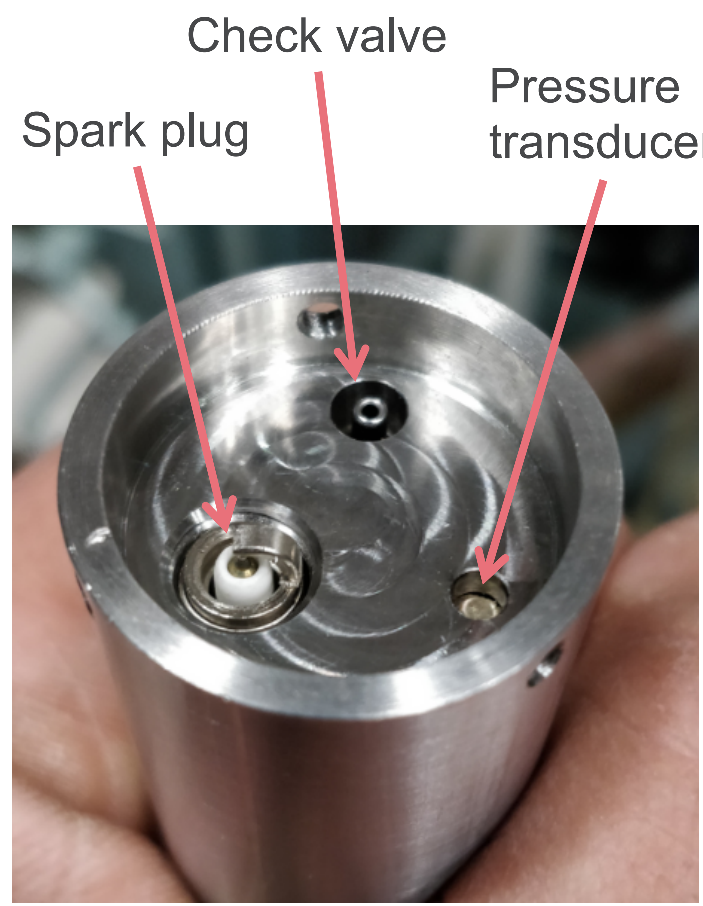






PRE-CHAMBER IGNITER DESIGN

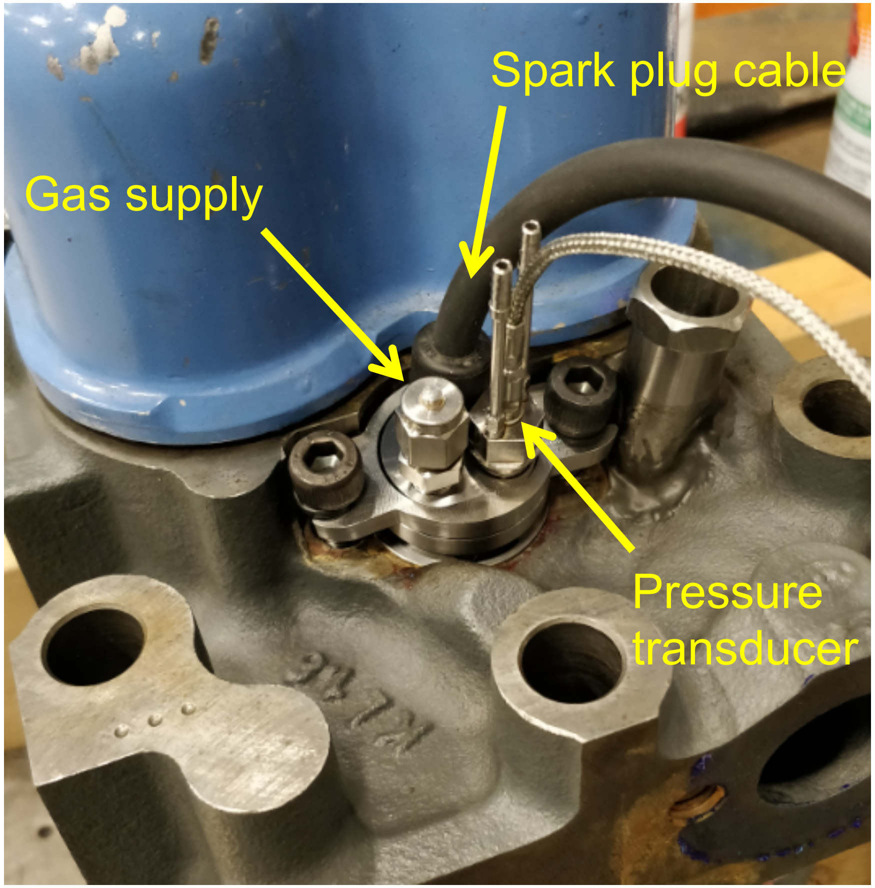
Version 1, completed in October 2018



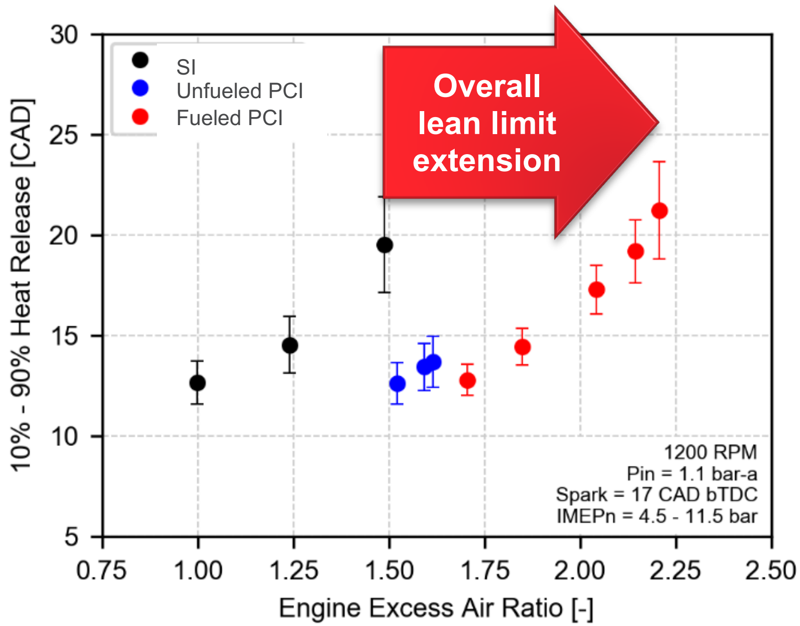
PRE-CHAMBER IGNITER DESIGN

Version 1, completed in October 2018

Engine installation



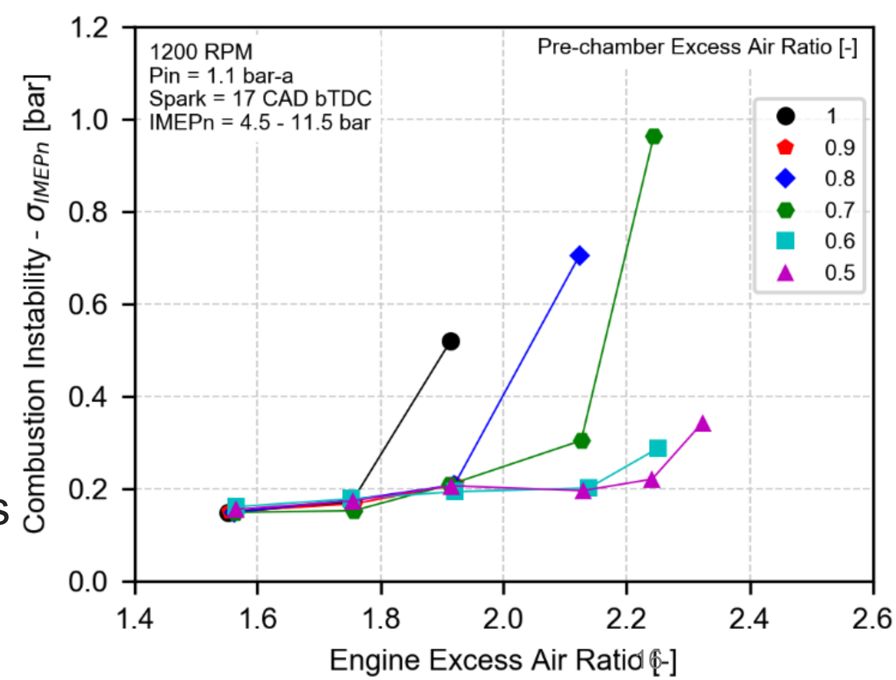
ACCOMPLISHMENTS: LEAN LIMIT EXTENSION (ANL)



ANL single-cylinder engine test results

- Unfueled PC extends lean limit to λ = 1.6 (same combustion duration/stability of SI)
- Fueled PC significantly extends the lean flammability limit and enables stable combustion at λ > 2.2 by leveraging fuel-rich mixture inside PC

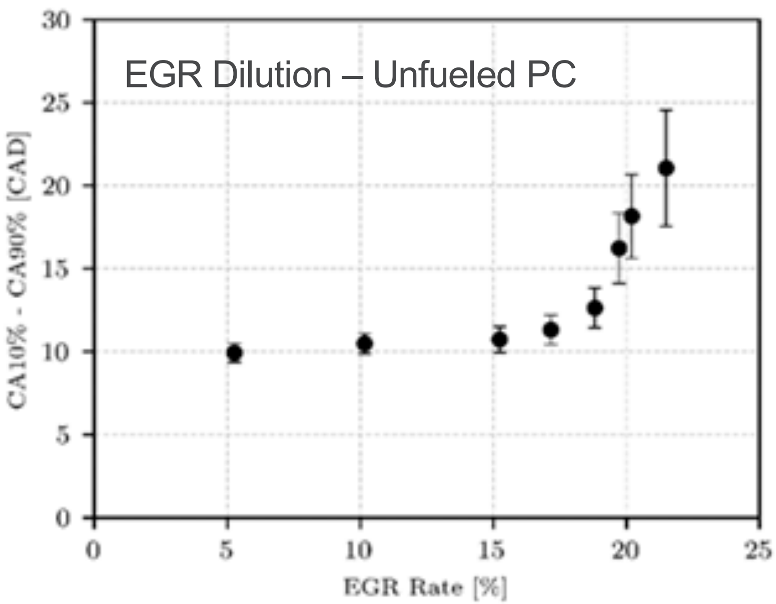
- Lean limit extension beyond λ ~ 1.8 requires fuel-rich mixture inside the pre-chamber
- No influence of mixture strength in the pre-chamber within flammability limits
- Data suggests that fuel-rich pre-chamber produces chemically active jets that readily react with a leaner charge

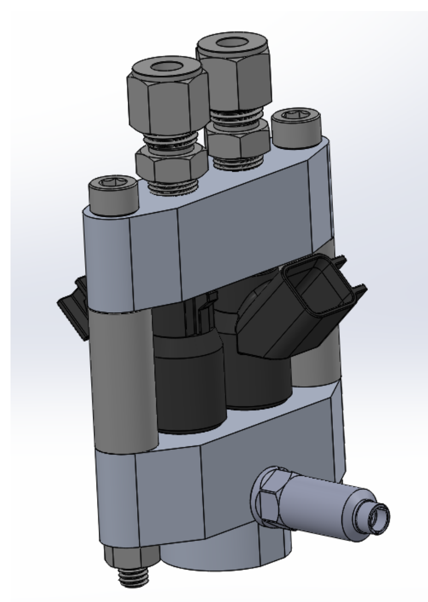


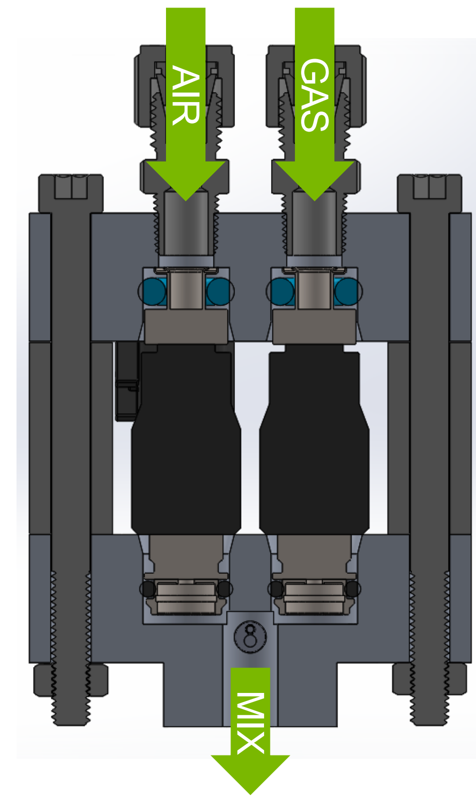
DILUTE COMBUSTION STUDIES

PC charged with fuel-only, air-only and fuel-air mixture

PC charging strategies for EGR dilution
- Unfueled (~ 22%)
- Fueled – Fuel only (< 22%)
- Fueled – Air only (~ 24%)
- Fueled – Air+Fuel Injection (tests currently underway)







Approach

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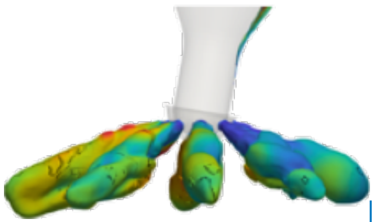

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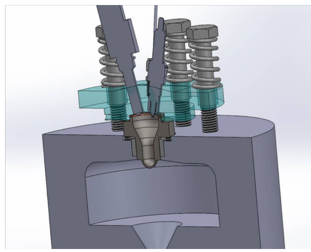

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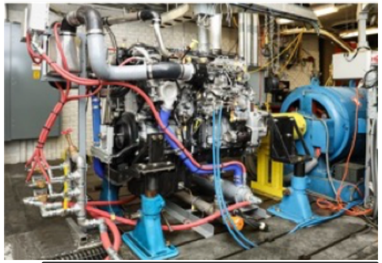

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AVAILABLE MODELS FOR PCSI ENGINE COMBUSTION

From literature:

Model	Application	Type	Group
RANS Multi-zone well-stirred reactor	rapid compression machine	passive	MSU [1]
RANS G-equation	gas engine	↑	ETH [2]
RANS ECFM-3Z	HPDI gas engine	active	LEC GmbH [3]
LES Flamelet Generated Manifold	constant-volume vessel	passive	ETH [4]
LES Multi-zone well-stirred reactor	rapid compression machine	↑	MSU [5]
LES Dynamic Thickened Flame Model	gas engine	active	CERFACS [6]

[1] Gentz et al., SAE 2015. [2] Xu et al., IJER 2018. [3] Kammel et al., SAE 2019. [4] Bolla, GasON EU H2020. [5] Gholamisheeri et al., CNF 2017. [6] Malé et al. FTC 2019.

Our Objectives

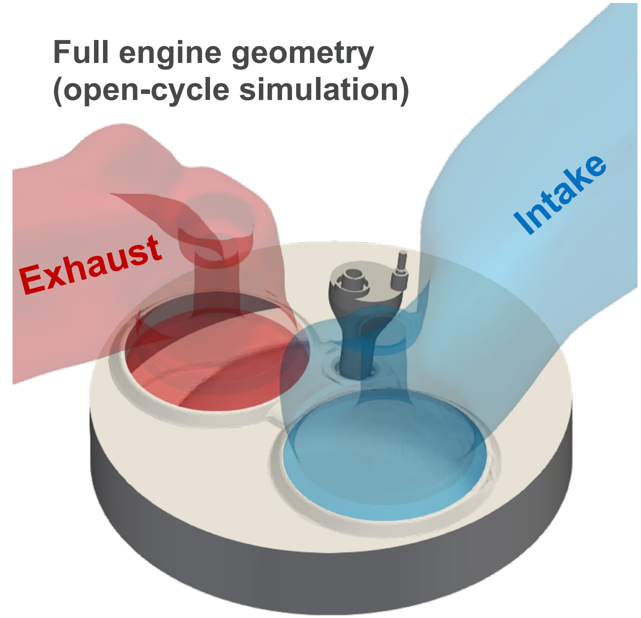
Question 1. What combustion models adopted in the engine modeling community are suitable to simulate pre-chamber ignition/combustion in a MD/HD NG engine?

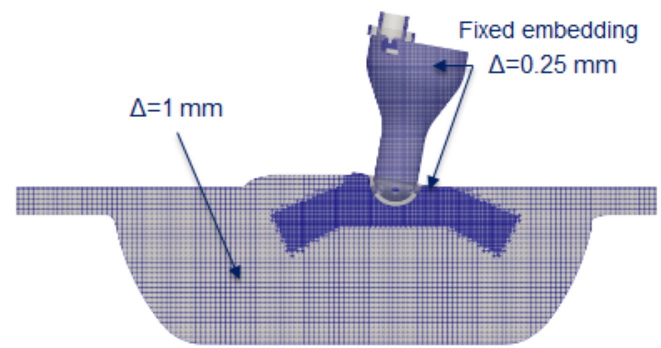
Question 2. How do the numerical predictions change depending on the specific engine operation (fueled vs. unfueled PC, stoichiometric vs. lean/EGR dilute)?

- **GOAL 1. Make assessment with CONVERGE CFD tool (most used by industry)**
- **GOAL 2. Identify model shortcomings and evaluate future improvements**

NUMERICAL SETUP

CFD Code	CONVERGE v2.4		
Turbulence	**RANS** RNG k-ε		
Ignition	Source Deposition (WSR/GEQN) or ISSIM model (ECFM)		
Combustion	**MZ-WSR**	**G-equation**	**ECFM**
	GRI-Mech 3.0	Burned region: Chemical equilibrium Laminar flame speed: tabulated database Turbulent flame speed: Peters' correlation	Burned region: Chemical equilibrium Laminar flame speed: tabulated database **ECFM discarded after preliminary analysis on closed-cycle simulations**
Grid size	main-chamber	1 mm	
	pre-chamber	0.25 mm	
	turbulent jet region		
	spark region	0.125 mm	
AMR	Vel/Temp	0.5 mm	

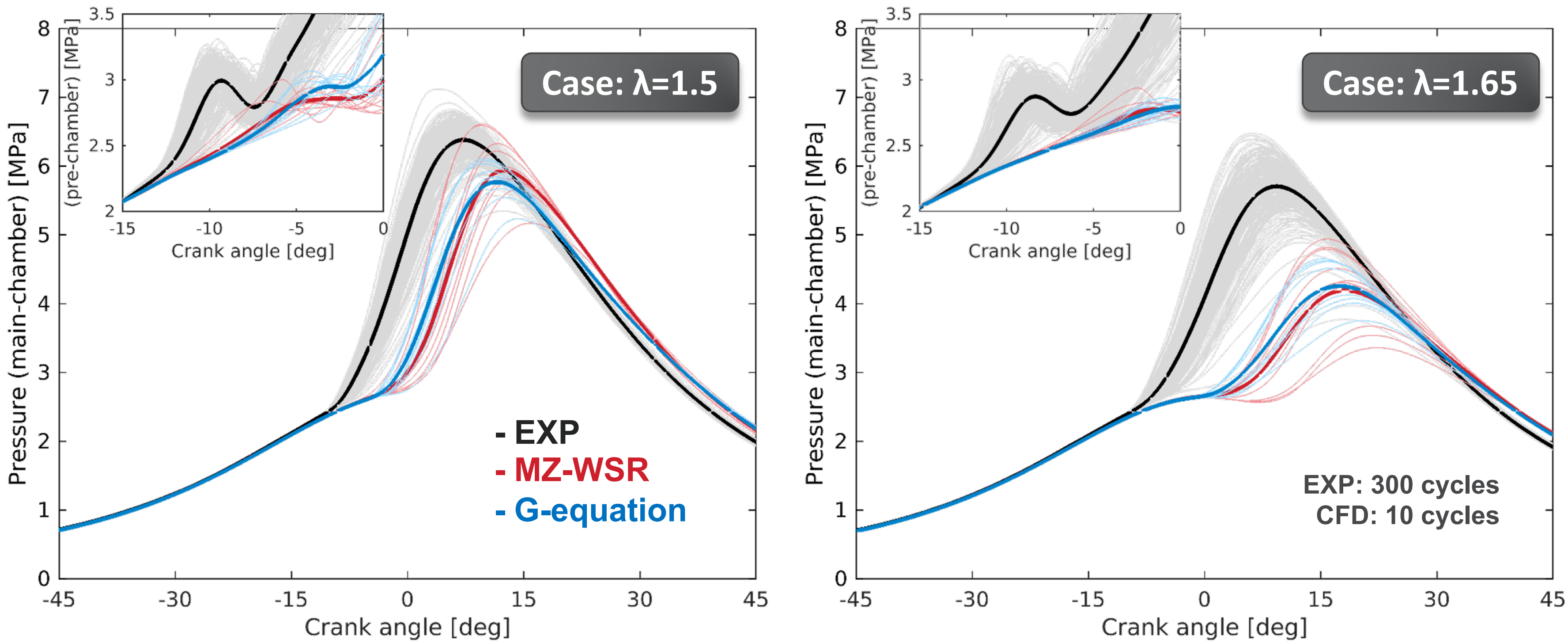




- Mesh strategy for production RANS cases
- High-fidelity LES performed w finer meshes ($\Delta \approx 40\mu m$)

UNFUELED PCSI SIMULATIONS (MODEL UNTUNED)

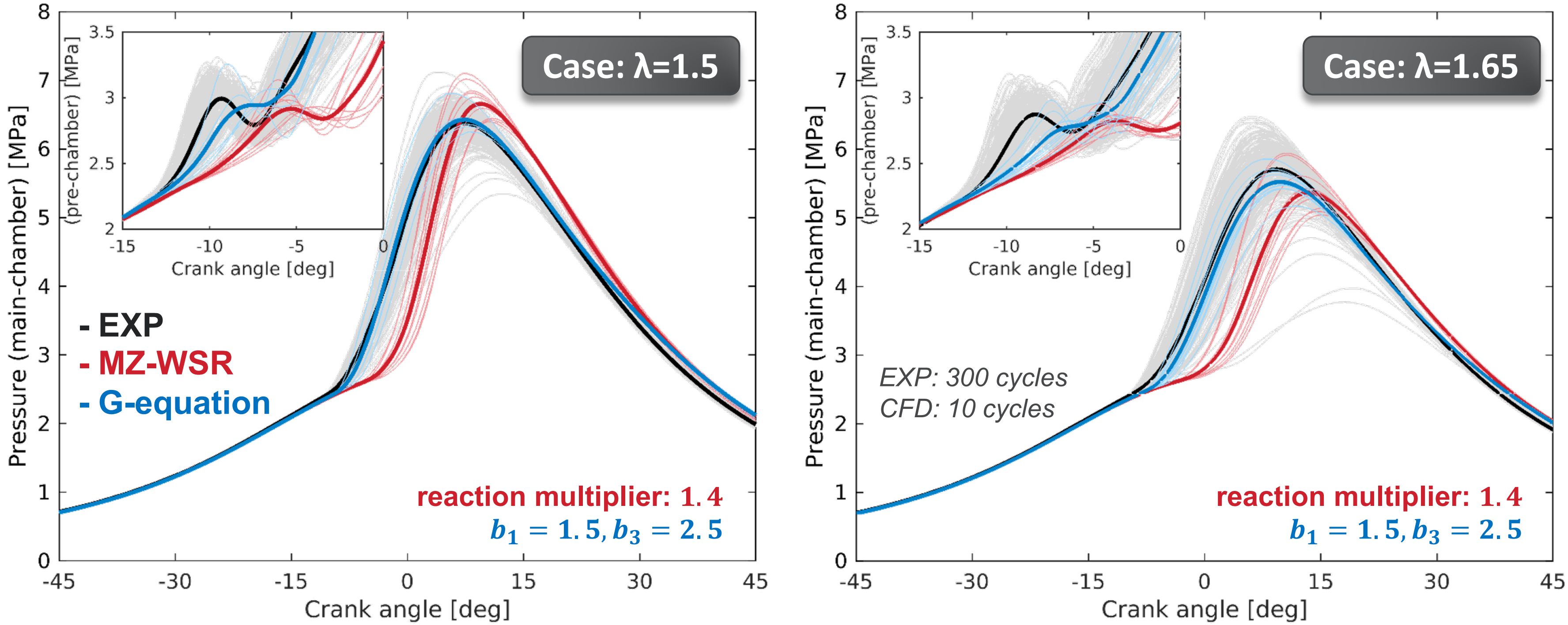
- **G-Equation and MZ-WSR were used to run multi-cycle simulations**
- **Both failed to match experiments without tuning the model**



- Δp_{PC-MC} was not captured accurately (slow PC combustion)
- Subsequent combustion in the MC was slow as well
- Agreement gets worse at increasing λ (lean mixtures)

UNFUELED PCSI SIMULATIONS (MODEL TUNED)

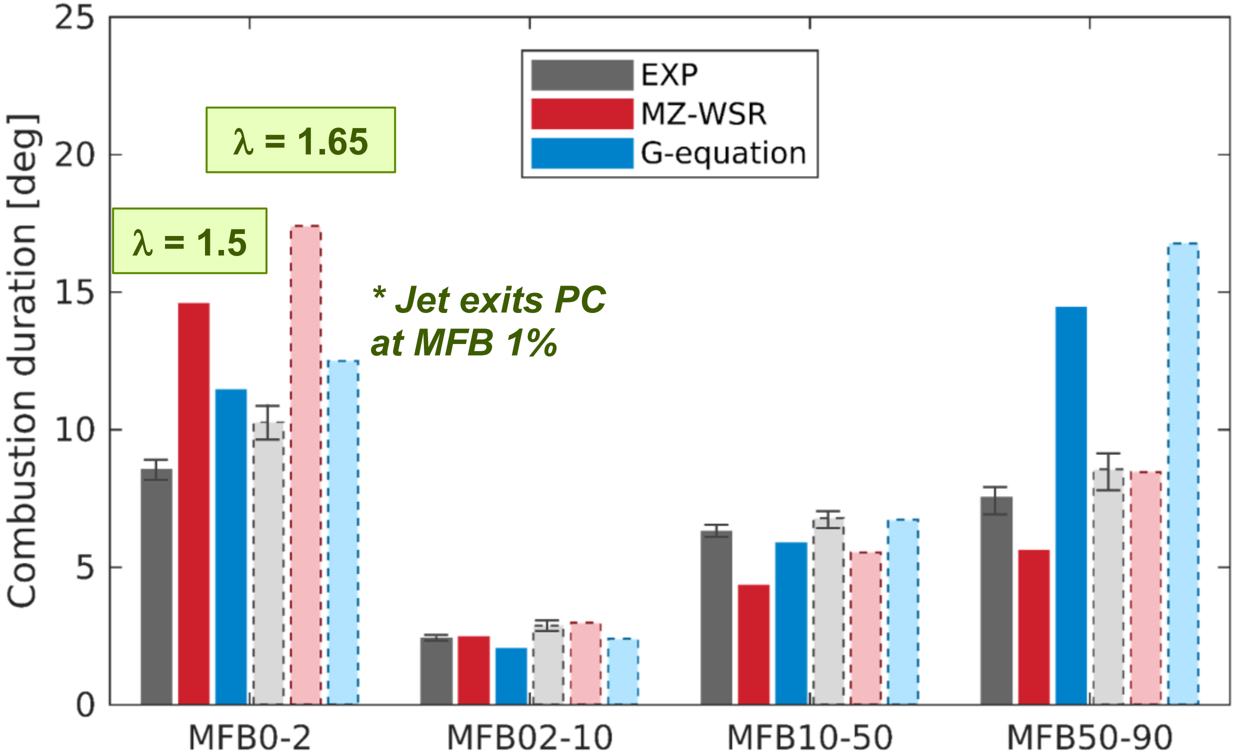
G-equation showed better potential to capture the combustion phasing in both chambers with model constant tuning.

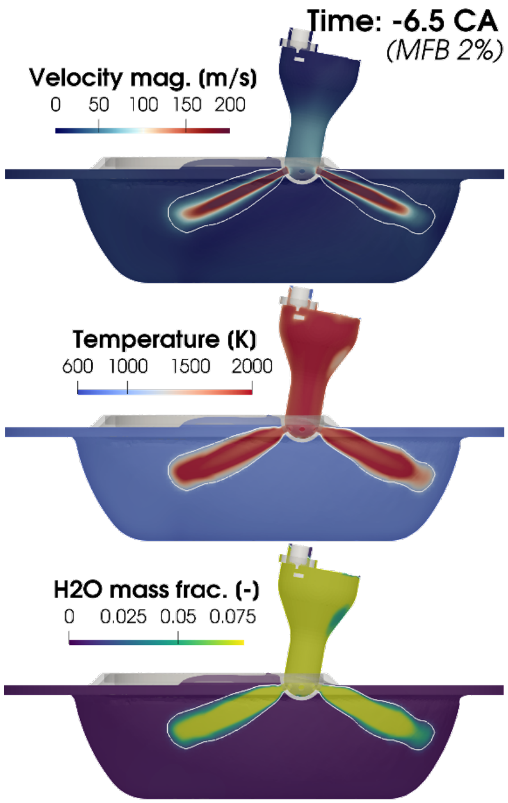


- ➢ Small turbulent scales in the PC could be taken into account by tuning the b_3 model constant (conventional SI tuning targets large scale turbulence, b_1)
- ➢ Similar effective tuning is not possible with the MZ-WSR approach. Small scales and large scales are not decoupled

UNFUELED PCSI SIMULATIONS (MODEL TUNED)

G-equation allowed advancing the combustion phasing in PC by tuning.





- Turbulent jets from PC were mainly composed of high-temperature, combustion product species with extremely high ejection velocity.
- Reasonable tuning in MZ-WSR model could not provide fast-enough combustion in PC and over-predicted the combustion rate in MC.
- G-equation consistently over-predicted MFB 50-90% (under evaluation)

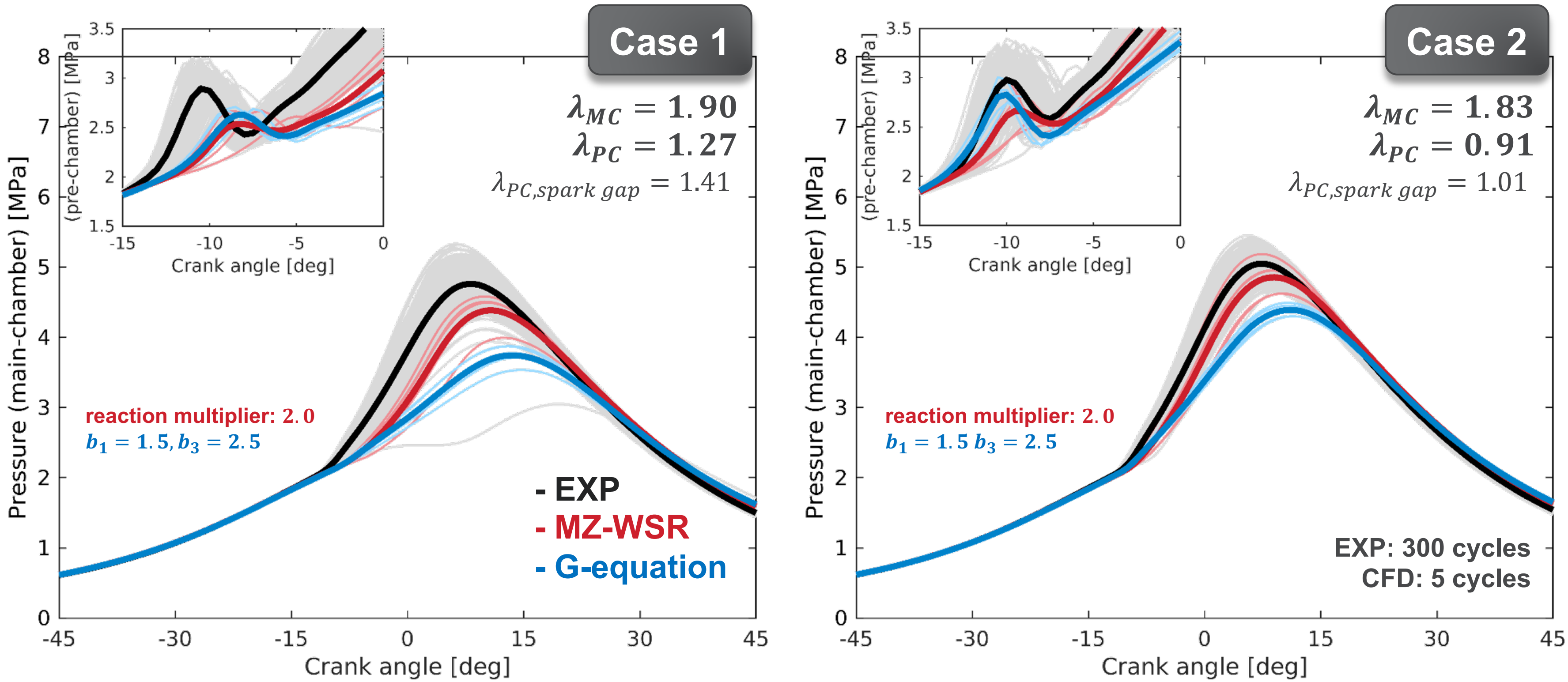
ANALYSIS OF PCSI COMBUSTION REGIME

Small nozzle diameter led to small scale turbulence inside pre-chamber during compression and finally resulted in multi-combustion regimes.

- Flame combustion regime span widely across Borghi-Peters diagram
- Strong turbulence-chemistry interaction when the jets exit from the PC
- Need for flame diagnostics tool and an advanced combustion model which has more general validity and does not require repetitive tuning

FUELED PCSI SIMULATIONS (UNTUNED)

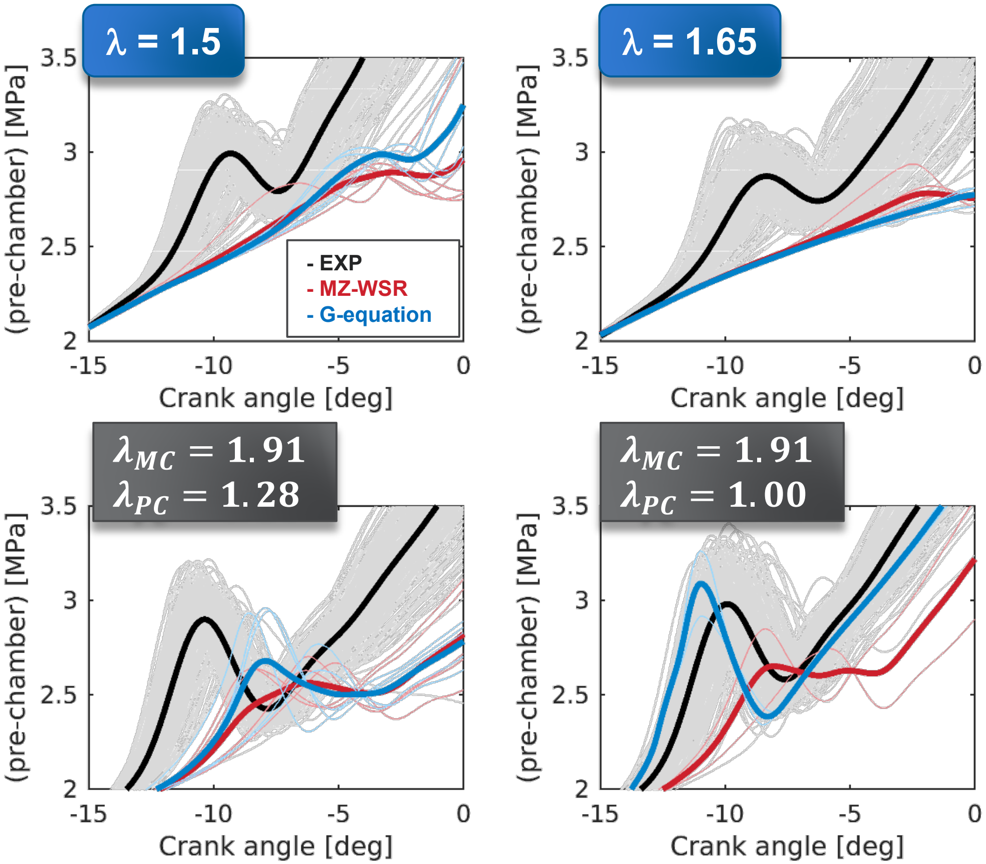
Both models resulted in better agreement on the combustion phasing for both chambers as the $\lambda_{PC} \rightarrow 1$.



- ➢ MZ-WSR had low pressure rise in PC but turned to fast combustion in MC.
- ➢ G-equation showed slow combustion rate in MC even the combustion phasing in PC was well-matched.

ANALYSIS OF IGNITION PROCESSES IN PRE-CHAMBER

1. **Challenges for ignition/flame growth models at ultra-lean PC conditions**
2. **Better agreement when PC gets richer, thus requiring less aggressive model tuning (or no model tuning at all)**



SUMMARY AND NEXT STEPS

- All RANS models we tested (MZ-WSR, G-Equation, ECFM) somewhat failed to match the combustion phasing from experiments. Main cause was the slow combustion in the PC.
- Small-scale turbulence in the PC was due to the small nozzle. G-equation accounts for both large and small-scale turbulence, and showed potentials to provide better agreement with experiments by model tuning. MZ-WSR could not explicitly take the turbulence effect into account for the combustion.
- PCSI combustion span widely in the combustion regime diagram, from thin reaction zone regime ultimately into flamelet region. Strong TCI is expected when the jets exit from the nozzles. A more comprehensive combustion model is required to eliminate repetitive tuning.
- Initial flame kernel growth was the main issue of PCSI modeling at lean PC conditions (i.e. unfueled PC). Fueled PC required less or no tuning at all (stoichiometric mixture in the PC)

- Flame diagnostics tool and advanced combustion modeling required to improve validity across the wide range of flame regimes
- Additional high-fidelity LES to provide insight into flame growth and flame/hot gases jets across the PC orifice
- Advanced ignition model formulation

Approach

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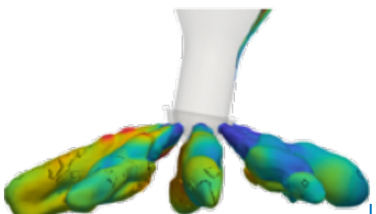
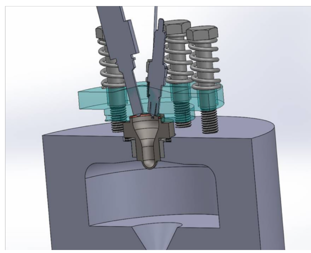




Simulation | **Bench Scale** ↔ **Single Cylinder** ↔ **Multi Cylinder**

Simulation

Engine Sim. (ANL)
High fidelity CFD focusing on PCSI output mixing, with ignition and flame propagation models.

Chamber Sim. (NREL)
Zero dimensional (0D) and CFD map PCSI composition output to explore main chamber ignition sensitivity.

Bench Scale

Chamber Exp't. (NREL)
PCSI added to constant volume chamber to study pre-chamber variable effects on main chamber ignition over lean / dilute conditions.

Catalyst Exp't. (ORNL)
Synthesize novel methane oxidation catalysts (MOCs) and evaluate performance with PCSI NG engine exhaust conditions.

Single Cylinder

Metal Engine Exp't. (ANL)
Single cylinder engine experiments with borescope access to study PCSI effects on lean / dilute operation and efficiency / engine-out emissions tradeoffs.

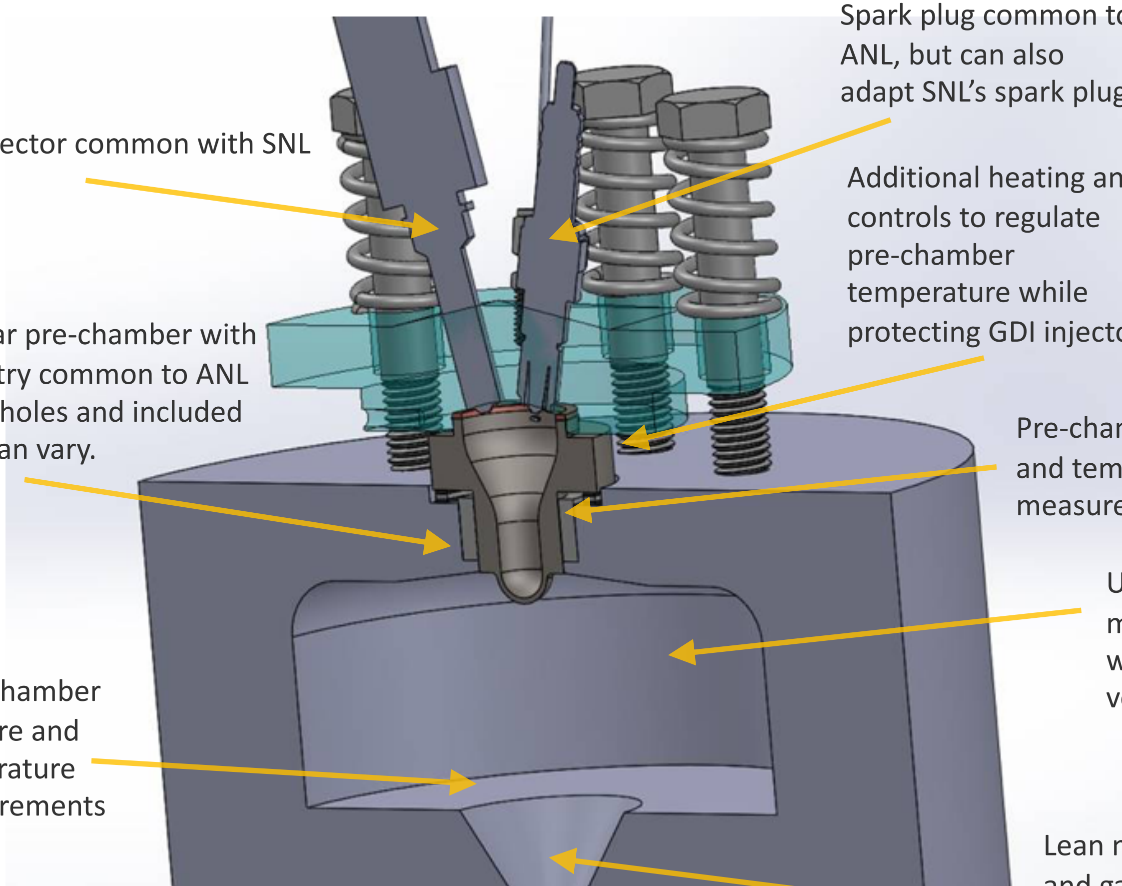
Optical Engine Exp't. (SNL)
Single cylinder engine experiments to study PCSI output penetration to main chamber and characterize flame propagation vs. sequential autoignition.

Multi Cylinder

Metal Engine Exp't. (ORNL)
Modified HD engine with PCSI in all cylinders to study dilution tolerance, conduct thermodynamic analysis of efficiency potential tradeoffs related to lean / dilute combustion with PCSI, and provide exhaust information for MOC studies.

Bench Scale			Single Cylinder			Multi Cylinder
NREL Chamber Exp't.	NREL Chamber Sim.	ORNL Catalyst Exp't.	ANL Engine Sim.	ANL Metal Engine	SNL Optical Engine	ORNL Metal Engine

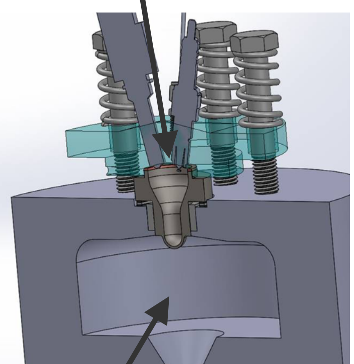
Advanced Fuel Ignition Delay Analyzer + PCSI



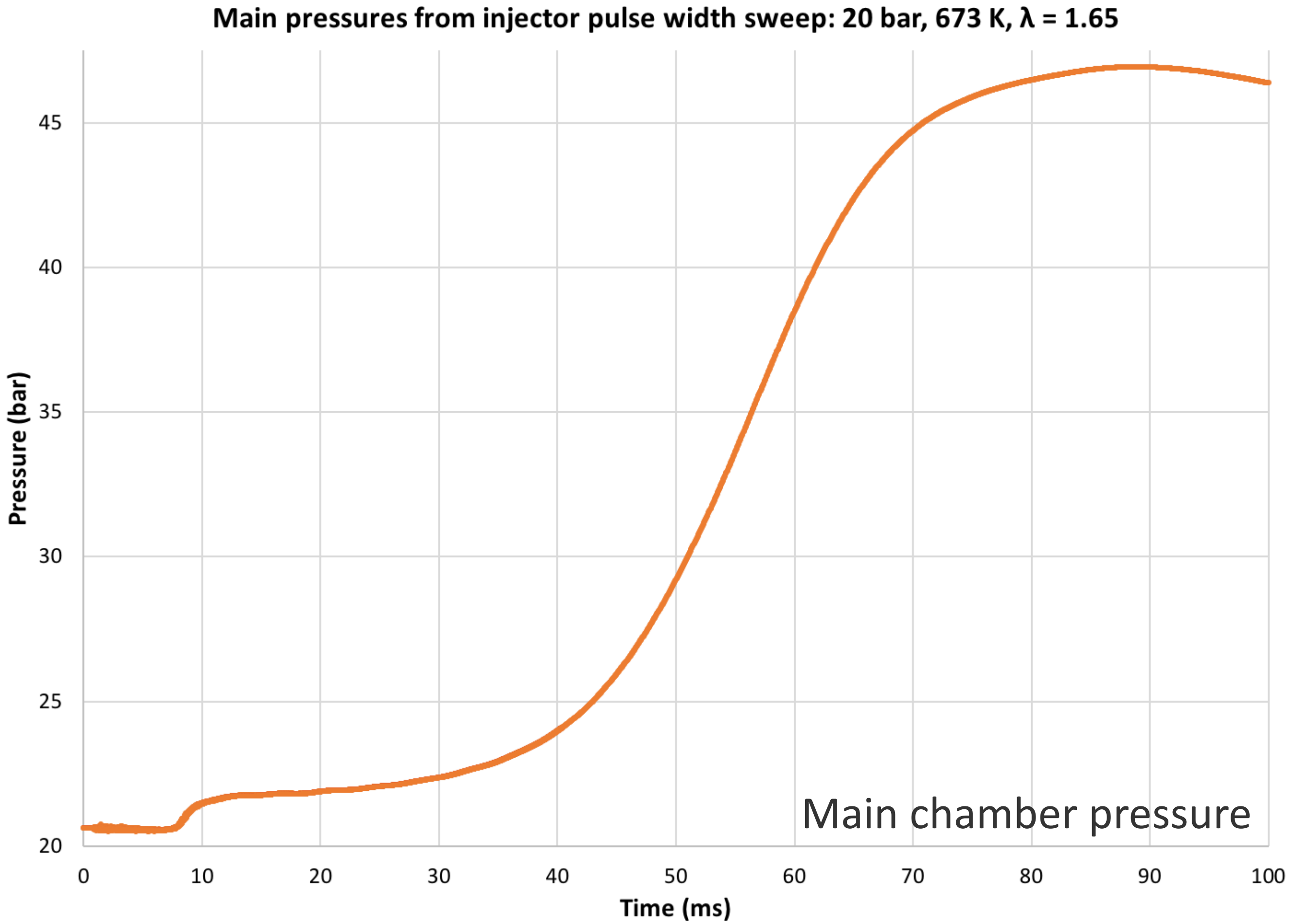
A modular PCSI design was adapted to the AFIDA, with significant commonality to ANL and SNL’s designs, and no permanent modifications to the AFIDA.

Effects of PC stoichiometry on main combustion

2.5 ms λ = 0.62



20 bar, 673K
λ = 1.65



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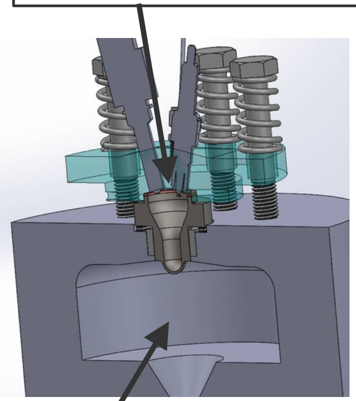

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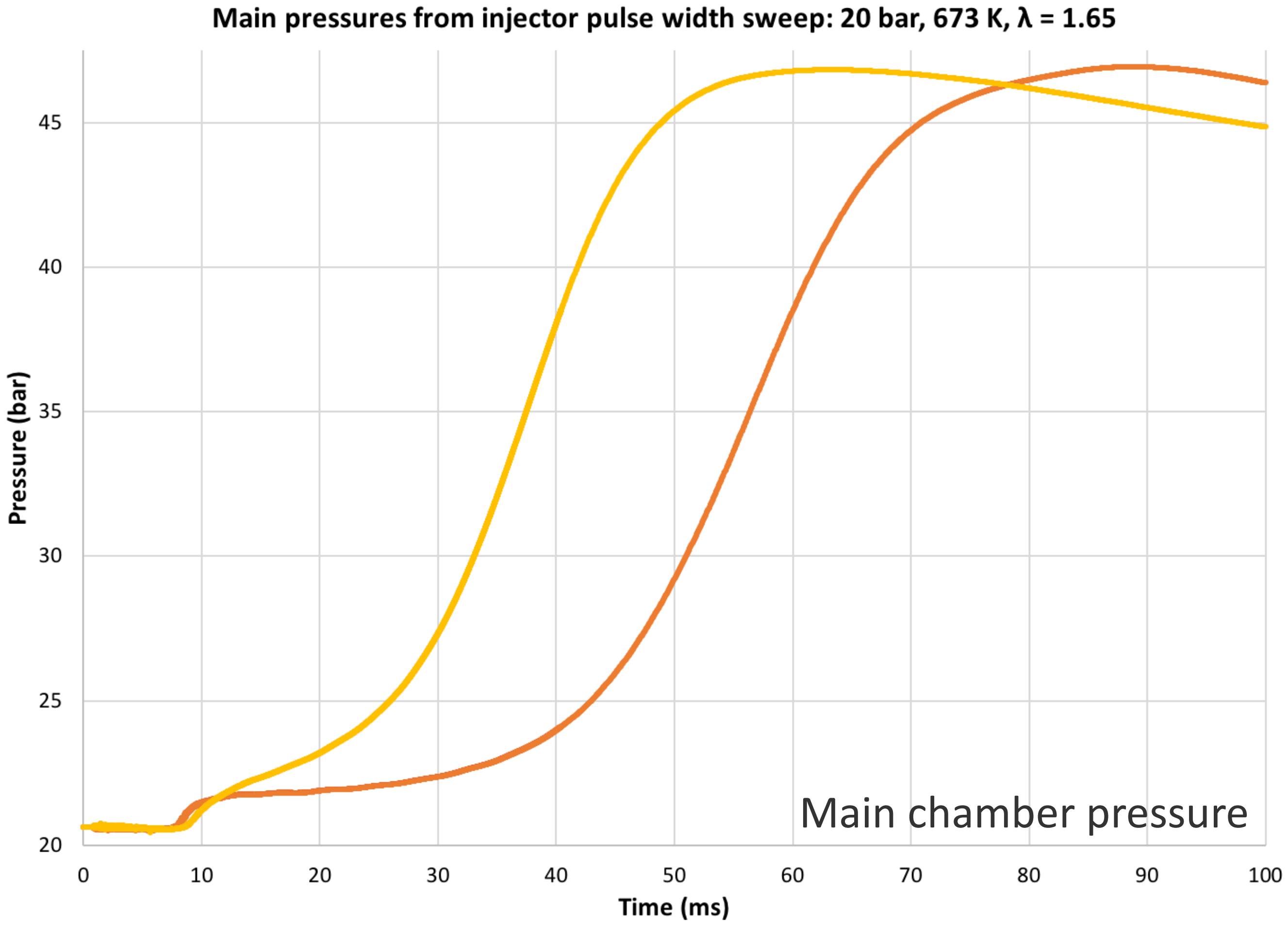

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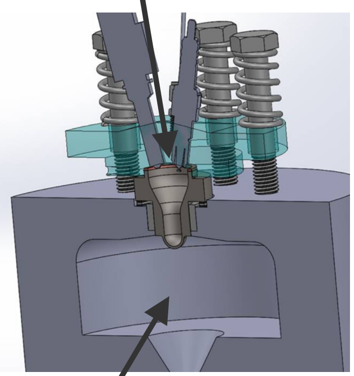

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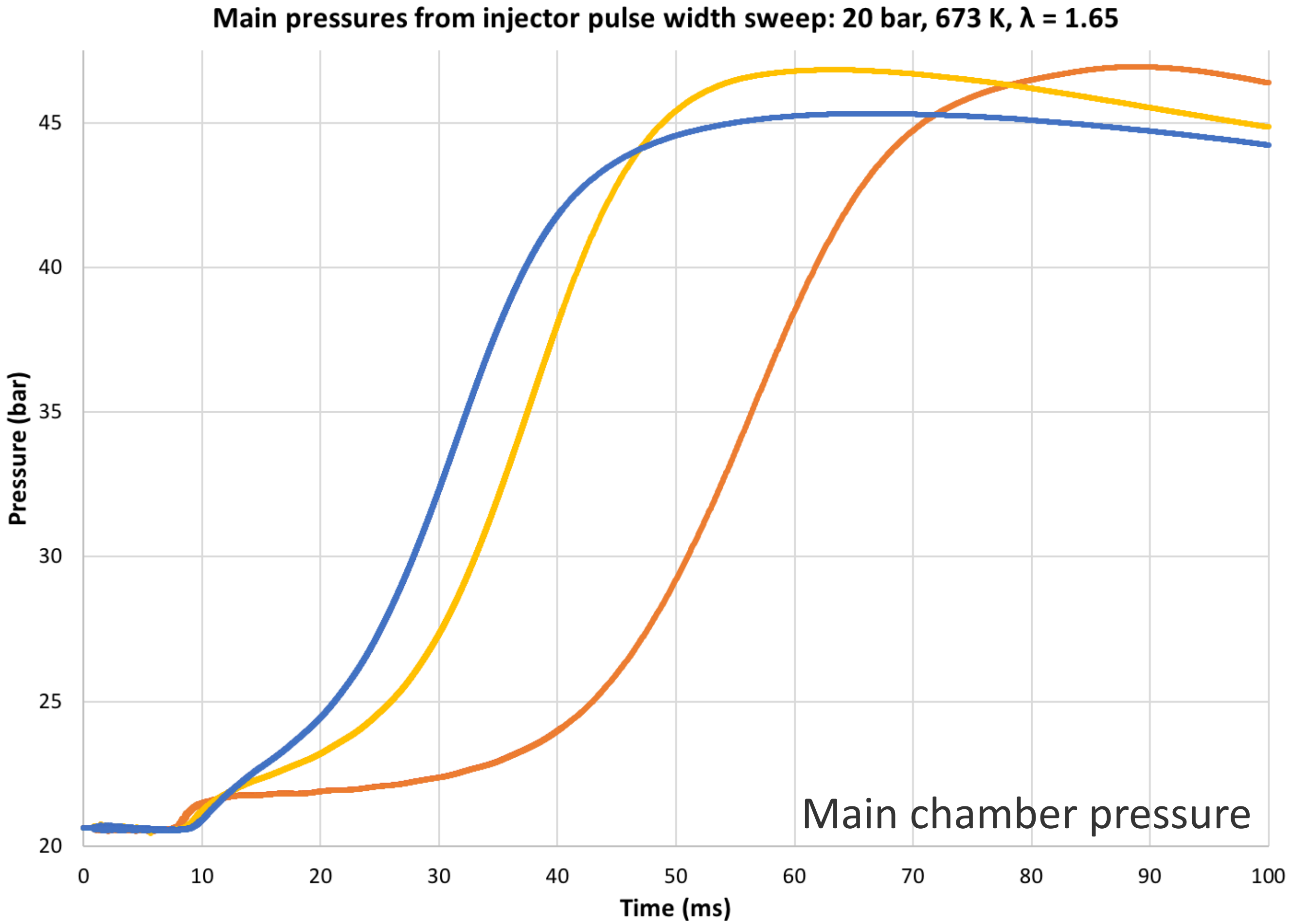

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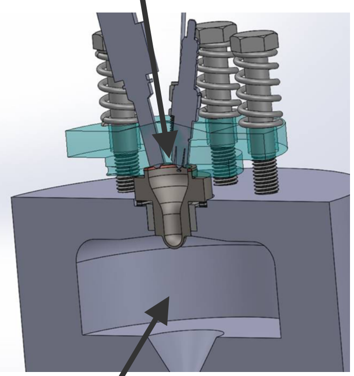

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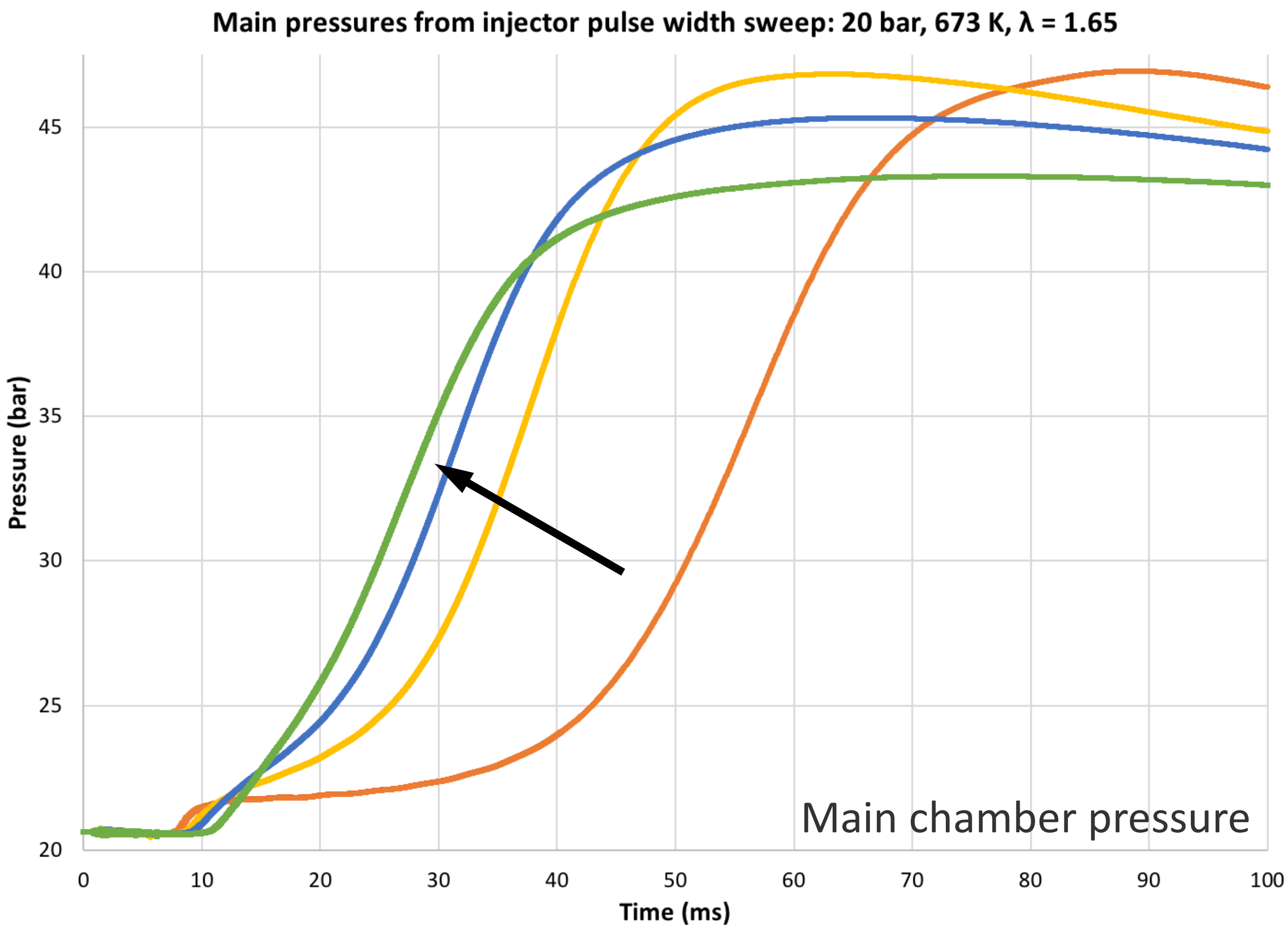

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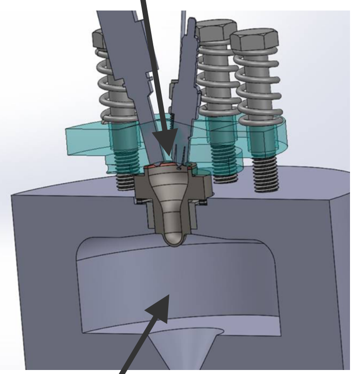

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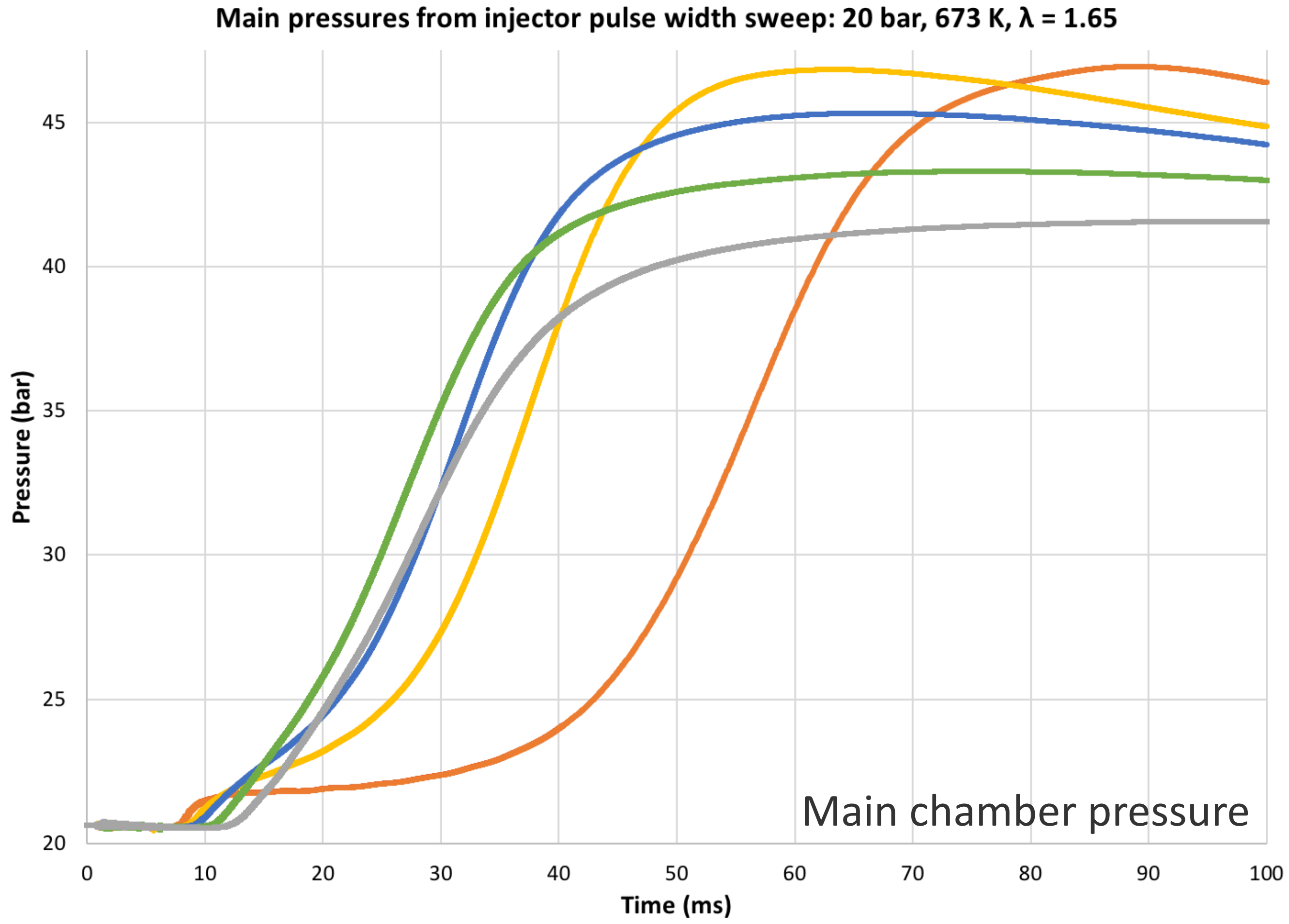

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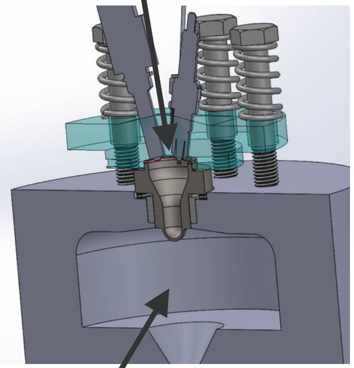

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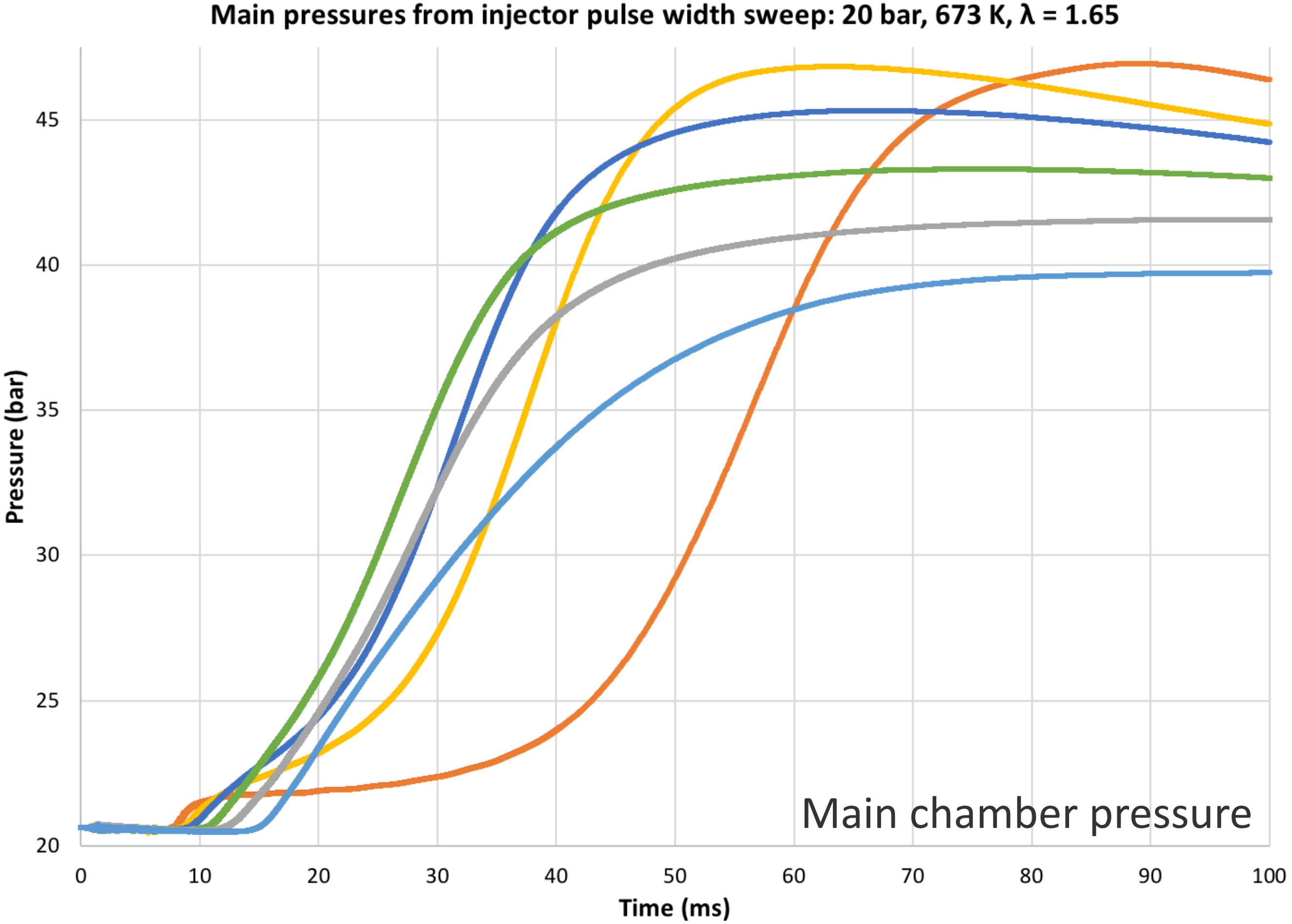

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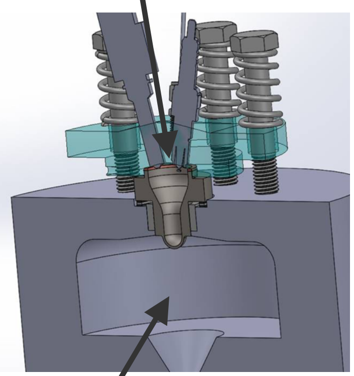

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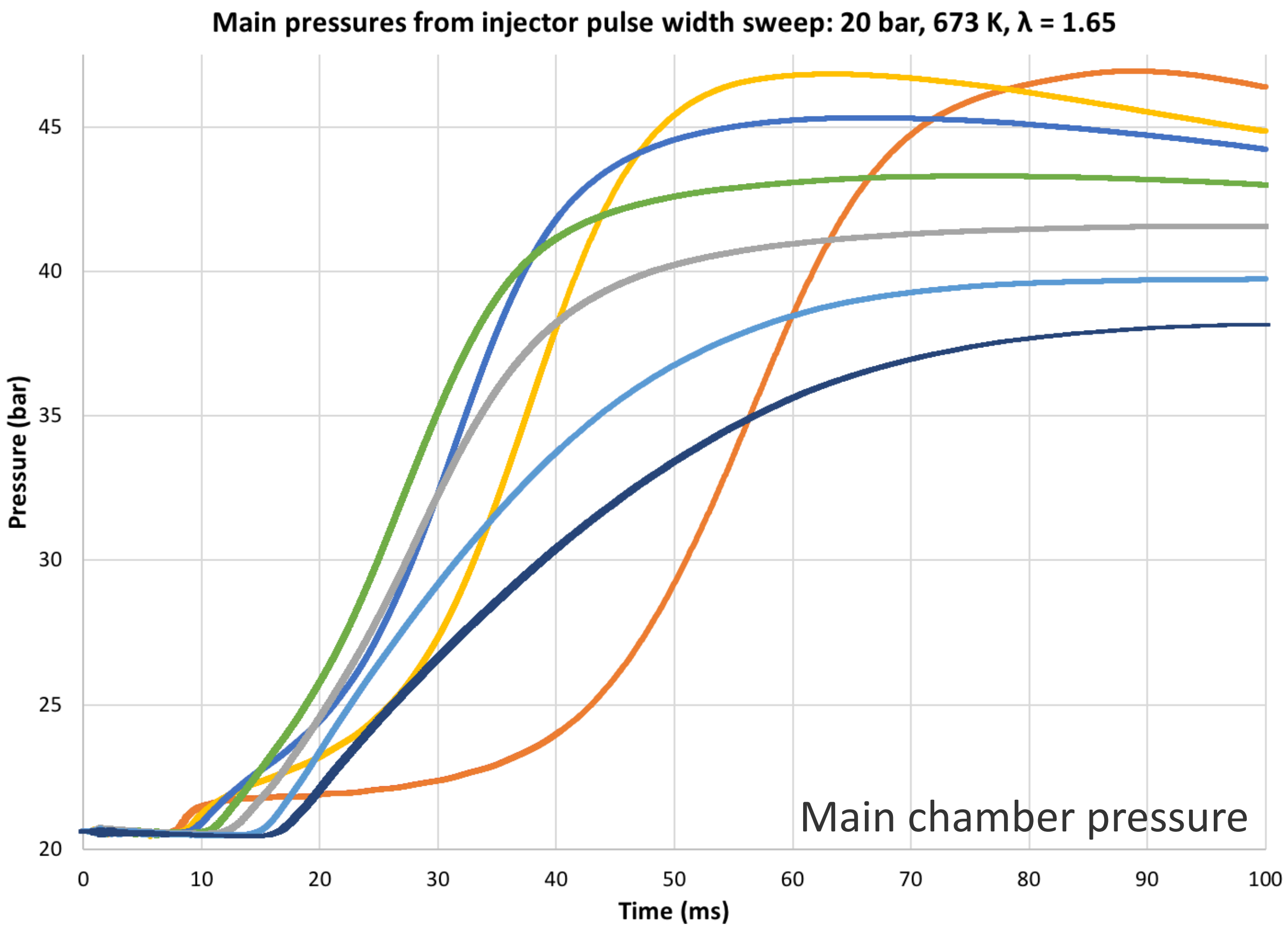

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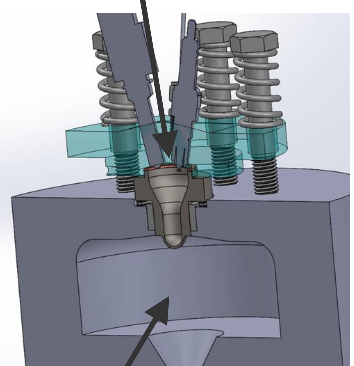

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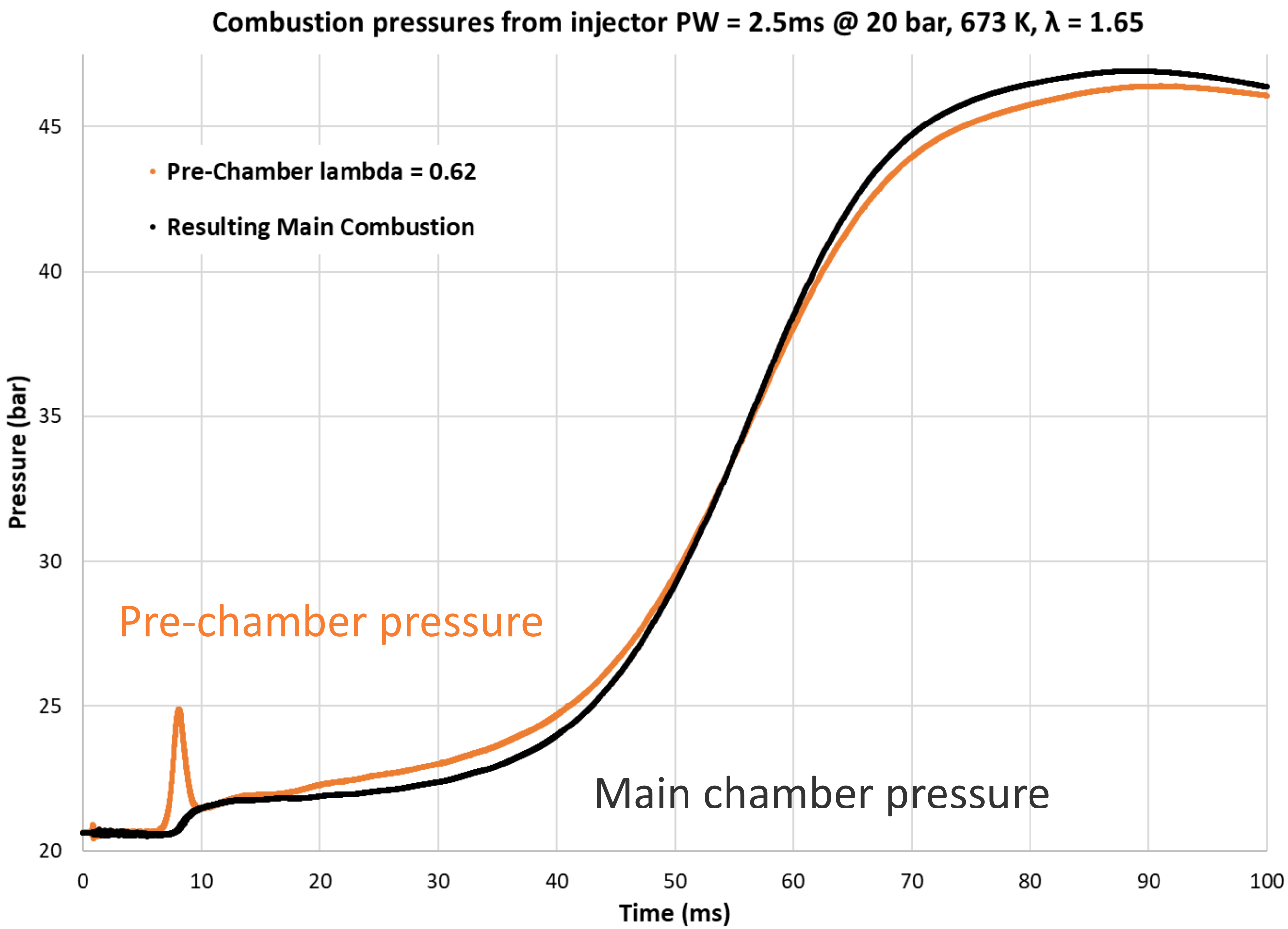

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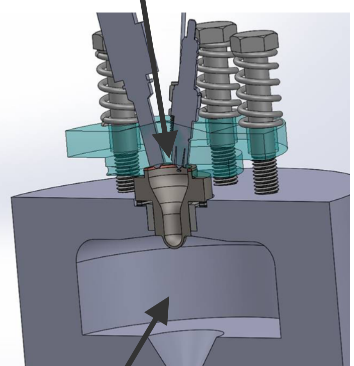

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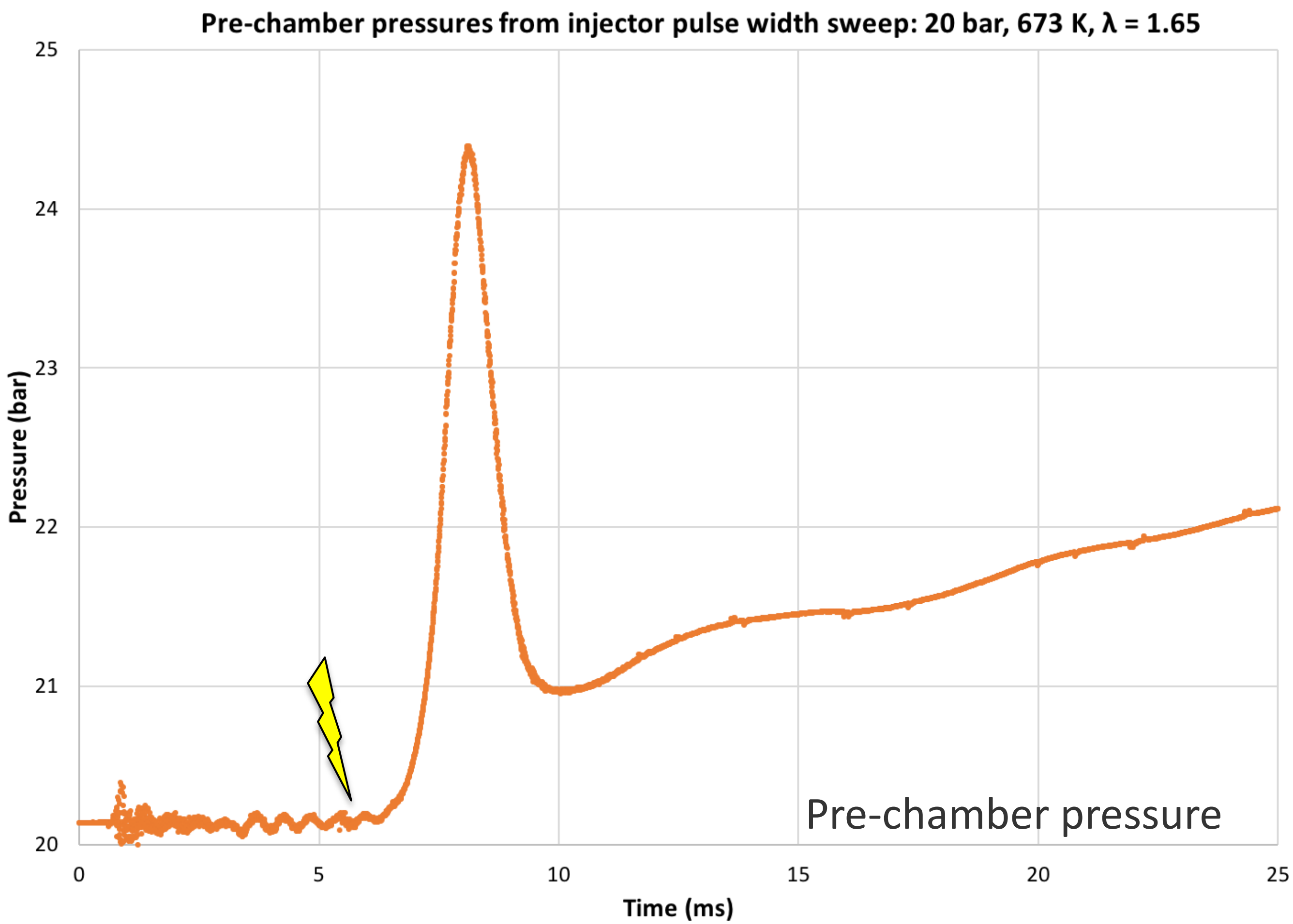

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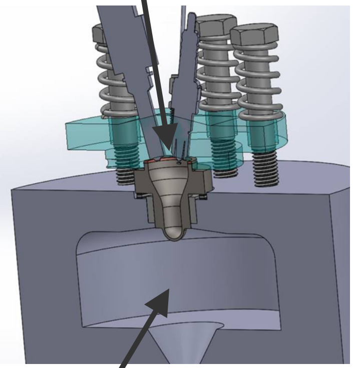

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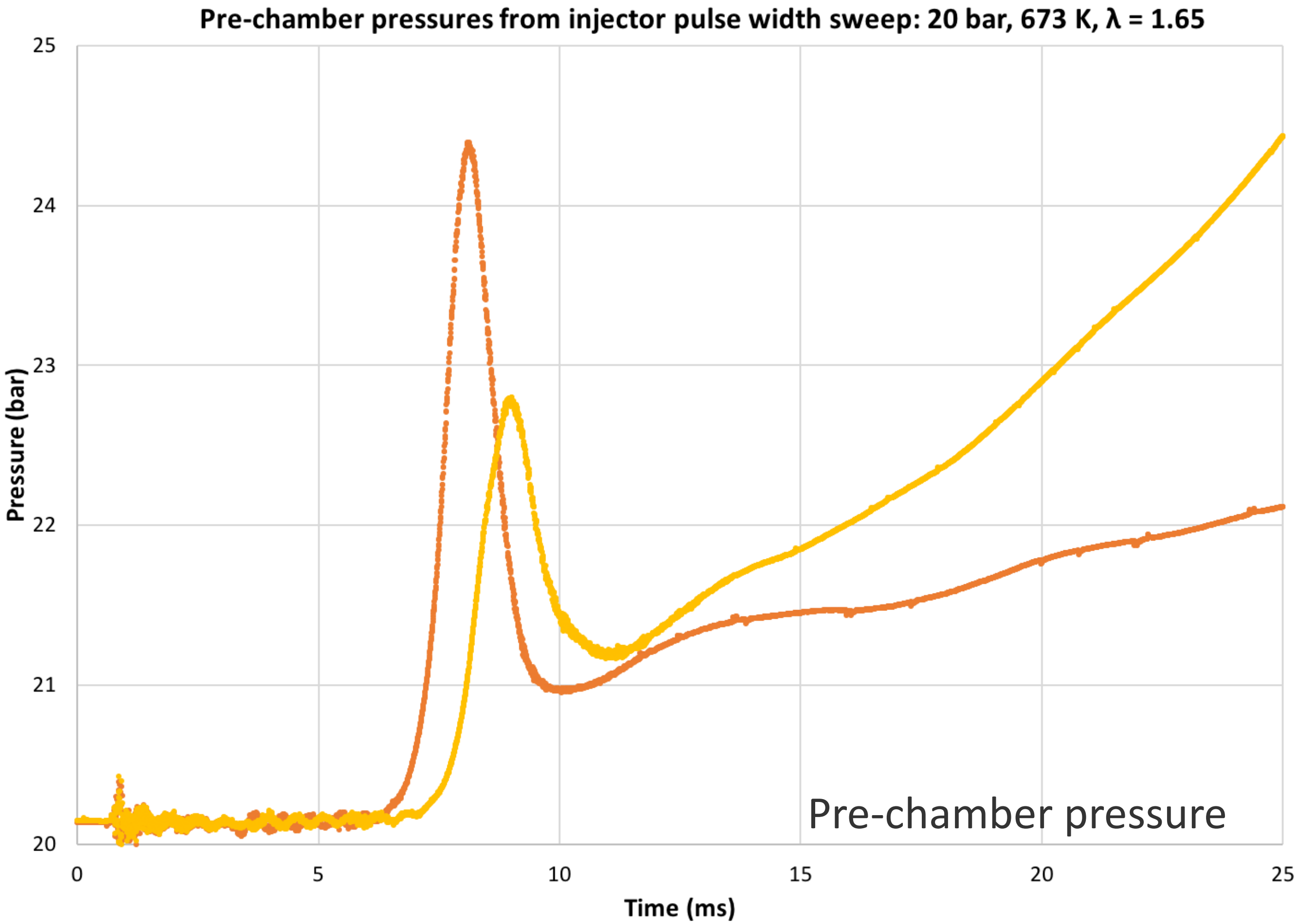

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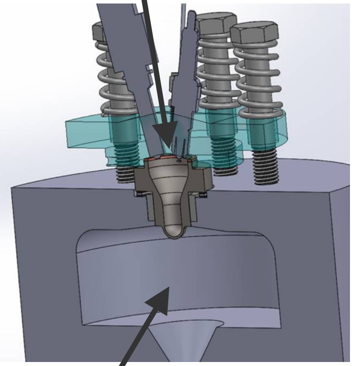

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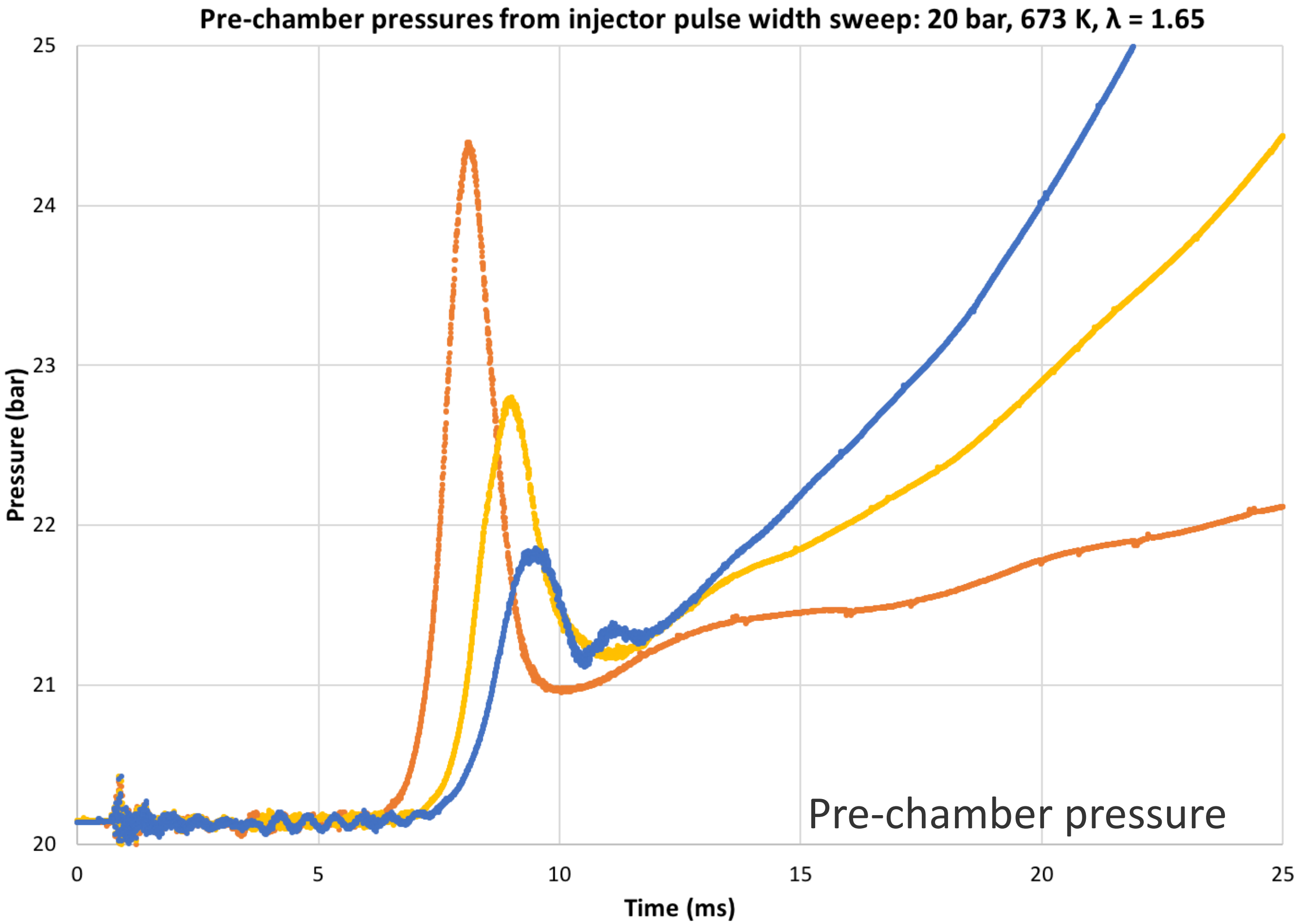

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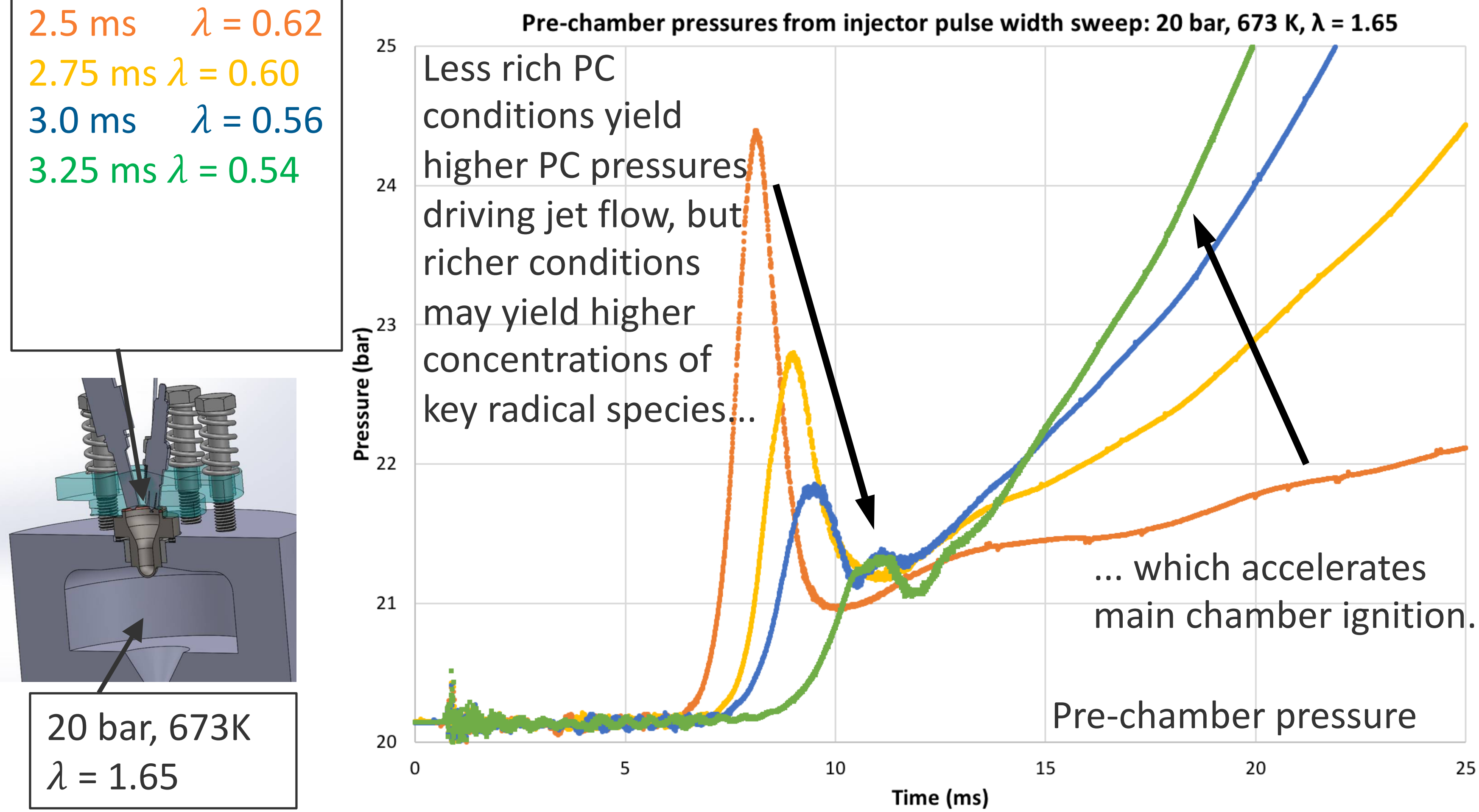

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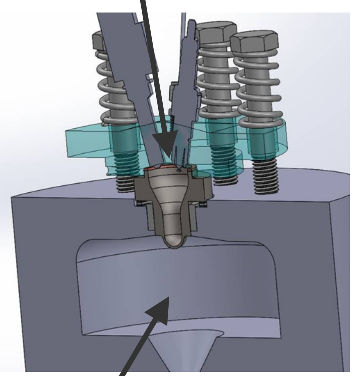

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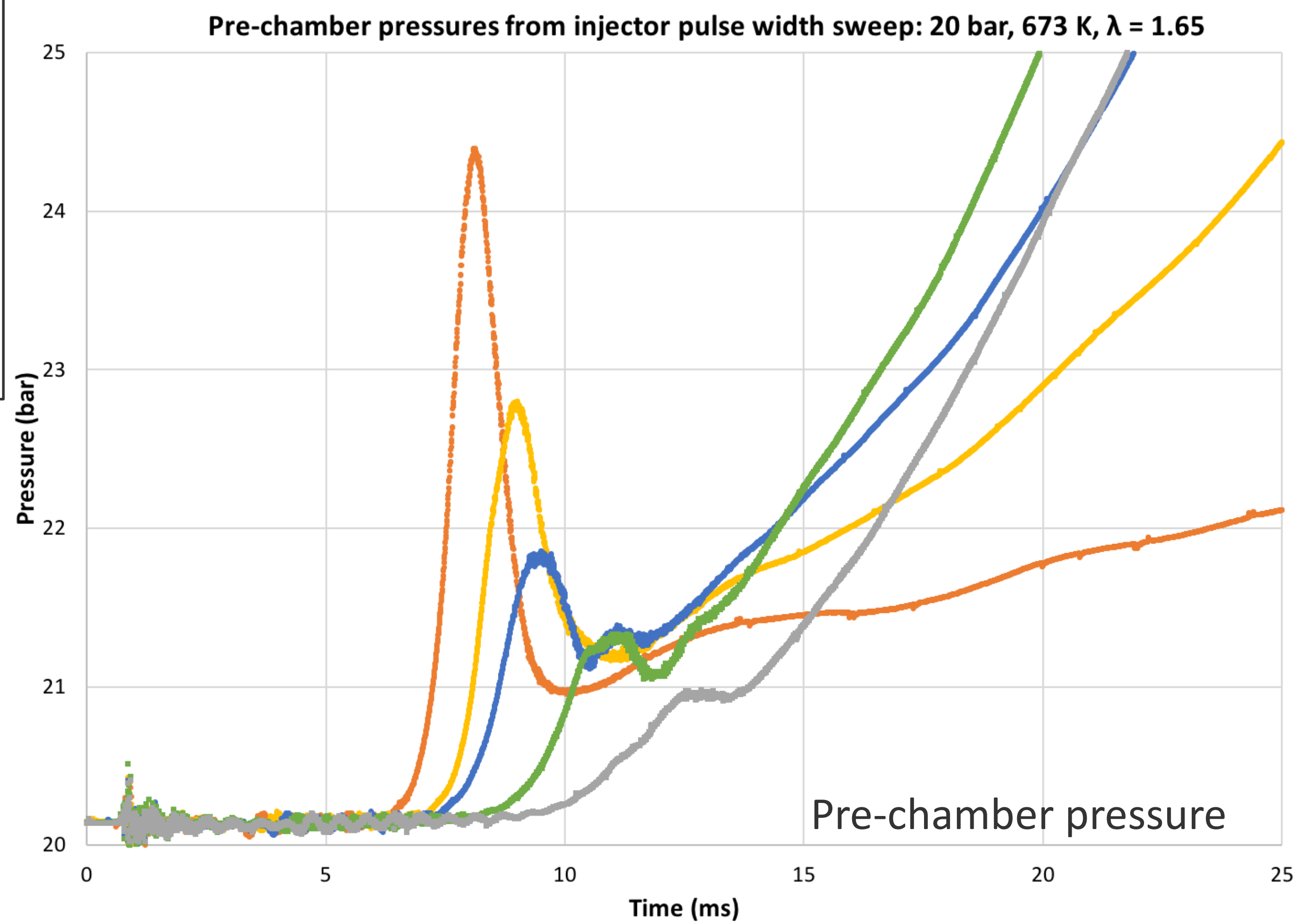

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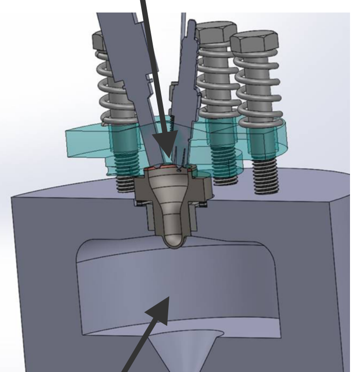

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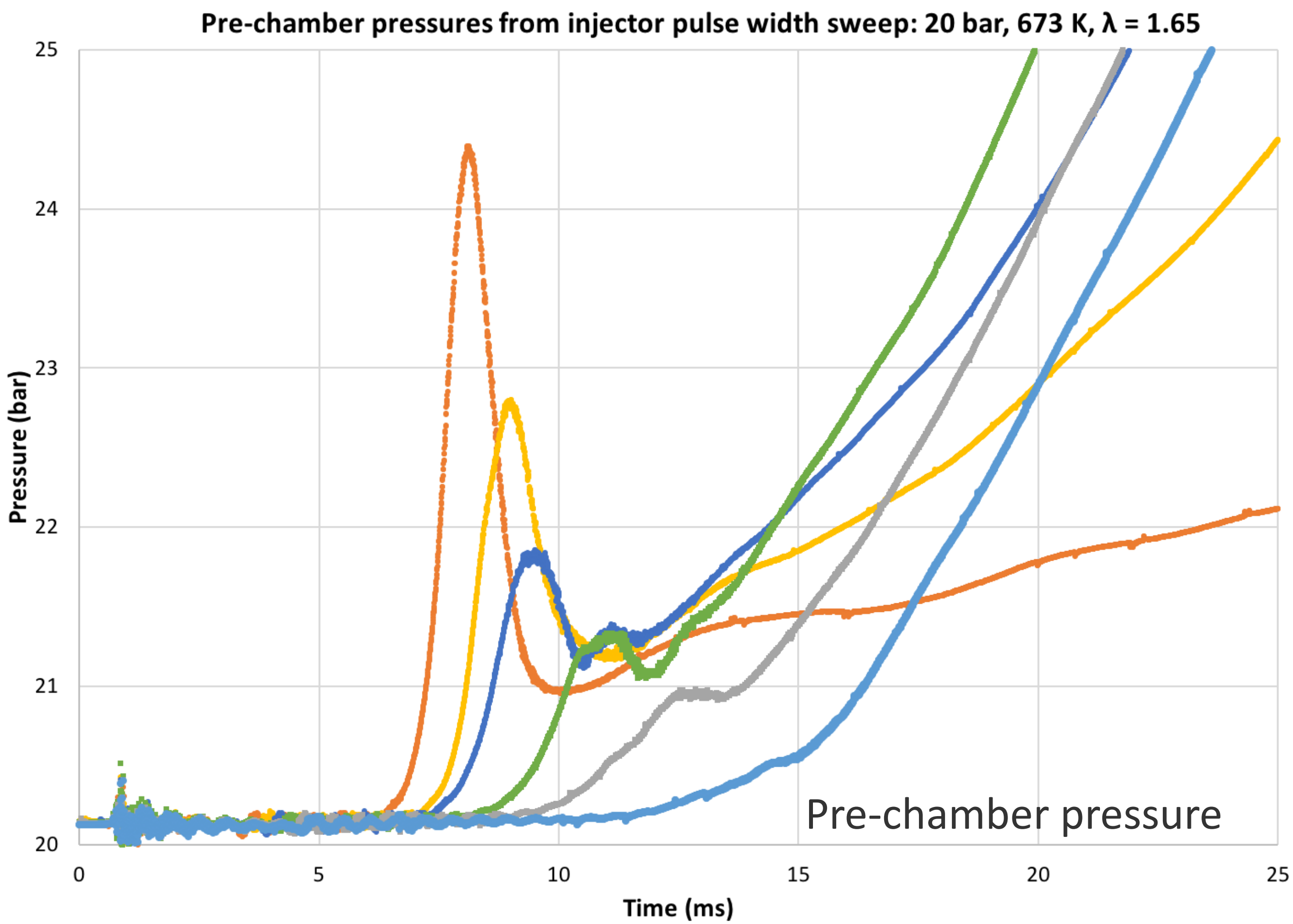

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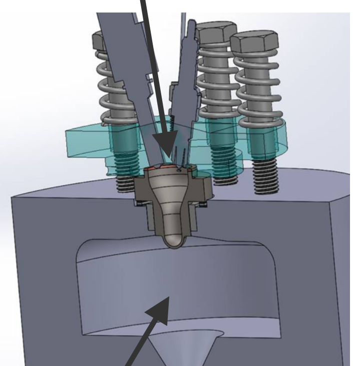

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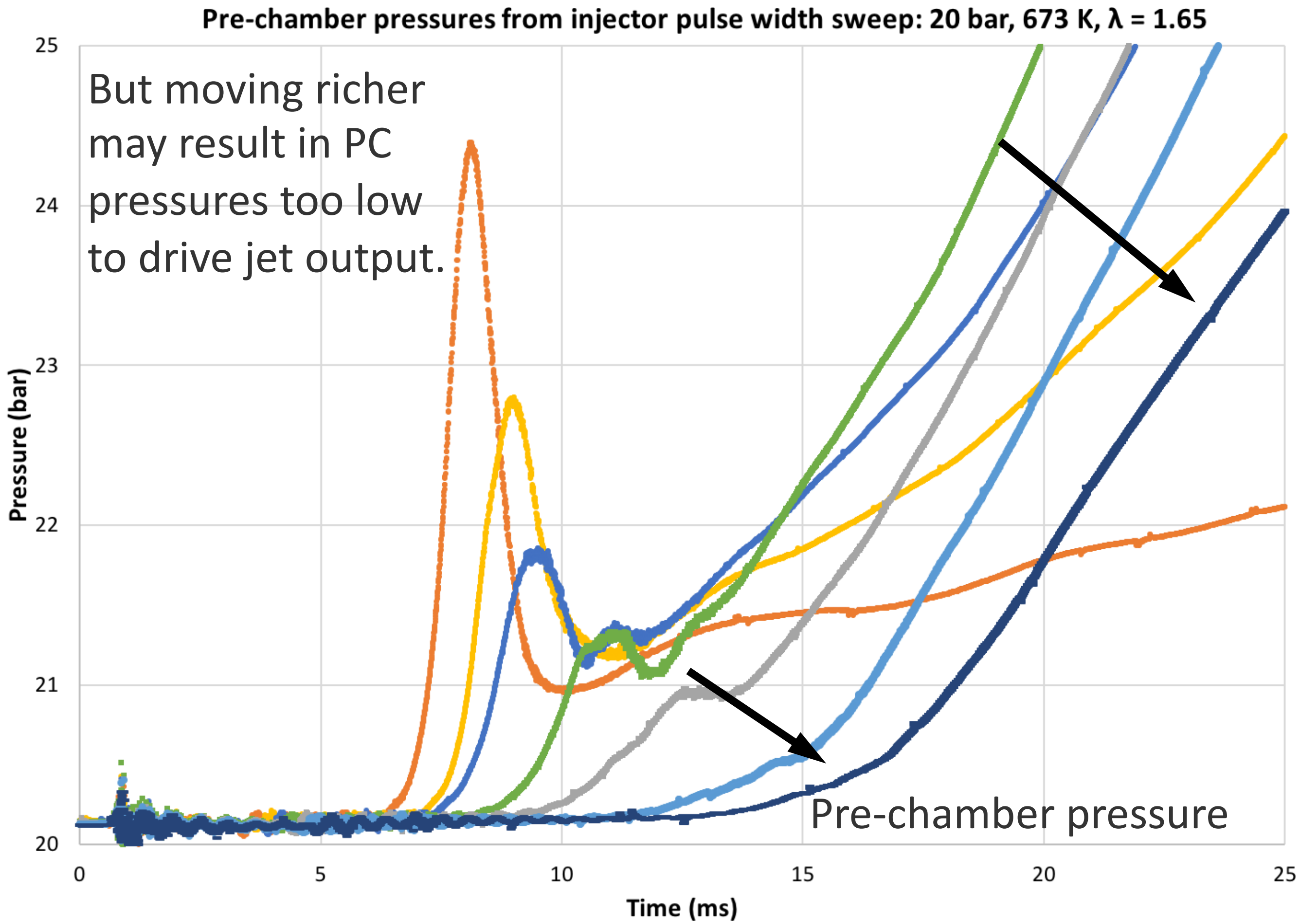
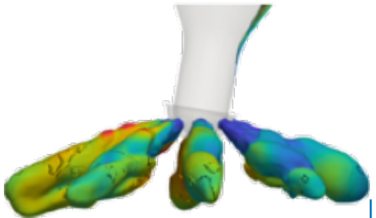


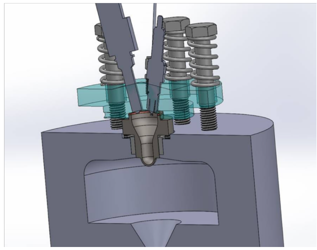
CFD simulation

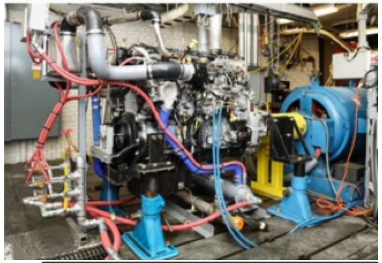
- Mechanism: 30 species GRI3.0
- initial λ = 1.9
- P_0 = 20 bar
- T_0 MC = 703 K
- T_0 PC = 535 K
- Injector PW= 3.5 ms
- Spark time = 6.64 ms
- Fuel injected mass = 6 mg
- (effective PC λ = 0.45)

Approach

Modular PCSI designs with as much commonality as possible are used across all platforms







Simulation

Bench Scale ↔ Single Cylinder ↔ Multi Cylinder

Simulation

Engine Sim. (ANL)
High fidelity CFD focusing on PCSI output mixing, with ignition and flame propagation models.

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Single cylinder engine experiments with borescope access to study PCSI effects on lean / dilute operation and efficiency / engine-out emissions tradeoffs.

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Single cylinder engine experiments to study PCSI output penetration to main chamber and characterize flame propagation vs. sequential autoignition.

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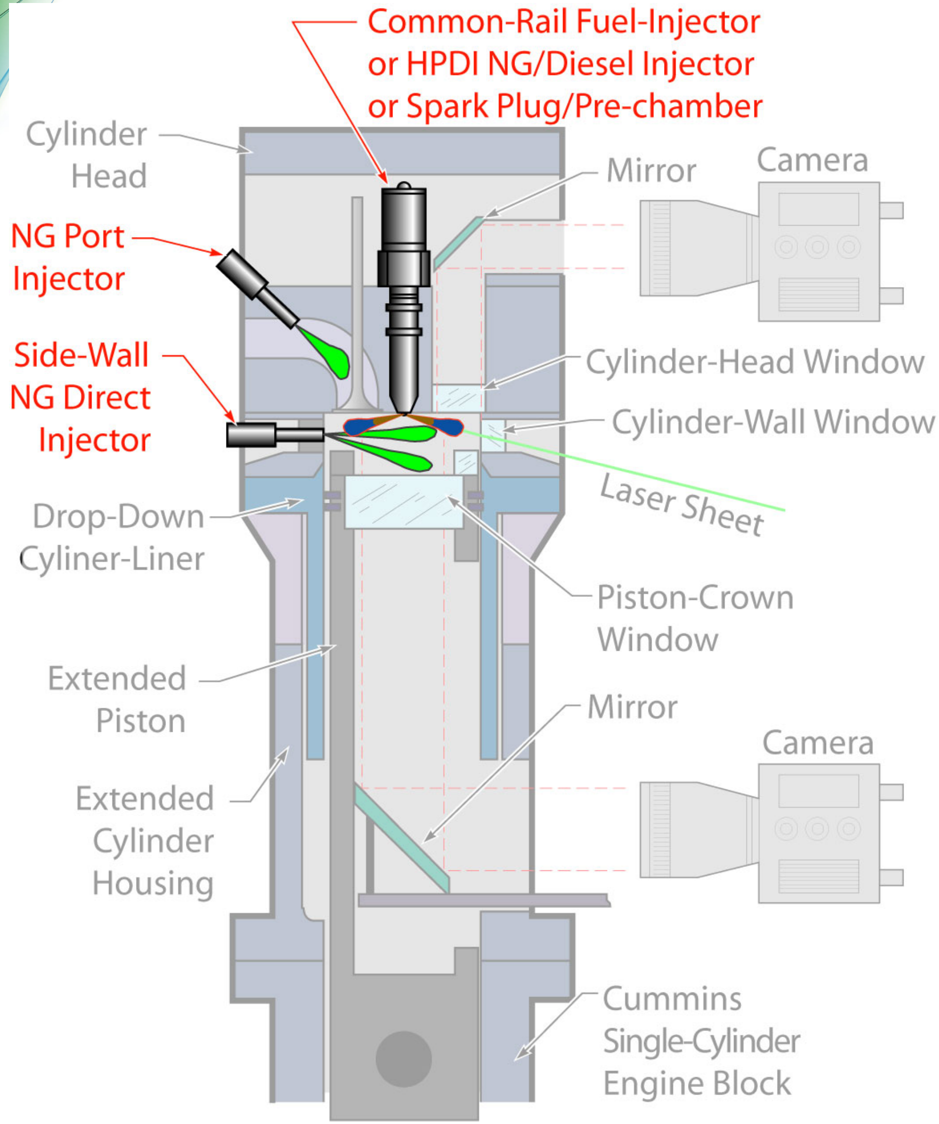
Modified HD engine with PCSI in all cylinders to study dilution tolerance, conduct thermodynamic analysis of efficiency potential tradeoffs related to lean / dilute combustion with PCSI, and provide exhaust information for MOC studies.

Bench Scale			Single Cylinder			Multi Cylinder
NREL Chamber Exp't.	NREL Chamber Sim.	ORNL Catalyst Exp't.	ANL Engine Sim.	ANL Metal Engine	SNL Optical Engine	ORNL Metal Engine

SNL (B1-B3): Modify HD optical engine with active natural gas pre-chamber for fundamental mixing & combustion data



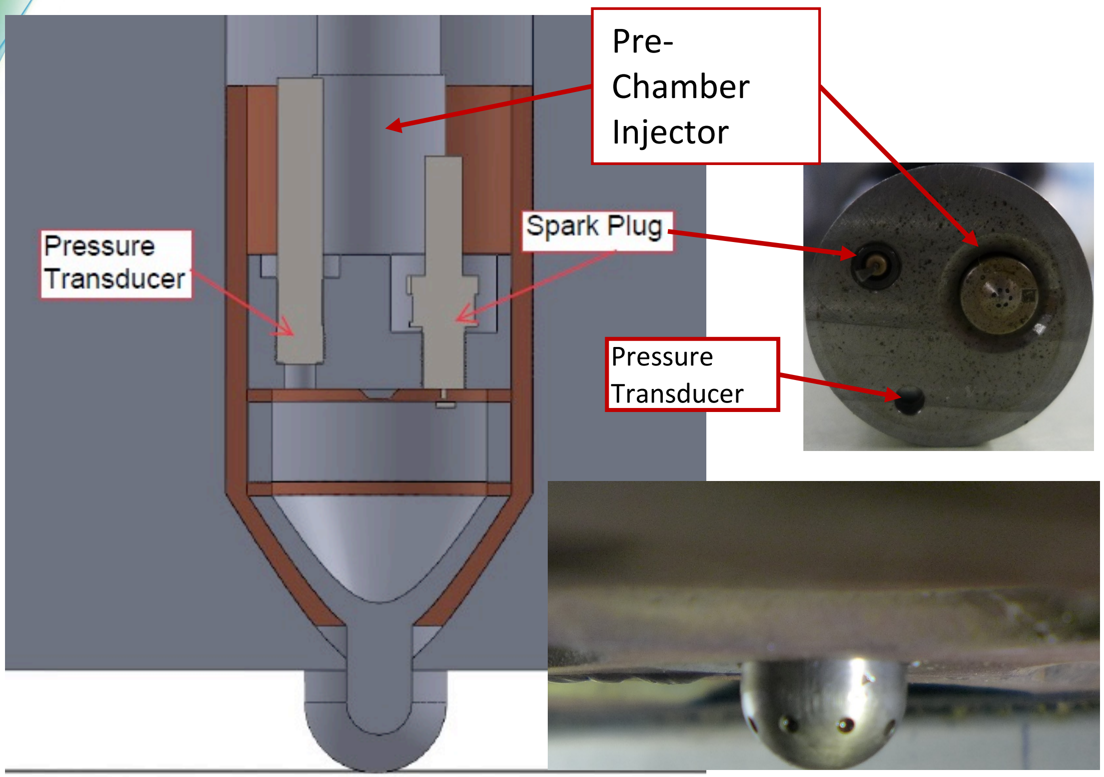
SNL Task Statement (B1-B3): Adapt a PCSI module to a HD optical single-cylinder engine and use laser/imaging diagnostics for the ignition-jet as it emerges from the pre-chamber, mixes with and ignites the premixed main-chamber gases, and subsequently drives the progression of main-chamber combustion, whether flame propagation or sequential autoignition

- **B1** (Inadequate science base / simulation tools)**:** Provide phenomenological and quantitative data including ignition-jet penetration rates, spatial and temporal progression of intermediate combustion species to identify modes of ignition and combustion, and/or sources of combustion inefficiency in the late cycle

  Also use optical data to validate **NREL** and **ANL** simulations and aid interpretation of **ORNL** metal-engine data so that together the labs can develop a conceptual-model description of PCSI

- **B2** (EGR/lean limits), **B3** (hot-spot pre-ignition): Use conceptual model and fundamental understanding as basis that will provide a fundamental basis for developing operating strategies and hardware to mitigate barriers B2 & B3

HD optical engine modified to add fueled natural gas pre-chamber for fundamental mixing & combustion data



<u>Pre-chamber injector abbreviations:</u>

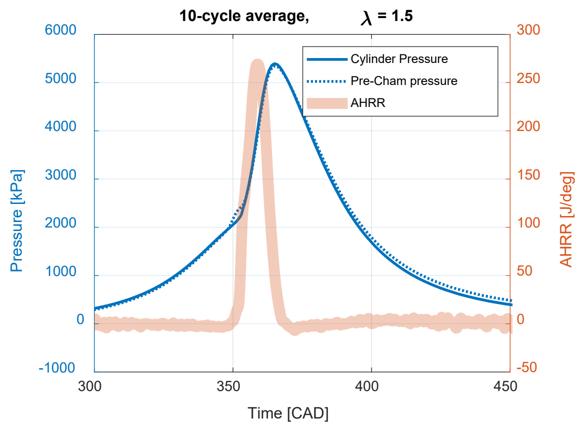
- SSE: Start of Solenoid Energizing
- ESE: End of Solenoid Energizing
- DSE: Duration of Solenoid Energizing

<u>1st generation pre-chamber</u>

- 3% of main-chamber volume
- Number of holes: 8
- Hole size: 1.6 mm
- Included angle: 130°
- Nozzle plane parallel to cylinder head
- Tip protrusion: 10.6 mm below the fire deck
- Fueling: GDI injector
- Pressure: uncooled piezoelectric
- Spark plug: miniature "Rimfire"

For stable (low COV) λ=1.5 unfueled pre-chamber, combustion imaging shows cycle-to-cycle variations

<u>Operating conditions</u>
- Speed: 600 RPM
- Spark: 343 CAD
- Lambda: 1.5
- IMEPg: 543 kPa
- IMEPg COV: 1.7%

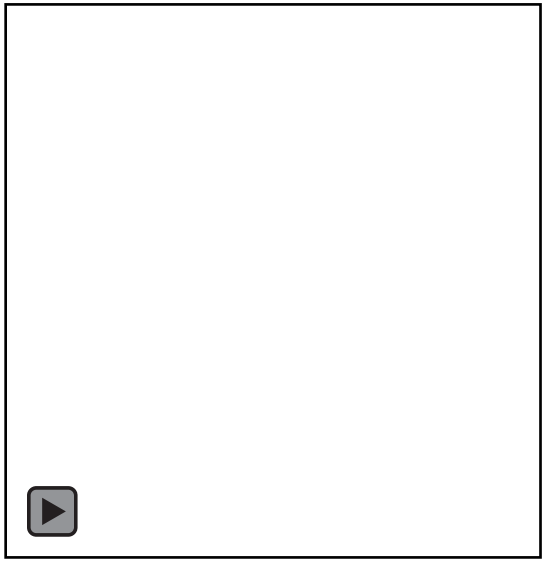


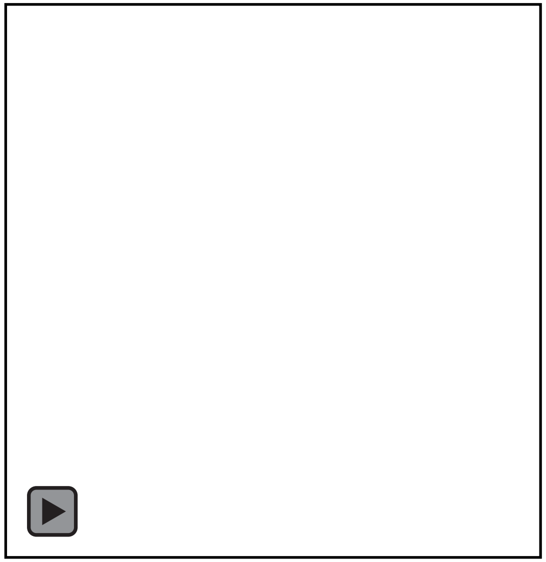
Visible Combustion Luminosity Imaging
(broadband chemiluminescence, no filtering)

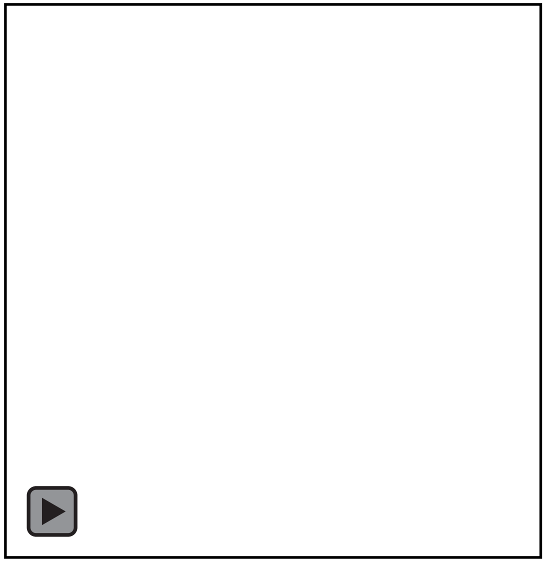
- Pre-chamber pressure rises above main-chamber pressure after spark, indicating ignition
  - Later pressure differences may be partly due to thermal effects on uncooled transducer
- Large cycle-to-cycle variation in timing of individual jet ignition and luminosity of pre-chamber jets
  - Early luminosity fluctuates on-and-off in some jets

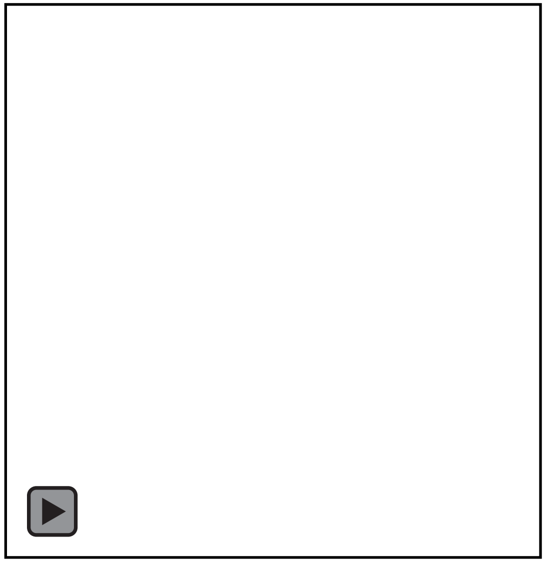
Imaging: increasing jet-to-jet & cycle-to-cycle variability, non-luminous pre-chamber jets w/ ignition delay at leanest mixtures

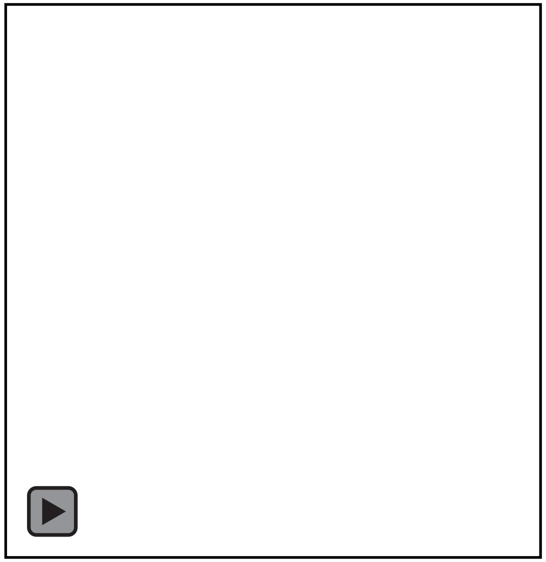
- Identical camera settings
- As with AHRR & pressure rise, combustion luminosity is weaker with increasing λ
- At λ>=1.7, no consistent luminosity from pre-chamber jets before main-chamber ignition
  - Transition of ignition mechanism from actively burning jets to diesel-like ignition delay



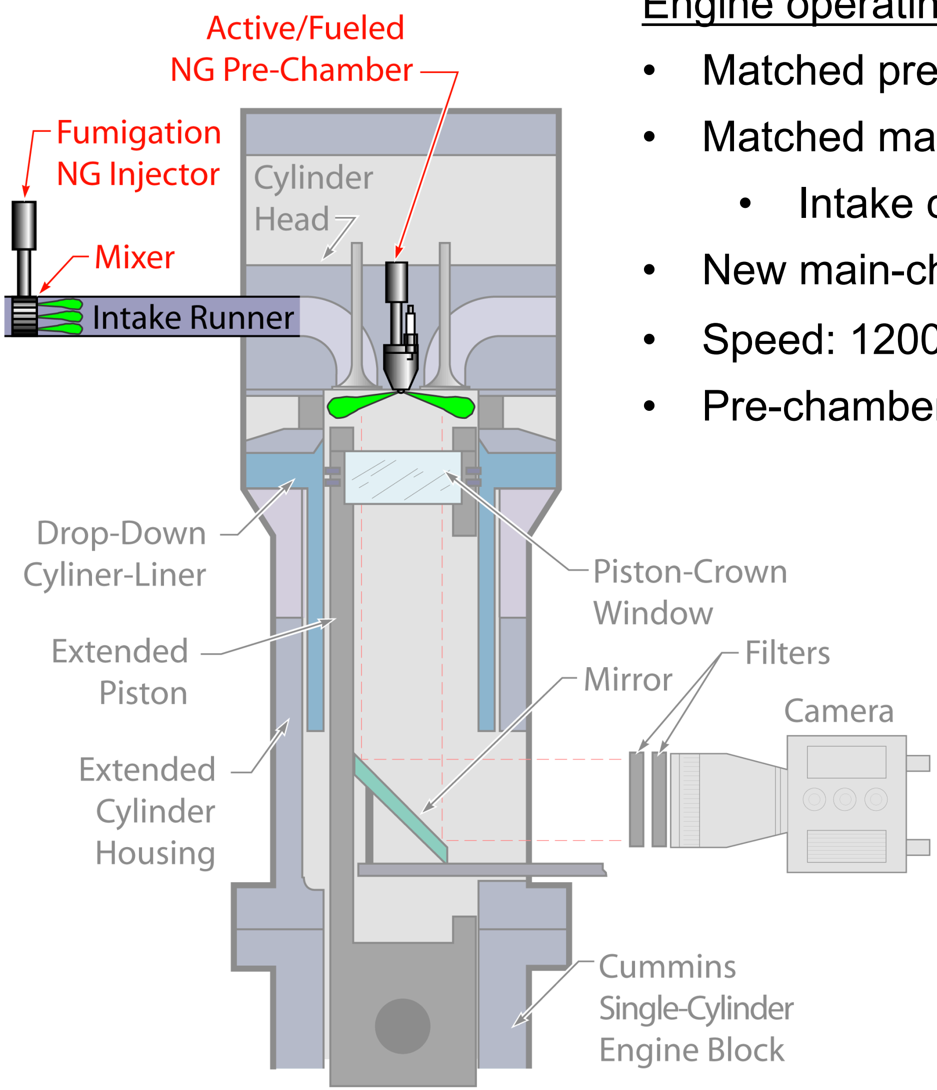








Second round of optical experiments use common pre-chamber design (ANL, NREL, SNL) and target operating conditions



Engine operating conditions:

- Matched pre-chamber design (from ANL, NREL also)
- Matched main-chamber conditions at spark:19bar, 730K
  - Intake conditions: 1.05bar, 314K
- New main-chamber fueling: fumigation in intake runner
- Speed: 1200 rpm
- Pre-chamber spark timing: 343 CAD

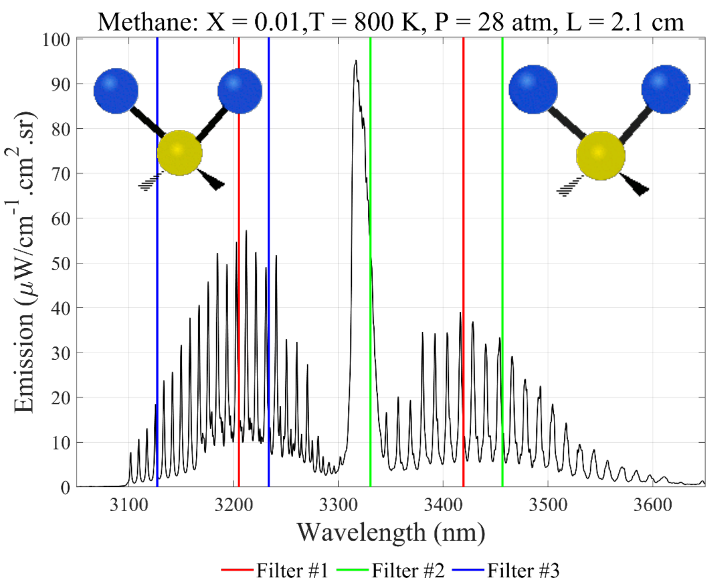
Parameter sweeps:

- Prechamber-only fueling
  - SSE 270-240 CAD at λ_{pre} = 1.45
  - λ_{pre} 0.61-1.84 at SSE = 270 CAD
  - λ_{pre} 0.75-1.65 at ESE = 337 CAD
- Unfueled pre-chamber
  - λ_{main} 1.5-1.7
- Fueled pre-chamber
  - λ_{pre} 0.49-1.65 at λ_{main} = 1.65
  - λ_{main} 1.65-2.60 at λ_{pre} = 0.93

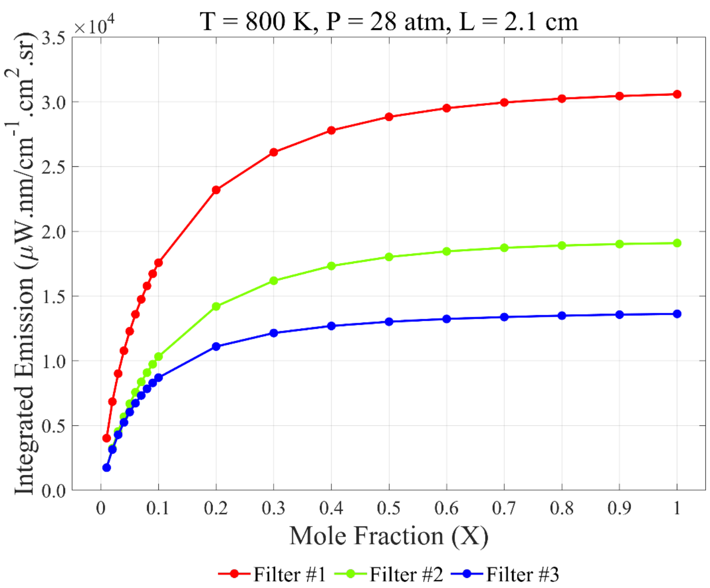
Infrared (IR) emission imaging: combustion or compression-heating increases vibration of C-H bonds in hydrocarbons

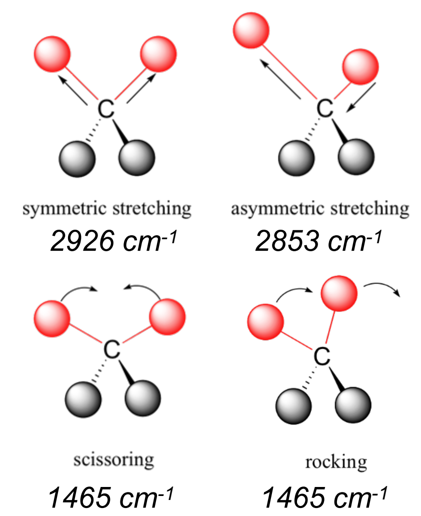
- All hydrocarbons, including natural gas components (methane, ethane, ethylene, acetylene, propane, etc.) emit in the infrared near 3.3 μm (3000 cm^{-1}) due to thermally excited vibration of C-H bonds, or "C-H stretch"
- Emission is strong enough for imaging when heated by compression to ~700 K or more, providing a means to quickly and easily detect hot in-cylinder fuel
  - IR emission signal is strongly dependent on temperature, and begins to saturate approaching stoichiometric natural gas, so IR intensity must be interpreted with care

HITRAN based Simulated Emission Spectrum



Integrated Emission Intensities for Quantification





Unfueled pre-chamber misfires for $\lambda_{Pre} = \lambda_{Main} > 1.70$; $\lambda_{Pre} = 0.93$ pre-chamber extends lean limit beyond $\lambda_{Main} = 2.40$

- At $\lambda_{Main}=1.70$, OH* chemiluminescence images throughout main chamber are much more luminous for fueled ($\lambda_{Pre} = 0.93$) than unfueled ($\lambda_{Pre}=1.70$) pre-chamber

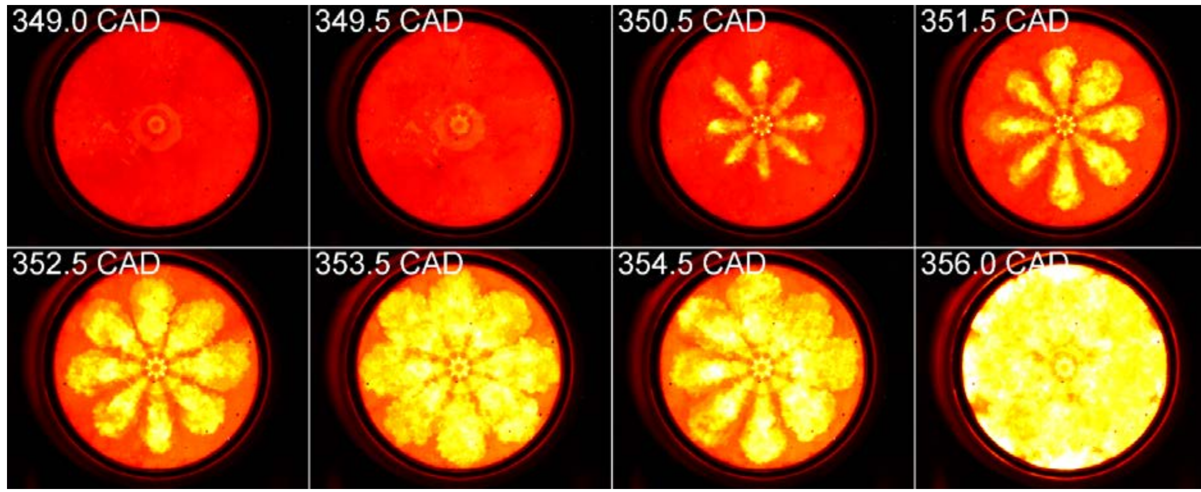
Unfueled Pre-Chamber

Fueled Pre-Chamber

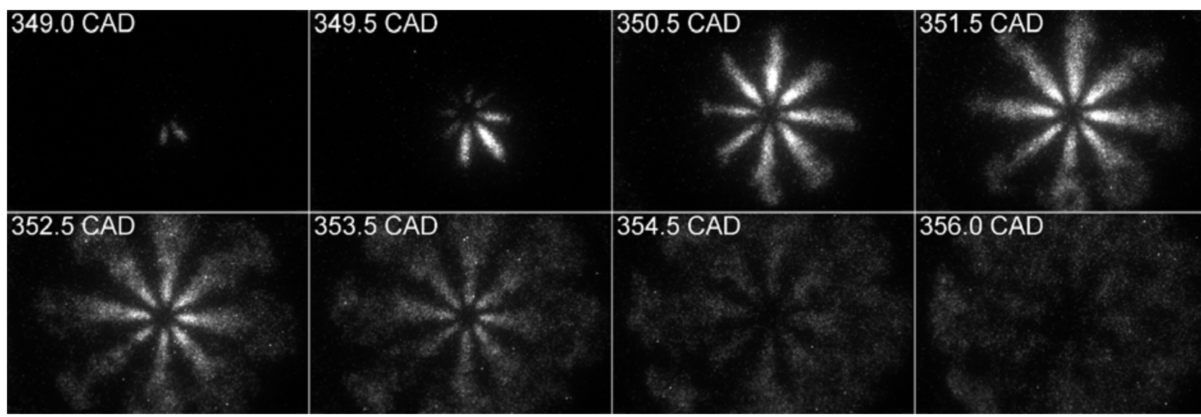
Fueled pre-chamber, λ_{Pre} = 0.93, λ_{Main} = 2.60: distinct flame propagation not apparent in OH* chemiluminescence

- Cycle-to-cycle variability in main-chamber ignition for IR images (not due to pre-chamber)
  - OH* images are from single cycle; IR image sequence assembled from one per cycle
- IR and OH* show progression of combustion through main chamber, but flame not distinct

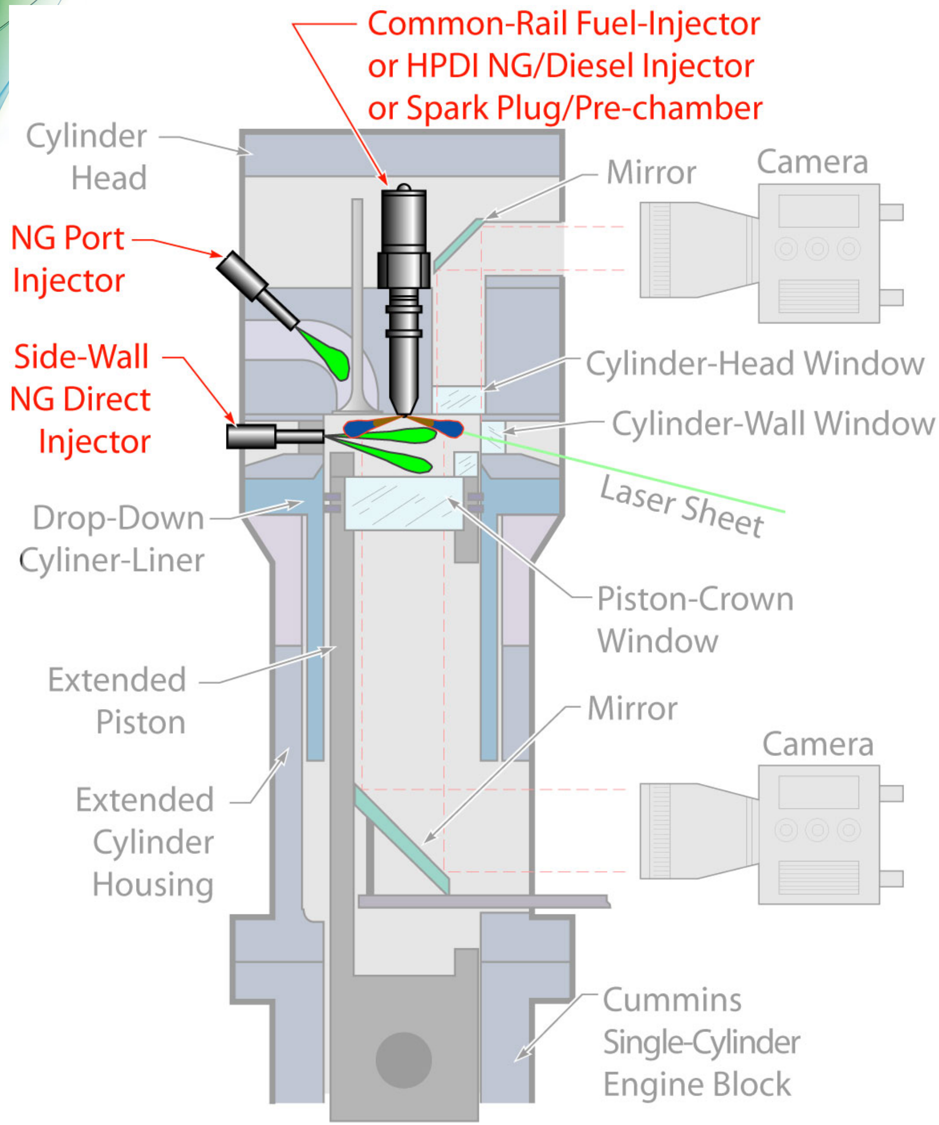
Infrared Imaging



OH Chemilum.*



Future work for HD optical engine with active natural gas pre-chamber for fundamental mixing & combustion data

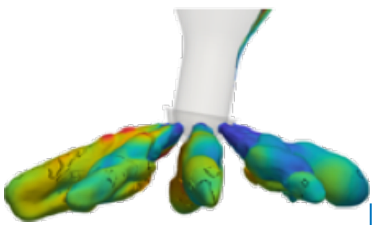


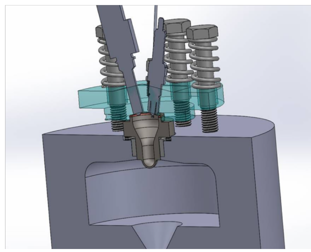
Next Steps:

1. Complete design and fabrication of third-generation pre-chamber assembly with automotive-scale spark plug, improved sealing, and improved clamping
2. Gather engine performance and combustion imaging data along the EGR dilution and/or lean-mixture limits to characterize the in-cylinder processes affecting stability and efficiency
3. Utilize other laser/imaging diagnostics to measure additional in-cylinder quantities
   a) Infrared and/or fuel-tracer imaging for penetration/spreading-angle of reacting and/or non-reacting pre-chamber jets
   b) Combustion radical chemiluminescence and/or fluorescence imaging for ignition/combustion location and mode of propagation

Approach

Modular PCSI designs with as much commonality as possible are used across all platforms





Simulation ↔ **Bench Scale** ↔ **Single Cylinder** ↔ **Multi Cylinder**

Simulation

Engine Sim. (ANL)
High fidelity CFD focusing on PCSI output mixing, with ignition and flame propagation models.

Chamber Sim. (NREL)
Zero dimensional (0D) and CFD map PCSI composition output to explore main chamber ignition sensitivity.

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Technical Accomplishments and Progress

B1: Science base
B2: Dilution
B3: Pre-ignition

PCSI adapted multi-cylinder engine enables dilution tolerance and thermodynamic studies

OAK RIDGE National Laboratory

- ORNL adapted a prototype modular MAHLE PCSI design to the DD13… a robust system with engineering support was necessary, while still allowing links to ANL metal and SNL optical single cylinder engine studies, and ANL simulations

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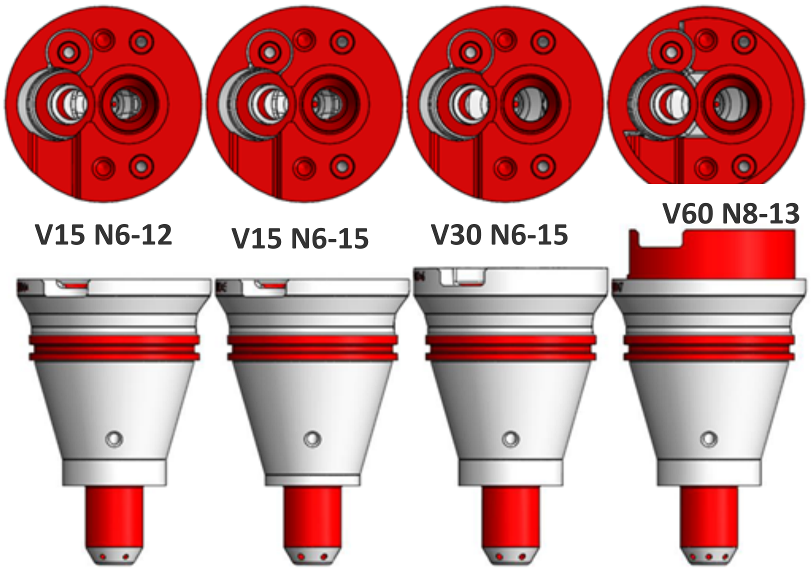
B3: Pre-ignition

PCSI adapted multi-cylinder engine enables dilution tolerance and thermodynamic studies

Prototype MAHLE PCSI modules

	V15 N6-12	V15 N6-15	V30 N6-15	V60 N8-13
Volume	1.5 cc	1.5 cc	3.0 cc	6.0 cc
# of nozzle holes	6	6	6	8
Nozzle hole diam.	1.2 mm	1.5 mm	1.5 mm	1.3 mm

Pre Chamber Bodies for MCE DD13



All data and images on this page is covered under the following patents: US9353674, JP6383820

- ORNL adapted a prototype modular MAHLE PCSI design to the DD13… a robust system with engineering support was necessary, while still allowing links to ANL metal and SNL optical single cylinder engine studies, and ANL simulations
- **Focused dilution tolerance studies** will link with single-cylinder studies and simulations
- **1st and 2nd law studies** will provide insight on how PCSI shifts thermodynamic balances and to understand what additional opportunities for improved efficiency exist
- Will provide **exhaust composition data to MOC study**

MCE: Multi-cylinder engine

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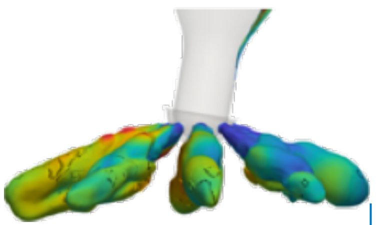

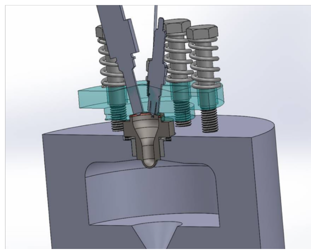

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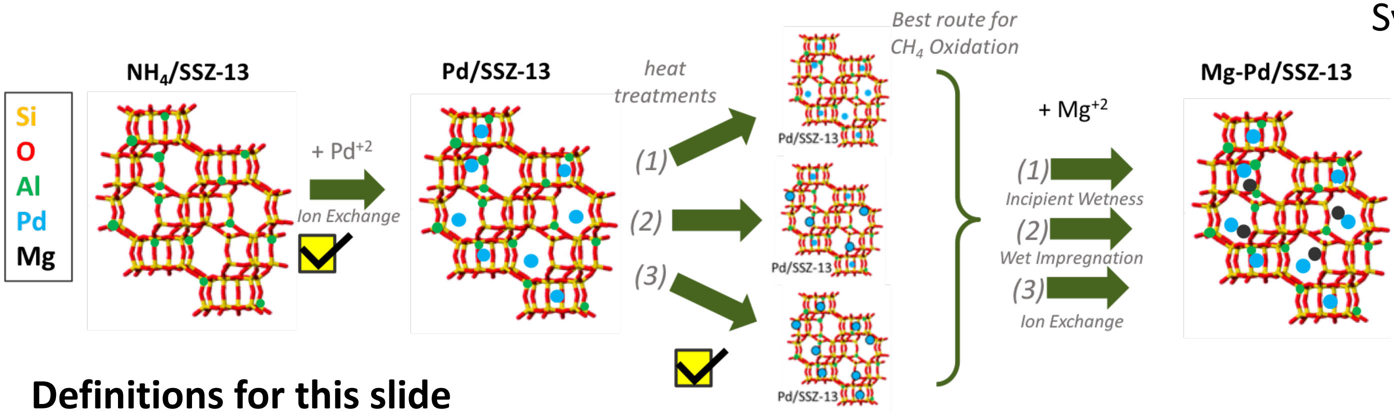
Technical Accomplishments and Progress

Developing new Methane Oxidation Catalyst (MOC) for low temperature CH4 conversion



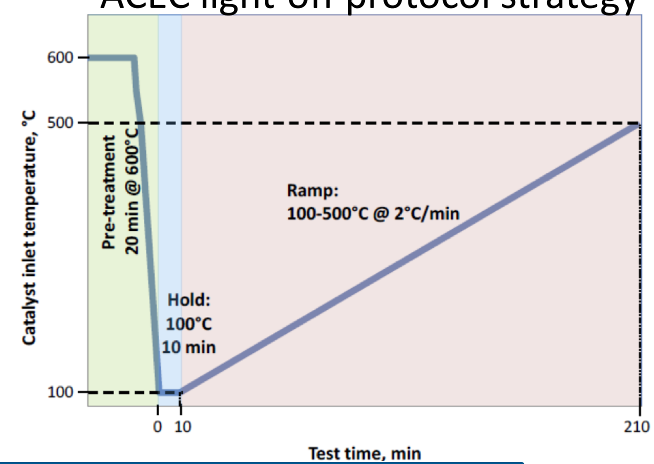
Synthetic exhaust composition

	Lean-MOC
	[200 $L_{flow}/(g_{cat}*h)$]
H_2O	12%
O_2	9%
CO_2	6%
CH_4	3000 ppm
CO	2000 ppm
NO	500 ppm
Ar	Balance

Definitions for this slide

Al: Aluminum
Ar: Argon
cat: Catalyst
CH_4: Methane
CO: Carbon monoxide
CO_2: Carbon dioxide
g: Gram
h: Hour
H: Hydrogen (chemical element)
H_2O: Water
L: Liter
Mg: Magnesium
min: Minute
NH_4: Ammonium
NO: Nitric oxide
O: Oxygen (chemical element)
O_2: Oxygen (molecular allotrope)
Pd: Palladium
ppm: Parts per million
Si: Silicon
SSZ-13: Aluminosilicate zeolite mineral possessing 0.38 × 0.38 nm micropores

ACEC light-off protocol strategy



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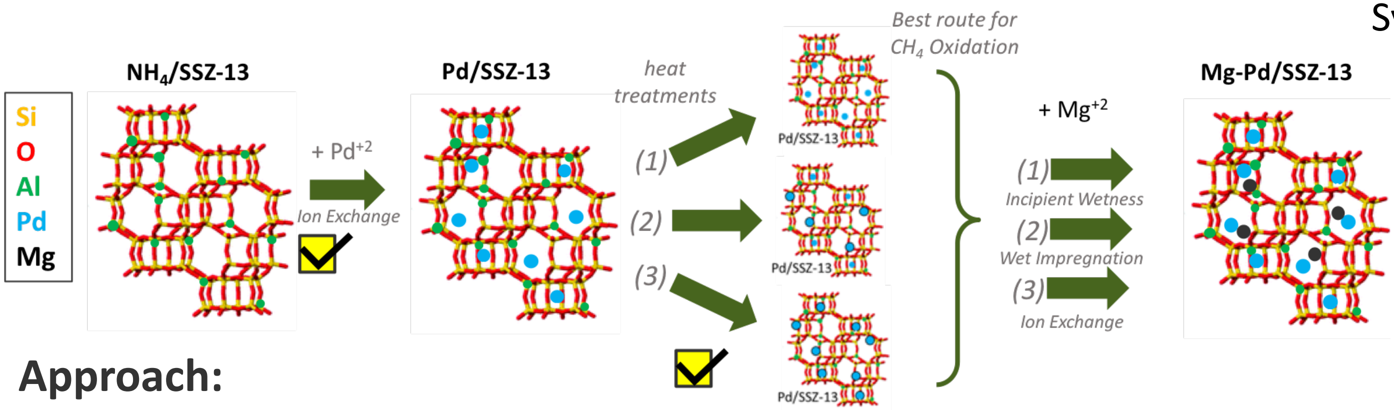

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Ar	Balance

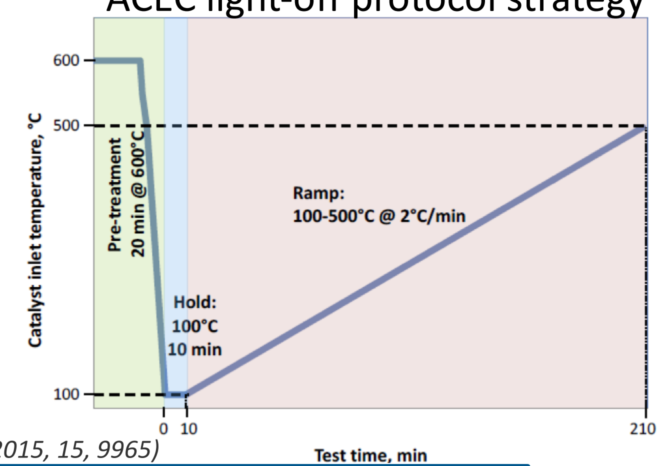
Approach:

- ORNL synthesized a series of catalysts to lower light-off temperature of methane (CH_4) oxidation
  - modifying the Pd active site to promote H abstraction using Mg

Accomplishments:

- Completed synthesis of Pd/SSZ-13 and Mg /SSZ-13
- Examined multiple calcination and hydrothermal treatments
- Evaluated MOCs on a gas flow reactor using a synthetic exhaust flow for a lean natural gas engine
  - Followed U.S. DRIVE (ACEC) catalyst protocol

ACEC light-off protocol strategy



Modified base Si-O chabazite cage structure from (Martin, N.; Moliner, M.; Corm, A. Chem. Commun., 2015, 15, 9965)

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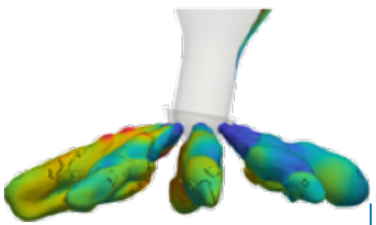

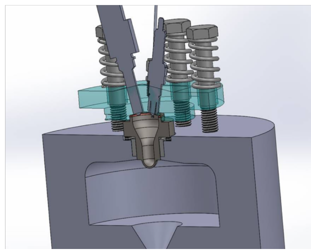

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Remaining Challenges and Barriers

While the ANL, NREL, ORNL, and SNL research tasks are highly collaborative and integrated, they are still low TRL in nature…

B1: Science base
- We are developing a fundamental science base and simulation tools to predict fluid-mechanical and chemical-kinetic processes governing PCSI

B2: Dilution
- Our conclusions will apply generally to design of PCSI for highly dilute / lean combustion, rather than to specific hardware / strategy optimization

B3: Pre-ignition
- Although insight will be gained, fully addressing pre-ignition at high loads is outside the scope

B4: CH4 catalysts
- We will have bench-scale MOC research, but not full catalyst development or engine integration

Additional research and development is necessary for industry to commercialize high efficiency NG engine based on PCSI.

Summary: Fundamental experiments & simulation to improve PCSI MD/HD NG engine systems

- ANL, NREL, ORNL, and SNL are collaborating to **identify, understand, and simulate fundamental phenomena that limit** pre-chamber spark-ignition (PCSI) system efficiency for MD/HD natural gas engines
- The project uses **simulations and coordinated experiments** to connect bench-scale and single-cylinder facilities to practical multi-cylinder engine and emissions-control hardware
- To **extend the lean/EGR dilution limits and/or shorten the burn duration**, modes of jet-ignition and resulting progression of main-chamber combustion must be **better understood and then predicted through simulation**
- To reduce emissions-control constraints on engine operating conditions, **factors controlling methane oxidation** must be better understood and new approaches must be developed to **extend the low-temperature limits of catalysts**
- Initial results have pointed toward unexpected in-cylinder jet-to-jet variability, certain inadequacies of state-of-the art models, and encouraging directions for new methane oxidation catalysts

This project is a collaboration between ANL, NREL, ORNL, and SNL. The project team members wish to thank Kevin Stork and DOE Vehicle Technologies Office for support of this research.

Thank You

www.nrel.gov

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Transforming ENERGY

Cummins Westport
The Natural Choice

2019/20 NG Products

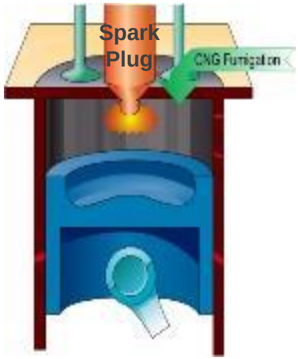
Yemane Gessesse

Feb 4, 2020

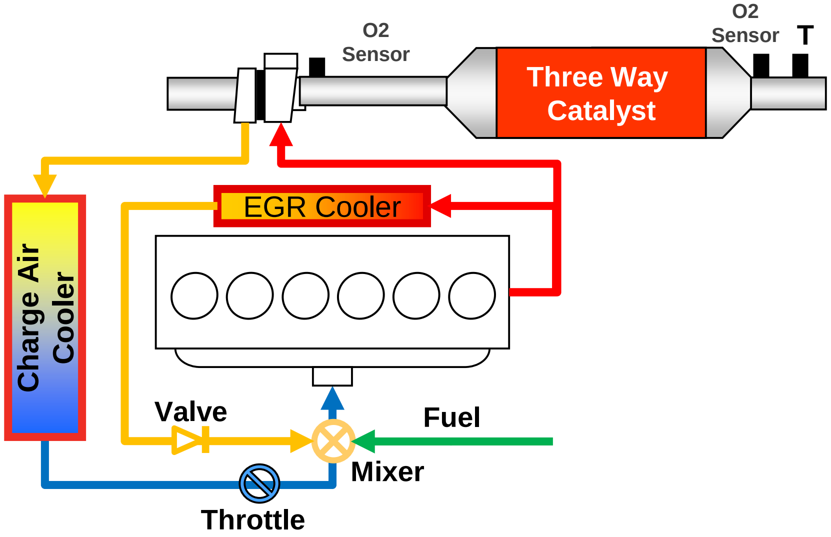
Cummins Westport Products

- CWI Natural Gas Engines
  - 8.9L in 2007 at 0.2 gm NOx, 0.02 gm in 2017
  - 11.9L in 2013 also at 0.2gm NOx, 0.02 gm in 2018
  - 6.7L in 2016 at 0.1gm NOx, 0.02 gm in 2020
- Predominant presence in North America
  - EPA/CARB compliant
  - Euro VI Phase D (8.9L only)
- Some global presence
  - Europe, South America, India and China

Cummins NG Engine Architecture



Spark Ignited



- Cummins Westport engines feature spark ignition with Stoichiometric / EGR combustion
- This combustion technology was introduced in 2007 with the ISL G, the first heavy duty engine to meet the EPA 2010 standards (0.2 g/bhp-hr NOx, 0.01 g/bhp-hr PM)
- ***SEGR Technology capability provides pathway to Near Zero NOx and GHG emissions***
- Cummins Westport engines are factory built, natural gas engines that are based on Cummins diesel engine platforms with nearly 80% parts commonality

Move to Zero … new for 2020

- ✓ **Certified to Near Zero**
- ✓ **On-Board Diagnostics**
- ✓ **EPA/ARB Ultra Low emissions certification**
- ✓ **Lowest Emission MD and HD engines in North America**

CNG LNG RNG

ISX12N™

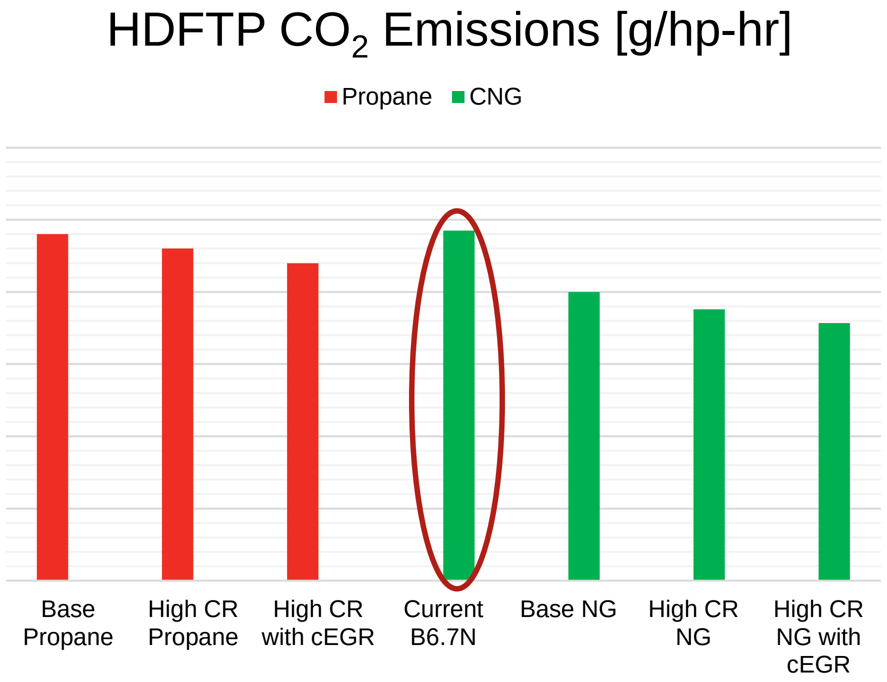
L9N™

B6.7N™

Certified to Near Zero (Optional Ultra Low) NOx 0.02g/bhp-hr

Cummins Westport

MD Engine CO_2 Potential



240 to 260 hp (nominal range)

Propane

- R&T based Propane engine
- High CR will bring it down by ~4-6%
- Another ~5% benefit due to cEGR

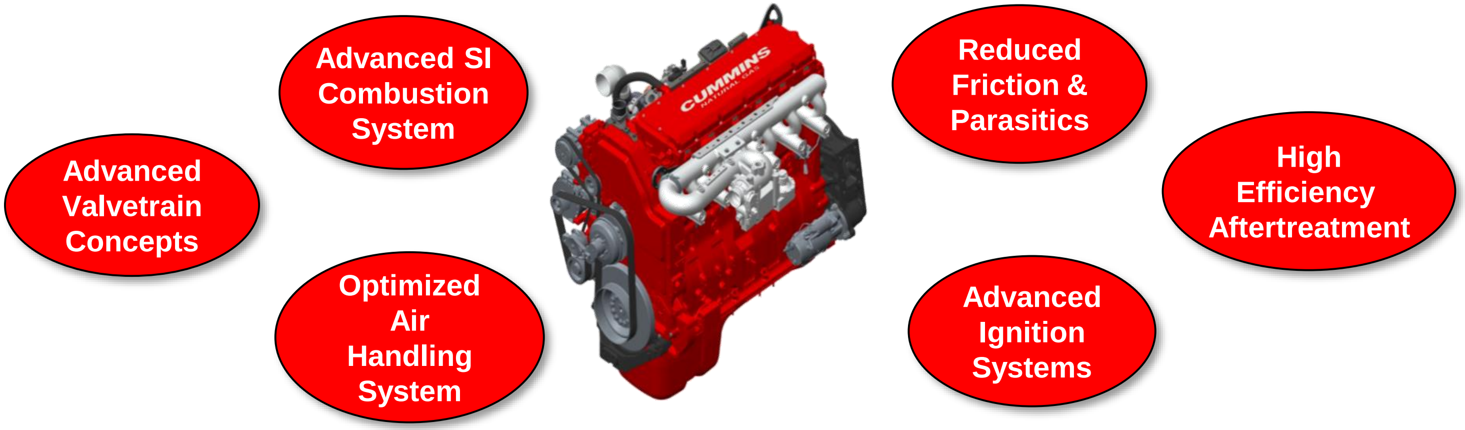
Natural Gas

- Current B6.7N engine
- R&T based NG will be ~20% lower
- Higher CR will bring it down 4-6%
- Another 5% benefit due to cEGR

HD Engine Research Program Objectives

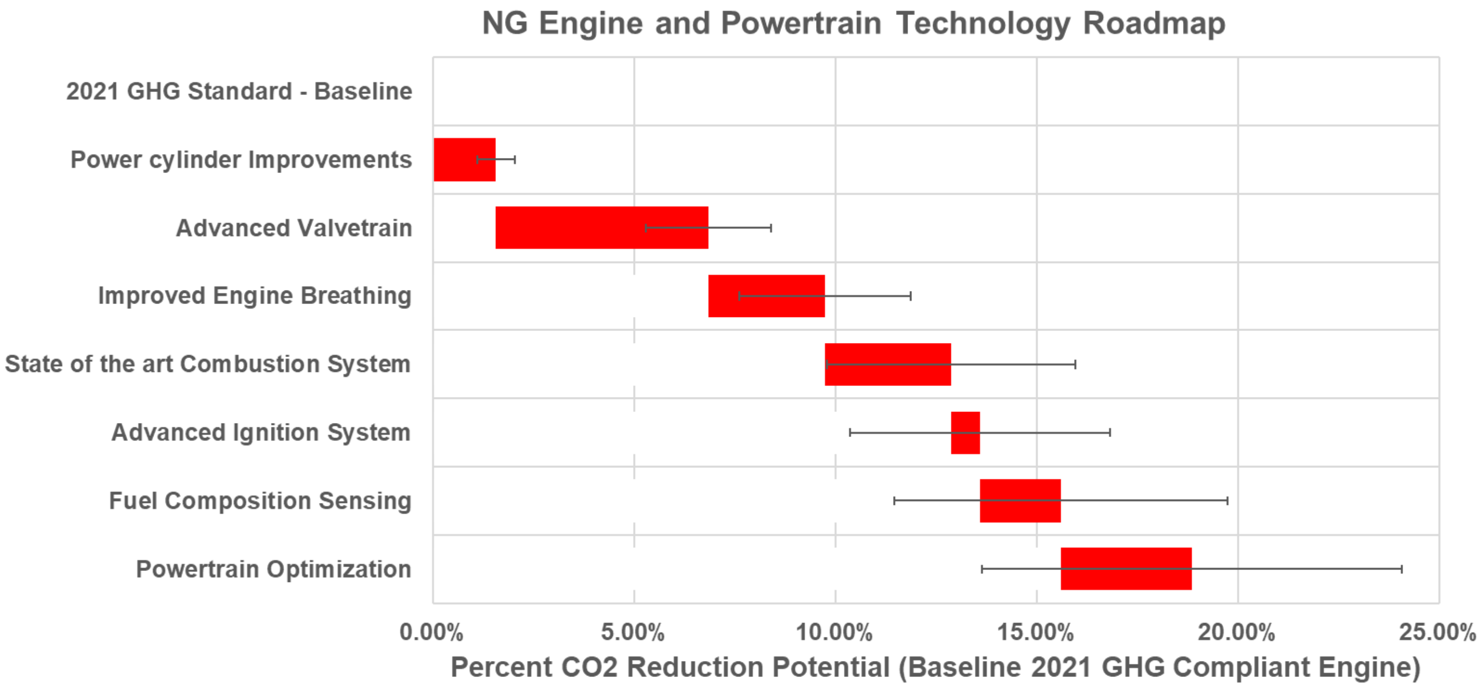
- Natural gas specific combustion system design that utilizes optimized charge motion and cooled Exhaust Gas Recirculation (EGR) that is building upon a proven high cylinder pressure capable heavy-duty base engine platform in the 12 to 15 liter displacement range.
- Demonstrate a 10%-16% cycle average (RMCSET) and peak efficiency improvement.
- Maintain 0.02 g/bhp-hr NO_X capability with a plan to reduce aftertreatment cost.
- Demonstrate a diesel like torque curve rating of 450-500 bhp and 1550-1800 lb-ft peak torque.
- Develop an engine integrated on a global platform to enable up to 20% system cost reduction.

Architecture Selection



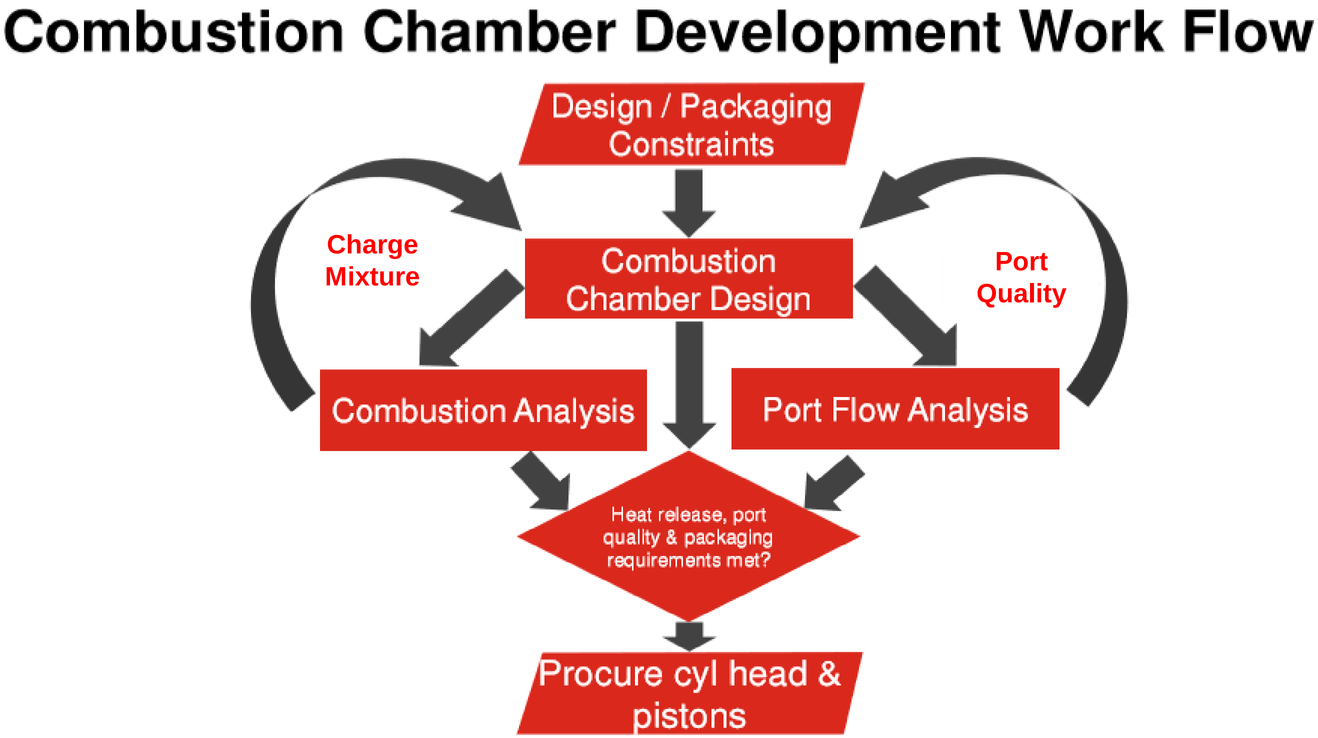
- DOE/CEC/SCAQMD/Cummins Funded
- Improve Efficiency 10-16% over current product
- Provide diesel like torque curve

CO_2 Reduction Potential



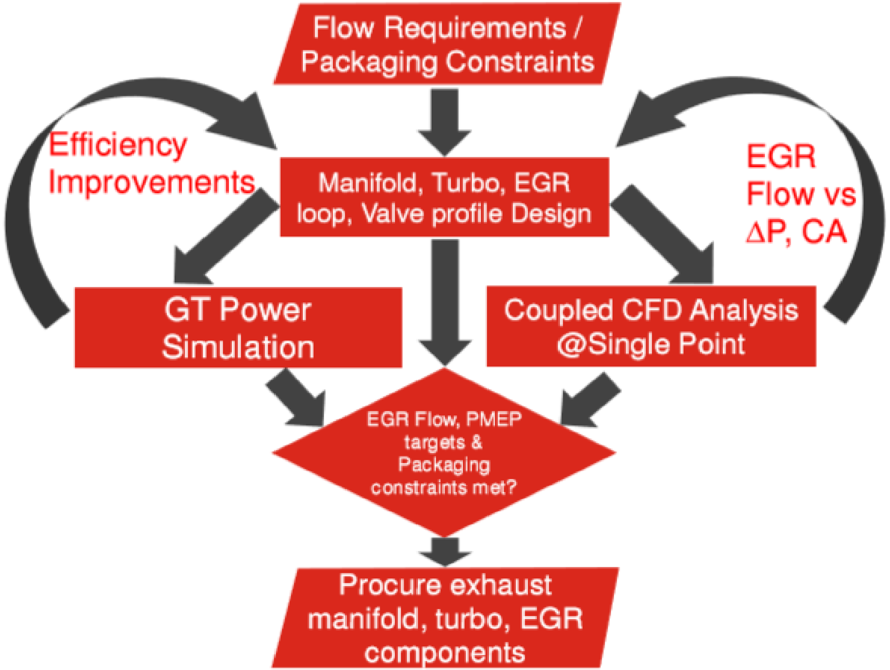
Error bars represent stack-up of uncertainty while chart values represent average estimated improvements

Charge Motion Combustion Chamber Optimization

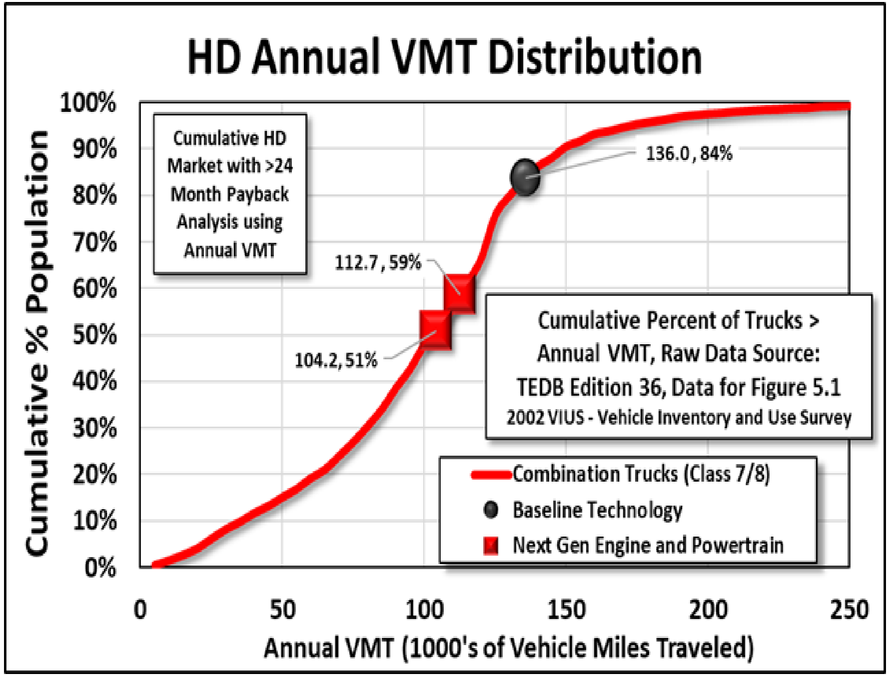


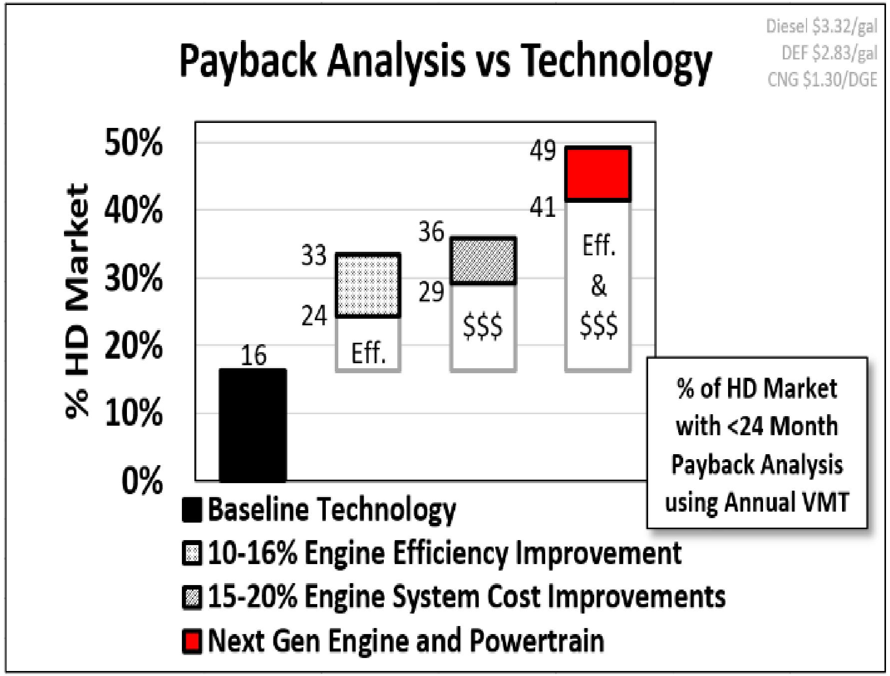
Air Handling System Optimization

Engine Efficiency Improvement Work Flow

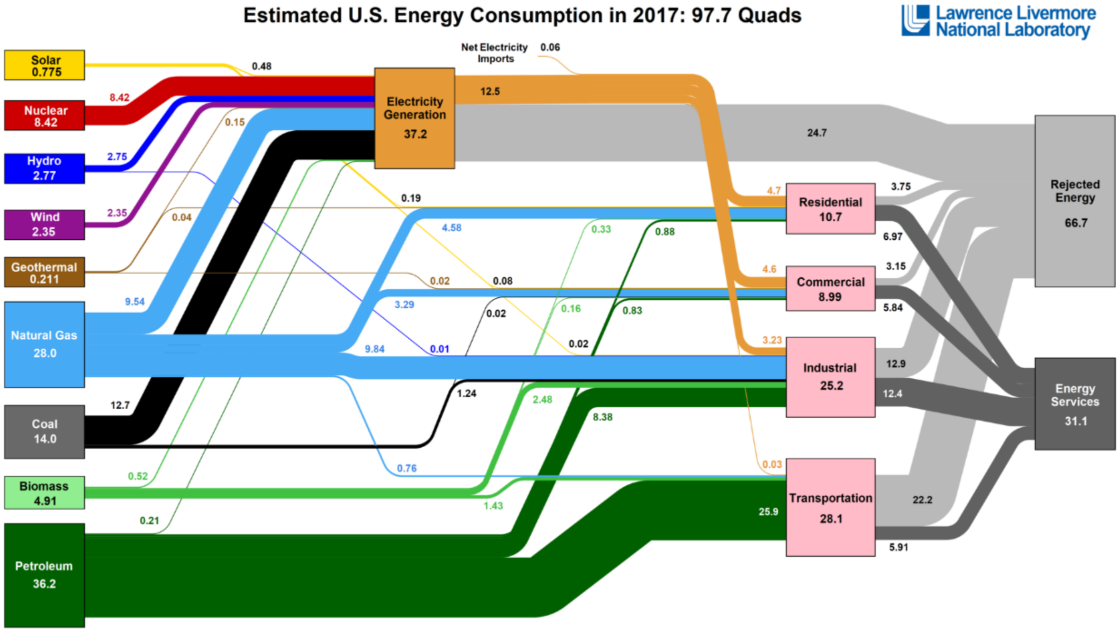


Impact of Efficiency and Cost on Market Potential





Laurence Livermore Energy Flow Chart for USA



Source: LLNL April, 2018. Data is based on DOE/EIA MER (2017). If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. This chart was revised in 2017 to reflect changes made in mid-2016 to the Energy Information Administration's analysis methodology and reporting. The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 65% for the residential sector, 65% for the commercial sector, 21% for the transportation sector, and 49% for the industrial sector which was updated in 2017 to reflect DOE's analysis of manufacturing. Totals may not equal sum of components due to independent rounding. LLNL-MI-410527

- Coal, Natural gas and Nuclear power produced the bulk of the electricity in 2017
- Petroleum was used for Internal combustion engines and for industrial application predominantly
- Aggregate efficiency of the electric power generation is at 33% while that for transportation is at 21%
- Converting transportation to EV will require increasing the Electricity generation capacity significantly

Questions

Development, Demonstration and Testing of Low-NOx Natural Gas Engines in Port Yard Trucks w/ Development of Innovative Gas Composition Sensor

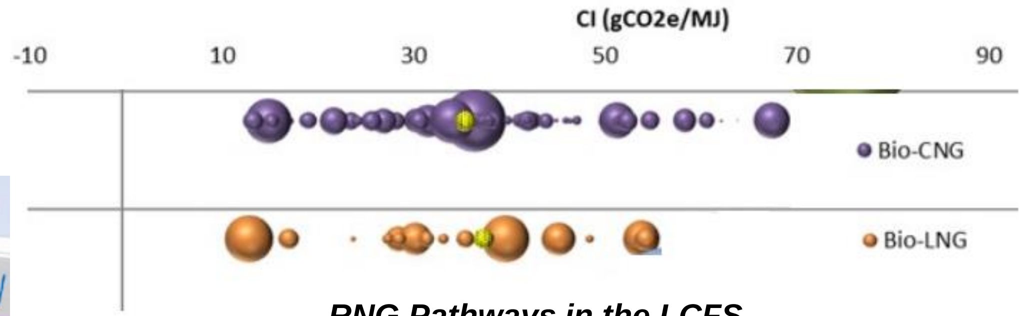
CEC PIER Grant #PIR-16-016

Natural Gas Vehicle Technical Forum

February 4, 2020

Prime Contractor: GLADSTEIN, NEANDROSS & ASSOCIATES

Subcontractor: UCR College of Engineering- Center for Environmental Research & Technology



RNG Pathways in the LCFS

GNA Overview

CORE SERVICES

Technical
GNA helps vehicle and equipment managers implement clean fuel development strategies.

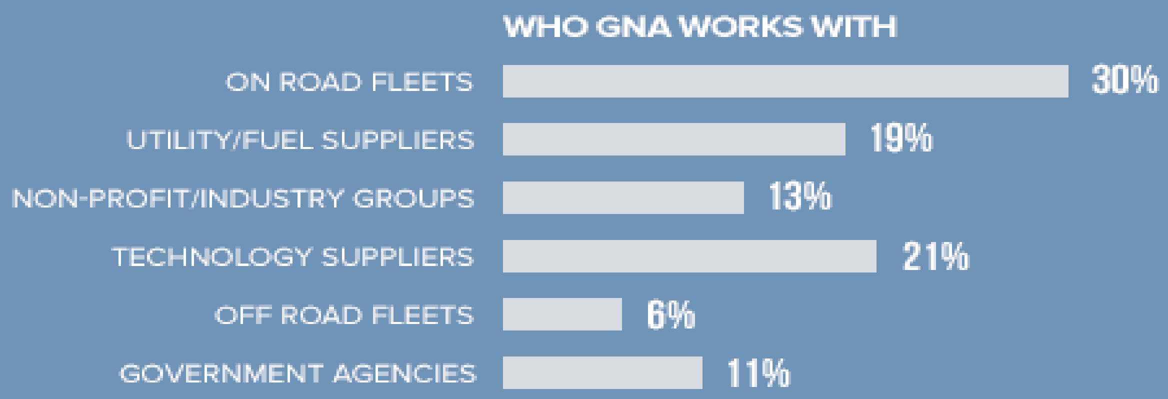
Funding
GNA helps companies track, evaluate, and apply for funding programs.

Creative
GNA Creative offers a full suite of communications, design, and media services.

Strategy
GNA has decades of expertise in energy, alternative fuels, and transportation.

25 YRS
of clean transportation experience

$606M
dollars in secured funding for clients



GNA produces major **clean transportation** conferences.

ACT EXPO
CELEBRATING 10 YEARS

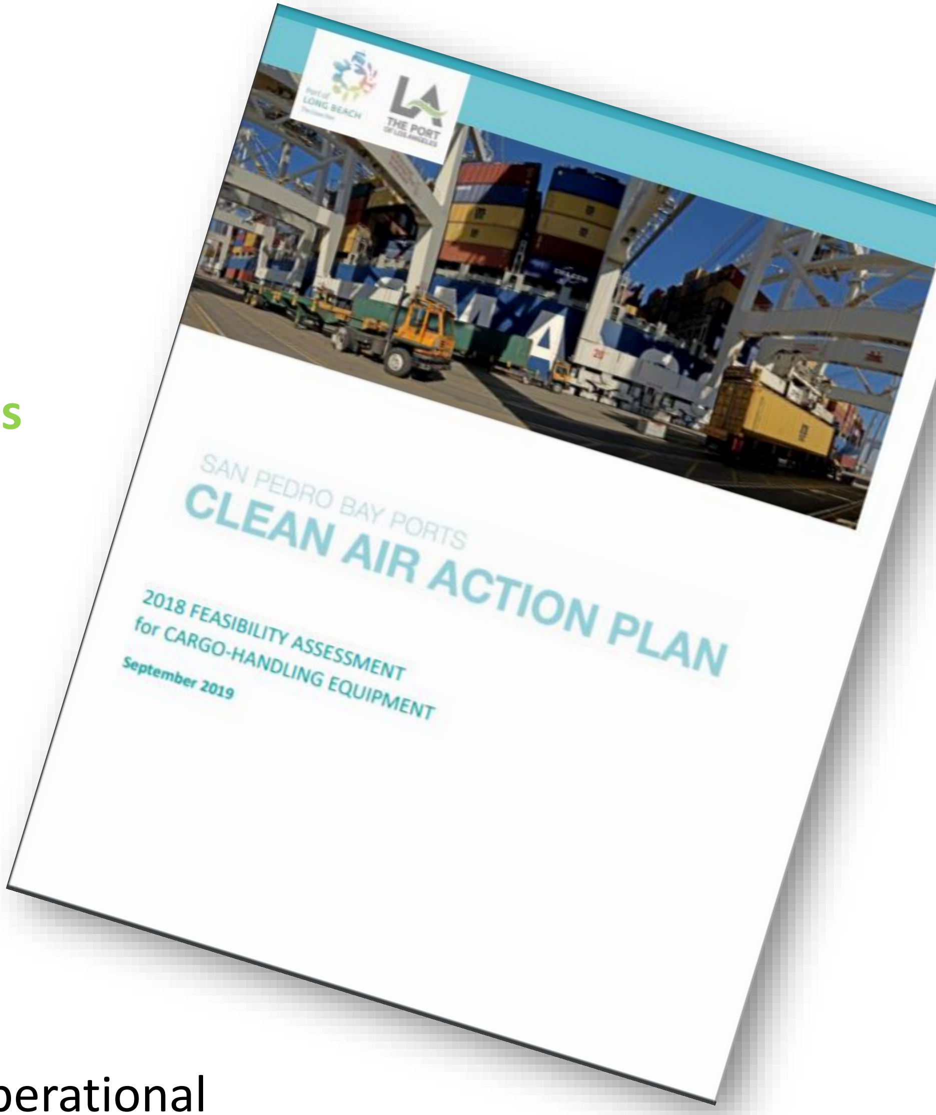
CONFERENCE MAY 11-14, 2020 EXPO MAY 12-13, 2020
LONG BEACH CONVENTION CENTER LONG BEACH, CALIFORNIA

3500+	650+	250+	60+	18+	125+
clean transportation stakeholders	registered fleet operators	sponsors and exhibitors	advanced vehicles on display	co-located industry events & workshops	expert industry speakers

Project Background and Purpose

- **Yard Trucks**:
  - ➢ Leading source of emissions at San Pedro Bay Ports
  - ➢ One focus of CAAP 2018 “Feasibility Assessment for CHE”
- **Key Conclusion of Assessment**: Yard tractors with **NZE natural gas** (and **ZE battery-electric**) architectures need <u>demo time</u> to prove they are truly “feasible” for broad-scale deployment by MTOs
- **Applicable CWI Low-NOx NG Engines:**

Engine	Displ.	NOx Cert	Yard Tractor Commercial Status	Units Deployed at SPBPs
L9N	8.9 L	0.02	Available since ‘16 (special order)	20 (initiated August 2019)
B6.7N	6.7 L	0.10*	Available since ‘18 (special order)	2 (initiated May 2019)



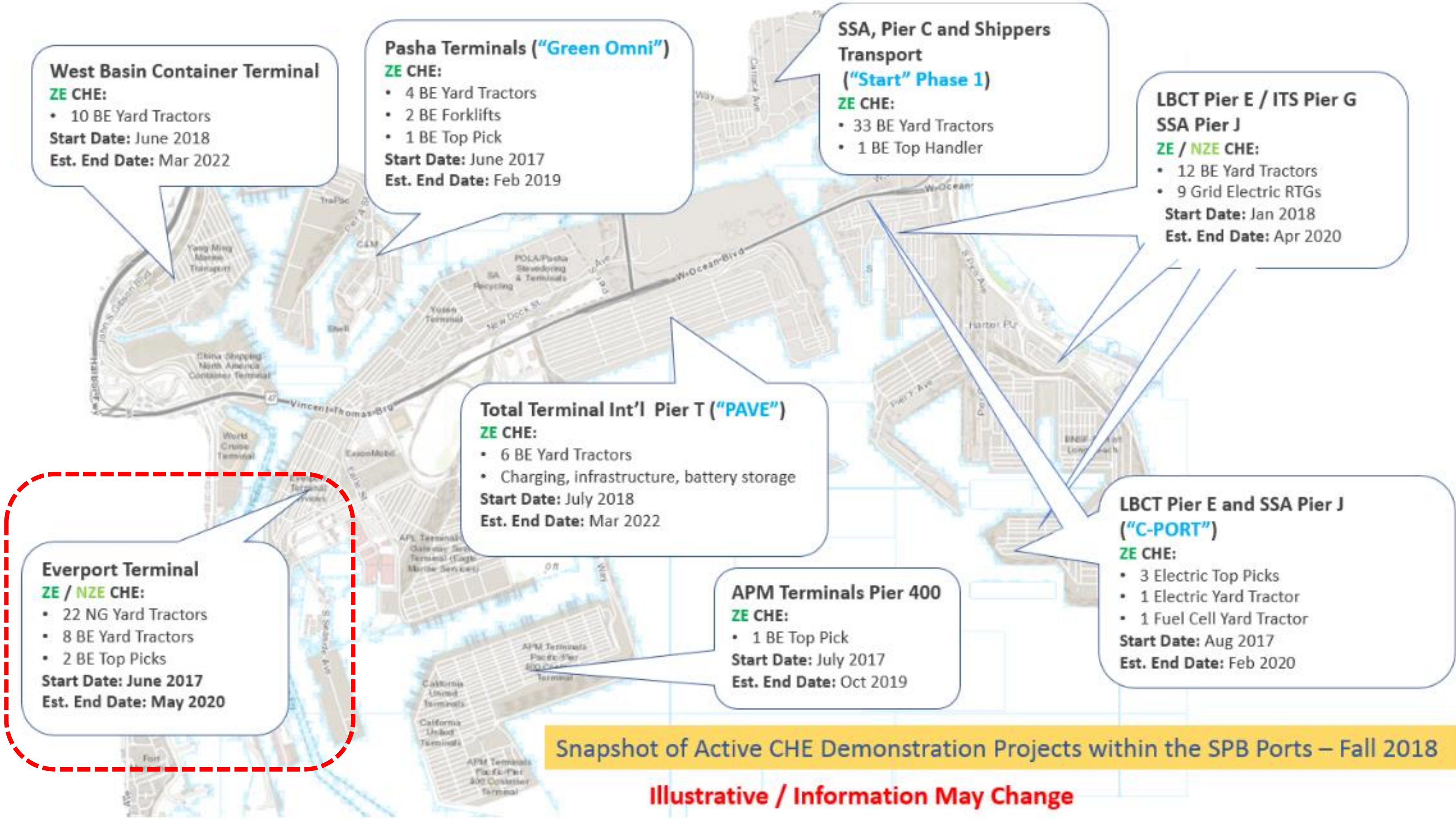
- **Status:** Neither engine has yet undergone sufficient real-world operational experience or in-use emissions testing (especially in an MTO CHE application)
- **Key Premise of Project**: 6.7L version is the more “right-sized” engine for yard hostler applications

Yard Hostlers: Workhorse CHE at Container Terminals

- A typical terminal at the San Pedro Bay Ports operates between 100 and 200 yard tractors.
- Units operated for 16-20 hours per day
- Refueled between shifts, consuming 20-25 DGE/shift
- LNG or other alt fuel implementations of yard tractors typically need to operate for **two shifts** in between fueling events due to mobile fueling challenges.

Context for CEC 6.7L LNG Yard Tractor (YT) Demo

- **SPB Ports**: strongly need demos of CHE with ZE / NZE architectures
- Many major demos are underway
  - ➢ Wide array of MTOs & CHE types
  - ➢ Most are just beginning
- **GNA/UCR 6.7L YT project:** part of broader CEC-funded demo at EverPort (POLA)
- Includes **22 Capacity LNG YTs**:
  - ✓ **20 units:** 8.9L CWI LNG engines certified to "NZE" 0.02 g/bhp-hr NOx
  - ✓ **2 units**: 6.7L "right-sized" CWI LNG engines certified to ONLS (certified to 0.1, but moving to 0.02)
- **GNA-UCR project** (PIR-16-016):
  - ➢ Focused on the two 6.7L units
  - ➢ Includes comparative in-use and chassis dyno testing of other YTs: 8.9L LNG, BEV, baseline diesel



Snapshot of Active CHE Demonstration Projects within the SPB Ports – Fall 2018

Illustrative / Information May Change

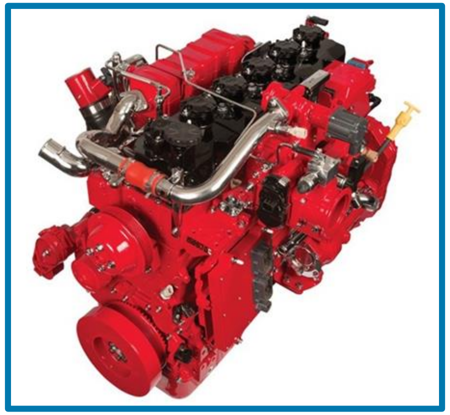
Project Background and Purpose

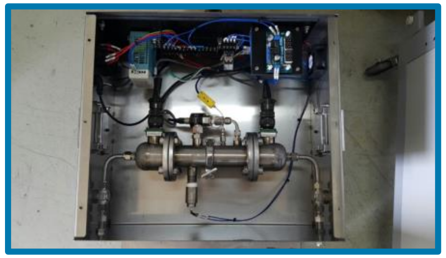
Three Overarching Project Objectives:

1) **Develop and demonstrate** two LNG yard hostlers with "right-sized" low-NOx CWI ISB6.7 G engines (feed into CAAP feasibility assessments)

2) **Conduct comparative emissions testing** (baseline diesel, LNG hostlers being delivered to EverPort with NZE 8.9L CWI engine)

3) **Develop and bench-test innovative gas composition sensor** technology under development by UCR CE-CERT





Overview: Major Tasks and Timeline

- Purchase / deploy two LNG hostlers with OLNS-certified ISB6.7
  - Help pave pathway for CWI to certify ISB6.7 to 0.02 ("NZE") Nox level
- Conduct comparisons* in real-world service at SoCal host site(s)
- Conduct emissions and performance testing* at UCR CE-CERT on chassis dyno
- Continue / advance CE-CERT's development and testing of NG sensor technology
  - Compare using samples of NG with varying composition
- <u>Project timeline</u>: ~32 months (ending in Q2 2020)

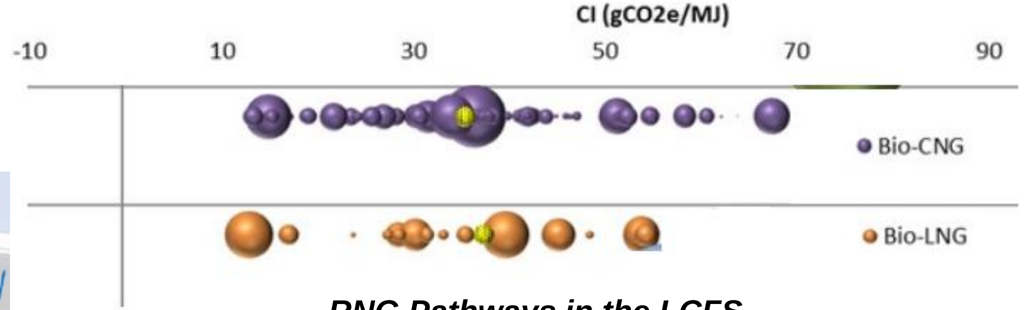
*Emissions / chassis testing as available from host site:
1) baseline diesel, 2) Capacity 8.9-L NZE, 3) 3) battery-electric

Part 1:

Field Demonstration of Two LNG Yard Hostlers with CWI 6.7L Engines Certified to CARB OLNS (0.10 g/bhp-hr)

Prime Contractor: GLADSTEIN, NEANDROSS & ASSOCIATES

Subcontractor: UCR College of Engineering- Center for Environmental Research & Technology



RNG Pathways in the LCFS

Project Technical Advisory Committee

- *GNA / UCR established a diverse **Technical Advisory Committee***
- *TAC members provided valuable guidance on 1) YT field demonstration and emissions testing, and 2) gas sensor functionality and bench testing*

Organization / Agency / Company	Role / Representing
South Coast AQMD - TAO	Government – Local
National Renewable Energy Lab	Government – Federal
Port of Los Angeles	Port Authority / Landlord
Pacific Merchant Shipping Association (PMSA)	Trade Org for MTOs
EverPort Terminal Services	End Users
California Cartage	
Cummins Westport, Inc.	Engine OEMs
Cummins Engine Company	
Clean Energy / CNGVP	RNG Provider / Trade Org
SoCal Gas	Local Gas Utility
Renewable Natural Gas Coalition	RNG Expert / Trade Org
California Energy Commission	Project Funder / Oversight
Gladstein, Neandross & Associates	Prime Contractor
UC-Riverside CE-CERT	Subcontractor

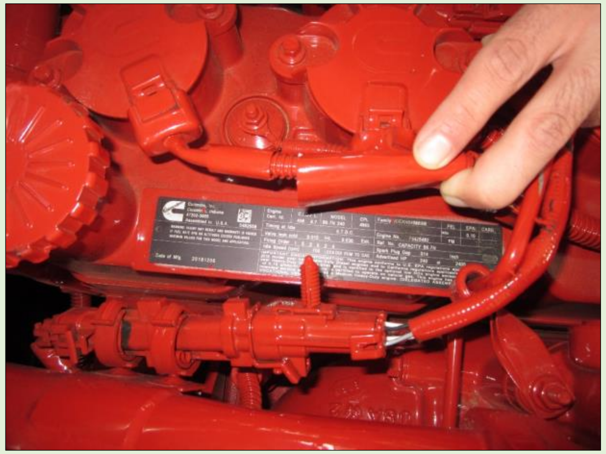
Pre-Demo Launch with Key Partners: ACT Expo, April 2019

Capacity Trucks: stepped up to manufacture LNG yard tractors, including the first two for port duty using CWI's 6.7L engine.

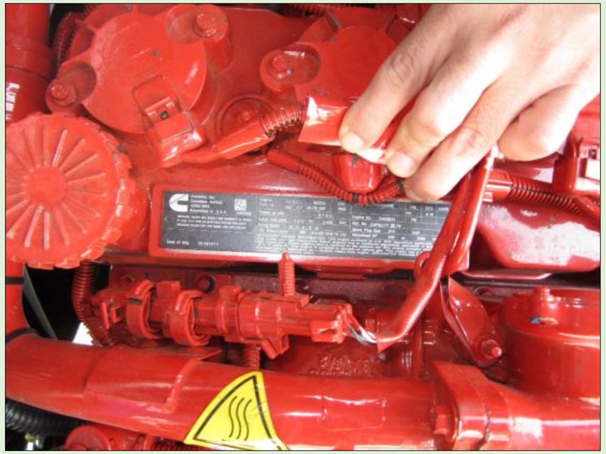
Everport Terminal Services: stepped up to demonstrate 22 LNG yard tractors in real-world CHE service.

Final Fuel System and Initial Receipt Testing: Agility (April 2019)

Truck No. 482



Truck No. 483



Demonstration Implementation: May 2019

Data collection focus: Portable Activity Monitoring Systems (PAMS)

- PAMS data loggers acquire CAN bus data from J1939 diagnostic ports
- **May 2019** at CalCartage (initial host site):

  -Configured PAMS loggers for Capacity LNG units
  -Installed on both 6.7L test units
- **July 2019** at Everport (permanent host site):

  -PAMS also installed on other YT types for comparative testing:

  √ Capacity baseline diesel (Cummins 2014)
  √ Capacity 8.9L LNG
  √ BYD battery electric UTRs

PAMS installed in J1939 port of Unit #483 LNG yard tractor

Tank Conditioning & Acceptance Testing @ CalCartage (May 2019)

Rear view of the Capacity chassis cab

CalCartage workers trained on LNG engine

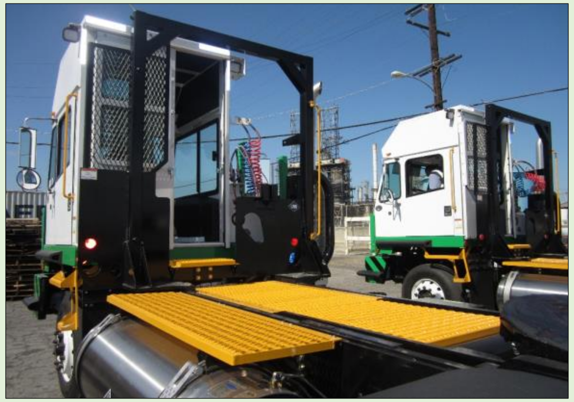
CalCartage worker fuels truck with Applied LNG's on-site "Orca" LNG fuel system

CalCartage's portable LNG fueling "Orca"

Chart LNG fuel tank (~75 DGE) receiving LNG

LNG tank registers 225 psi after fueling

Installation of PAMS, Host Site Training: CalCartage (May 8, 2019)



Trucks get Portable Activity Monitoring Systems (PAMS) installed; PAMS device plugged into the LNG UTR's J1939 port

GNA inspects Capacity UTRs and trains CalCartage drivers on UTR features and operational procedures.

LNG Unit No. 482 moves a full, extremely heavy 20-foot container at CalCartage.

LNG Unit No. 483 is connected to a container at CalCartage so GNA can observe warranty issue to address.

Results at CalCartage (Interim Host Site)

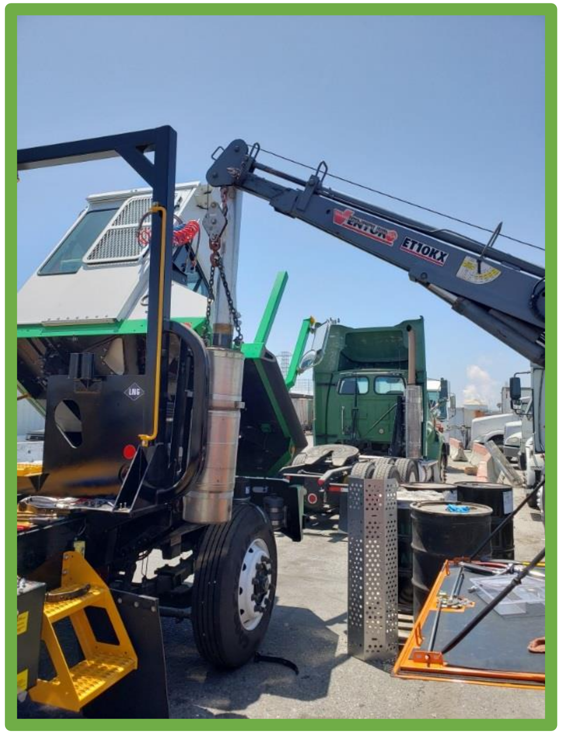
- **Operation:**
  - ✓ Approximately 100 hours logged on each tractor
  - ✓ CalCartage was in process of decommissioning its site
  - ✓ Significant downtime for warranty fixes **(pre-production units)**
- **Driver and Management Feedback:**
  - ✓ **Performance (driver comments):**
    - "As good as diesel"
    - "Very good," but "nothing is as good as diesel"
  - ✓ **Comfort: "**As good or better than diesel"
  - ✓ **Ergonomics / Layout:** numerous small suggestions about design improvements (Kalmar fleet, evaluating Capacity for first time)
  - ✓ **Ease of Fueling:** comparable to old LNG units, slower than diesel
  - ✓ **Ability to Accomplish 2 Shifts:** not measured at CalCartage

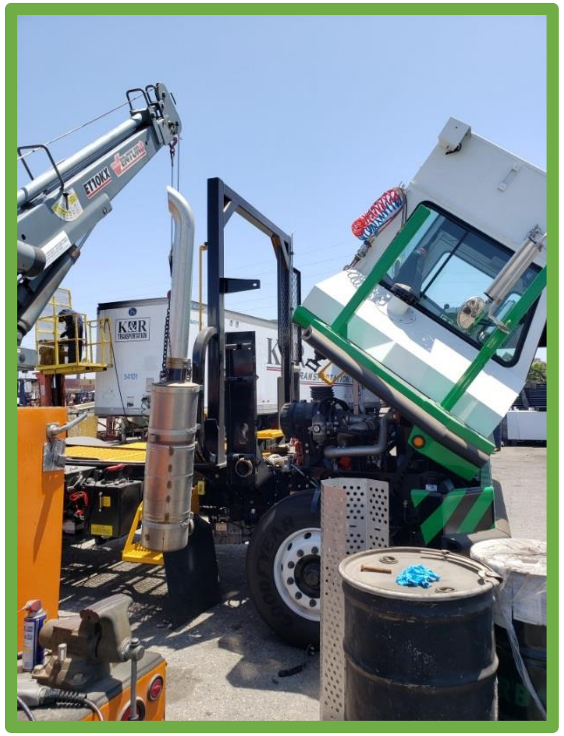
Unit #482 w/ diesel tractor (top), Unit #483 awaits warranty work

Accomplishments and Results at CalCartage **(continued)**

Unit #482 showing ***fractures*** *in the original muffler bracket assembly*

Unit #482 getting muffler assembly removed for replacement with newly designed bracket





CalCartage Warranty Fix #2: July 12-15 (Redesigned Muffler Bracket Assembly)

Note: Unit #483 received the same warranty fixes.

Permanent / Final Host Site: Everport Terminals

6.7L LNG units transferred to Everport
July 2019

Why Everport?

- Typical size, makeup and duty cycles for a major SPBP marine terminal
  - ✓ 2 berths, 205 acres, 8 ship to shore cranes
  - ✓ >100 yard tractors
  - ✓ Terminal capacity = 1.8 M TEUs per year
- Lease lasts through 2028
- Host site for multiple ZE and NZE yard tractor projects

LNG Training at Everport: conducted by GNA July 2019

“LNG Physics and Handling 101”:

- GNA-designed training session
  - ✓ Attended by ~30 Everport staff (management, drivers, fuelers, union reps)
  - ✓ Designed to complement training by Clean Energy, Agility
- Live demo performed by GNA’s CEO Erik Neandross
- Provided a clear understanding about LNG:
  - Basic physical and chemical properties
  - Production and end use in transportation
  - General handling and safety characteristics
- Used desktop displays to vaporize LNG, re-liquefy it; demo lighter than air; relative safety during spills, etc.
- Live presentation augmented with slide presentation

Technology Transfer: Design and Fabrication of LNG Tank Guards

CalCartage Original Tank Guards (~2009)

EverPort Re-Design (2019)

(Top) California Cartage yard manager hosts EverPort's shop staff (right) to view design / dimensions of older LNG tank guards

(Bottom) Close-up of original tank guard "template" (equipped on MSRC-funded LNG yard tractors, circa 2009)

Next Generation: robust new tank guard that EverPort designed, fabricated and installed on all 22 Capacity LNG yard tractors

Demo Launch at Host Site 2 (Everport): July-August 2019

Everport's newly operational LNG fueling station

6.7L LNG tractor (#483) at Everport LNG fueling station

August 20: Inspecting BYD battery-electric tractor for data port to install PAMS

UCR field engineer installing PAMS on diesel control YT at Everport

UCR technician retrieving PAMS data from a 6.7L LNG YT

Crankcase Filter Clogging Issue at Everport

October 2019:
6.7L LNG YT #341's crankcase filter clogged from emulsified oil

Comments from Cummins about CCV Emulsification Issue

- Diesel oil has additives that are meant to attract and hold soot in the oil
- When this is used in a CNG engine that has no soot, these additives end up grabbing onto water molecules
- This leads to excessive emulsifications, which are normal in CNG engines, but increased if engine never gets operated at high load / up to normal operating temperature
- Nonetheless, “CCV filters should not be plugging with emulsifications.” B6.7N and L9N NG engines should only be running oil that meets CES20092 specification
- Everport’s unit with CCV filter plugged (LN0341) appears to have an oil filter that was “changed at some point”
- Also, ECM image showed 46% idle time; Everport confirmed it was idled / moved around yard frequently before put in service
- Given this, (Cummins) is not surprised that CCV filter plugged prematurely
- Recommendation: change CCV filter and oil in system (which apparently did not meet the above spec)
- Also, (Cummins) noticed “some issues with CCV install by Capacity”
  - installation requirements for CCV filter state CCV blow-by hoses MUST be insulated, and Cummins supplies insulated hoses with the engine/CCV kit
  - Use of “split loom” as insulation is not sufficient
  - Not sure if blue silicone hose is rated for handling oil (Capacity installation also used blue silicone for the oil return hose)

Comments (January 2020) by **Capacity Trucks (Engineering Dept.)**

- Testing period at Everport is <u>going very well</u> for both pre-commercialization TJ 9000 models (separate CWI NG engines):
  - Two (2) units with **B6.7N** (**0.1 g/bhp-hr**)
  - Twenty (20) units L9N (**0.02 g/bhp-hr**)
- Oil emulsification problem has been resolved (working with Cummins)
- Capacity / Harbor Diesel continue to conduct warranty repairs and general servicing
- Compared to the 8.9L, the smaller 6.7L engine:
  - Is more efficient
  - Has adequate power to satisfy Everport’s operational needs
- <u>Capacity believes its future yard trucks “will be equipped with the 6.7L engines”</u>

<u>TJ9000:</u>

- *Single-axle yard jockey truck*
- *GCWR up to 242,000 lbs.*
- *Designed for intermodal or warehouse and distribution duty cycles.*

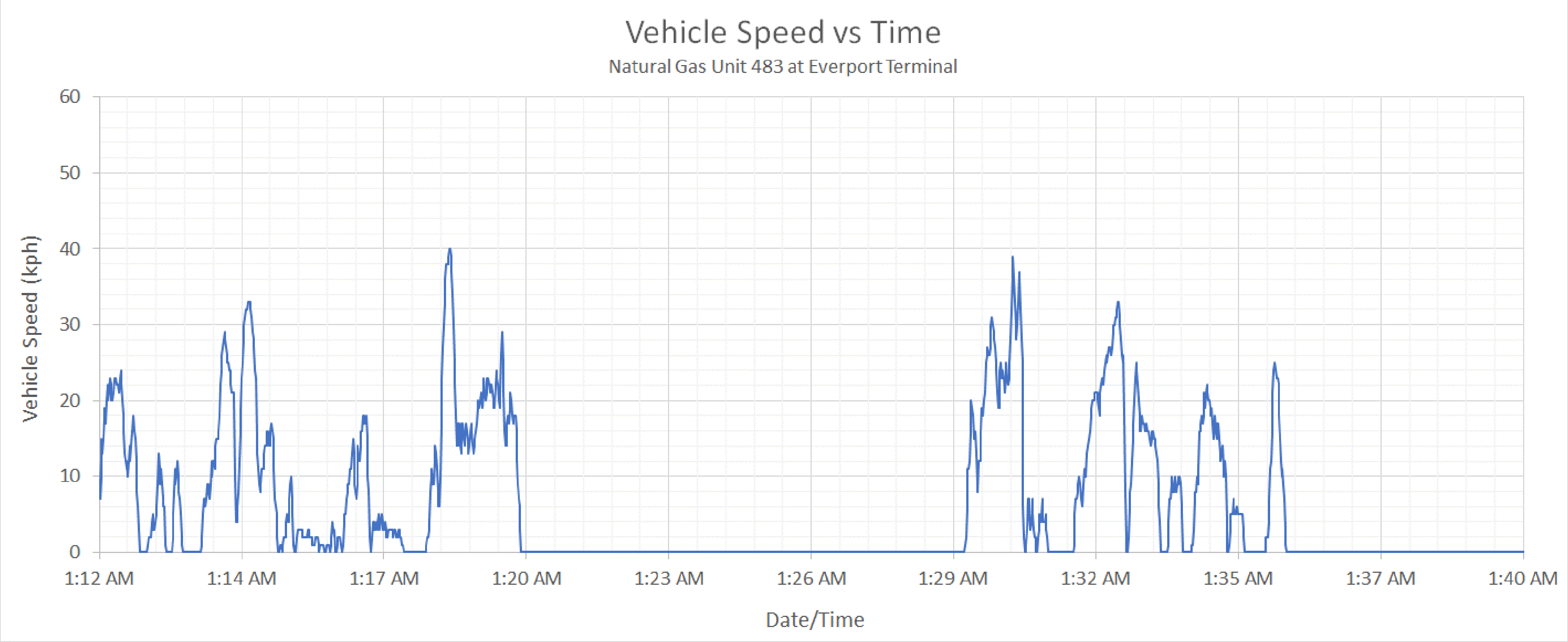
Preliminary Findings from PAMS Data Collection and Reduction

Data Collection at CalCartage and Everport Terminal

- UCR equipped yard trucks with PAMS data loggers to collect ECM and GPS data
- CalCartage
  - PAMS installed on both 6.7L NG test units
  - Collected approximately 100 hours of data per unit
- Everport Terminal
  - PAMS installed on five units
    - (2) 6.7L NG test units
    - (1) 8.9L NG yard truck
    - (1) 6.7L diesel yard truck (control)
    - (1) BYD battery-electric yard truck
  - Collected approximately 200 hours of data for diesel baseline
  - Collected ~20 hours of data on 6.7L NG test unit.
  - Attempting to recover additional PAMS loggers and data

Preliminary Analysis at Everport Terminal – Duty Cycle

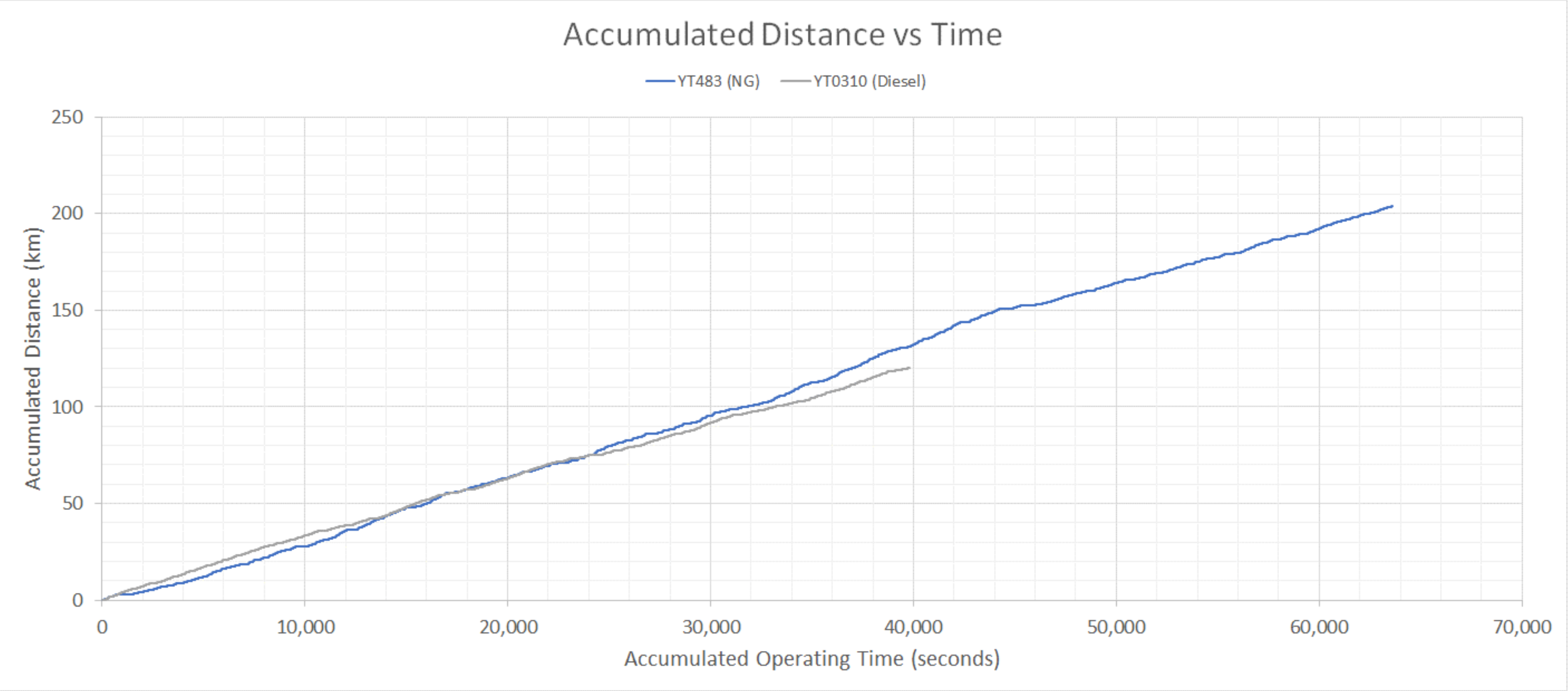
- Duty cycles for yard trucks are low speed, high transient, with extended idle
- Operational profiles vary based on the work being done on the terminal (ship, rail, stacks)



Preliminary Analysis at Everport Terminal – Duty Cycle

- Diesel and NG operations may not be identical on the same day
- Searched diesel data set for operational period with similar characteristics to NG data set for best apples-to-apples comparison

Unit	YT483 (NG)	YT0310 (Diesel)
Hours Operated	17.65	11.05
Distance (km)	203.8	120
Avg Speed (mph)	7.18	6.75
Avg Speed ex-Idle (mph)	17.0	14.9
% Idle	32%	27%
Avg HP	38.3	48.2
Avg Fuel Rate (l/hr)	9.4	9.1
Avg RPM	1217	1278
Avg %Torque	25.3	24.6
Work Done (hp-hr)	676.6	532.3
Total Fuel Use (liters)	165.5	101.0
BSFC (gal/hp-hr)	0.065	0.050
Avg Fuel Economy (mpg)	2.91	2.81
Avg Fuel Economy (gph)	2.48	2.42



Preliminary Analysis at Everport Terminal – Fuel Efficiency

- To date, no complaints regarding 6.7L NG performance or failures (other than previously noted)
- 6.7L NG units appear to be operating comparably to diesel units. Idle time, torque %, average speed, and average fuel rates are all similar.
- Per-hour fuel consumptions within 3% of diesel. However, BSFC fuel consumption is 29% higher.
- Continuing analysis. Will also look at chassis dyno testing for comparisons under controlled cycles.

Unit	YT483 (NG)	YT0310 (Diesel)
Hours Operated	17.65	11.05
Distance (km)	203.8	120
Avg Speed (mph)	7.18	6.75
Avg Speed ex-Idle (mph)	17.0	14.9
% Idle	32%	27%
Avg HP	38.3	48.2
Avg Fuel Rate (l/hr)	9.4	9.1
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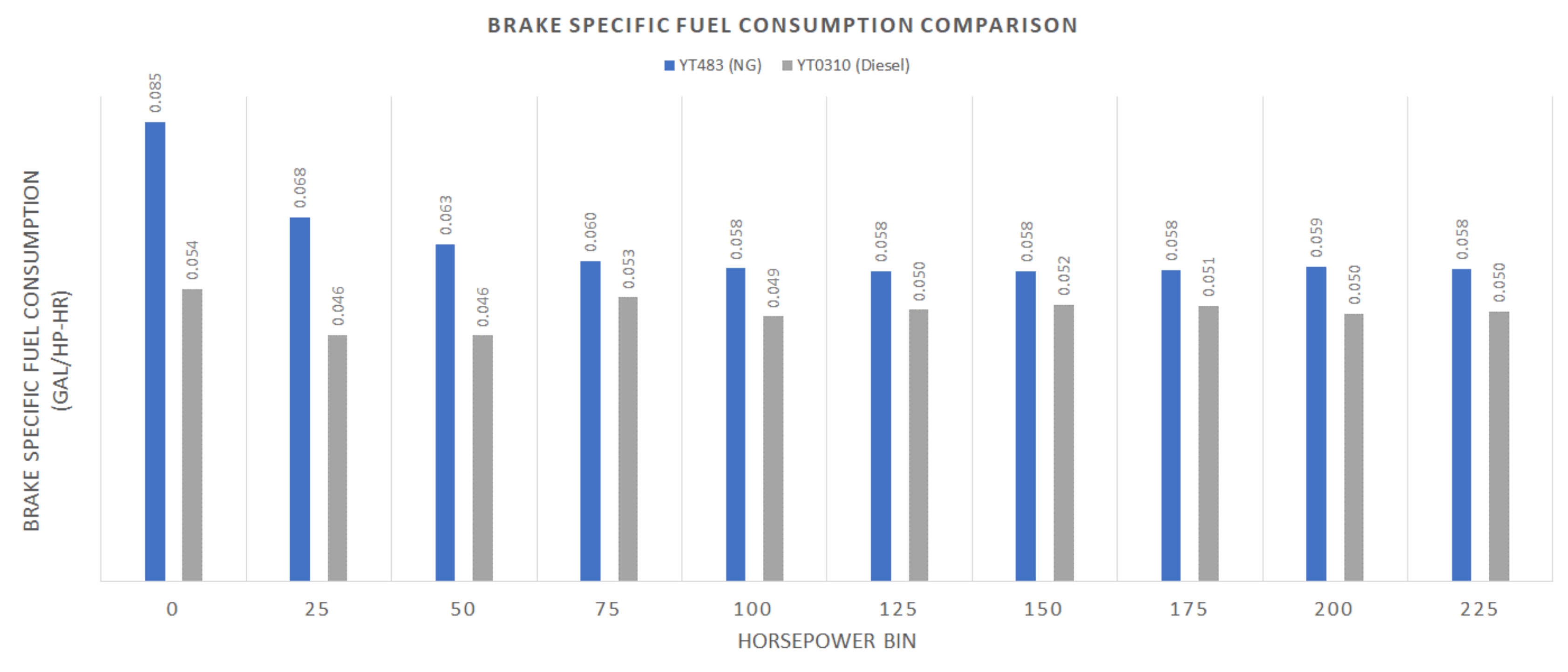
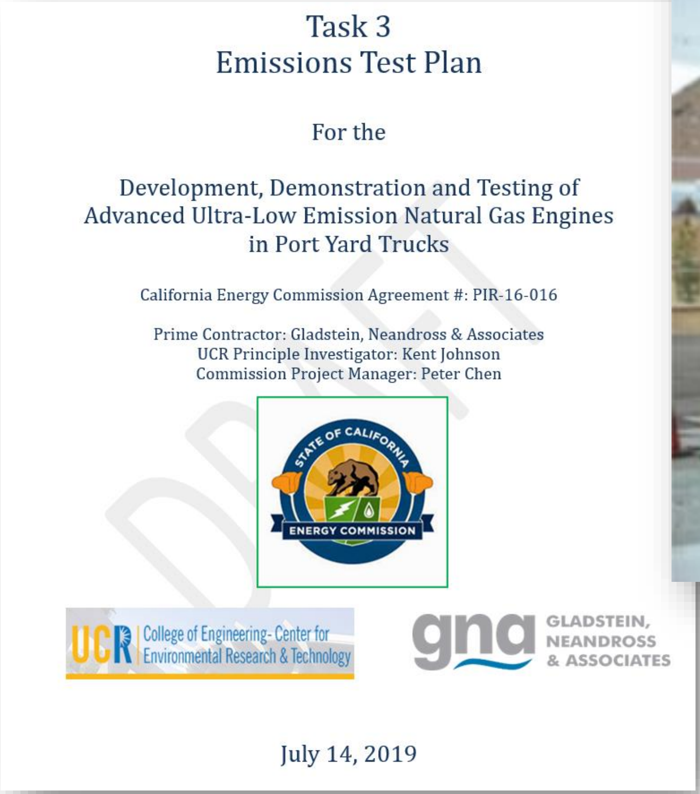


Test Plans for UCR-CE-CERT:
Gas Composition Sensor and Chassis Dyno Emissions

Emissions Test Plan: Prepared July 2019

<u>Chassis dyno testing at UCR is expected to begin in February</u>

- UCR drafted Emissions Test plan
- Exact schedule subject to:
  - ✓ UCR chassis dyno availability
  - ✓ EverPort's needs for YTs
  - ✓ Transport logics (YTs on typical low-boy trailer are taller than 14 foot CHP limit)
- GNA / UCR working on details of / logistics for simulating RNG test fuel


Task 3
Emissions Test Plan

For the

Development, Demonstration and Testing of
Advanced Ultra-Low Emission Natural Gas Engines
in Port Yard Trucks

California Energy Commission Agreement #: PIR-16-016

Prime Contractor: Gladstein, Neandross & Associates
UCR Principle Investigator: Kent Johnson
Commission Project Manager: Peter Chen

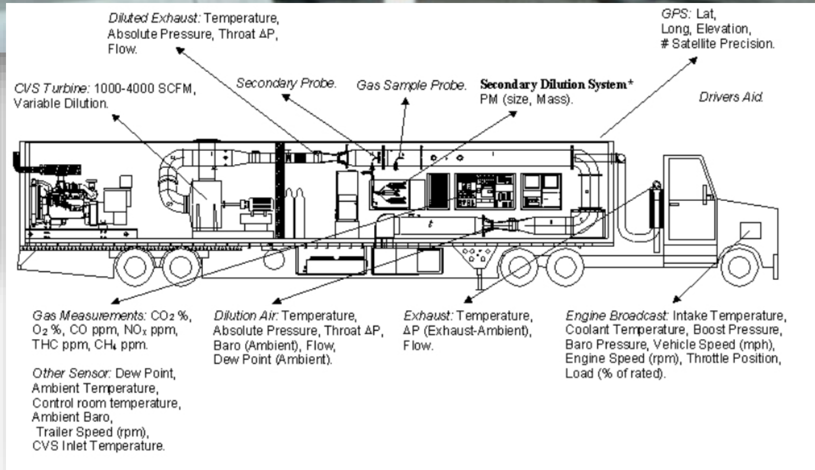
STATE OF CALIFORNIA ENERGY COMMISSION

UCR College of Engineering- Center for Environmental Research & Technology

gna GLADSTEIN, NEANDROSS & ASSOCIATES

DRAFT

July 14, 2019



Fuel Supply Summary

- SOW calls for emissions testing using NG of varying composition
  - Physical RNG OR simulated blend based on actual RNG composition
- Current plan:
  - Reviewed CARB report (Project #13-418) on composition of RNG facilities in California
  - Most gas injected into the pipeline is high purity, upgraded gas
  - Some facilities show modest levels of diluents
  - Discussions with CWI on gas compositions and methane index numbers of interest for commercial application of sensor.
  - Developed four blends reflecting pipeline gas, mid-MI gas, and low-MI gas
- Fuel will be supplied using bottle gases at the test lab

Table 4 Recommended NG fuel properties for testing

Fuel	MI	CH_4	C_2H_6	C_3H_8	C_4H_{10}	CO_2
Pipeline LNG (LNG)	95.0	95	3.5	0.6	0.3	0
RNG 1	75	87	8	2	0.5	2.50%
RNG 2	> 65	77	12	5	1	5%
Extreme MI (ExMI)	> 65	89.5	-	10.5	-	-

[1] The pipeline LNG will be sourced from a local Riverside area and represent typical LNG for CA. The RNG 1 and 2 were selected based on properties identified from the literature four RNG fuels (Appendix E) and based on recommendations from the TAC (Cummins and CWI), see Appendix E. The extreme MI were blended based on discussion with CWI and their testing experience where it is recommended to have a MI of just at 65 with CH4 and C3H8 and no ethane or butane.

UCR CE-CERT Fuel Composition Sensor Testing:
Completed August 2018

- Test plan drafted by UCR CE-CERT in mid-2018
- Included specifics about test procedures, gas composition for mixtures to be tested, proposed test matrix, etc.
- Implementation of Plan required adjustments as testing proceeded
- UCR completed final report on sensor testing in Q3 2019
- Results summarized in separate part of presentation

UCR Sensor Test Plan

CEC Contract #PIR-16-016
Prime Contractor: GNA
Subcontractor: UCR CE-CERT

UCR CE-CERT Sensor Test Plan
July 2018

This document describes CE-CERT's test plan for the methane number (MN) sensor development. This plan includes four sub tasks, 1) selection of gas mixtures, 2) test matrix, 3) model, and 4) test setup.

GNA Note: UCR's work to develop this plan actually falls in Task 3 under the revised project schedule. Implementing the testing is under Task 4. Jon Leonard, GNA, February 20, 2019.

Task 4.1 Gas selection

The gas selection includes specific gas blends found in the U.S. These blends will be selected for their range of Standard Natural Gas for Methane Number Data Base (MNDB). Five gases with methane number (MN) varying in between 65 and 90 will be selected for the MNDB development and actual sensor testing. These are standard compositions from Texas pipeline, Rocky Mountain pipeline, Peruvian LNG, Associated high ethane and Associate high propane gas. Another natural gas standard of MN around 65 was added by increasing propane concentration of Associate high propane gas. Pure Methane gas is also selected for the reference purpose. The proposed test gases are summarized in Table 1.

Table 1: Gas composition of the selected gas mixtures

Description	Methane mole %	Ethane mole %	Propane mole %	I-butane mole %	N_2 mole %	CO_2 mole %	MN	Wobbe # MJ/m^3	H/C ratio	MON
Rocky Mountain pipeline	94.5	3.5	0.6	0.3	0.35	0.75	93.58	50.69	3.89	131.5
Peruvian LNG	88.3	10.5	0	0	1.2	0	84.11	51.60	3.81	125.6
Associated High Ethane	83.65	10.75	2.7	0.2	2.7	0	74.51	51.61	3.71	119.7
Associated High Propane	87.2	4.5	4.4	1.2	2.7	0	74.31	51.61	3.70	119.6
Low MN Gas	82.8	4.5	8.8	1.2	2.7	0	65.07	52.99	3.58	113.9
Methane	100	0	0	0	0	0	107.62	50.72	4.00	140.1

Task 4.2 Test matrix

Table 2 shows the proposed test matrix to perform for the evaluation and machine learning of the MN sensor algorithm. The total combination of experiments and data sets for the initial database will be four temperatures (possibly up to six), four pressure (1 to 4 bar), and six factorial of gases (arbitrary mix of six gases by 10% step). The anticipated matrix preparation timeline is April 2018, see schedule in Figure 2.

Part 2:

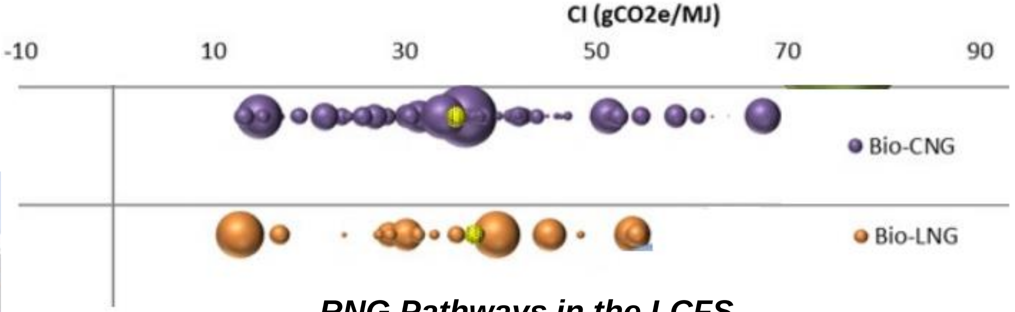
UCR CE-CERT Gas Composition Sensor

(Summary Presented

on behalf of Dr. Kent Johnson, UCR CE-CERT)

Prime Contractor: GLADSTEIN, NEANDROSS & ASSOCIATES

Subcontractor: UCR College of Engineering- Center for Environmental Research & Technology

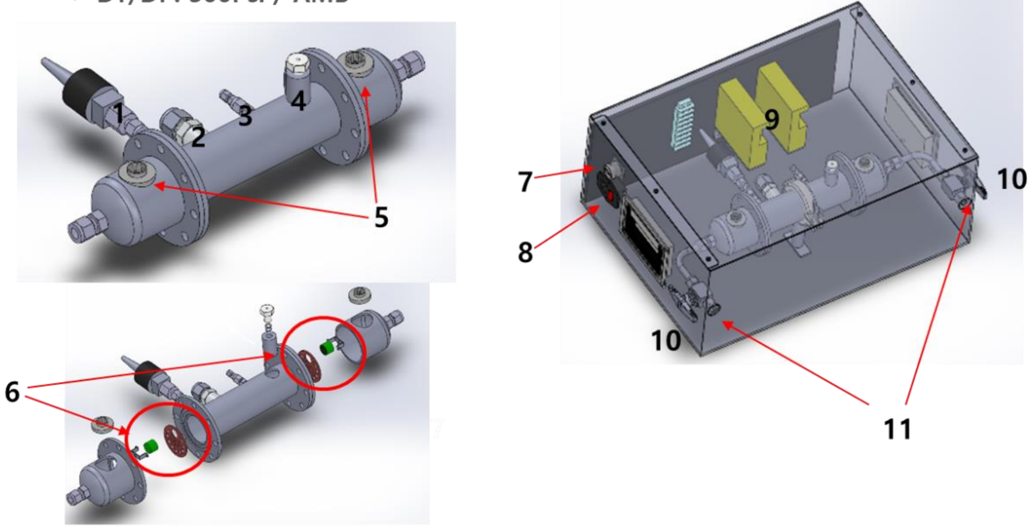


RNG Pathways in the LCFS

Task 4 Fuel composition sensor: Design and Calibration Setup

- Methane prediction ~ 5% target
- Range of pressure, temperature and methane index values

✓ Size: 480 x 350 x 200 (w x d x h, mm)
✓ DT/DP: 300Psi / AMB
✓ Port: 3/8"



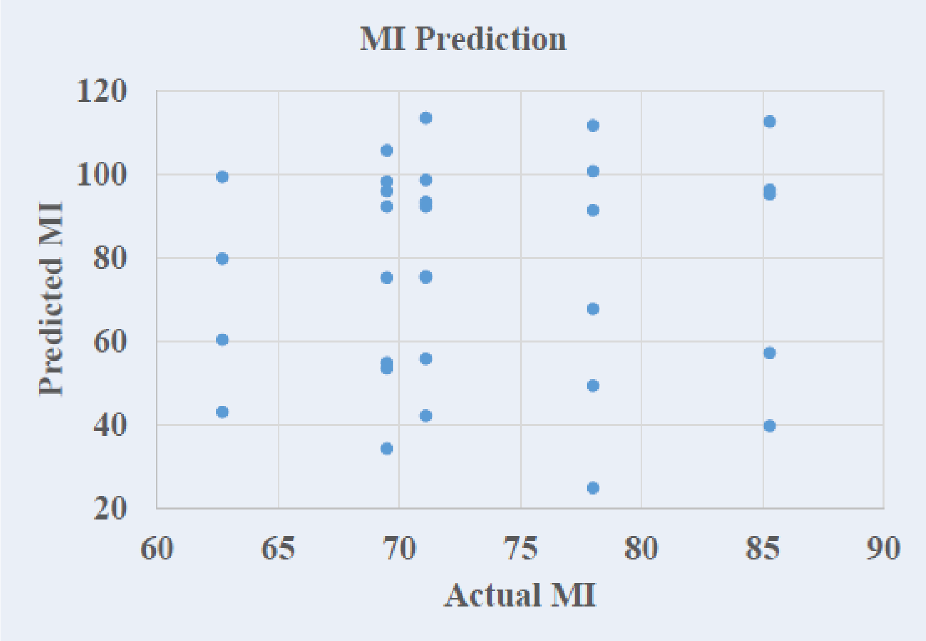
1. Pressure Transmitter
2. Spare Port (1/2")
3. Temperature Sensor
4. TC Sensor Connector
5. MS Connector For Diastance Sensor
6. Distance Sensor Unit
7. Data Connector
8. Power Consent
9. Electric Module
10. On/Off Valve (3/8")
11. Oil In/Out Nozzle (3/8")

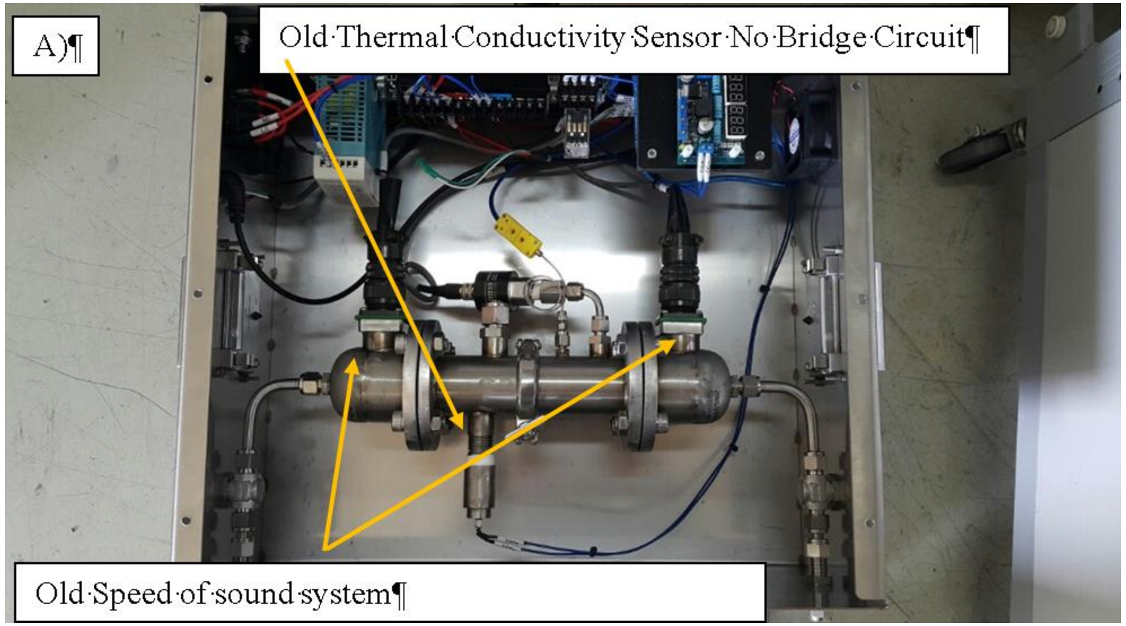
Description	Methane	Ethane	Propane	I-butane	N_2	CO_2	MI
Rocky Mountain	94.5	3.5	0.6	0.3	0.35	0.75	**85.3**
Peruvian LNG	88.3	10.5	0	0	1.2	0	**78**
Associated High Ethane	83.65	10.75	2.7	0.2	2.7	0	**71.1**
Associated High Propane	87.2	4.5	4.4	1.2	2.7	0	**69.5**
Low MN Gas	82.8	4.5	8.8	1.2	2.7	0	**62.7**
Methane	100	0	0	0	0	0	**100**

Composition						Temperature (K)	Pressure, bara (psia)	Thermal Conductivity (W/m K)	Sound Velocity (m/s)	MN
CH_4	C_2H_6	C_3H_8	Iso-C_4H_{10}	N_2	CO_2					
0.828	0.045	0.088	0.012	0.027	0.000	26	6.89 (100)	0.03995	416.1	62.7
0.828	0.045	0.088	0.012	0.027	0.000	26	3.45 (50)	0.03692	412.3	62.7
0.828	0.045	0.088	0.012	0.027	0.000	26	1.22 (17.7)	0.03454	409.2	62.7

Task 4 Fuel composition sensor: Progress Ver. 01 June 2018

- Methane prediction >> 5% target
- Stop testing range of conditions and investigate solution
- Identified speed of sound has high error. Investigate solution





Task 4 Fuel composition sensor: Progress Ver. 02 – Sep 2018

- Enhanced speed of sound measurement (Figure 1)
- Enhanced thermal conductivity measurement to refine approach (Figure 2)

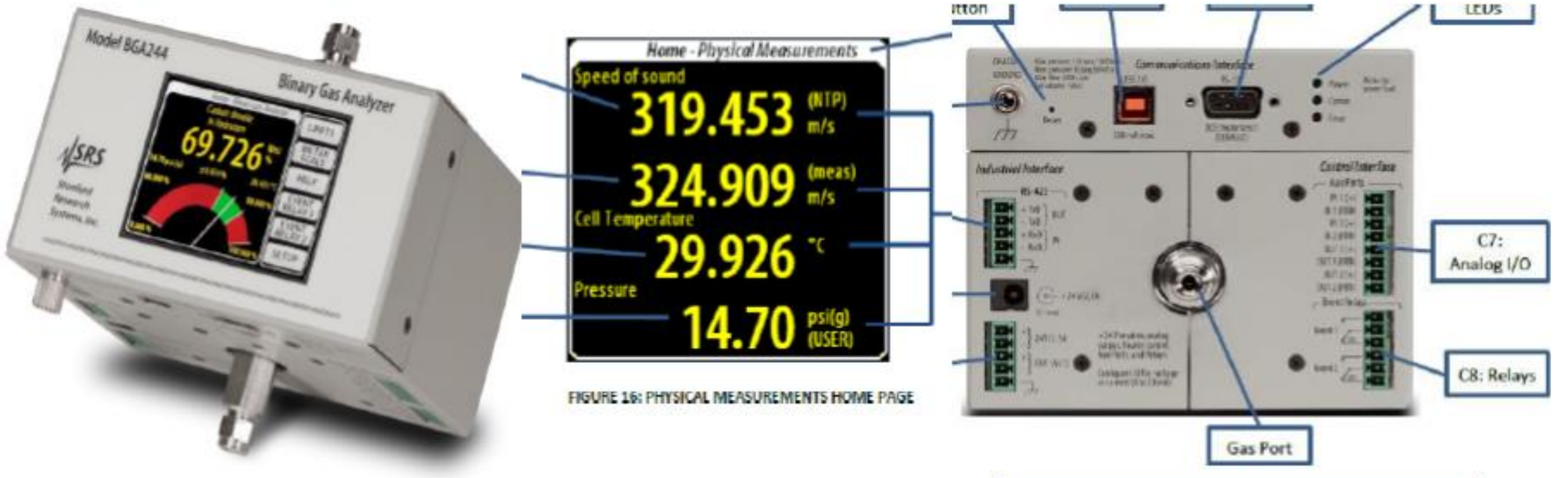
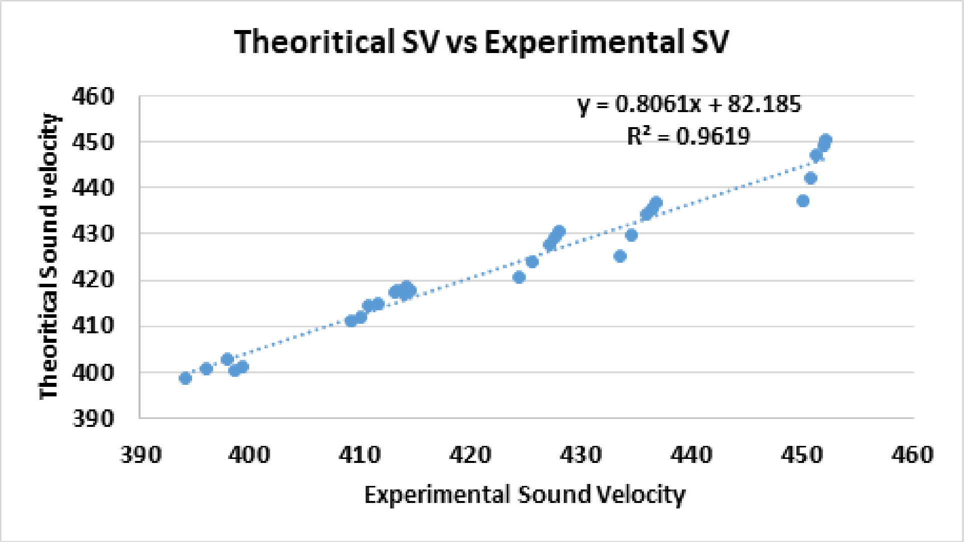


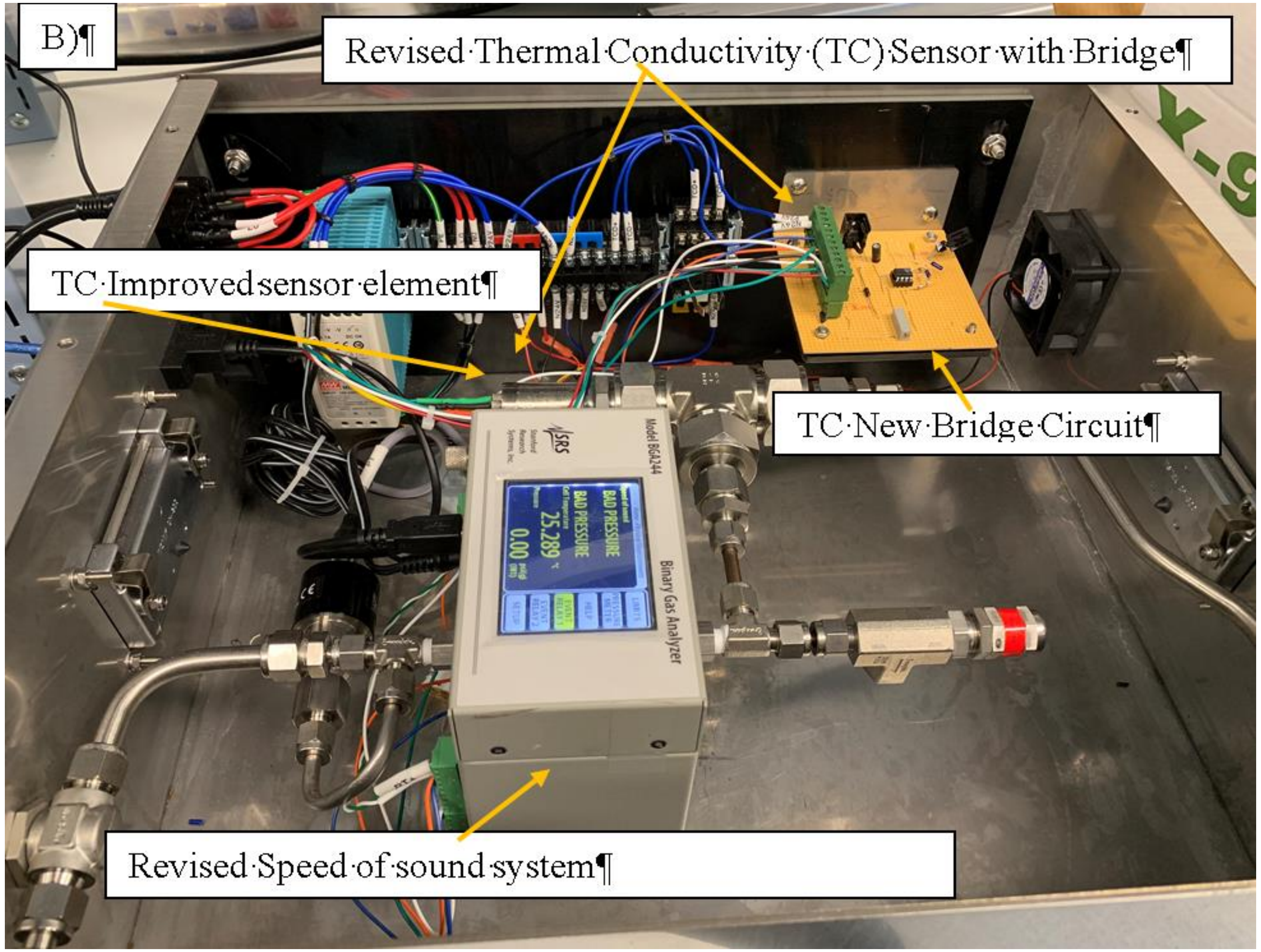
Figure 1 Revised speed of sound design using off-the shelf measurement system integrated into the sensor setup

Figure 2 Revised thermal conductivity sensor design with Wheatstone bridge circuit design

Task 4 Fuel composition sensor: Progress Ver 02 Sept 2018

- Methane prediction ~ 10%
- Discuss with CWI and Cummins
- Cummins requesting <5%, actual ~2%
- Thus, simulate results on Chassis





Project Summary: Tangible Accomplishments to Date

- Formed TAC and implemented meeting in December 2017
- Built and deployed two "first-of-kind" Capacity LNG yard hostlers (OLNS 6.7L CWI engines)
- Prepared and implemented Demonstration Test Plan
- Performed successful technology transfer to inform CHE fleets about emerging NG tractors
- Conducted training, installed PAMS, and initiated demo at CalCartage (May 7, 2019)
- Performed warranty fixes / improvements on tractors (transmission, muffler brackets)
- Moved demo to permanent host site (Everport Terminals) in July 2019
- Conducted "LNG Physics and Handling" training at Everport (July 2019 and September 2019)
- Obtained, reviewed, reduced and output PAMS data from both host sites
- Interviewed and documented feedback from drivers, fuelers and management (both sites)
- Prepared gas composition Sensor Test Plan, performed bench testing (**UCR presentation**)
- Prepared Emissions Test Plan
- Initiated Fuel Supply Plan (for UCR CE-CERT testing)

Project Summary: Intangible Accomplishments to Date

- Successfully encouraged Capacity to manufacture and sell yard hostlers with 6.7L OLNS-certified natural gas engine
- Facilitated / enabled Capacity to discover that a **6.7L** LNG yard tractor is a **"less costly, more efficient product"** for MTOs to displace diesel tractors
  - Capacity Engineering: "future products will use 6.7L CWI engine"
- Facilitated CWI's decision to certify 6.7L NG engine at 0.02 g/bhp-hr (SPBP market)
- Helped support the key goal of the San Pedro Bay Ports to deploy, test and characterize the feasibility of **NZE** (and **ZE**) yard tractor fuel-technology platforms

Thank You!

UCR | College of Engineering- Center for Environmental Research & Technology

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GNA / UCR gratefully acknowledges

1) Project funding from CEC
2) Technical guidance from Peter Chen, Jerry Wiens, and all members of the TAC
3) Capacity Trucks (Jeff Coombs, Wes Downing) and Harbor Diesel (Art Havens)
4) CalCartage (Bob Lively, Jesus Ramirez)
5) Everport Terminals (Rob Brown, Geoffrey Romano, Ron Neal)
6) Cummins Westport (Tom Swenson, Chip House)

South Coast AQMD

200 Vehicle In-Use Emissions Testing Program

Natural Gas Vehicle Technology Forum | Sam Cao - Air Quality Specialist | February 4, 2020

Objectives

Identify technology benefits/shortfalls, feed information into future R&D opportunities, future regulation development and improve emissions inventory estimates

Total Vehicles Recruited

219

22 Vehicle OEMs, 9 Engine OEMs, 200 PAMS, 100 PEMS, 60 Chassis, 10 On-Road Trailer

Vocations Covered

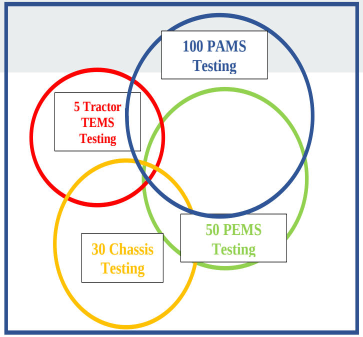
5

25 Fleet Participants: Delivery (44), Goods Movement (95), Transit Bus (21), School Bus (27) and Refuse (32)

Technologies Covered

9

Propane (4), CNG 0.02 (28), CNG 0.2 (79), No SCR Diesel (10), Diesel 0.2 (72), Diesel-Hybrid (6), BEV (12), FCEV (2), HDPI (4)



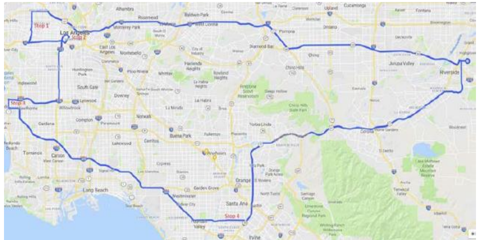
Experimental

1. **(200) PAMS** – ECM + telematics data logging for up to 4 weeks, fleet survey and maintenance/fuel records collection. Data to be used from new cycle development

2. **(100) PEMS testing** – one full-day operation, NTE analysis, ECM + telematics, regulated gaseous data only

3. **(60) Chassis** – Fully lab equipment, regulated and unregulated gaseous, PM, PN, toxic and metals analysis, subset of 8 chassis cycles depending on vocation, 4 new cycles developed from PAMS

4. **(10) On-road trailer testing** – Full lab equipment (same as chassis) on 4 real-world routes in SCAB (drayage, goods movement x2, grocery)



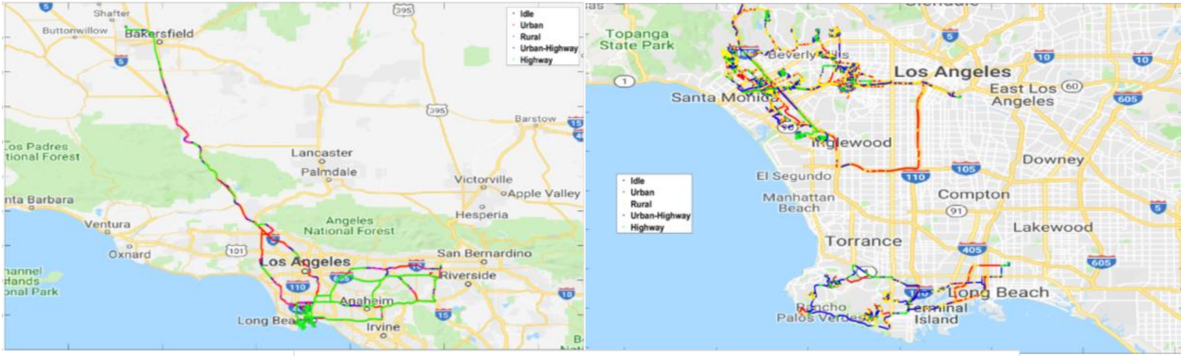
Testing Phase Update

Testing Phase	Assigned	Recruited	Completed
Portable Activity Monitoring System (PAMS)	200	219	206 (complete)
Portable Emissions Measurement System (PEMS)	100	100	94
Chassis Dynamometer	60	62	34
Real-World In-Use Trailer	10	10	5

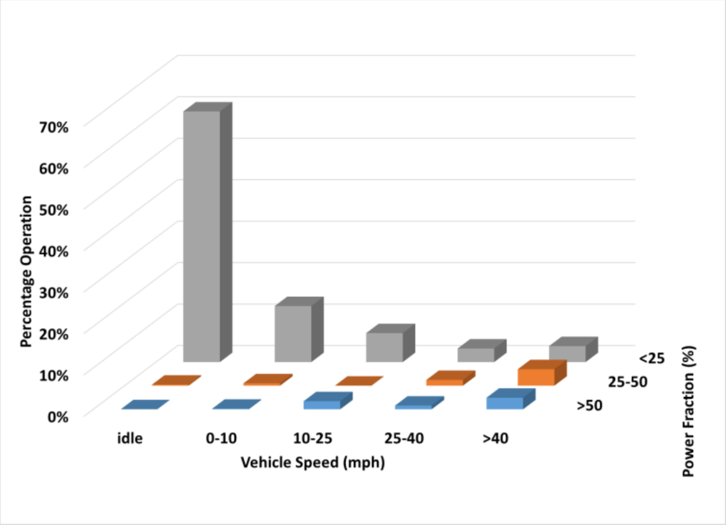
Testing Target Completion – May 2020

South Coast AQMD

Preliminary Key Findings - PAMS



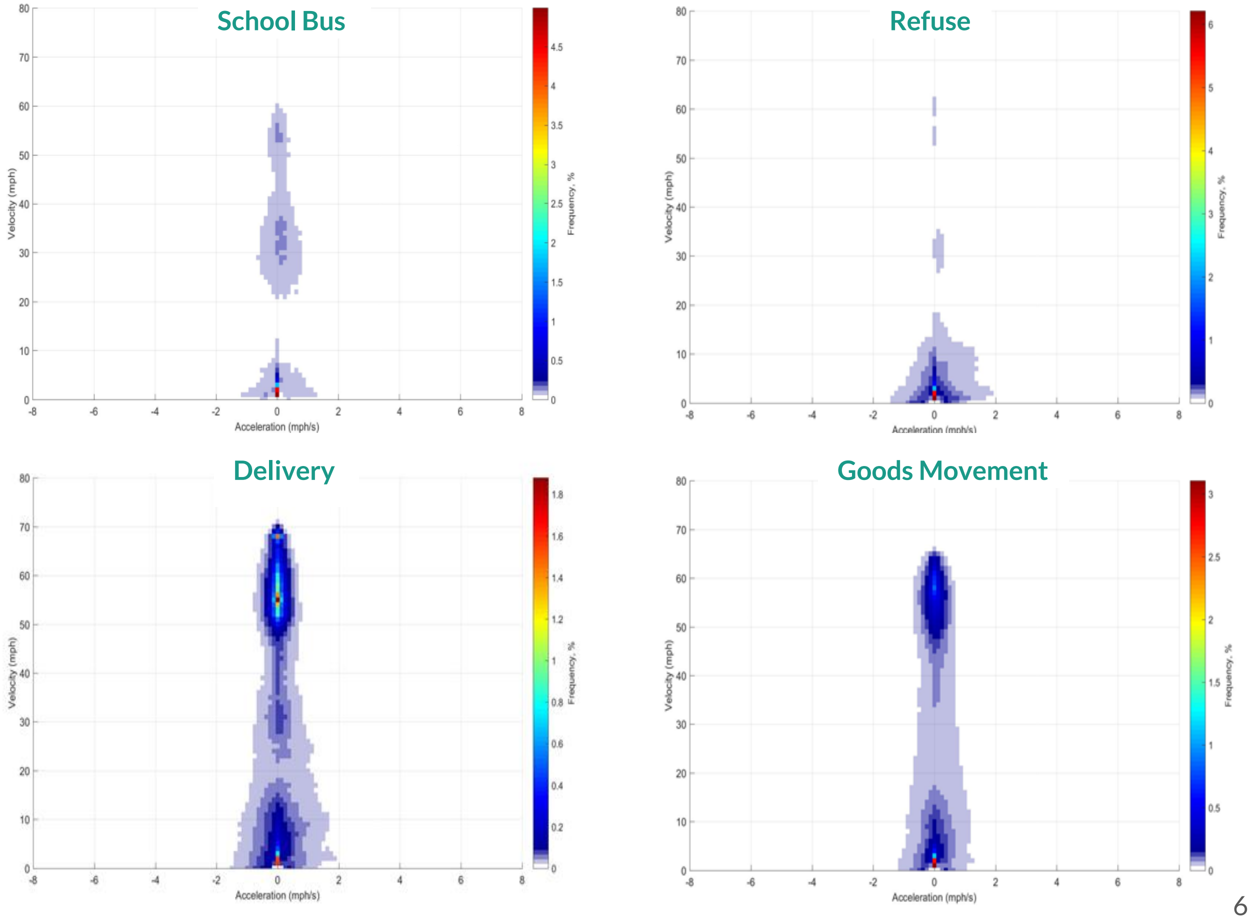
- Idle, low-speed, low power operation dominated the activity data set
- Higher vehicle speed for delivery and goods movement, transit and school buses lower, refuse lowest
- More detailed vocation specific analysis to be done in final report
- PAMS data submitted to CARB for additional analysis



Top: A real-world route and speed characteristics of goods movement trucks (left), refuse (right)
Bottom: Distribution of vehicle speed and power bins of CNG goods movement trucks (WVU)

Preliminary Key Findings - PAMS

- Distinct speed profiles per vocation, as expected
- Idle time : 34-46% (UCR data set , more in WVU data set)
- Data used for new duty cycle development

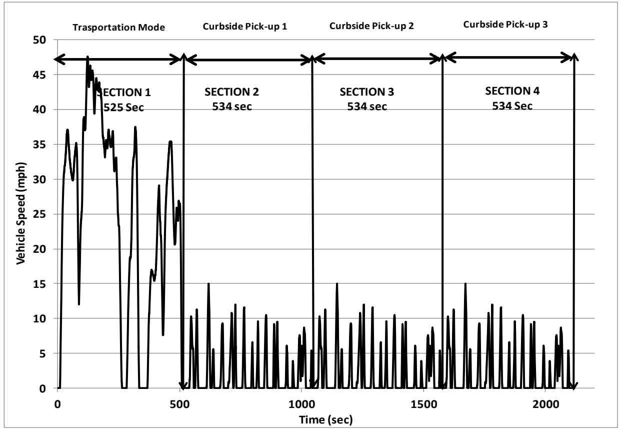


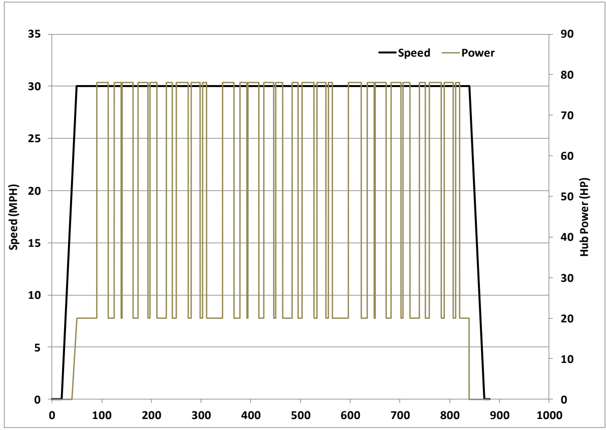
Source: UCR VMT data analysis

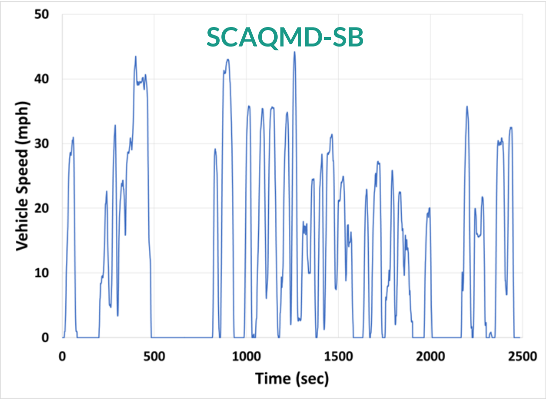
New Chassis Test Cycles Developed

- Standard cycles: UDDS, CARB HHDDT, CBD, OCTA
- New cycles derived from this study : Goods Movement Cycle, SCAQMD School Bus, Delivery, Modified SCAQMD refuse

Modified SCAQMD Refuse + Compaction Cycle for Hydraulic Load







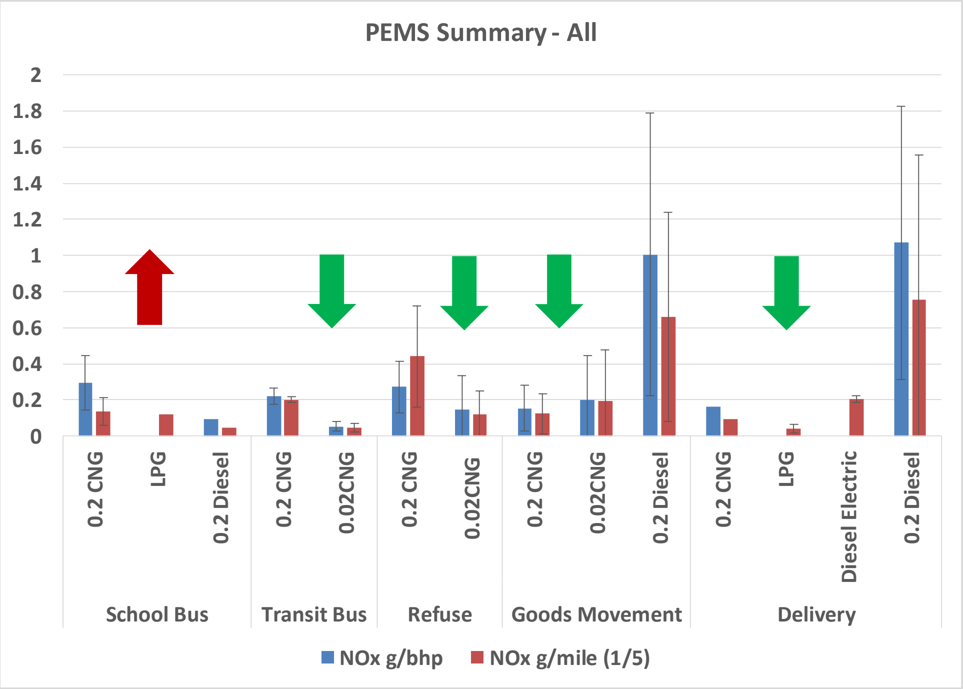
Source: Final chassis test plan, submitted to SCAQMD

Final Chassis Test Matrix

	Test Cycle	Vocation				
		Transit	School Bus	Refuse	Delivery	Goods Movement
	UDDS	X	X	X	X	X
	CARB HHDDT				X	X
new	Modified SCAQMD Refuse Cycle			X		
new	Port Drayage Cycle (Markov)/GMC					X
	CBD	X				
	OCTA	X				
new	South Coast School Bus (Markov)		X			
new	Delivery (Markov)				X	

Preliminary Findings – PEMS

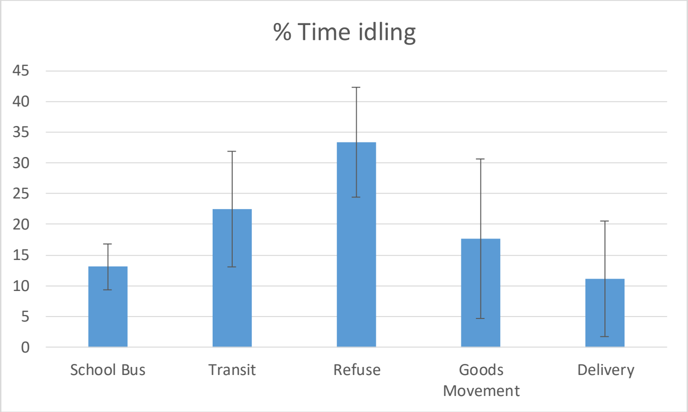
- One day of operation, gaseous only, ~ 50 vehicles
- NOx emissions vary greatly by technology and vocation but in general 0.02 CNG < 0.2 CNG /LPG < diesel 0.2
- Goods Movement and Delivery category highest emissions and variability suggest further break down and investigation
- CNGs across the board lower variability

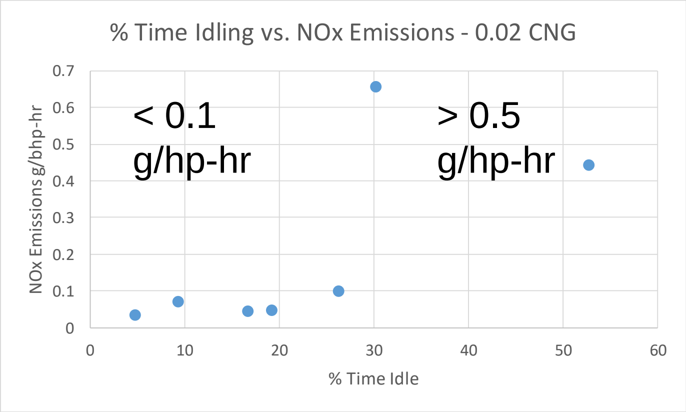


Source: UCR interim report to SCAQMD

Preliminary Findings – PEMS

- Idling (2%-50% observed) impacts in-use emission greatly, more investigation needed
- Traditional engine dyno certification cycles/chassis cycles does not reflect the low-load operation
- Key to compare PEMS data to chassis data

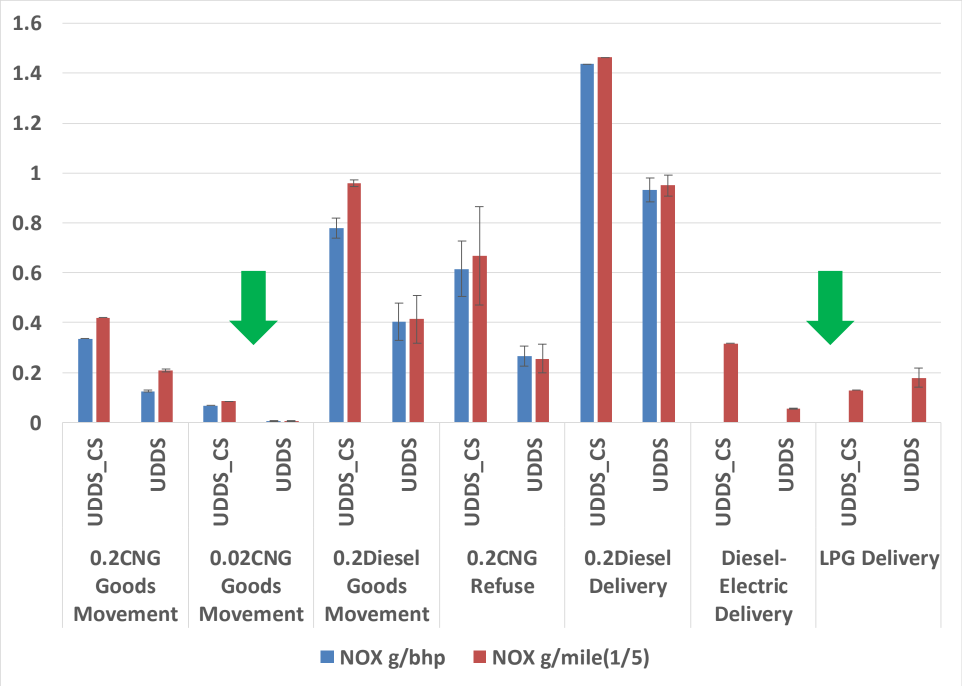




Source: UCR & WVU interim report to SCAQMD

Preliminary Findings – Chassis – All

- Limited data set, ~17 vehicles, pre-2010 diesel removed
- NOx emissions vary by vehicle vocation and technology
- CNG/LPG 76%-99% lower compare to 0.2 diesel baseline
- 0.02 CNG 98%+ lower than 0.2 CNG

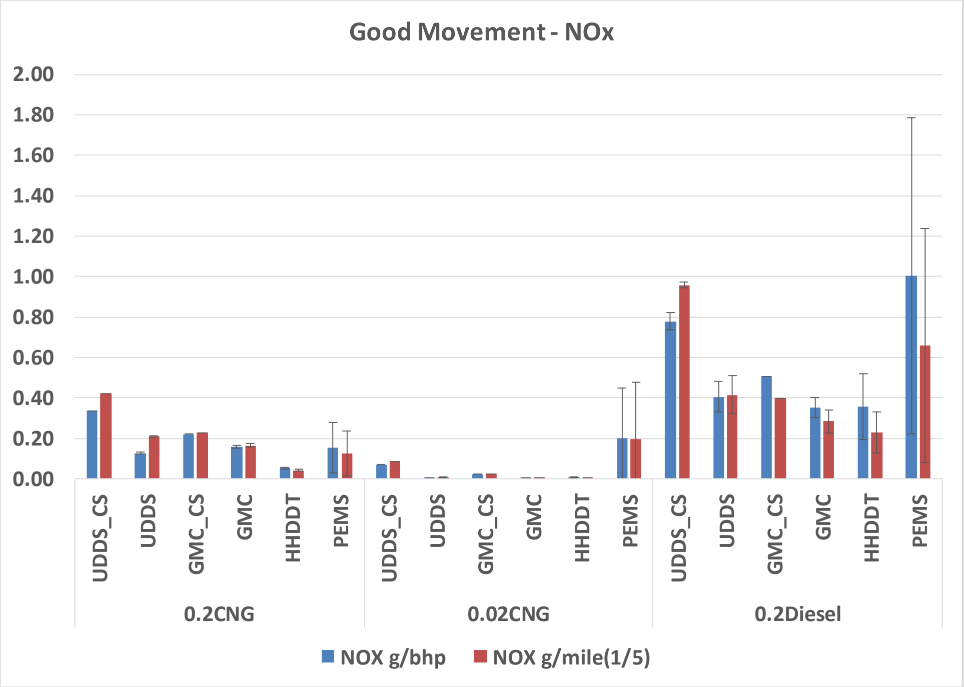


[1]Diesel-electric engine bhp-hr invalid (no powertrain work)
[2]LPG vehicle ECM data not available

Source: UCR&WVU interim report to SCAQMD

Preliminary Findings – Chassis - GM

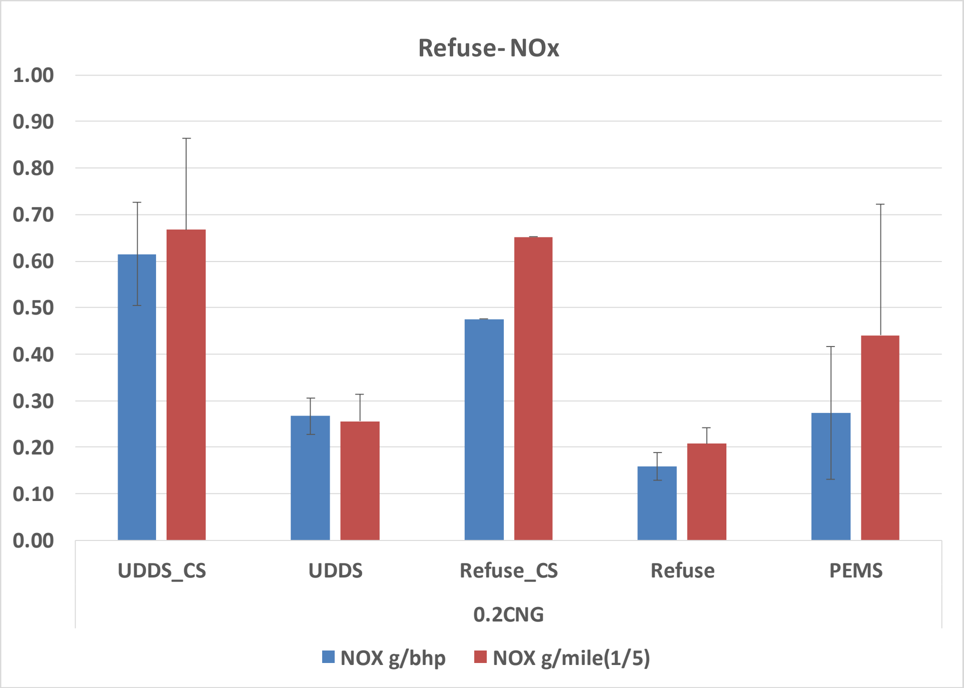
- Vocation specific chassis cycles more represented to true in-use emissions
- Chassis finding 0.02 CNG < 0.2 CNG < 0.2 Diesel
- PEMS finding suggest additional investigation needed



Source: UCR&WVU interim report to SCAQMD

Preliminary Findings – Chassis - Refuse

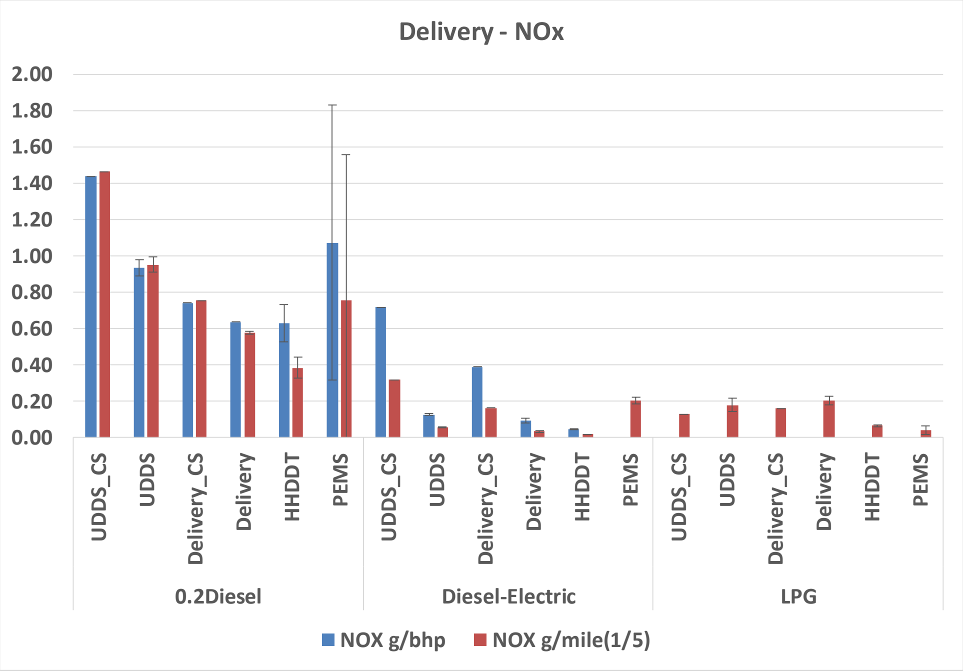
- Slightly higher emission on refuse cycle
- Refuse 0.2 CNG also higher emissions compare to other vocations due to nature of refuse duty cycle
- Chassis data inline with PEMS
- Current data set all 0.2 CNGs, more 0.02 CNGs, and 0.2 diesels planned



Source: UCR & WVU interim report to SCAQMD

Preliminary Findings – Chassis – Delivery

- Delivery category highest 0.2 diesel emissions (highest one was a class 8 truck), finer breakdown?
- Diesel electric presents a excellent emissions reduction pathways towards diesel Low NOx
- LPG: UDDS 83%, Delivery 80%, HHDDT 94% lower
- PEMS results comparable



Source: UCR & WVU interim report to SCAQMD

In-Use Emissions - Key for Future NOx Regulation

- CARB released Staff White Paper outline plans for next rounds of low NOx rule making, significantly changes to HDIUT
- EPA CTI outlines similar in-use requirements
- Onboard sensor based measurement, Remote sensoring

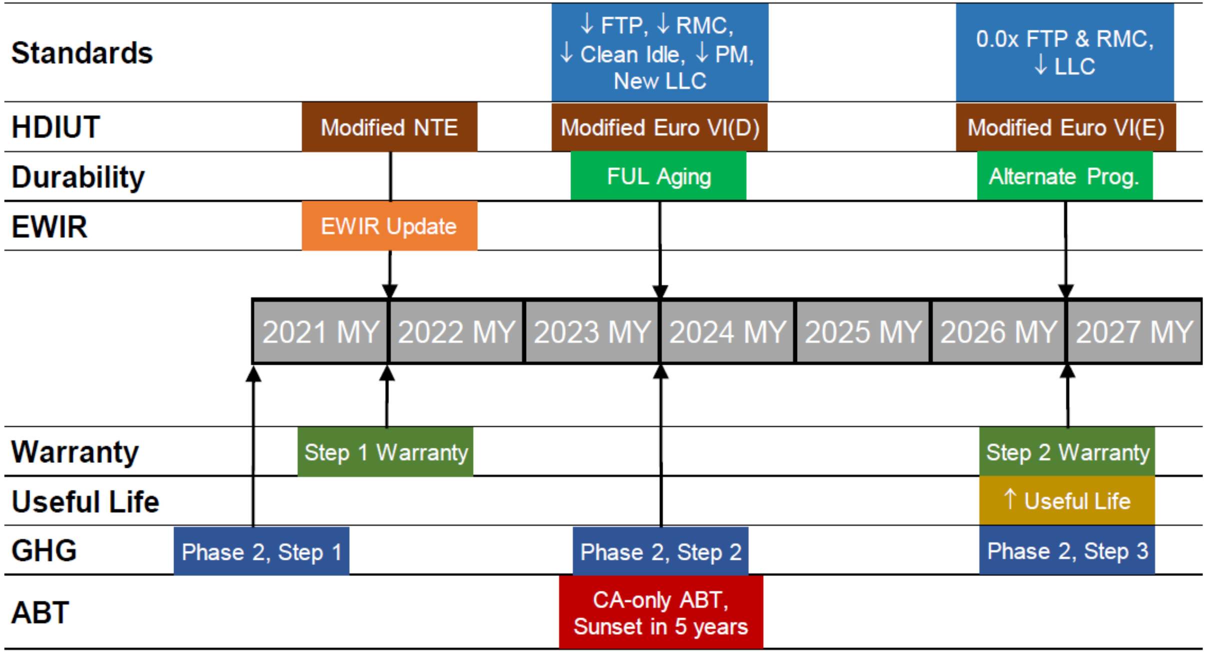


Figure 12 CARB Heavy-Duty Low NOx Rulemaking Implementation Timeline

Source: CARB Staff White Paper

Team

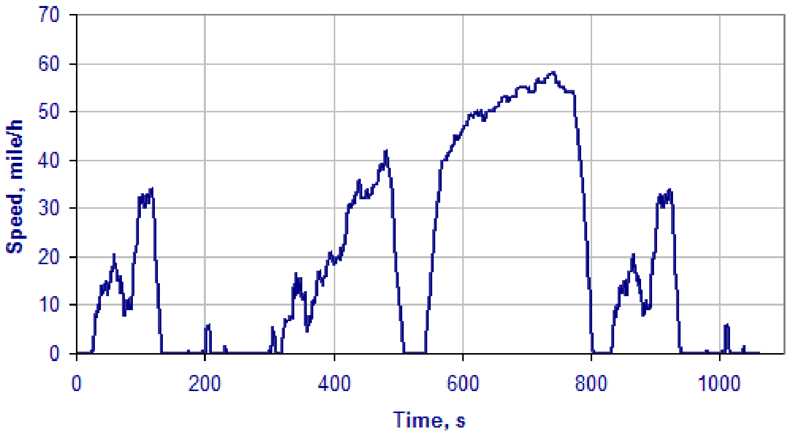
Contractors: WVU, UCR/CE-CERT

Funding Partners: CEC, CARB, SoCalGas and South Coast AQMD

South Coast AQMD

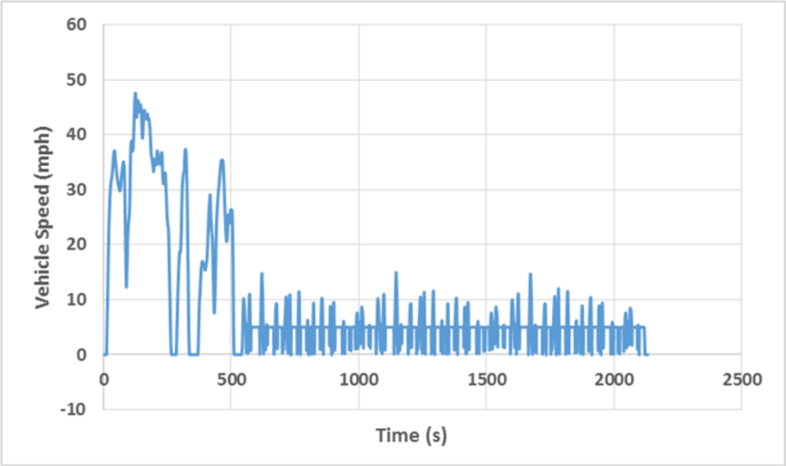
Thank you.

HD-UDDS Cycle



-Ave. Speed: 18.86 mph / 30.4 km/h
-Max. Speed: 58 mph / 93.3 km/h

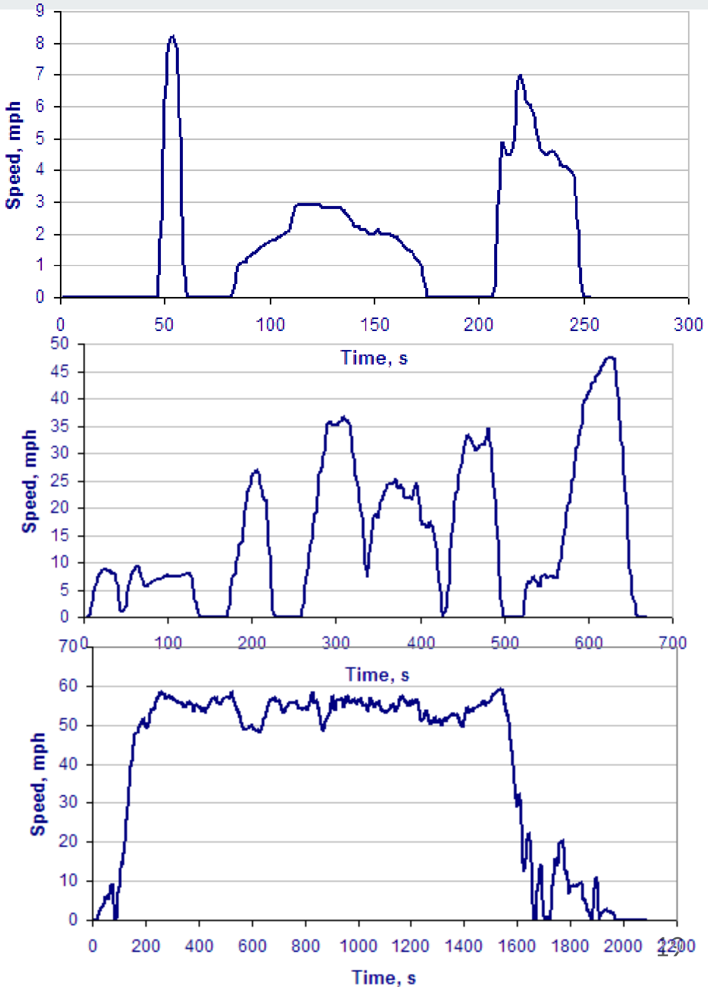
AQMD RTC Cycle



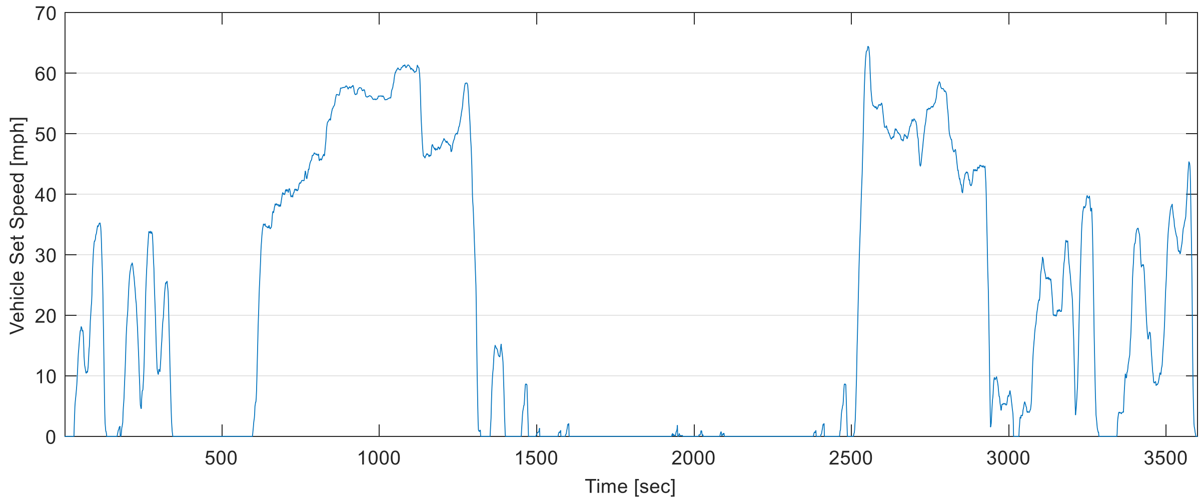
-Ave. Speed: 9.57 mph
-Max. Speed: 47.6mph

HHDDT Cycle

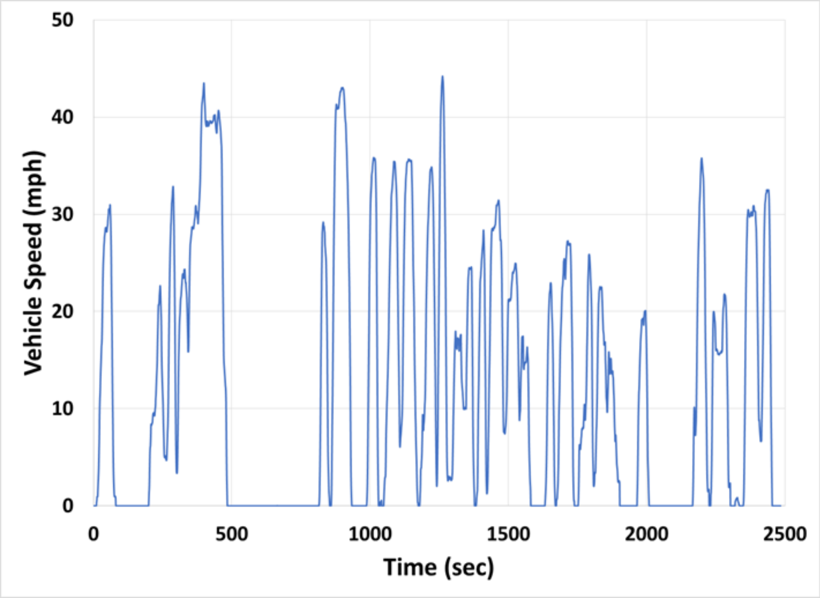
Parameter	HHDDT Creep	HHDDT Transient	HHDDT Cruise	UDDS
Duration, s	253	668	2083	1063
Distance, mi	0.124	2.85	23.1	5.55
Average Speed, mph	1.77	15.4	39.9	18.8
Stops/Mile	24.17	1.8	0.26	2.52
Max. Speed, mph	8.24	47.5	59.3	58
Max. Acceleration, mph/s	2.3	3.0	2.3	4.4
Max. Deceleration, mph/s	-2.53	-2.8	-2.5	-4.6
Total KE, mph^2	3.66	207.6	1036	373.4
Percent Idle	42.29	16.3	8.0	33.4



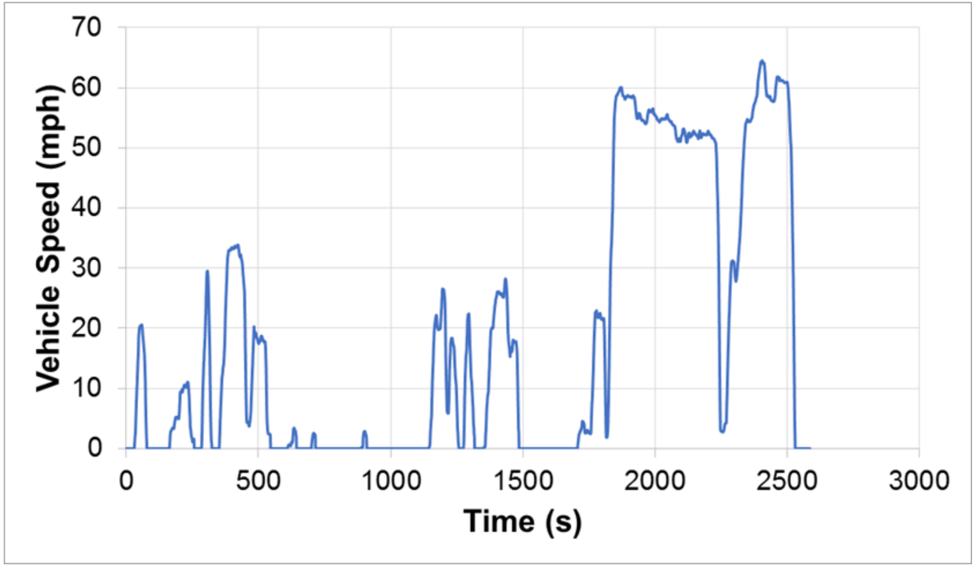
South Coast AQMD



Cycle	GMC
Cycle duration [sec]	3600
Cycle distance [miles]	20.1
Avg. vehicle speed [mi/h]	20.1
Max. vehicle speed [mi/h]	64.1
Avg. RPA [1)] [m/s²]	0.1054
Share [%] (time based)	
- idling (≤2 km/h)	42.18
- low speed (>2≤50 km/h)	22.97
- medium speed (>50≤90 km/h)	14.33
- high speed (>90 km/h)	20.52



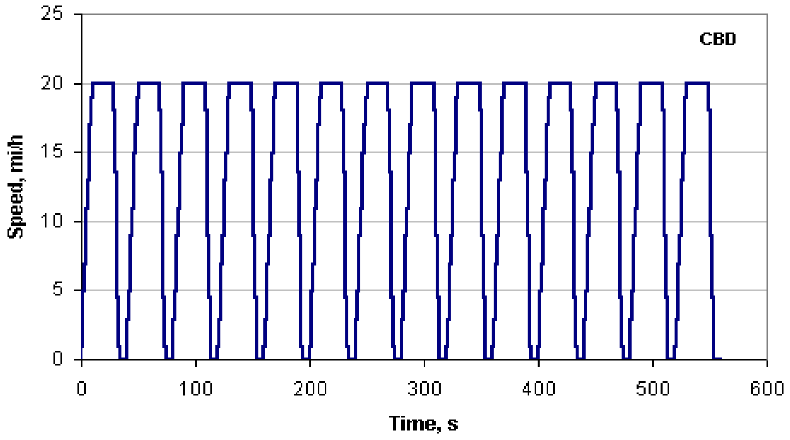
School bus cycle
Ave. Speed: 12.3 mph / 19.68km/h
Max. Speed: 45 mph / 72 km/h



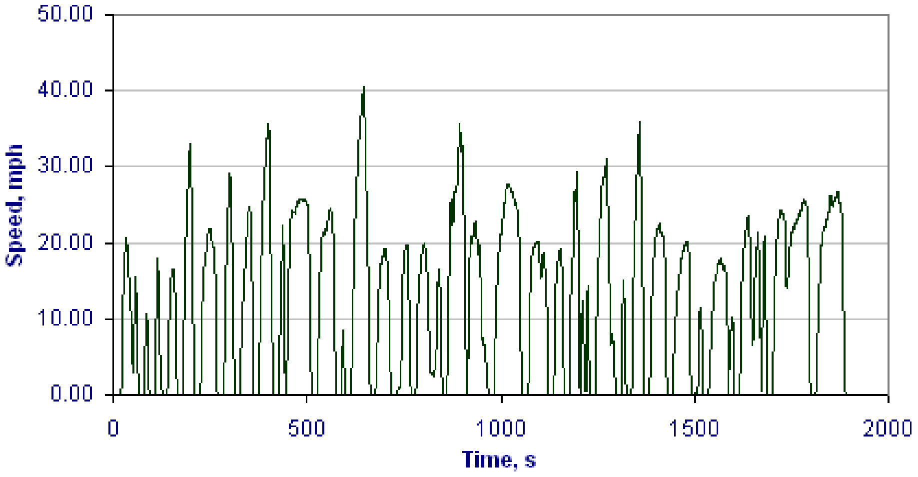
Delivery cycle
Ave. Speed: 17.4 mph / 27.84km/h
Max. Speed: 64 mph / 102.4 km/h

Test Cycles

CBD cycle



OCTA cycle



-Ave. Speed: 12.6 mph / 20.2 km/h
-Max. Speed: 20 mph / 32.18 km/h

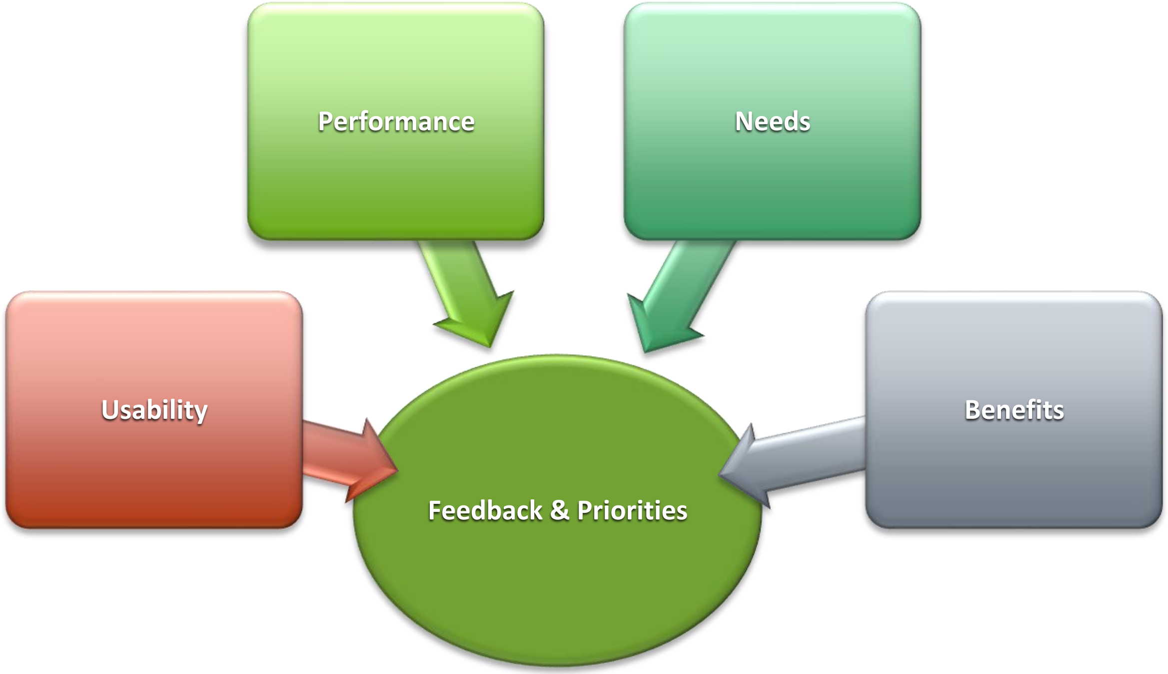
-Ave. Speed: 12.4 mph / 19.8 km/h
-Max. Speed: 40.6 mph / 64.9 km/h

DOE Clean Cities Listening Sessions

Dennis Smith
John Gonzales
February 4th, 2020

Sessions Held

- 35 Coalitions have held 47 Listening sessions
- Discuss challenges. “Warts and All”



Technical Barriers

- **Fuel Gauge Inaccuracy**
  - **Temperature compensation. Relationship between gauge and range.**
  - **Full and consistent fills**
- **Tank Packaging, Payload and life**
  - **Location and weight**
  - **Tank life with heavy duty vehicles/life of vehicle**
- **Maintenance frequency/cost**
  - **Pistons, Spark Plugs, Valves and Valve adjustments**
  - **Oil carryover and component affects, sensor failures**

Other Challenges

- **Lack of Training – Technicians, Drivers, Emergency Responders**
- **Lack of competent repair facilities**
- **Supply Chain challenges**
- **Lack of OEM product options/ vehicle and engine**
- **Range Anxiety**

Compressed Natural Gas (CNG) End of Life (EOL) Tank Performance

HEXAGON

Natural Gas Vehicle Technology Forum 2020

Brian Burks, PhD
VP Engineering
Hexagon Digital Wave, LLC
5 February 2020

Agenda

HEXAGON

- Background
- Cylinder population
- Test Methods
- Data and Results
- Next Steps

Background

HEXAGON

- The use of natural gas vehicle tanks for fuel systems is regulated by the Department of Transportation National Highway and Transportation and Safety Administration (DOT/NHTSA)
- Federal Motor Vehicle Safety Standard 304 (FMVSS 304) details the safety requirements for tank design
- Detail four (4) types of tank designs
  - Type 1 – Seamless metallic
  - Type 2 – Hoop wrapped metallic liner
  - Type 3 – Fully wrapped metallic liner
  - Type 4 – Fully wrapped non-load sharing liner
- Type 3 and Type 4 tanks were the focus of the present study
  - Advanced Type 1 tank periodic inspection is well documented
  - Type 2 tanks provide unique inspection challenges and are not in heavy utilization
- 49 CFR §571.304 requires that all tanks have a label applied on them stating '*Do Not Use After ____' inserting the month and year that mark the end of the manufacturer's recommended service life for the container*
- Not a unique problem
  - Other composite cylinder constructions have reached the end of their initial service lives
  - Regulatory authorities have looked for means to ease financial constraints on asset owners
  - Significant challenge in assessing the integrity of the composite overwrap, as viable inspection methods had not become available until recently

Cylinder Population

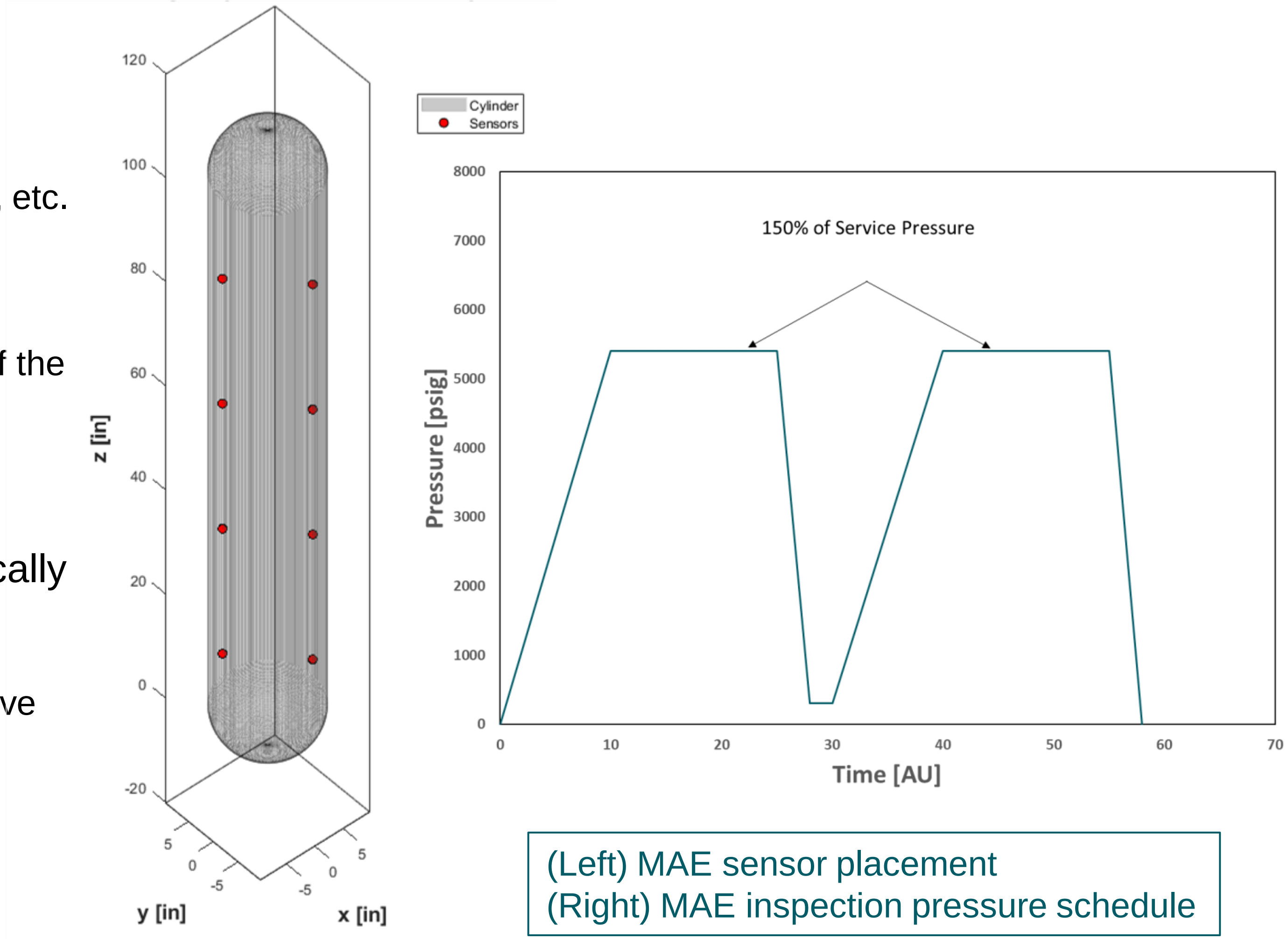
- LA Metro Transit Authority graciously supplied 101 tanks of Type 3 and Type 4 construction
- Tanks were utilized in bus service for a full 15 year service life
- Tanks were nominally 16” in diameter and 10’ in length
- Estimated that tanks were filled from 1000 psig to 4400 psig 6 times a week
- Results in ~4700 cycles being placed on each tank

Test Methods

- Visual Inspection – CGA C6.2 and C6.4
- Modal Acoustic Emission (MAE) –
  - Advanced non-destructive evaluation (NDE) technique that has been adopted by ASME, NBIC, and DOT/PHMSA for the periodic inspection of composite pressure vessels
  - National Board Inspector’s Code Supplement 10
  - Department of Transportation Pipeline and Hazardous Materials Association (DOT/PHMSA)
- Burst Pressure Testing – 49 CFR §571.304 (S7.2.2)
  - Requires a minimum ratio of 2.25 burst pressure to service pressure
- Hydrostatic Pressure Cycle Test – 49 CFR §571.304 (S8.1.1-4)
  - 13,000 cycles from 10% of service pressure to service pressure
  - 5,000 cycles 10% of service pressure to 125% of service pressure
- ISO 11439 §A.17 – Notch Tolerance
  - Matching replicates – half subjected to burst, half subjected to fatigue cycle and burst
- ISO 11439 §A.20 and CSA B339 localized impact procedure – Impact Tolerance
  - Matching replicates – half subjected to burst, half subjected to fatigue cycle and burst

Inspection Method Details

- Visual inspection – external and internal
  - Cuts, gouges, impact, thermal damage, chemical attack, etc.
- Modal Acoustic Emission (MAE) testing
  - Place sensors on the surface of the tank under test and capture transient elastic stress waves which propagate if the microstructure is failing as the test article is stressed
  - Unique sensor response enables damage mechanism classification
- Composite pressure vessel MAE inspection specifically tailored to reject on
  - Fiber tow fracture
  - Local instability of the composite as a result of progressive failure
- Inherent in a MAE test is a proof pressure test



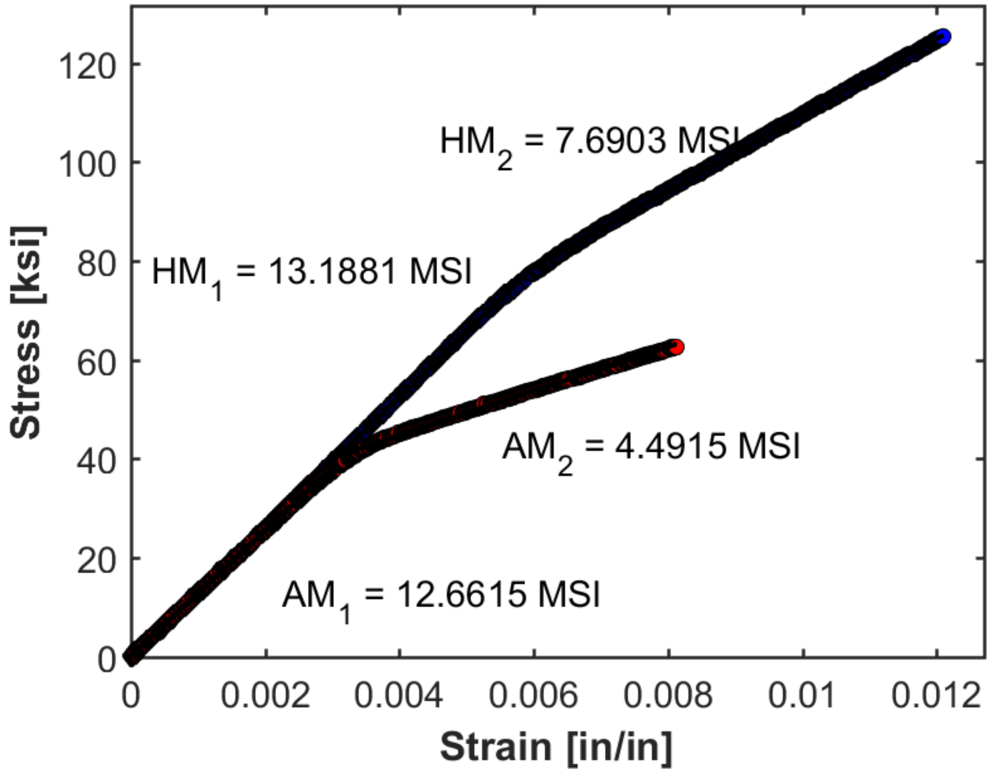
(Left) MAE sensor placement
(Right) MAE inspection pressure schedule

Burst Pressure Testing

- Vessels were all hydraulically burst in containment
- Pressure transducer was attached to the dead end of the vessel under test allowing for a stable and settled pressure reading
- Hoop and axial strain was acquired for principal stiffness measurement
- MAE data was taken on 2 channels located mid-cylinder side wall and spaced apart 180° radially
- Burst pressure was taken as the highest recorded pressure prior to rupture

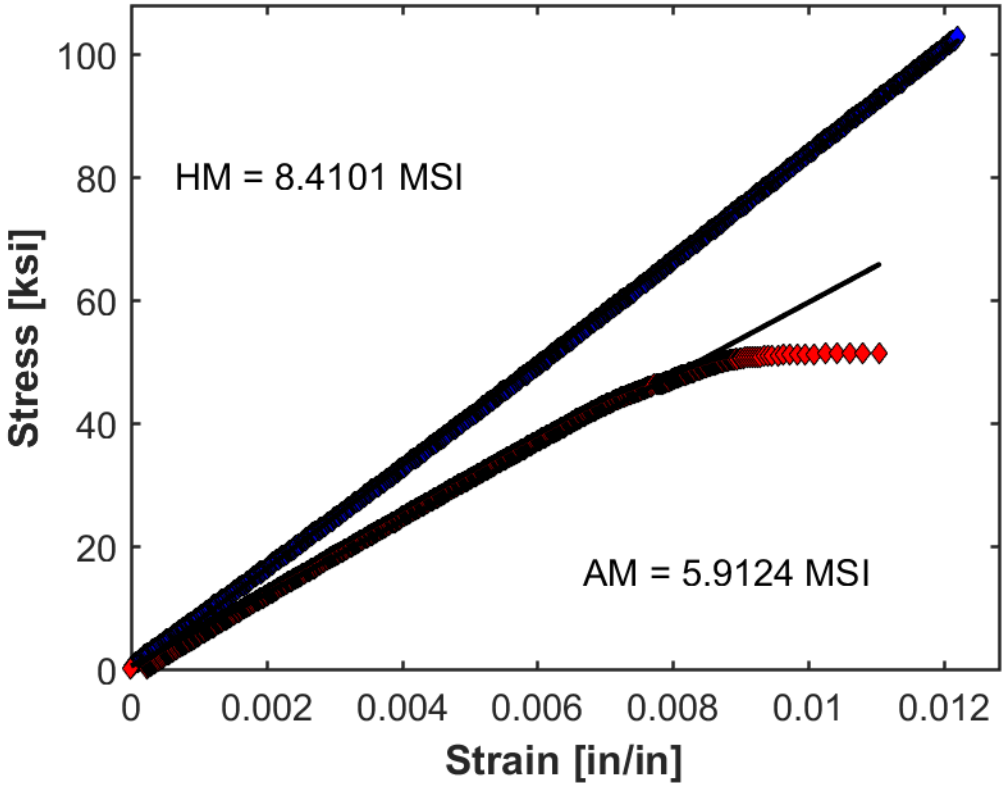
Burst Testing – Type 3 Mechanical Response

- Classic bi-linear elastic response
  - Liner is contributing to laminate stiffness at low strain levels
  - Post yield, the liner tangent modulus is quite low resulting in reduced stiffness response
- All EOL tanks met 49 CFR §571.304 minimum burst-service pressure requirements

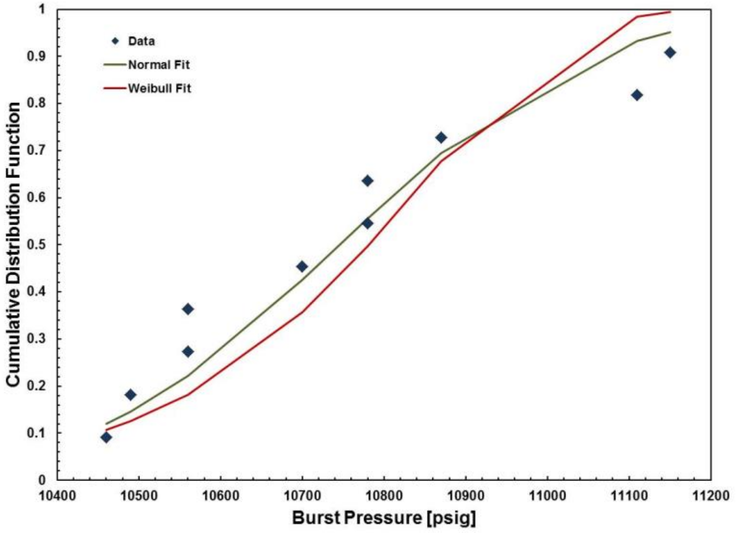


Burst Testing – Type 4 Mechanical Response

- Linear elastic response through burst
  - Stiffer hoop response than axial response
- All EOL tanks met 49 CFR §571.304 minimum burst-service pressure requirements

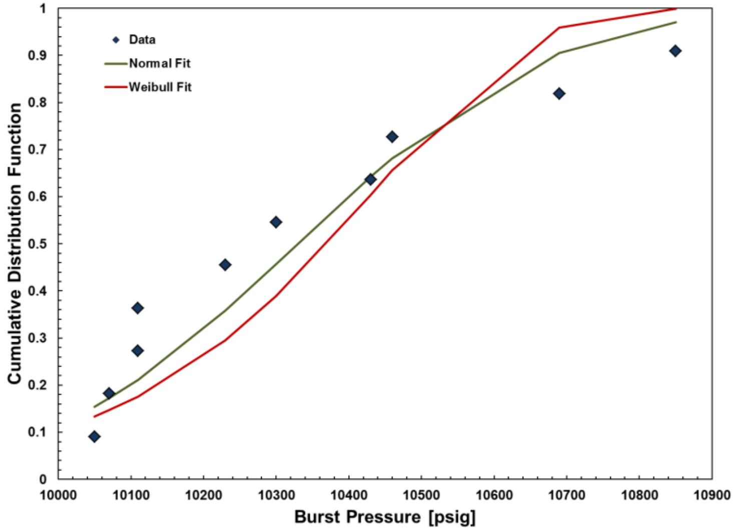


Burst Pressure Testing Results



Type	Cylinder S/N	Cylinder Manufacture Date	Burst Pressure [psig]	NGV2 Burst Pressure Met [Pass/Fail]	HM1 [Msi]	HM2 [Msi]	AM1 [Msi]	AM2 [Msi]
3	ALT810N - 2565	11-01	10780	Pass	14.6	8.1	13.2	5.0
3	ALT810N - 3991	03-02	10870	Pass	12.9	7.6	12.2	4.7
3	ALT810N - 3993	03-02	10560	Pass	13.2	7.7	12.7	4.5
3	ALT810N - 1976	09-01	11110	Pass	12.8	7.1	12.1	4.2
3	ALT810N - 2099	10-01	10560	Pass	12.5	6.7	12.4	3.9
3	ALT810N - 2107	10-01	10460	Pass	12.0	6.8	11.6	4.1
3	ALT810N - 3858	03-02	11150	Pass	13.5	7.7	13.0	4.7
3	ALT810N - 3884	03-02	10700	Pass	13.2	7.5	12.7	4.5
3	ALT810N - 4049	03-02	10780	Pass	13.2	7.5	14.6	5.3
3	ALT810N - 2189	10-01	10490	Pass	13	7.7	13.4	4.7

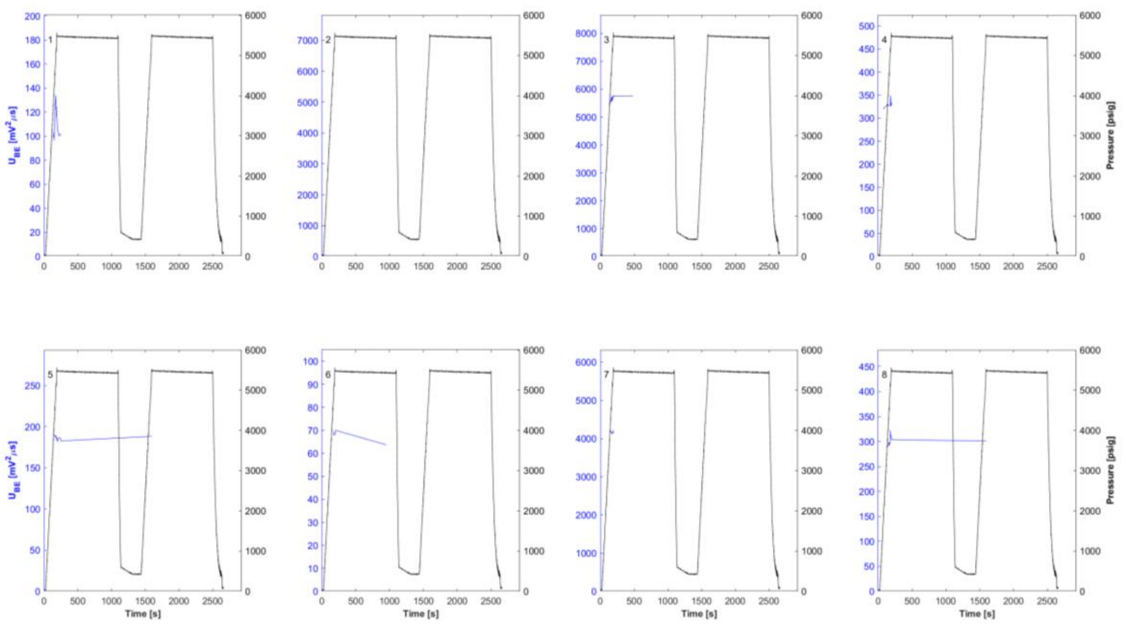
Type	Cylinder S/N	Cylinder Manufacture Date	Burst Pressure [psig]	NGV2 Burst Pressure Met [Pass/Fail]	HM1 [Msi]	AM1 [Msi]
4	314 - 051	10-00	10430	Pass	8.0	10.7
4	314 - 144	10-00	10690	Pass	10.0	7.0
4	316 - 007	10-00	10460	Pass	8.4	5.9
4	319 - 037	10-00	10300	Pass	8.2	8.4
4	305 - 163	08-00	10070	Pass	8.6	6.5
4	309 - 181	08-00	10110	Pass	8.3	7.7
4	314 - 050	10-00	10230	Pass	8.4	5.9
4	309 - 026	08-00	10050	Pass	8.0	6.4
4	305 - 160	08-00	10110	Pass	8.1	5.7
4	319 - 012	10-00	10850	Pass	8.2	7.3



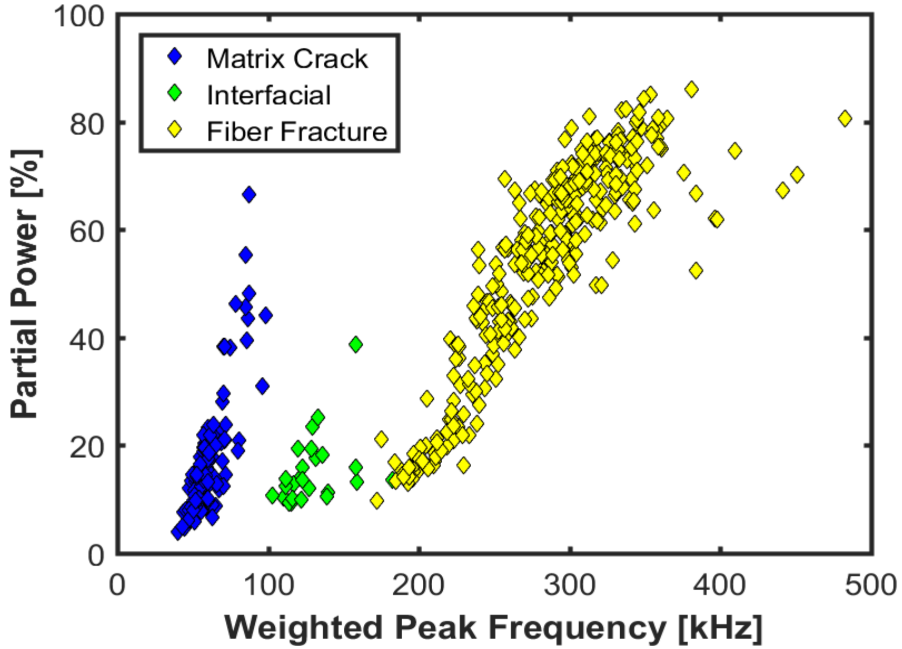
Burst Testing – MAE Response

- Prior to burst
  - All EOL tanks PASSED visual inspection
  - All EOL tanks PASSED proof pressure test
  - All EOL tanks PASSED MAE inspection

- During burst, MAE data taken as the cylinder was failed showed a clear natural clustering of damage mechanism types
  - Physics based forward predictive finite element modeling allowed the clusters to be assigned to various damage mechanisms[1,2]



Local instability plot from MAE inspection of ALT810N-2565



Damage mechanism clustering analysis from burst test MAE data

1. MGR Sause, S Horn, “Simulation of Acoustic Emission in Planar Carbon Fiber Reinforced Plastic Specimens,” Journal of Nondestructive Evaluation 2010, **29**, 123-142.
2. B Burks, M Kumosa, “A Modal Acoustic Emission Signal Classification Scheme Derived from Finite Element Simulation,” International Journal of Damage Mechanics 2014, **23**(1), 43-62.

Hydraulic Fatigue Cycle Testing

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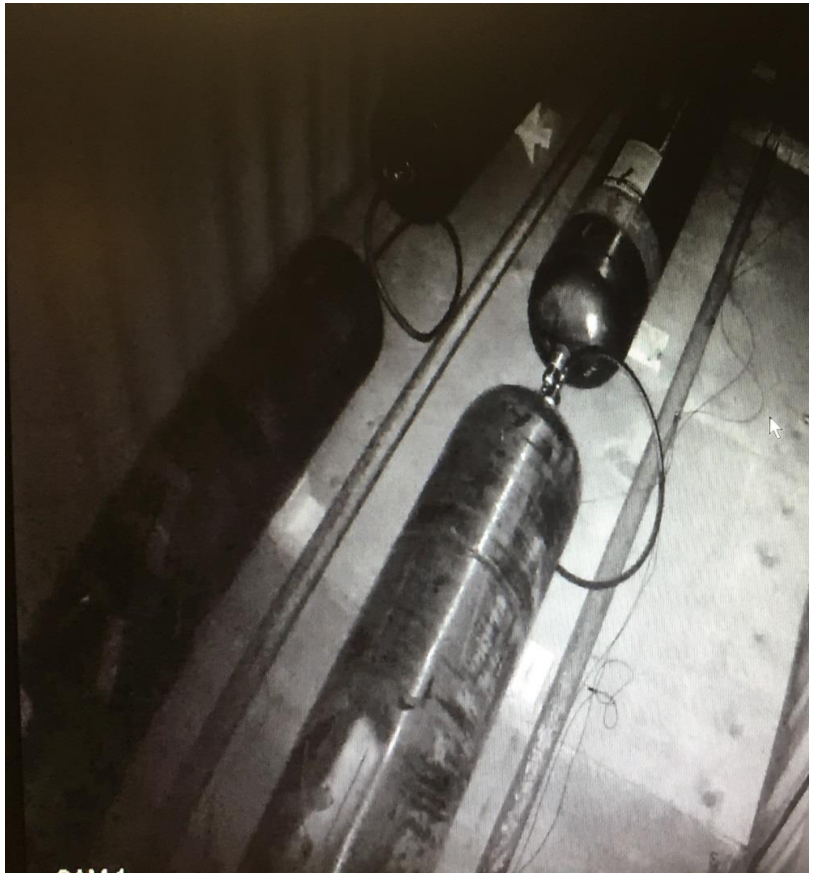
- 20 vessels were hydraulically fatigue cycled
- Hydraulic fatigue cycle test was performed in accordance with 49 CFR §571.304 (S8.1.1-4)
  - 13,000 fatigue cycles from 10% of service pressure to 100% of service pressure
  - 5,000 fatigue cycles from 10% of service pressure to 125% of service pressure
- Approximately **820,000** gallons of fluid were moved between 10% and 125% of service pressure to achieve this fatigue test program
- Tanks were fatigue cycled in parallel typically 4 tanks at a time
- Principal stiffness was measured as a function of number of applied fatigue cycles
  - Monitoring for gradual loss of stiffness indicating degraded vessel integrity
  - Used a Damage Parameter (*D*) to quantify

$$D_i = \frac{E_i}{E_0}$$



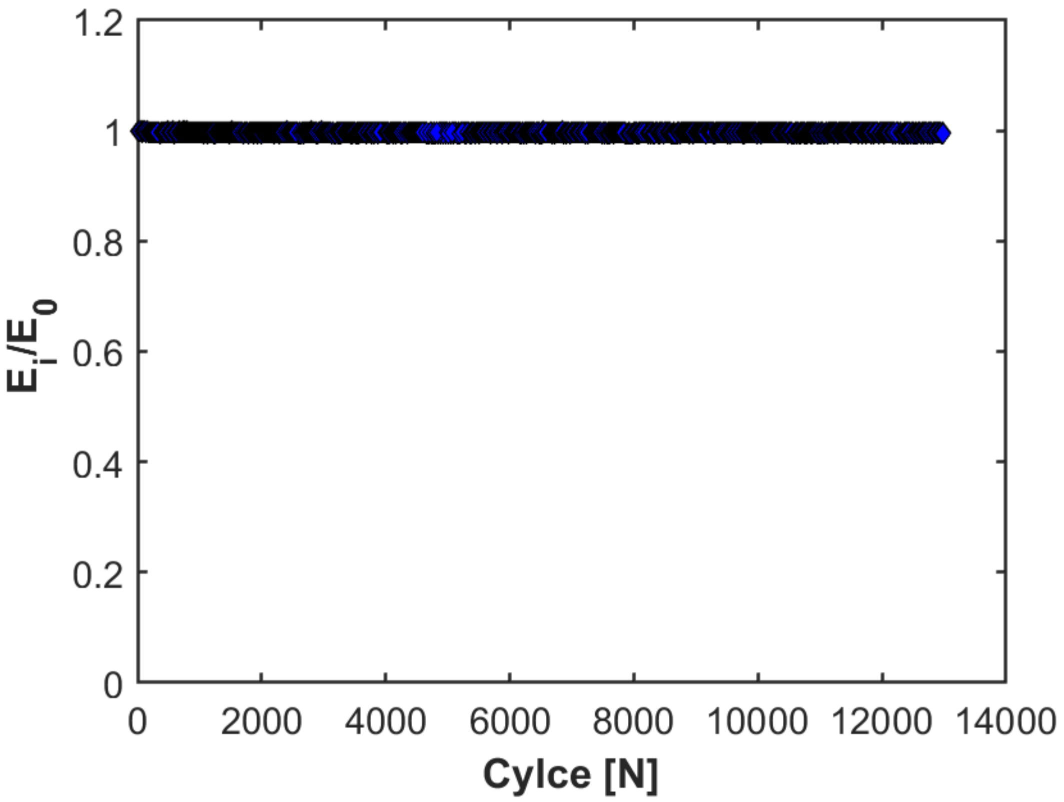
Four (4) tanks being simultaneously fatigue cycled tested

Hydraulic Fatigue Cycle Testing – Pre-test MAE Inspection

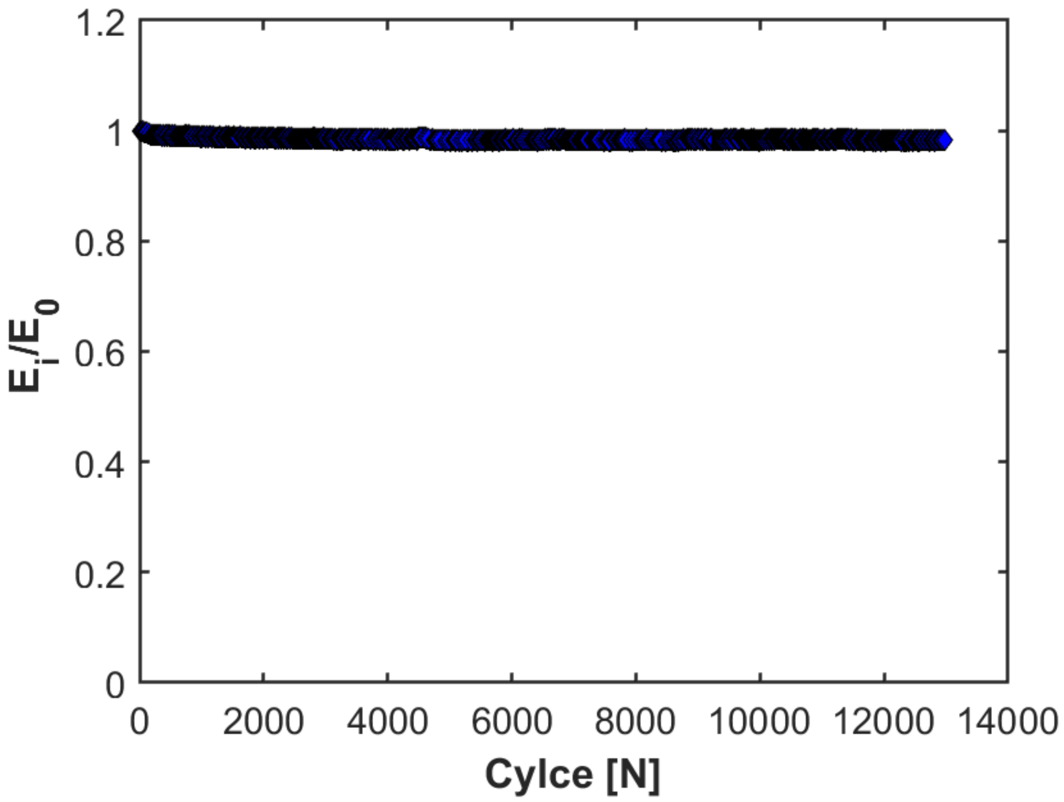
- Prior to hydraulic fatigue cycle testing
  - All tanks PASSED visual inspection
  - All tanks PASSED proof pressure test
  - All tanks PASSED MAE inspection
- All tanks PASSED 49 CFR §571.304 S8.1.1-4 fatigue cycle testing requirements
- A second MAE inspection was performed post hydraulic fatigue cycle test
  - All tanks PASSED MAE inspection
- One tank of each design variant was subjected to a leak test per CGA C6.4 post fatigue cycle test to verify integrity post fatigue cycle test
  - Both tanks PASSED the leak test and exhibited no signs of leakage

Hydraulic Fatigue Cycle Testing – Type 3 and Type 4 Mechanical Response Service Pressure Stress Range

ALT810N-2996 (Type 3 tank) Damage Parameter response during service pressure fatigue cycle testing

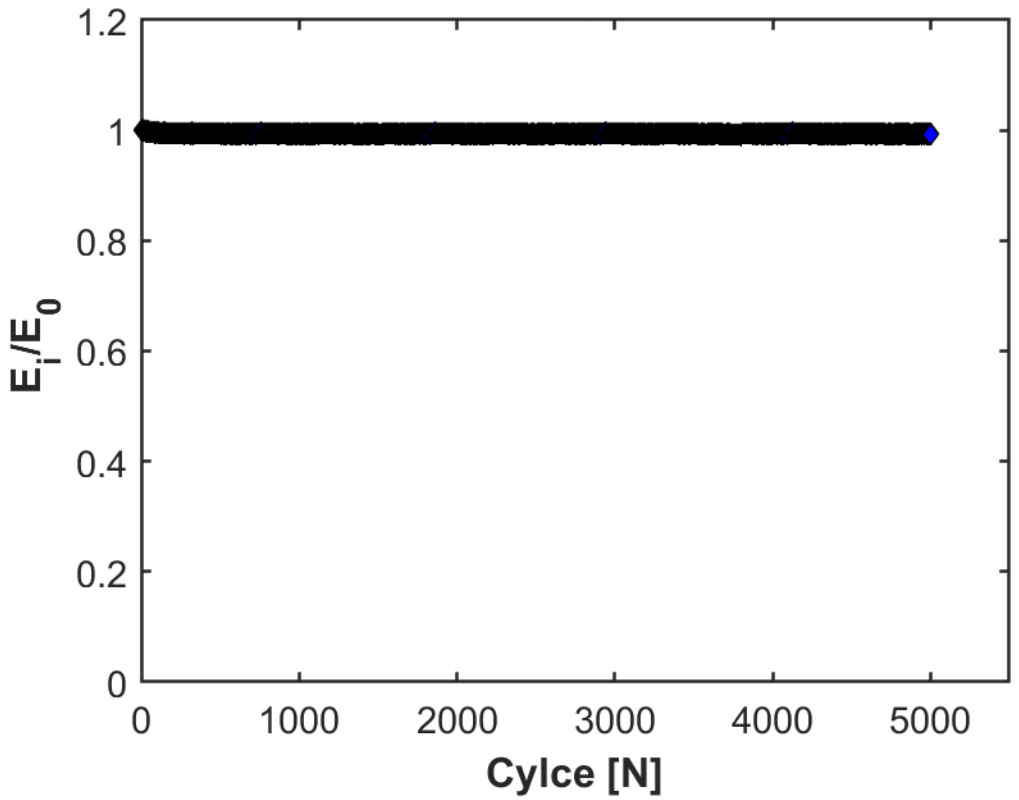


313-045 (Type 4 tank) Damage Parameter response during service pressure fatigue cycle testing

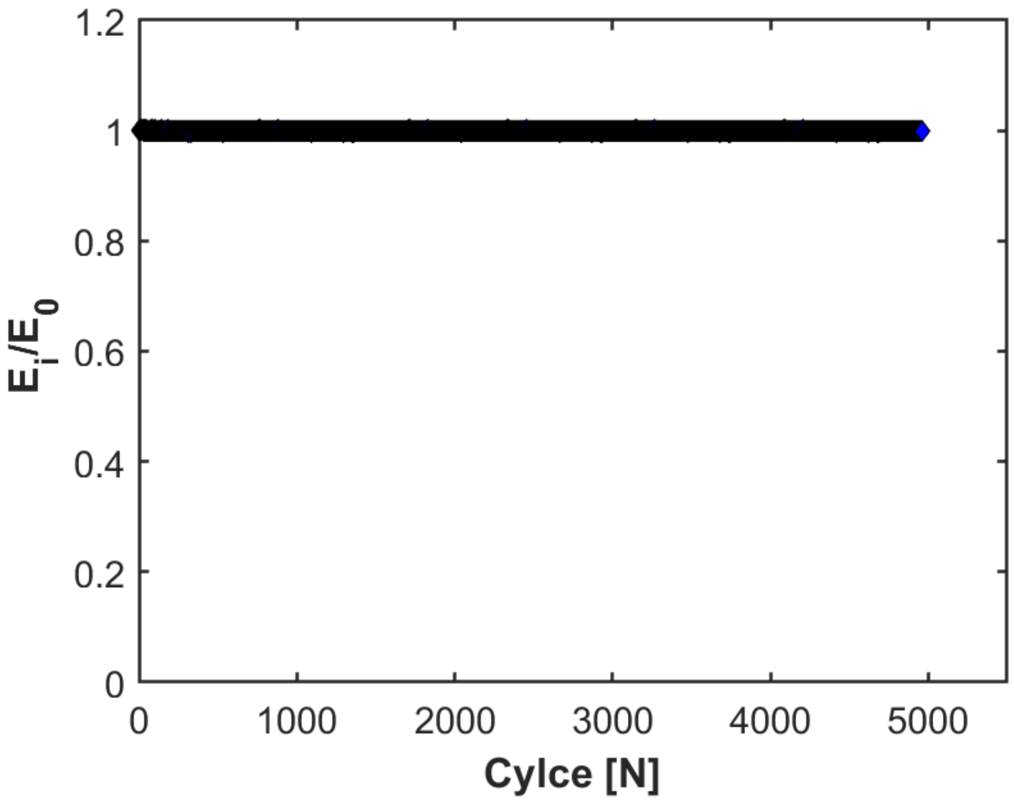


Hydraulic Fatigue Cycle Testing – Type 3 and Type 4 Mechanical Response High Stress Range

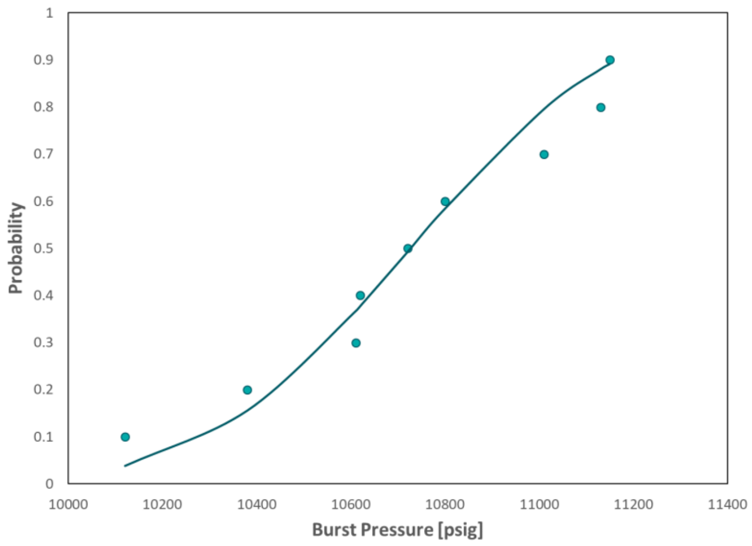
ALT810N-2996 (Type 3 tank) Damage Parameter response during service pressure fatigue cycle testing



313-045 (Type 4 tank) Damage Parameter response during service pressure fatigue cycle testing

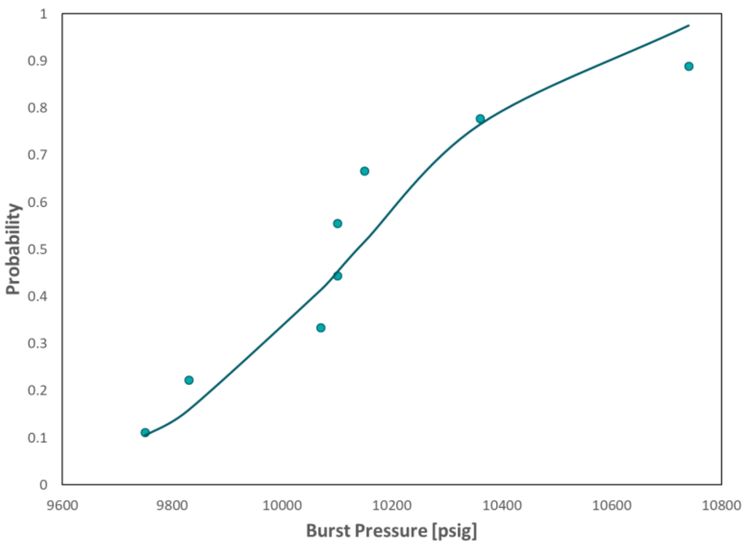


Hydraulic Fatigue Cycle Testing – Burst Testing Results



Tank Design Type	Manufacturer's Make	Tank S/N	Manufacture Date	NGV2 Fatigue Cycle Test Result [Pass/Fail]	Burst Pressure [psig]	NGV2 Burst Pressure Requirement [Pass/Fail]	MAE Acceptance Requirement [Pass/Fail]	HM1 [MSI]	HM2 [MSI]	AM1 [MSI]	AM2 [MSI]
3	ALT810N	3653	02/02	Pass	10720	Pass	Pass	12.3	7.2	11.3	4.4
3	ALT810N	2351	10/01	Pass	-	-	Pass	-	-	-	-
3	ALT810N	3733	03/02	Pass	10800	Pass	Pass	13.0	6.2	14.1	4.8
3	ALT810N	2353	10/01	Pass	10120	Pass	Pass	12.7	7.1	13.6	4.7
3	ALT810N	2740	12/01	Pass	10620	Pass	Pass	13.8	7.5	14.2	5.2
3	ALT810N	2403	10/01	Pass	10610	Pass	Pass	12.8	6.7	12.2	4.3
3	ALT810N	3735	03/02	Pass	10380	Pass	Pass	12.5	7.5	10.1	-
3	ALT810N	3323	02/02	Pass	11010	Pass	Pass	13.1	6.9	12.8	4.6
3	ALT810N	2996	12/01	Pass	11130	Pass	Pass	13.1	7.4	12.7	4.7
3	ALT810N	3326	02/02	Pass	11150	Pass	Pass	12.8	7.3	11.6	4.4

Tank Design Type	Manufacturer's Make	Tank S/N	Manufacture Date	NGV2 Fatigue Cycle Test Result [Pass/Fail]	Burst Pressure [psig]	NGV2 Burst Pressure Requirement [Pass/Fail]	MAE Acceptance Requirement [Pass/Fail]	HM1 [MSI]	AM1 [MSI]
4	RE36A16-120MG	313-063	10/00	Pass	9750	Pass	Pass	7.7	6.8
4	RE36A16-120MG	309-032	08/00	Pass	9830	Pass	Pass	7.8	7.0
4	RE36A16-120MG	319-020	10/00	Pass	10150	Pass	Pass	7.9	5.6
4	RE36A16-120MG	313-046	09/00	Pass	10100	Pass	Pass	8.1	7.6
4	RE36A16-120MG	309-025	08/00	Pass	10360	Pass	Pass	7.4	6.1
4	RE36A16-120MG	309-186	08/00	Pass	10100	Pass	Pass	7.8	6.4
4	RE36A16-120MG	313-045	09/00	Pass	-	-	Pass	-	-
4	RE36A16-120MG	319-007	10/00	Pass	10070	Pass	Pass	7.8	6.1
4	RE36A16-120MG	319-051	10/00	Pass	10740	Pass	Pass	7.9	6.3
4	RE36A16-120MG	314-048	10/00	Pass	9310*	Pass	Pass	7.8	6.4



*314-048 burst pressure not considered valid due to mechanical pump failure and mixed mode burst/static fatigue failure

Notch Tolerance Testing – ISO 11439 §A.17

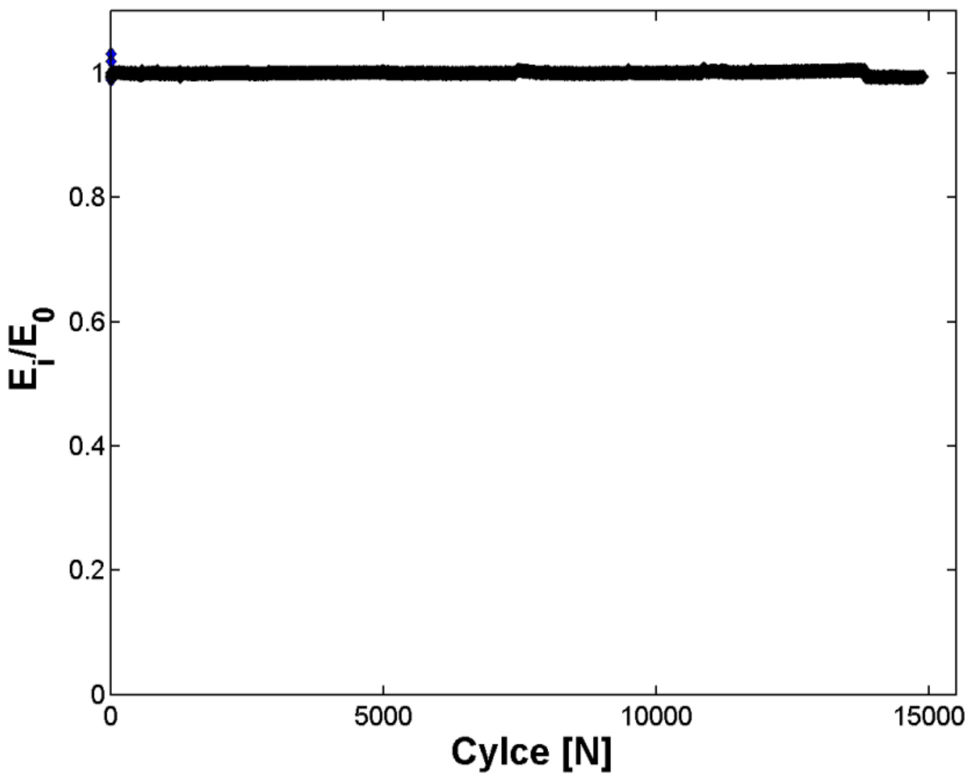
Cylinder Information			Long Notch		Short Notch	
Cylinder Design Type	Manufacturer's Design Designation	Cylinder S/N	Notch Depth [in]	Notch Width [in]	Notch Depth [in]	Notch Width [in]
3	ALT810N	3651	0.031	8.0	0.050	1.1
3	ALT810N	3742	0.031	8.0	0.050	1.0
3	ALT810N	1995	0.030	8.3	0.052	1.3
3	ALT810N	2744	0.032	8.0	0.051	1.3
4	RE36A-120MG	319-006	0.031	8.0	0.050	1.0
4	RE36A-120MG	316-008	0.030	8.0	0.051	1.0
4	RE36A-120MG	316-014	0.031	8.2	0.052	1.1
4	RE36A-120MG	309-117	0.031	8.2	0.051	1.1

Notches machined into cylinder sidewall

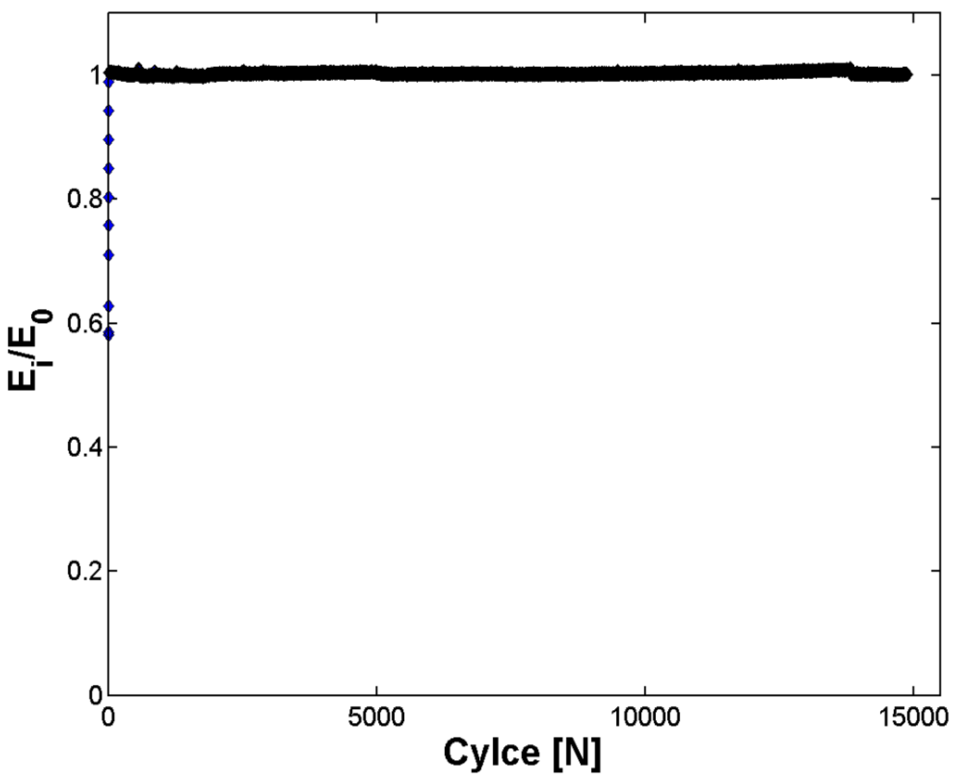
- Notch tolerance testing was done in accordance with ISO 11439 §A.17
- Two notches machined into each cylinder sidewall
  - Notch 1: L = 8.00”; ↓ = 0.030”
  - Notch 2: L = 1.00”; ↓ = 0.050”
- Test protocol calls for half the replicates to be fatigue tested, the other half to be subjected to a burst test
- All specimens were MAE inspected after notches were introduced
- Fatigue specimens subjected to 15,000 cycles from 10% of service pressure to 105% of service pressure
- Burst specimens were burst directly after the MAE test

Notch tolerance Fatigue Cycle Testing – Type 3 and Type 4 Mechanical Response 105% Service Pressure Stress Range

ALT810N-1995 (Type 3 tank) Damage Parameter response during fatigue cycle testing with a notch

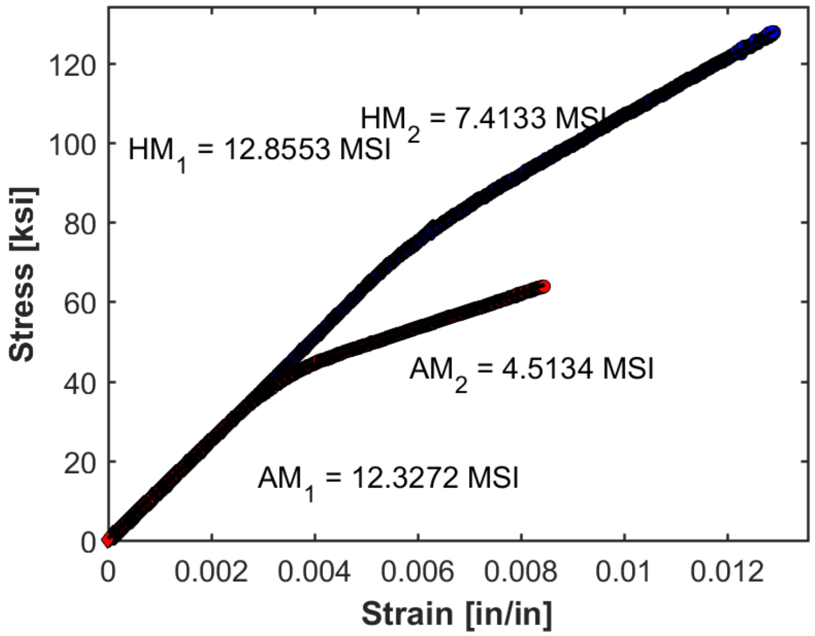


309-117 (Type 4 tank) Damage Parameter response during fatigue cycle testing with a notch



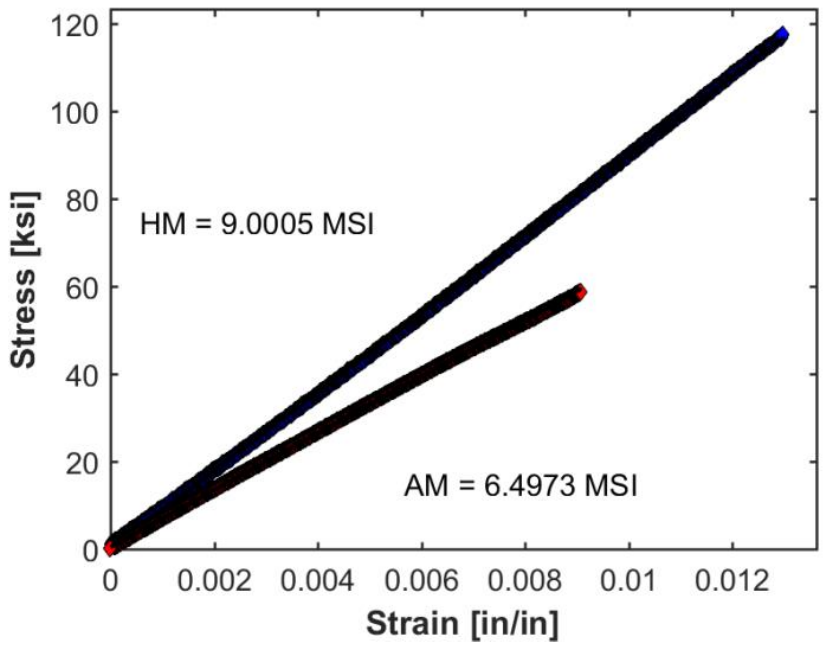
- All notched fatigue specimens achieved 15,000 cycles to 105% of service pressure
- No degradation in stiffness during fatigue cycle testing detected

Notch Tolerance Testing – Results



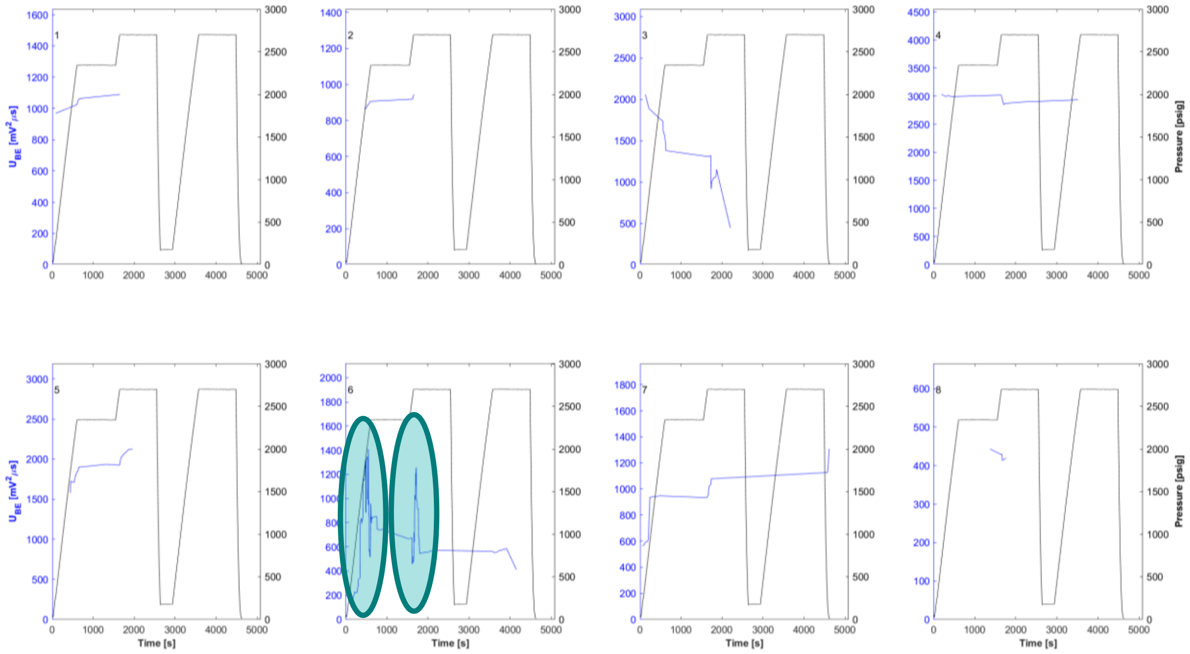
Cylinder Design Type	Manufacturer's Design Designation	Cylinder S/N	Cylinder Manufacture Date	Test Procedure	Burst Pressure [psig]	NGV2 Burst Pressure Met [Pass/Fail]	MAE Inspection Result	Percentile of EOL Distribution	HM1 [MSI]	AM1 [MSI]	HM2 [MSI]	AM2 [MSI]
3	ALT810N	3651	Feb-02	EOL	10510	Pass	Fail	16.58%	12.7	13.4	7.2	8.2
3	ALT810N	3742	Mar-02	EOL	10655	Pass	Fail	35.41%	12.8	12.3	7.4	4.5
3	ALT810N	1995	Sep-01	Fatigue/EOL	9830	Pass	Fail	0.01%	12.7	12.7	7.2	4.4
3	ALT810N	2744	Dec-01	Fatigue/EOL	9860	Pass	Fail	0.01%	12.7	13	7.3	4.9

Cylinder Design Type	Manufacturer's Design Designation	Vessel S/N	Cylinder Manufacture Date	Test Procedure	Burst Pressure [psig]	NGV2 Burst Pressure Met [Pass/Fail]	MAE Inspection Result	Percentile of EOL Distribution	HM [MSI]	AM [MSI]
4	RE36A-120MG	319-006	Oct-00	EOL	10000	Pass	Fail	11.51%	9	6.5
4	RE36A-120MG	316-008	Oct-00	EOL	9460	Pass	Fail	0.08%	8.6	7.2
4	RE36A-120MG	316-014	Oct-00	Fatigue/EOL	9240	Pass	Fail	0.00%	8.1	6.6
4	RE36A-120MG	309-117	Aug-00	Fatigue/EOL	9220	Pass	Fail	0.00%	8.4	6.3

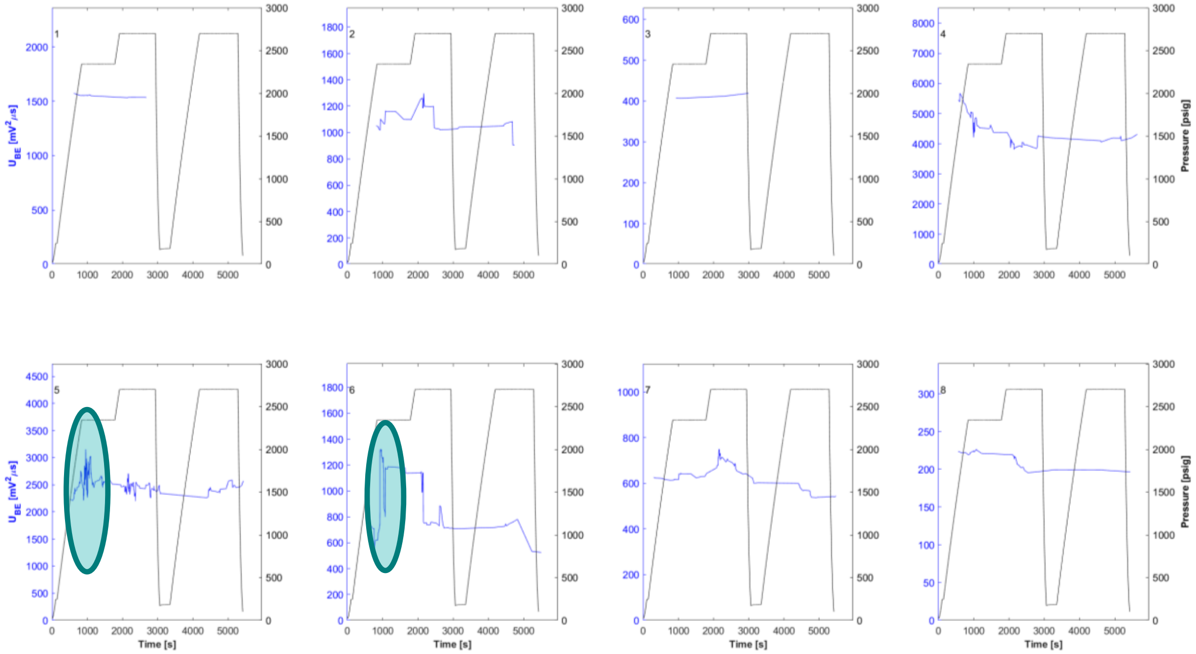


Notch Tolerance Testing – MAE Results

Local instability plot for ALT810N-1995 prior to fatigue cycle testing



Local instability plot for 316-014 prior to fatigue cycle testing



Impact Tolerance Testing – ISO 11439 §A.20 and CSA B339 Localized Impact

- Impact tolerance is desirable in automotive applications where accidents can occur
- Three (3) impact scenarios were considered
- Impact testing done per ISO 11439 §A.20
  - Cylinder dropped in horizontal orientation from 48” height on to flat concrete surface
- Localized impact testing from CSA B339 half height
  - Cylinder dropped in horizontal orientation on to a piece of steel angle iron such that the side wall of the cylinder is impacted in a localized fashion
- Localized impact testing from CSA B339 full height
  - Cylinder dropped in horizontal orientation on to a piece of steel angle iron such that the side wall of the cylinder is impacted in a localized fashion
  - 2x the amount of potential energy as standard ISO 11439 impact
- Two replicates for each design type and impact scenario
  - First replicate for each design type was fatigue cycle tested from 10% to 105% of service pressure for up to 15,000 cycles
  - Second replicate for each design type was subjected to an EOL burst test
- All specimens were MAE inspected prior to fatigue and/or EOL burst testing

Impact tolerance Fatigue Cycle Testing – Type 3 and Type 4 Mechanical Response 105% Service Pressure Stress Range

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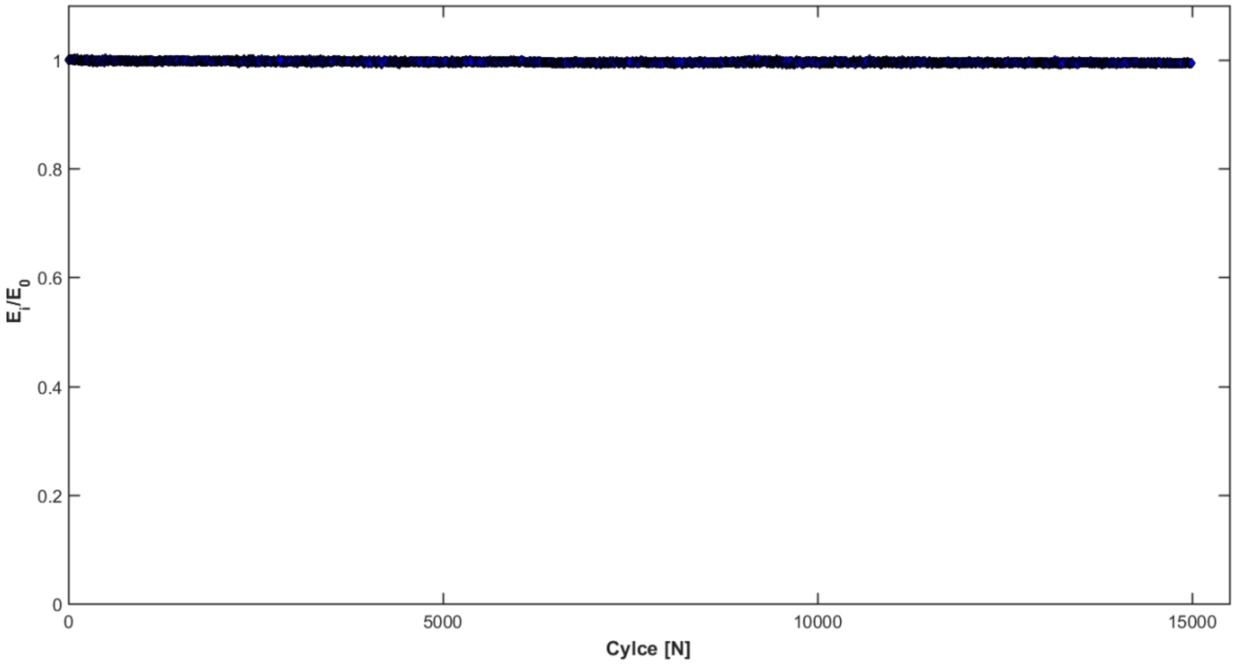
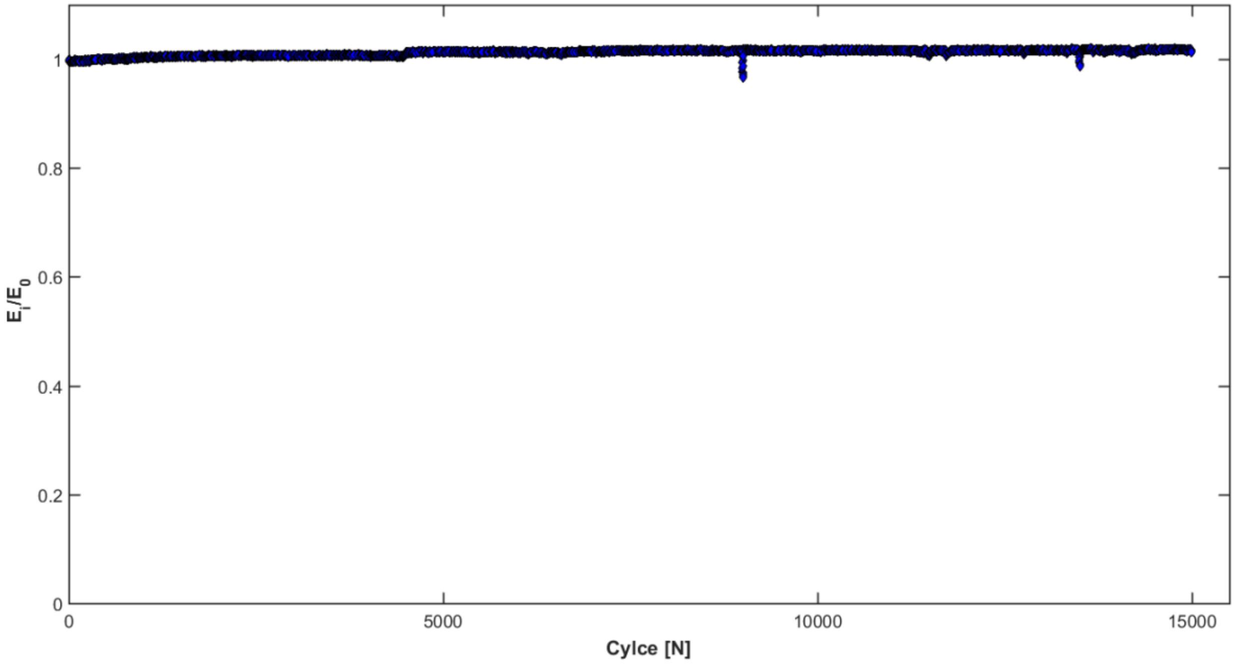
ALT810N-2188 (Type 3 tank) Damage Parameter response during fatigue cycle testing with impact

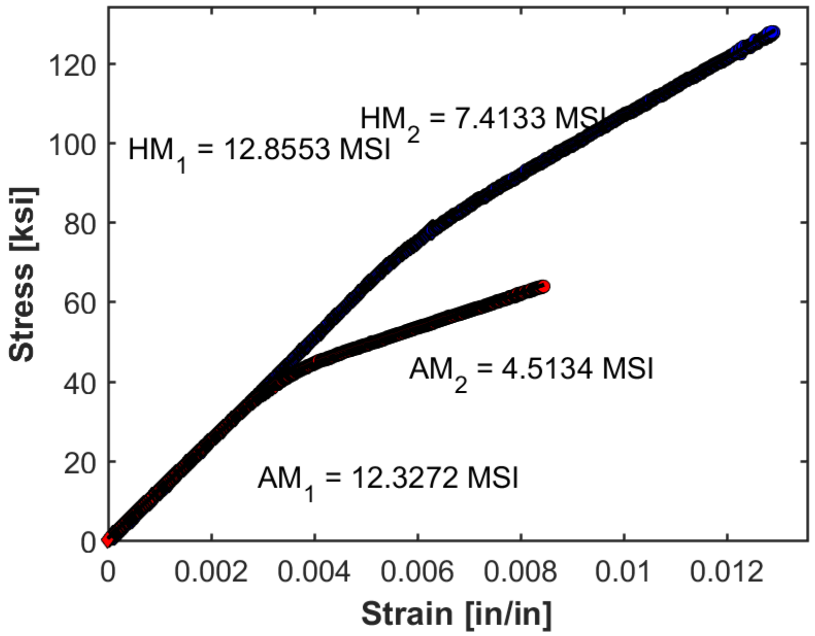


305-164 (Type 4 tank) Damage Parameter response during fatigue cycle testing with impact damage



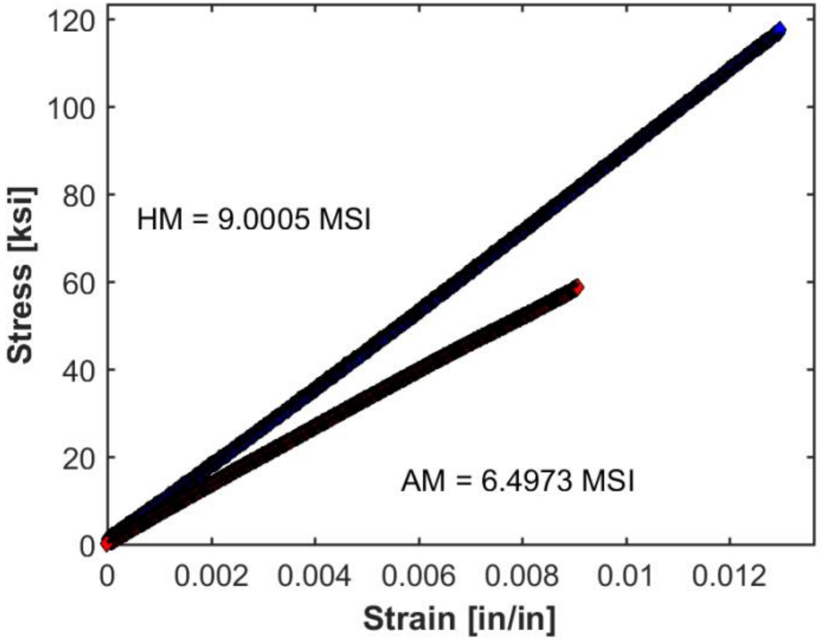
- All impacted fatigue specimens achieved 15,000 cycles to 105% of service pressure
- No degradation in stiffness during fatigue cycle testing detected

Impact Tolerance Testing – Results



Cylinder Design Type	Manufacturer's Design Designation	Vessel S/N	Cylinder's Manufacture Date	Test Procedure	Burst Pressure [psig]	NGV2 Burst Pressure Met [Pass/Fail]	MAE Result [Pass/Fail]	Percntile of EOL Distribution	HM1 [Msi]	AM1 [Msi]	HM2 [Msi]	AM2 [Msi]
Type 3	ALT810N	3324	Feb-02	Horizontal ISO 11439 Impact + EOL Burst	11345	Pass	Pass	99.3%	13.7	11.5	7.8	4.3
Type 3	ALT810N	2188	Oct-01	Horizontal ISO 11439 Impact + Fatigue + Burst	10220	Pass	Pass	1.5%	12.7	11.4	7.1	3.9
Type 3	ALT810N	4105	Apr-02	Horizontal ISO 11439 Impact onto steel angle + EOL Burst	9625	Pass	Pass	0.0%	12.9	11.8	7.7	4.8
Type 3	ALT810N	2562	Oct-01	Horizontal ISO 11439 Impact onto steel angle + fatigue + EOL Burst	8700	Pass	Pass	0.0%	12.3	12.3	7.7	6.1
Type 3	ALT810N	2191	Oct-01	Double height horizontal ISO 11439 Impact onto steel angle + EOL Burst	6110	Fail	Fail	0.0%	13.4	13.0	-	-
Type 3	ALT810N	2104	Oct-01	Double height horizontal ISO 11439 Impact onto steel angle + fatigue + EOL Burst	7440	Fail	Fail	0.0%	13.8	12.3	7.4	4.7

Cylinder Design Type	Manufacturer's Design Designation	Vessel S/N	Cylinder's Manufacture Date	Test Procedure	Burst Pressure [psig]	NGV2 Burst Pressure Met [Pass/Fail]	MAE Result [Pass/Fail]	Percntile of EOL Distribution	HM1 [Msi]	AM1 [Msi]
Type 4	RE36A16-120MG	309-022	Aug-00	Horizontal ISO 11439 Impact + EOL Burst	10215	Pass	Pass	33.79%	8.3	6.4
Type 4	RE36A16-120MG	305-164	Aug-00	Horizontal ISO 11439 Impact + Fatigue + Burst	8715	Pass	Pass	0.00%	8.3	7.8
Type 4	RE36A16-120MG	305-159	Aug-00	Horizontal ISO 11439 Impact onto steel angle + EOL Burst	5400	Fail	Fail	0.00%	8.3	6.1
Type 4	RE36A16-120MG	319-001	Oct-00	Horizontal ISO 11439 Impact onto steel angle + fatigue + EOL Burst	5400	Fail	Fail	0.00%	8.0	6.7
Type 4	RE36A16-120MG	309-023	Aug-00	Double height horizontal ISO 11439 Impact onto steel angle + EOL Burst	6160	Fail	Fail	0.00%	8.1	6.7
Type 4	RE36A16-120MG	313-047	Sep-00	Double height horizontal ISO 11439 Impact onto steel angle + fatigue + EOL Burst	7160	Fail	Fail	0.00%	8.0	5.6



Impact Tolerance Testing – MAE Results

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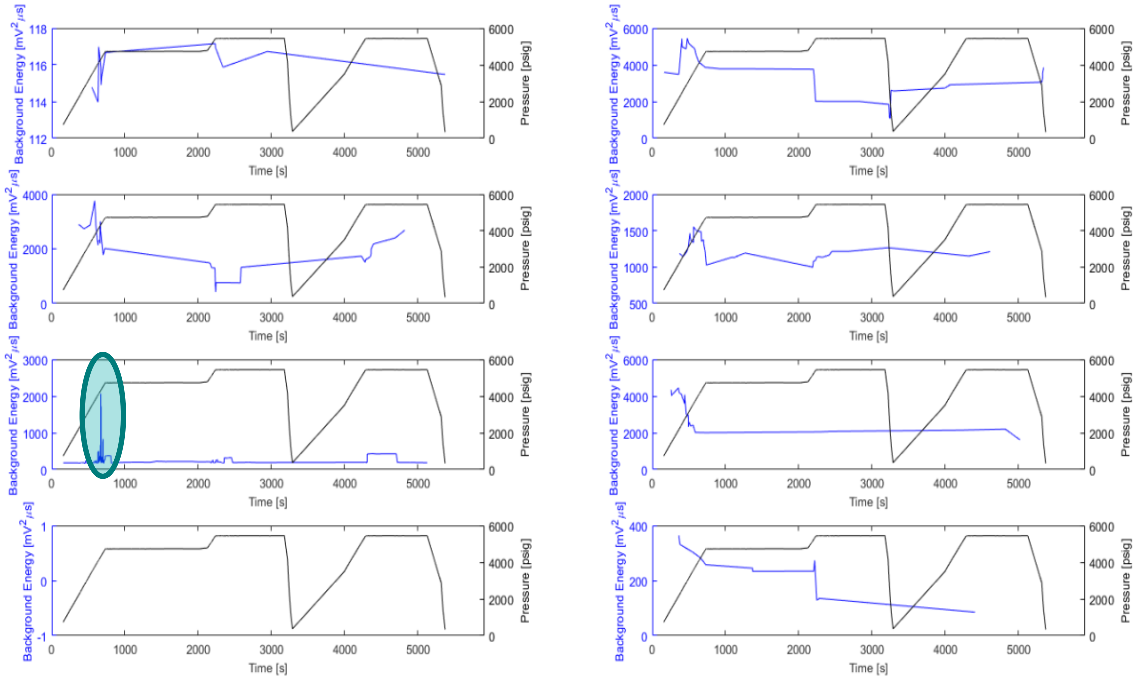
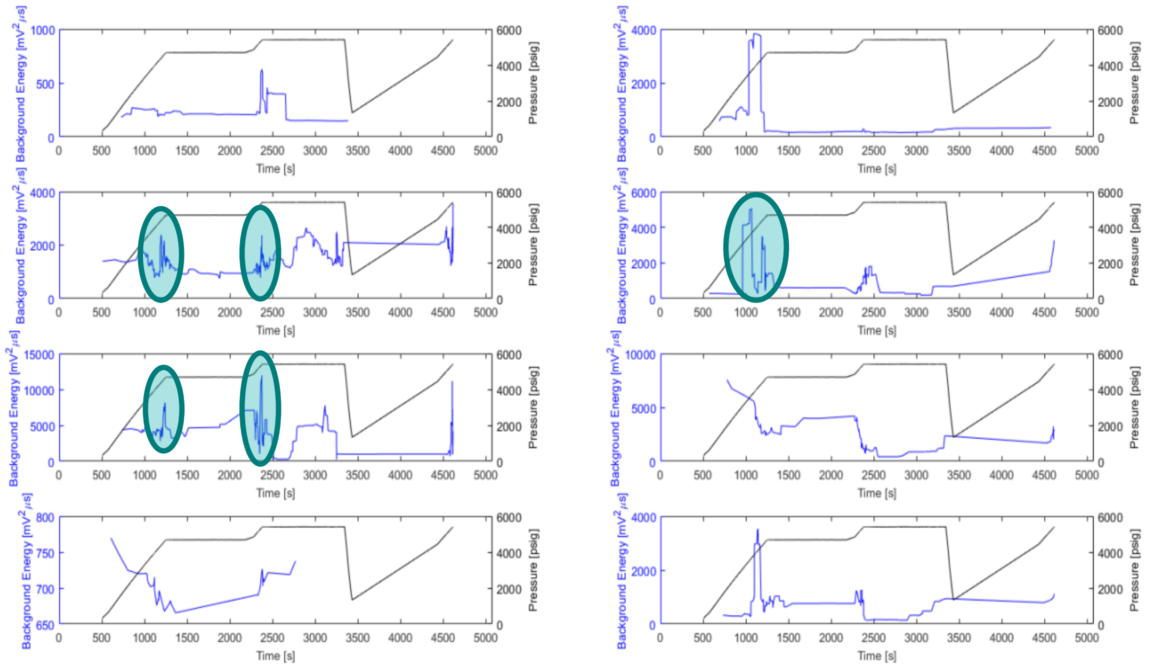
Local instability plot for ALT810N-1995 prior to fatigue cycle testing



Local instability plot for 316-014 prior to fatigue cycle testing



Impact Tolerance Testing – MAE case study

- Tank inspection summary:
  - **Passed** CGA C6.4 external visual inspection
  - **Passed** proof pressure test
  - **Failed** MAE inspection
- Damage mechanisms in the impact location indicative of local instability were detected by MAE
  - Fiber tow fracture detected at the impact location
  - Source location from MAE waveforms pointed back to the impact site as the unstable region
- Tank 305-159 failed catastrophically at **53.5%** of lot burst strength
- Tank 305-159 failed at **67%** of government regulated minimum burst strength (FMVSS 304)

Field failure incident of a CNG tank

Conclusions

- Type 3 and Type 4 NGV2 tanks at the end of recommended service life
  - Met 49 CFR §571.304 burst pressure performance requirements
  - Met 49 CFR §571.304 hydraulic fatigue cycle test performance requirements
  - Met ISO 11439 Notch tolerance performance testing requirements
  - Met ISO 11439 Impact tolerance performance testing requirements
- Localized impact damage can be highly deleterious to tank performance
  - Traditional inspection methods (visual and proof pressure) may not always be capable of identifying composite tanks with compromised structural integrity
- Modal Acoustic Emission (MAE) testing proved capable of identifying compromised tanks where traditional inspection methods could not
  - MAE shown to be able to discriminate damage mechanism type – important from a false positive perspective
  - MAE shown to be able to locate a weakened region of the vessel where no visual indications existed
- This data has been synthesized into a comprehensive technical report that will be made available

Thank you for your attention

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CNG Fuel Tank End of Life Testing

Aaron Williams
NGVTF
February 5th, 2020

Outline

- Background & Objectives
- Project Results – Brian Burks
- Findings & Next Steps
- Discussion

Industry Challenge

NG vehicles can last longer than their fuel tanks

15.1 years

Transit bus avg retirement age

19%

In service beyond retirement age

15 / 20 / 25 years

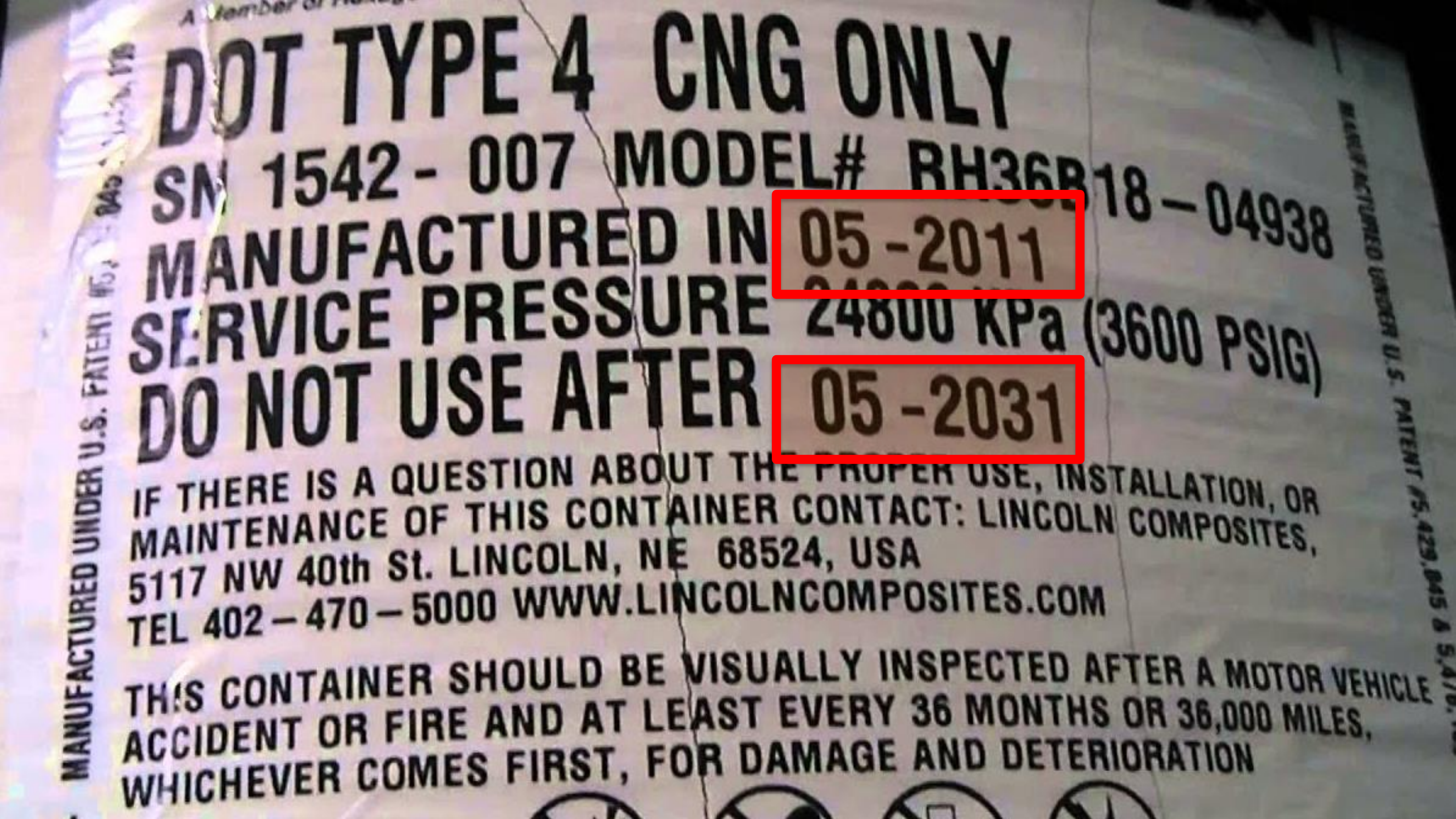
Fuel Tank Useful Life

US DOT Report No. FTA VA-26-7229-07.1

Tank Design and Safety Standards

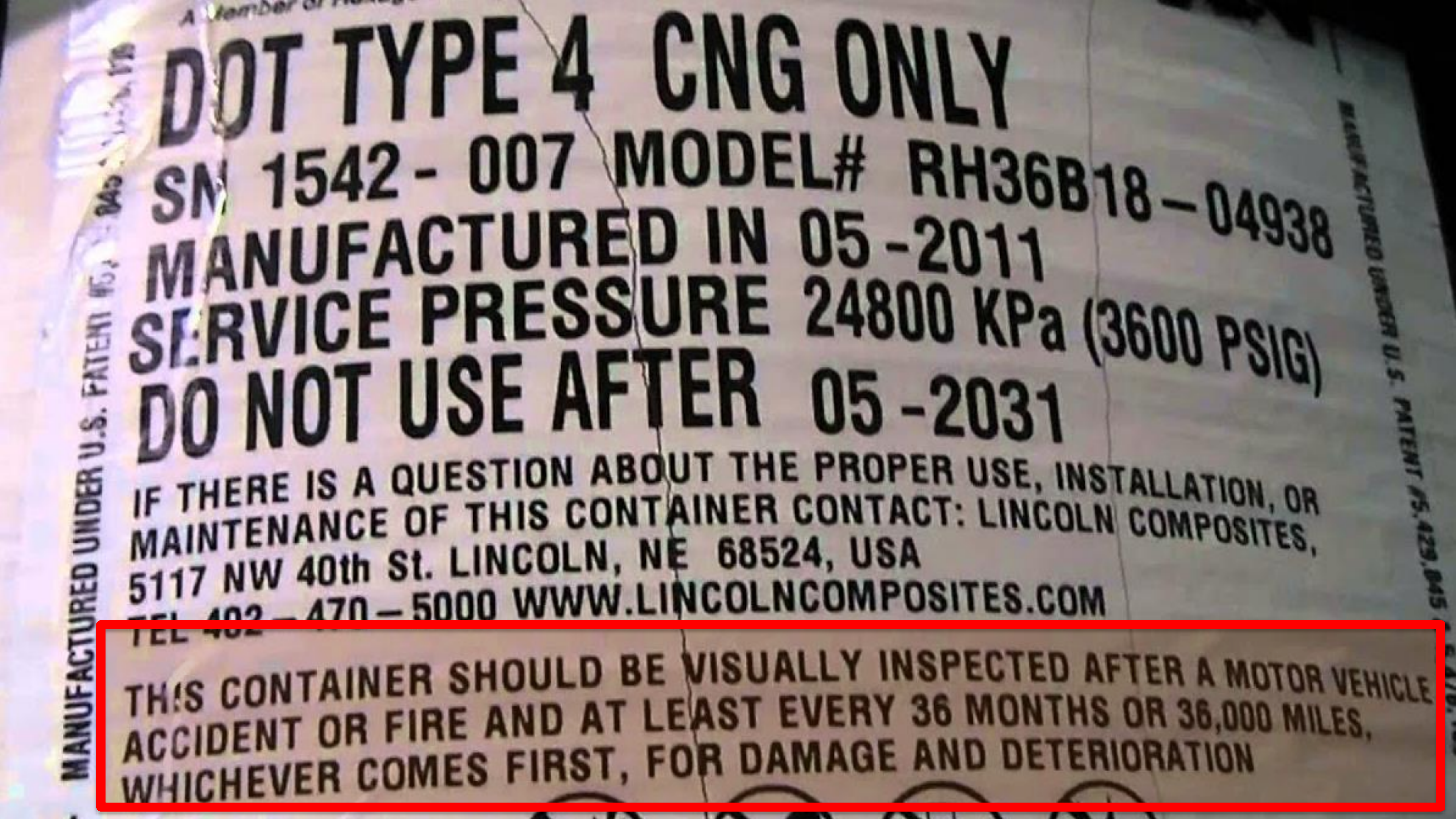
- CNG Fuel Tanks **shall be manufactured, inspected, marked, tested, equipped and used** in accordance with ANSI NGV 2 and FMVSS 49 CFR 571.304.
- Fuel Tanks **should be visually inspected** at least every 36 months or 36,000 miles, whichever comes first.
- Fuel Tanks that have reached their labeled expiration date (EOL) or been condemned by inspection **shall be removed from service (and destroyed)**.
- Vehicles **shall be labeled at the fueling connection** with the EOL date and the date for the next inspection.
- Tanks must be labelled with do not use after date

  "(h) The statement: 'Do Not Use After ______' inserting the month and year that mark the end of the manufacturer's recommended service life for the container."


DOT TYPE 4 CNG ONLY
SN 1542-007 MODEL# RH36B18-04938
MANUFACTURED IN 05-2011
SERVICE PRESSURE 24800 kPa (3600 PSIG)
DO NOT USE AFTER 05-2031
IF THERE IS A QUESTION ABOUT THE PROPER USE, INSTALLATION, OR MAINTENANCE OF THIS CONTAINER CONTACT: LINCOLN COMPOSITES, 5117 NW 40th St. LINCOLN, NE 68524, USA
TEL 402-470-5000 WWW.LINCOLNCOMPOSITES.COM
THIS CONTAINER SHOULD BE VISUALLY INSPECTED AFTER A MOTOR VEHICLE ACCIDENT OR FIRE AND AT LEAST EVERY 36 MONTHS OR 36,000 MILES, WHICHEVER COMES FIRST, FOR DAMAGE AND DETERIORATION
MANUFACTURED UNDER U.S. PATENT
MANUFACTURED UNDER U.S. PATENT #5,429,845

Safety Challenges

- Replacing tanks has potential to introduce acute hazards
  - Proper installation of fittings and mounting components compared to original
- Not economical to replace tanks
- Vehicles are likely in operation with expired tanks
  - No consistent methods to track expired tanks


DOT TYPE 4 CNG ONLY
SN 1542 - 007 MODEL# RH36B18 – 04938
MANUFACTURED IN 05 - 2011
SERVICE PRESSURE 24800 KPa (3600 PSIG)
DO NOT USE AFTER 05 - 2031
IF THERE IS A QUESTION ABOUT THE PROPER USE, INSTALLATION, OR MAINTENANCE OF THIS CONTAINER CONTACT: LINCOLN COMPOSITES, 5117 NW 40th St. LINCOLN, NE 68524, USA
TEL 402 – 470 – 5000 WWW.LINCOLNCOMPOSITES.COM
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MANUFACTURED UNDER U.S. PATENT
MANUFACTURED UNDER U.S. PATENT #5,429,845

Safety Challenges

- Visual inspection method
  - Opportunity for human error
  - Qualitative and subjective measure
  - Non-visible damage
  - Non-conservative

Project Objectives

- 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
- Develop better methods for evaluating tanks

Project History

- Subcontracted Digital Wave
- Started in 2016
- Paused in 2017 & 2018
- Concluded in 2019

DIGITAL WAVE

HEXAGON™

Modal Acoustic Emission (MAE)

- MAE is a non-destructive evaluation technique
- MAE captures stress waves which propagate through a structure as strain energy releases due to damage

SCBA Study

- Digital Wave conducted similar study on SCBA tanks
- Awarded by US Navy in 2012
- Evaluated carbon fiber composite overwrapped cylinders with 15-year service life
- MAE could detect burst strength within 10%

Project Outline

- 101 Tanks sourced from LA Metro
- Visually Inspected
- Artificially Damaged
  - Notching or Impacting
- Fatigued Cycled
- Burst Tested
- Modal Acoustic Emission (MAE) Evaluation

Digital Wave Presentation

Findings & Next Steps

- End of Life tanks passed burst requirements
- Visual inspection results were non-conservative
- Modal Acoustic Emission (MAE) shows promise
  - Can we supplement visual inspection techniques?
  - Can we requalify End of Life tanks for extended use?
- Next steps . . .

Discussion

NRELTransforming ENERGY

NREL BEB Evaluation Results

Leslie Eudy
National Renewable Energy Lab
NGVTF
Feb 5, 2020

NREL Role in ZEB Evaluation

- 3rd party evaluation of advanced technology in real-world service
  - Established evaluation protocol provides consistent data collection and reliable analysis
  - Unbiased results in common format
  - Comparison to baseline conventional technology

Transit Agencies

Share information with the transit industry that will aid in advanced technology purchase decisions & fleet operations

Government

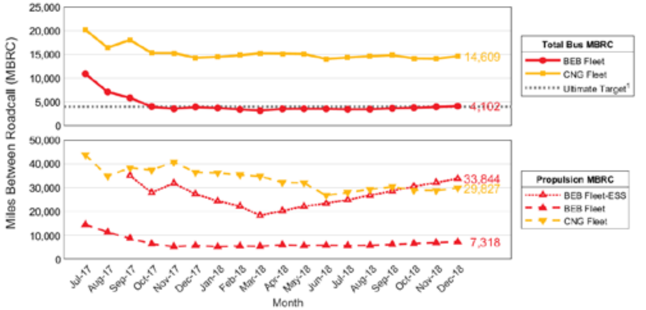
Provide feedback to federal, state and local government to understand technology status and prioritize funding for necessary R&D

OEMs

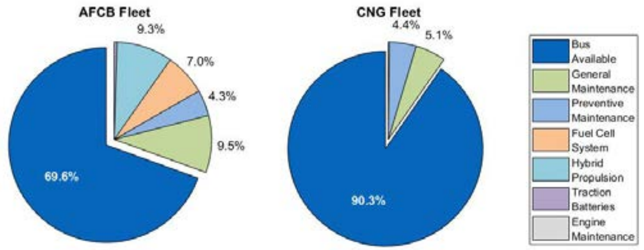
Collaborate with tech providers to understand status and share performance results for ZEB and baseline buses

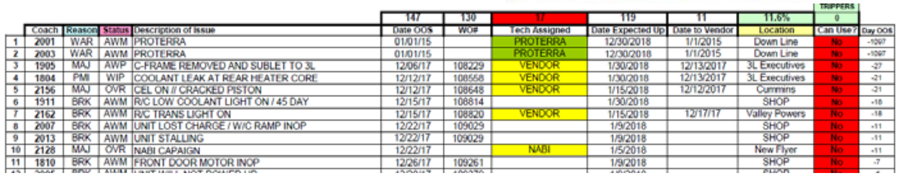
Data Collection Metrics

- Fueling/charging records – cost and efficiency calculations
- Maintenance records – cost per mile by system
- Daily bus use & availability – reliability
- Roadcalls – reliability
- Utility data – charging efficiency for BEBs
- Fleet experience – lessons learned



1. Ultimate Target adopted from: FCTO Program Record #12012, Sept. 2012, *http://www.hydrogen.energy.gov/pdfs/12012_fuel_cell_bus_targets.pdf*





					147	130	17	119	11	11.6%	TRIPPERS 0	
	Coach	Reason	Status	Description of Issue	Date OOS	WO#	Tech Assigned	Date Expected Up	Date to Vendor	Location	Can Use?	Day OOS
1	2001	WAR	AWM	PROTERRA	01/01/15		PROTERRA	12/30/2018	1/1/2015	Down Line	No	-1097
2	2003	WAR	AWM	PROTERRA	01/01/15		PROTERRA	12/30/2018	1/1/2015	Down Line	No	-1097
3	1905	MAJ	AWP	C-FRAME REMOVED AND SUBLET TO 3L	12/06/17	108229	VENDOR	1/30/2018	12/13/2017	3L Executives	No	-27
4	1804	PMI	WIP	COOLANT LEAK AT REAR HEATER CORE	12/12/17	108558	VENDOR	1/30/2018	12/13/2017	3L Executives	No	-21
5	2156	MAJ	OVR	CEL ON // CRACKED PISTON	12/12/17	108648	VENDOR	1/15/2018	12/12/2017	Cummins	No	-21
6	1911	BRK	AWM	R/C LOW COOLANT LIGHT ON / 45 DAY	12/15/17	108814		1/30/2018		SHOP	No	-18
7	2162	BRK	AWM	R/C TRANS LIGHT ON	12/15/17	108820	VENDOR	1/15/2018	12/17/17	Valley Powers	No	-18
8	2007	BRK	AWM	UNIT LOST CHARGE / W/C RAMP INOP	12/22/17	109029		1/9/2018		SHOP	No	-11
9	2013	BRK	AWM	UNIT STALLING	12/22/17	109029		1/9/2018		SHOP	No	-11
10	2128	MAJ	OVR	NABI CAPAIGN	12/22/17		NABI	1/5/2018		New Flyer	No	-11
11	1810	BRK	AWM	FRONT DOOR MOTOR INOP	12/26/17	109261		1/9/2018		SHOP	No	-7

NREL BEB Evaluation Fleets

Past or ongoing evaluations at four transit agencies

Foothill Transit – West Covina, CA

- *12 Proterra 35-ft BEBs, 2 Proterra 40-ft BEBs, on-route, fast charge*
- In-service date: beginning March 2014
- NREL evaluation: April 2014 – December 2019
- Baseline: CNG buses
- Status: ongoing through December 2020

FHT BEB Specifications

ZEB Identifier	BEB 35FC	BEB 40FC
Number of Buses	12	2
Bus Manufacturer	Proterra	Proterra
Bus model	BE 35	Catalyst
Bus length/height	35 ft / 129 in	42.5 ft / 134 in
Charging strategy	Fast-charge, on-route	Fast-charge, on-route
Motor	Permanent magnet, UQM, PP220	Permanent magnet, UQM, PP220
Rated Power (kW)	220 (peak)	220 (peak)
Energy Storage, type	Lithium-titanate	Lithium-titanate
Capacity	368 volts, 88 kWh	331 volts, 106 kWh

County Connection – Concord, CA

- *4 Gillig 29-ft trolley replica BEBs, in-depot & inductive on-route charging*
- In-service date: November 2016
- NREL evaluation: June 2017 – May 2018
- Baseline: diesel and diesel trolley replica buses
- Status: Complete – report published[1] December 2018

CCCTA BEB Specifications

ZEB Identifier	BEB
Number of Buses	4
Bus OEM	Gillig
Bus Length/Height	29 ft / 102 in
Charging Strategy	Plug-in, on-route inductive charger
Motor	BAE Systems
Rated Power (kW)	200 kW (peak)
Energy Storage	NiMgCo
Capacity	100 kWh

1. https://www.nrel.gov/docs/fy19osti/72864.pdf

Long Beach Transit – Long Beach, CA

- *10 BYD 40-ft BEBs, in-depot & inductive on-route charging*
- In-service date: beginning March 2017
- NREL evaluation: January 2018 – December 2019
- Baseline: CNG buses
- Status: 1st year evaluation complete – report in progress

LBT BEB Specifications

ZEB Identifier	BEB
Number of Buses	10
Bus OEM	BYD
Bus Length/Height	41 ft / 11.4 ft
Charging Strategy	Plug-in, on-route inductive charger
Motor	2, BYD
Rated Power (kW)	90 kW
Energy Storage	LiFePO4
Capacity	295 kWh

King County Metro – Seattle, WA (TIGGER)

- *3 Proterra 40-ft Catalyst BEBs, on-route fast charging station*
- In-service date: April 2016
- NREL evaluation: April 2016 – March 2017
- Baseline: diesel, diesel hybrid, and electric trolley buses
- Status: Complete – report published[1] February 2018

KC Metro BEB Specifications

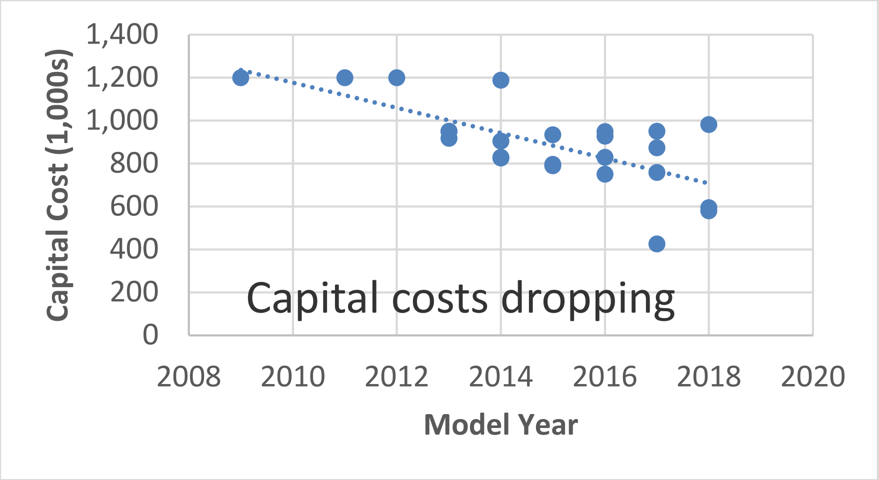
ZEB Identifier	BEB
Number of Buses	3
Bus OEM	Proterra
Bus Length/Height	40 ft / 126 in
Charging Strategy	Fast-charge, on-route
Motor	Permanent magnet, UQM, PP220
Rated Power (kW)	220 (peak)
Energy Storage	Lithium-titanate
Capacity	331 volts, 106 kWh

1. https://www.transit.dot.gov/sites/fta.dot.gov/files/docs/research-innovation/115086/zero-emission-bus-evaluation-results-king-county-metro-battery-electric-buses-fta-report-no-0118.pdf

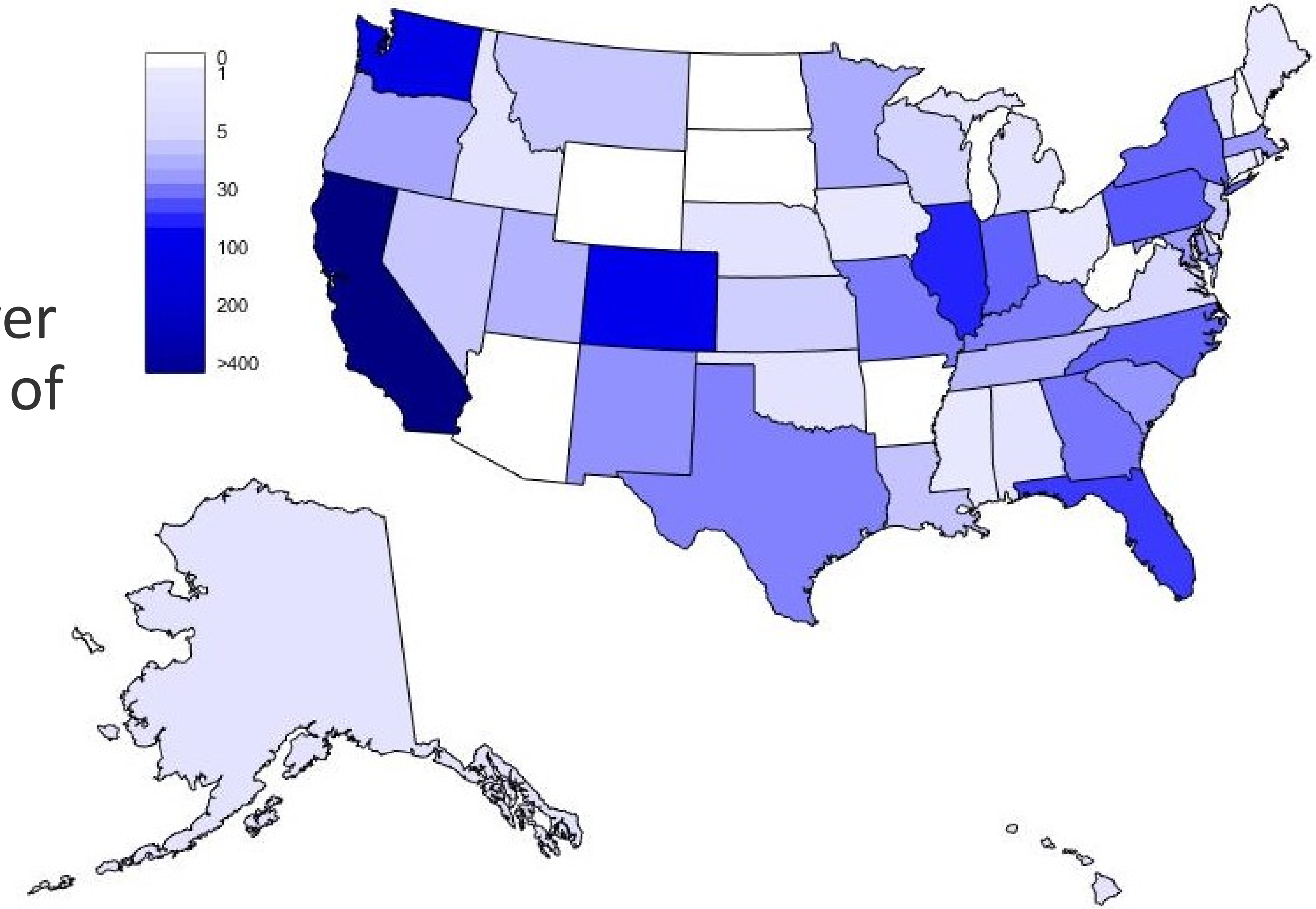
Successes for BEBs in Transit

Increasing Interest Leads to BEB Growth in the U.S.

- Around 350 BEBs in operation today
- Orders bring total to ~ 1,250
- Current deployments cover 43 states and the District of Columbia



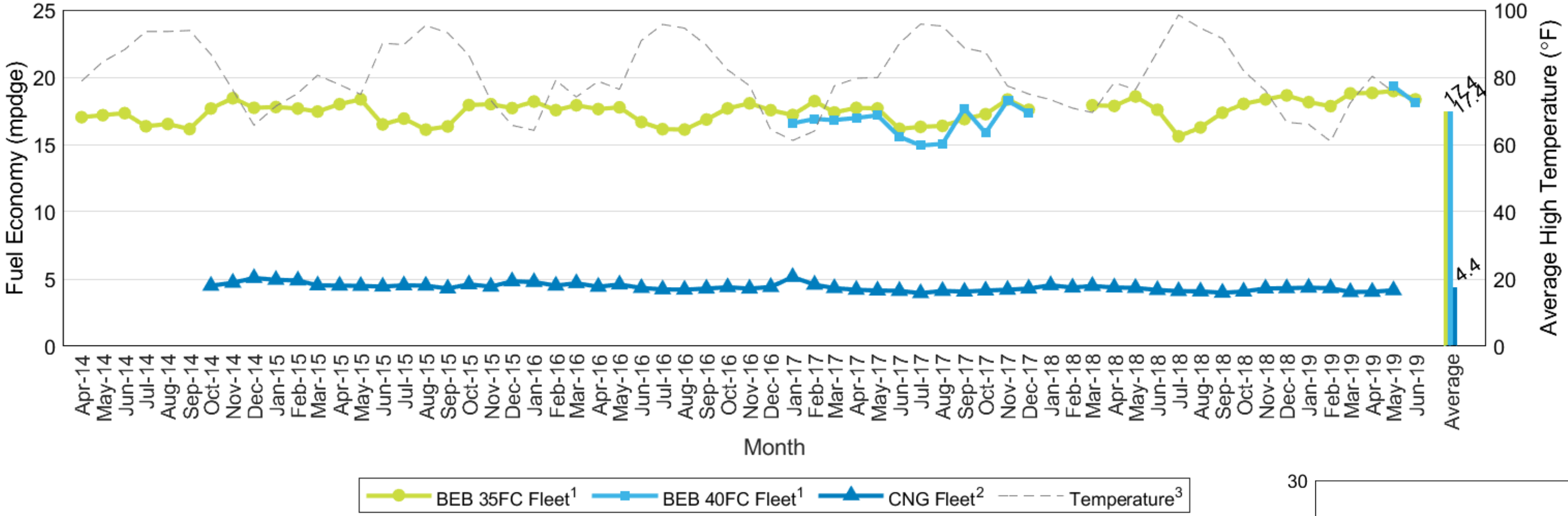
Current and Planned BEBs

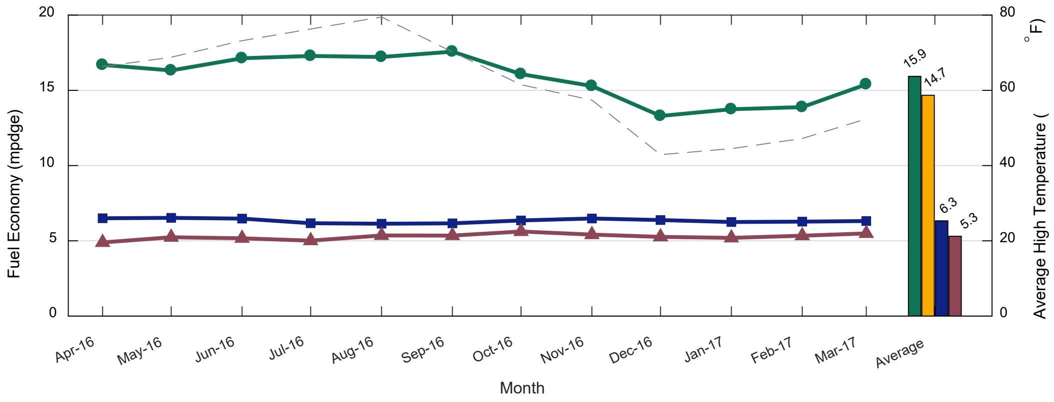


BEBs Available from Multiple OEMs in the U.S.

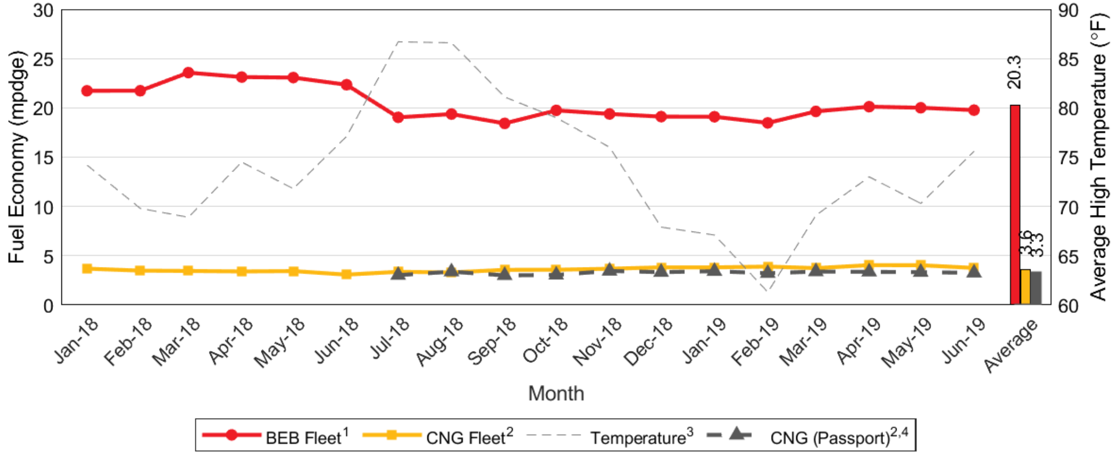
OEM	Length	Seated Passengers	Charge Strategy	Energy kWh	Advertised Range	Altoona Tested
BYD	30, 40, 60	22 - 55	plug in, inductive charging option	197 - 591	144 - 200	Yes, 60 ft in process
Gillig	35, 40	38	plug-in	440	200	No
Greenpower	30 - 45	25-100	plug in	210 - 478	>250	No
New Flyer	35, 40, 60	32 - 61	on-route or plug in	150 - 600	>200	Yes
Nova	40	41	on-route	76	25	Yes
Proterra	35, 40	28 - 40	on-route or plug in	94 - 660	55 - 426	Yes

Efficiency up to 5X Over Conventional Tech



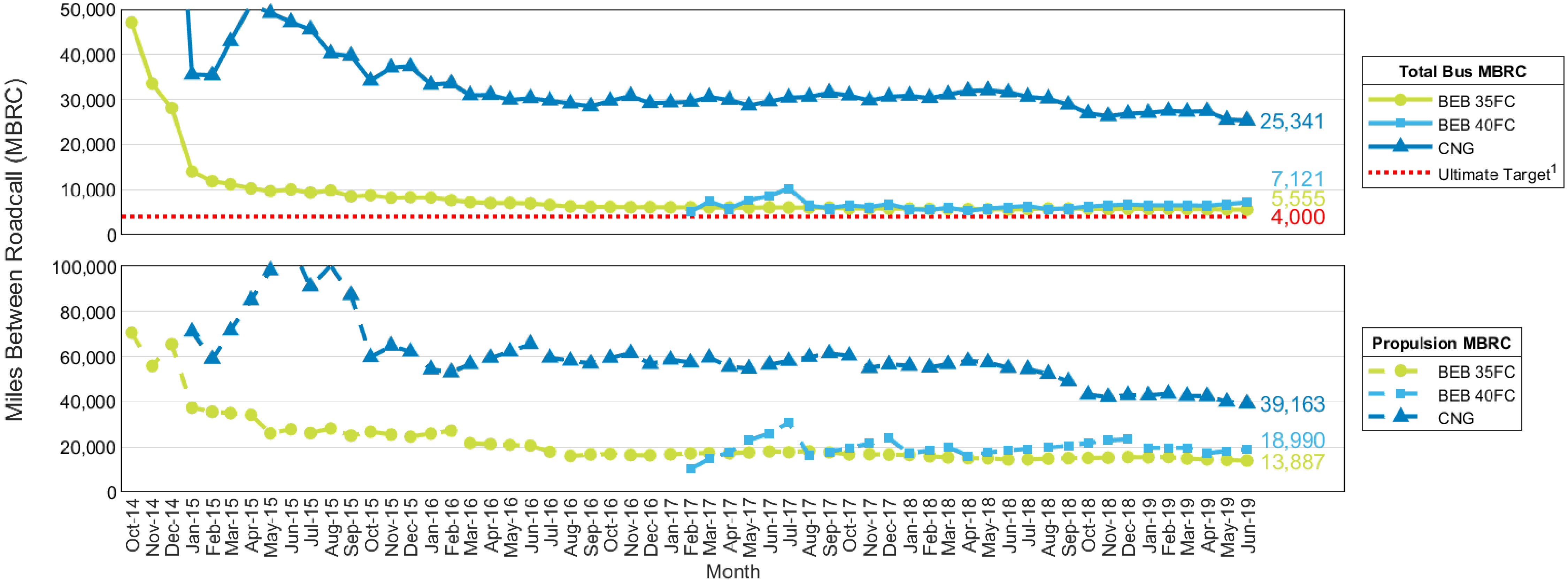


146 gge/dge



1. BEB electrical energy converted from kWh to diesel gallon equivalent (dge): 37.64 kWh/dge
2. CNG fuel energy reported in diesel gallon equivalent (dge)
3. Average high temperatures at Long Beach Daugherty Airport; data acquired from: *https://www.ncdc.noaa.gov/*
4. 1200-series CNG buses operating on Passport route (Sep 2015 - Aug 2016)

Reliability Trend Stabilizing Above Target



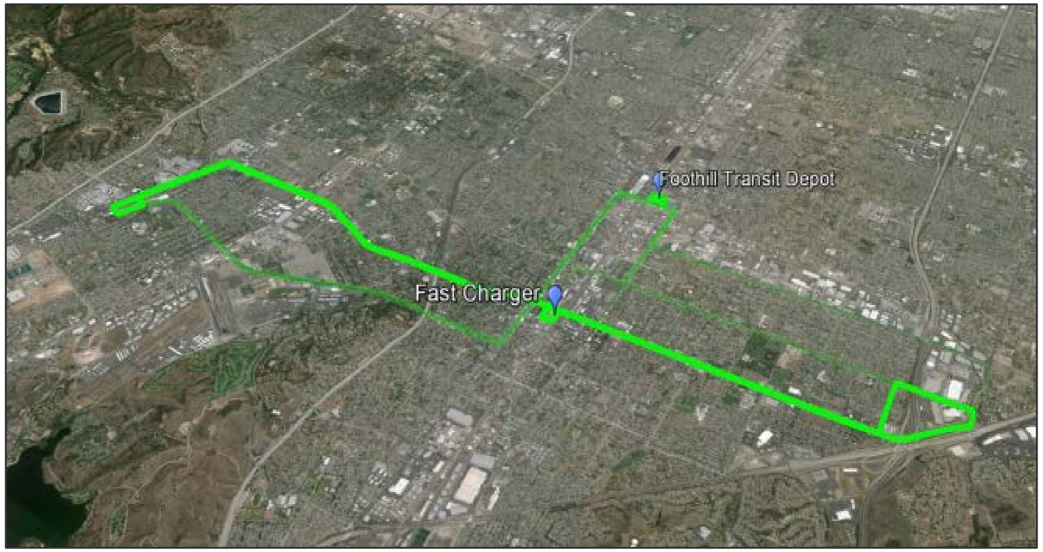
1. Ultimate Target adopted from: DOE FCTO Program Record #12012, Sept. 2012, *http://www.hydrogen.energy.gov/pdfs/12012_fuel_cell_bus_targets.pdf*

35-ft and 40-ft BEBs are exceeding ultimate MBRC target.

Key Challenges for Implementing BEBs

BEB Efficiency Highly Variable

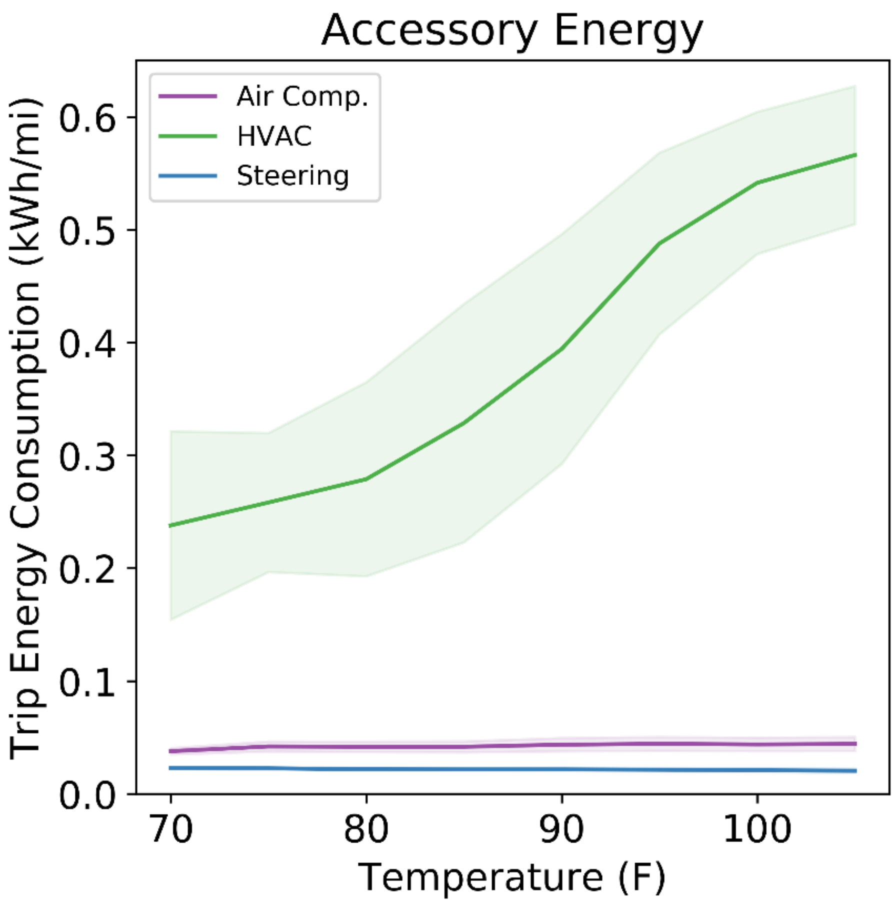
- Duty-cycle: route length, average speed, number of stops, terrain
  - ➢ Limited by requirements for longest routes
  - ➢ May need to adjust scheduling to accommodate BEB range
  - ➢ More buses may be required to meet service
- Operator driving style
- HVAC use – worse for cold climates
  - ➢ Option for fuel fired heater



BEB Efficiency Reduced by HVAC Use

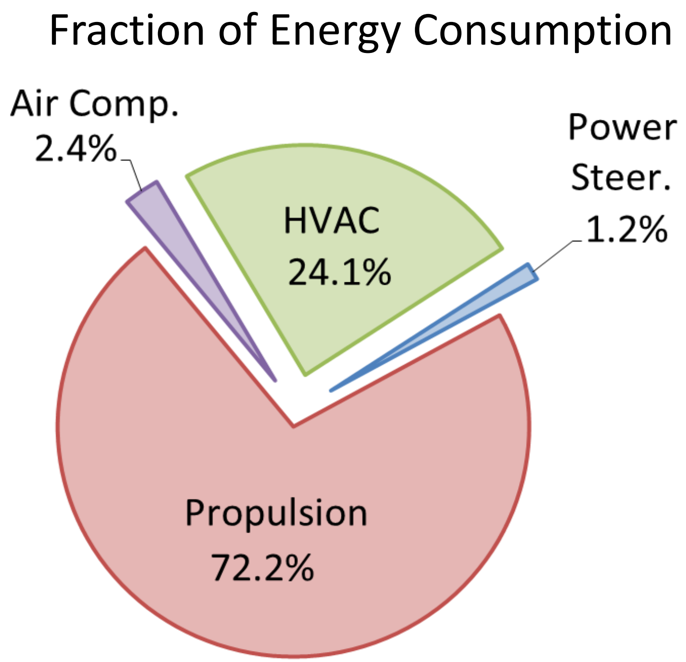
HVAC Dominating Accessory Use

- Largely temperature dependent



Electric Bus Statistics

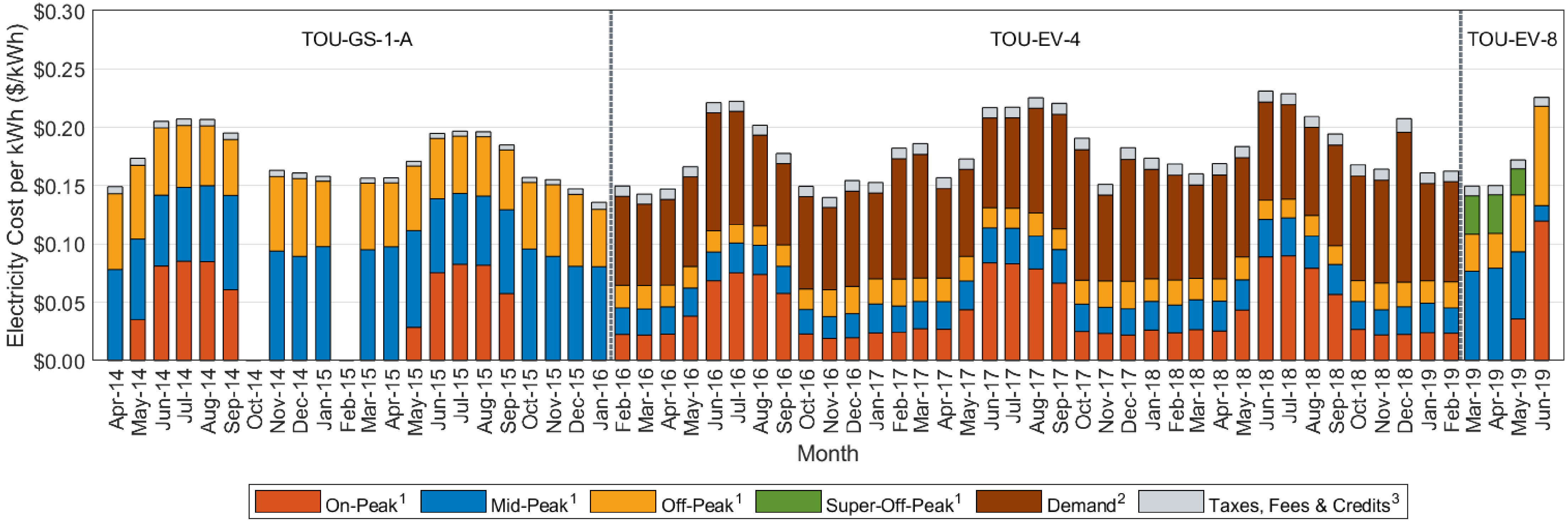
Total Energy Consumption (kWh/mi)	1.78 ± 0.21
Air Compressor (Wh/mi)	43.3 ± 5.8
HVAC (Wh/mi)	428.2 ± 130.8
Steering (Wh/mi)	21.5 ± 1.5
Max SOC (%)	76.1 ± 17.7
Min SOC (%)	66 ± 19



Utility Rate Structure Varies by Provider

- Electricity costs can be high depending on multiple factors.
- Utility grid demand
  - Determine power needs for buses
  - May require added transformer, or upgrades to local infrastructure
- Understand electricity rate structure for better planning
  - Utility base rates
  - Demand charges
  - Time of use charges
  - Summer verses winter rates
- Public utilities in some areas (like California) have developed specific rate structures to facilitate EV adoption

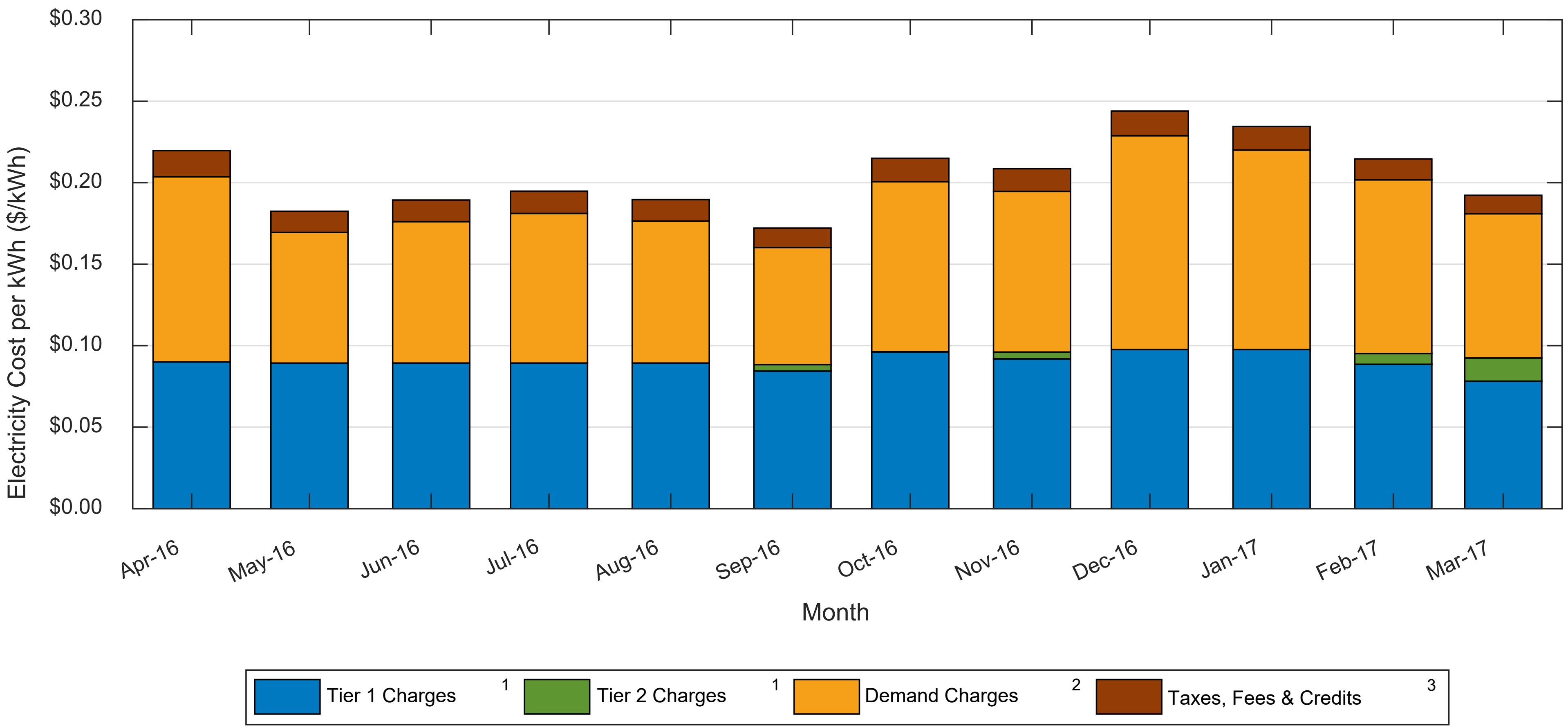
Utility Rate Structure: Example 1



1. On-Peak, Mid-Peak, Off-Peak and Super-Off-Peak charge categories include respective costs for delivery and generation
2. Rate structure changed to TOU-EV-4 February 2016, introducing demand charges, and changed to TOU-EV-8 March 2019, eliminating demand charges
3. 'Taxes, Fees & Credits' category includes all remaining utility bill items (positive & negative charges)

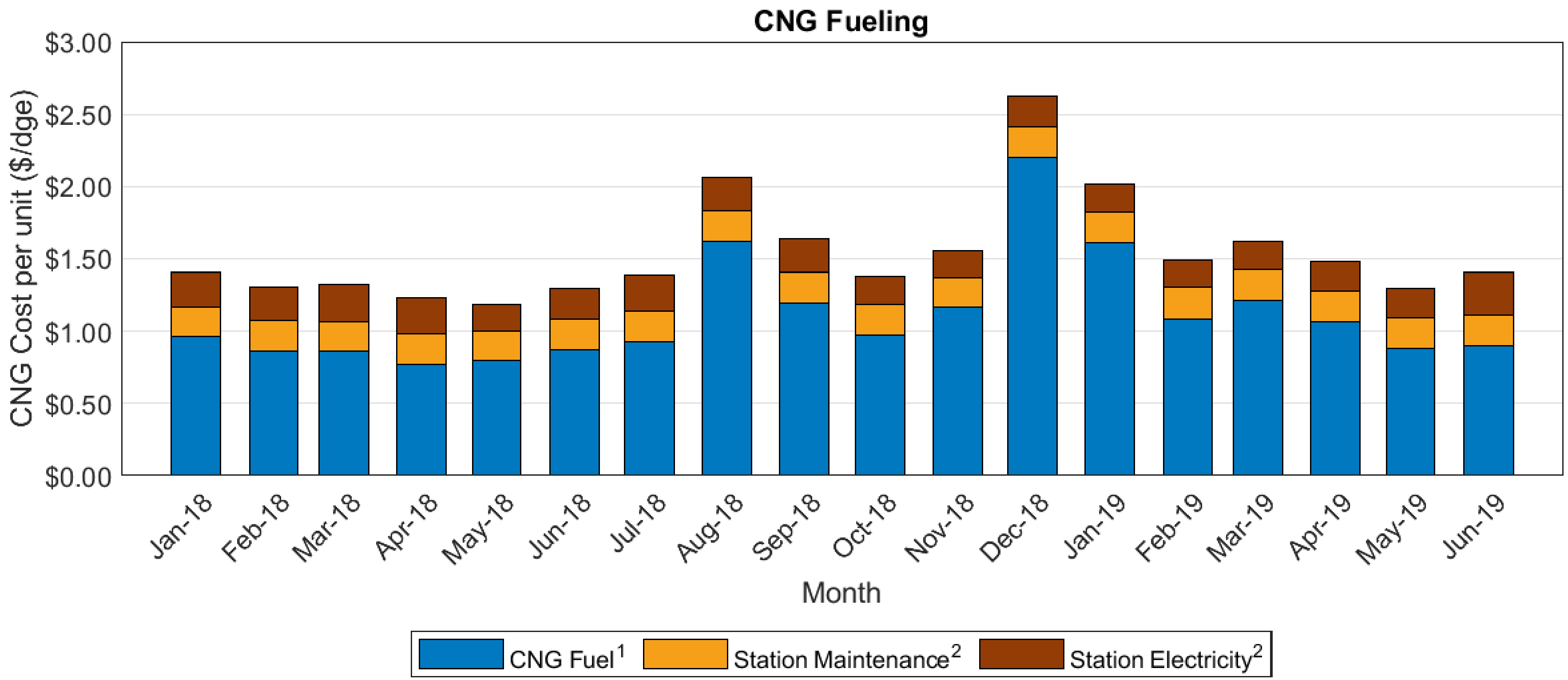
- Data are based on utility billing periods, not calendar months
- Seasonal rates apply: average summer rate (Jun–Sep): $0.21/kWh; average winter rate (Oct–May): $0.16/kWh
- Average rates under each rate structure: TOU-GS-1-A = $0.17/kWh; TOU-EV-4 = $0.18/kWh; TOU-EV-8: $0.18/kWh
- Average rate for first half of 2019 calendar year: $0.17/kWh; overall average: $0.18/kWh

Utility Rate Structure: Example 2



1. Tier 1 electric rate is applied to the first 20,000 kWh used per month; Tier 2 rate is applied to all additional energy
2. Demand Charges are incurred for charging rates > 50 kW
3. 'Taxes, Fees & Credits' includes all remaining utility bill items (positive & negative charges)

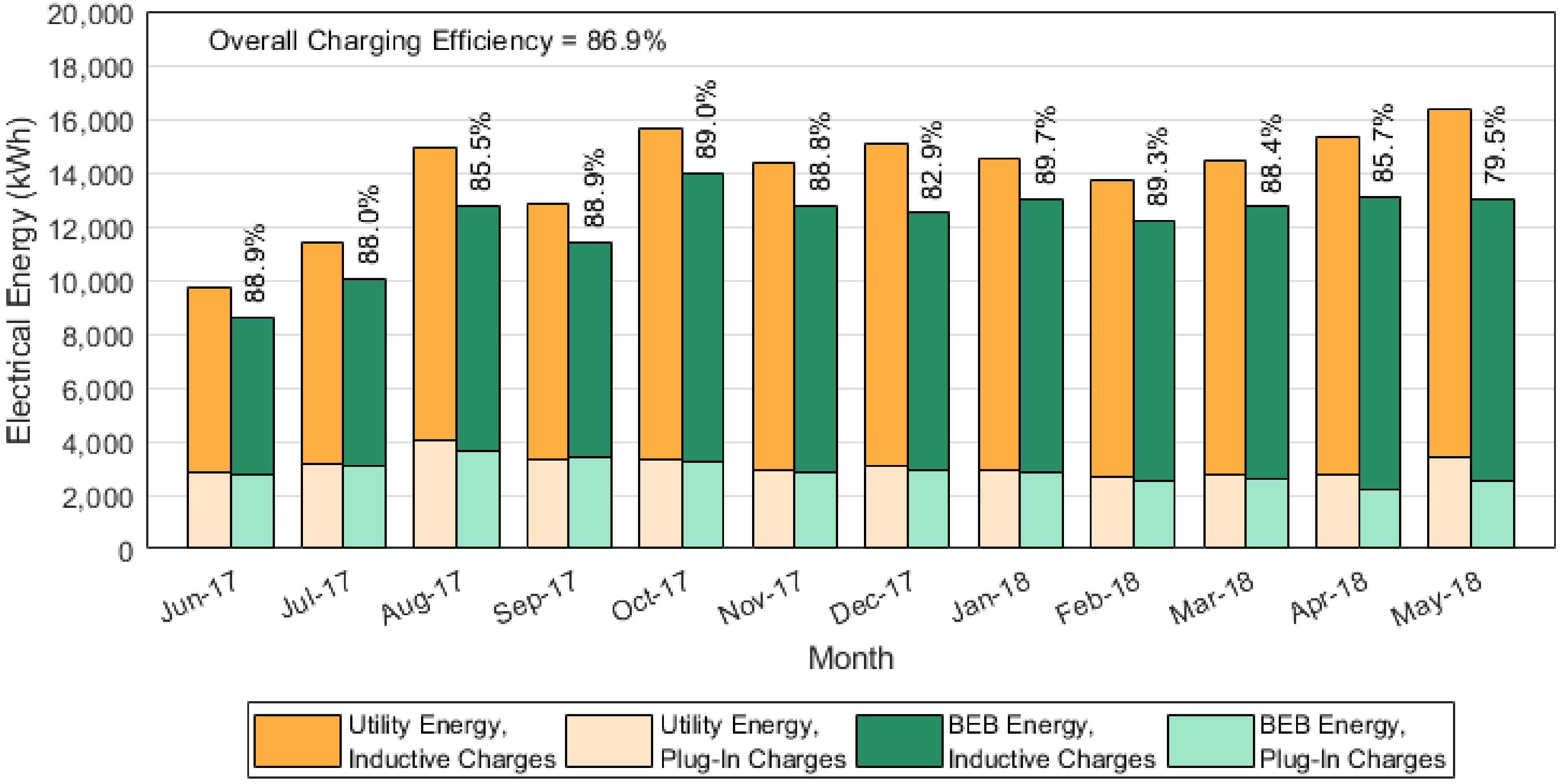
CNG Cost Example



1. CNG Fuel represents the commodity cost for CNG
2. Station Maintenance and Station Electricity represent the O&M cost for the CNG station

- CNG prices increased in August 2018 and December 2018 due to temporary disruptions in regional CNG supply.

BEB Charging Efficiency Losses

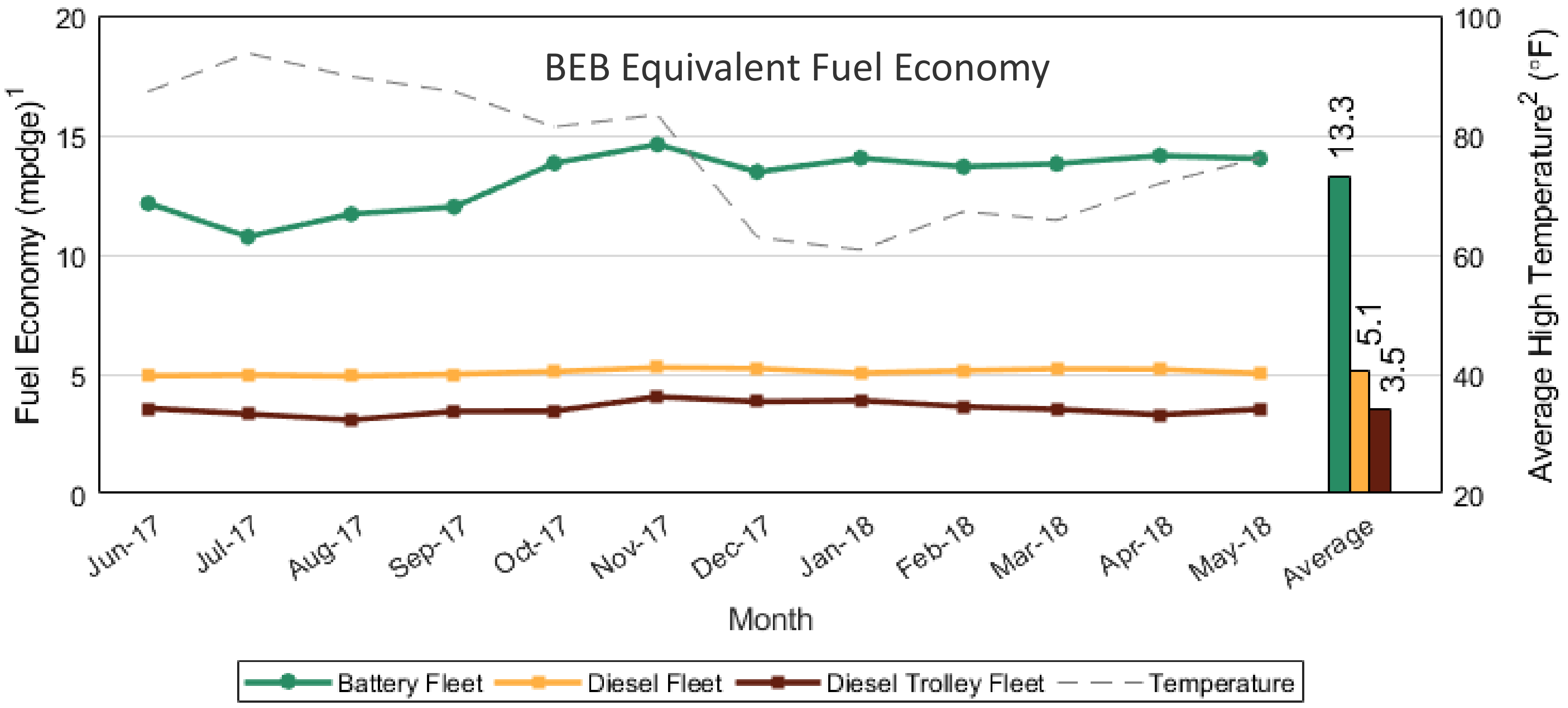


1. Data labels indicate the overall charging efficiency for each month (Inductive charging and Plug-In charging combined)

Plug-in charging: 92.8% Inductive charging*: 85.2%

*Cooling system for 1st-gen. inductive charger oversized to ensure maximum uptime.

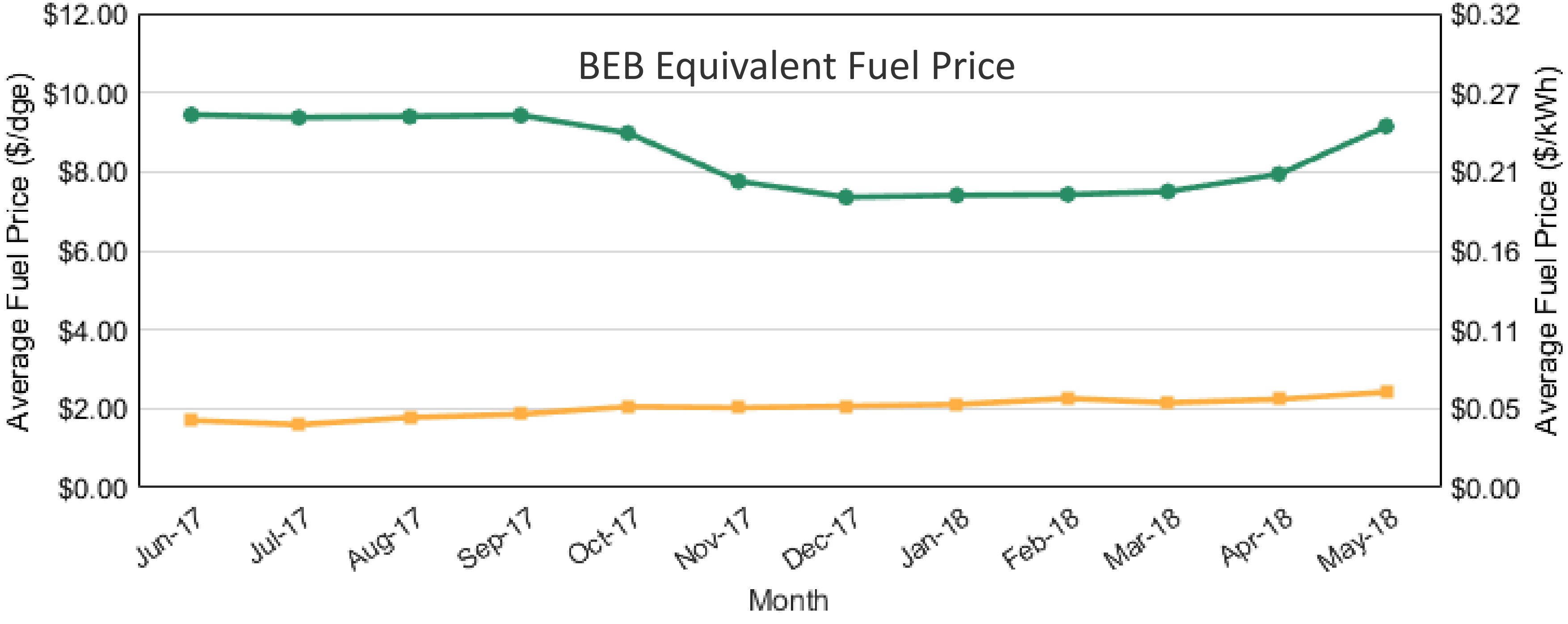
High Electricity Cost Can Negate Efficiency Benefit



1. BEB electrical energy converted to diesel gallon equivalent (dge); conversion factor = 37.64 kWh/diesel gallon, based on the energy content of electricity (3,414 Btu/kWh) and diesel fuel LHV (128,488 Btu/gal).
2. Average high temperatures at Buchanan Field Airport; data acquired from: *https://www.ncdc.noaa.gov/*

BEB equivalent fuel economy 3.8x higher than the diesel trolley buses in the same service.

High Electricity Cost Can Negate Efficiency Benefit

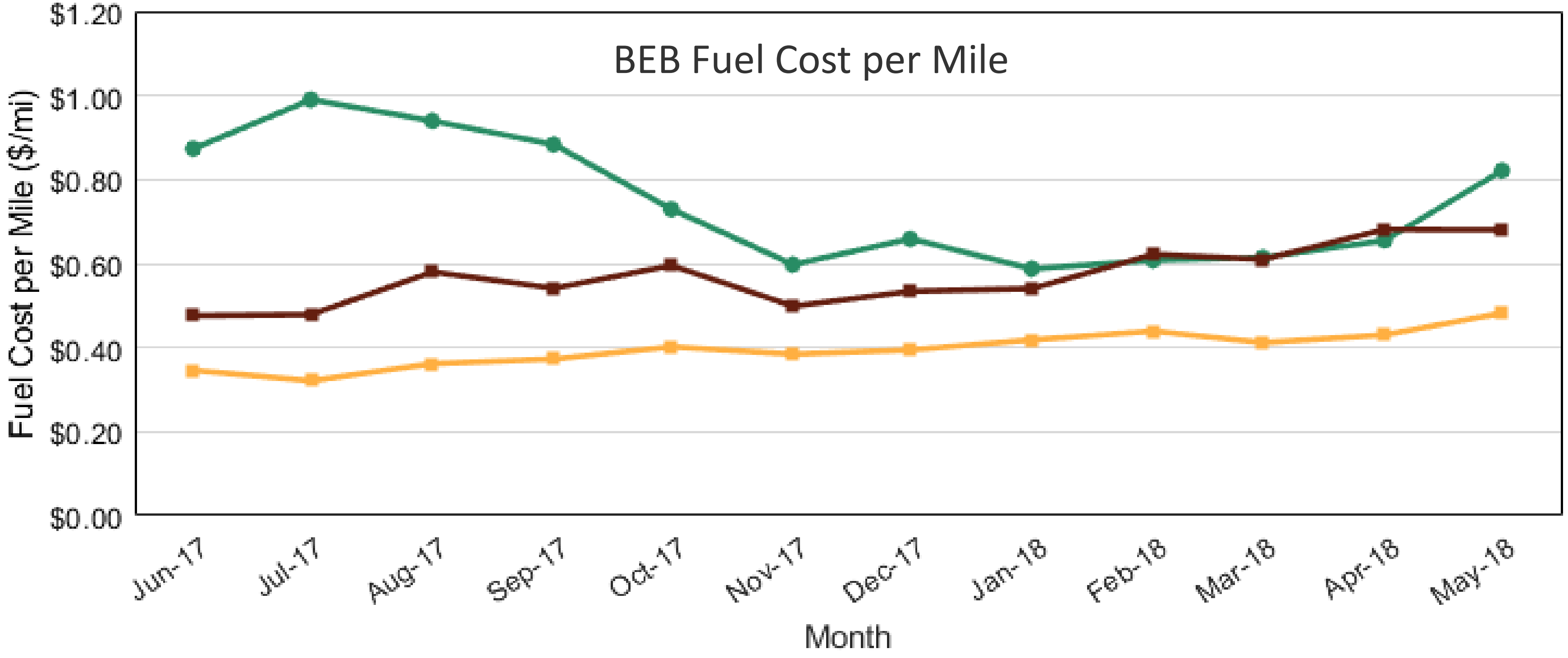


	Electricity Price (dge)[1]	Diesel Price
Data period average	$8.39/dge	$2.01/dge

1. Electrical energy converted to diesel gallon equivalent (dge), conversion factor = 37.64 kWh/diesel gallon; based on the energy content of electricity (3,414 Btu/kWh) and diesel fuel LHV (128,488 Btu/gal).

BEB equivalent fuel price for electricity 4.2x higher than the diesel fuel price.

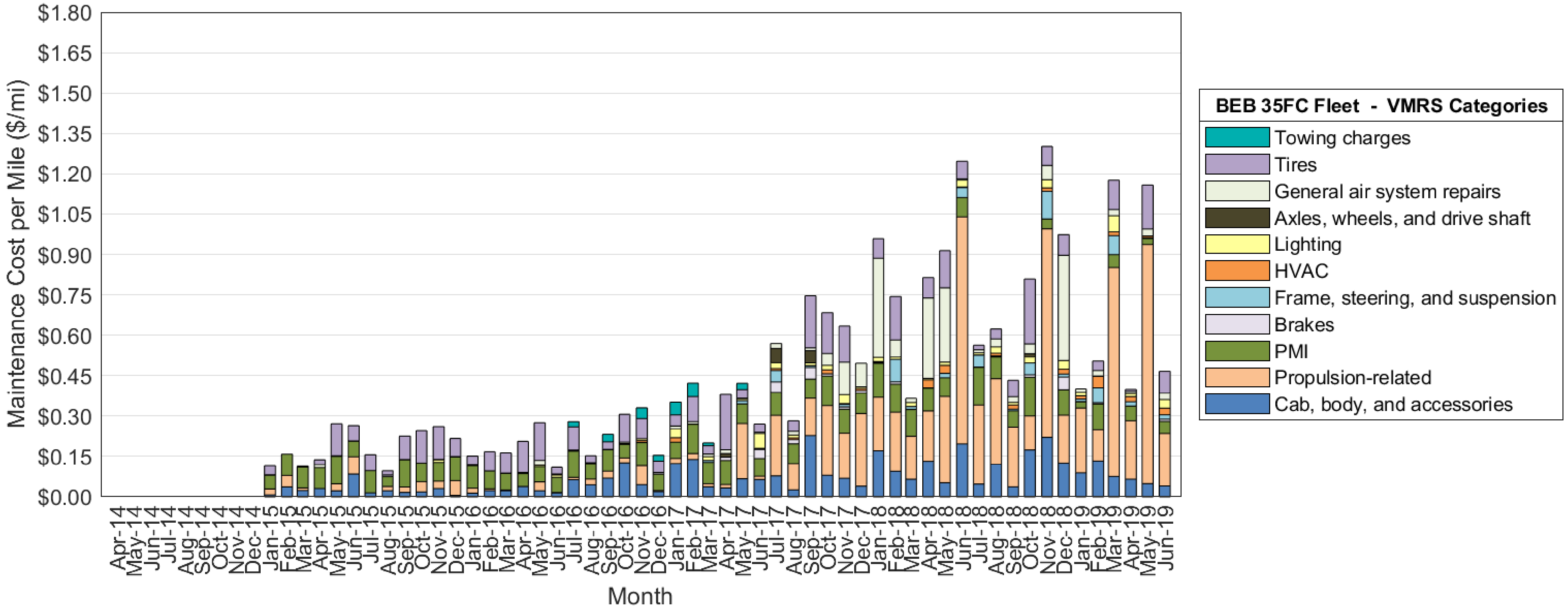
High Electricity Cost Can Negate Efficiency Benefit



	Battery Fleet	Diesel Fleet	Diesel Trolley Fleet
Average fuel cost/mi	$0.73/mi	$0.40/mi	$0.54/mi
Average fuel price	$0.22/kWh	$2.01/gal	

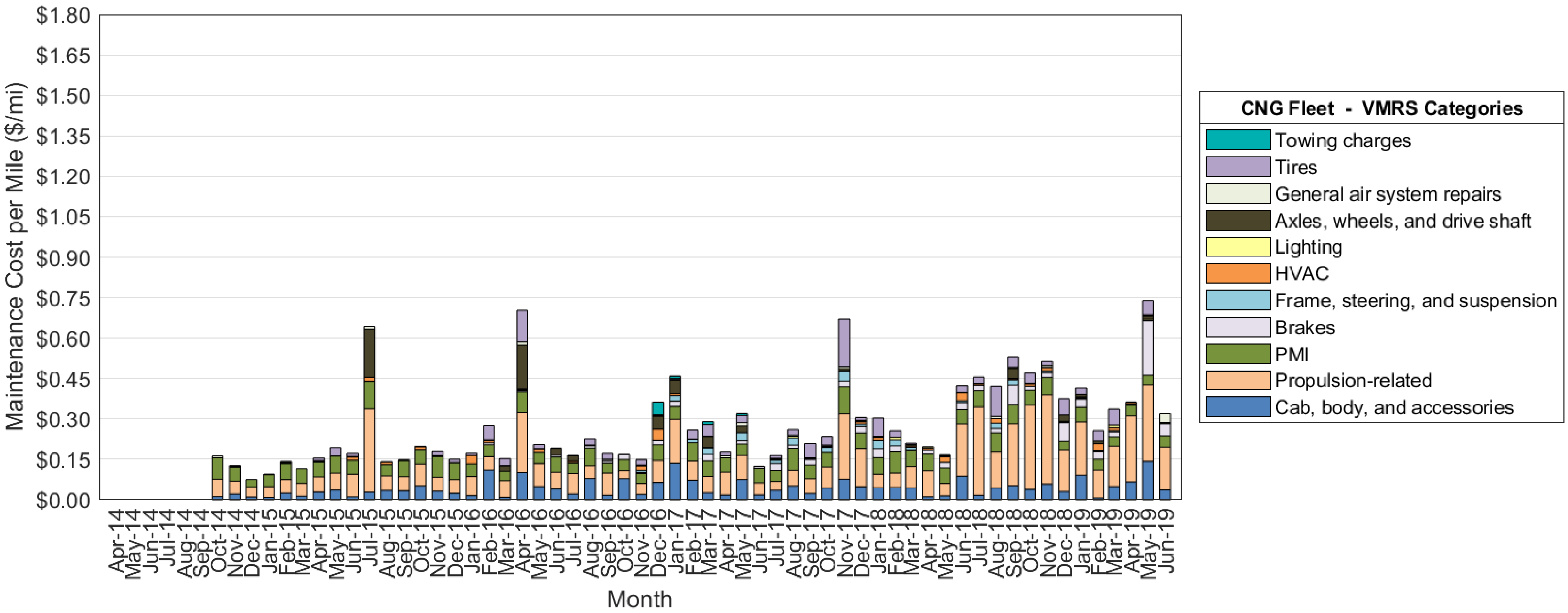
BEB fuel cost per mile 1.8x higher than the diesel buses.

Maintenance Costs by Vehicle System: BEBs



- The primary driver for the higher propulsion-related cost was issues with the low-voltage batteries
- High-cost parts and multiple labor hours were required for several repairs including DC-DC converters, traction motor, transmission, suspension, and electrical system.

Maintenance Cost by System: CNG Fleet



- CNG bus maintenance cost increases over time as the buses age and pass the warranty period.
- During the high-cost months, multiple buses reached the mileage for a major PM.
- Higher propulsion system costs: tune-ups, exhaust issues, cooling system, and engine control module failures.

Questions?

www.nrel.gov

Leslie Eudy

303-275-4412

leslie.eudy@nrel.gov

Web site: https://www.nrel.gov/hydrogen/fuel-cell-bus-evaluation.html

NREL Transforming ENERGY

Natural Gas Vehicle Technology Forum

TRENDS AND ISSUES ASSOCIATED WITH RENEWABLE NATURAL GAS (RNG)

MARIANNE MINTZ

February 5, 2020
Downey, CA

Argonne NATIONAL LABORATORY

OUTLINE

- What, Why and How of RNG
- Emissions Benefits
- National Trends
- Regional Trends
- Issues

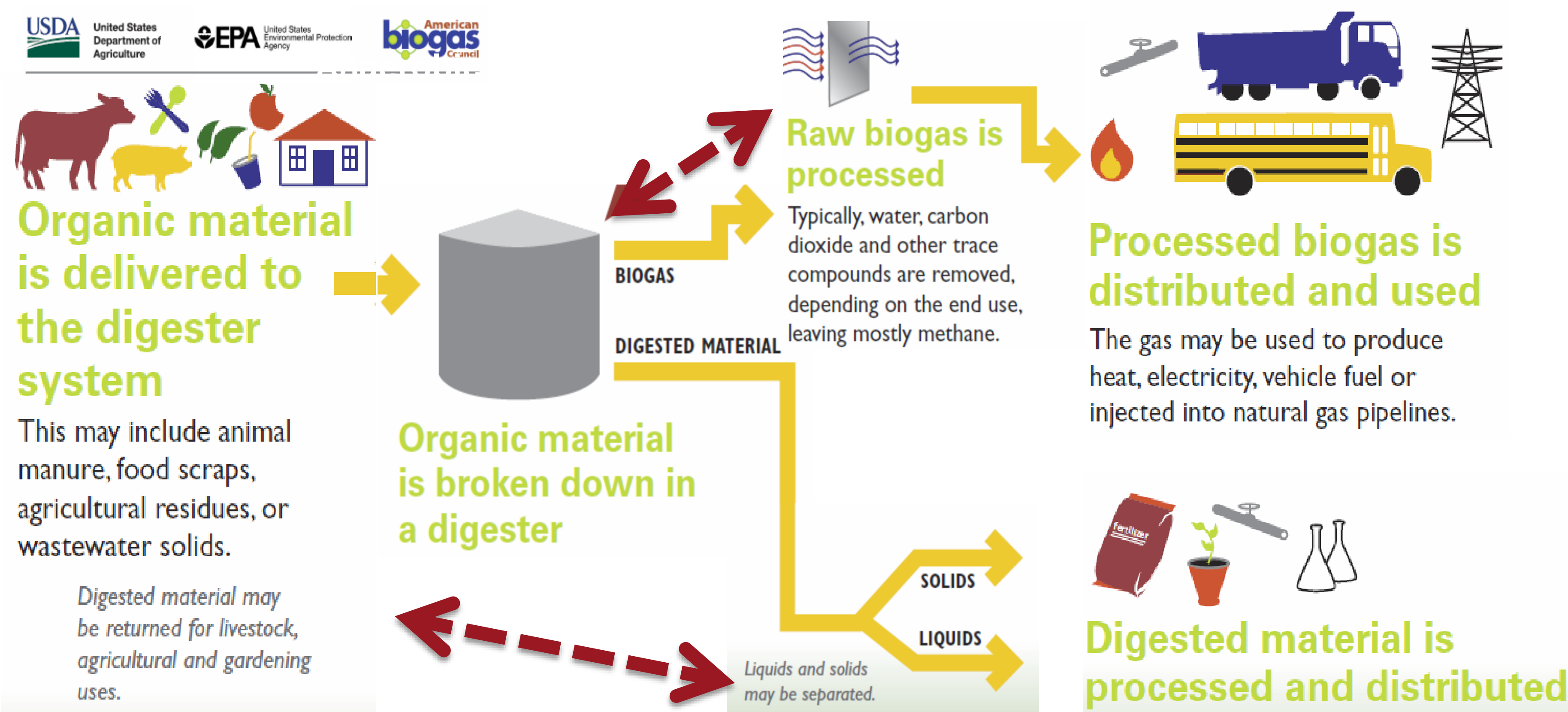
Images M. Mintz

A FEW KEY POINTS

Biogas is produced from anaerobic digestion of organic material.
RNG is upgraded biogas.

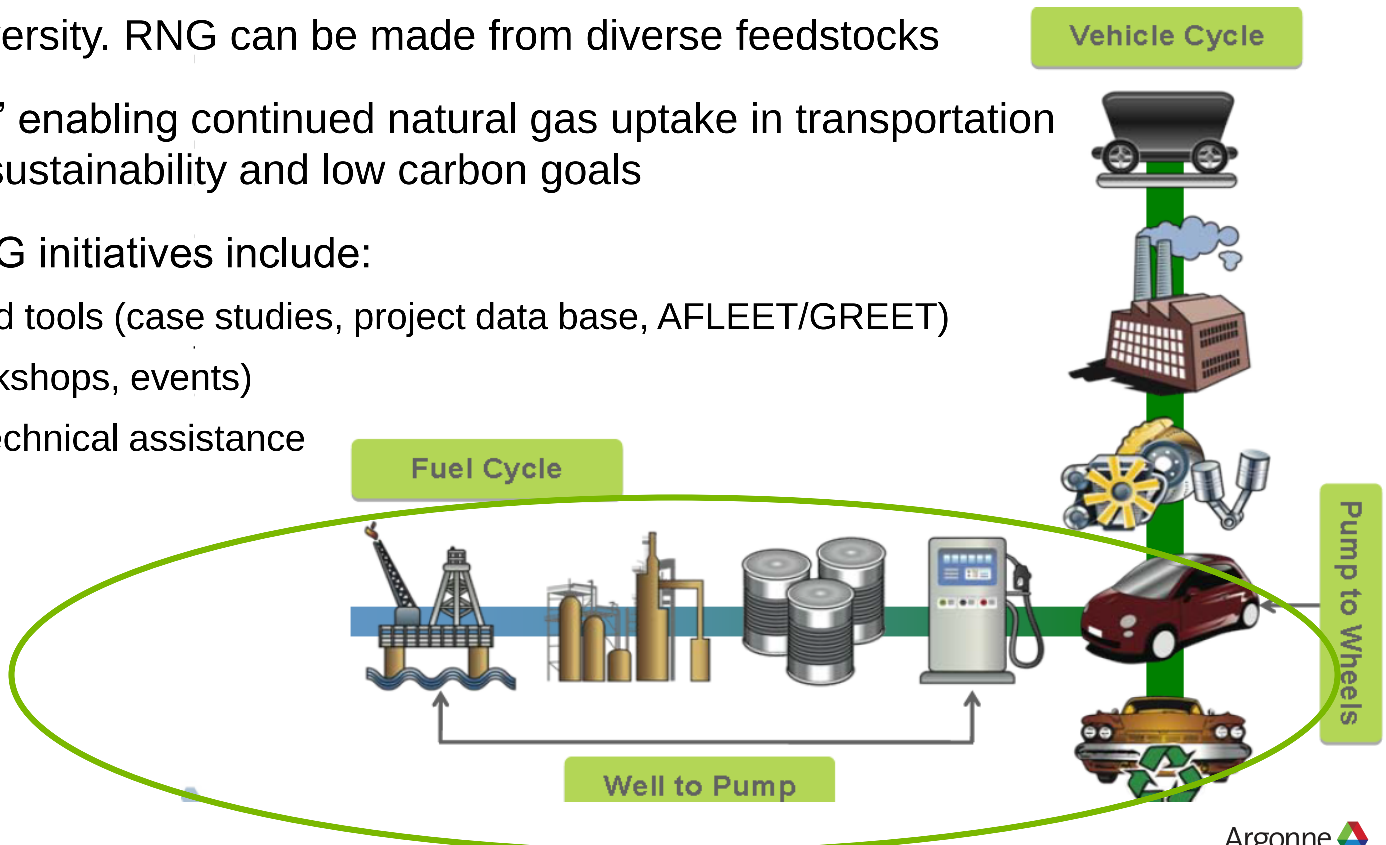
- RNG is renewable because it is produced from organic waste.
- Natural decomposition produces biogas (50-70% methane, 25-30 times more potent than CO2).
- RNG is produced by upgrading biogas to >98% methane.
- RNG can be used **without modification** in any natural gas-fueled engine.
- RNG can be **safely injected** into natural gas pipelines.
- RNG can help **meet environmental, economic and energy goals**.
- 1 million Btu (MMBtu) = 1 dekatherm (dth) ~ 1000 cubic feet (cf)
- 1 ethanol gal equivalent (ege) = 75,700 Btu = 0.66 gge = 1 RIN
- RNG production is expanding rapidly.

RNG CAN BE PRODUCED AND USED IN A CLOSED LOOP PROCESS

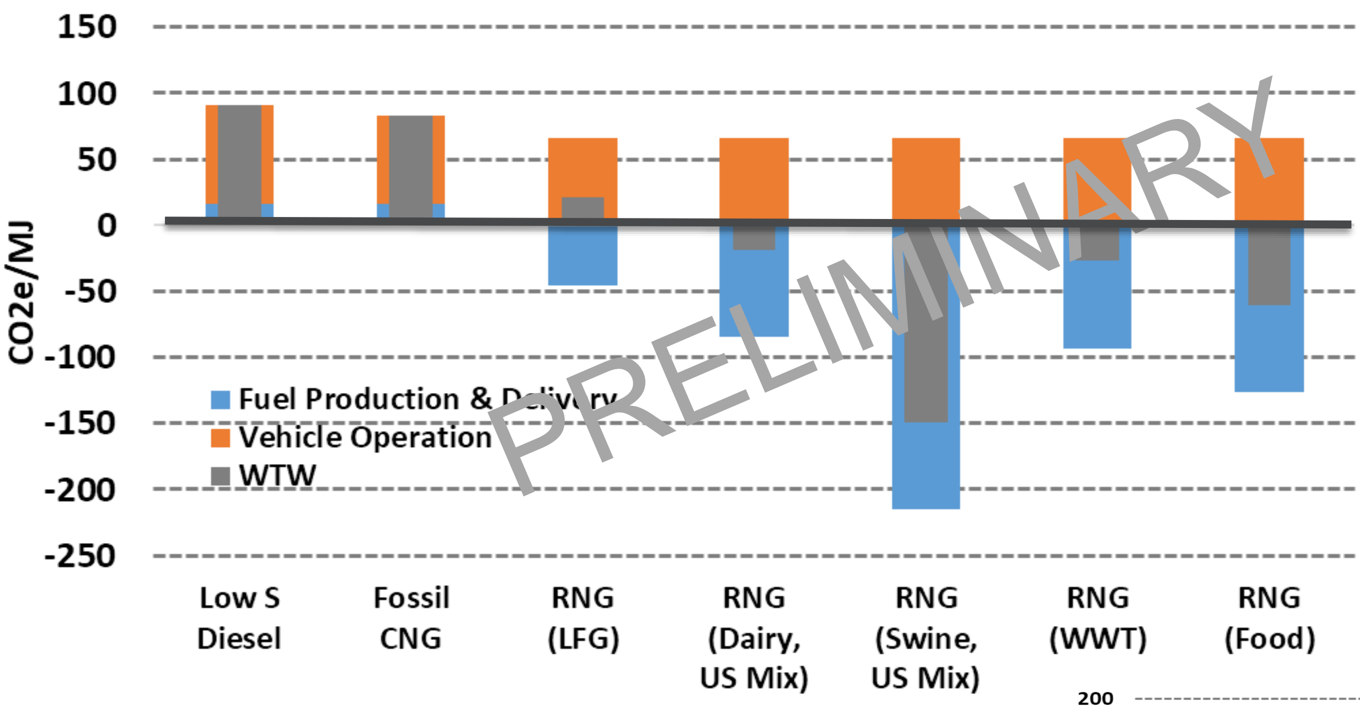


VEHICLE TECHNOLOGIES OFFICE'S CLEAN CITIES NETWORK SUPPORTS RNG

- Aligns with green fleets and alternative fuels
- Combines ("pump-to-wheel") emissions benefits of natural gas vehicles with renewables' upstream ("well-to-pump") GHG reductions
- Promotes sustainability, renewable resources, and economic benefits
- Supports fuel diversity. RNG can be made from diverse feedstocks
- "Greens the grid" enabling continued natural gas uptake in transportation while achieving sustainability and low carbon goals
- Clean Cities' RNG initiatives include:
  - Information and tools (case studies, project data base, AFLEET/GREET)
  - Outreach (workshops, events)
  - Training and technical assistance

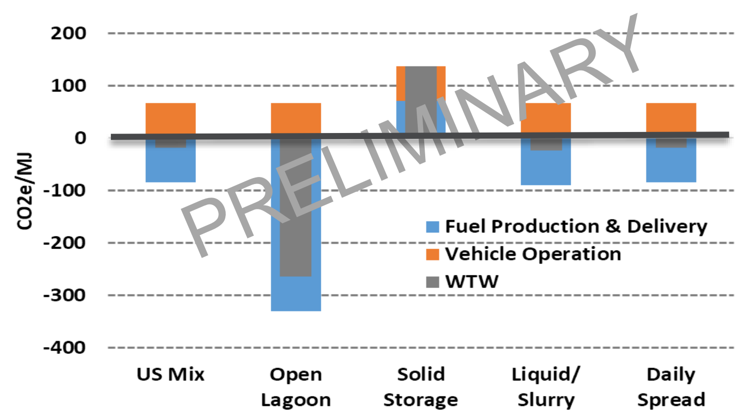


MANY RNG PATHWAYS REDUCE WELL-TO-WHEEL (WTW) GHG EMISSIONS



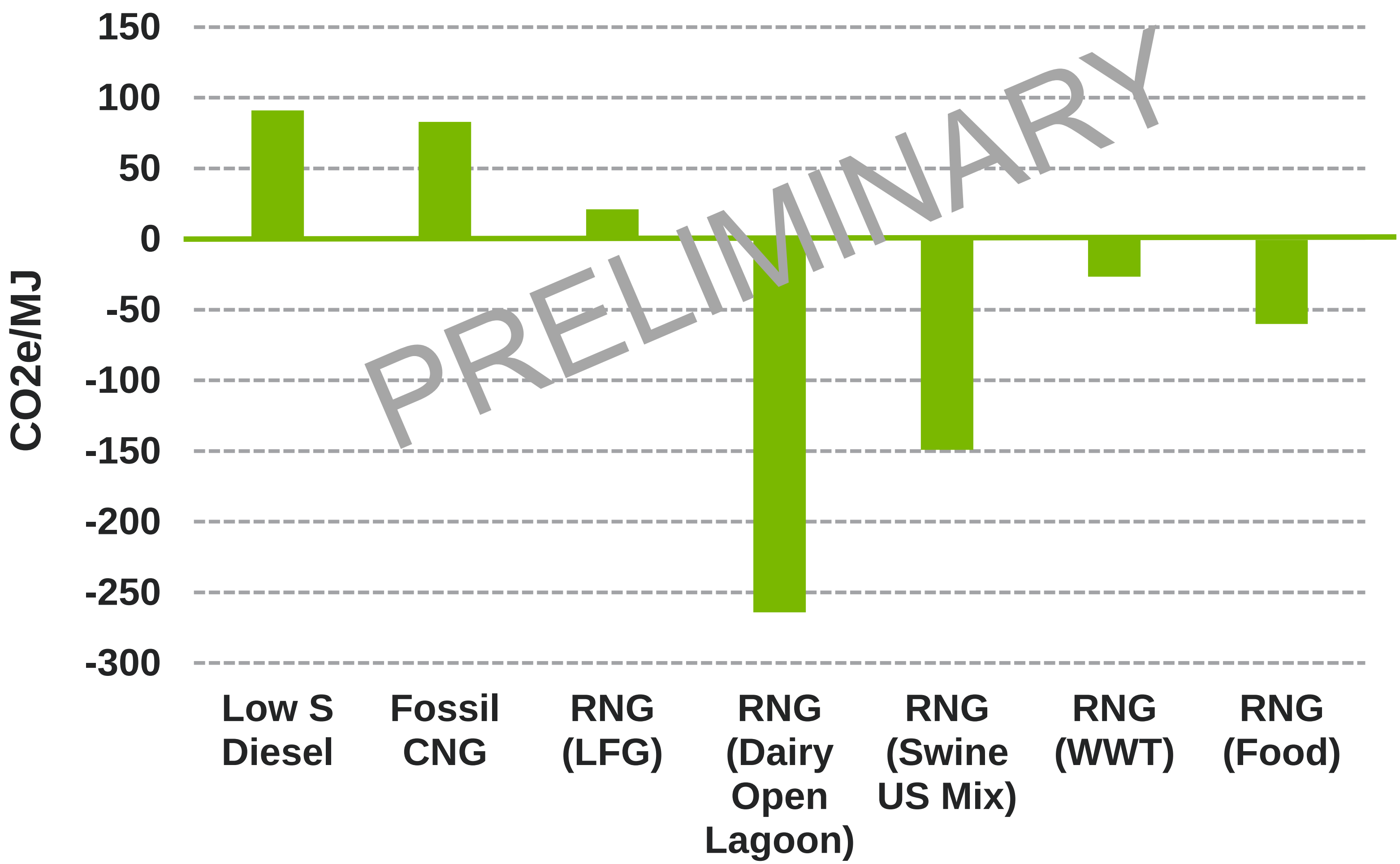
GREET 2019, https://greet.es.anl.gov.

- Operational emissions equivalent for fossil & renewable NG.
- CI score = WTW or net g CO2e/MJ.
- Many variables affect WTW or CI score (e.g., existing manure management system, climate, feedstock composition, digester technology, etc.).



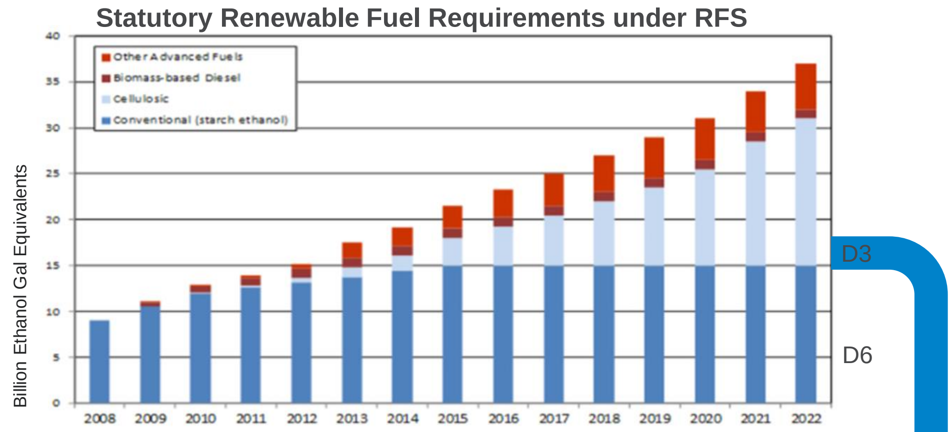
CARBON INTENSITY IS PARTICULARLY LOW FOR HIGH GHG-EMITTING REFERENCE CASES

Depending on reference case, RNG can dramatically lower GHG emissions

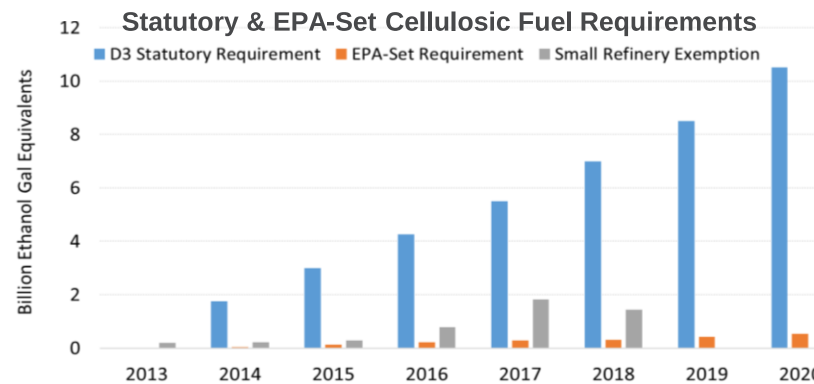


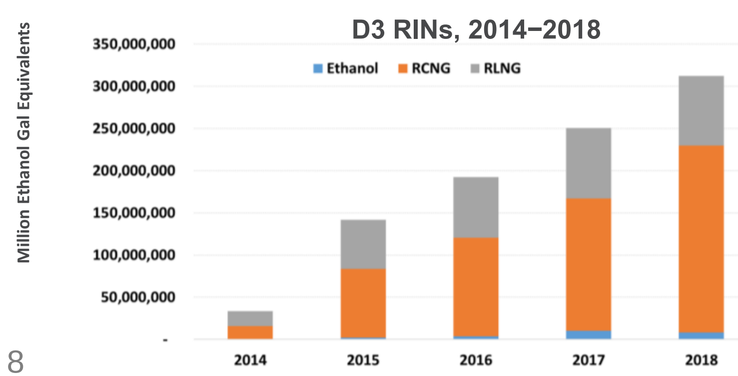
RENEWABLE FUEL STANDARD (RFS) BOOSTED RNG

- RFS placed **statutory requirements** on refiners & importers to supply renewable fuels.
- Small refiners can get exemptions **(SREs).**
- Requirements measured in ethanol gal equivalents, **Renewable Identification Numbers (RINs),** that can be traded in lieu of physical transfer**.**
- Each RIN has one of 5 codes **(D3−D7)** based on its source and GHG emissions.
- Due to technical constraints, EPA reduced cellulosic fuel (D3) requirements & expanded eligibility to **RNG**.
- Today RNG accounts for >97% of D3 RINs.
- Electricity from organic sources also eligible for e-RINS though EPA has not approved any pathways.



Source: Alternative Fuels Data Center (http://www.afdc.energy.gov/laws/RFS.html)



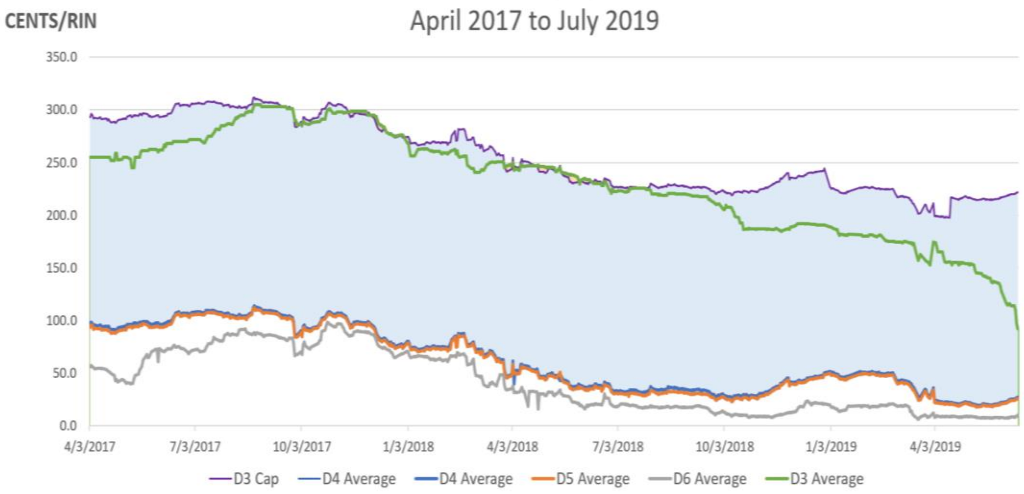


Source: Argonne National Lab based on https://www.epa.gov/fuels-registration-reporting-and-compliance-help/rins-generated-transactions

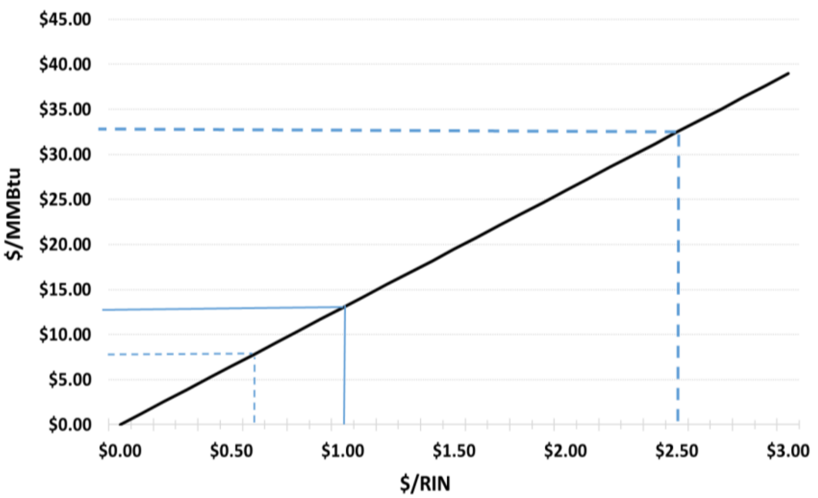
MODEST INCREASES IN CELLULOSIC REQUIREMENTS & LARGE EXEMPTIONS DISRUPTED RIN MARKETS

D3 RINs dropped from ~$2.50/ege historically to $.46/ege (green curve) in 8/19 when EPA granted 32 Small Refinery Exemptions

RIN Price by D Code



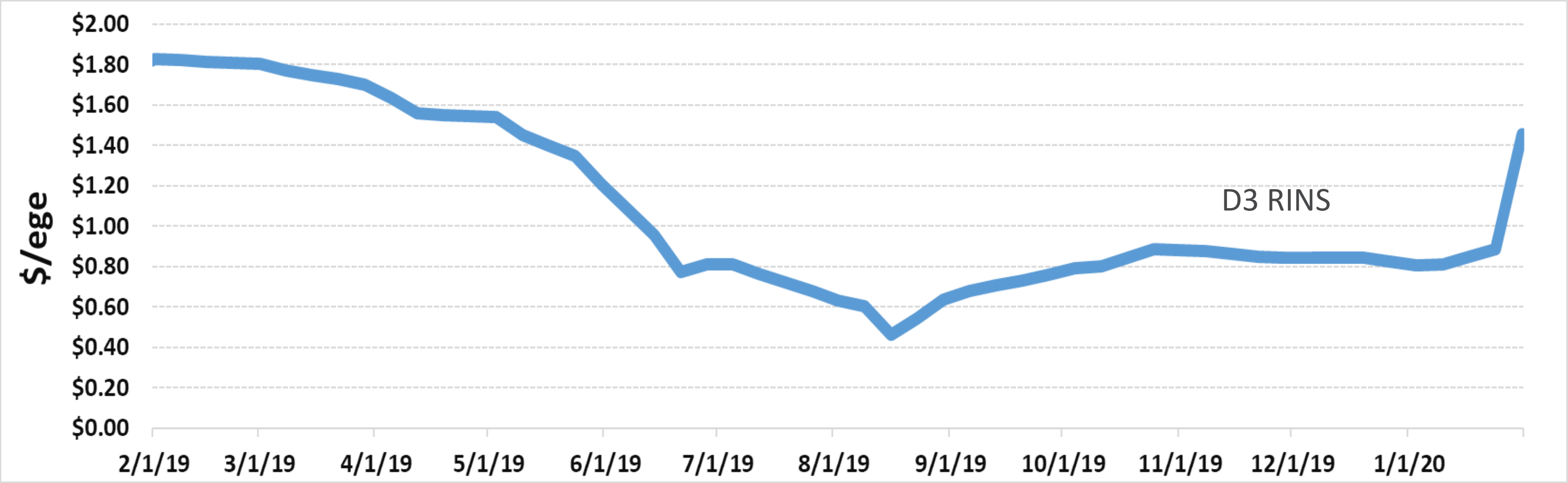
RIN Price in $/MMBtu



Source: *Digging into D3 Pricing*, EcoEngineers webinar, Aug. 7, 2019. Courtesy EcoEngineers.

D3 RINS STABILIZED ~$.80 FROM OCT–JAN

Then rose sharply after January 24 court ruling against EPA on SREs



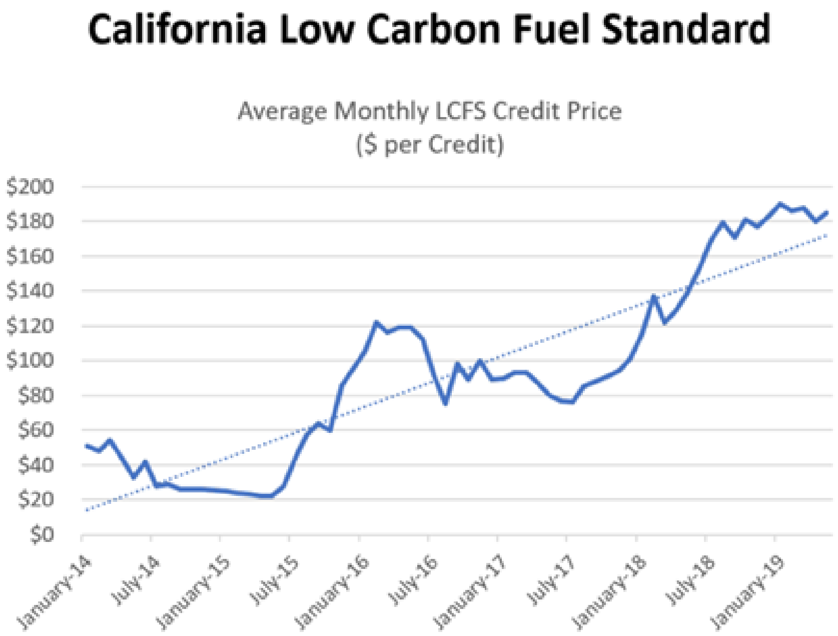
On 1/31/20, D3 RINs closed at $1.45

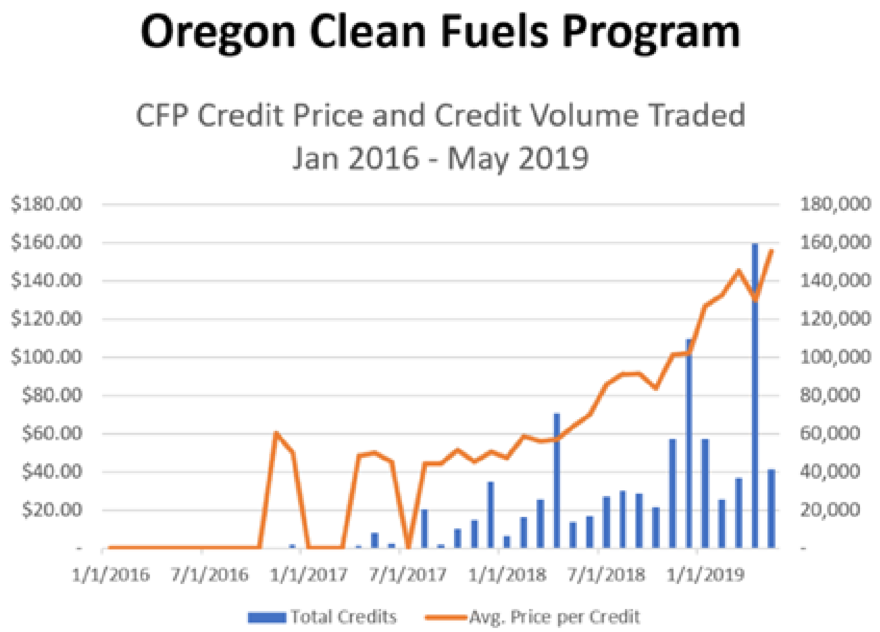
Future prices depend on demand (cellulosic fuel requirements less waivers, and voluntary market)

BUT CREDIT VALUES ON CALIFORNIA AND OREGON CLEAN FUEL MARKETS CONTINUE RISING

CA credits trading at >$200/t CO_2; OR credits at ~$160/t

Credits are “stackable” and can be additional to RINs.





Source: *Digging into D3 Pricing*, EcoEngineers webinar, Aug. 7, 2019. Courtesy EcoEngineers.

ARGONNE RNG DATABASE SUMMARIZES & CONFIRMS TRANSPORTATION APPLICATIONS AS OF 3/31/19

KEY: Value from LMOP

Value from other public sour[ce] *Note that individual values are drawn from different sources, and so may appear inconsistent-- e.g., gas going for upgrading may be more than total amount of gas collected*

Value calculated from other info

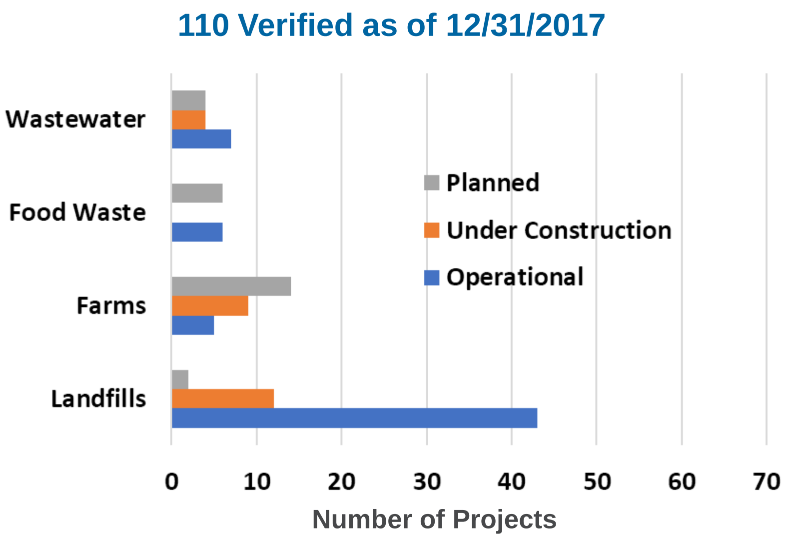
owner/developer

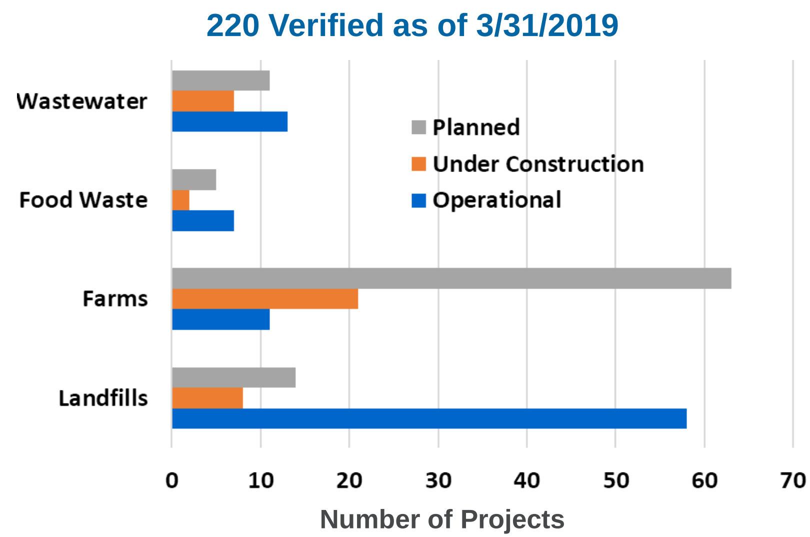
	LANDFILL PROJECT INFORMATION									REPORTED OUTPUT, CAPACITY, END USE											
8	Status	Project Name	Owner	Waste In Place (tons)	Daily intake, tons	State	Upgrading Start Date	Developer(s)	Description	LFG Flow to Upgrading Project (mmscfd)	Total LFG Collected (mmscfd)	Upgraded gas, MMBTU/yr	RNG Disposition	GGE/yr	Capacity, GGE/yr	Electricity production	Annual metric tonnes CO2e eliminated	End User(s)	RIN Registrant?	Further Information
9																				
10	VERIFIED OPERATIONAL																			
11	OPERATIONAL	City of Fort Smith Landfill (Morrow Renewables)	Fort Smith Department of Sanitation	8,552,007		AR	5/11/2006	Morrow Renewables, LLC, Cambrian Energy Development, LLC	Physical solvent process with patented enhancements and catalytic oxygen removal - removes CO2, H2O, H2S, siloxanes, and other impurities from LFG. Creates high BTU RNG injected into the pipeline infrastructure. Gas used down the pipeline for vehicle fuel	2.7	3.312	534,600	Pipeline	4,764,961		N/A		s Oklahoma Gas Corpora	Yes	http://www.swtimes.com/business/fort-smith-landfill-provides-natural-gas-local-utility; http://morrowrenewables.com/highBTU-plant-projects.html
12	OPERATIONAL	Altamont Landfill (Waste Management)	Waste Management, Inc.	57,857,143		CA	9/1/2009	The Linde Group; High Mountain Fuels	Creates LNG to fuel 300 garbage trucks; WM delivers it to their locations in the SF Bay Area mostly - Oakland, Livermore and San Leandro - with occasional deliveries to Castroville; generates electricity from landfill gas powered turbines and windmills. System's multi-step process includes compression, chilling, adsorption, and membranes to remove impurities, cleaned LFG is then cooled to -260 deg F to create 13,000 gal/day LNG for garbage trucks.	3.6	8.33	552,836	Vehicle fuel	4,927,500	4,927,500	to "power LNG plant and 8000 homes annually".		Waste Management, Inc.	Yes	http://www0.wm.com/federal/case-studies/altamont.html; LNG production figures ibid and http://www.energy.ca.gov/2014publications/CEC-500-2014-054/CEC-500-2014-054.pdf http://altamontlandfill.wm.com/index.jsp http://ecocomplex.rutgers.edu/ATF_BiomassFuels_LindeLNG_Luftglass.pdf http://energy-vision.org/case-studies/WM-Altamont-
13	OPERATIONAL	Milam Recycling and Disposal Facility (Waste Management)	Waste Management, Inc.	16,000,000		IL	3/10/2015	WM Renewable Energy, LLC	Facility designed to process 3,500 cfm LF. Gas is transported via natural gas pipelines to WM's CNG fueling stations and CNG trucks. Upgrading equipment: CO2/siloxane: Air Liquide membrane with carbon polisher. Nitrogen/Oxygen: ARI PSA.	3.6	5.05	576,000.00	Pipeline	5,133,964.38	5,486,000	2.4 MW for RNG plant demand, none	242,390	Ameren Illinois Company (natural gas	Yes	https://www.wmsolutions.com/locations/details/id/31 https://waste-management-world.com/a/waste-management-opens-19m-landfill-gas-grid-injection-facility-in-illinois
14	OPERATIONAL	Johnson County Landfill (formerly Deffenbaugh) (WM, Aria)	Landfill, Waste Management; upgrading operation, Aria Energy	30,000,000		KS	9/1/2001	Funds Group; Enpower Corp.; Aria (formerly Landfill Energy Systems); SouthTex	Creates high BTU RNG injected into the pipeline infrastructure; uses a modified Selexol-type scrubbing system	7	7	1,150,000	Pipeline	10,250,103			673,300	Kansas Pipeline, SMUD for electricity	Yes	http://www.wm.com/location/missouri/deffenbaugh/index.jsp http://www.kdheks.gov/waste/workshops/works10/presentations/martinjay-collectinggasandmaintainingcompliance-2010.pdf https://www.arb.ca.gov/fuels/lcfs/2a2b/apps/ce-ksc-cng-rpt-052815.pdf
15	OPERATIONAL	Jefferson Davis Parish Landfill	Jefferson Davis Parish Sanitary Landfill Commission	9,584,310		LA	4/1/2008	Morrow Renewables, LLC	Physical solvent process with patented enhancements and catalytic oxygen removal - removes CO2, H2O, H2S, siloxanes, and other impurities from LFG. Creates high BTU RNG injected into the pipeline infrastructure for use as vehicle fuel	2.14	2.14	409,311	Vehicle fuel	3,648,243		N/A	205,840	South Pipeline; Shell Energy	Yes	https://wastebits.com/location/jefferson-davis-parish-sanitary-landfill http://www.countyoffice.org/welsh-landfill-welsh-la-1b7/
16	OPERATIONAL	St. Landry Parish Landfill	St. Landry Parish Solid Waste Disposal District	2,750,000		LA	4/13/2012	BioCNG; St. Landry Parish Solid Waste Disposal District	Department cars, light duty trucks and a light duty van, and the solid waste district's utility trucks. Membrane removes CO2, silica medium removes silica, volatile organic compounds removed by charcoal-like compound, coconut based medium to remove other VOCs, Sulfatreat to remove H_2S. 50 cfm LFG produces 250 gallons of gasoline equivalent (GGE)/day; convert LFG to bioCNG vehicle fuel for 1 passenger van, 5 sedans & 10 fleet pick-up trucks	0.3024	0.3096	180,000	Vehicle fuel	172,000	262,800	N/A	24,179	Parish, 1 passenger van Sherriff office, 10 Refuse	Yes	project/ http://www.tetratech.com/en/projects/st-landry-parish-landfill-biocng-project-louisiana https://www.epa.gov/sites/production/files/2016-05/documents/05_k_martin_presentation.pdf https://wasteadvantagemag.com/st-landry-parish-solid-waste-disposal-district-turning-landfill-gas-into-biofuel/
17	OPERATIONAL	Richfield Landfill ("Blue Sky") (Blue Skies Energy)	Richfield Landfill, Inc.			MI	11/1/2006	Blue Skies Energy, LLC	Uses UOP Separex Membrane Technology to create pipeline quality natural gas from LFG. Aria Energy buying all output.	2.066	2.066	447,000	Pipeline				170,875	Great Lakes Gas Transmission Compan	Yes	http://www.nthconsultants.com/richfield-sanitary-landfill.html http://www.mlive.com/news/flint/index.ssf/2014/04/potential_buyer_of_richfield_l.html http://www.mlive.com/news/flint/index.ssf/2012/11/state_deq_official_says_new_ri.html

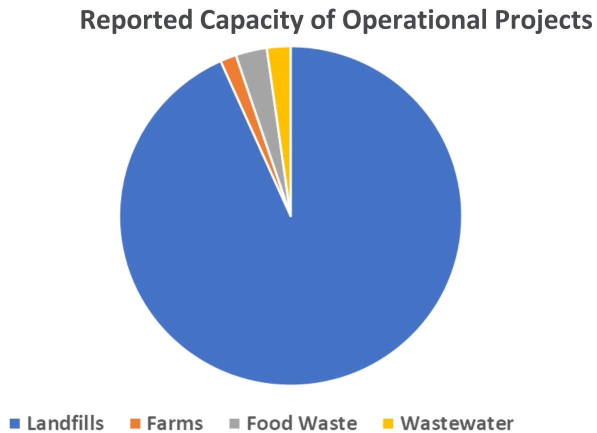
Overview | Farms | Food_Waste | Landfills | WWT | Other_Waste | TOTALS | List Values | Notes | OPERATIONAL PROJECTS

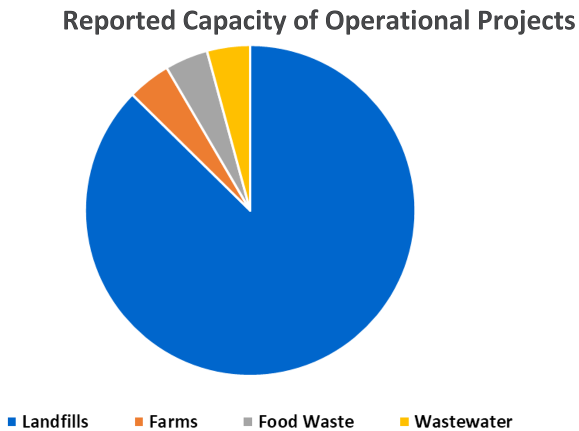
https://www.anl.gov/es/reference/renewable-natural-gas-database

MOST RNG PROJECTS ARE LANDFILL-BASED THOUGH FARM & WASTEWATER SHARES ARE GROWING



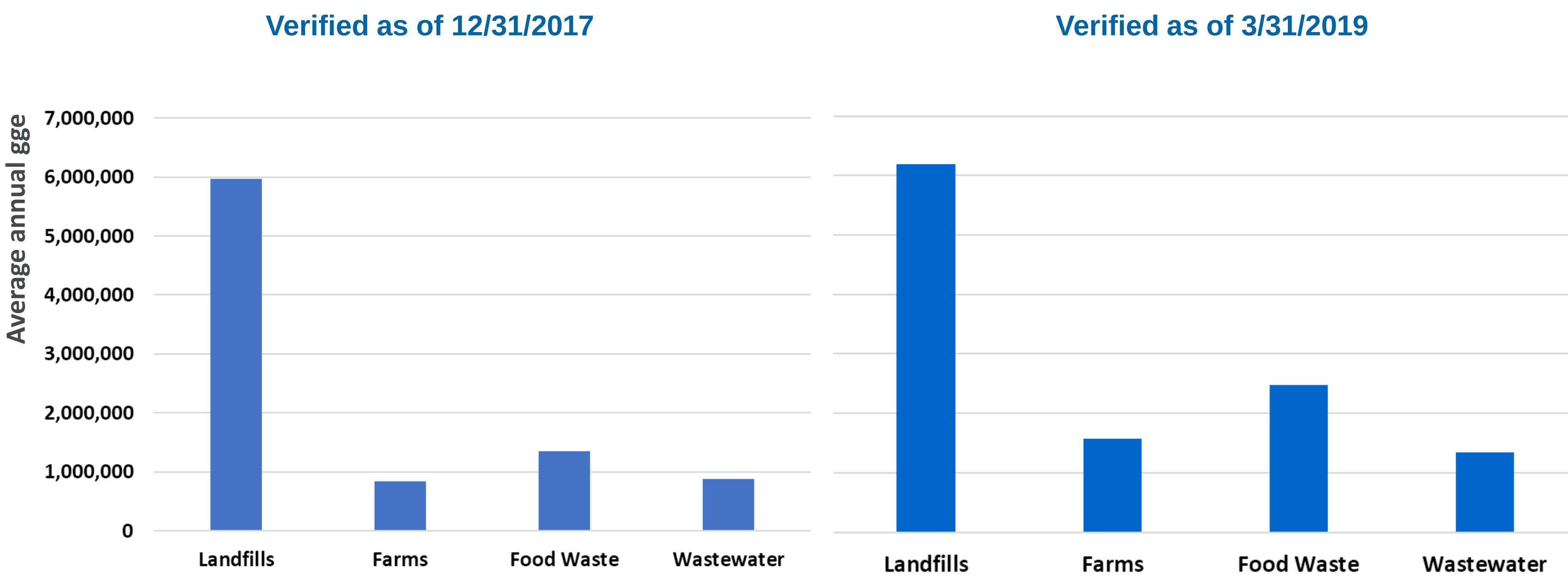






Landfills still account for >87% nameplate capacity

CAPACITY IS GROWING ACROSS ALL TYPES OF OPERATIONAL RNG PROJECTS



- Average capacity of operational farm and food waste projects rose by over 80% in last 15 months
- Average capacity of WWT projects rose by over 50%

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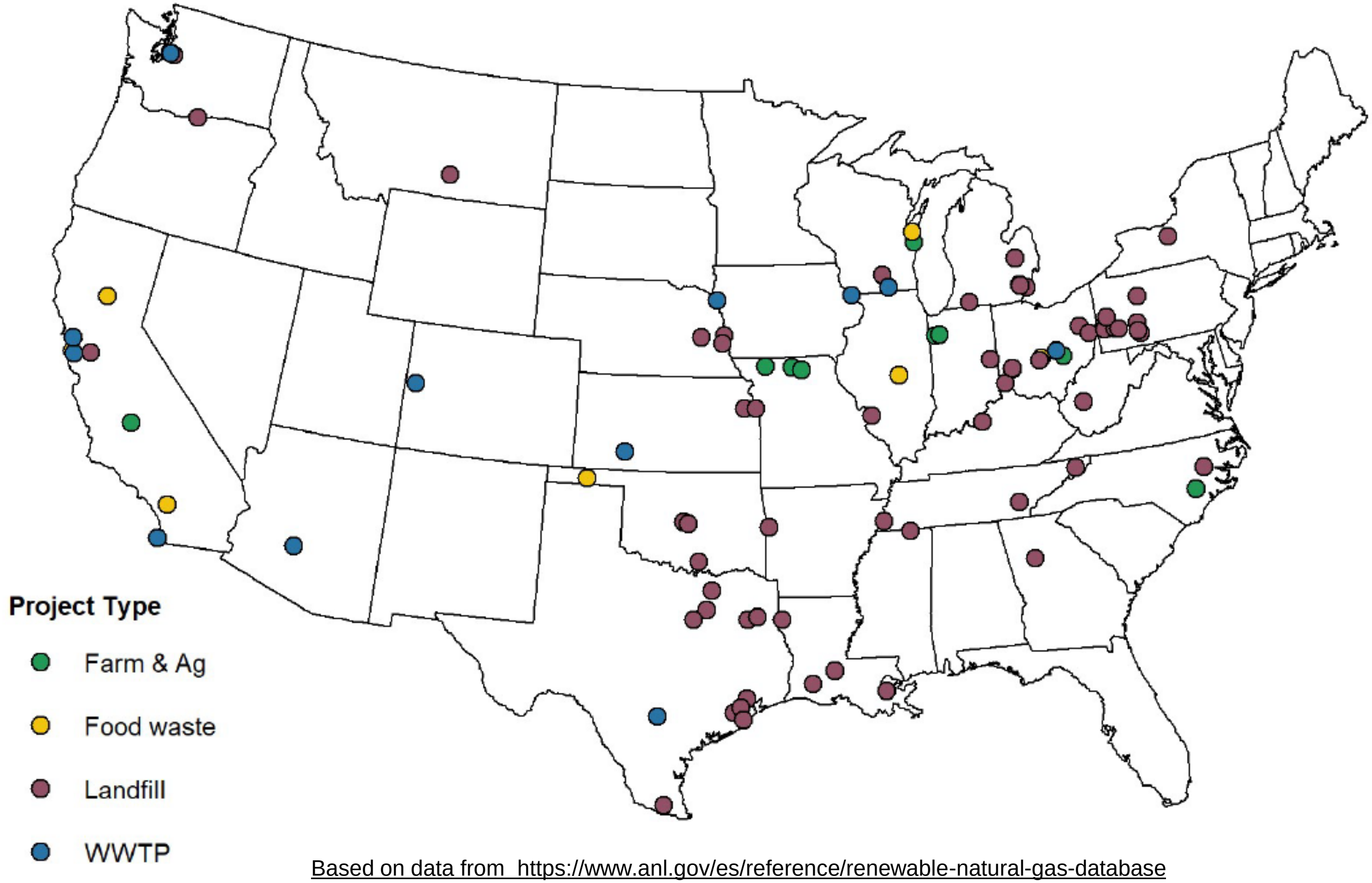
89 PROJECTS CURRENTLY PRODUCE RNG FOR ONSITE FUELING OR PIPELINE INJECTION

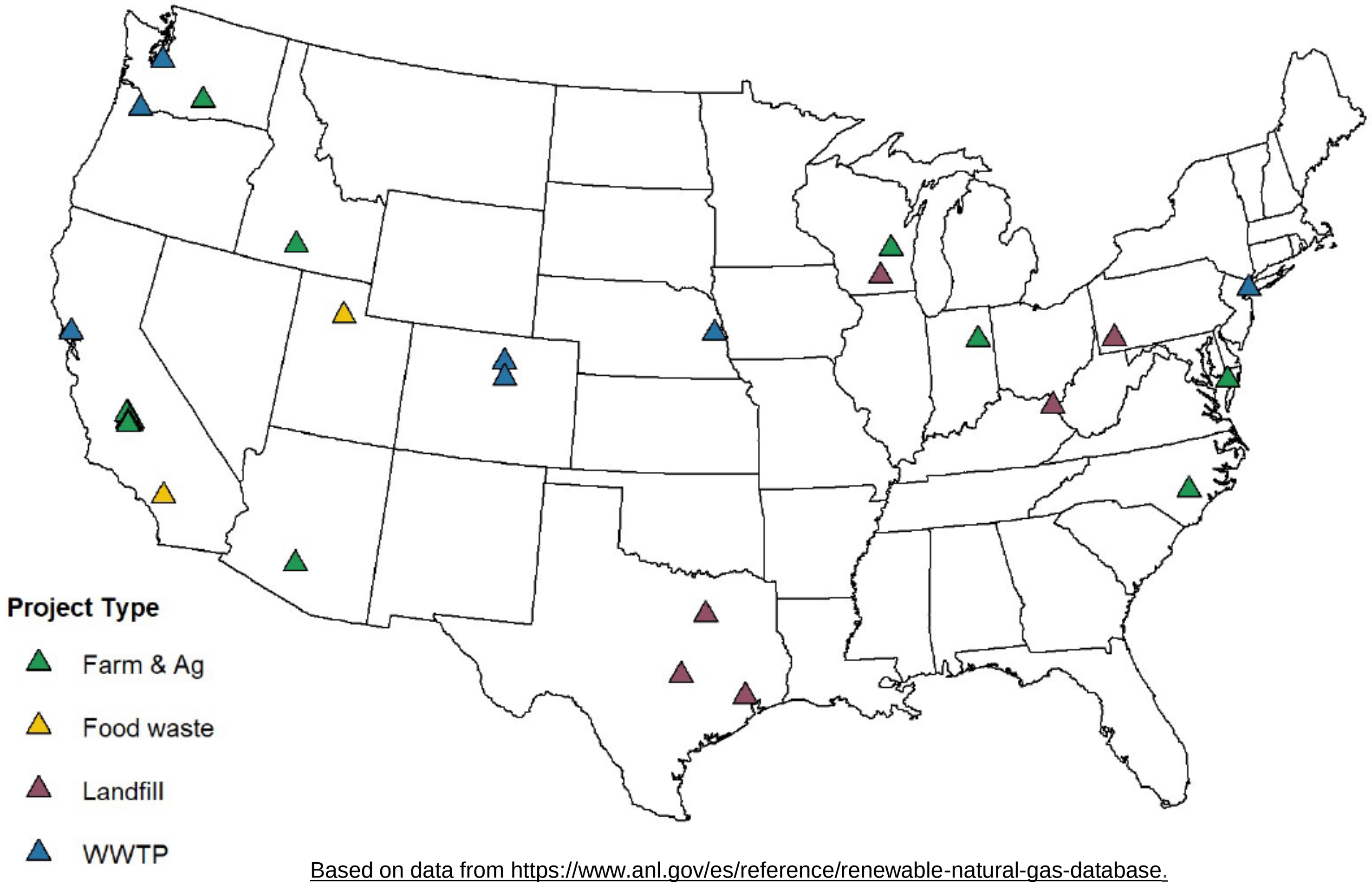
RNG is produced all over the US, though some states have more projects than others. Landfill-based projects are concentrated in central and Appalachian states



Based on data from https://www.anl.gov/es/reference/renewable-natural-gas-database

38 PROJECTS ARE UNDER CONSTRUCTION

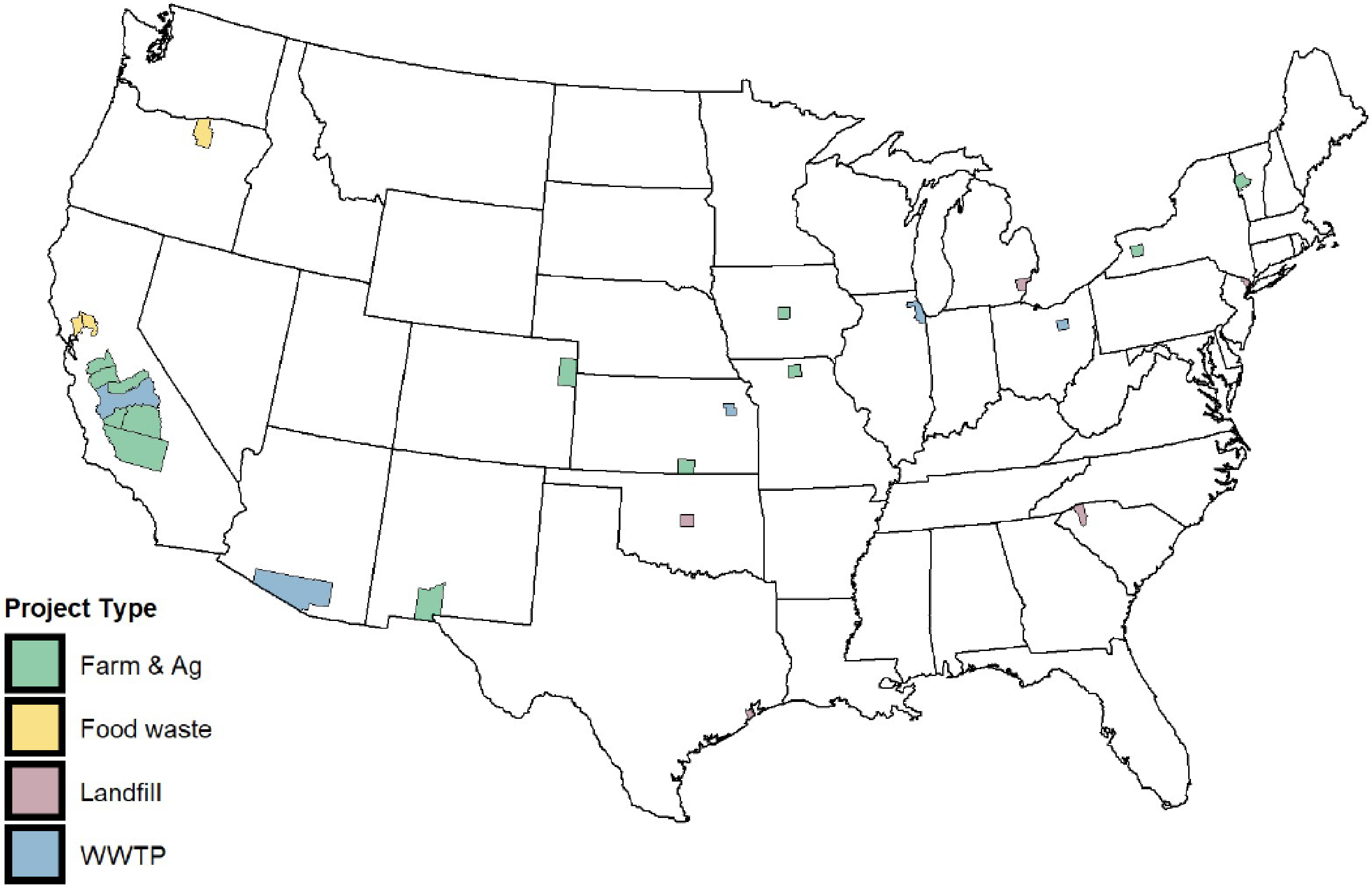
Relatively more farm and WWTP projects are currently under construction. East and West coasts are seeing relatively more activity.



Based on data from https://www.anl.gov/es/reference/renewable-natural-gas-database.

93 PLANNED PROJECTS SUGGEST TRENDS

Farm projects dominate, likely due to attractive Carbon Intensity scores
California policies encourage in-state projects, especially dairy & WWTP + pipe injection



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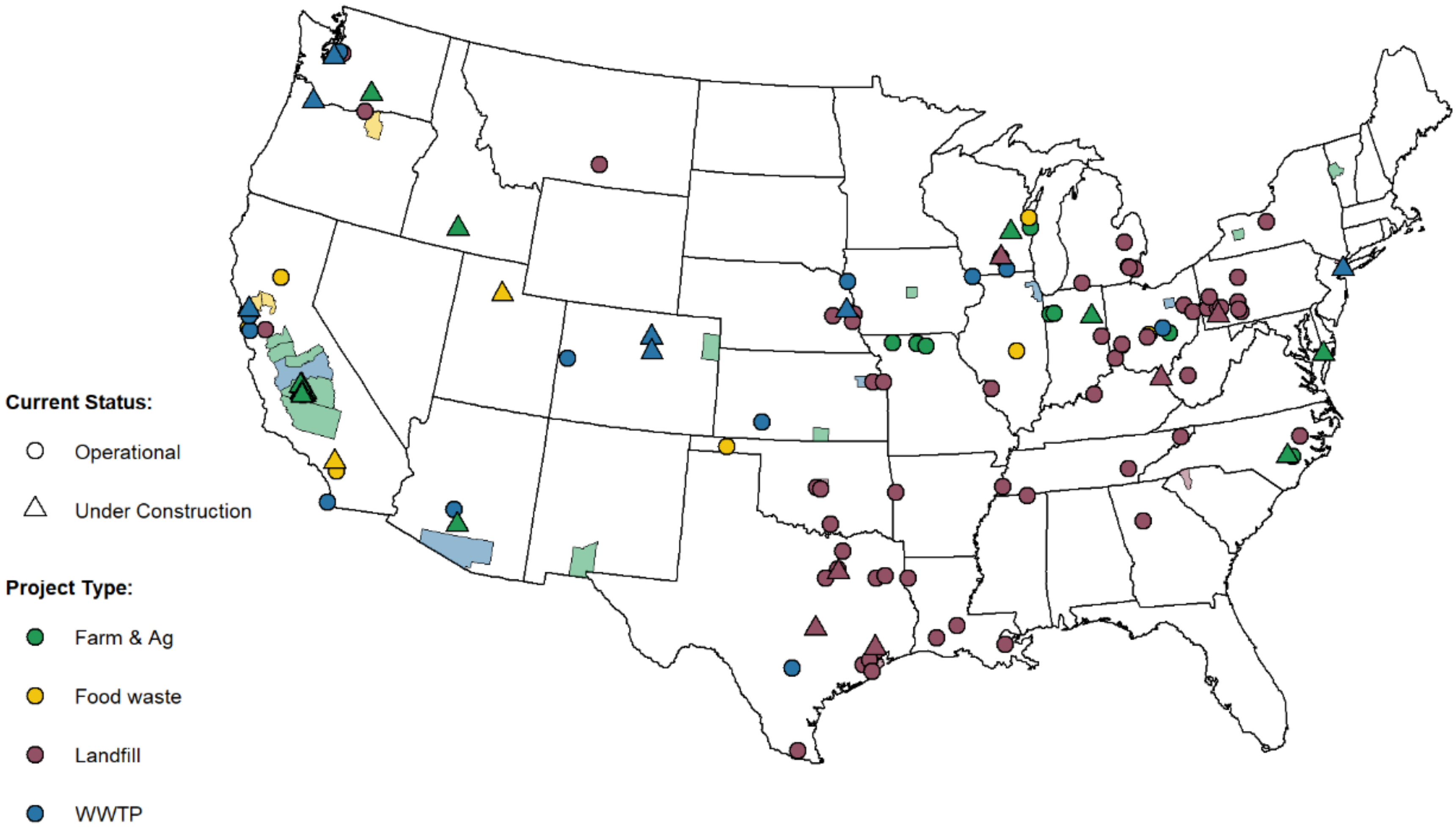
AS OF 3/31/19, 220 PROJECTS OPERATIONAL, UNDER CONSTRUCTION OR PLANNING TO PRODUCE RNG FOR TRANSPORTATION



RNG FOR TRANSPORTATION: OPERATIONAL, UNDER CONSTRUCTION & PLANNED PROJECTS

From food waste, landfills, WWTPs in CA (as of 3/31/19)

	Status	Project	City	County
Food	Operational	Blue Line Biogenic CNG	S San Francisco	San Francisco
		CR&R Perris Transfer Stn	Perris	Riverside
		Northstate Rendering	Oroville	Butte
	Under Construction	Rialto Bioenergy	Rialto	San Bernardino
		Napa Recycling & Waste Serviccs		Napa
		UCD Renewable Energy AD		Yolo
LFG	Operational	Altamont Landfill	Livermore	Alameda
	Planned	BENA		Kern
		Newby Island		Santa Clara
WWT	Operational	City of San Mateo WWTP	San Mateo	San Mateo
		Las Gallinas Vy San District	San Rafael	Marin
		Point Loma WWTP	San Diego	San Diego
	Under Construction	Ellis Creek Water Recycling	Petaluma	Sonoma
	Planned	Fresno Clovis WWT		Fresno
		LACSD Joint Water Pollution Control		Los Angeles
		Pleasant Grove WWT		Placer

RNG FOR TRANSPORTATION: OPERATIONAL, UNDER CONSTRUCTION & PLANNED PROJECTS

From farms/agriculture in CA (as of 3/31/19)

Circle A Dairy	Pixley	Pixley
R Vander Eyk Dairy	Tulare	Tulare
4K Dairy	Pixley	Tulare
Bosman Dairy	Pixley	Tulare
Cornerstone	Tipton	Tulare
Decade Centralized	Tulare	Tulare
FM Jerseys	Tipton	Tulare
K&M Visser Dairy	Pixley	Tulare
Legacy Dairy	Pixley	Tulare
Little Rock	Tipton	Tulare
Lone Oak 1	Hanford	Kings
Pixley Dairy	Pixley	Tulare
River Ranch	Hanford	Kings
Riverview Diary	Pixley	Tulare
Sousa and Sousa	Tipton	Tulare
Vander Poel	Pixley	Tulare
Williams Family	Pixley	Tulare

ABEC Lakeview Farms	Kern
Ackerman Dairy	Stanislaus
Aukeman Dairy	Tulare
Belonave Dairy	Kern
Bos Farms Dairy	Tulare
BV Dairy	Kern
Cloverdale Dairy	Kings
De Groot North	Kings
De Groot South	Kings
DJ South	Madera
Double D	Stanislaus
Double J	Tulare
Double L	Kings
Dykstra	Tulare
El Monte	Tulare
Five H	Merced
Hamstra Dairy	Tulare
Hollandia Farms	Kings
Hoogendam	Merced
Horizon Jersey	Tulare
Jacobus De Groot #2	Tulare

Maple Diary	Kern
Meirinho	Merced
Mellema Diary	Tulare
Milky Way	Tulare
Mineral King	Tulare
Moonlight Dairy	Tulare
Rancho Sierra Vista	Tulare
Red Rock	Merced
Riverbend	Tulare
Rob Van Grouw	Tulare
Rocking Horse	Kings
Rockshar	Merced
S&S Dairy	Tulare
T&W Dairy	Kern
Trilogy Dairy	Kern
Udder Dairy	Tulare
Valadao	Kings
Vander Wounde	Merced
Vista Verde	Madera
Western Sky	Kern
Wreden Ranch Dairy	Kings

TRENDS & ISSUES AFFECTING RNG PROJECTS

- Major shifts in market for RNG
  - Transportation vs. utility market
  - CA vs. local markets
  - NG engines vs. CHP vs. natural gas grid
  - Collapse in D3 RINs and near-saturation in CA transportation market
- Lots of players/complexity in RNG projects and RIN market
  - Developers, investors, utilities, fuel retailers, fleets, regulators (waste, land use, emissions)
  - Obligated parties, compliance specialists, marketers bundling RINs
- Look to the states (and utilities)
  - Mandated methane reductions, waste diversion, Renewable Portfolio Standards
  - Carbon reduction goals and RNG shares, customer choice and environmental attributes
  - Interconnection issues and requirement to buy lowest cost gas
  - Increased competition for low Carbon fuels
- D-3 RIN values highly uncertain (especially SREs)
  - RFS relatively blunt instrument. All pathways qualifying for D code get same incentive.
  - LCFS-type policies are more robust, incentivizing continuous improvements
- Outlook for RNG continues to be bright
  - RNG still “low hanging fruit”
  - Improvements enable ever lower CI pathways in short term
  - More states considering LCFS, limits on fossil gas, fossil gas restrictions

Thank You

mmintz@anl.gov

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NGVAMERICA

Natural Gas Vehicles for America

NGV Technology Forum

February 2020

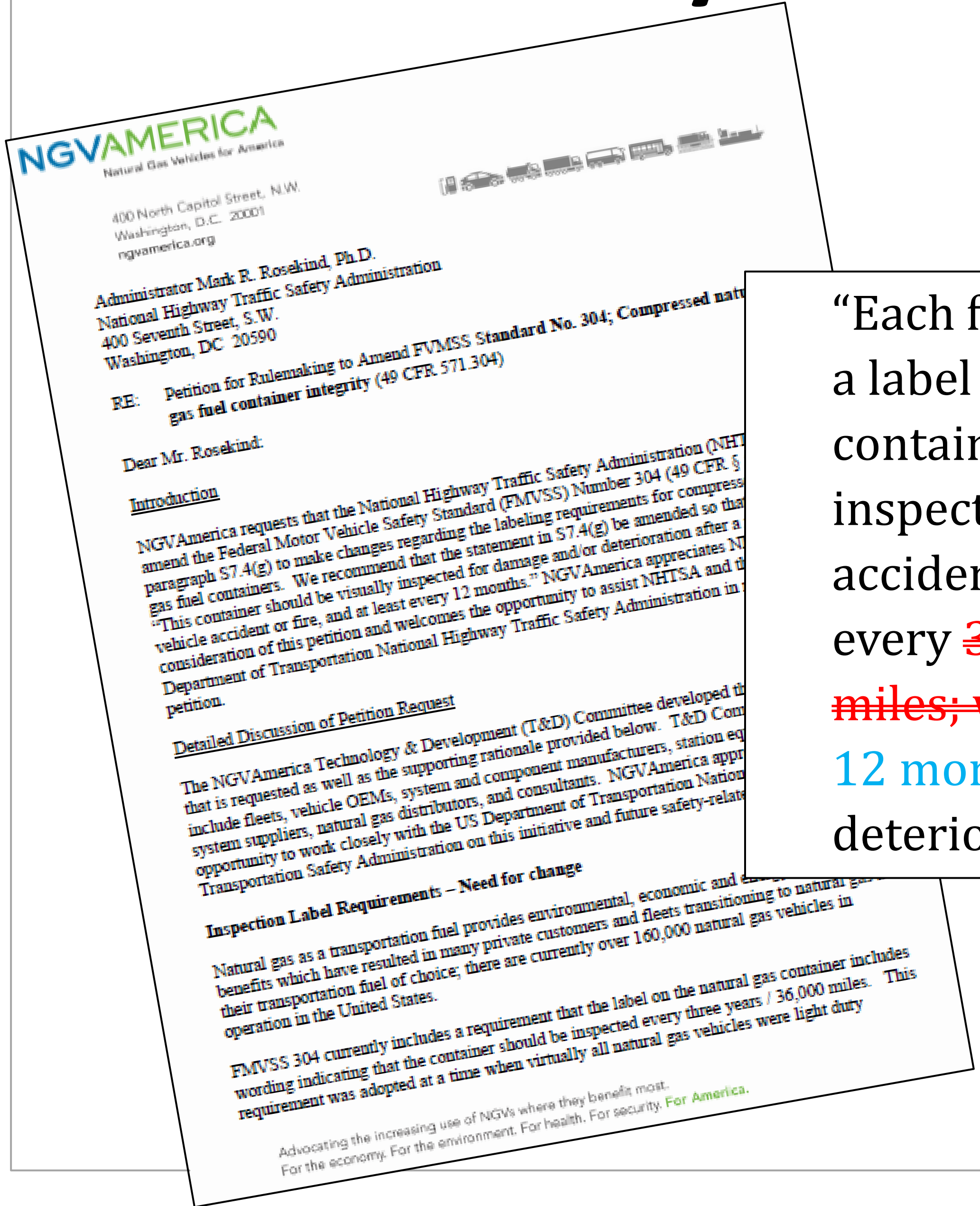
Downey, California

Incident Investigation & Root Cause Analysis Working Group

- Lead incident investigations
- Educate the NGV industry on root cause of incidents
- Communicate incident investigations to the industry and codes and standard development organizations

NGVAMERICA

CNG Fuel System Inspection Working Group


NGVAMERICA
Natural Gas Vehicles for America

400 North Capitol Street, N.W.
Washington, D.C. 20001
ngvamerica.org

Administrator Mark R. Rosekind, Ph.D.
National Highway Traffic Safety Administration
400 Seventh Street, S.W.
Washington, DC 20590

RE: Petition for Rulemaking to Amend FMVSS Standard No. 304; Compressed natu
gas fuel container integrity (49 CFR 571.304)

Dear Mr. Rosekind:

Introduction

NGVAmerica requests that the National Highway Traffic Safety Administration (NHT
amend the Federal Motor Vehicle Safety Standard (FMVSS) Number 304 (49 CFR §
paragraph S7.4(g) to make changes regarding the labeling requirements for compress
gas fuel containers. We recommend that the statement in S7.4(g) be amended so tha
"This container should be visually inspected for damage and/or deterioration after a
vehicle accident or fire, and at least every 12 months." NGVAmerica appreciates N
consideration of this petition and welcomes the opportunity to assist NHTSA and t
Department of Transportation National Highway Traffic Safety Administration in
petition.

Detailed Discussion of Petition Request

The NGVAmerica Technology & Development (T&D) Committee developed th
that is requested as well as the supporting rationale provided below. T&D Com
include fleets, vehicle OEMs, system and component manufacturers, station eq
system suppliers, natural gas distributors, and consultants. NGVAmerica appr
opportunity to work closely with the US Department of Transportation Nation
Transportation Safety Administration on this initiative and future safety-relate

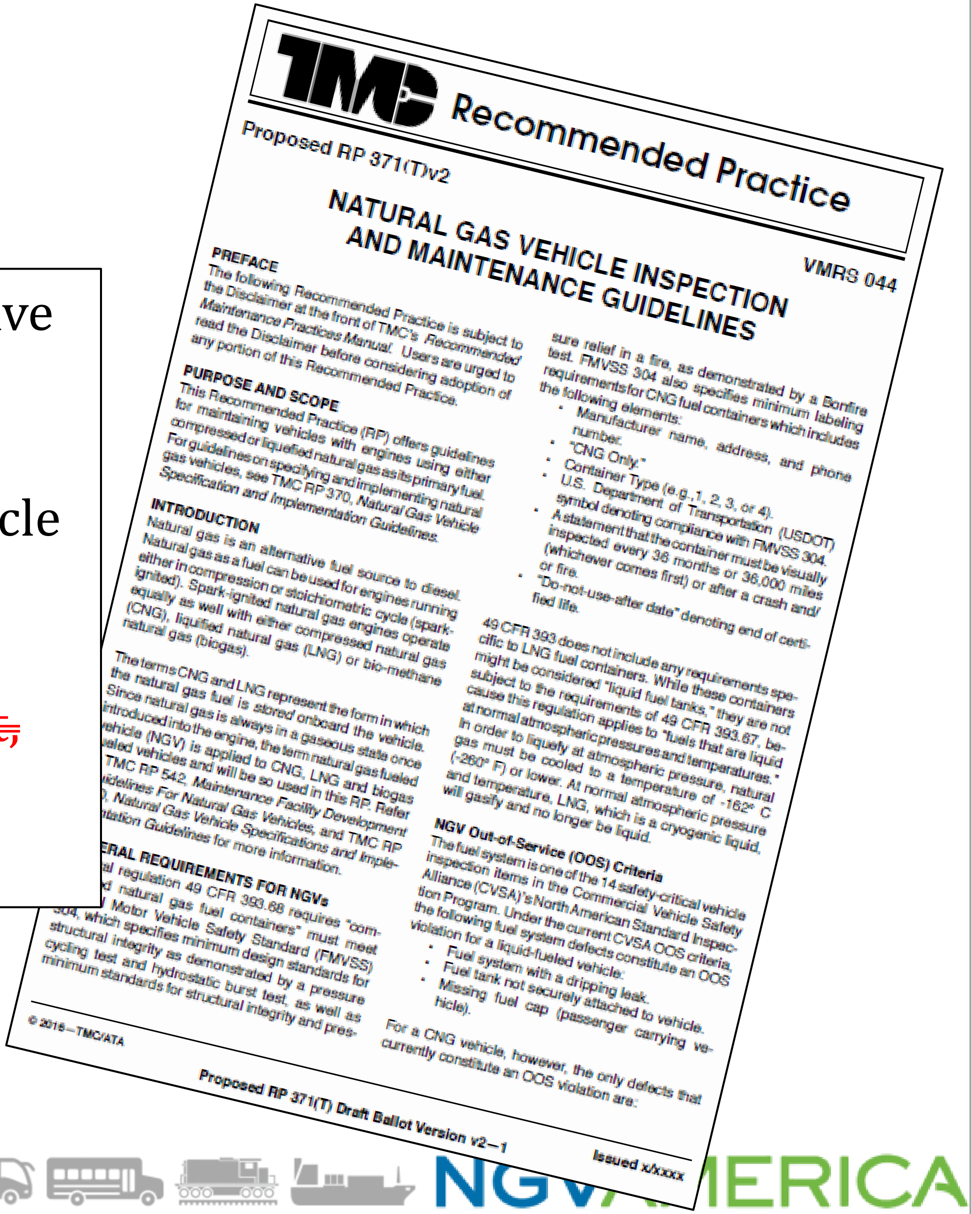
Inspection Label Requirements – Need for change

Natural gas as a transportation fuel provides environmental, economic and
benefits which have resulted in many private customers and fleets transitioning to natural gas
their transportation fuel of choice; there are currently over 160,000 natural gas vehicles in
operation in the United States.

FMVSS 304 currently includes a requirement that the label on the natural gas container includes
wording indicating that the container should be inspected every three years / 36,000 miles. This
requirement was adopted at a time when virtually all natural gas vehicles were light duty

Advocating the increasing use of NGVs where they benefit most.
For the economy. For the environment. For health. For security. For America.

“Each fuel container shall have a label that states "This container should be visually inspected after a motor vehicle accident or fire and at least every ~~36 months or 36,000 miles; whichever comes first,~~ 12 months for damage and deterioration"


TMC Recommended Practice

Proposed RP 371(T)v2

VMRS 044

NATURAL GAS VEHICLE INSPECTION AND MAINTENANCE GUIDELINES

PREFACE
The following Recommended Practice is subject to the Disclaimer at the front of TMC's Recommended Maintenance Practices Manual. Users are urged to read the Disclaimer before considering adoption of any portion of this Recommended Practice.

PURPOSE AND SCOPE
This Recommended Practice (RP) offers guidelines for maintaining vehicles with engines using either compressed or liquefied natural gas as its primary fuel. For guidelines on specifying and implementing natural gas vehicles, see TMC RP 370, Natural Gas Vehicle Specification and Implementation Guidelines.

INTRODUCTION
Natural gas is an alternative fuel source to diesel. Natural gas as a fuel can be used for engines running either in compression or stoichiometric cycle (spark-ignited). Spark-ignited natural gas engines operate equally as well with either compressed natural gas (CNG), liquified natural gas (LNG) or bio-methane natural gas (biogas).

The terms CNG and LNG represent the form in which the natural gas fuel is stored onboard the vehicle. Since natural gas is always in a gaseous state once introduced into the engine, the term natural gas fueled vehicle (NGV) is applied to CNG, LNG and biogas fueled vehicles and will be so used in this RP. Refer TMC RP 542, Maintenance Facility Development Guidelines For Natural Gas Vehicles, and TMC RP Natural Gas Vehicle Specifications and Implementation Guidelines for more information.

ERAL REQUIREMENTS FOR NGVs
al regulation 49 CFR 393.68 requires "compressed natural gas fuel containers" must meet Motor Vehicle Safety Standard (FMVSS) 304, which specifies minimum design standards for structural integrity as demonstrated by a pressure cycling test and hydrostatic burst test, as well as minimum standards for structural integrity and pres-

sure relief in a fire, as demonstrated by a Bonfire test. FMVSS 304 also specifies minimum labeling requirements for CNG fuel containers which includes the following elements:
- Manufacturer name, address, and phone number.
- "CNG Only."
- Container Type (e.g., 1, 2, 3, or 4).
- U.S. Department of Transportation (USDOT) symbol denoting compliance with FMVSS 304.
- A statement that the container must be visually inspected every 36 months or 36,000 miles (whichever comes first) or after a crash and/or fire.
- "Do-not-use-after date" denoting end of certified life.

49 CFR 393 does not include any requirements specific to LNG fuel containers. While these containers might be considered "liquid fuel tanks," they are not subject to the requirements of 49 CFR 393.67, because this regulation applies to "fuels that are liquid at normal atmospheric pressures and temperatures." In order to liquefy at atmospheric pressure, natural gas must be cooled to a temperature of -162° C (-260° F) or lower. At normal atmospheric pressure and temperature, LNG, which is a cryogenic liquid, will gasify and no longer be liquid.

NGV Out-of-Service (OOS) Criteria
The fuel system is one of the 14 safety-critical vehicle inspection items in the Commercial Vehicle Safety Alliance (CVSA)'s North American Standard Inspection Program. Under the current CVSA OOS criteria, the following fuel system defects constitute an OOS violation for a liquid-fueled vehicle:
- Fuel system with a dripping leak.
- Fuel tank not securely attached to vehicle.
- Missing fuel cap (passenger carrying vehicle).

For a CNG vehicle, however, the only defects that currently constitute an OOS violation are:

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Proposed RP 371(T) Draft Ballot Version v2—1

Issued x/xxxx

NGVAMERICA

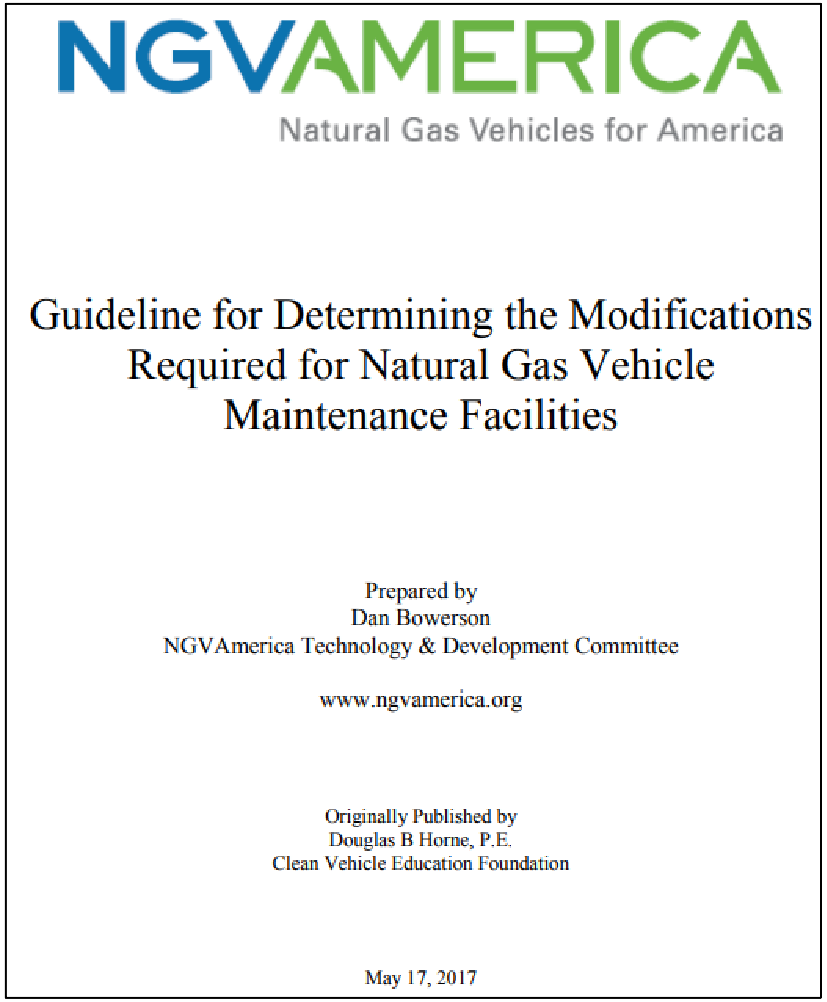
CNG Fuel System Inspection Working Group

“Each fuel container shall have a label that states "This container should be visually inspected after a motor vehicle accident or fire and at least every ~~36 months or 36,000 miles; whichever comes first,~~ 12 months for damage and deterioration"

- DOT proposed rule issued June 21, 2019
- August 2019 NGVAmerica submits comments
- Waiting on final rule

- NGVAmerica guidance document for CNG fuel system inspections is available
  - Pre-Service Visual Inspection
  - Cursory Visual Inspection – pre/post trip
  - General Visual Inspection – PM events
  - Detailed Inspection – annual

Maintenance Facility Modification



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Natural Gas Vehicles for America

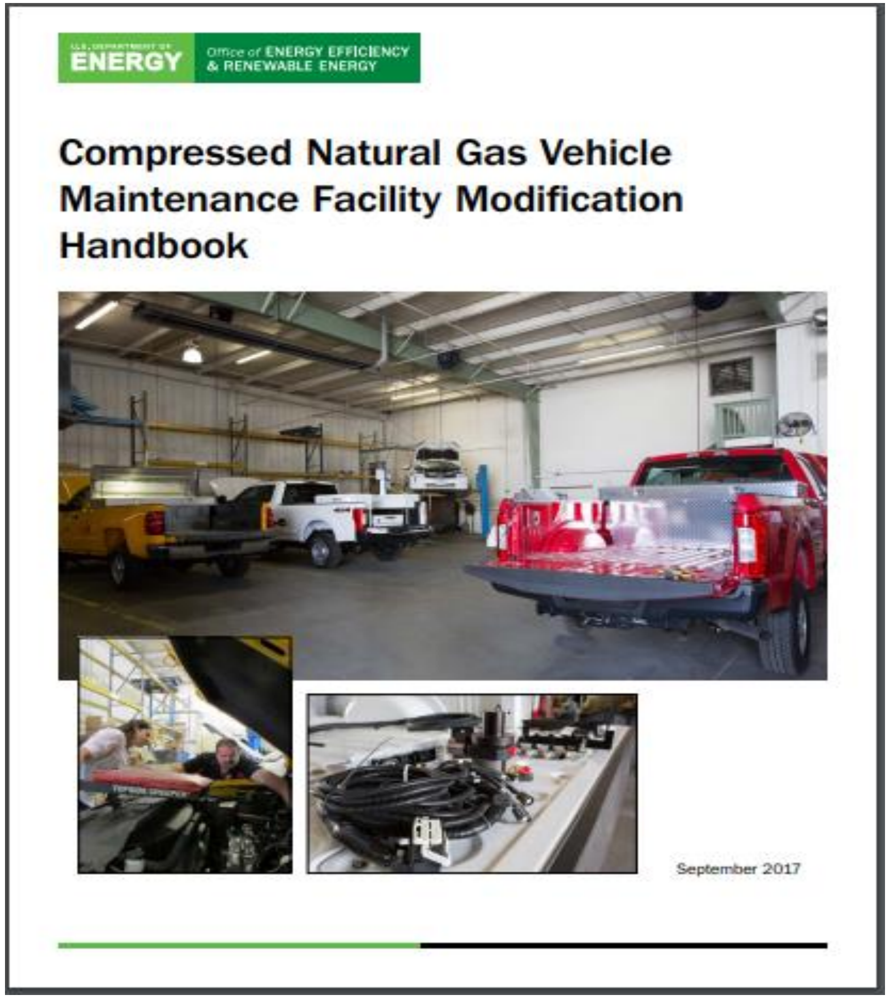
Guideline for Determining the Modifications Required for Natural Gas Vehicle Maintenance Facilities

Prepared by
Dan Bowerson
NGVAmerica Technology & Development Committee

www.ngvamerica.org

Originally Published by
Douglas B Horne, P.E.
Clean Vehicle Education Foundation

May 17, 2017



U.S. DEPARTMENT OF ENERGY | Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

Compressed Natural Gas Vehicle Maintenance Facility Modification Handbook

September 2017

- ➢ May 2017 NGVAmerica Guidance published
- ➢ Sept. 2017 NREL Guidance published

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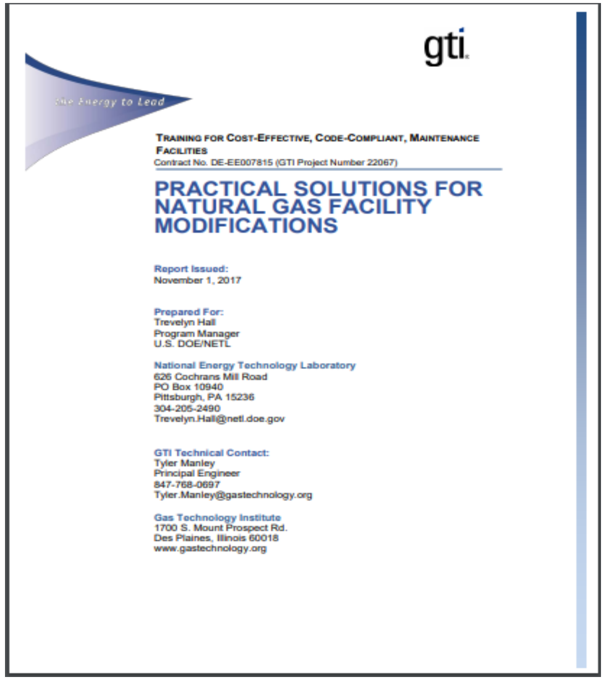
Maintenance Facility Modification

- U.S. Department of Energy funded educational outreach and guidance
  - http://www.Altfuelgarage.org
  - https://www.cleanfuelsohio.org/safe-gas-garage


gti

TRAINING FOR COST-EFFECTIVE, CODE-COMPLIANT, MAINTENANCE FACILITIES
Contract No. DE-EE007815 (GTI Project Number 22067)

PRACTICAL SOLUTIONS FOR NATURAL GAS FACILITY MODIFICATIONS

Report Issued:
November 1, 2017

Prepared For:
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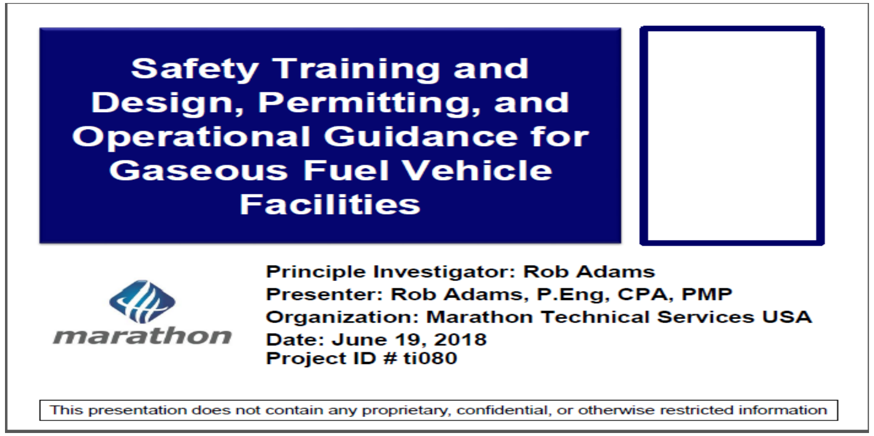

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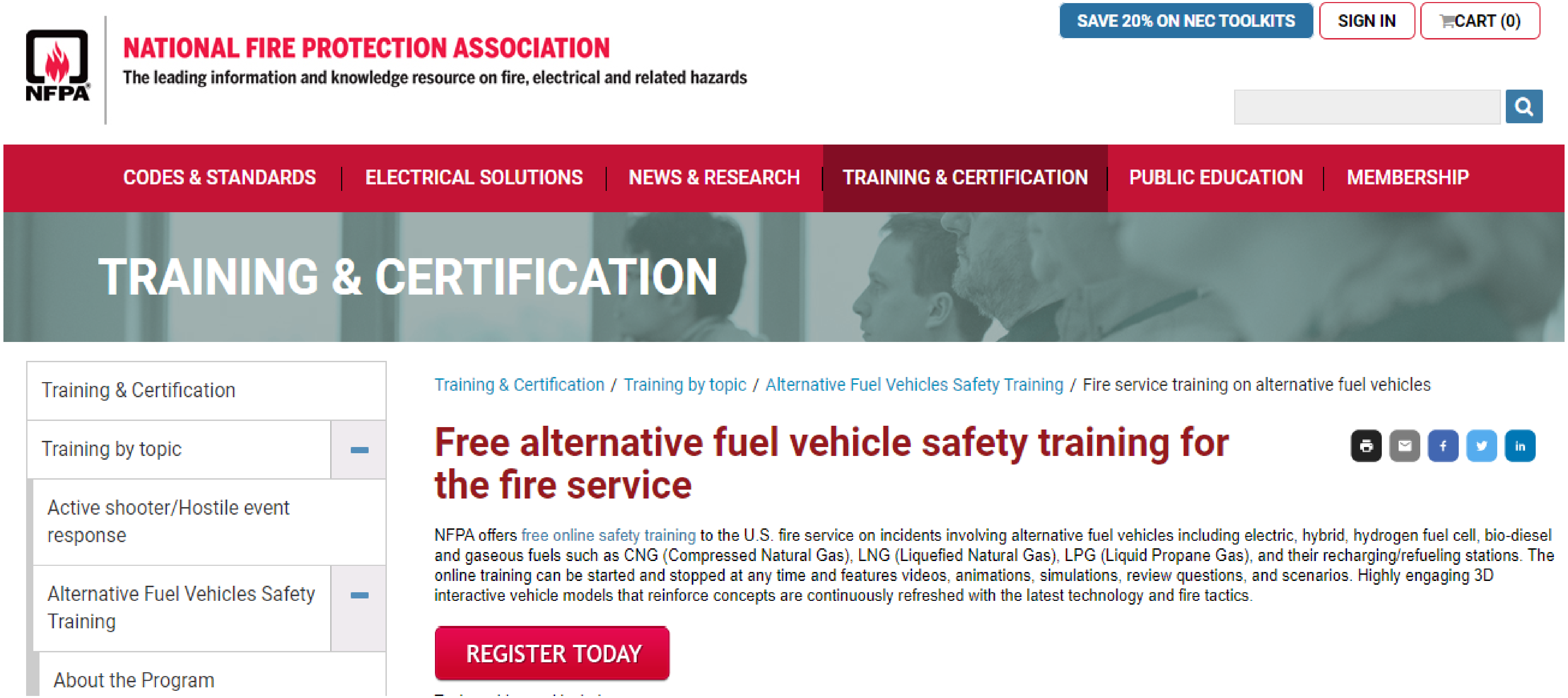
NFPA Training



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TRAINING & CERTIFICATION

- Training & Certification
- Training by topic
  - Active shooter/Hostile event response
  - Alternative Fuel Vehicles Safety Training
    - About the Program

Training & Certification / Training by topic / Alternative Fuel Vehicles Safety Training / Fire service training on alternative fuel vehicles

Free alternative fuel vehicle safety training for the fire service

NFPA offers free online safety training to the U.S. fire service on incidents involving alternative fuel vehicles including electric, hybrid, hydrogen fuel cell, bio-diesel and gaseous fuels such as CNG (Compressed Natural Gas), LNG (Liquefied Natural Gas), LPG (Liquid Propane Gas), and their recharging/refueling stations. The online training can be started and stopped at any time and features videos, animations, simulations, review questions, and scenarios. Highly engaging 3D interactive vehicle models that reinforce concepts are continuously refreshed with the latest technology and fire tactics.

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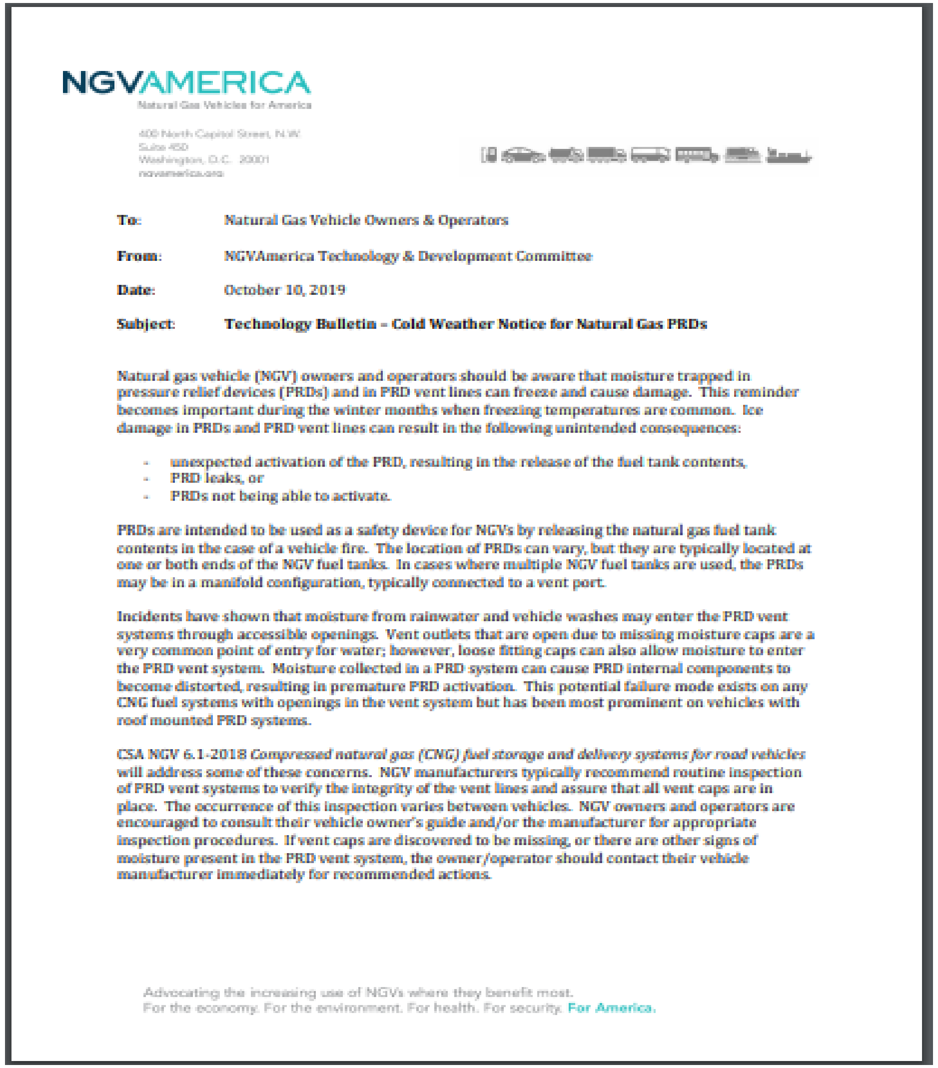
Cold Weather Advisory



NGVAMERICA
Natural Gas Vehicles for America

400 North Capitol Street, N.W.
Suite 450
Washington, D.C. 20001
ngvamerica.org

To: Natural Gas Vehicle Owners & Operators

From: NGVAmerica Technology & Development Committee

Date: October 10, 2019

Subject: **Technology Bulletin – Cold Weather Notice for Natural Gas PRDs**

Natural gas vehicle (NGV) owners and operators should be aware that moisture trapped in pressure relief devices (PRDs) and in PRD vent lines can freeze and cause damage. This reminder becomes important during the winter months when freezing temperatures are common. Ice damage in PRDs and PRD vent lines can result in the following unintended consequences:

- unexpected activation of the PRD, resulting in the release of the fuel tank contents,
- PRD leaks, or
- PRDs not being able to activate.

PRDs are intended to be used as a safety device for NGVs by releasing the natural gas fuel tank contents in the case of a vehicle fire. The location of PRDs can vary, but they are typically located at one or both ends of the NGV fuel tanks. In cases where multiple NGV fuel tanks are used, the PRDs may be in a manifold configuration, typically connected to a vent port.

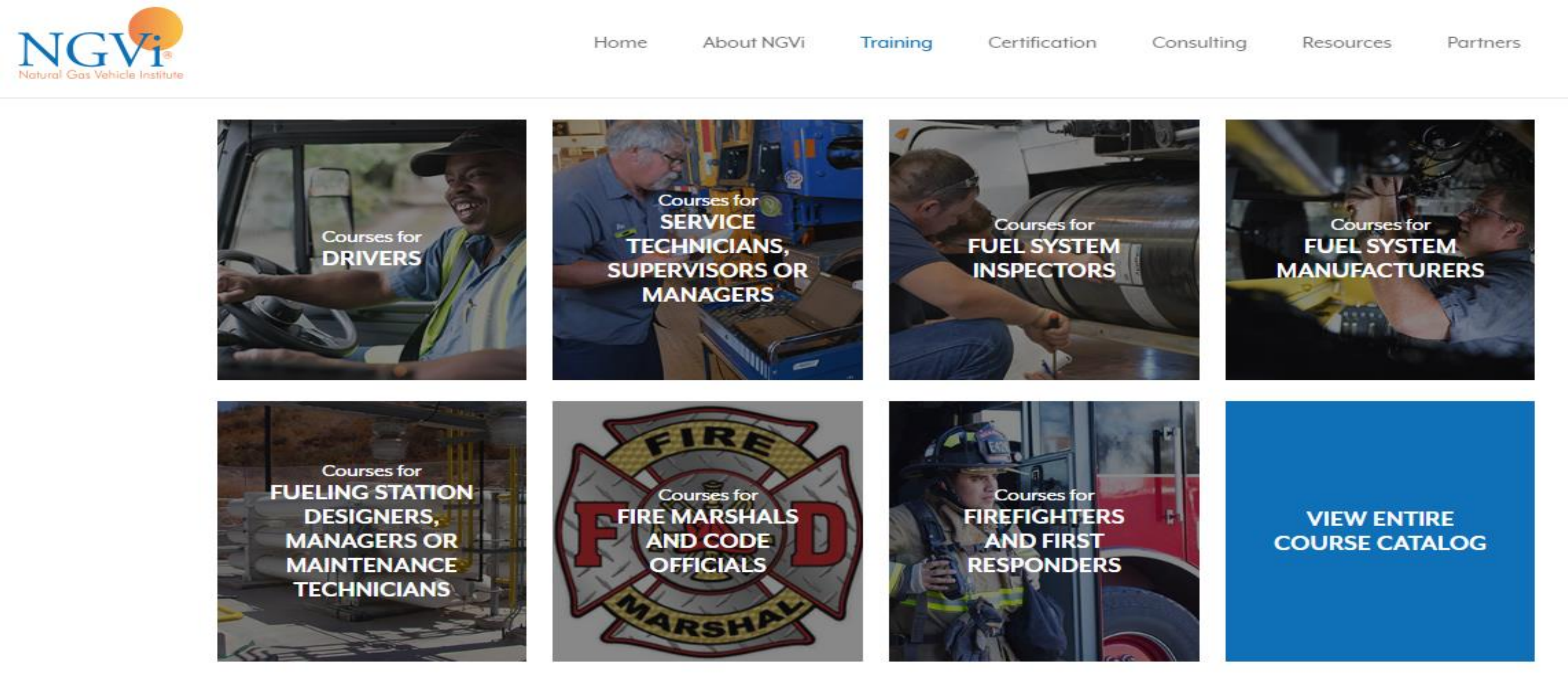
Incidents have shown that moisture from rainwater and vehicle washes may enter the PRD vent systems through accessible openings. Vent outlets that are open due to missing moisture caps are a very common point of entry for water; however, loose fitting caps can also allow moisture to enter the PRD vent system. Moisture collected in a PRD system can cause PRD internal components to become distorted, resulting in premature PRD activation. This potential failure mode exists on any CNG fuel systems with openings in the vent system but has been most prominent on vehicles with roof mounted PRD systems.

CSA NGV 6.1-2018 *Compressed natural gas (CNG) fuel storage and delivery systems for road vehicles* will address some of these concerns. NGV manufacturers typically recommend routine inspection of PRD vent systems to verify the integrity of the vent lines and assure that all vent caps are in place. The occurrence of this inspection varies between vehicles. NGV owners and operators are encouraged to consult their vehicle owner's guide and/or the manufacturer for appropriate inspection procedures. If vent caps are discovered to be missing, or there are other signs of moisture present in the PRD vent system, the owner/operator should contact their vehicle manufacturer immediately for recommended actions.

Advocating the increasing use of NGVs where they benefit most.
For the economy. For the environment. For health. For security. For America.

- Issued in October 2019
- Promoted in newsletter
- Issued press release

More Training Options



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Natural Gas Vehicles for America

Jeffrey Clarke

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202.824.7364

A Systematic Approach to Achieving >10% Efficiency Improvement on Heavy Duty Natural Gas Engine

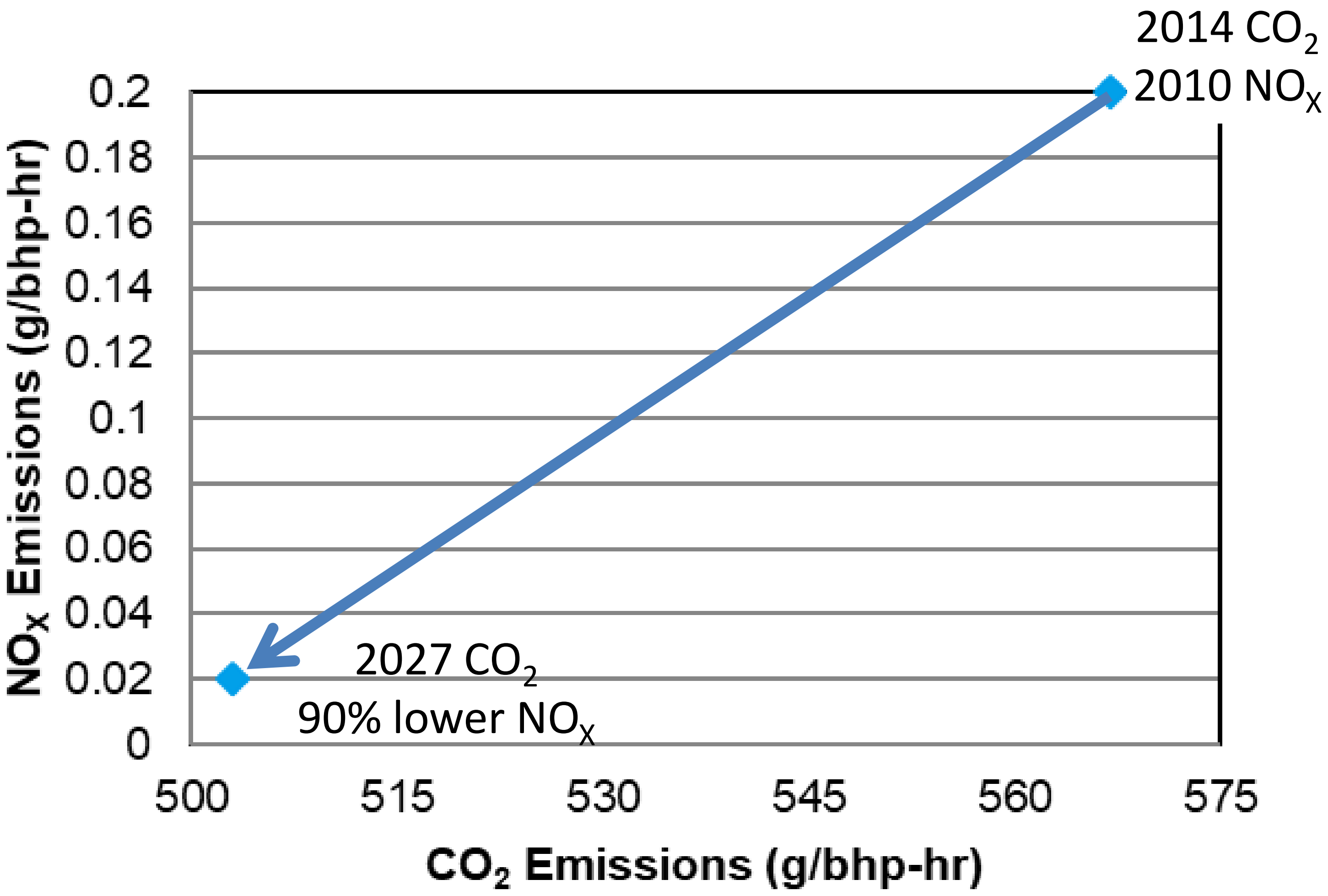
SOUTHWEST RESEARCH INSTITUTE®

Michael Kocsis

February 5, 2020

US Emissions Regulations

- Staged NO_X approach (California)
  - 2022-23: change NTE carve-outs
  - 2024-26: NO_X reduced to 0.05-0.08 g/bhp-h
  - 2027-on: NO_X further reduced
- Separate requirements for engines and vehicles
  - 4-5% reduction in CO_2 from the engine by 2027
  - 19-25% reduction in CO_2 for entire truck by 2027



Achieving Low NO_x

- A demonstration using a ISX12 G **achieved 0.02 g/bhp-h NO_x** [1]
  - Most of the NO_x emissions were contributed to the cold start time before catalyst light-off
    - TWC very efficient at converting NO_x once it is up to temperature (typically 350° C)
  - Keys to success:
    - Close coupled and underfloor catalyst
    - Aggressive spark retard for fast catalyst heating
    - Close control of equivalence ratio during tip-in and tip-out
    - Modeling of engine warm-up to correct long time constant volumetric efficiency changes
  - **~1% CO_2 penalty (FTP)**

NO_x Emissions Comparison, g/bhp-hr

	FTP			RMC-SET	WHTC		
	Cold	Hot	Composite		Cold	Hot	Composite
Baseline	0.247	0.093	0.115	0.012	0.310	0.308	0.308
Low NO_x Engine	0.065	0.001	**0.010**	0.001	0.043	0.006	**0.011**
Reduction	**74%**	**99%**	**91%**	**92%**	**86%**	**98%**	**96%**

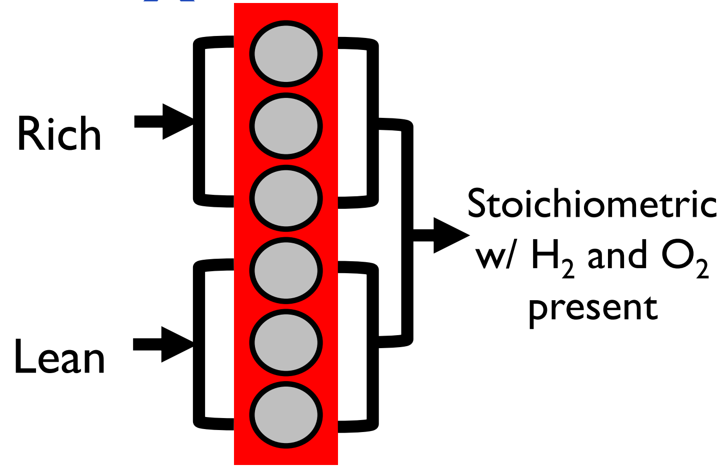
Other Emissions Comparison

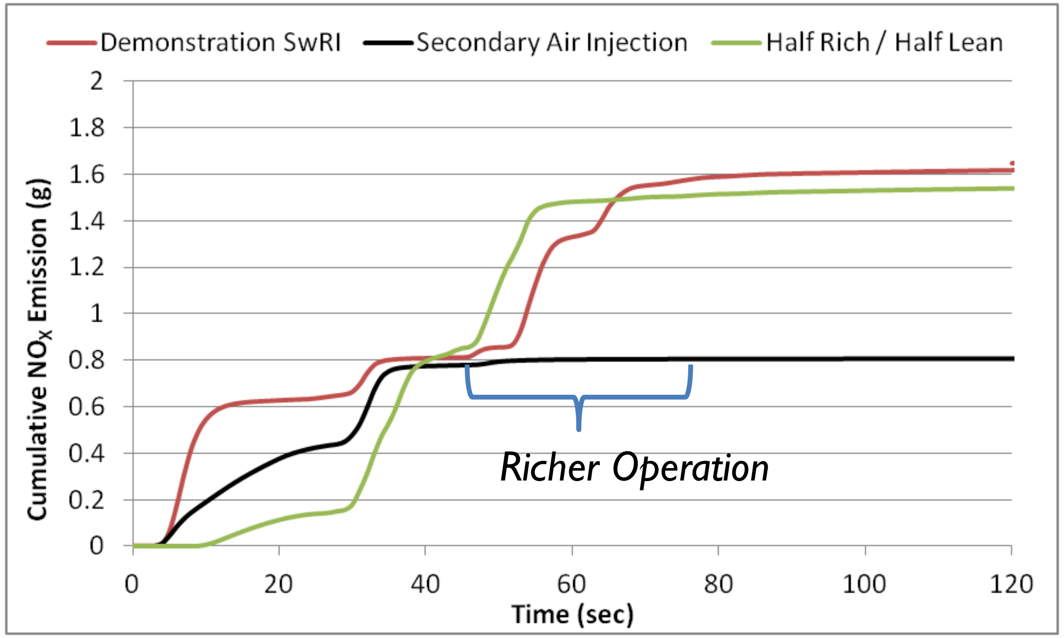
	Pollutant	FTP	RMC-SET	WHTC
Baseline	CH_4, g/bhp-hr	0.96	1.20	1.54
	NH_3, avg. ppm	76	162	100
	CO_2, g/bhp-hr	542	454	510
Low NO_x Engine	CH_4, g/bhp-hr	0.15	0.92	0.10
	NH_3, avg. ppm	52	37	44
	CO_2, g/bhp-hr	547	445	513
Reduction	CH_4, g/bhp-hr	84%	23%	94%
	NH_3, avg. ppm	32%	77%	56%
	CO_2, g/bhp-hr	**-0.9%**	2.0%	-0.6%

[1] SAE 2017-01-0957

Recovering CO_2 Penalty from Low NO_X

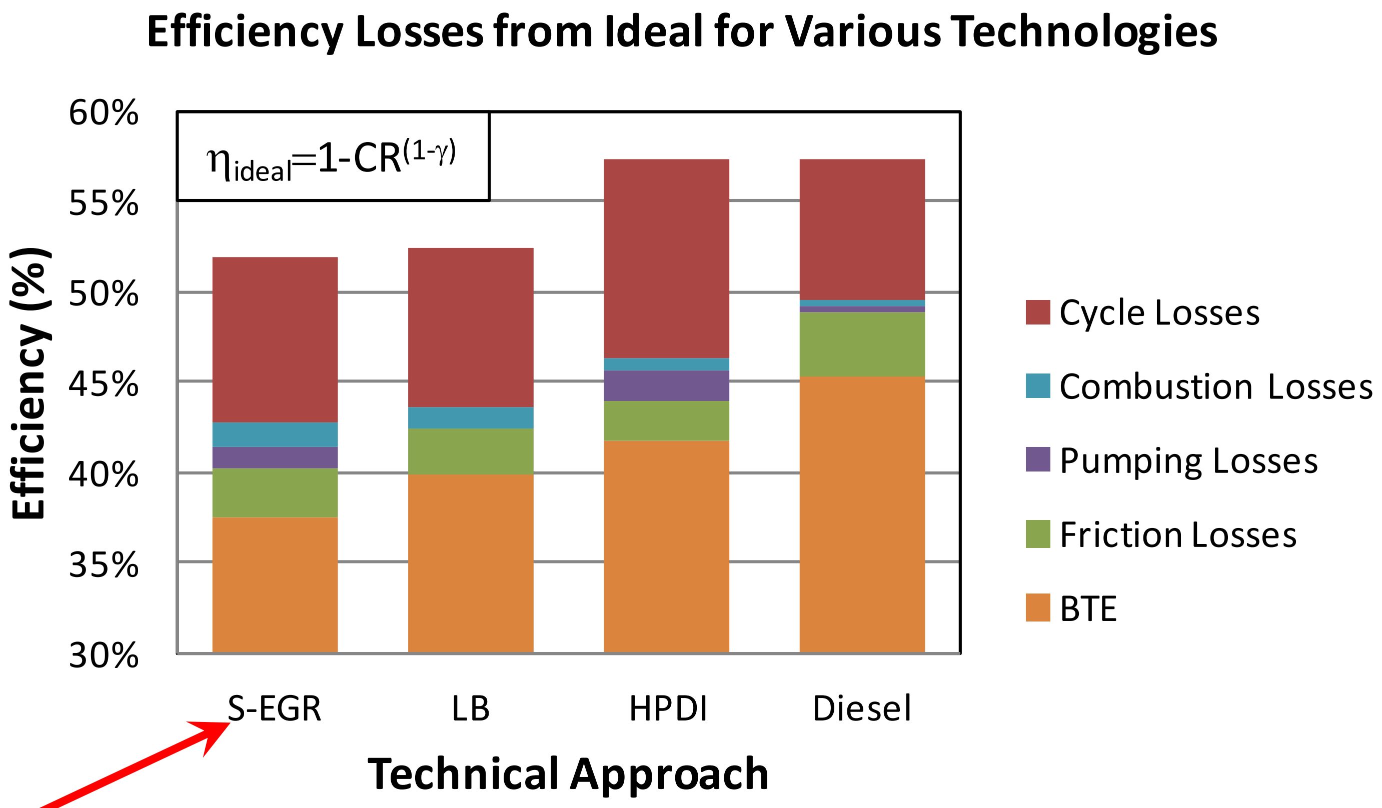
- Catalytic oxidation of H_2 and O_2 occurs at low temperatures and is exothermic
  - Helping to achieve fast light-off
- To achieve fast light-off, multiple methods for delivering H_2 and O_2 to the catalyst were evaluated [2]
  - Half cylinders rich/half cylinders lean
    - Cold-start NO_X emissions comparable to CARB Demonstration
    - 35% lower CO emissions and 1.2% BSFC benefit
  - Overall rich operation with exhaust air pump (Reference)
- **Both solutions meet 2017 GHG Standard**





Efficiency Losses from Ideal Cycle Efficiency for NG Engines with Various Technical Approaches

- Cycle losses
  - Heat transfer
  - non-optimum phasing
- Combustion
  - Unburned HC, CO
  - Combustion duration
- Pumping
- Friction



Due to capability for low emission, this is the current approach for HD NG engines

Natural Gas Dedicated EGR Engine for Improved On-Highway Efficiency

SOUTHWEST RESEARCH INSTITUTE®

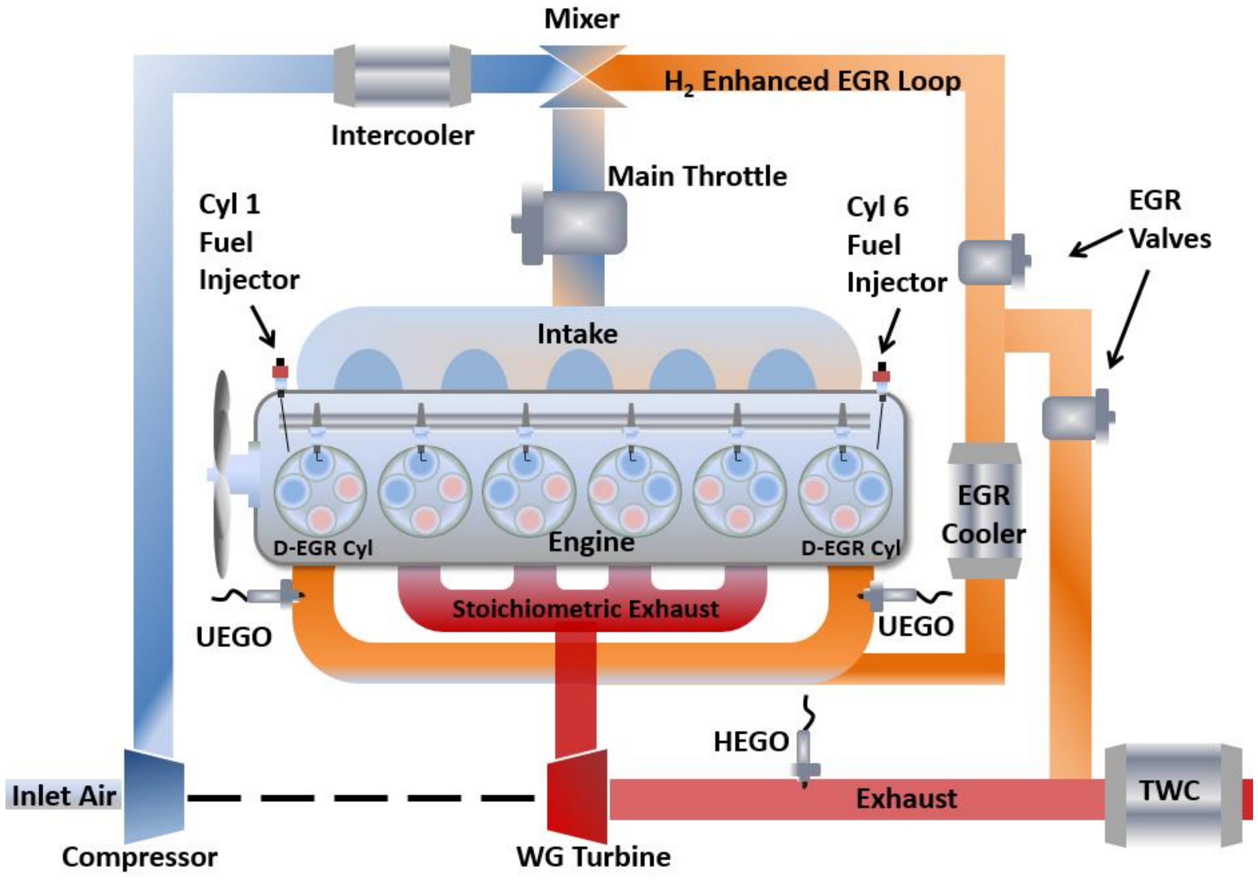
CALIFORNIA
ENERGY
COMMISSION

Contract Number: PIR-16-025

Final report pending approval

SwRI's Solution

- SwRI proposed D-EGR on a Cummins Westport ISX12 G engine combined with an advanced ignition system, charge motion development and high efficiency turbo as a potential solution



Natural Gas Engine Development

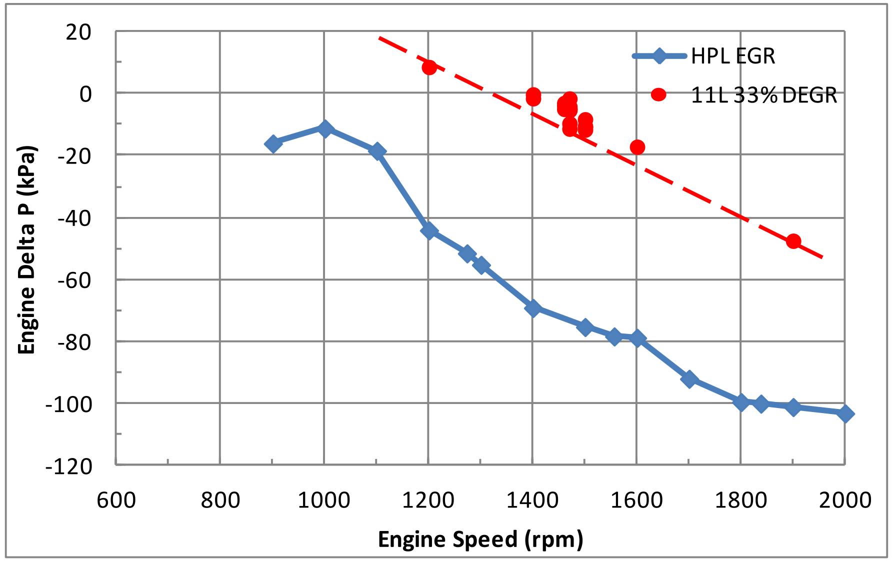
Two main goals:

- Improve Natural Gas engine efficiency by 10%
- Achieve 0.02 g/bhp-hr NO_X emissions over the U.S. Heavy-Duty FTP, RMC-SET and the European WHTC

2014 ISX12 G
2010 U.S. Heavy-Duty emissions standards
293 kW @ 1800 RPM // 2100 Nm @ 1200 RPM
Stoichiometric – single-point, upstream fueling
Three-way catalyst

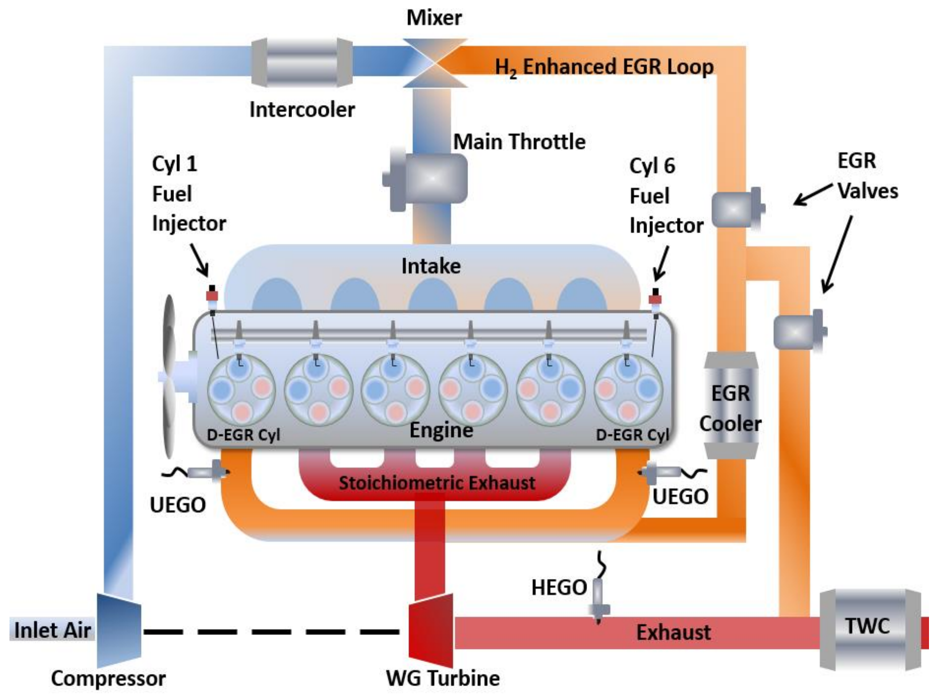
Potential Areas for Improvement

- Piston has large amounts of squish to generate turbulence needed for fast burn rates
  - Open bowl piston design will reduce heat transfer
    - Charge motion / ignition system needs to improve burn rates
- Turbo matching
  - D-EGR cylinders act as EGR pump; turbine does not need to be sized to provide the pressure ratio necessary to flow EGR
- Higher EGR rate will allow for higher CR

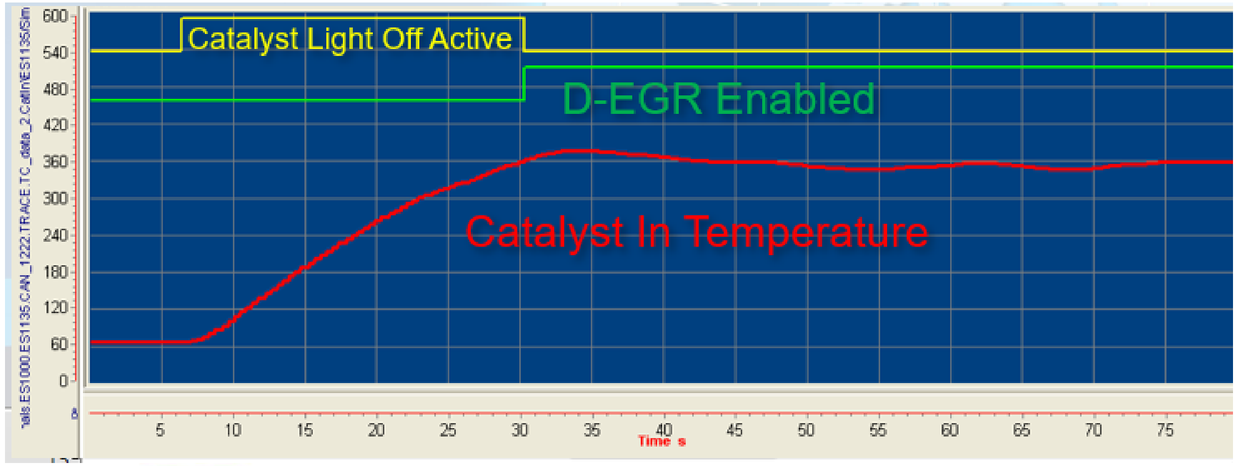


0.02 g/bhp-hr NO_x

- SwRI previously demonstrated 0.02 g/bhp-hr NO_x on CARB Low NO_x project [1]
- D-EGR technology enables faster catalyst heating
  - Exhaust from D-cyl bypasses turbo
  - Demonstrated on LD gasoline vehicle
    - 85% reduction in NO_x on FTP75



5 deg C Cold Start

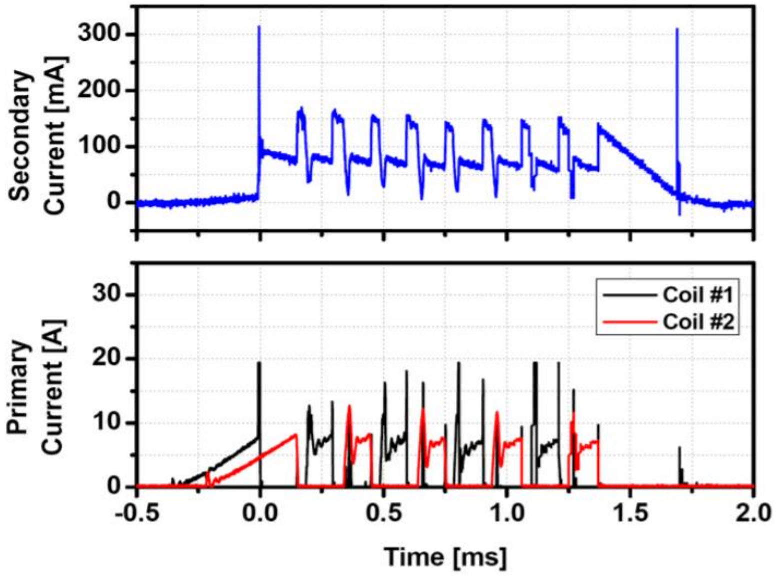


Stock (EPA) / D-EGR / % Change	Bag 1	Bag 2	Bag 3	FTP	HWFET
Fuel Economy (Test uses Regal GS dyno coefficients) [MPG]	23	22.2	26.7	23.5	37.4
	24	25.1	28.7	25.7 / 25.8	41.4 / 45.2
	4.6%	12.9%	7.4%	**9.5%**	**10.7%**
Fuel Economy (Test uses Regal Premium dyno coefficients) [MPG]	24	23.1	28.4	24.5	43.6
	25.6	27	30.7	27.7	47.6
	7%	17%	8%	**13.1%**	**9.2%**
NOx [g/mi] (rel. to Regal Premium)				0.013	0.003
	0.005	0.001	0.002	0.002	0.000
				85%	100%

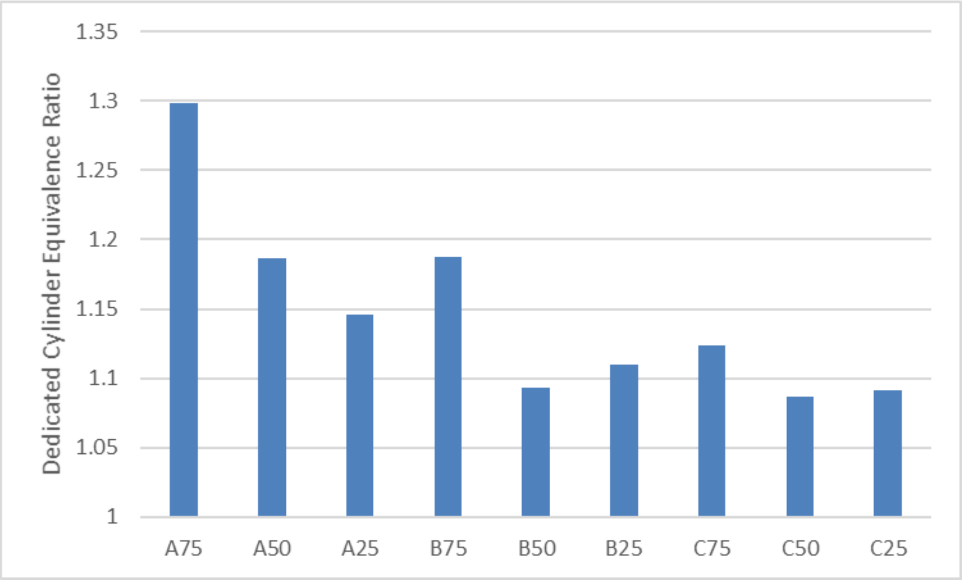
Ignition System Evaluation

Dual Coil Offset

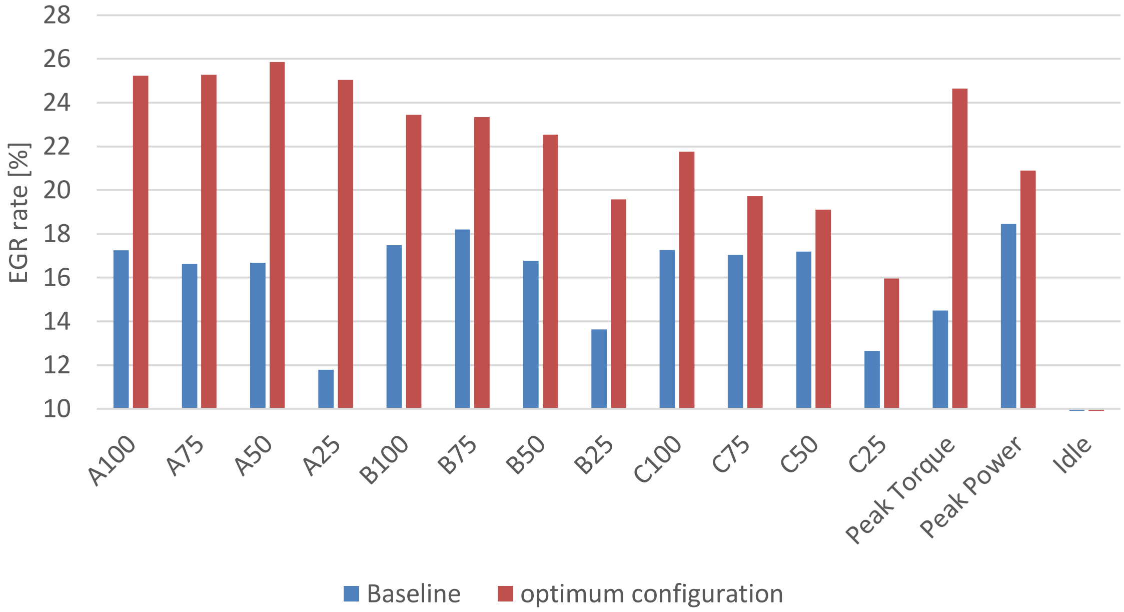
- Continuous discharge ignition
- Capable of D-EGR operation at all conditions with high squish pistons
  - Reduced squish pistons decreased EGR tolerance
  - Stoichiometric operation of dedicated cylinders



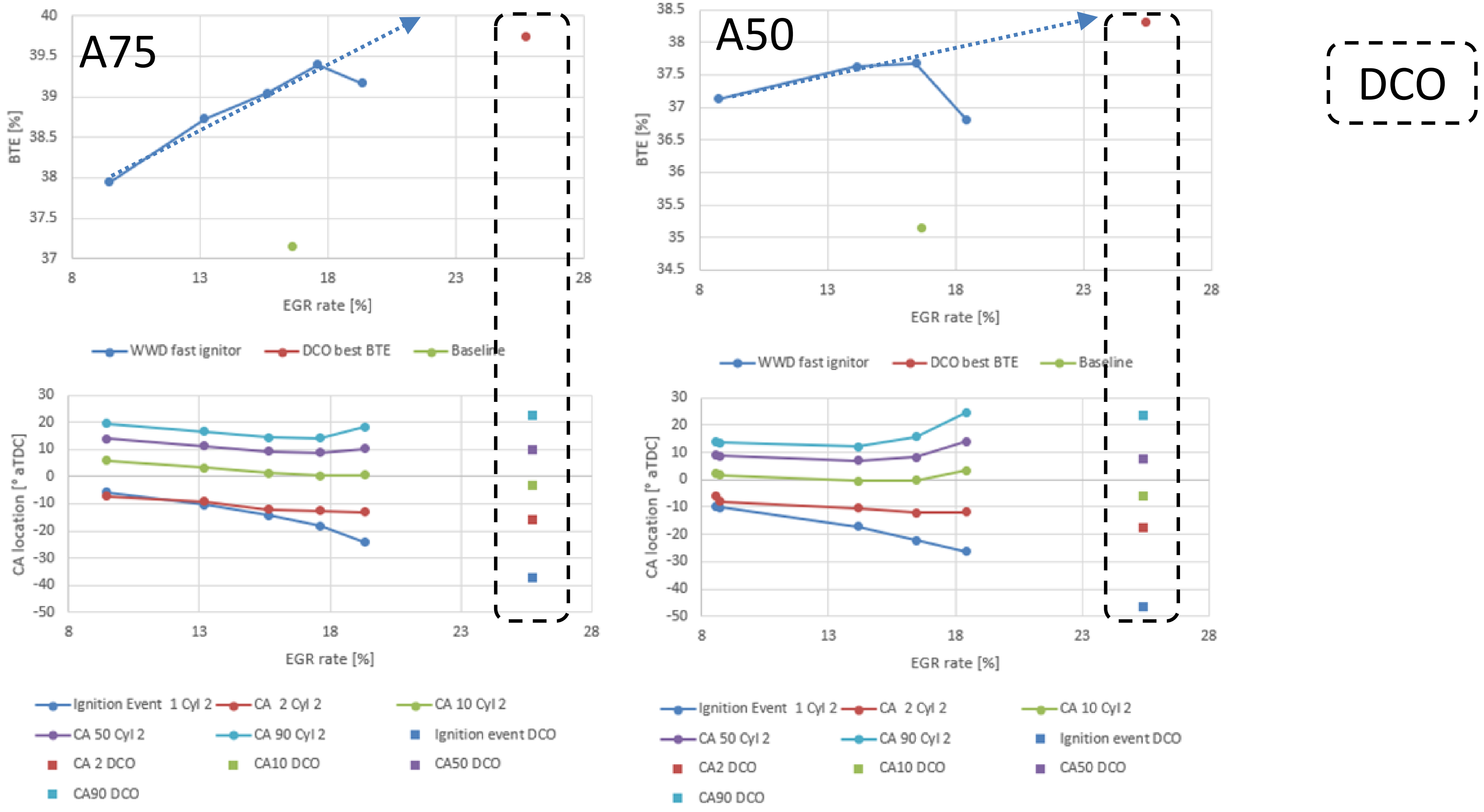
0.8 squish ratio, 11.7:1 CR pistons, ~28% EGR



0.54 squish ratio, 13.2:1 CR pistons

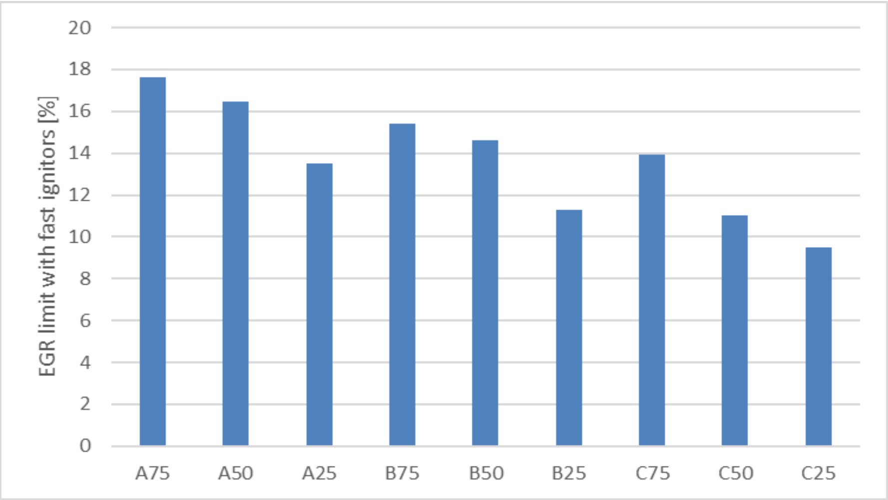


Woodward Advanced Fast Ignitor Efficiency Potential

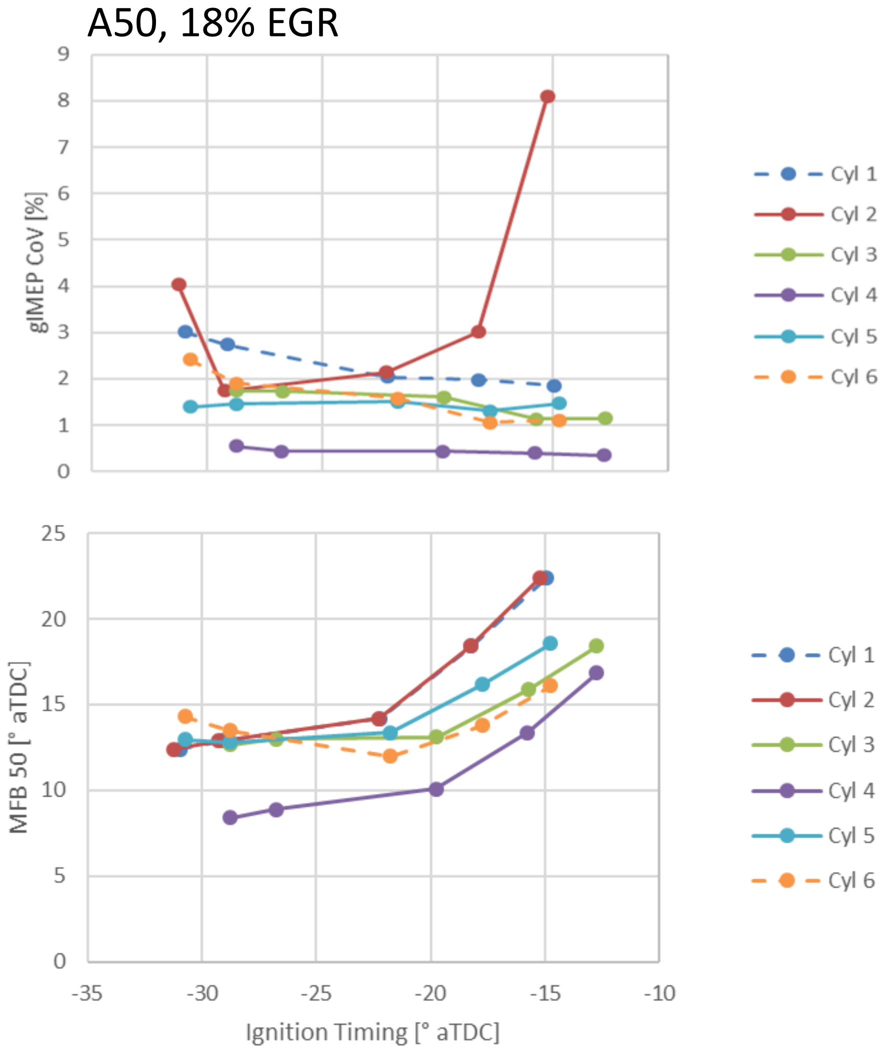


Woodward Advanced Fast Ignitor

- Stable combustion at all modal points
  - Reduced EGR rate compared to DCO



- Low margin of ignition timing authority (15 degCA) for good stability
- Pre-ignition potential at high loads
  - EGR reduced pre-ignition tendency, but EGR tolerance not high enough to mitigate



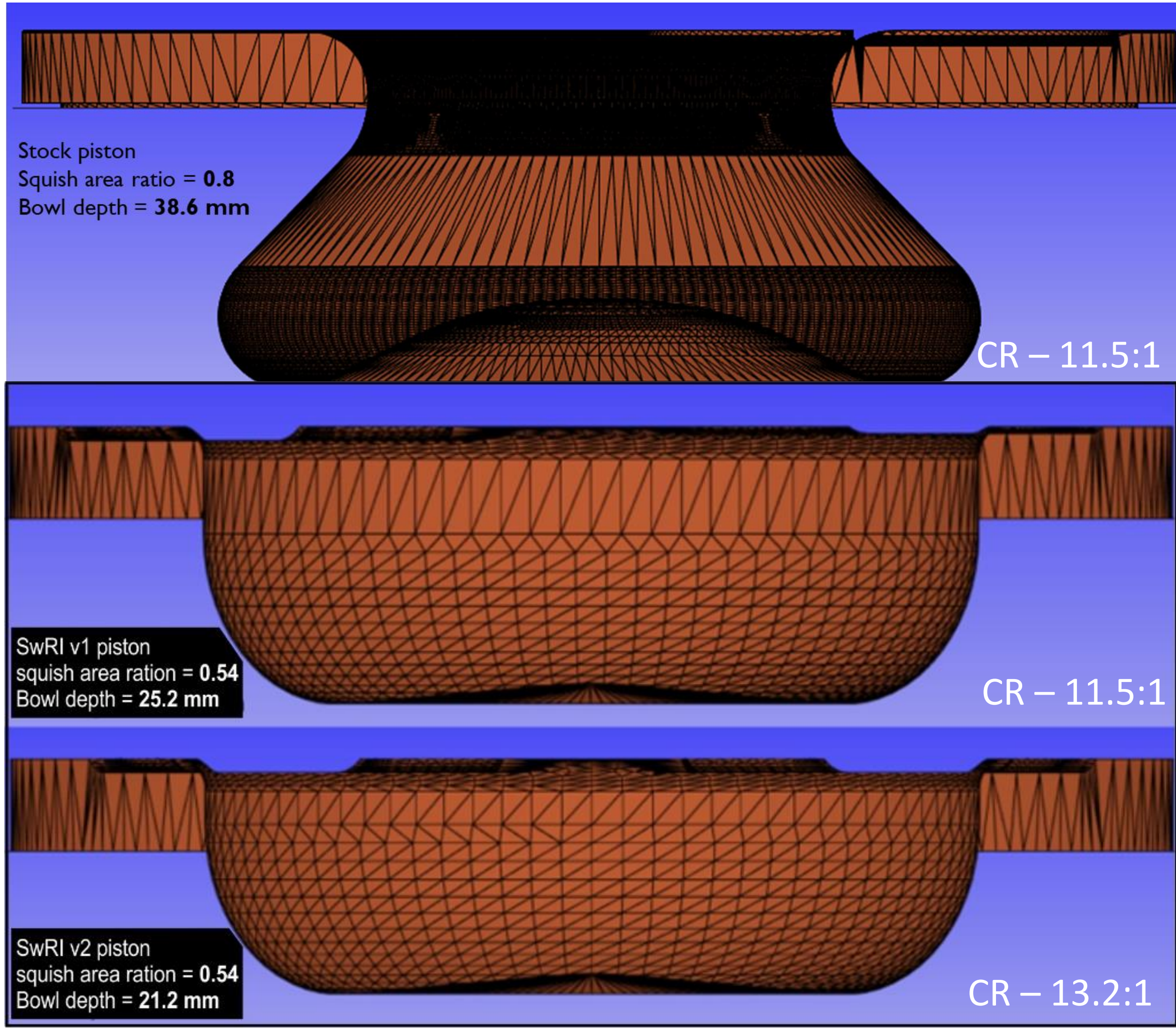
Piston Development

Piston Development

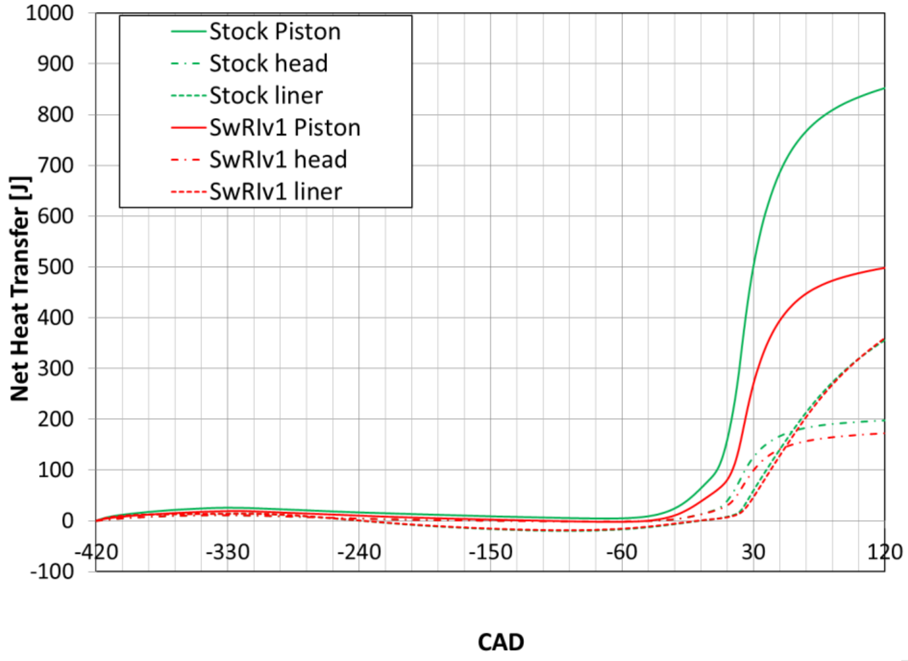
- Stock piston
  - Re-entrant type bowl piston
    - High squish area ratio (0.8)
  - Re-entrant bowl pistons result in high heat losses

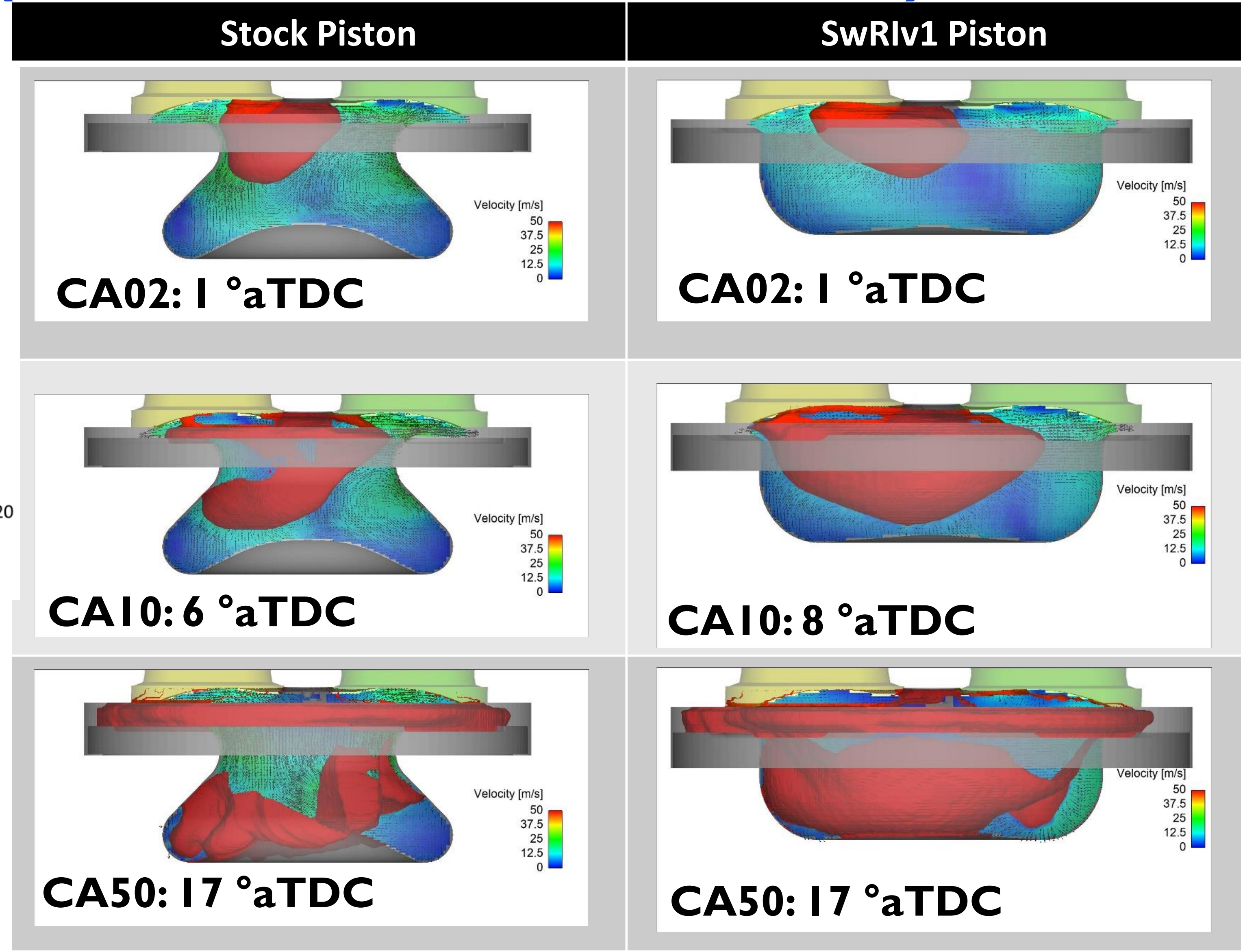
- The SwRIv1 piston had a reduced squish area ratio (of 0.54)
  - Reduces heat loss but still keep squish at effective levels for good combustion

- SwRIv2 piston increased compression ratio



Wall Heat Transfer (Stock vs. SwRIv1 Pistons)

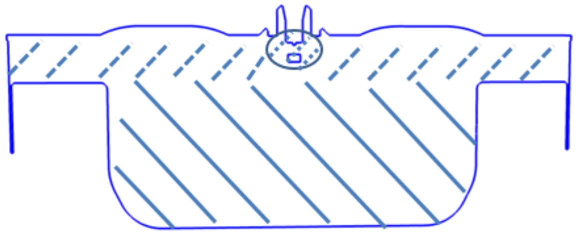


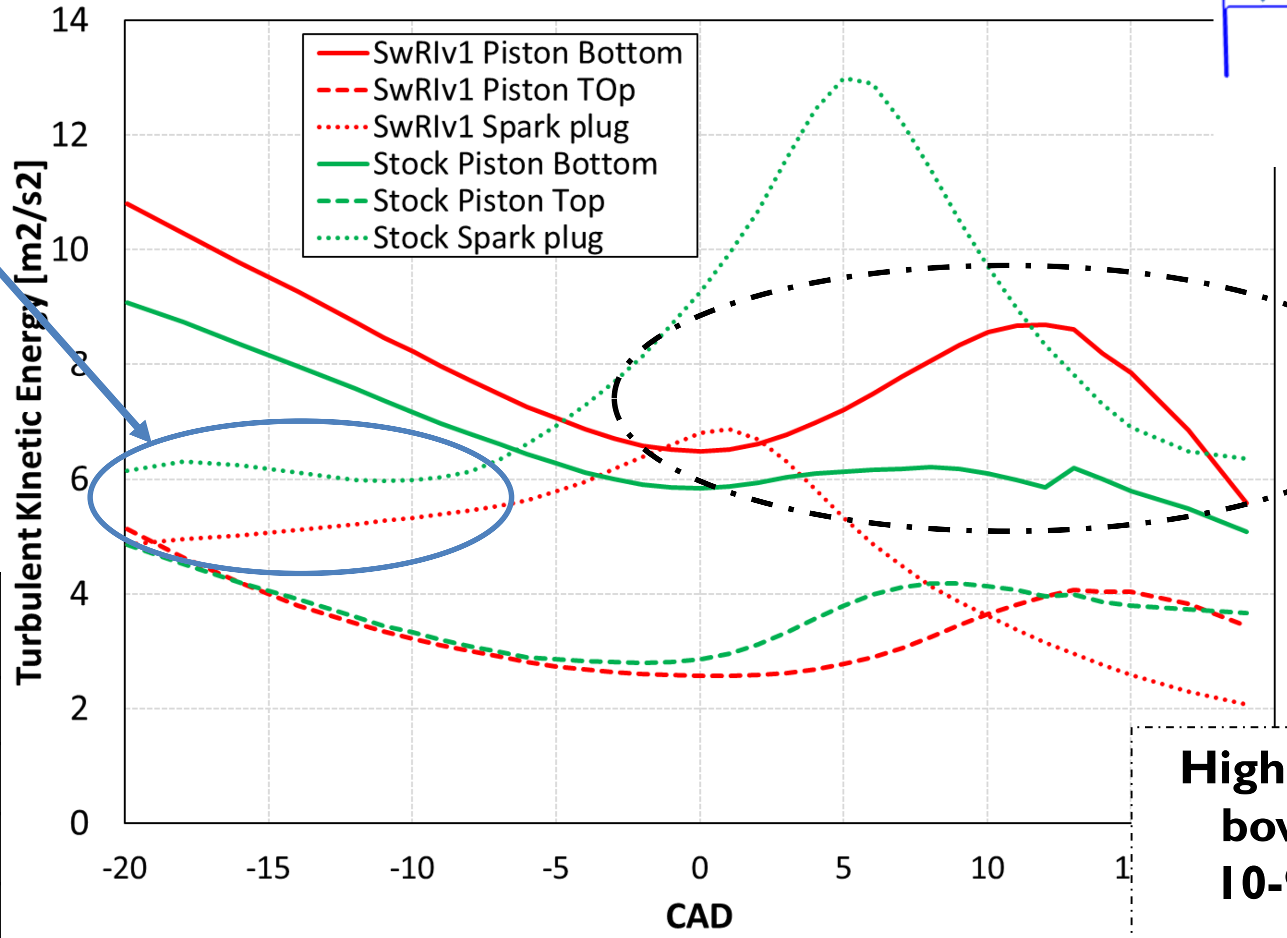


- **Significantly less flame-piston interaction with the SwRIv1 piston**
- **Less heat loss with the SwRIv1 piston led to better ITE**

TKE Measurements : Spark Gap, In-bowl & Out-of-bowl

- **Stock piston has high TKE near spark plug leading to shorter 0-10 burn duration**

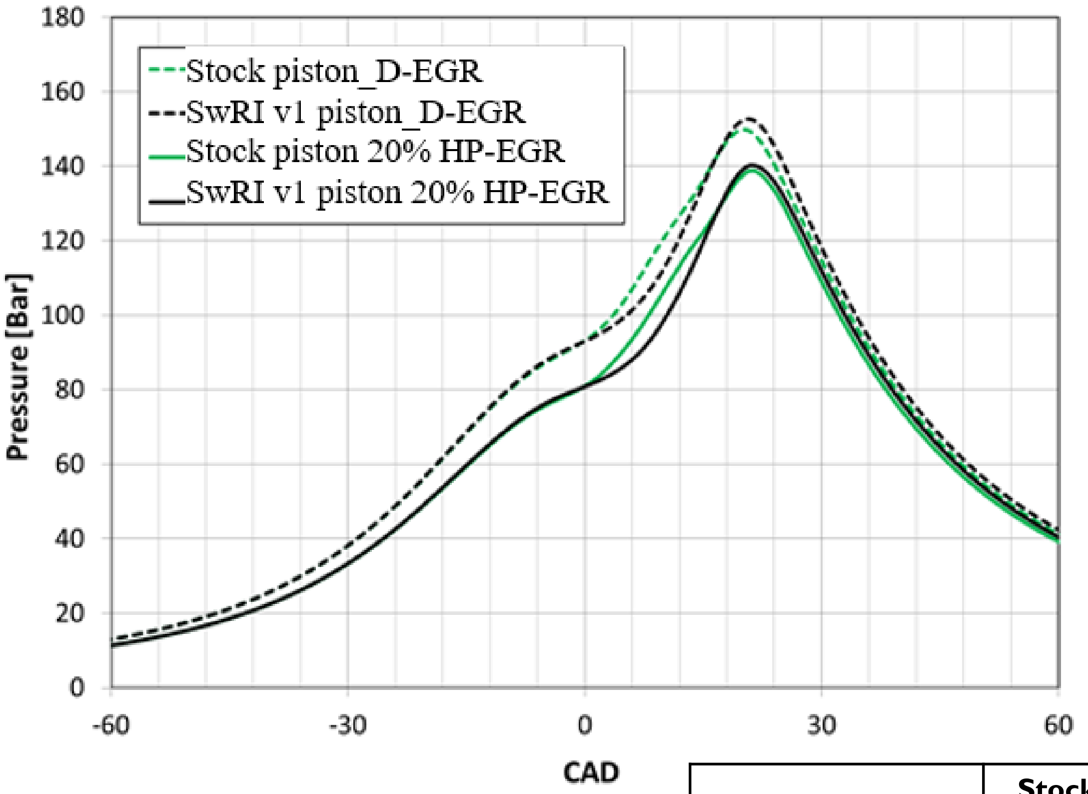


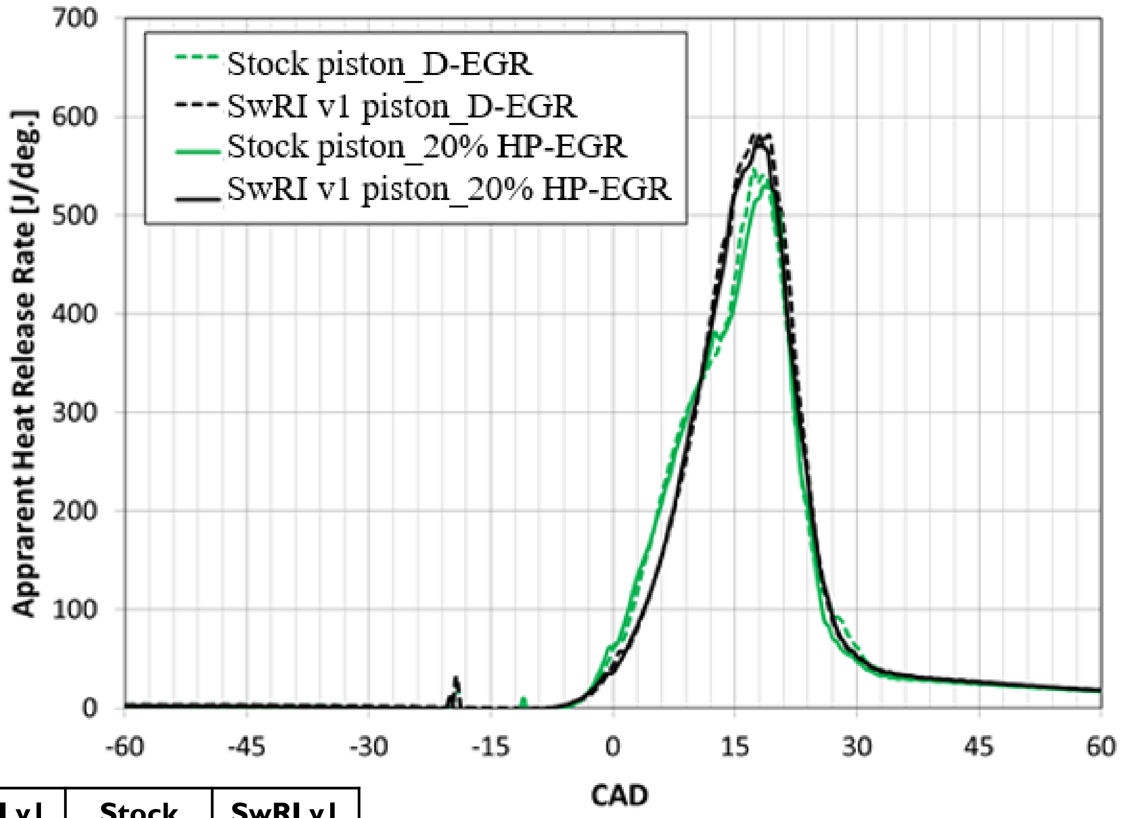


	Stock Piston	SwRIv1 Piston
CA0 (deg.)	-10.5	-10.5
CA10 (deg.)	6	8
CA50 (deg.)	16.6	16.8
CA90 (deg.)	24.8	25.7
CA10-90 (deg.)	18.8	17.7

High TKE inside the piston bowl zone led to faster 10-90 burn duration for SwRIv1 piston

30% D-EGR vs. 20% HP-EGR (Stock and SwRIv1 Pistons)

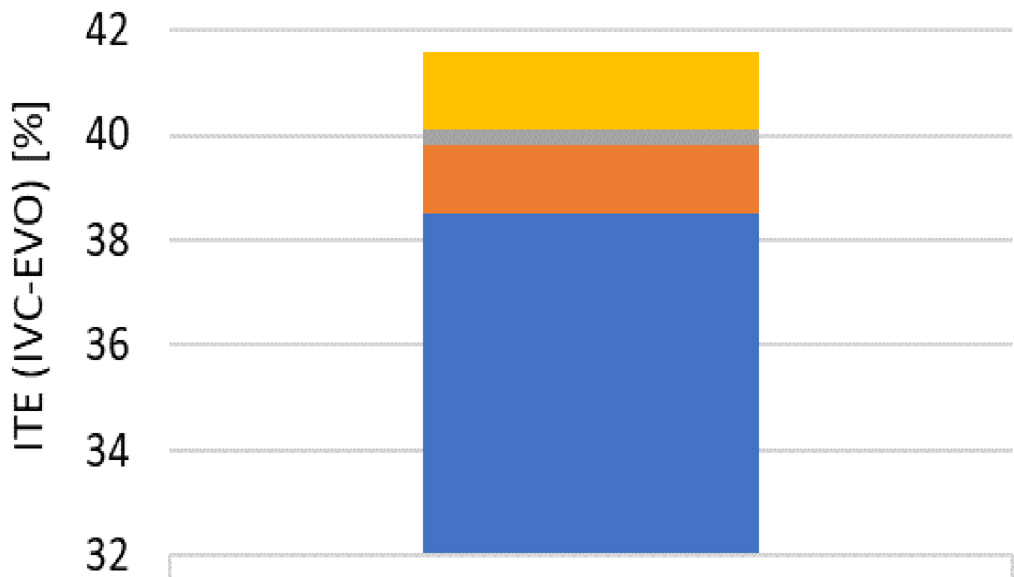




	Stock HP-EGR	SwRI v1 HP-EGR	Stock D-EGR	SwRI v1 D-EGR
CA10 (deg.)	6	8	5.7	7.5
CA50 (deg.)	16.6	16.8	16.5	16.9
CA90 (deg.)	24.8	25.7	26.1	26.3
CA10-90 (deg.)	18.8	17.7	20.4	18.8
ITE (%) IVC –EVO	38.5	39.8	38.9	40.1

Better efficiency (~0.8% points) for 30% D-EGR over 20% HP-EGR case

Stage-Wise ITE Improvements (from CFD Results)

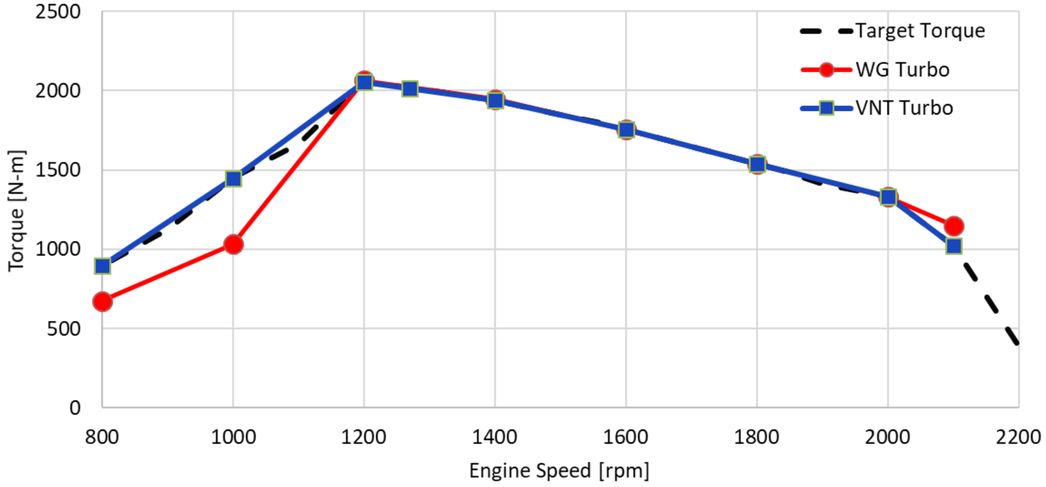


	ITE Increase
SwRI V2 - D EGR	+ 1.5
SwRI V1 - D-EGR	+ 0.3
SwRI V1 - 20% HP-EGR	+ 1.3
Baseline - 20% HP-EGR	38.5

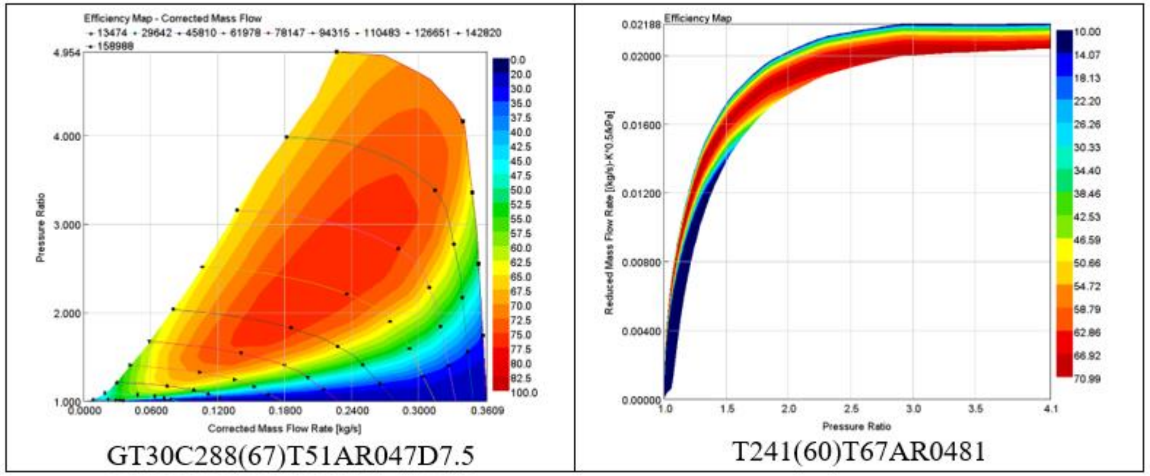
Turbo Matching

Turbo Selection

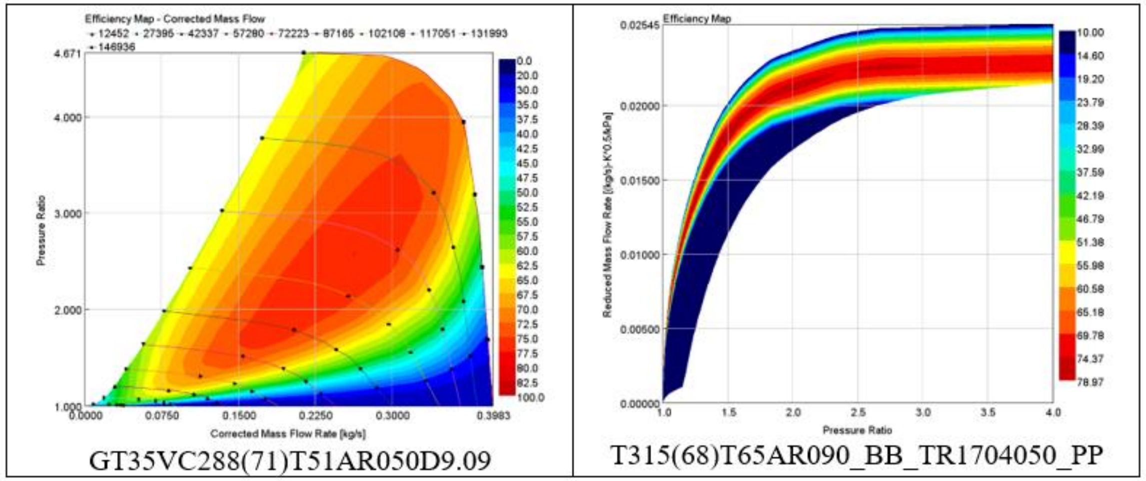
- Flow data from GT-Power provided to Garrett
  - Simple turbo (68% turbine efficiency, 72% compressor efficiency)
- VNT turbo predicted to achieve load target at all speeds
  - Selected for physical hardware testing



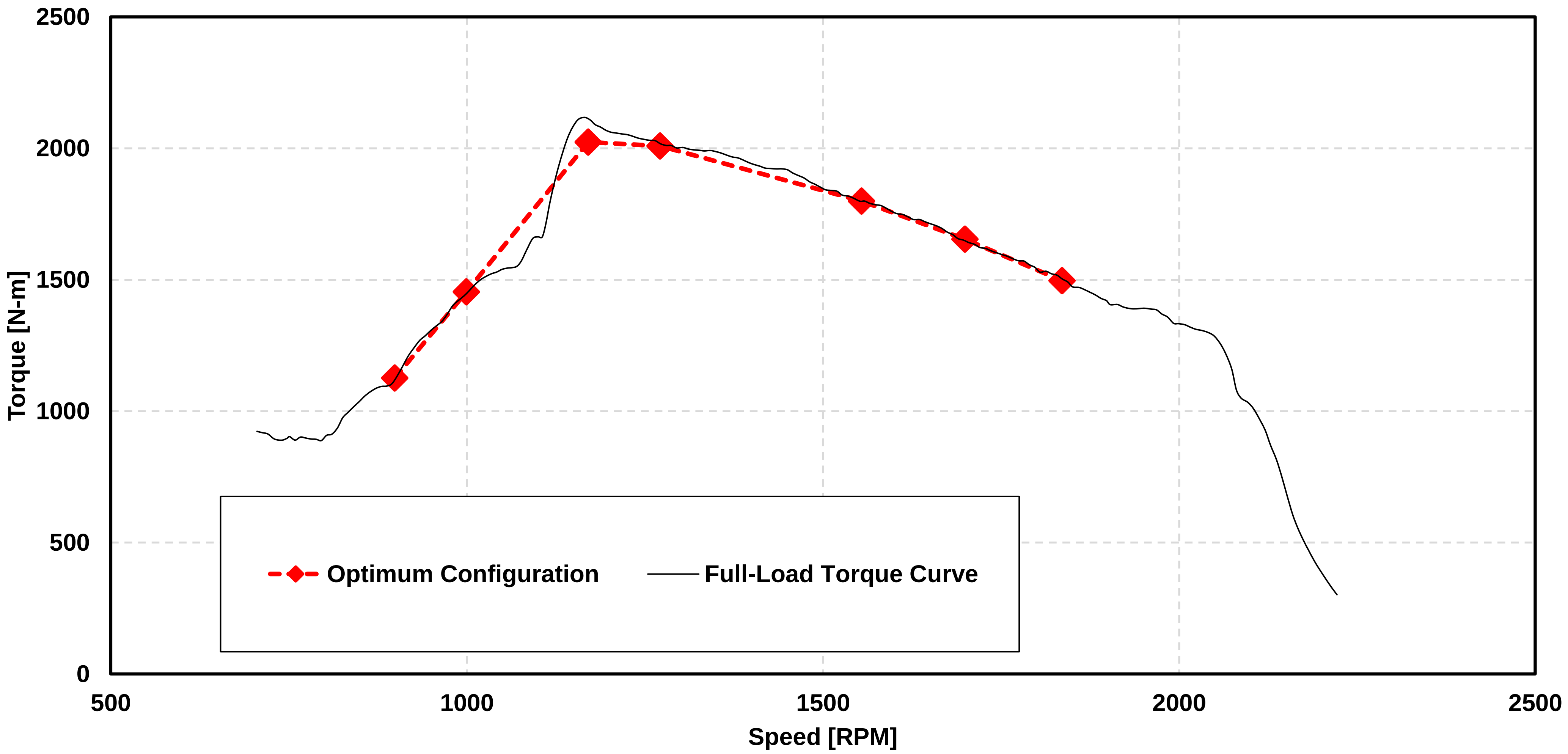
Fixed geometry turbine



Variable Nozzle Turbine



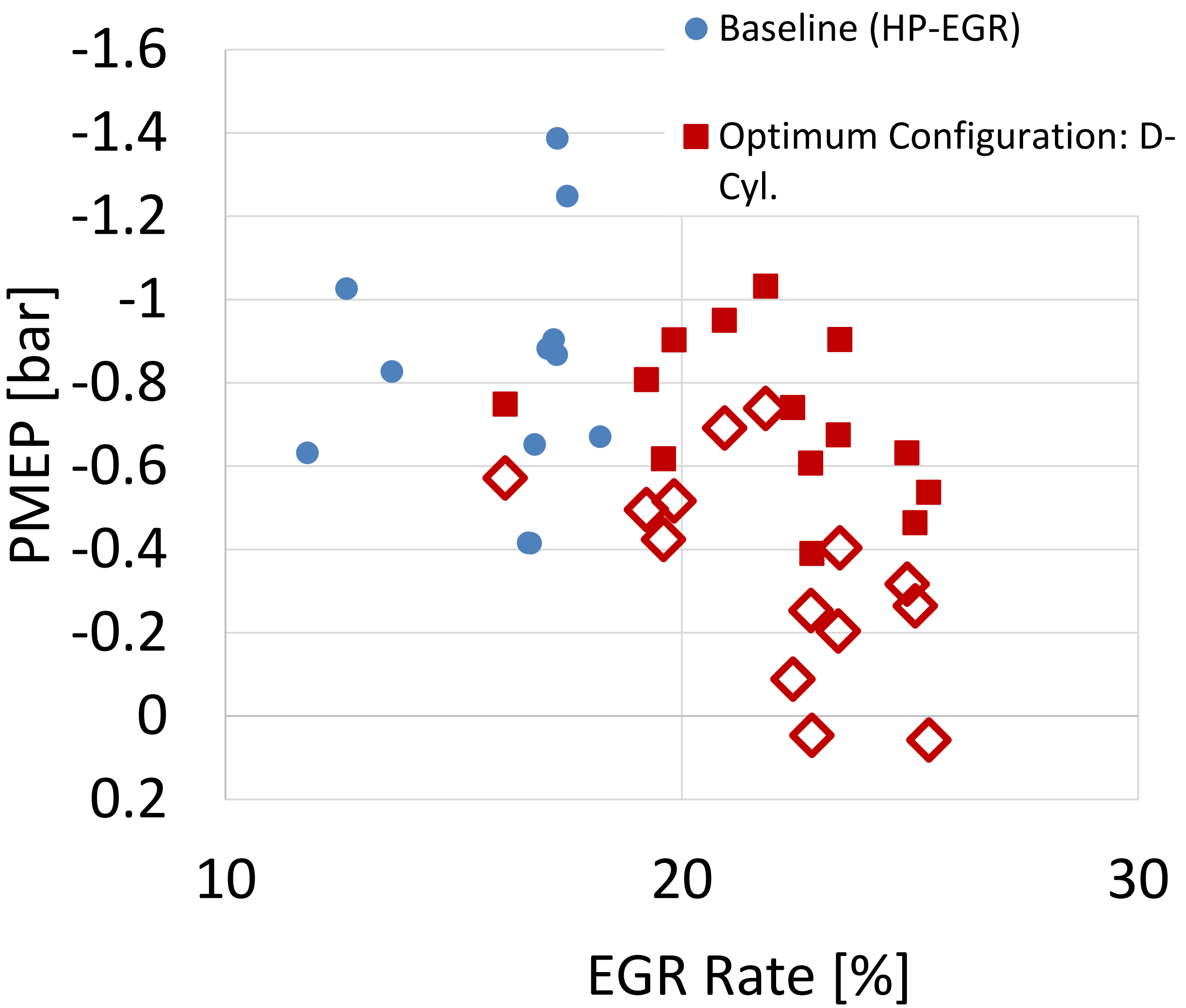
Torque Curve



Project Overview

D-EGR Improves Pumping Losses

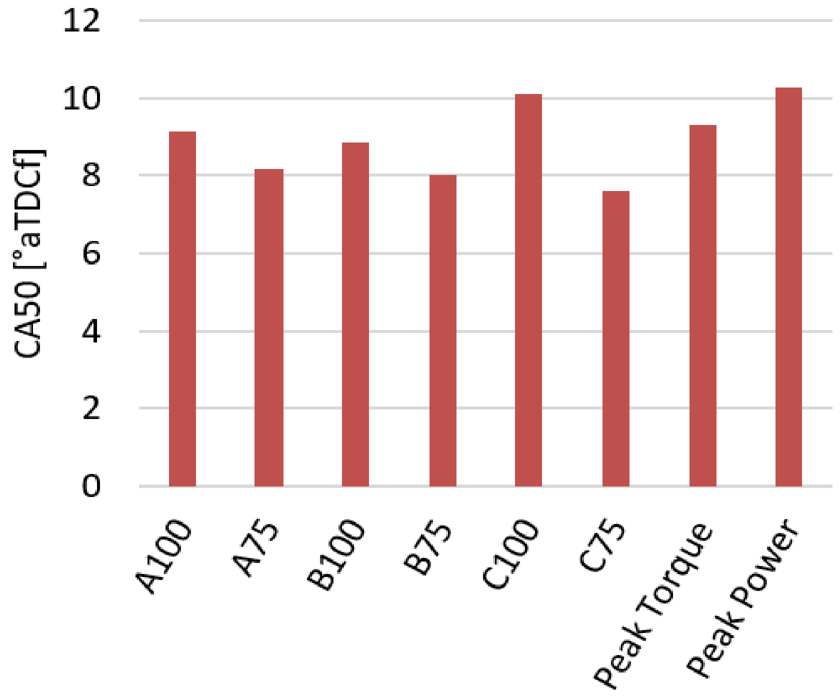
- Optimum configuration delivers more EGR at similar or better PMEP
  - PMEP improvement in main cylinders
    - Result of EGR delivery efficiency (from D-EGR configuration) and re-matched turbocharging system
  - PMEP of the dedicated cylinders was greater than the main cylinders but had less of a trend with EGR rate

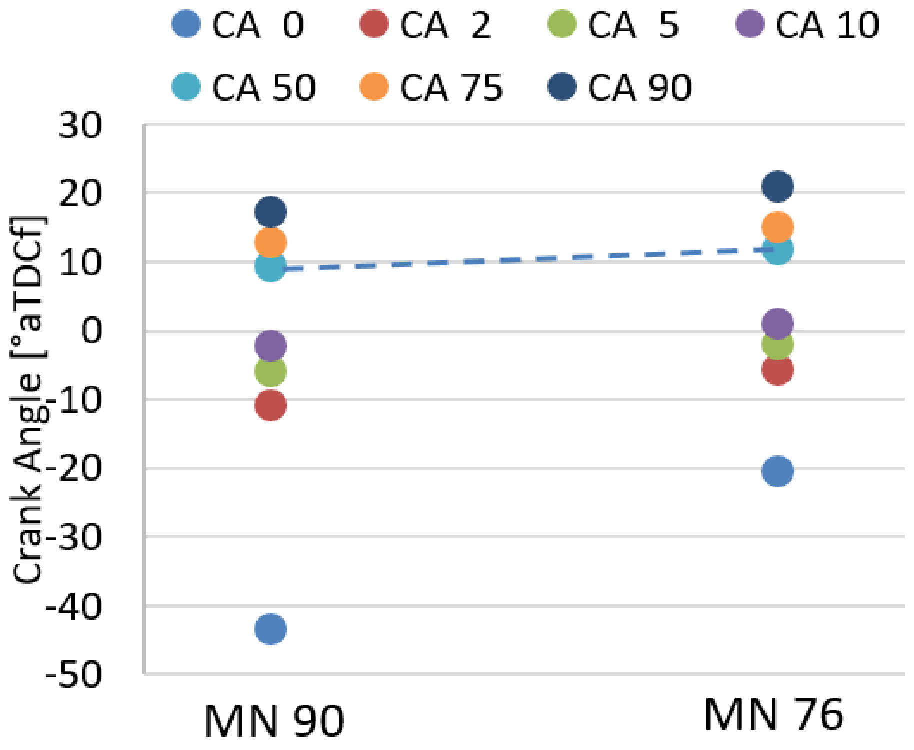


RMC set points + Peak torque and power (no idle)

Combustion Phasing

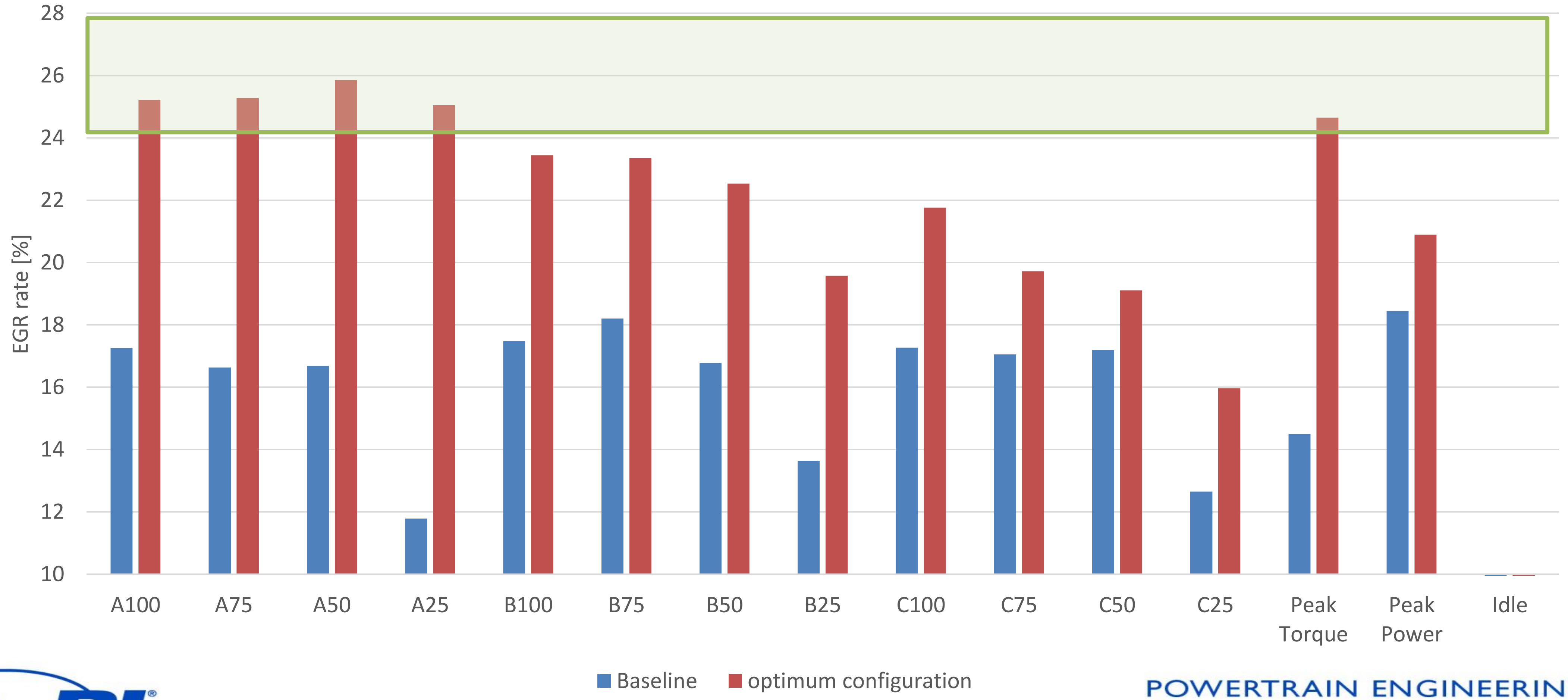
- MBT combustion phasing at high loads
- Robust to changes in Methane Number (MN)
  - Used bottled ethane (up to 20% by mass) to reduce methane number
  - Baseline recommended MN > 75





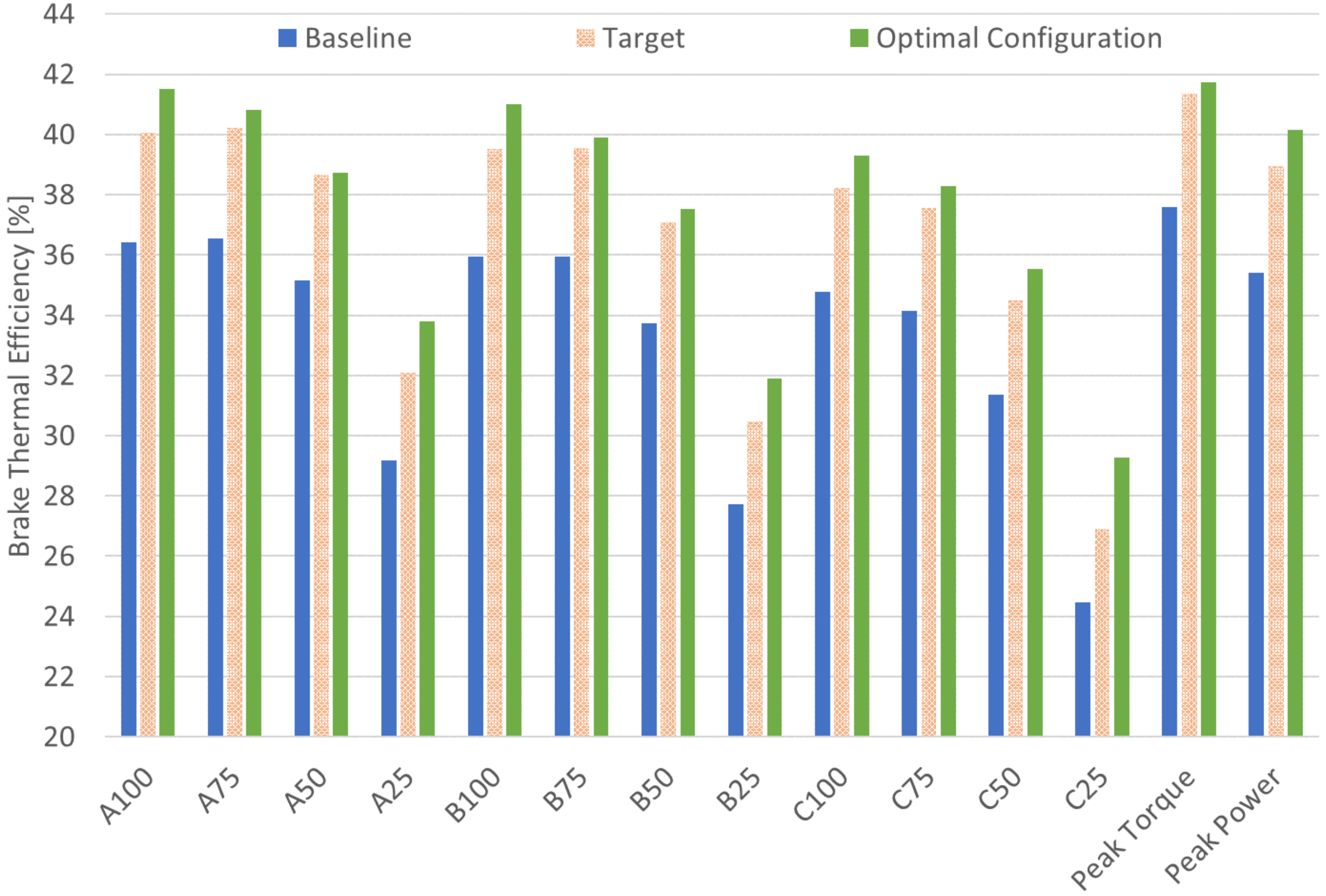
Modal Points EGR Rate

- EGR bled off at some conditions for combustion stability or efficiency
  - ~28% is full D-EGR rate with perfectly sealed bypass valve due to cylinder breathing imbalance
    - >24% EGR represents closed bypass valve
- All cylinders run at stoichiometric conditions



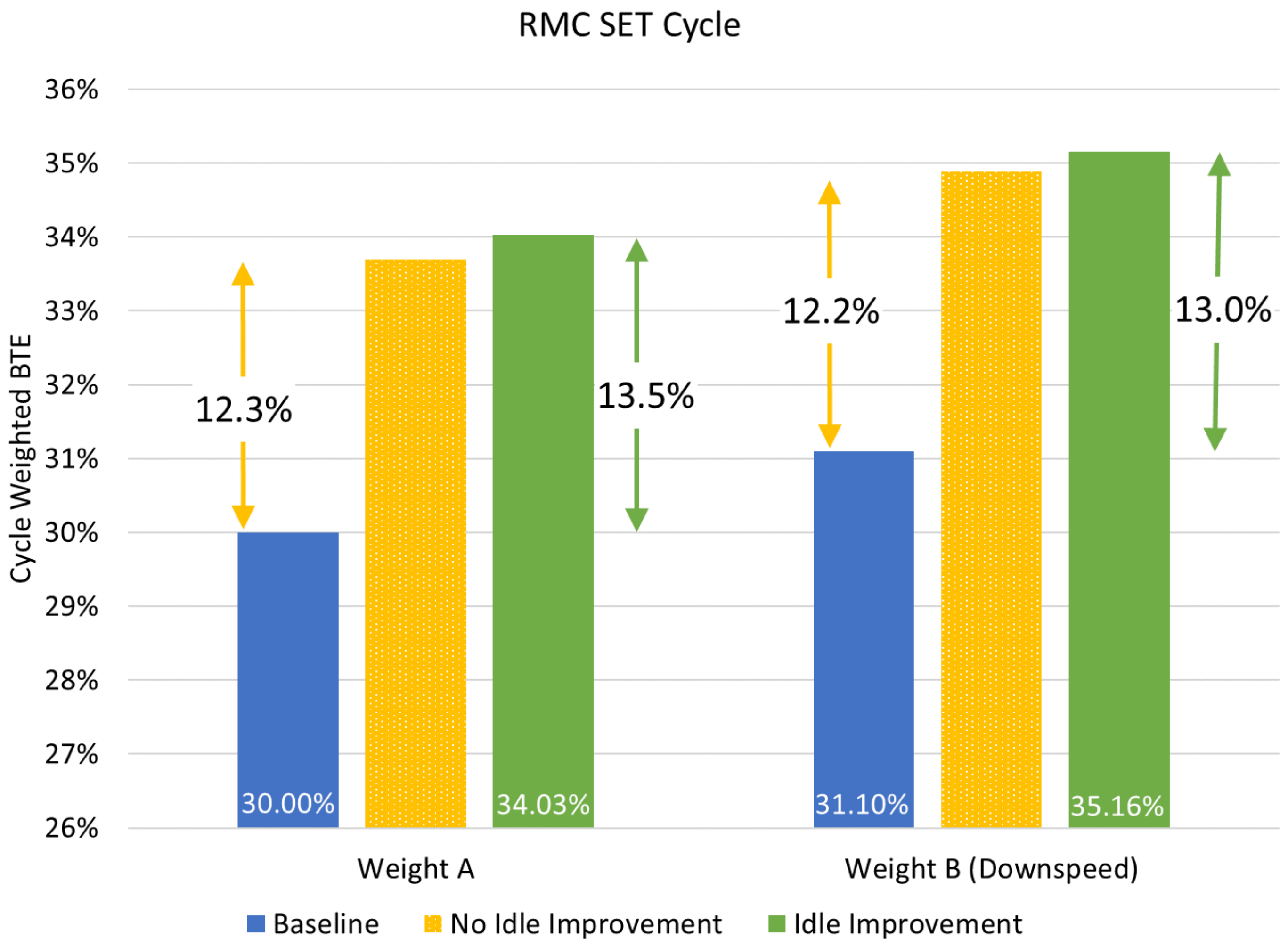
Modal Points BTE

- Met or exceeded BTE target for all points (41.7 % Peak BTE)



Project Summary

- Hardware changes
  - Continuous discharge ignition system
  - Dedicated EGR configuration
    - Stoichiometric operation
  - 13.2:1 Piston with 54% squish
  - VNT Turbocharger
- **12% Efficiency improvement**



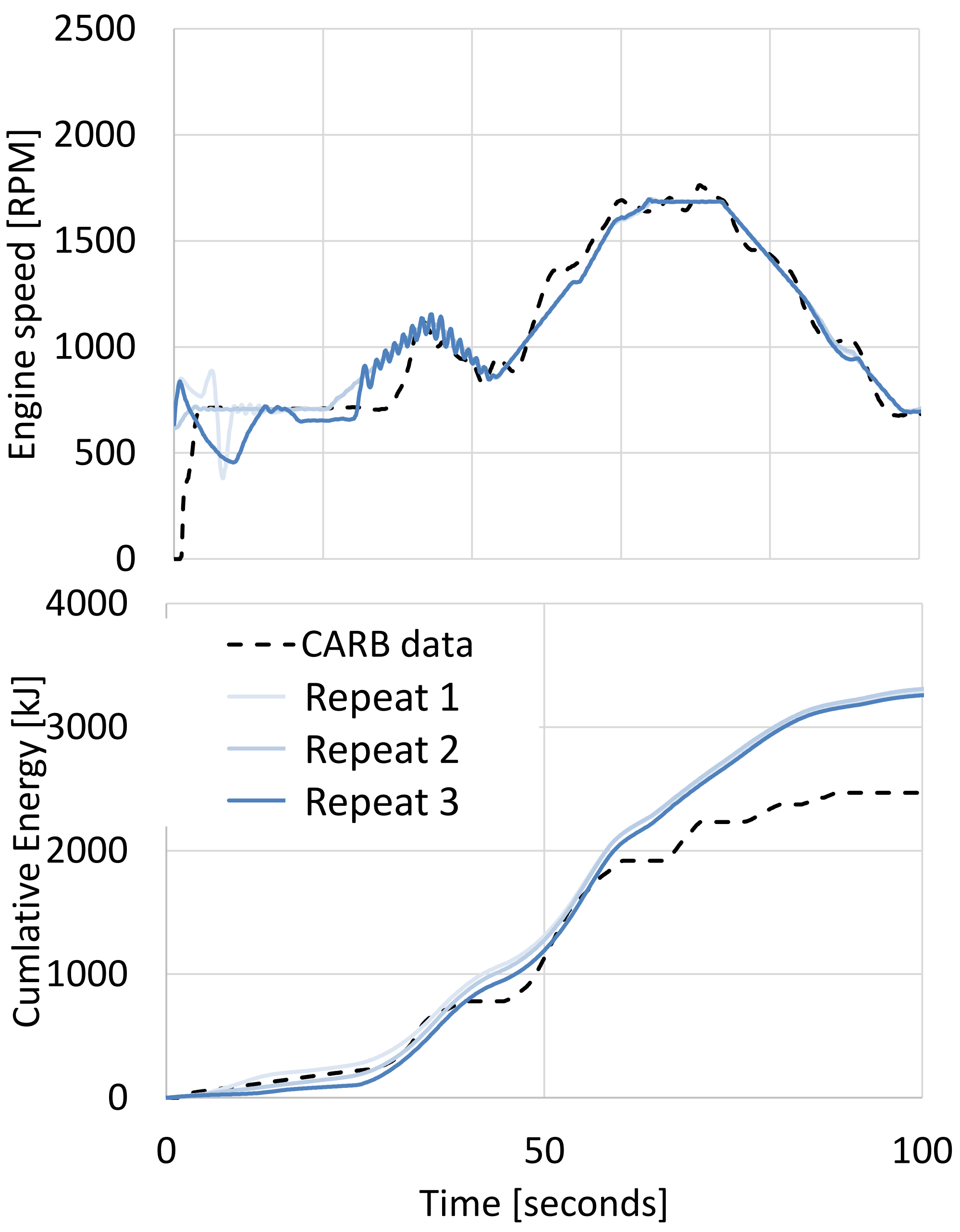
0.02 g/bhp-hr NO_x

Methodology

- A fully tuned transient controller was not developed due to base controller capabilities
- Cold start was simulated with engine in optimal configuration to show similar close-coupled catalyst temperatures using quasi-transient cycle
  - Ensures the light-off times were unaffected by D-EGR modifications
  - First 60-100 seconds key to success
- Optimal engine configuration
  - D-EGR, 13.2:1 CR, VNT, and J-gap plugs with DCO ignition system
  - D-EGR bypassed before the EGR cooler
    - During warm up the engine was operated without EGR
  - Thermostats left blocked open
    - Coolant would not heat up as fast as CARB testing
- Similar spark retard to CARB data was used
  - Spark timing based at 10° aTDC and advanced as needed to meet the load requirements

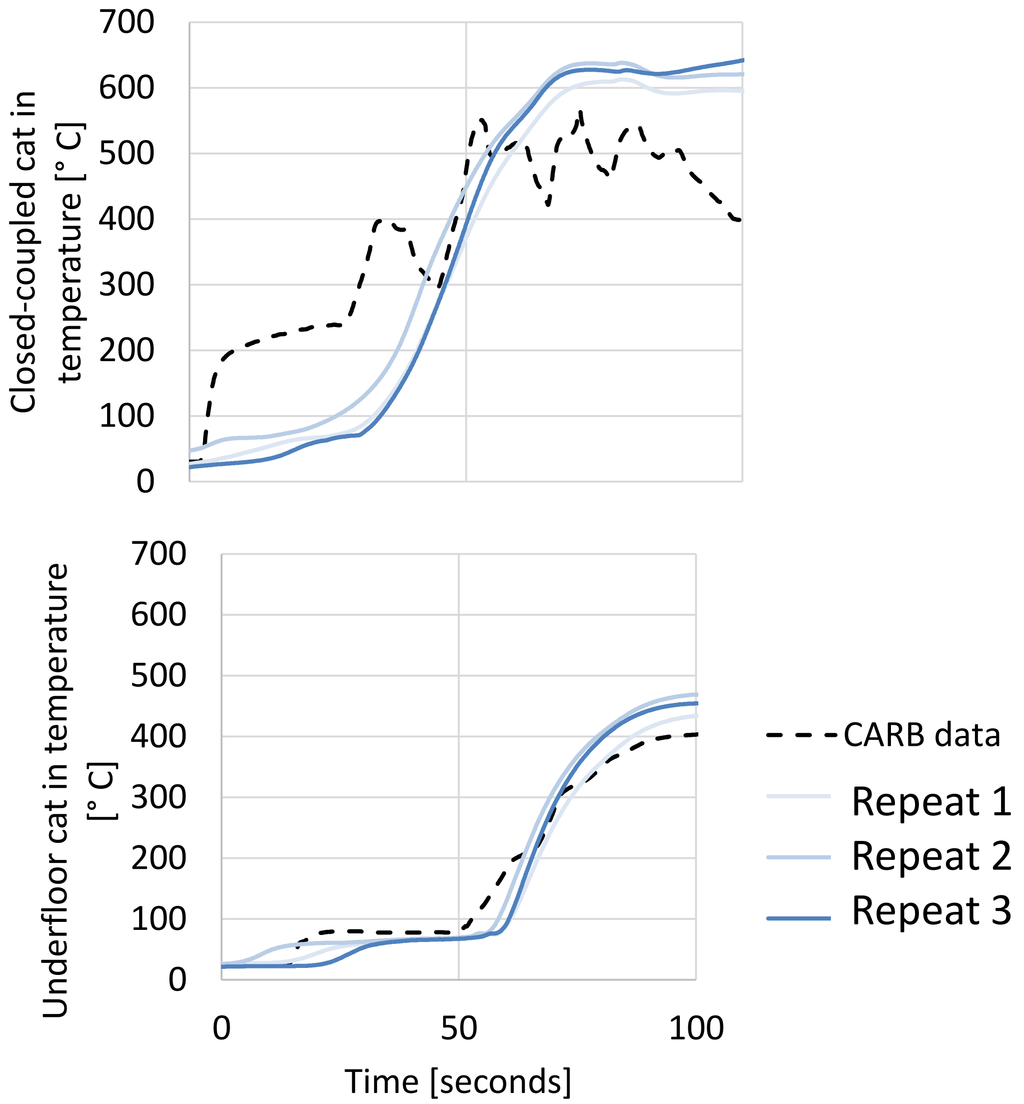
Demonstration Cycle

- The dyno and engine controller used for the demonstration was not capable of the full transient profile
  - A pseudo cycle was designed to have a speed and torque profile so the cumulative brake energy through the first 60-100 seconds of the FTP cycle were similar
  - The speed profile was maintained similar to the FTP
  - The torque peaks were aligned but controller was not capable of the full ramp rates or fuel cuts



Demonstration Results

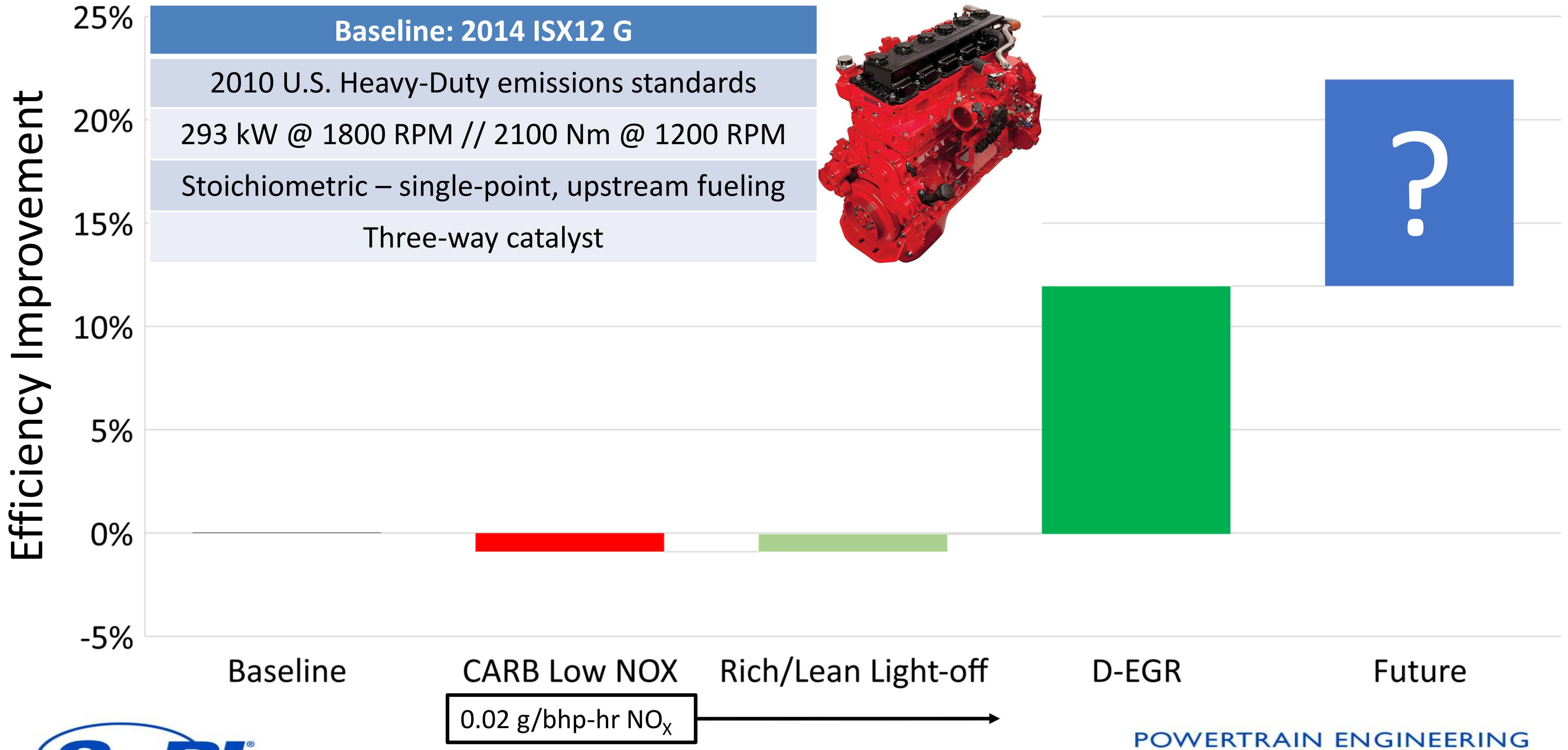
- Similar close-coupled catalyst light off time achieved (based on time to 350 °C)
  - CARB: ~35 seconds
  - D-EGR: ~50 seconds
  - Differences due to cycle and controller
- Both underfloor catalyst reached 350° C after ~75 seconds
- With proper calibration of transient controller, it is expected the D-EGR engine could meet 0.02 g/bhp-h NO_x



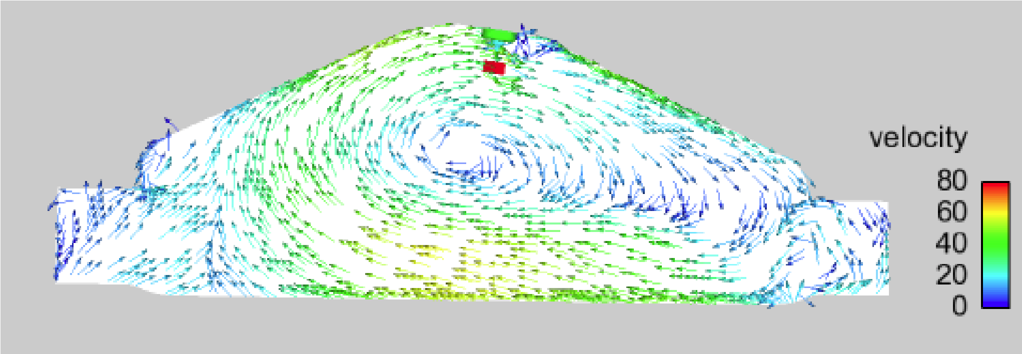
Natural Gas Engine Development Overview

Efficiency Improvement Summary

Baseline: 2014 ISX12 G
2010 U.S. Heavy-Duty emissions standards
293 kW @ 1800 RPM // 2100 Nm @ 1200 RPM
Stoichiometric – single-point, upstream fueling
Three-way catalyst



Technology Needs by Further Efficiency Gains



Pent roof combustion chamber design can optimize turbulence for natural gas combustion

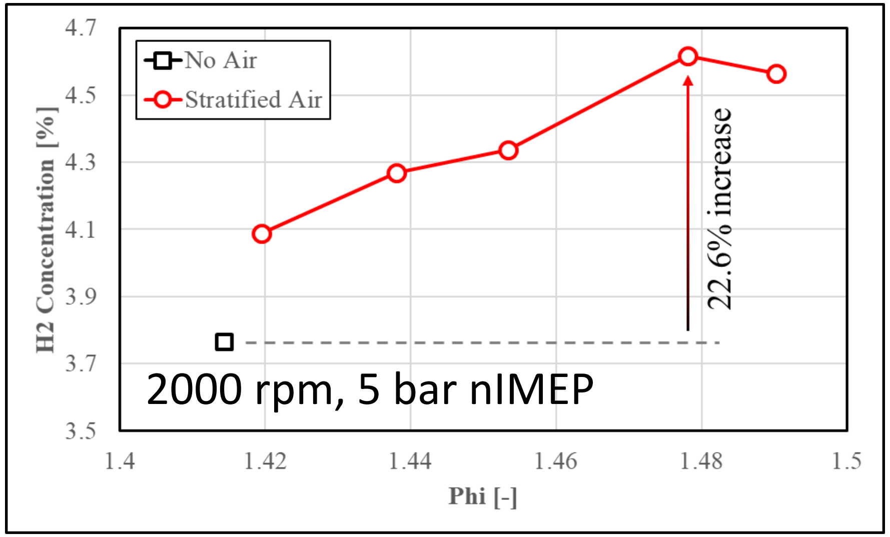
Stoichiometric-EGR TWC

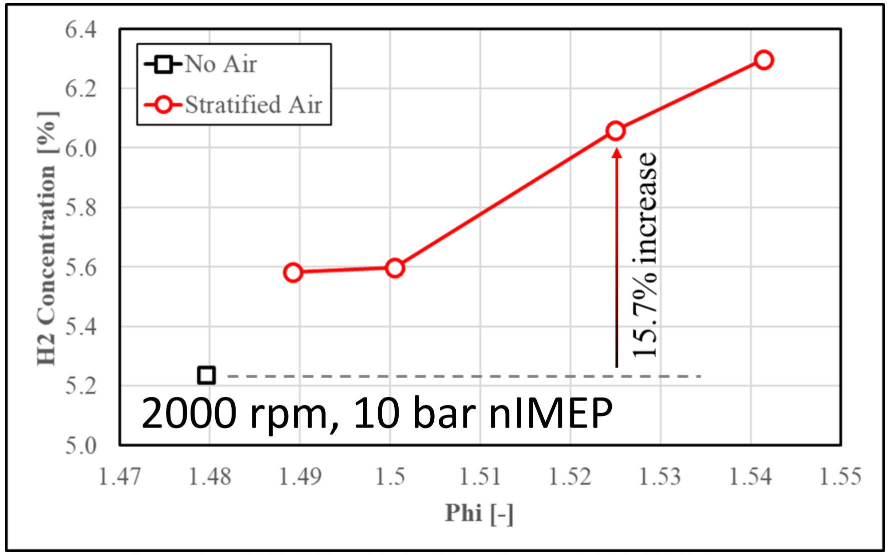
- EGR System Design to Reduce Pumping Losses
- Advanced High Energy Ignition
- Variable Valve Timing
- Pent Roof with Tumble
- Direct NG Injection

Stratified Air Injection – SwRI Internal Research

- Aachen University used air to generate turbulence around the spark plug
  (on a non EGR or D-EGR engine)
  - This made the mixture too lean
  - **For a globally rich mixture this would actually be a benefit!**
- Stratified air injection extended rich limit in Dedicated-cylinder
  - ***<u>Gasoline single cylinder engine</u>***
  - 22.6% increase in H2 concentration at 2000 rpm 5 bar nIMEP
  - 15.7% increase in H2 concentration at 2000 rpm 10 bar nIMEP

Nozzle tube: Provides better control over air flow direction





Conclusions

- ISX12 G efficiency was improved by 12%
  - Peak BTE: 41.7%
  - Demonstrated 0.02 g/bhp-hr NO_X potential
- For heavy-duty on-highway engines, stoichiometric with EGR is the preferred technology path through 2030
  - Several technology areas require investment to further improve efficiency
    - Explore methods of providing EGR with reduced pumping work (D-EGR)
    - Pent roof cylinder head
      - Promote rapid combustion (tumble) and reduce knock
      - Potential to improve dilution tolerance
    - Friction reduction
    - Combustion chamber design, including reduced crevice volume
    - Explore methods to increasing compression ratio (such as Miller Cycle)

Acknowledgements

California Environmental Protection Agency
Air Resources Board

STATE OF CALIFORNIA ENERGY COMMISSION
CALIFORNIA ENERGY COMMISSION

WOODWARD

SoCalGas A Sempra Energy utility®

Garrett
ADVANCING MOTION

Contact Info

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Group Leader R&D

Powertrain Engineering

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Achieving 0.02 g/bhp-hr NO_x Emissions from a Heavy-Duty Stoichiometric Natural Gas Engine Equipped with Three-Way Catalyst

SOUTHWEST RESEARCH INSTITUTE®

Presented at 2017 SAE World Congress
(SAE 2017-01-0957)

California Environmental Protection Agency
Air Resources Board

Engine Hardware Improvements

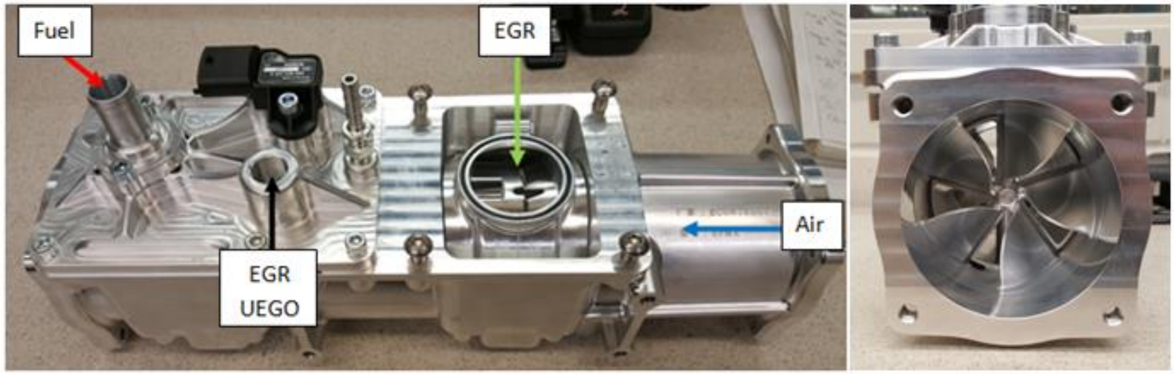
- The baseline engine was upgraded with new hardware and engine control unit/calibration to achieve the 0.02 g/bhp-hr NO_X emission target

Baseline Engine	Low NO_X Demonstration Engine
Single Underfloor TWC (22.4 L)	Close-coupled TWC (9 L) & Underfloor TWC (20 L)
Stock CM2180A ECM	Aftermarket EControls ECU
No CCV System	Full CCV System

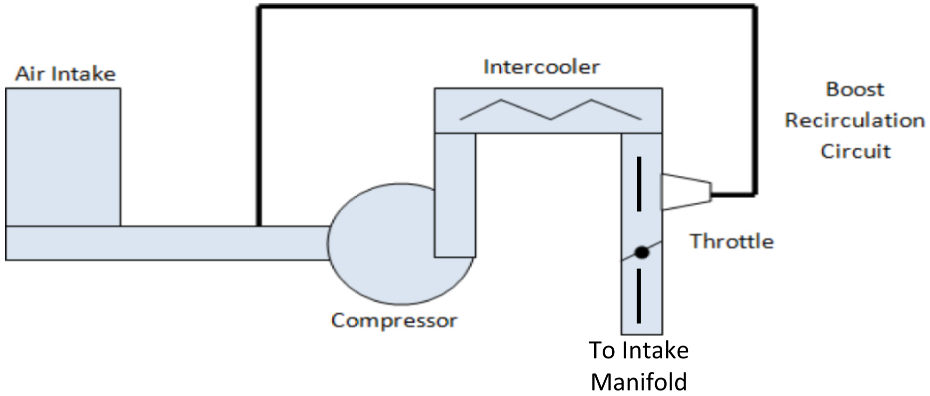
- Lower PM and gaseous emissions
- Lower oil consumption

Engine Hardware Improvements

- Additional hardware was added to increase the EGR tolerance and transient performance of the engine
- EGR Tolerance
  - Baseline: Capacitive discharge ignition coil system
  - Demonstration: Improved fuel-air-EGR mixer and higher energy DC ignition coil system



- Additional Improvements
  - Continuous flow valve (CFV) for fueling
  - Electronically controlled wastegate
  - Boost recirculation valve
  - Catalyst heating strategy



Closed Loop Fueling

Large focus on keeping the engine within closed loop fueling

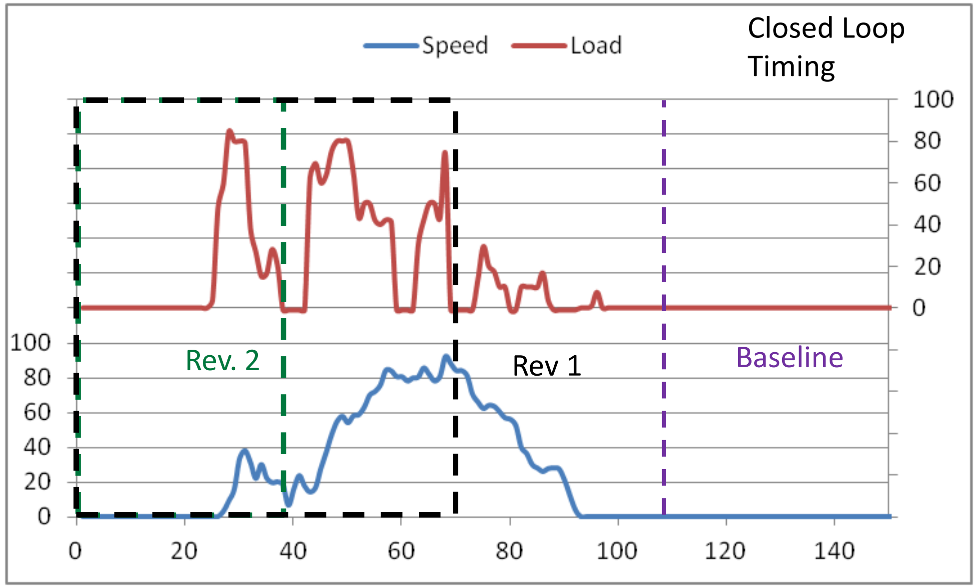
Baseline Engine

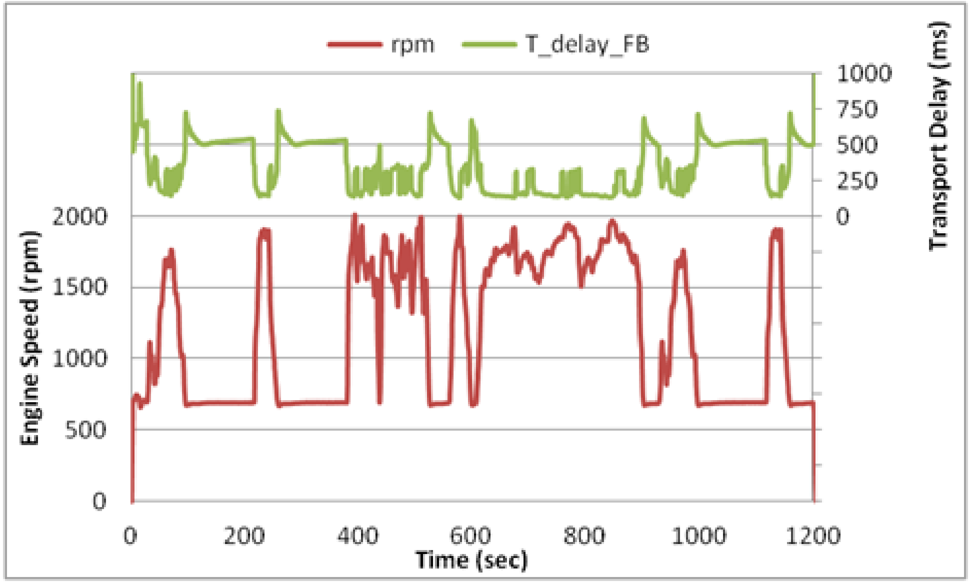
Switching O_2 sensor

UEGO Sensor

Low NO_X Demonstration Engine

- Pre- & post-catalyst switching O_2 sensors
- UEGO sensor located just downstream of turbocharger



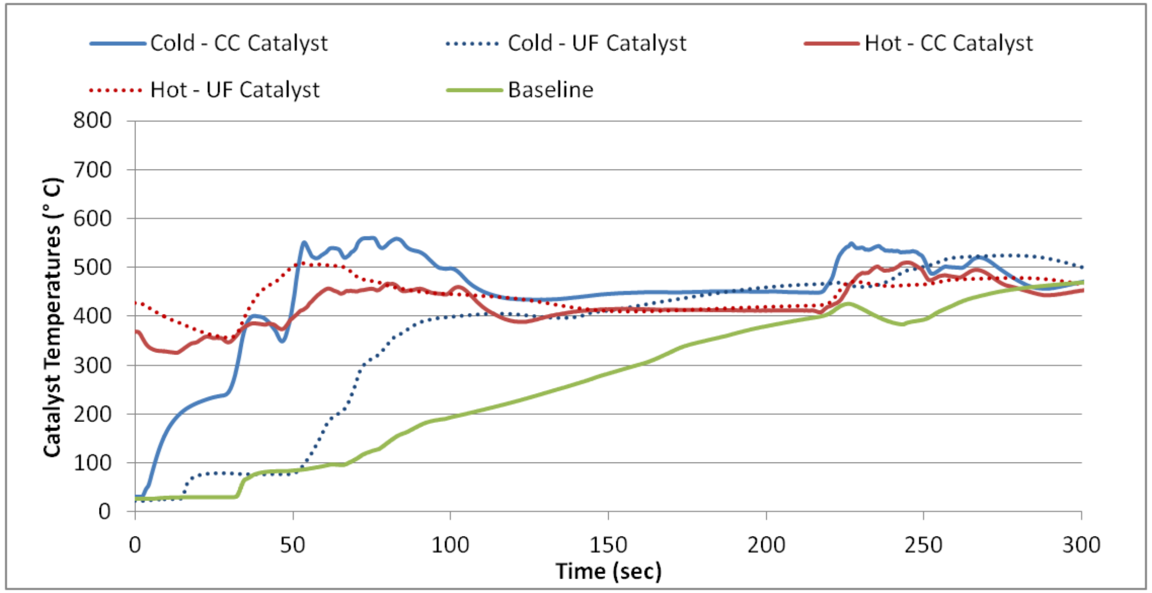


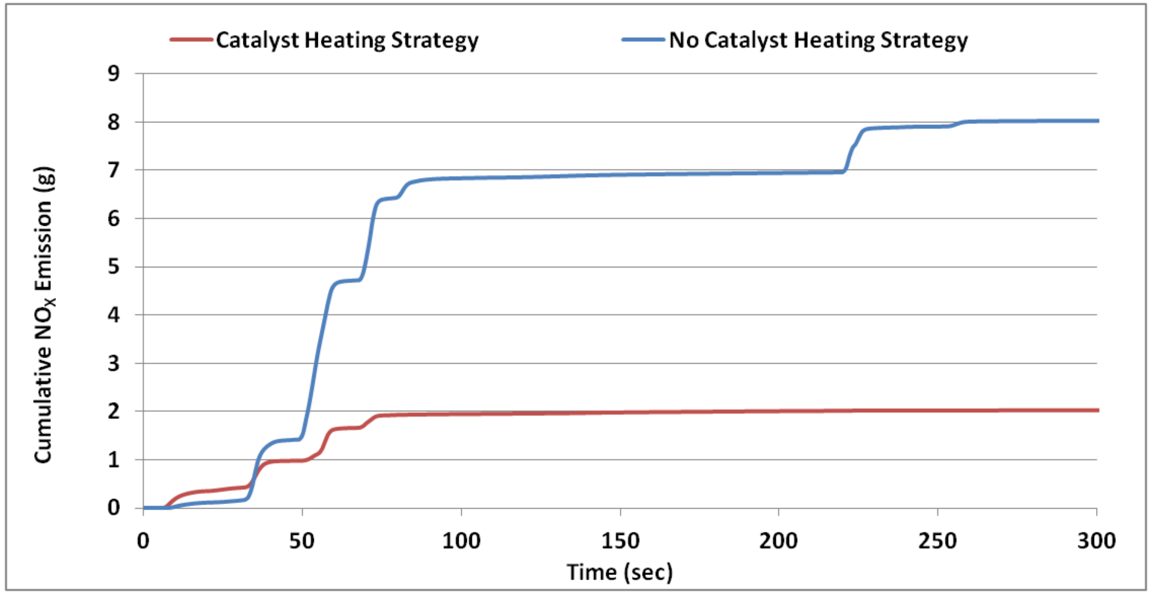
- Transport and feedback delay minimized
- Accurate measurements of fuel supply, intake and exhaust volume required
- Adjustment to long time constant volumetric efficiency

Cold Start Improvements

- Catalyst heating strategy
  - Ignition timing after TDC
  - Slight enrichment
  - EGR use disabled for first 30 seconds
  - Closed loop fueling at ~40 seconds

- Emissions difference
  - 4x increase in NO_X emissions without catalyst heating
  - Increase in cycle work without catalyst heating results in 3.4x increase in $BSNO_X$

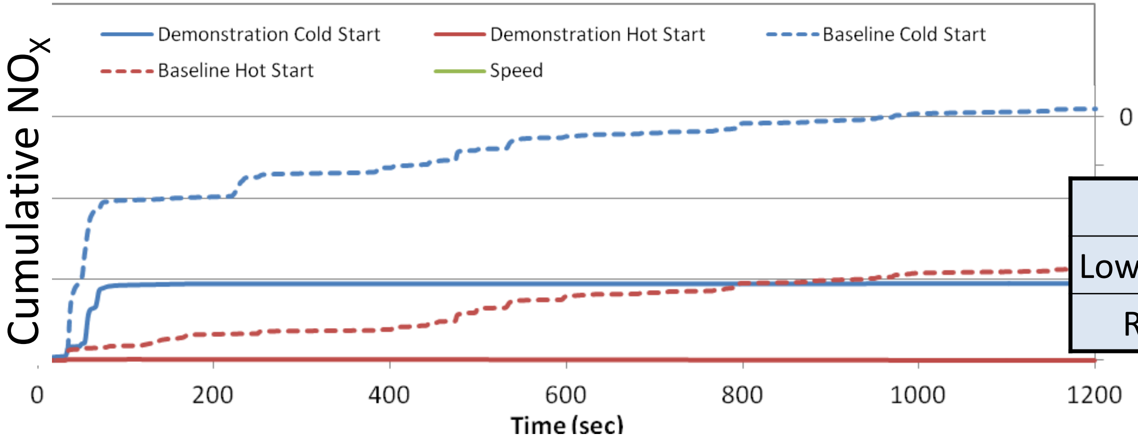




<0.02 g/bhp-hr NO_X Achieved

- Meets 2014 CO_2 standard
- Required:
  - Close-coupled and underfloor TWC
  - Rapid catalyst heating strategy
  - Improved AFR control
  - Improved EGR tolerance
    - » New hardware
- **~1% CO_2 penalty (FTP)**

Other Emissions Comparison				
	Pollutant	FTP	RMC-SET	WHTC
Baseline	CH_4, g/bhp-hr	0.96	1.20	1.54
	NH_3, avg. ppm	76	162	100
	CO_2, g/bhp-hr	542	454	510
Low NO_X Engine	CH_4, g/bhp-hr	0.15	0.92	0.10
	NH_3, avg. ppm	52	37	44
	CO_2, g/bhp-hr	547	445	513
Reduction	CH_4, g/bhp-hr	84%	23%	94%
	NH_3, avg. ppm	32%	77%	56%
	CO_2, g/bhp-hr	**-0.9%**	2.0%	-0.6%



NO_X Emissions Comparison, g/bhp-hr							
	FTP			RMC-SET	WHTC		
	Cold	Hot	Composite		Cold	Hot	Composite
Baseline	0.247	0.093	0.115	0.012	0.310	0.308	0.308
Low NO_X Engine	0.065	0.001	**0.010**	0.001	0.043	0.006	**0.011**
Reduction	**74%**	**99%**	**91%**	**92%**	**86%**	**98%**	**96%**

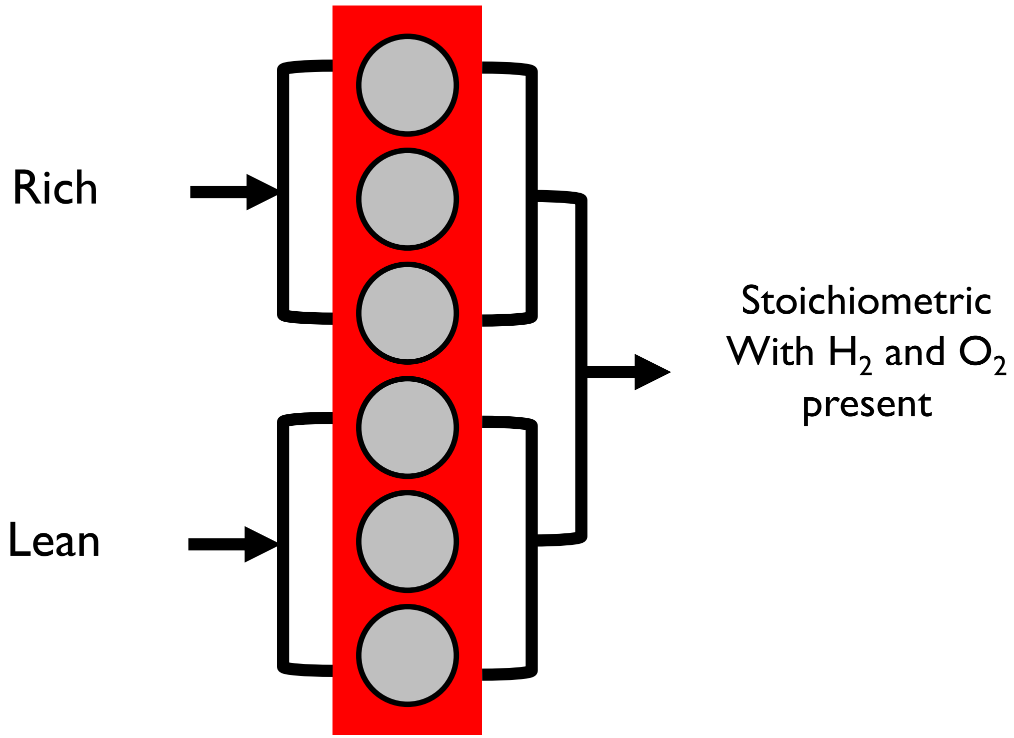
Achieving Fast Catalyst Light-Off from a Heavy-Duty Stoichiometric Natural Gas Engine Capable of 0.02 g/bhp-hr NO_X Emissions

SOUTHWEST RESEARCH INSTITUTE®

Presented at 2018 SAE World Congress
(SAE 2018-01-1136)

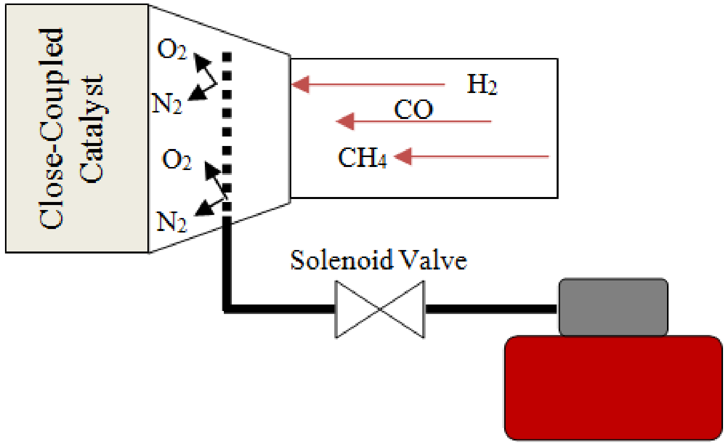
SwRI's Internal Research Approach

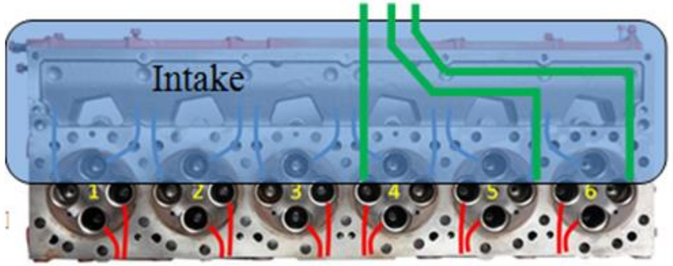
- Catalytic oxidation of H_2 and O_2 occurs at low temperatures and is exothermic; helping to achieve fast light-off
- **To achieve fast light-off of the close coupled catalyst, we evaluated multiple methods for delivering H_2 and O_2 to the catalyst from the engine**
  - Half cylinders rich/half cylinders lean
  - Overall rich operation with exhaust air pump



Test Setup

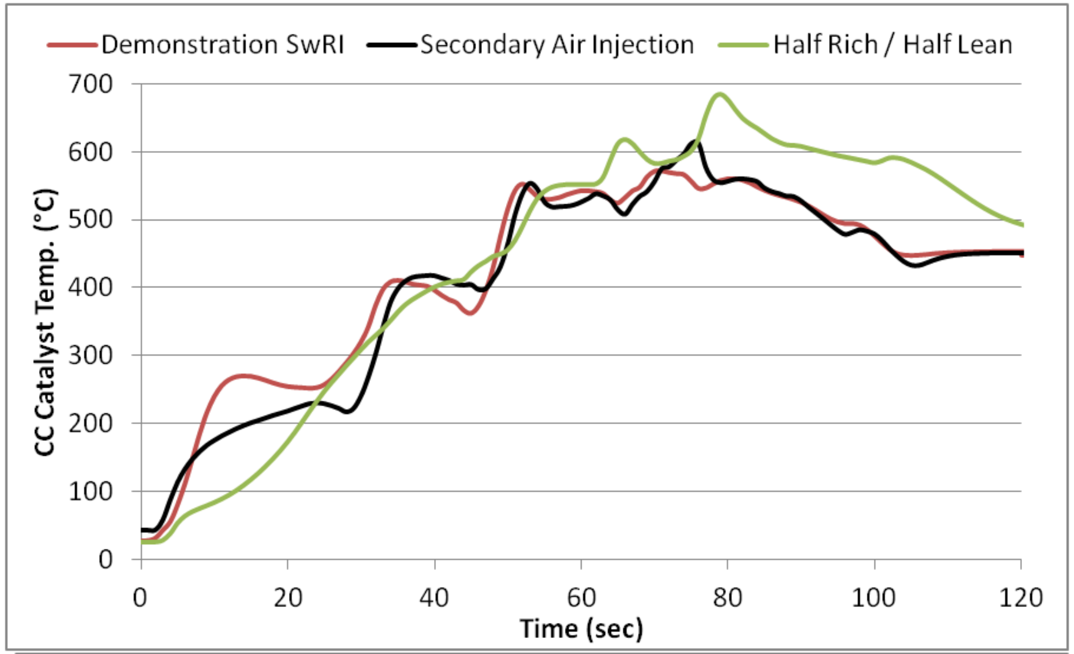
- **Preliminary tests run over first 60 seconds of FTP**
  - Allowed two cold-starts per day (engine and exhaust system at 25 °C)
- Secondary air injection system tested with two different pressures and with the tank pressurized and non-pressurized
- Half-rich / half-lean engine operation tested with two different splits for stoichiometric operation and one split for a rich-bias
- Two systems only active for opening idle (20 seconds)

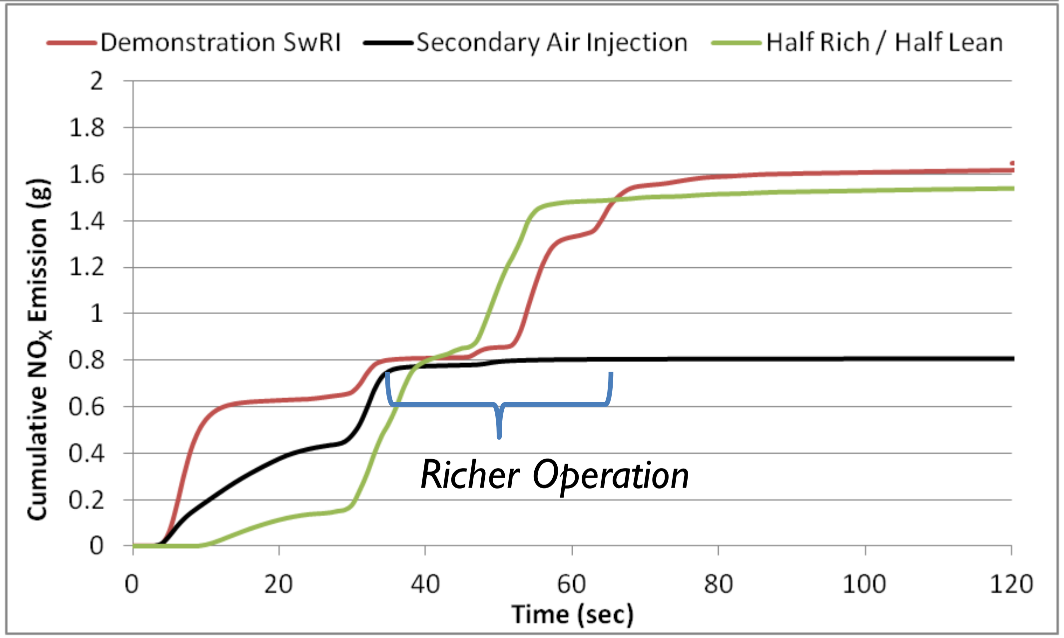




Test Results

- **Optimal secondary air-injection system and half-rich / half-lean results compared to CARB demonstration results**
  - 40 psig injection pressure with a pressurized tank and 5% enrichment yielded best results for secondary air injection
  - 1.25 ϕ / 0.85 ϕ split yielded best results for half-rich / half-lean (rich-bias)





Overall Results

- **Half-rich / half-lean**
  - Cold-start NO_X emissions comparable to CARB Demonstration
  - **35% lower CO emissions and 1.2% BSFC benefit**
  - System could be optimized to reduce transport delay between injectors and cylinders lowering CH_4 emissions
- **Both solutions meet 2017 GHG Standard**

	g/bhp-hr				
	NO_X	CO	CH_4	NMHC	CO_2
Secondary Air Injection	0.036	3.107	0.143	0.000	593.7
Half-Rich / Half-Lean	0.071	2.284	0.235	0.029	583.2
Low NO_X Demonstration	0.068	3.543	0.198	0.016	588.0

	Cold GHG (g/bhp-hr)	Hot GHG (g/bhp-hr)	Composite GHG (g/bhp-hr)
2014 Std	--	--	567.0
2017 Std	--	--	555.0
Secondary Air Injection	594.8	543.4	550.7
Half-Rich / Half-Lean	586.6	543.4	549.5
Low NO_X Demonstration	598.1	543.4	551.2

$GHG = CO_2 + 25(CH_4 - 0.1)$

Natural Gas Fueling Gas Expanding Technology

February 2020

Ted Barnes, P.E.
GTI

Discussion

- Background on GTI Infrastructure R&D
- Technology Focus – Near-Isentropic Expansion for Gas Cooling
- Details on GTI Technology: Pre-cooling CNG with Expander
  - Concept validation
  - Simulation
  - CAD Design
- Preliminary Costs/Siting/Safety Analysis

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

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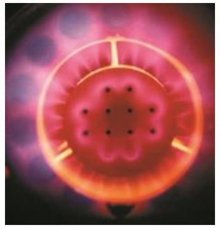
GTI Technology Expertise

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

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

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

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



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

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

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

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

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

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

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

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

NGV Infrastructure Sponsors - Thank you!!!

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NREL
NATIONAL RENEWABLE ENERGY LABORATORY

CALIFORNIA ENERGY COMMISSION

South Coast AQMD

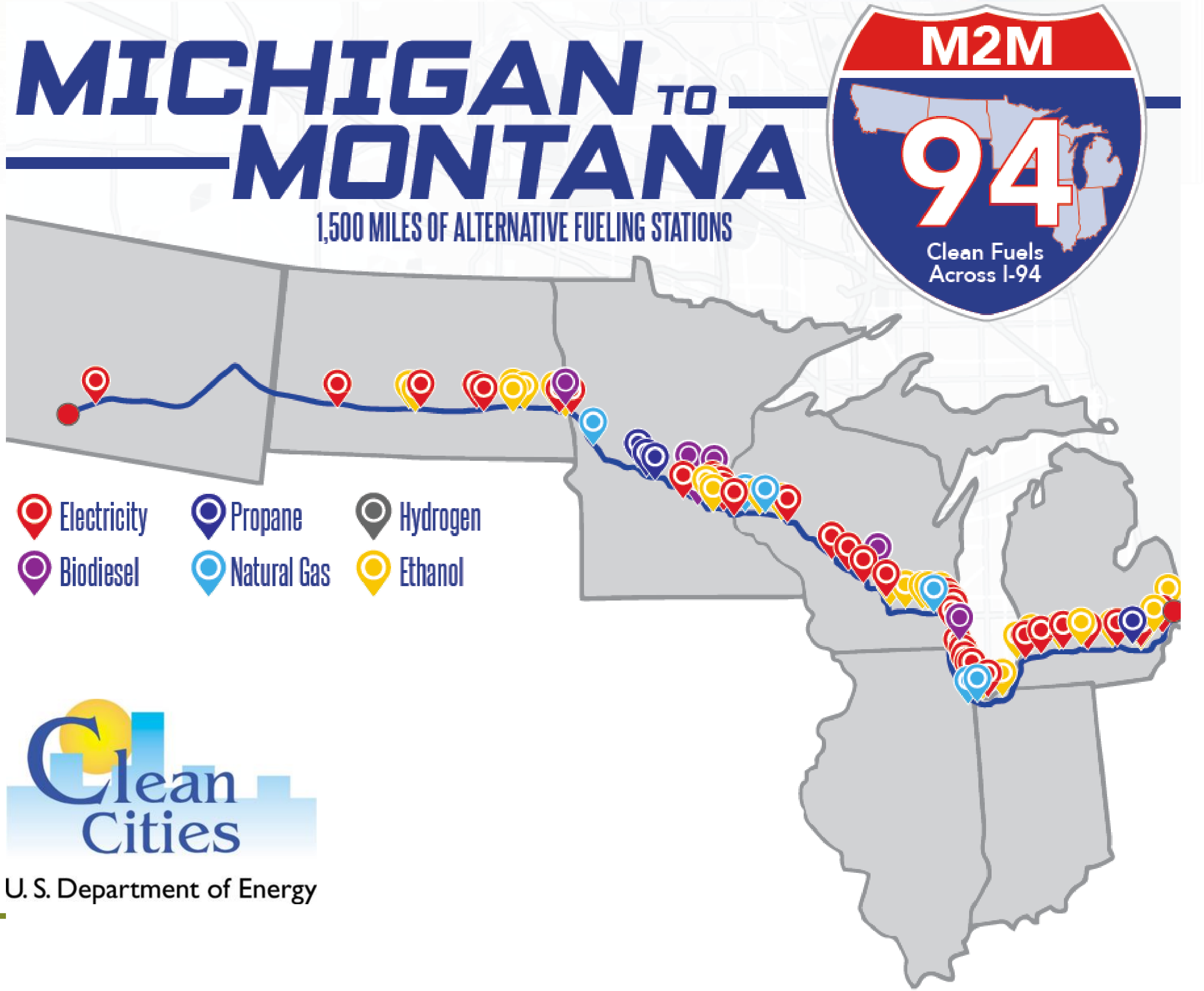
SoCalGas
A Sempra Energy utility

UTD
Utilization Technology Development

The Flame of Innovation
SMP

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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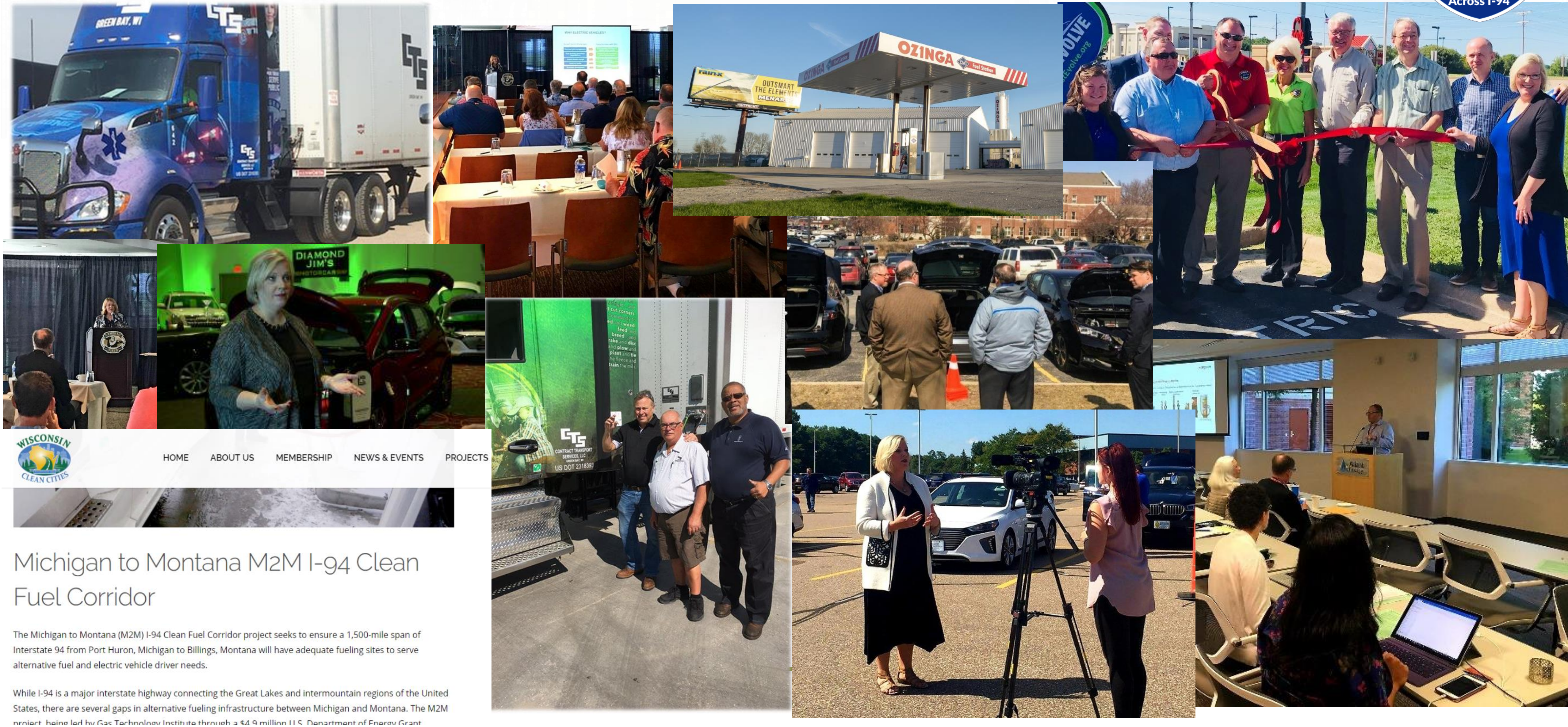
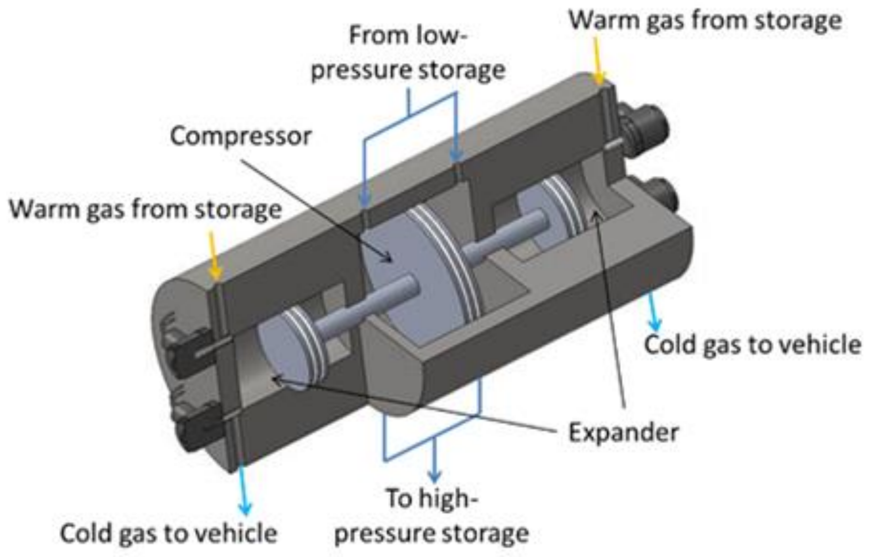
M2M Accomplishments and Progress



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

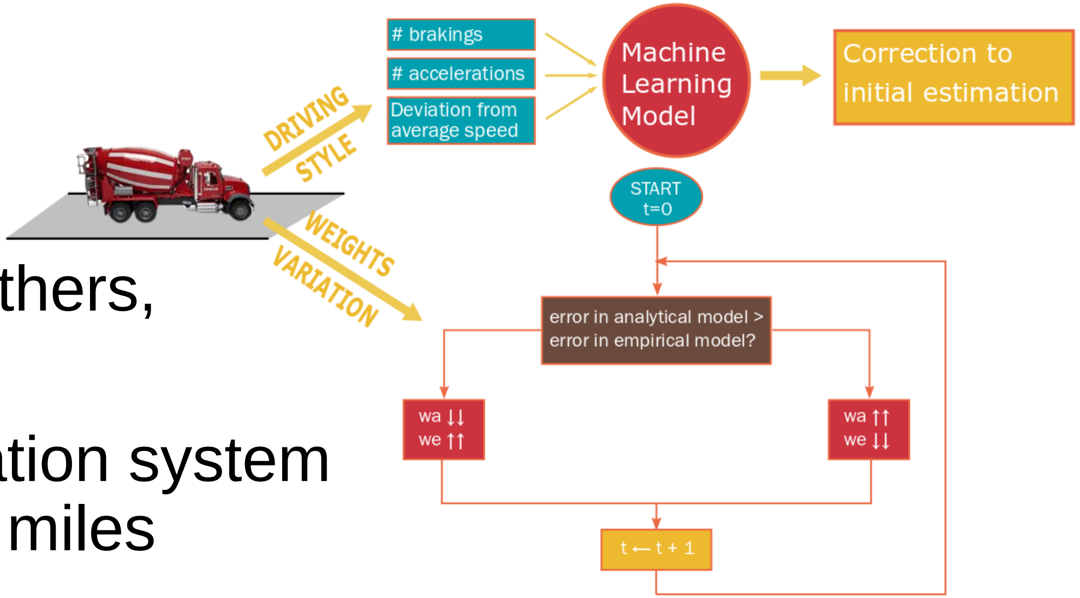


Smart Station Demonstration

- Award: US DOE -- DE-EE0008799
- Period of Performance: 10/2019 – 12/2022
- **Commercial Partners**:
  - Clean Energy, Kraus Global, Ozinga Energy
- Objective:
  - Collect data to quantify underfilling and transient thermodynamics
  - Deploy smart CNG dispensers and vehicles
  - Improve fills by up to 25%
  - Demonstrate smart stations at **5 sites across the country**

Next-Generation NGV Driver Information System

- Award: US DOE -- DE-EE0008802
- Period of Performance: 10/2019 – 12/2022
- Partners: Argonne National Lab, Ozinga Brothers, Chicago Area Clean Cities
- 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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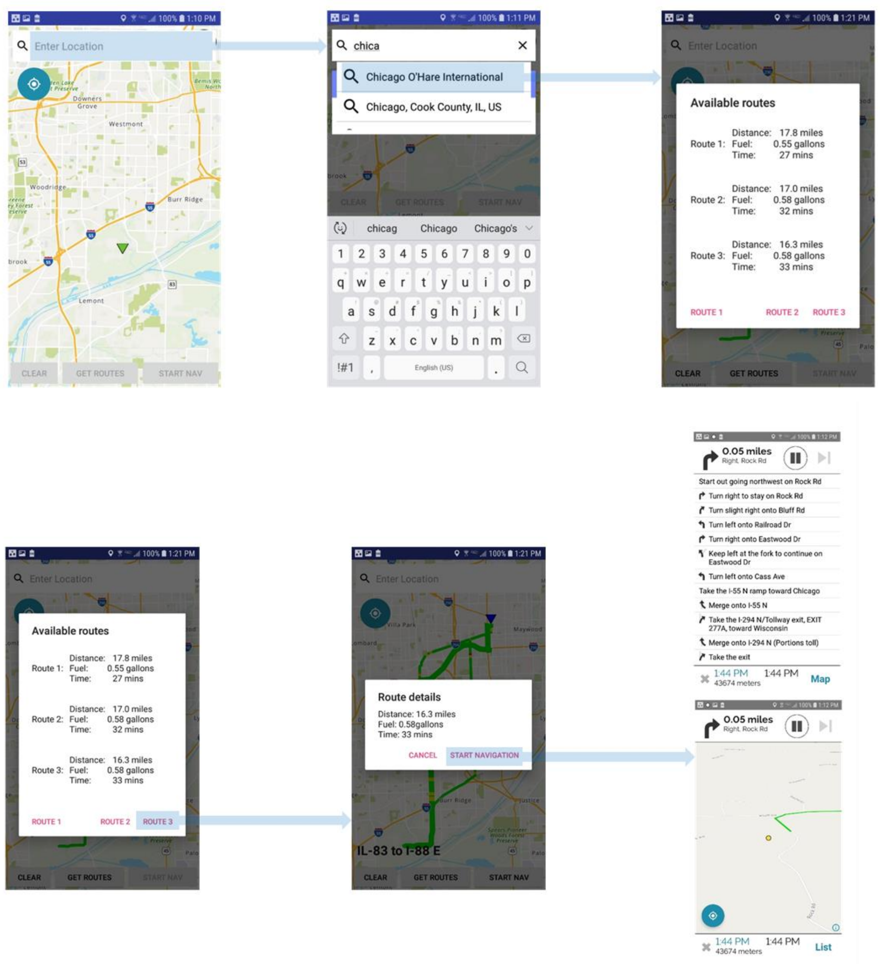
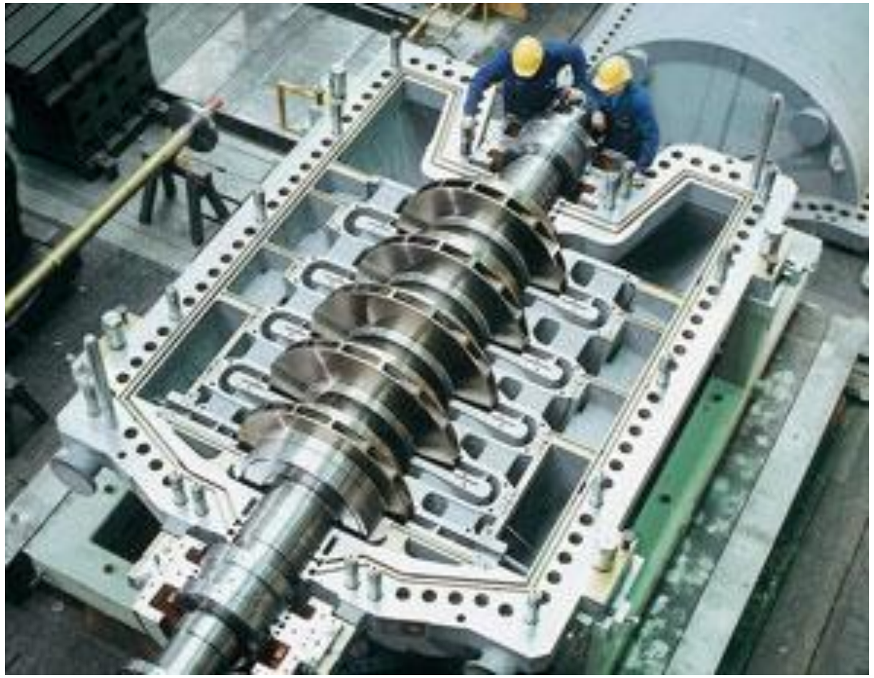
Next-Generation NGV Driver Information System

- Begin with baseline data collection across multiple sites/vehicle types utilizing onboard sensors
- Develop detailed models of onboard pressure vessel fuel properties from empirical data
- Create hardware for real-time, in-cab display for analysis and deployment
- Test and demonstrate the full system that includes sensors, models of on-board usable fuel and predictive fuel consumption, and driver interfaces.

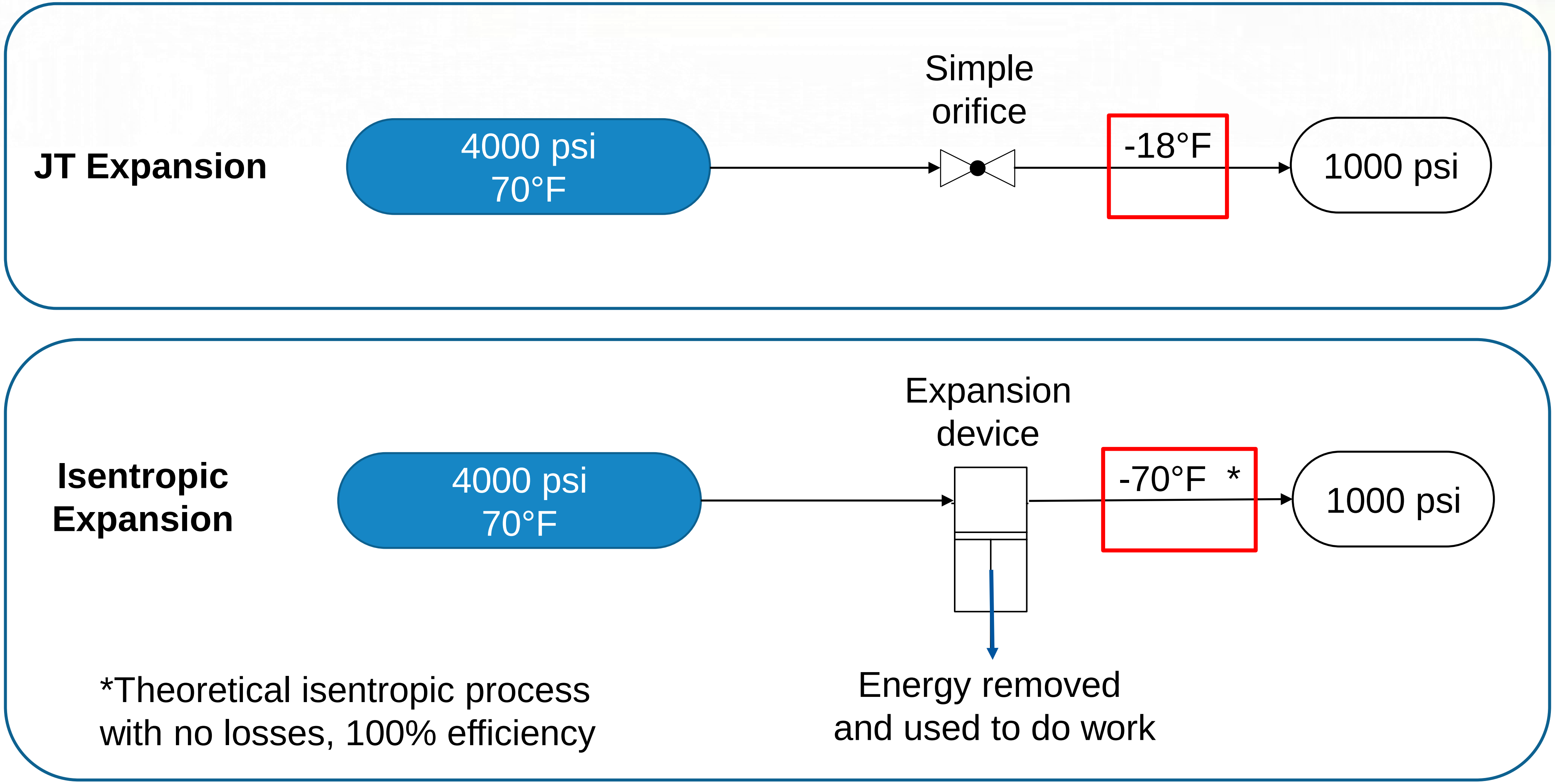


Technology Focus – Near-Isentropic Expansion for Cooling CNG

- Expanders remove energy from high pressure gas by allowing the gas to expand and using the pressure drop to produce mechanical work
- Turbo-expanders are common in large-scale, cryogenic applications
  - Removing NGLs from natural gas
  - Process step in making LNG
  - Cryogenic air separations
- Typically large, expensive machines
- Smaller units tend to be less efficient, expensive
- Design is tailored to one specific operating point
  - Efficiency much lower if operation changes

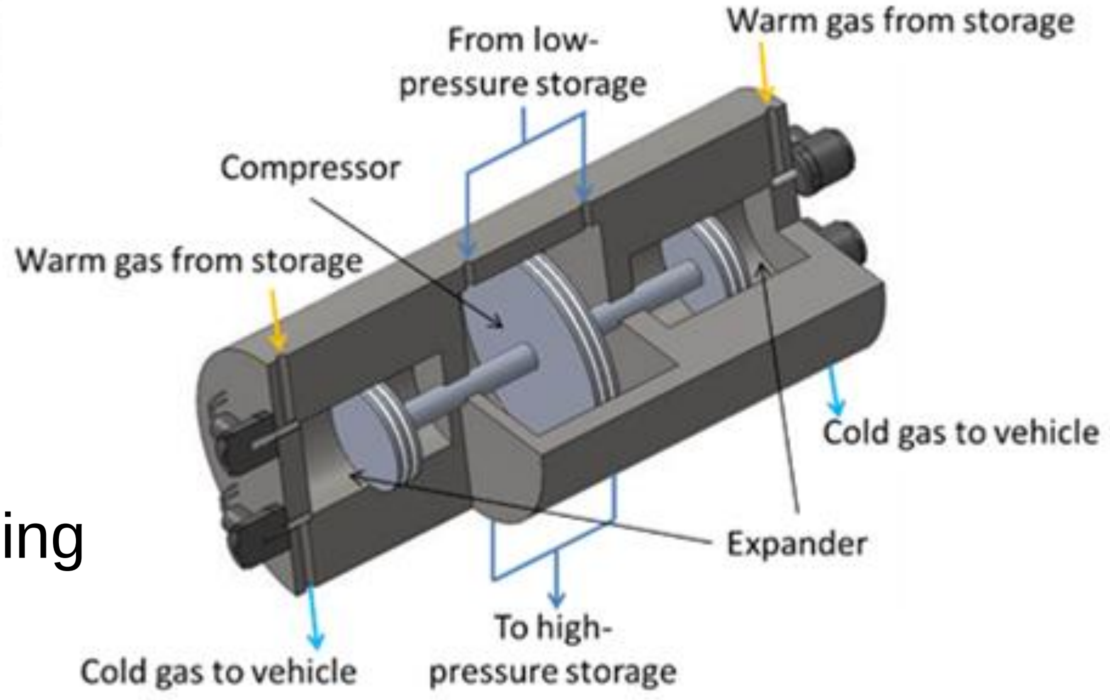


Joule-Thomson vs. Isentropic Expansion



GTI Linear Motor, Free-Piston Expander Concept

- Piston expander technology is nothing new
- Linear motor advancements are new
  - Lower cost
  - Improved control electronics
- Linear expander is best option for CNG fueling
  - Variable expansion ratio
  - Traditional seals
  - Work can be utilized for creating electricity or compressing gas



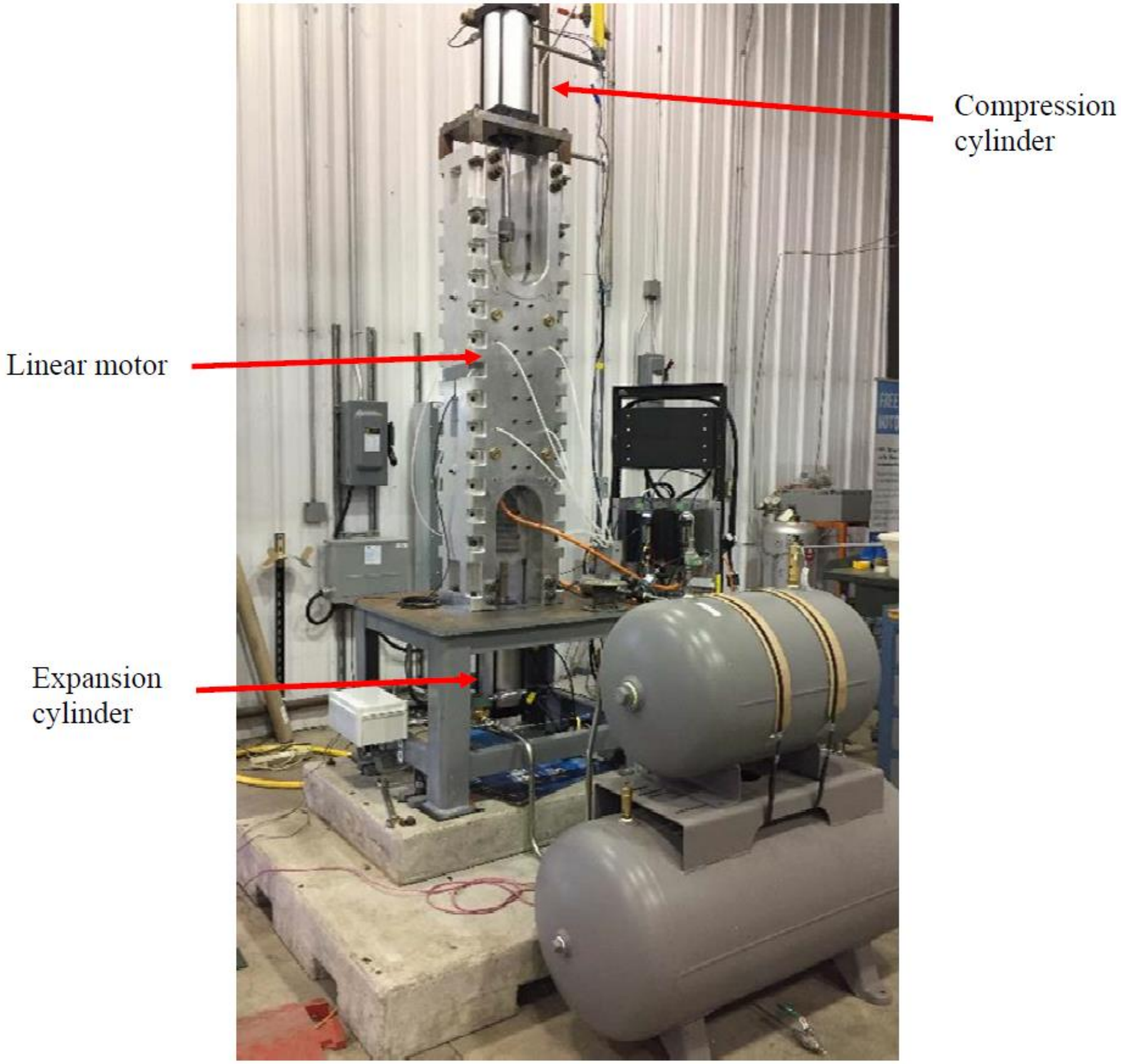
Advantages of a Linear Free-Piston Expander

- Flexibility is **required** for CNG application
  - Must maintain efficiency over full range of conditions
    - Pressures from ~4200 to ~400 psig
    - Flowrates from ~30 GGE/min to ~0.1 GGE/min
- Programmable to act as flow controller as well
- Simplicity
  - One central moving part
  - Linear motor electronics capable of controlling most aspects of operation

[2] *Segado et al, Int Cryocooler Conference, Boulder CO, 2012*

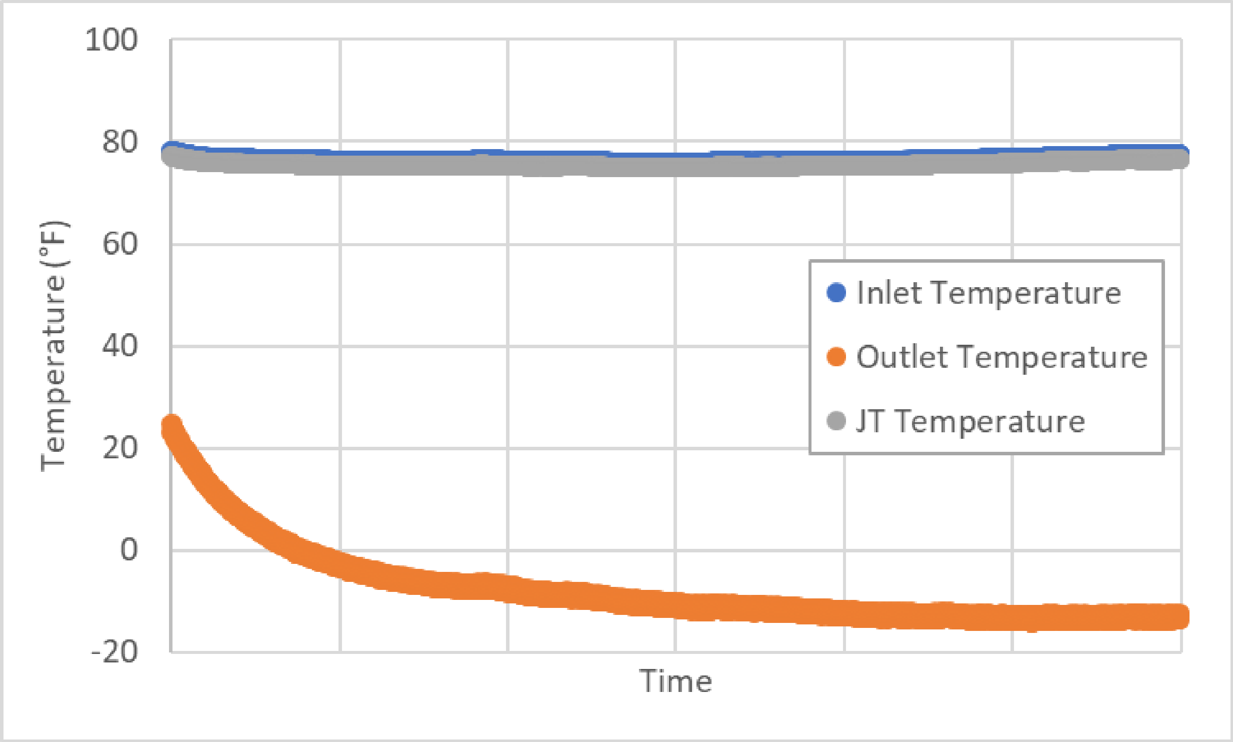
Test Apparatus Design and Fabrication

- Ability to leverage previous efforts and equipment to perform early-stage, concept validation testing
- Preliminary test system
  - Controlled using linear motors
  - Includes compression and expansion ends



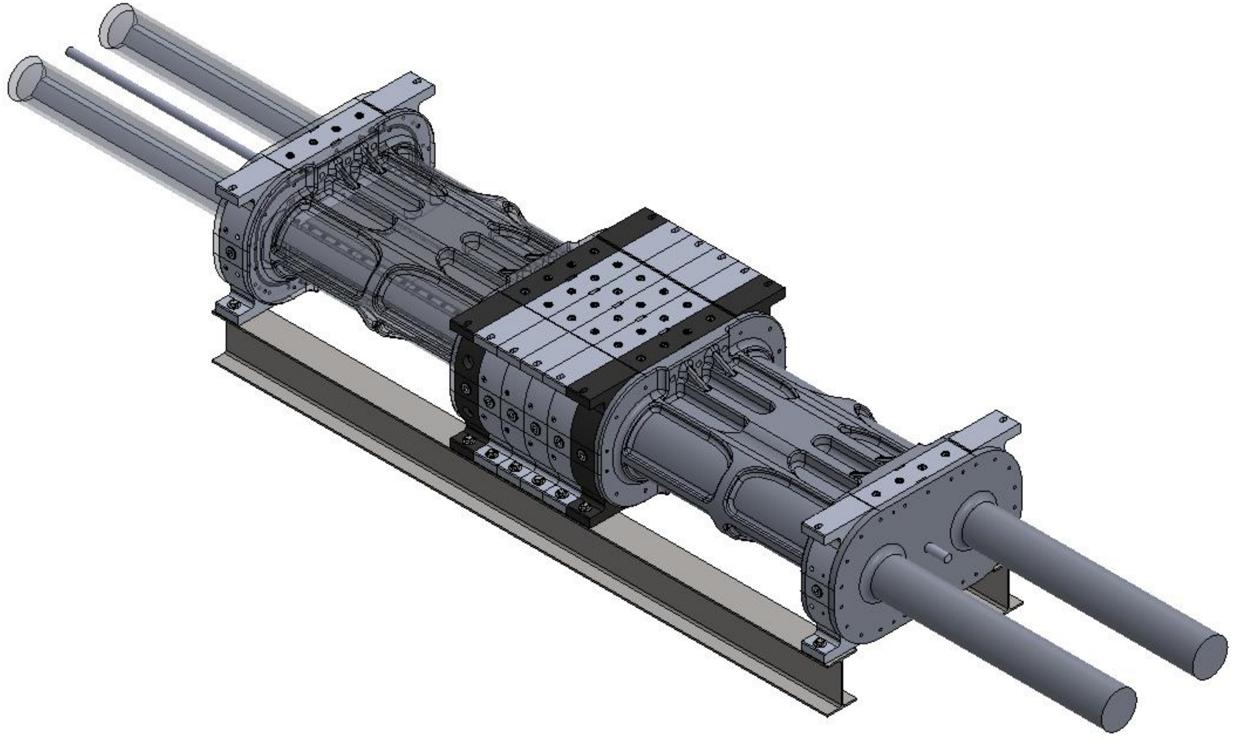
Testing with Low Pressure Nitrogen

- System designed and built at GTI
  - Demonstrates principal with nitrogen
  - 55 psi pressure drop



Design of Expander Prototype: Solid Model

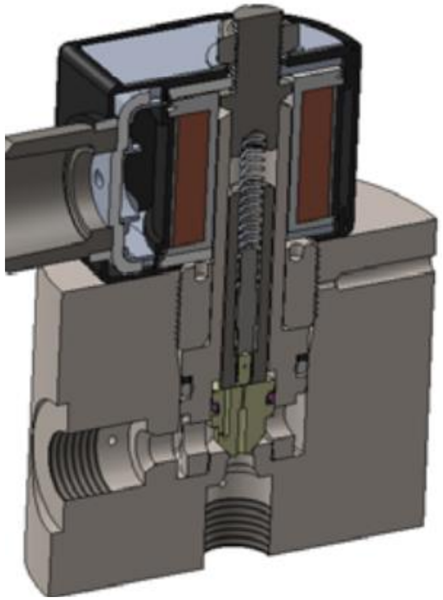
- Create preliminary linear motor frame design
- Semi-hermetic seal to 100 psig
  - Eliminate natural gas leaks
  - Non-hazardous environment
- Fabricating bearing sub-system test
- Detailed design will follow successful bearing testing



Preliminary Key Component Designs

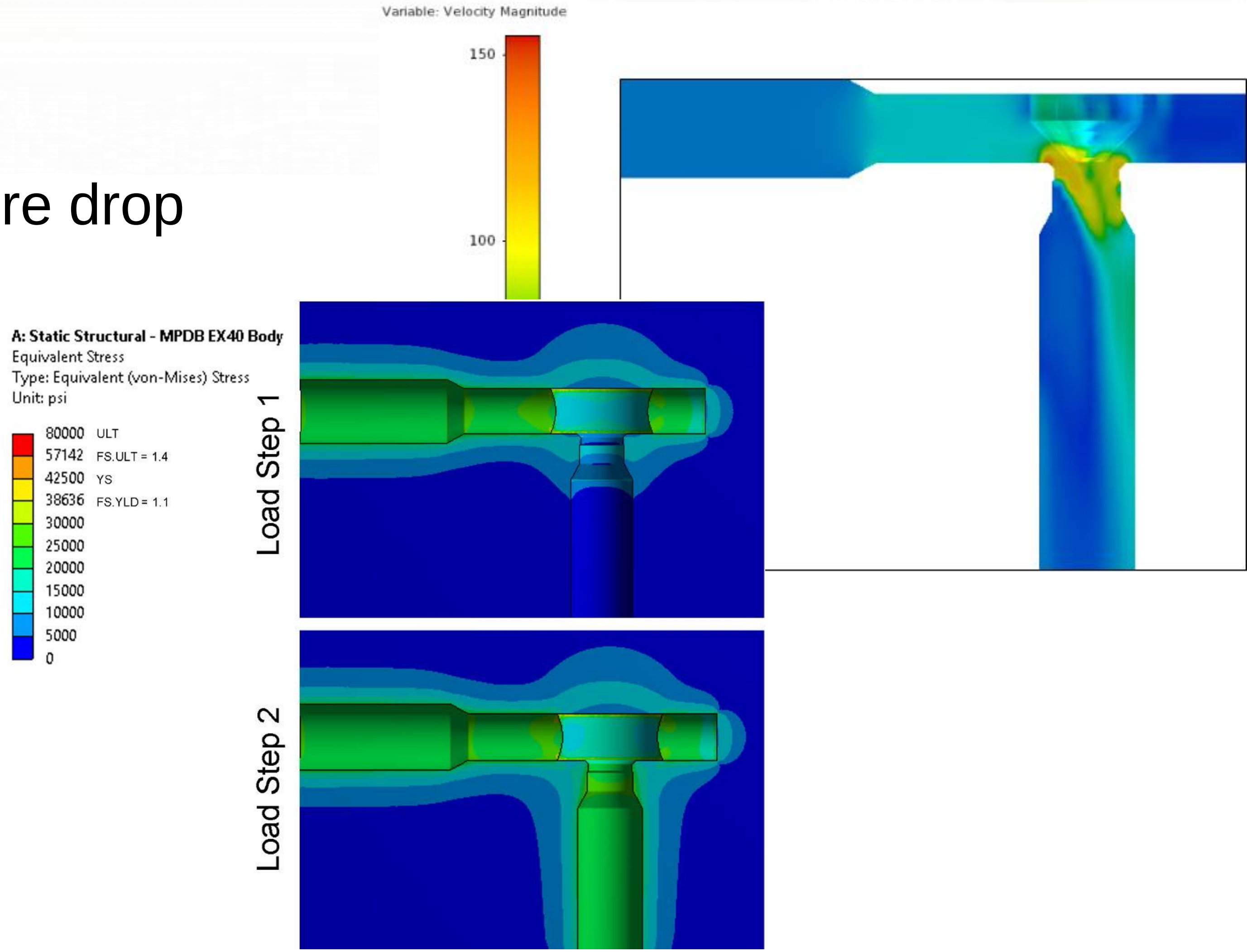


- Team is reaching out to component vendors
- Seals can likely use commercial solutions
  - Lip seals, split rings, or packing rings
- Valves
  - Commercial valves used for preliminary testing
  - Integrate commercial valves into expander to reduce dead volumes
  - Develop custom valves to improve speed, cost, & efficiency



Preliminary Key Component Designs

- Custom valve development
  - CFD used to evaluate pressure drop
  - FEA used to evaluate stress
  - FEA for cyclic loading
- Actuator concepts
  - Solenoid
  - Cam
  - Piston actuation



Preliminary Economic Analysis

- Bill of Materials started for prototype
  - Uses vendor and online quotes and engineering estimates
  - Includes all preliminary frame components
  - Includes estimates of fluid end costs
- Prototype Rough Cost: $45k for 800 SCFM unit = ~$56 / SCFM
  - Motors - $16k
  - Bearings - $10k
  - Frame – $7k
  - Expander fluid ends - $12k
- Proposed target $25 - $50 / SCFM

Preliminary Station Integration and Safety Analysis

- Advanced dispenser algorithm will be required so <u>over-filling</u> doesn’t occur
- Communications will be used to optimize fill
  - Real-time vehicle pressure and temperature
- Thermal buffer being modeled to protect downstream components from extreme temperatures
- Locating expander near dispenser would allow gas to stay cold during the fueling process
- Footprint: Size of final design expected to be smaller than a dispenser
- Additional applications could include virtual pipeline, marine, rail, etc.

Thank you!!!

U.S. DEPARTMENT OF ENERGY

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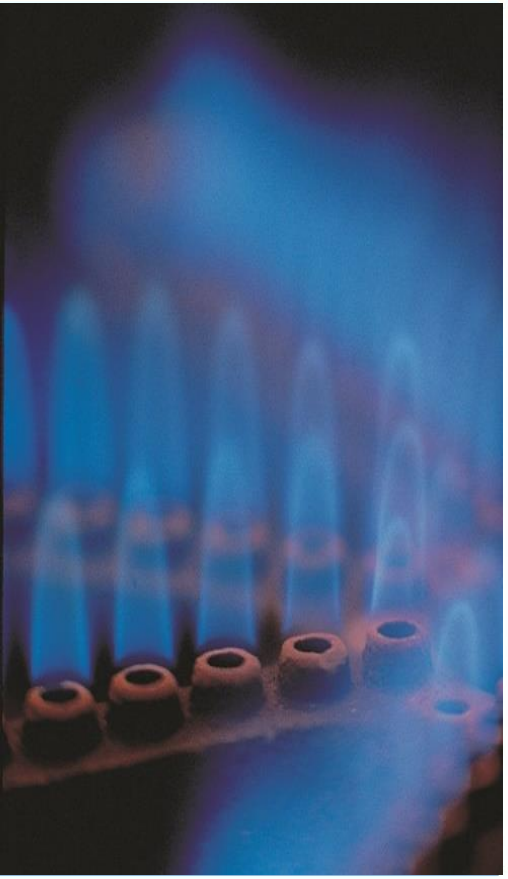
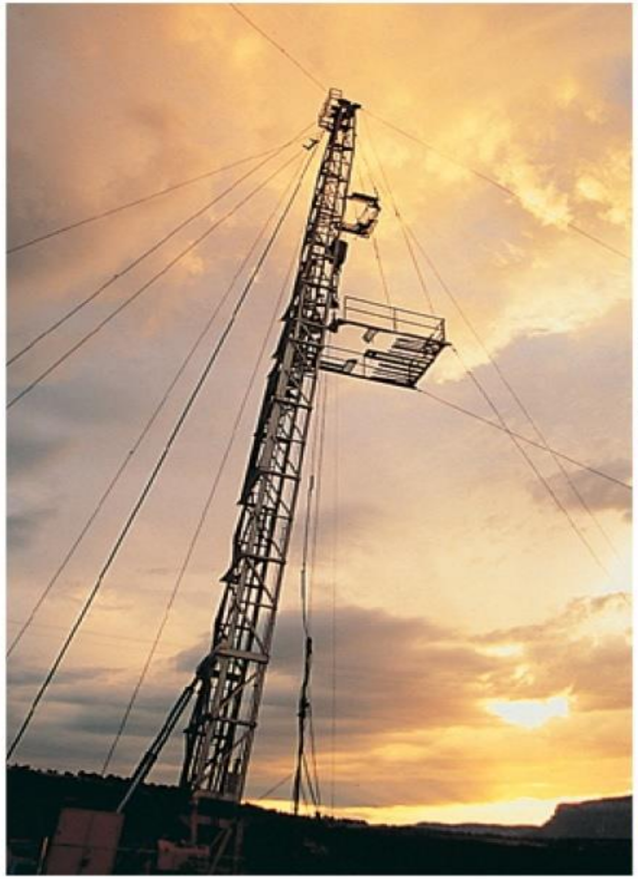
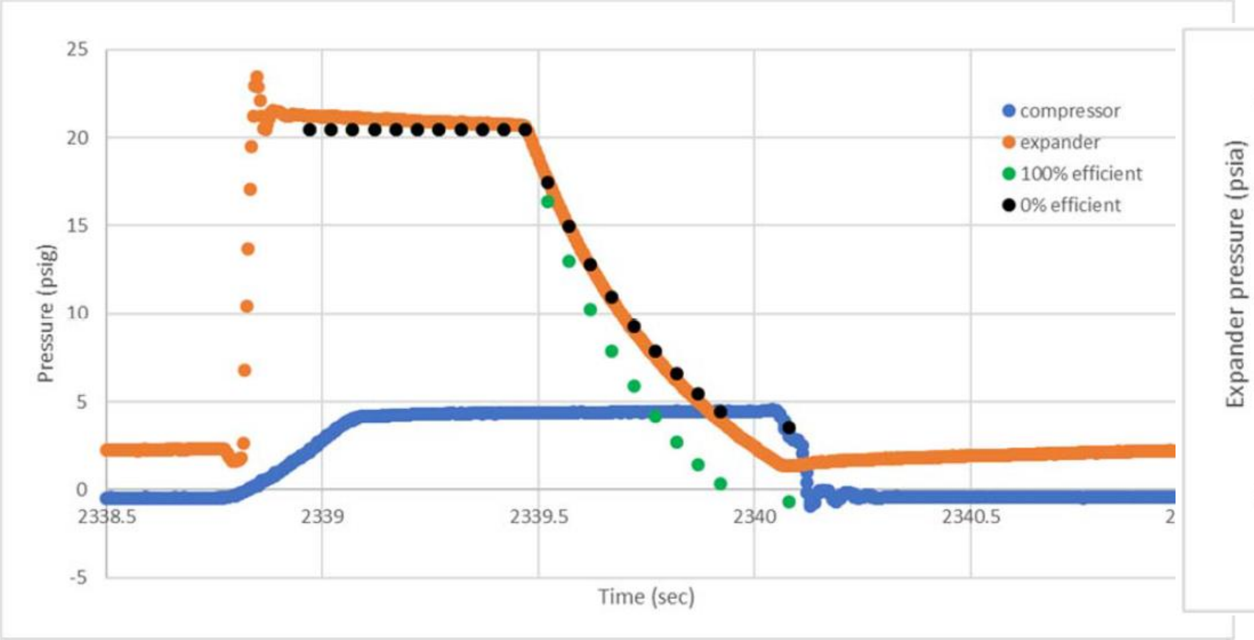
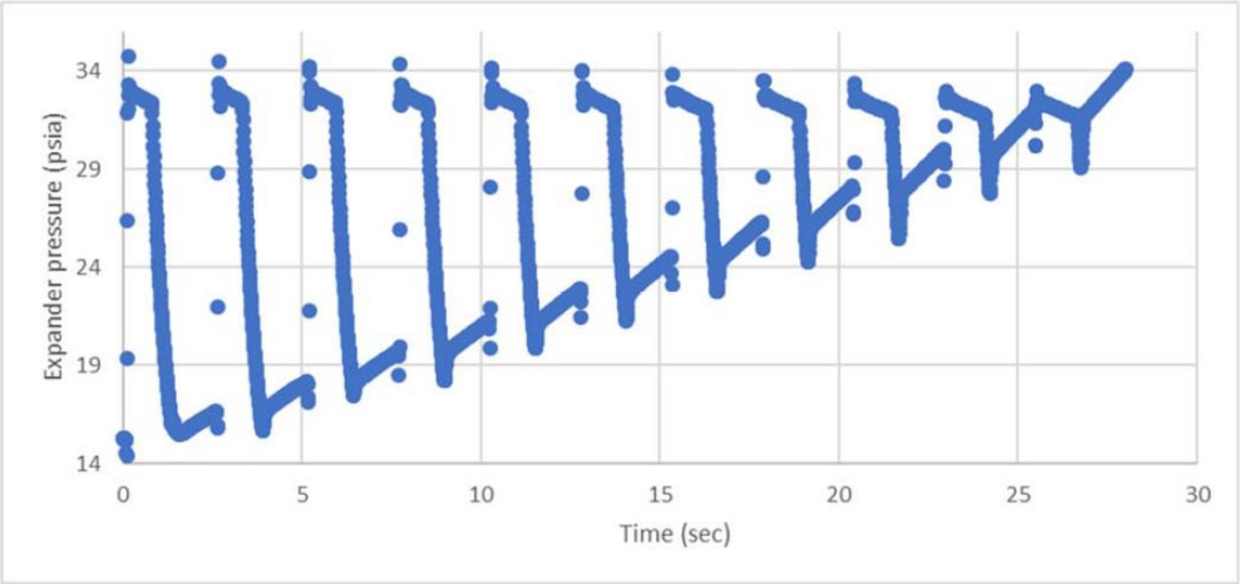



Test Apparatus Results

- Left: One expansion cycle
- Right: Expander filling a compressed nitrogen tank





Design of Expander Prototype: Model/Simulation

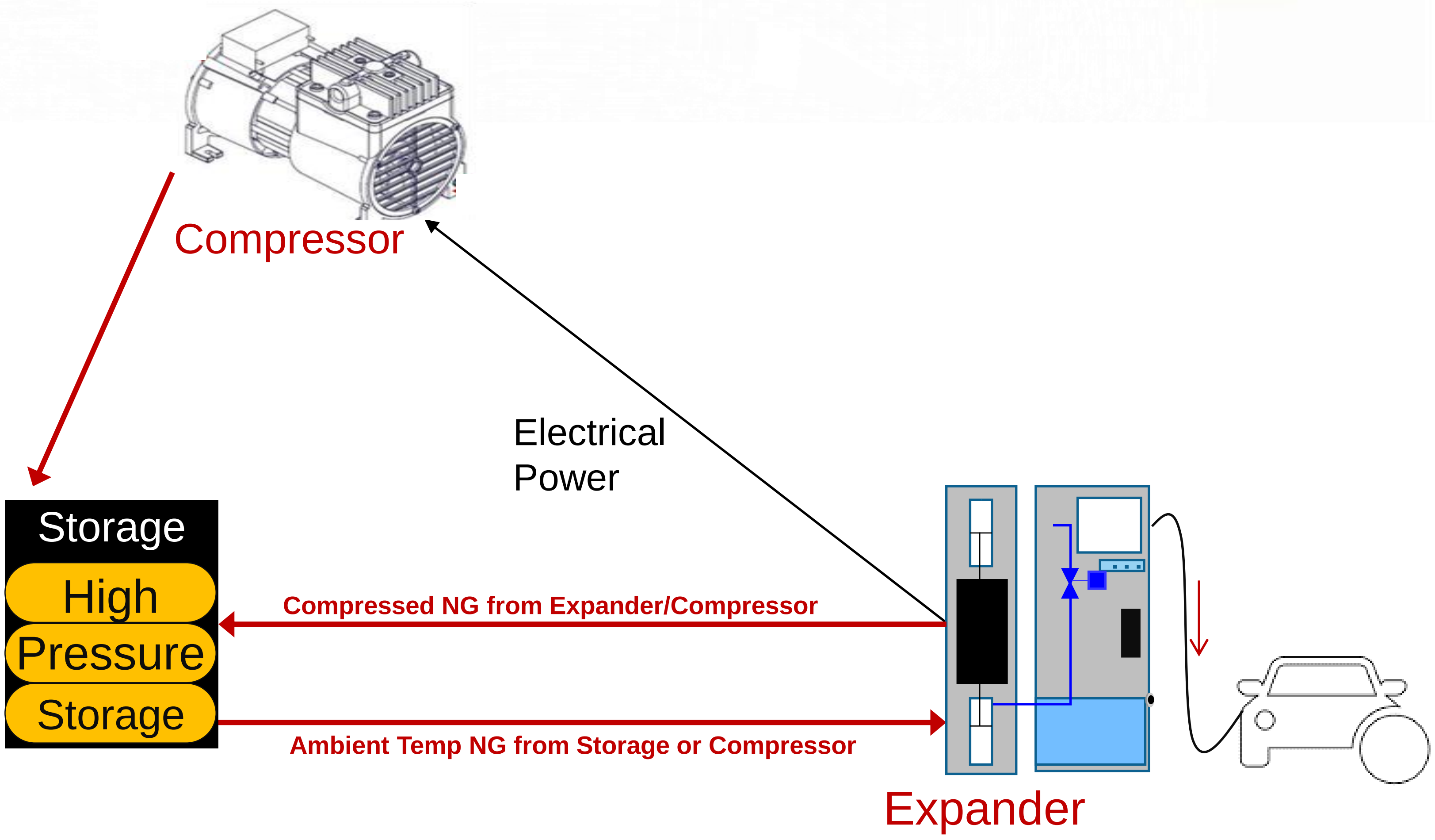
- Get simulation running with real gas properties using Matlab Simulink
- Achieve 100% efficiency in model
  - Inefficiencies include: Friction, heat transfer, valve timing & pressure drop
  - Friction and heat transfer can be "turned off"
  - Pressure drop can be minimized using large valves
  - Valve timing can be tuned to reach near 100% efficiency
- Reintroduce losses
  - Characterize above losses and add to simulation
- Design of experiment (DoE) to optimize expander design and performance

What’s Next?

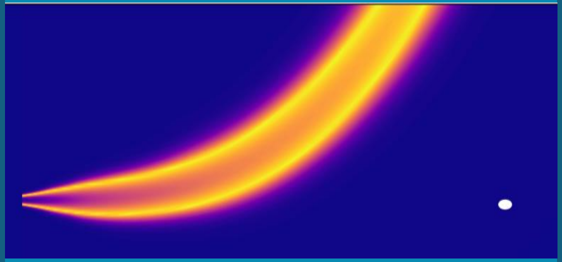
- Expander and Smart Stations: Move into final design and prototype build this year, testing starting in 2021
- Continue/Expand research on additional market segments
  - On-road engines and component improvements
  - Vehicle Demonstrations (hybrids, new applications,
  - Rail and Marine RD&D (including infrastructure)

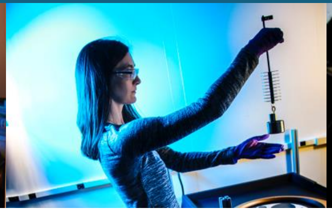
Expander Station Configuration

- Operation
  - System gets colder with fueling
  - Located near dispenser



Validation of Natural Gas Models Used in AltRAM





PRESENTED BY

Myra Blaylock

Cyrus Jordan – Graduate Intern

Ethan Hecht – Intern Mentor

Sandia National Laboratories

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SAND2020-1448C

AltRAM: Making alternative fuel safety science accessible through integrated tools

Integration platform for state-of-the-art alternative fuel safety models & data - **built to put the R&D into the hands of industry safety experts**

- AltRAM will provide a common platform for stakeholders conducting quantitative risk assessment and consequence analysis for hydrogen, natural gas, and propane autogas systems.
- Provide a scientific basis to ensure code requirements are consistent, logical, and defensible.
- Provide alternative fuel service providers a fast, effective way to analyze accident scenarios and compare the safety of system designs, facility and site designs, and operational environment parameters.

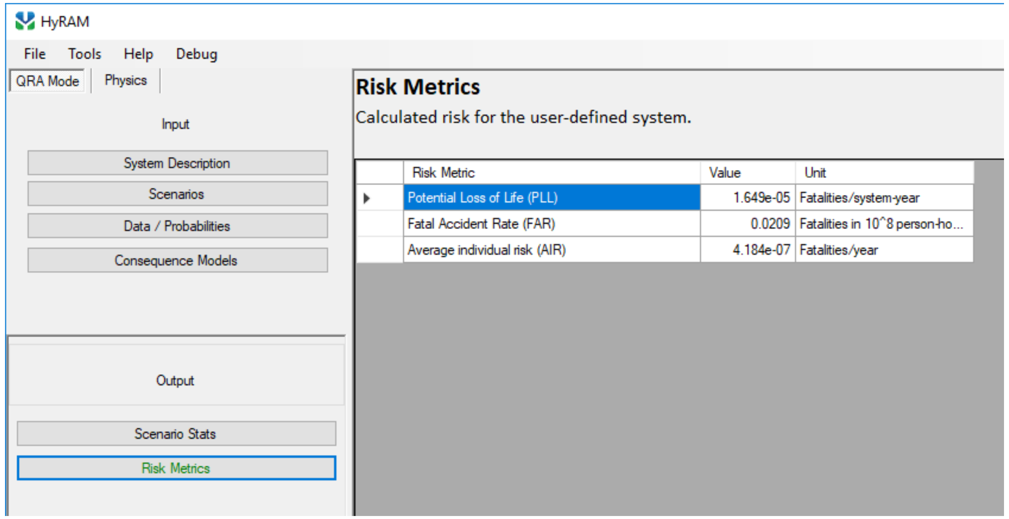
AltRAM: Making alternative fuel safety science accessible through integrated tools

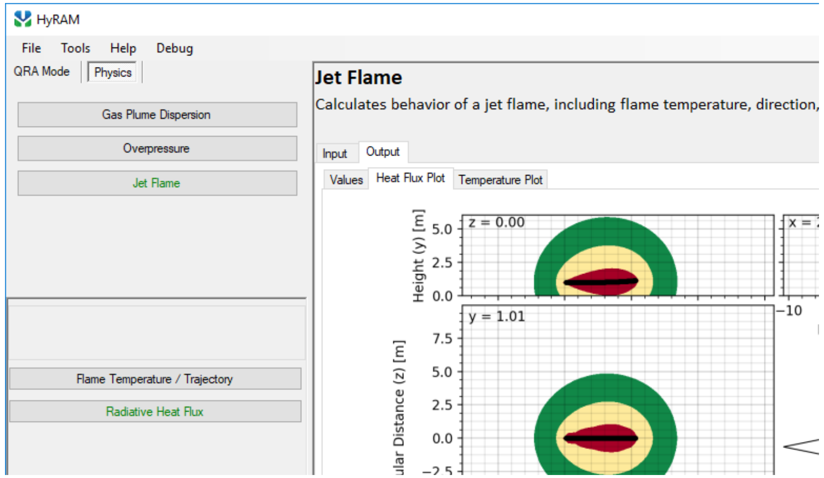
Core functionality:

- Quantitative risk assessment (QRA) methodology : fuel-specific for H_2, CNG, LNG, and LPG.
- Frequency & probability data for fueling component failures
- Fast-running, validated plume, flame, and overpressure models

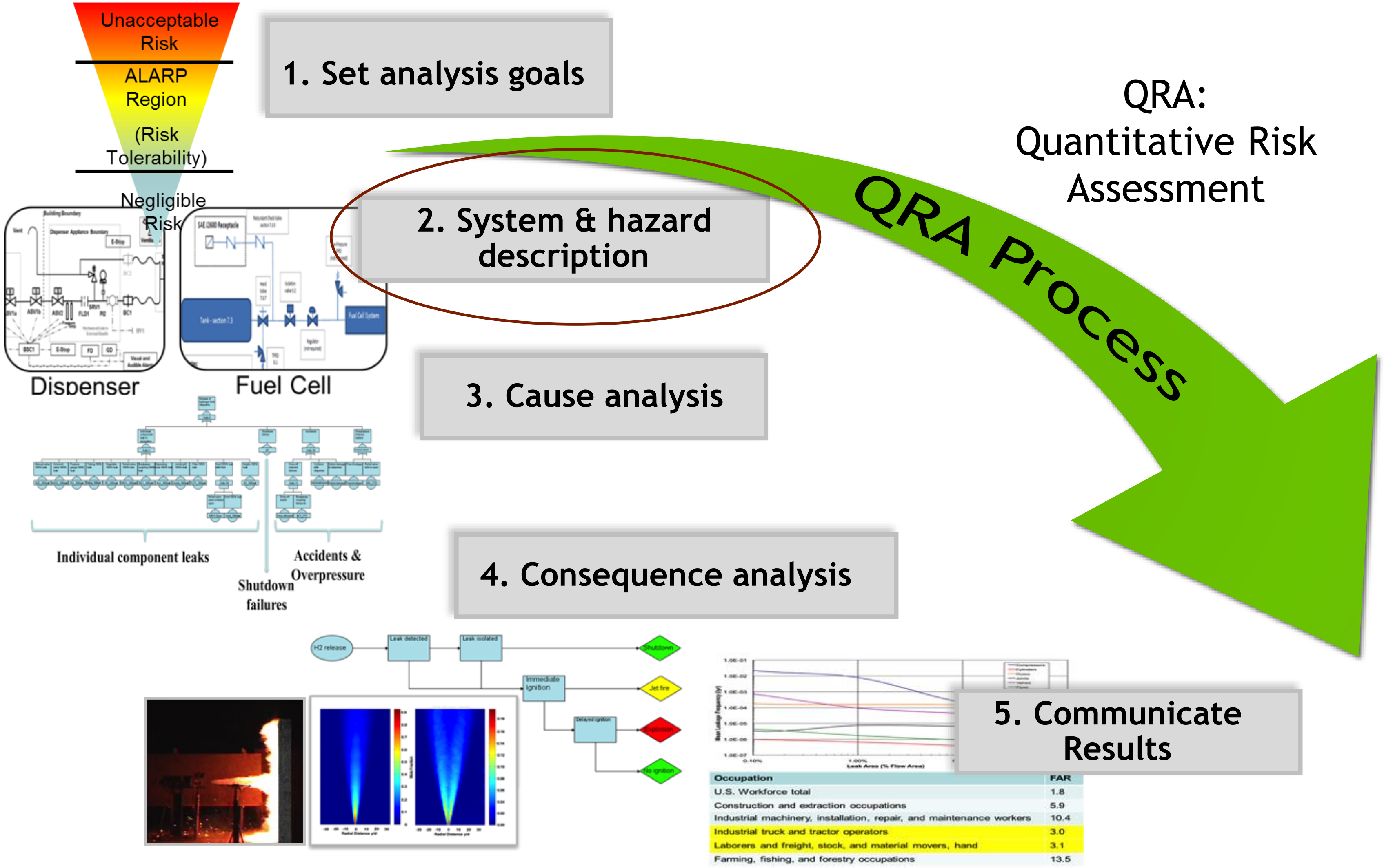
Key features:

- GUI & Mathematics Middleware
- Documented approach, models, algorithms
- Flexible and expandable framework; supported by active R&D





Building a Scientific Platform for Alternative Fuels QRA



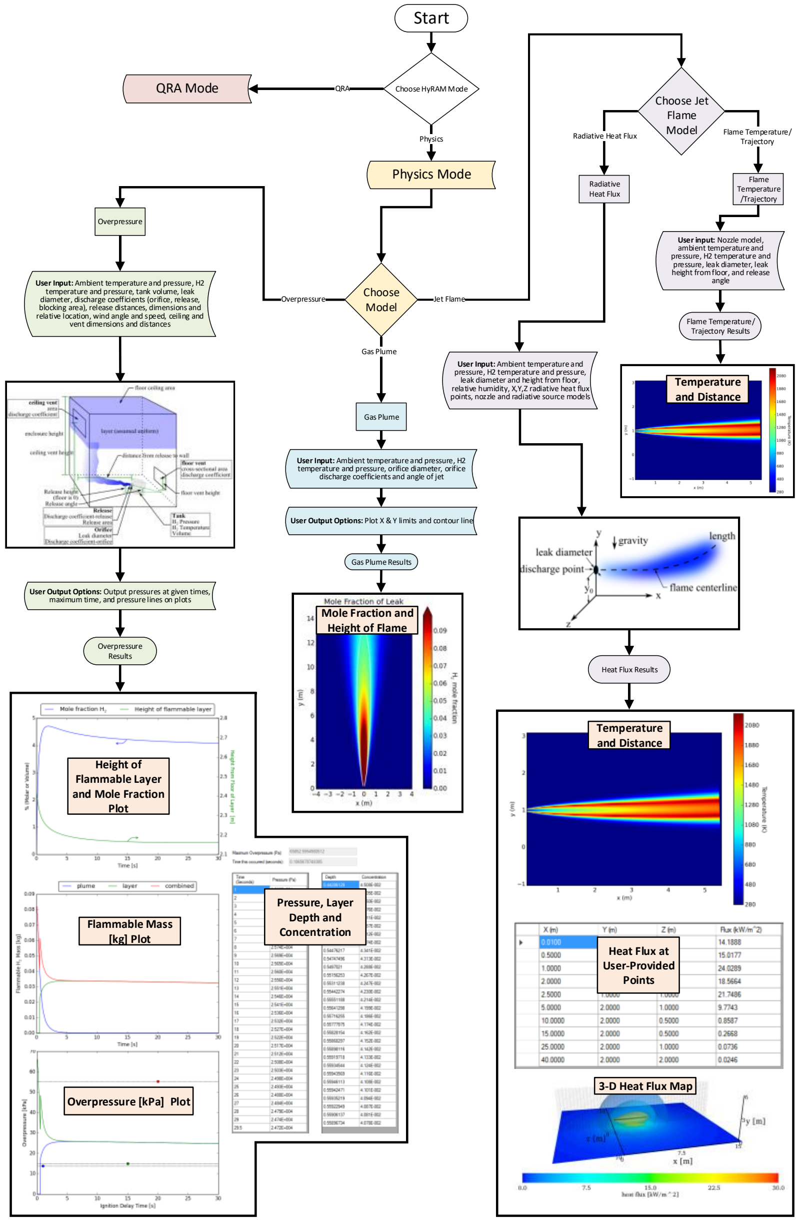
Major Elements of AltRAM Software: Physics Model

Physics models

- Properties of gases
- Unignited releases: Orifice flow; Notional nozzles; Gas jet/plume;
- Ignited releases: Jet flames; overpressures in enclosures
- Accumulation in enclosures*

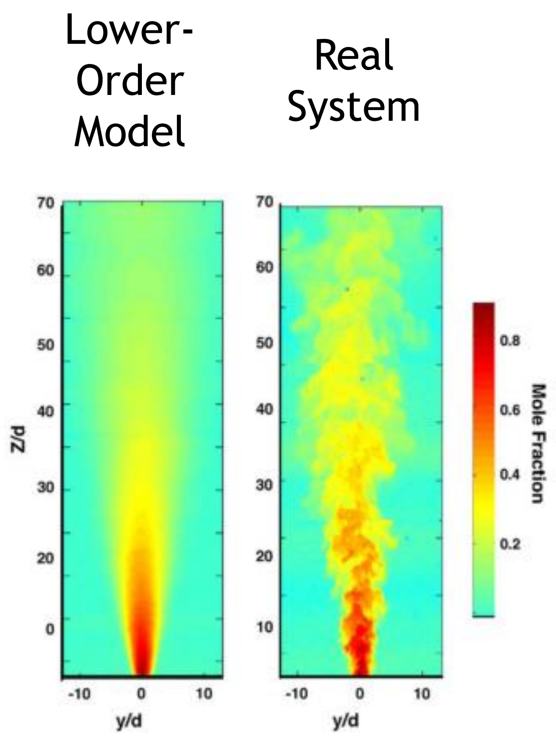
Documentation

- Algorithm report
- User guide



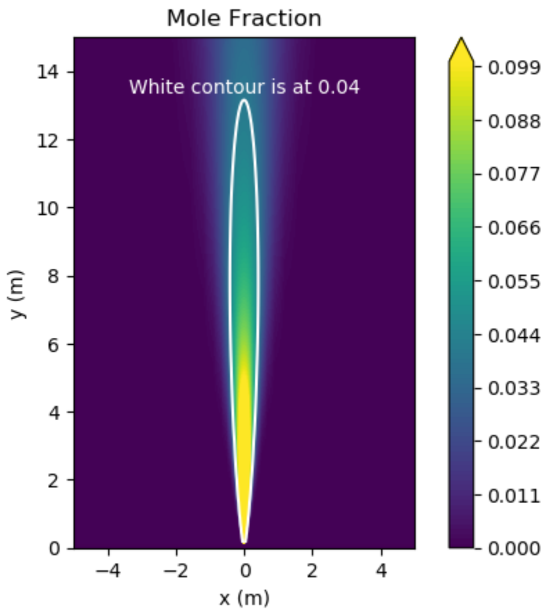
Benefits of Analytical Lower Order Models

- Short run-time
- Modeling expert not required
- Useful for quantification
  - If a leak occurs, how far away does the hazard get?
- Useful for comparisons
  - What is the effect on safety if a system size is reduced?

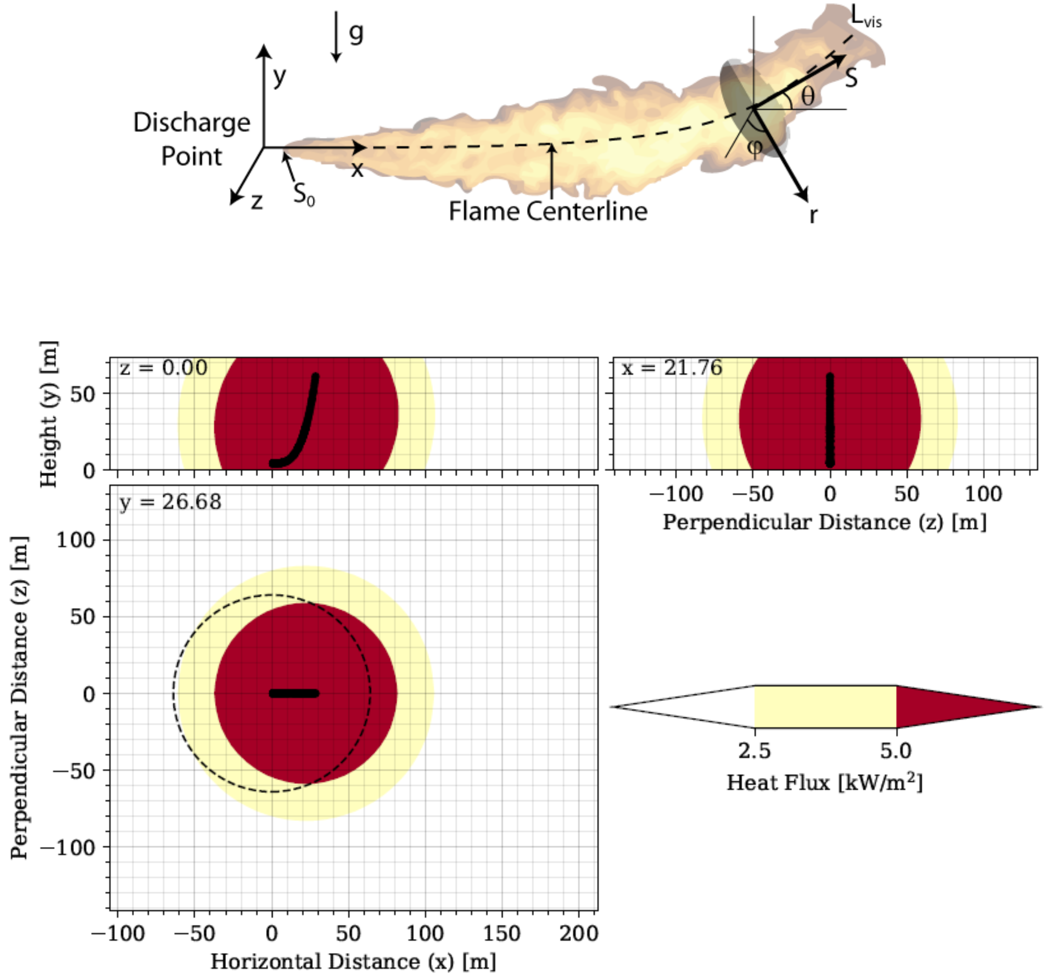


Validation of AltRAM Physics Models

Un-ignited Jet Plume



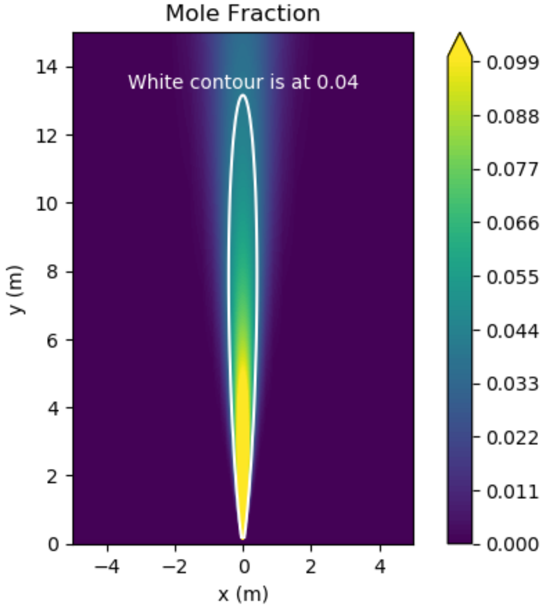
Jet Flame Temperature



CNG Plume Models

Validation of AltRAM Physics Models: Plumes

Un-ignited Jet Plume

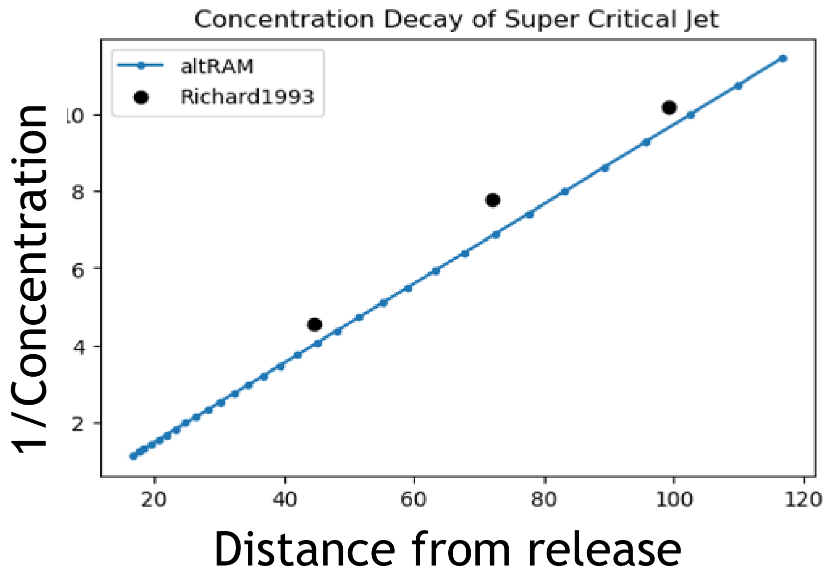


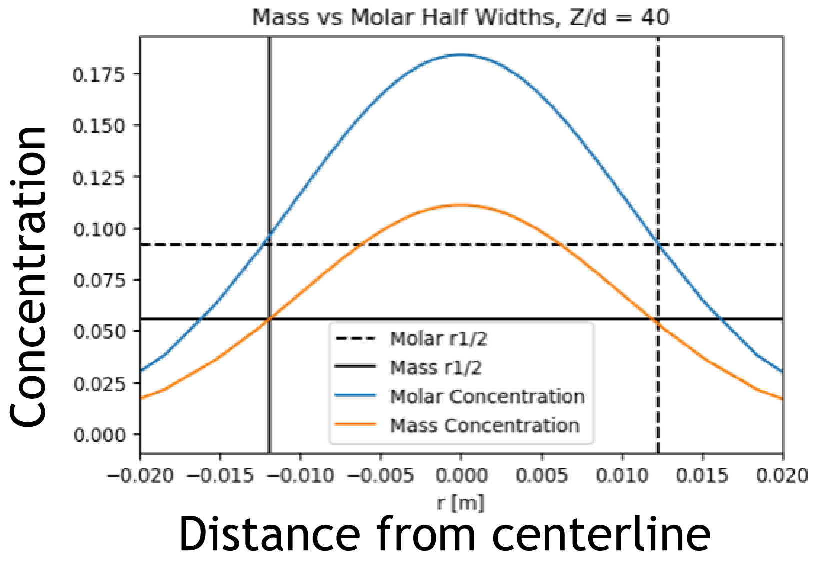
Centerline Concentrations/ Inverse Concentrations

- Plotted against distance from release point
- Slope : "k"

Half Width

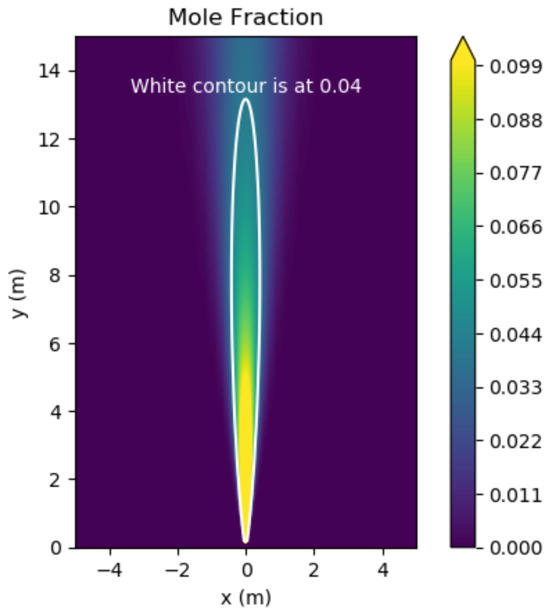
- Distance from centerline where concentration is half of the centerline
- Spread Rate:
  - When plotted against distance from release point
  - Slope : "m"





AltRAM Physics Models: Plume Model

Un-ignited Jet Plume



Published Experiments:

Sub-Sonic Flow

- Birch et al. (1978)
- Richard and Pitts (1993)
- Birch et al. (1984)

Choked Flow

- Birch et al (1984)
- Brennan(1984)
- Hankinson (2000)
- Birch et al (1988)
- Birch et al (1987)

CNG Plume Models :Sub-Sonic Flow

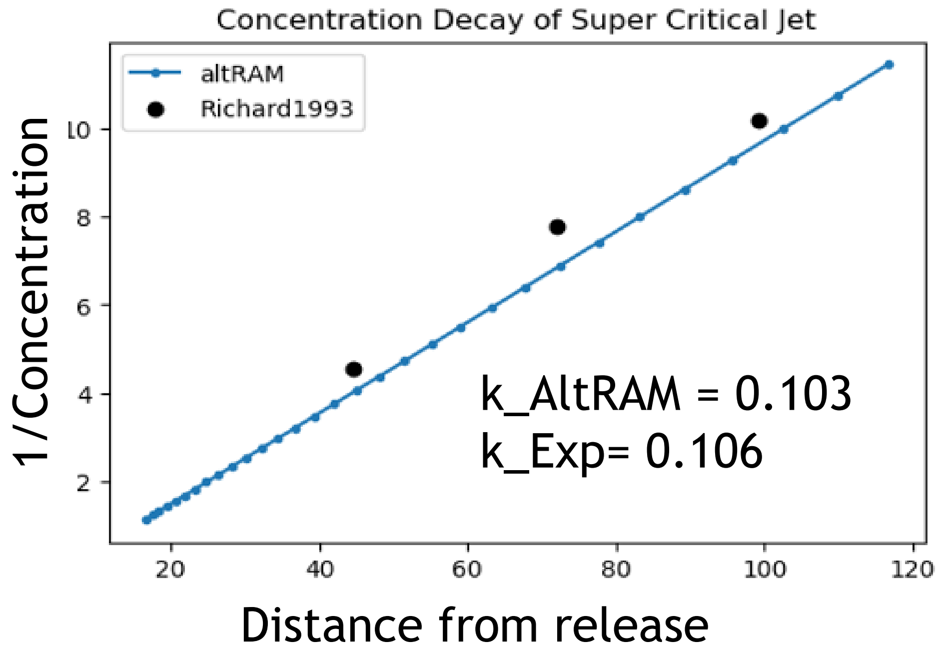
-Subsonic Concentrations are (Slightly) Underpredicted
-Half Widths Match Well

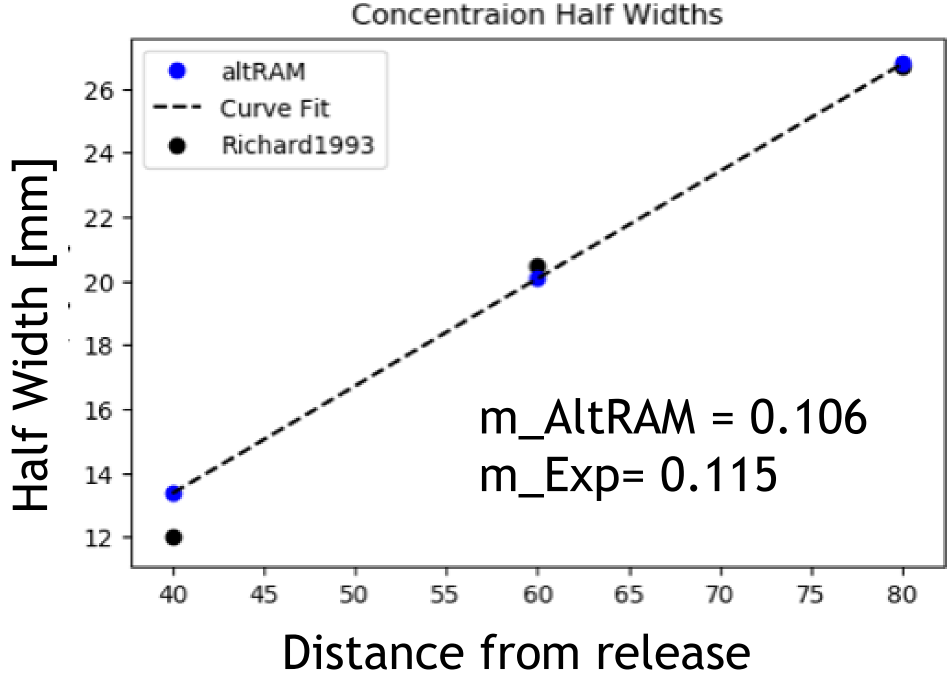
Richard and Pitts (1993)

Experimental Parameters

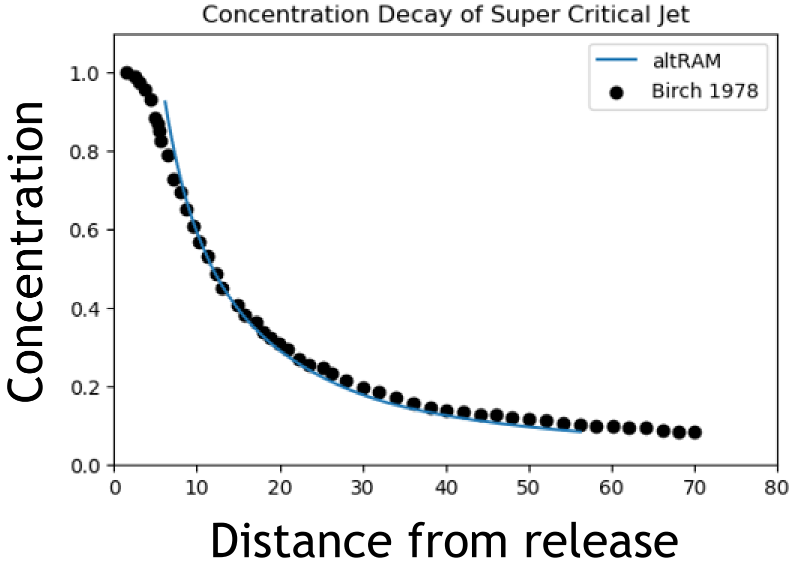
- Flow Conditions: **Subsonic**
- Gas Conditions:
  - Re = 25,000
- Gas Assumptions:
  - T = ambient, P = ambient, Cd = 1.0
- Nozzle Parameters:
  - D = 6.35mm
  - Pointing Upward
- Solutions
  - k Est = 0.103; k Lit = 0.106 (Slope)
  - **m Est = 0.106;** m Lit = 0.115 (Spread rate)

NOTE* Reported M Values
m = 0.11 – (Chen & Rodi 1980)
m = 0.106 – (Fischer 1979)





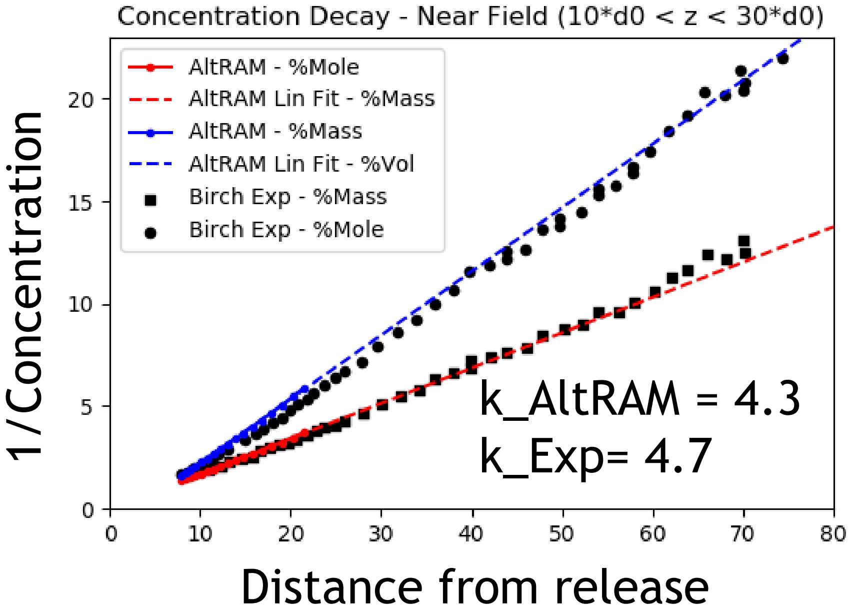
Near Field Concentration Trends are Better Than Far Field

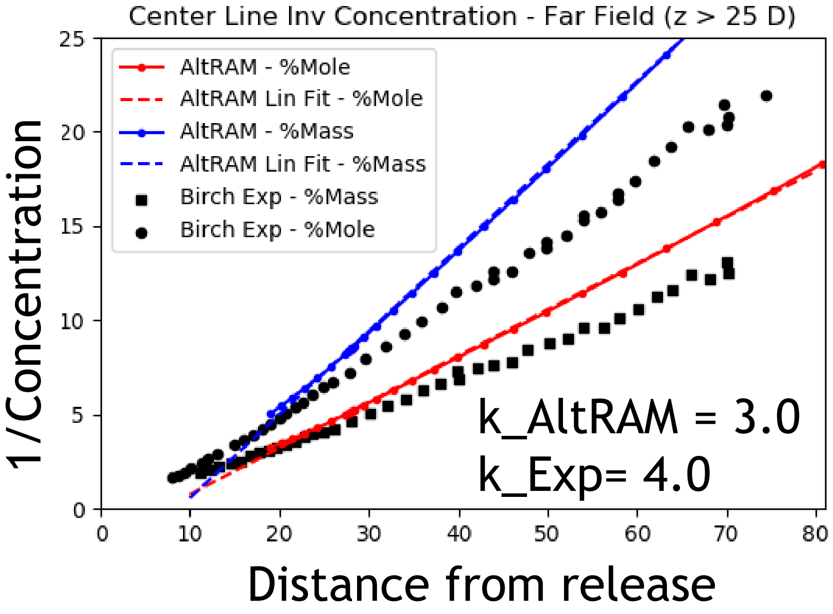


Birch et al. (1978)

Experimental Parameters

- Flow Conditions: **Subsonic**
- Gas Conditions:
  - Re = 16,000
- Gas Assumptions:
  - T = ambient, P = ambient, Cd = 1.0
- Nozzle Parameters:
  - D = 12.65mm ~ 0.5",
  - Pointing Upward
- Solutions (Slope)
  - k_Near Est = 4.31 ; k_Near Lit = 4.7
  - k_Far Est = 3.03 ; k_Far Lit = 4.0



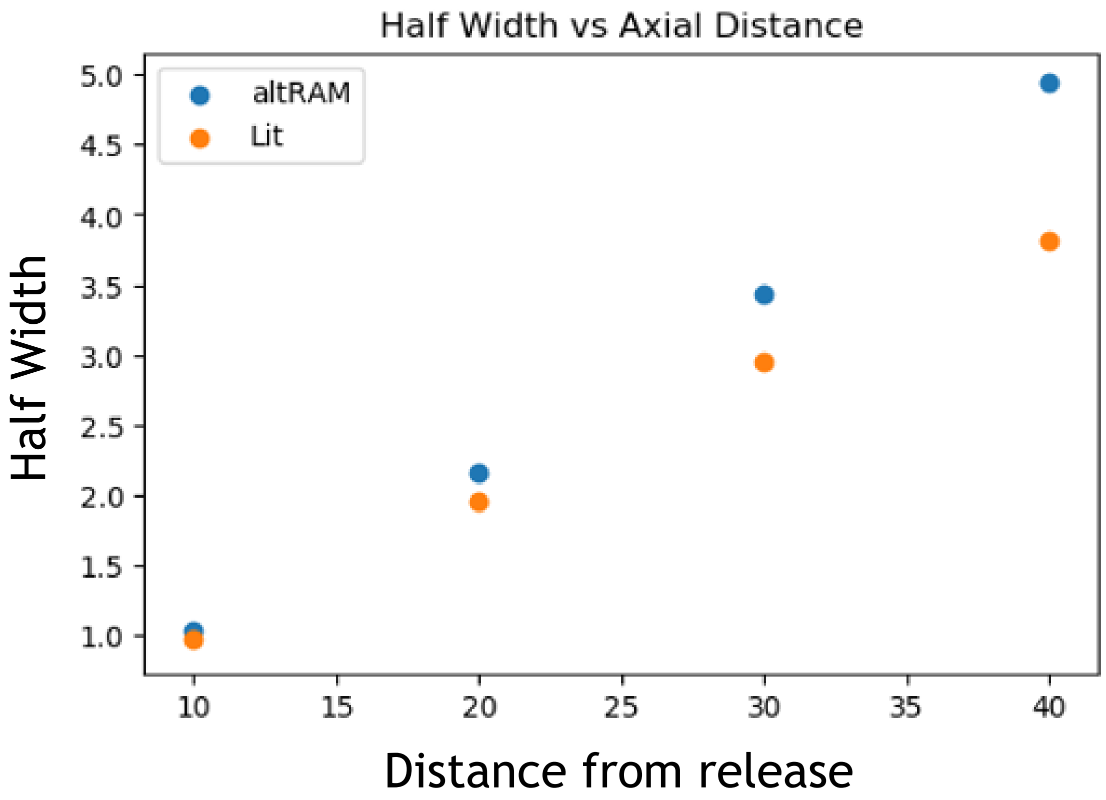


Near Field Half Width Values are Better Than Far Field

Birch et al (1978)

Experimental Parameters

- Flow Conditions: **Subsonic**
- Gas Conditions:
  - Re = 16,000
- Gas Assumptions:
  - T = ambient, P = ambient, Cd = 1.0
- Nozzle Parameters:
  - D = 12.65mm ~ 0.5"
  - Pointing Upward



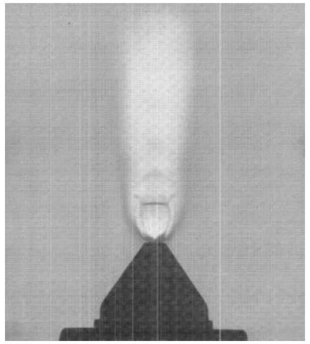
CNG Plume Models: Choked Flow

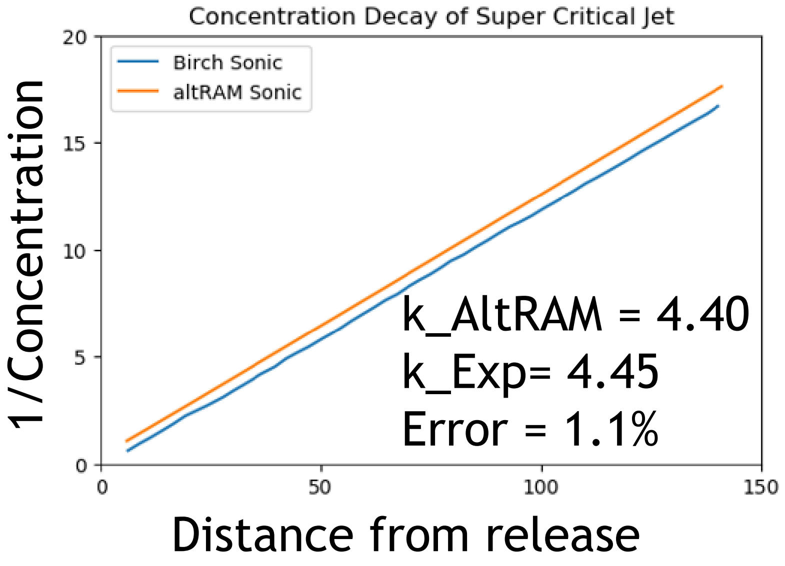
Sonic Plumes Match Better than Subsonic

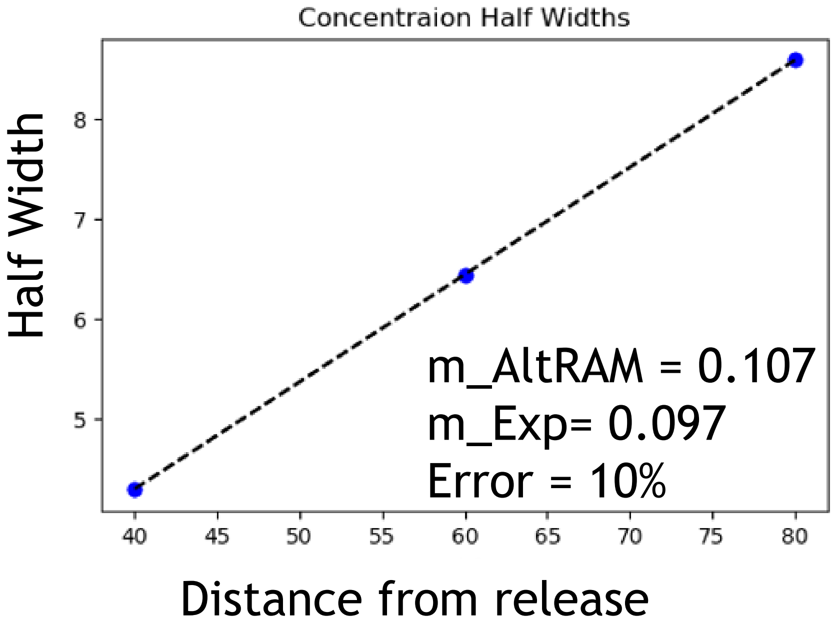
Birch et al (1984)

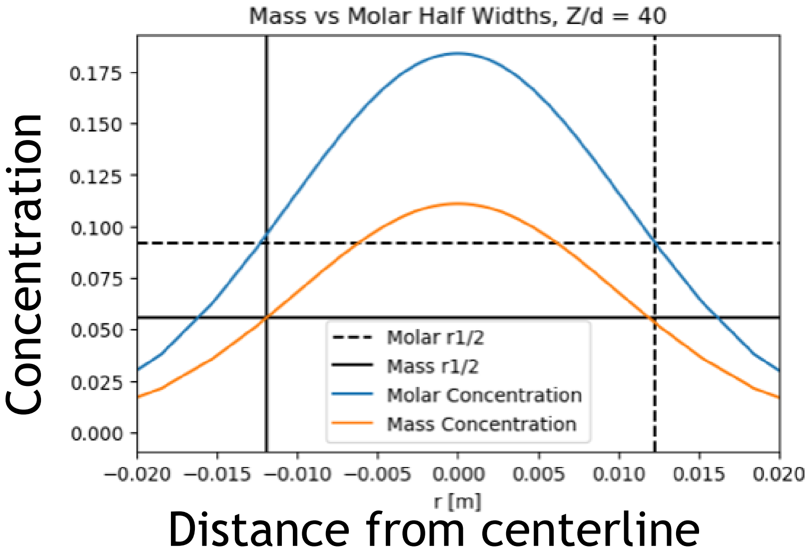
Experimental Parameters

- Flow Conditions: **Sonic**
- Gas Conditions:
  - T = ambient, P = 3.5 – 71 [bar]
- Nozzle Parameters:
  - D = 2.7mm, Cd = 0.85
  - Pointing Upward
- Solution
  - k Est = 4.398; k Lit = 4.45
  - m Est = 0.107; m Lit = 0.097
  - k Err = 1.1%; m Err = 10.3%









Data Collapses with Normalization by Nozzle Diameter

Birch et al (1984)

Experimental Parameters

- Flow Conditions: **Sonic**
- Gas Conditions:
  - T = ambient, P = 3.5 – 71 [bar]
- Nozzle Parameters:
  - D = 2.7mm, Cd = 0.85
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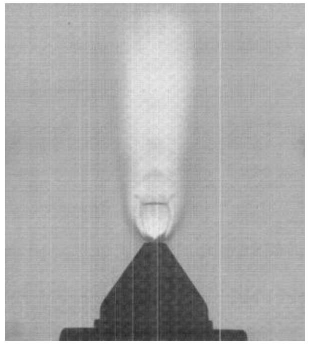
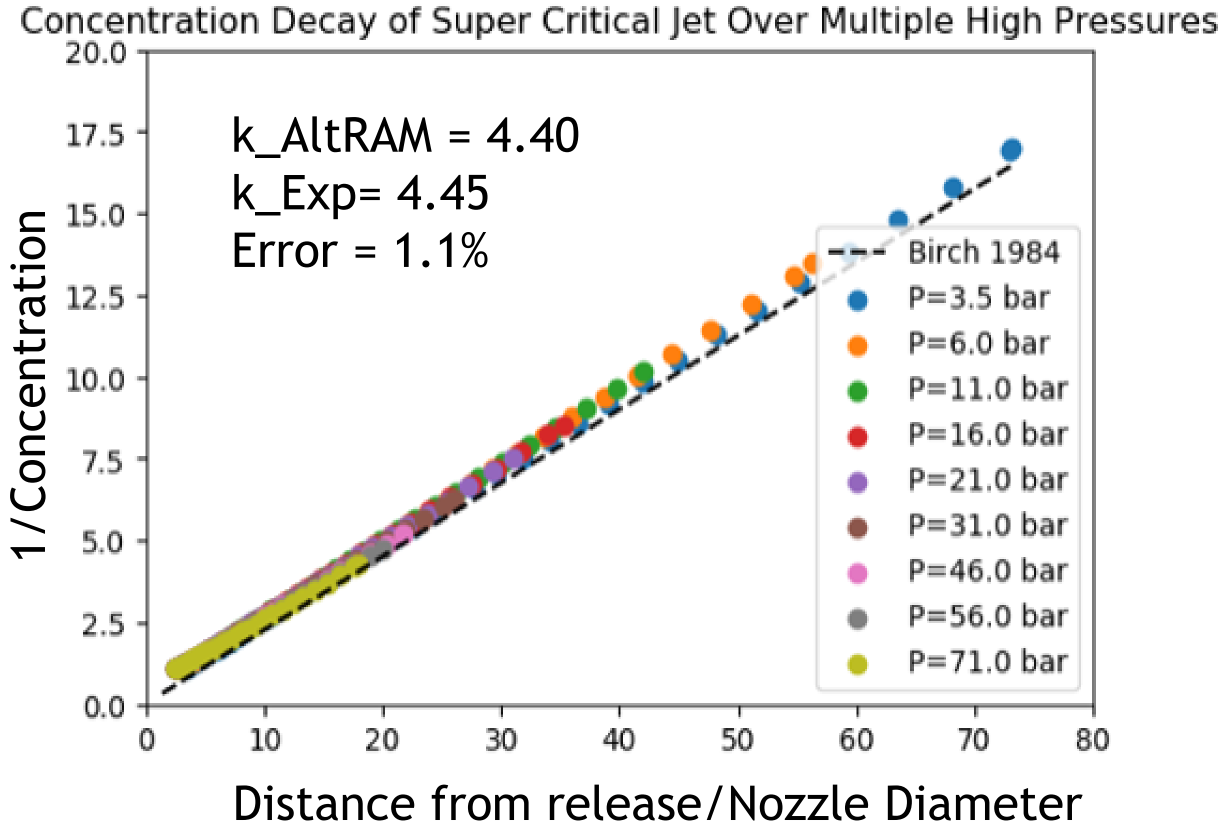
- Solution
  - k Est = 4.398; k Lit = 4.45



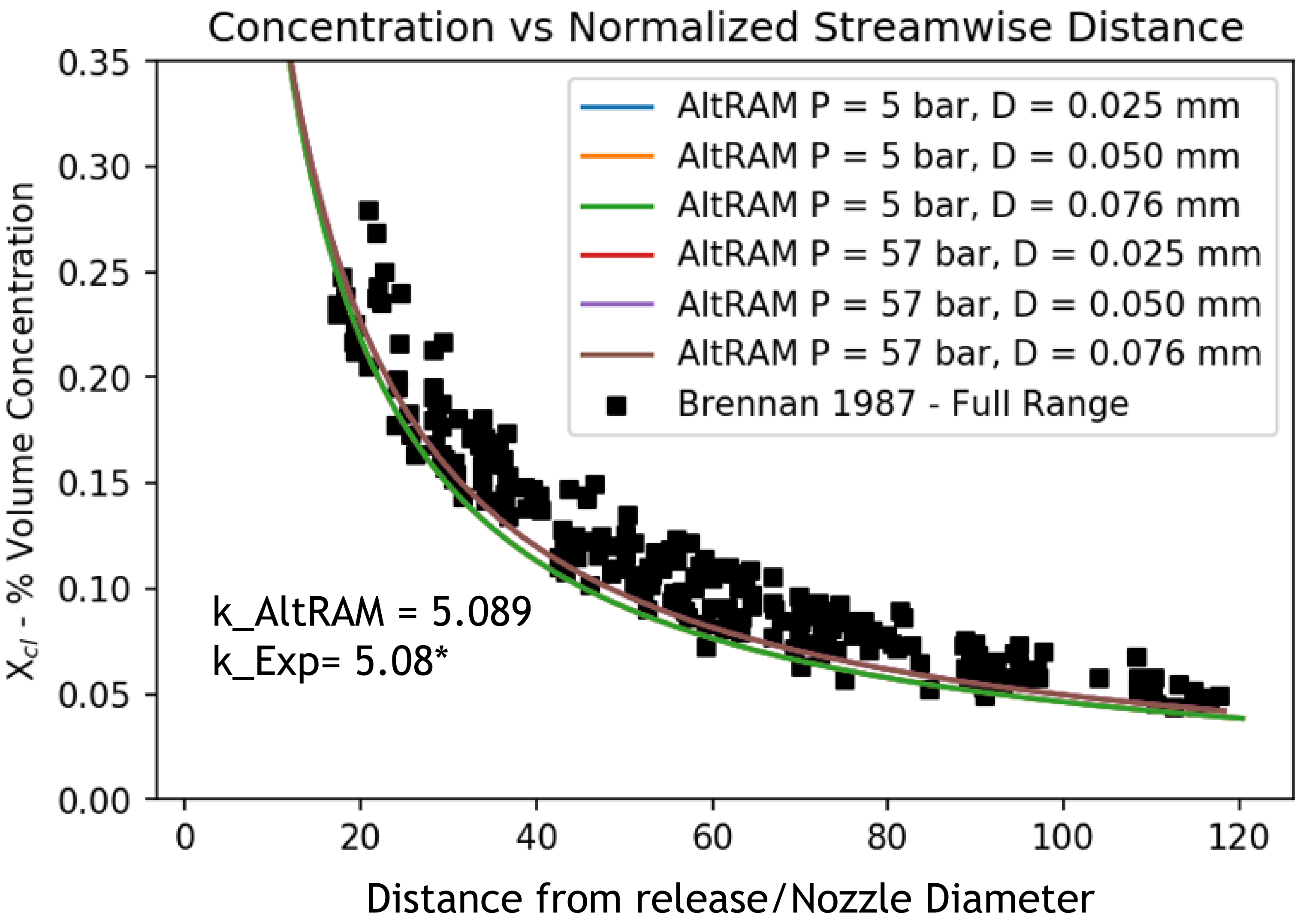


Data Collapses with Normalization by Nozzle Diameter

Brennan(1984)

Experimental Parameters

- Flow Conditions: **Sonic**
- Gas Conditions:
  - T = ambient, P = 70–110 [bar]
- Nozzle Parameters:
  - D = 25, 50, 76 mm
  - Cd = 0.85
  - Pointing Upward
- Wind:
  - Speed = 0-4, 4-6, 6-11 [m/s]
- Results:
  - klit = 5.08 for 0-4 m/s wind
  - ksim = 5.089



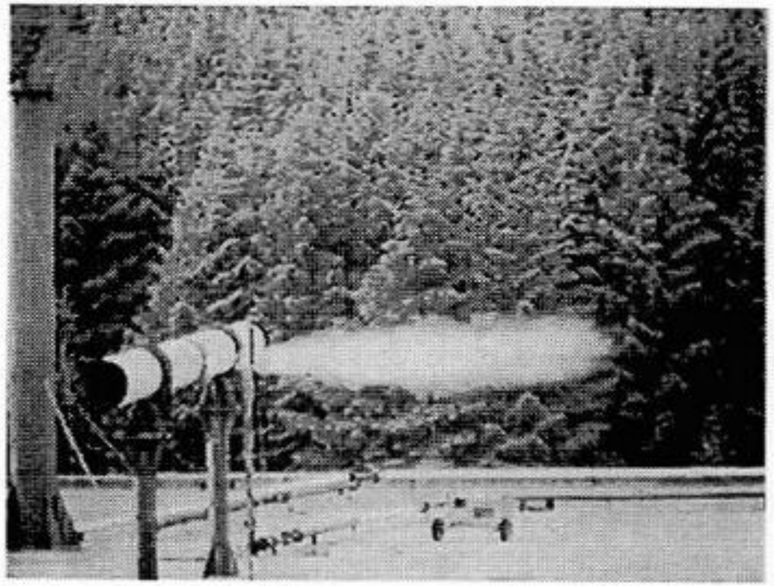
2D Concertation Maps Match

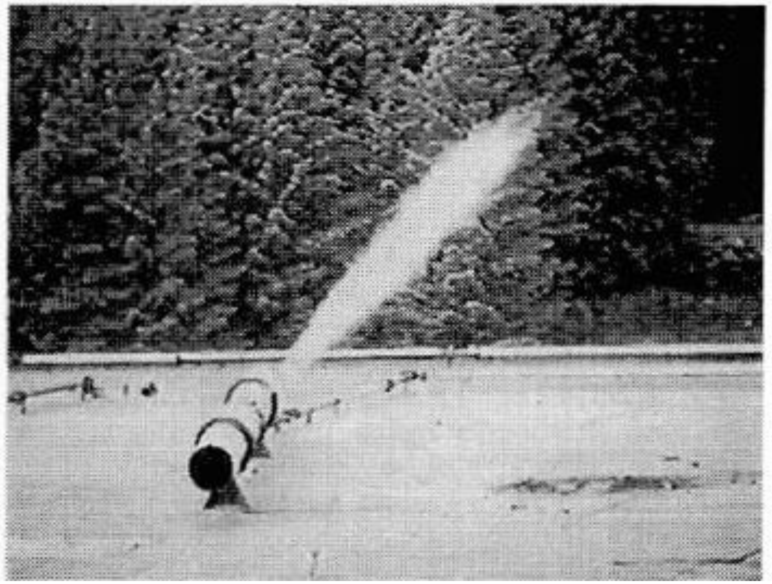
Hankinson (2000)

Experimental Parameters

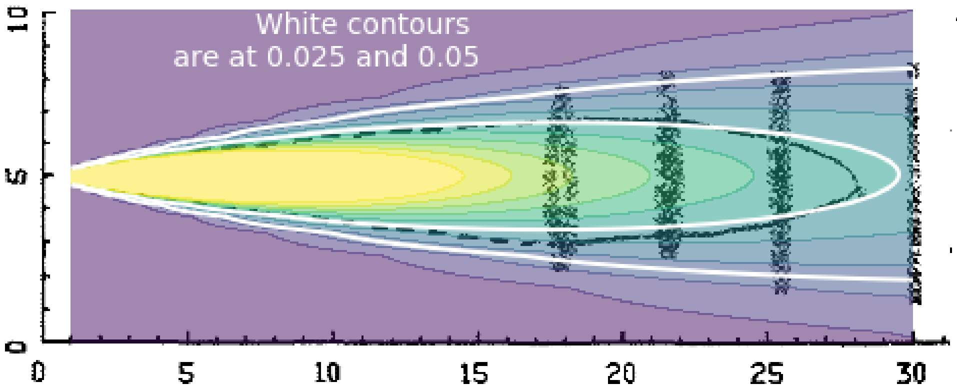
- Flow Conditions: **Choked**
- Gas Conditions:
  - P = 20 [bar], T = ambient
- Gas Assumptions:
  - T = ambient, P = ambient
- Nozzle Parameters:
  - D = 75mm
- Wind Conditions:
  - Direction = Coflow
  - Speed =7.2, 8.0 [m/s] (16-18 mph)
- Comments:
  - Wind increases turbulence thus increasing mixing / diffusion. Thus horizontal concentration lowers faster than simulation.
  - In 45° release vapor is being convected further horizontally in buoyant region due to wind.

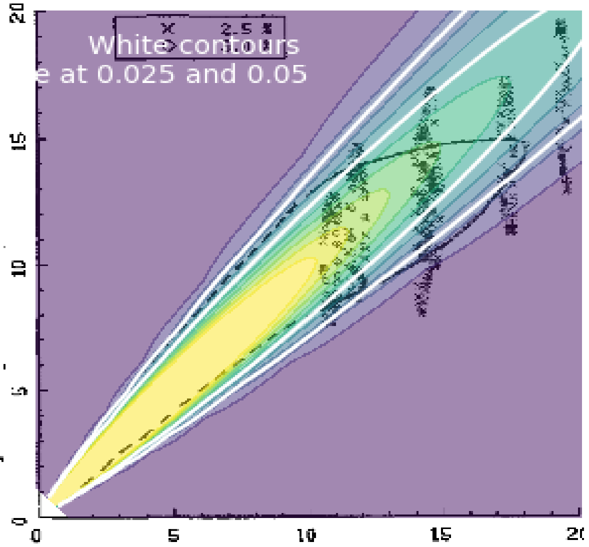
Test Configuration





Simulated Results





Take Aways from Plume Model Validation

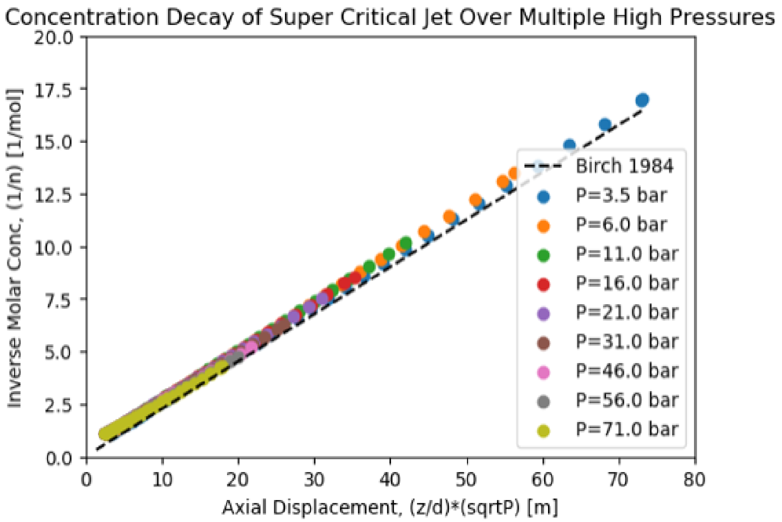
AltRAM models match well to multiple experiments

- Along the centerline, Half Width, 2D Plots

Choked flow measurements have smaller error than subsonic flow

For subsonic flow, it is more accurate to extrapolate from near field values than use the calculated far field values

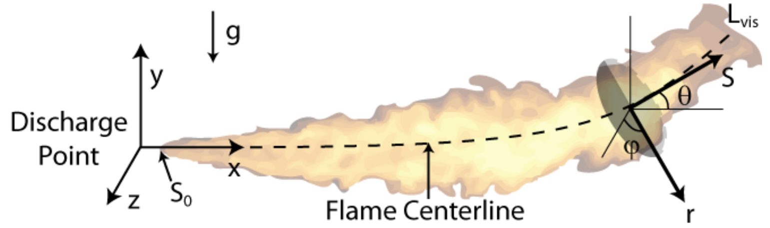
Data trends collapse when normalized: good indication for lower order models!



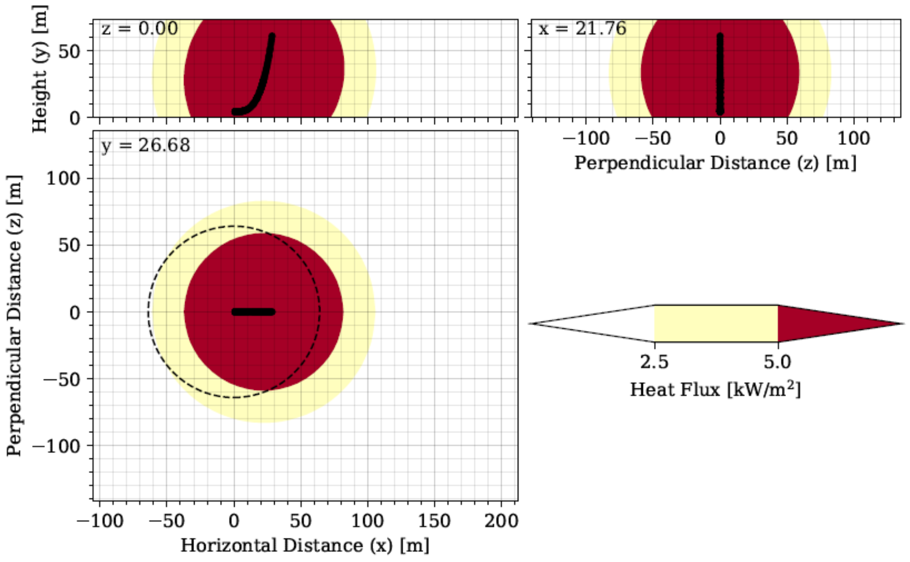
CNG Flame Models

Validation of AltRAM Physics Models: Flames

Jet Flame Temperature

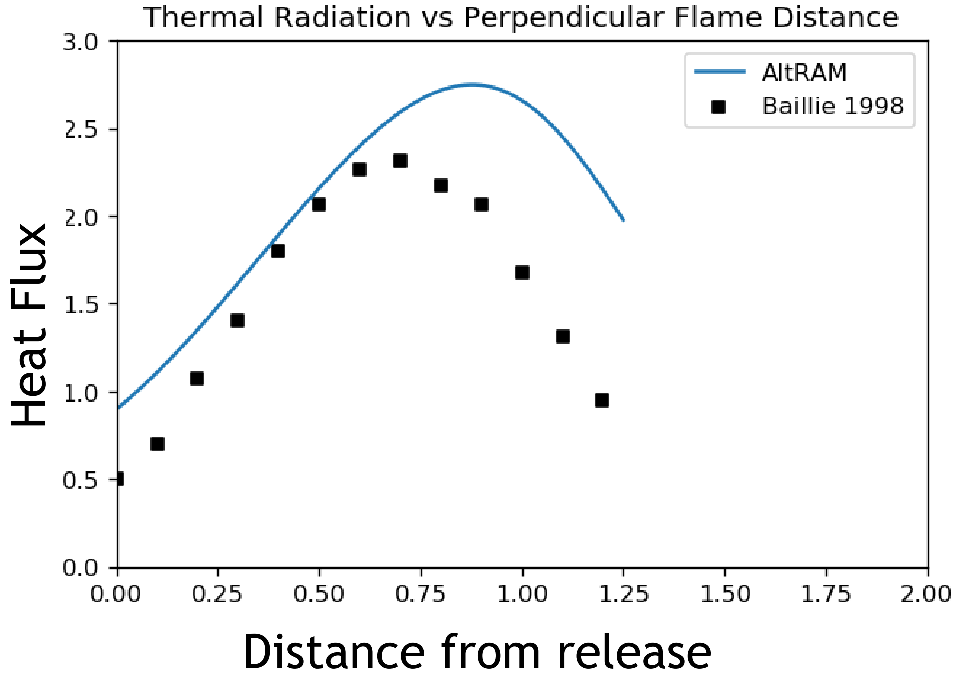


Jet Flame Heat Flux



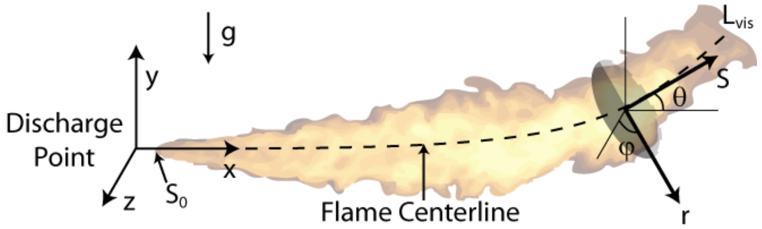
Heat Flux:

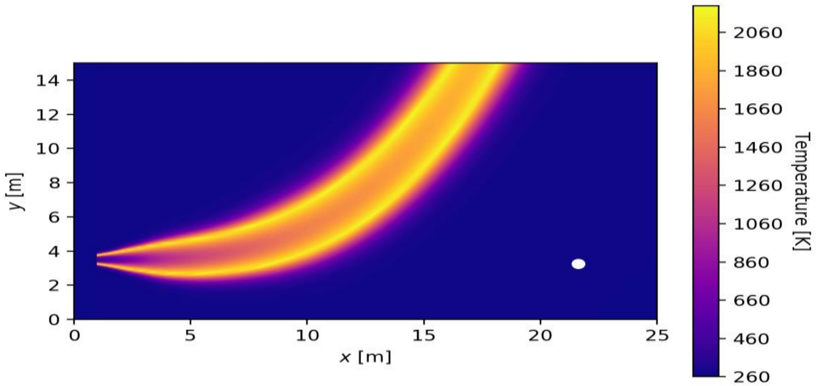
- Model calculates entire area
- Points that match experimental measurements are extracted
- Plotted against distance from release point



AltRAM Physics Models: Jet Flame Model

Flame Model





Published Experiments:

Sub-Sonic Flow

- Baillie (1998)

Choked Flow

- Lowesmith, et al. (2012)
- Hankinson, et al. (2000)
- Johnson (1994)
- Lowesmith (2013)
- Hankinson (2000)

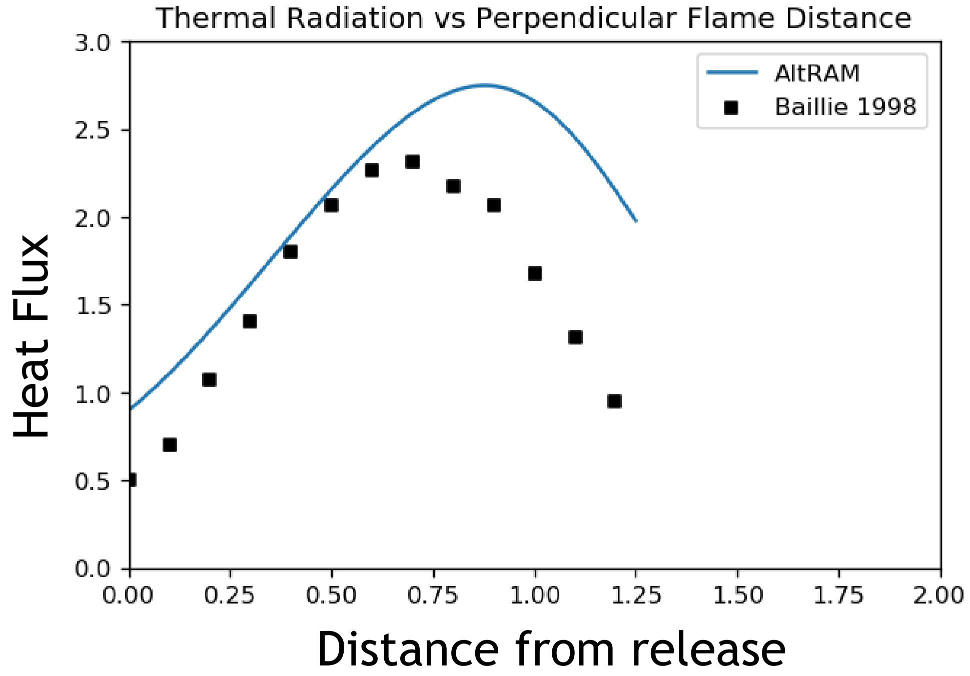
CNG Flame Models: Sub-Sonic Flow

Model Overpredicts Heat Flux

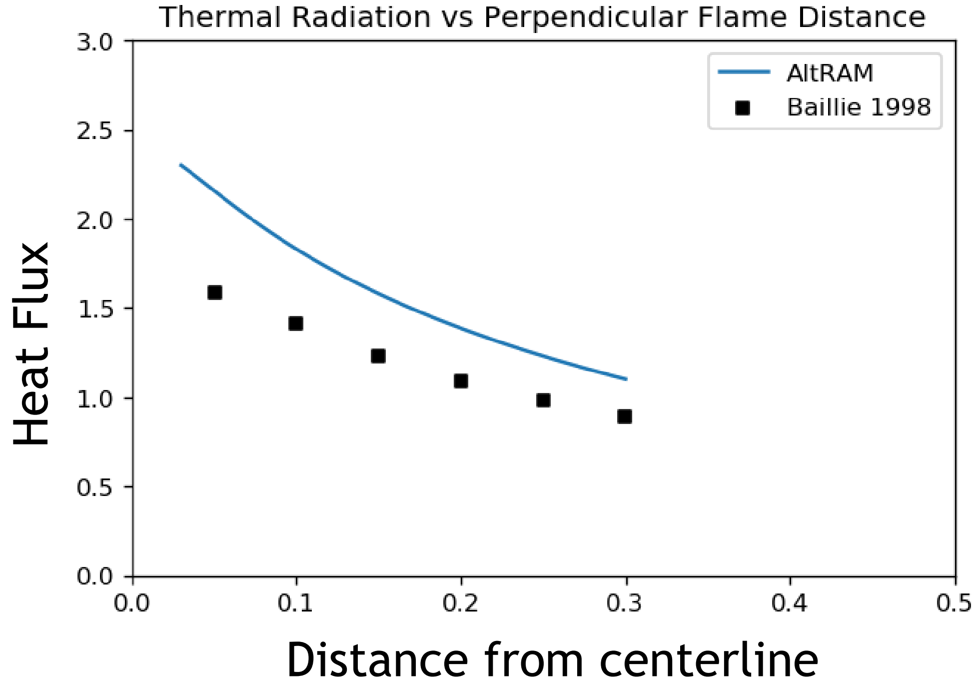
Baillie (1998)

Experimental Description:

- Jet Type: **Subsonic Lab Flame**
- Gas Conditions:
  - Pg = assumed ambient
  - Ug = 20 [m/s]
  - Tg = 267, 279, 281[k]
  - Composition = 99.99% CH4
- Ambient Conditions:
  - Ta, Pa = assumed standard ambient
- Nozzle Parameters:
  - D = 8.6 [mm]
  - Pointed upward
- Wind Conditions:
  - None
- Error Contributions:
  - Annular channel (ø23mm) Co-flow used to rim-stabilize flame



Vertical



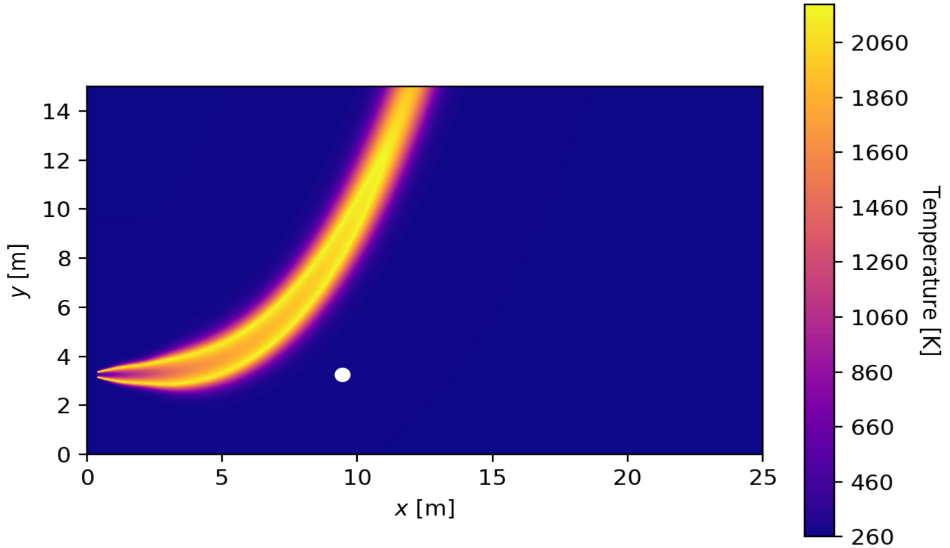
Axial

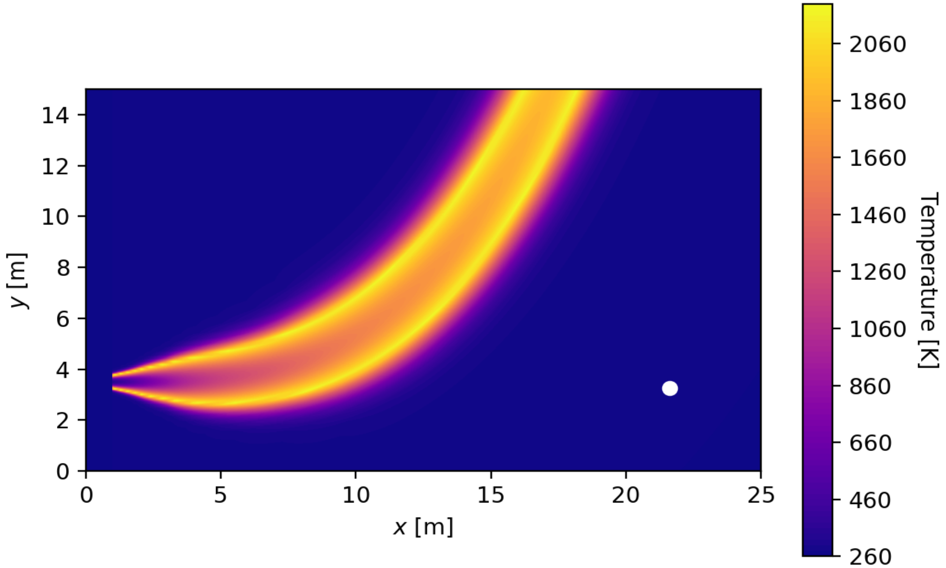
CNG Flame Models: Choked Flow

Flame Validation Observations

Buoyancy and Light Up Distance – Results Overpredict

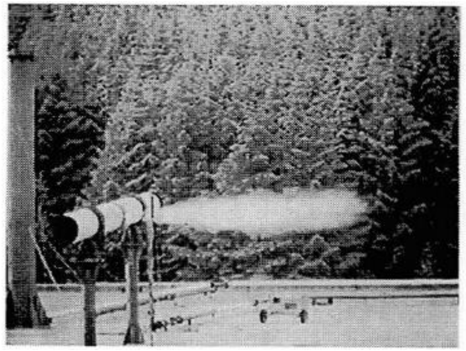
Lowesmith 2012

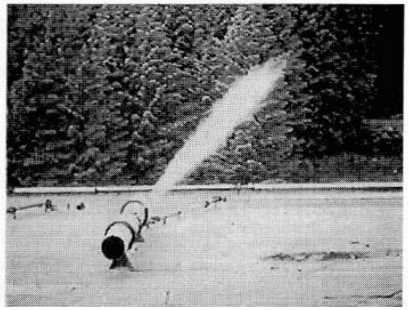


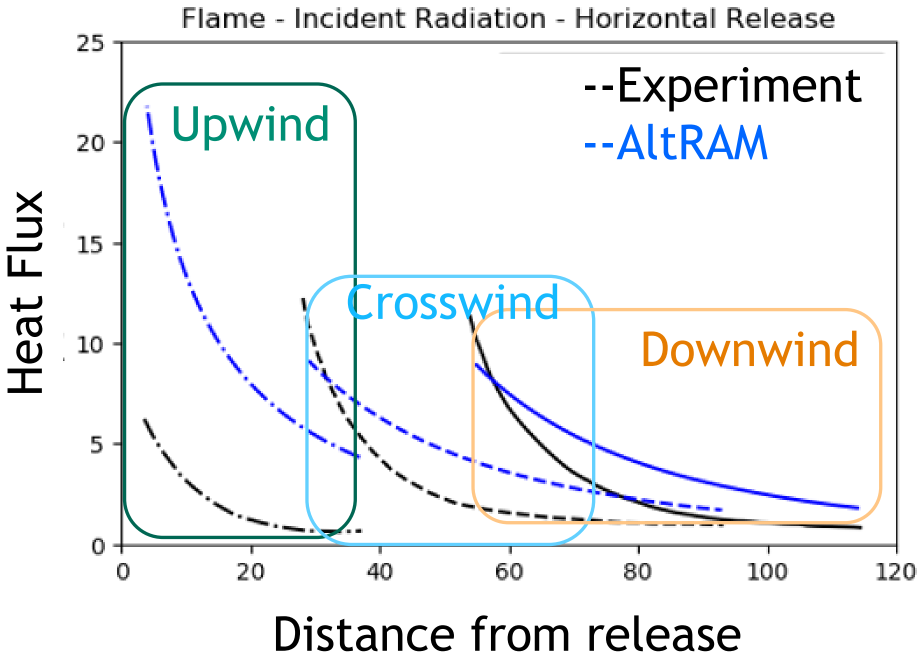


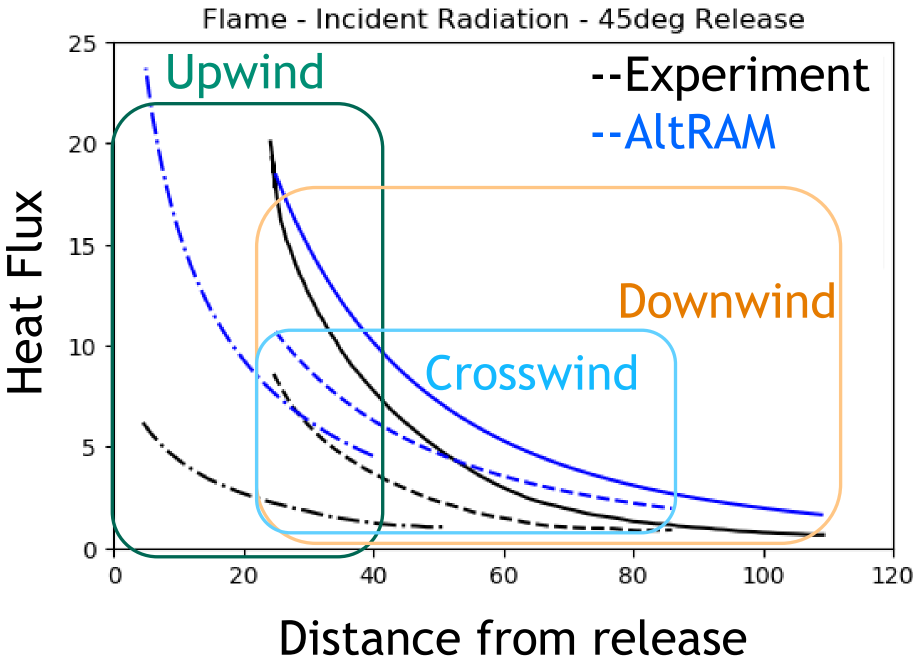
Models Overpredict Heat Flux

Hankinson (2000)









Exception: Model Underpredicts Heat Flux

Johnson (1994)

Experimental Description:
Large scale horizontal releases (3 exps).

- Jet Type: Horizontal Under Expanded Jet
- Release Direction = East
- Gas Conditions:
  - Pg = 2.0, 11.1, 66.1 [barg]
  - Tg = 267, 279, 281[k]
  - Composition = 94% CH4, 5.31% ethane
- Ambient Conditions:
  - T = 281, 282, 286 [k],
  - P = ambient
- Nozzle Parameters:
  - D = 152, 75, 20 mm
- Wind Conditions:

Wind measurement	test 1	test 2	test 3	unit
Velocity	0.3	3.9	6.9	m/s
Direction	326 (NW)	271 (W)	269 (W)	° from N

JOHNSON *et al.*

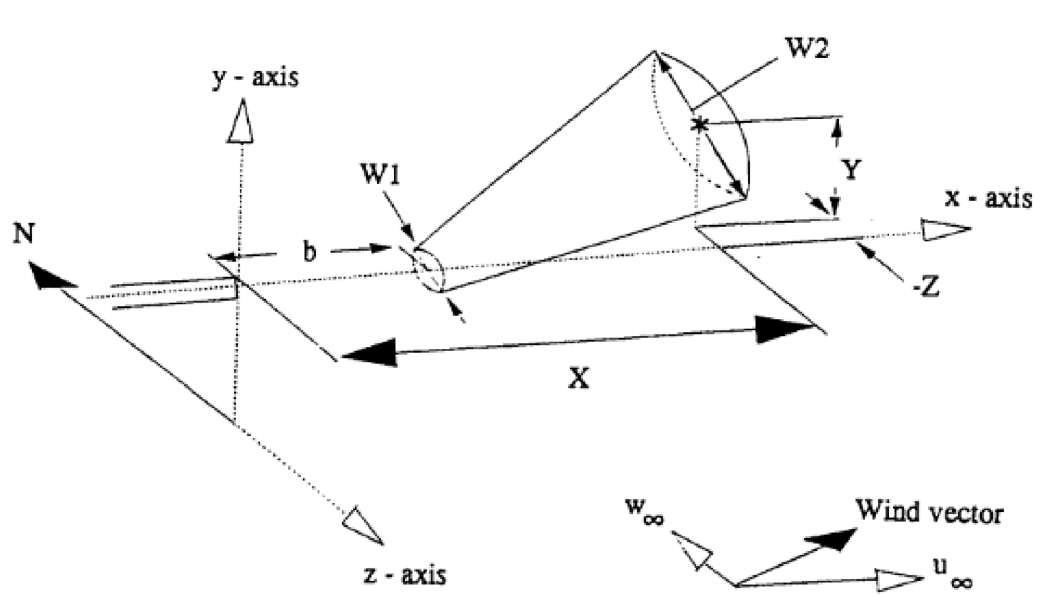
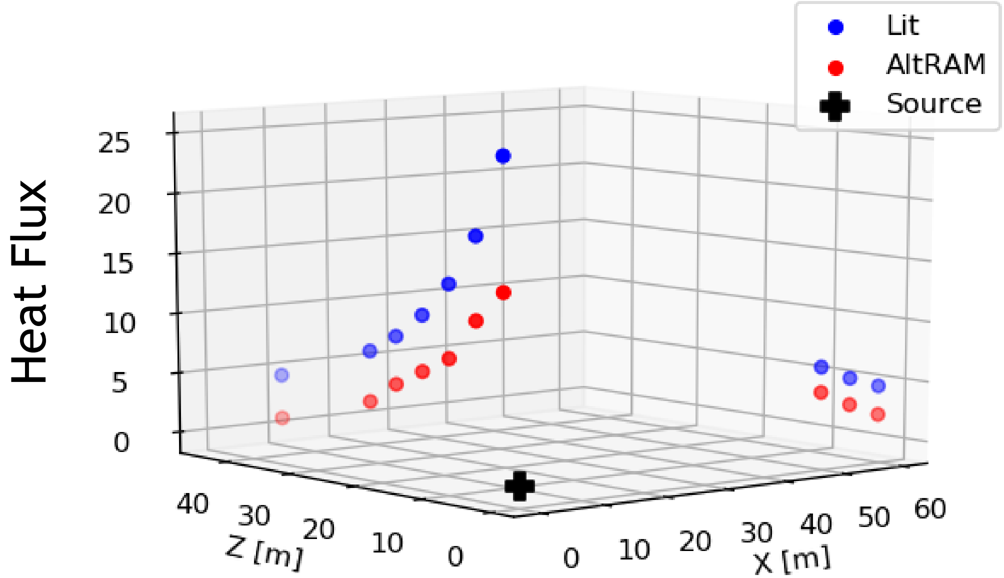


Figure 1. Horizontal release flame shape model.



Take Aways from Jet Flame Model Validation

AltRAM matches trends and values for heat flux calculations well

Most common is to over predict heat flux:

- Three papers overpredict (Lowesmith 2011, Hankison 2000, Lowesmith 2012)
- Wind direction is coflow or neutral

Under predicted for one paper:

- Johnson 1994 – Wind Counter-flow & Neutral – Under Predict…

Conclusion

Take Aways

AltRAM physics models match well to multiple experiments

- Plume concentrations

- Heat flux

Choked flow measurements have smaller error than subsonic flow

For subsonic flow, it is more accurate to extrapolate from near field values than use the calculated far field values

Heat flux tends to be overpredicted – errs on the side of safety

We are confident in these models for use in the Quantitative Risk Assessment

Up next:

Releasing AltRAM (with user and theory manual)

Expanding the model to Propane

References

C.J. Jordan, E.S. Hecht, M.L. Blaylock,
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C. D. Richards and W. M. Pitts. "Global density effects on the self-preservation behaviour of turbulent free jets". *J. Fluid Mech.* 254 (1993), 417–435.

G. Hankinson, B. J. Lowesmith, P. Genillon, and G. Hamaide. "Experimental Studies of Releases of High Pressure Natural Gas From Punctures and Rips in Above-Ground Pipework". In: *Vol. 1 Codes, Stand. Regul. Des. Constr. Environ. GIS/Database Dev. Innov. Proj. Emerg. Issues*. Vol. 1. ASME, 2000, V001T01A009.

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A. Johnson, H. Brightwell, and A. Carsley. "A model for predicting the thermal radiation hazards from large-scale horizontally released natural gas jet fires". *Process safety and environmental protection* 72 (1994), 157–66.

Thank you!

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Adsorbed Natural Gas

ANG

Bringing the benefits of NG at a fraction of the operational parameters of CNG

BP Holbrook

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Agenda

1. Who Is Ingevity?
2. ANG Technology and Field Tests
3. Where does ANG fit in the vehicle market?

genuine

The right people.
The right attitude.

longevity

Lasting customer relationships.
A history of success.

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ingenuity

Pushing the bounds of what's possible.

innovation

Extraordinary people.
Extraordinary results.

Our Purpose

Purify	Protect	Enhance

A team 1,600 strong, leading the way.

Leading global manufacturer of specialty chemicals and high performance carbon materials.

Creating high value-added products from renewable raw materials.

Meeting highly specialized, complex customer needs through proprietary formulated products.

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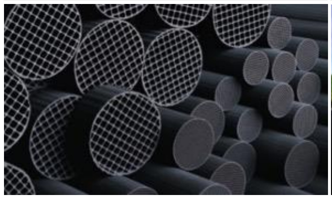
Company Overview

	Performance Materials	Performance Chemicals			
	Carbon Technologies	Pavement Technologies	Oilfield Technologies	Industrial Specialties	Engineered Polymers
					
2018 Sales	$400 million	$179 million	$114 million	$440 million	~$175 million(1)
Market Position	#1 in automotive	#1 or #2	#1 or #2 in oil-based muds	#1 or #2	#1
Applications	▪ Automotive ▪ Process purification	▪ Pavement preservation ▪ Recycling ▪ Evotherm® technologies	▪ Well Service Additives ▪ Production and Downstream	▪ Adhesives ▪ Agrochemicals ▪ Lubricants ▪ Inks ▪ Intermediates	▪ Coatings ▪ Resins ▪ Elastomers ▪ Adhesives ▪ Bioplastics
Select Competitors	CABOT kuraray	Nouryon ARKEMA	lamberti chemical specialties DRT	KRATON RESPOL RESINAS, S.A.	DAICEL BASF
Select Customers	DELPHI Aisan KAYSER AUTOMOTIVE SYSTEMS	ERGON HALLIBURTON	Flint Group SOLENIS Strong bonds. Trusted solutions.	ENNIS-FLINT arboris pine tree extracts	(2)

1) *We acquired the Engineered Polymers division via the acquisition of the Capa Caprolactone business from Perstorp Holdings AB on February 13, 2019. These amounts represent Ingevity management estimates of 2018 sales and adjusted EBITDA post acquisition on a full year basis.*
2) *Not disclosed due to NDAs and confidentiality.*

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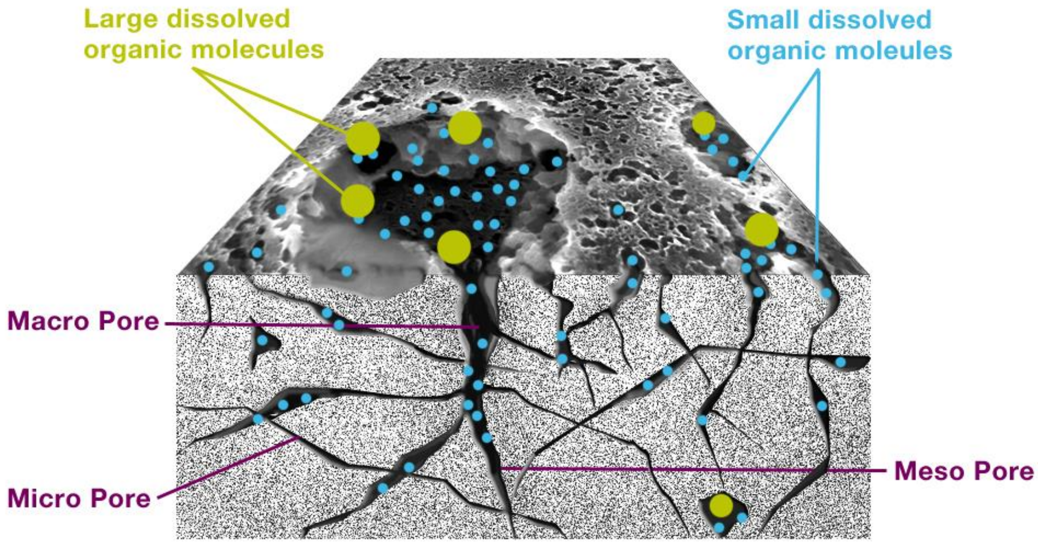
ANG Technology and Field Tests

Adsorbed Natural Gas



Activated Carbon

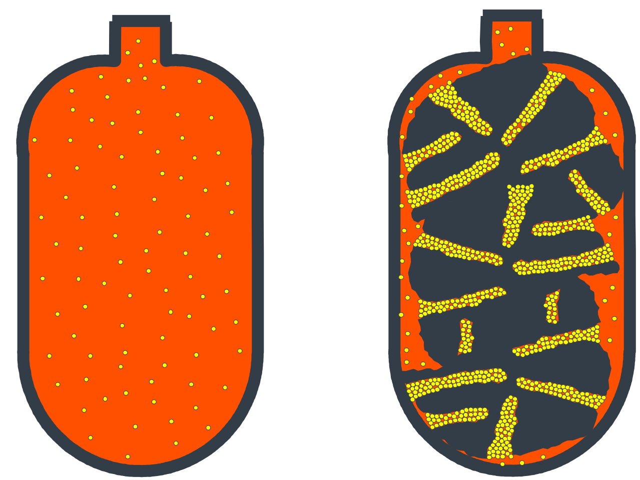
- Organic molecules are concentrated on the internal surface by physical attraction or chemical reaction
- Physical adsorption is reversible
- Pore size (classified by IUPAC)
    - micropore (< 20 Å)
    - mesopore (20 – 500 Å)
    - macropore (> 500 Å)

Adsorption…

- is the reversible binding of molecules to a surface
- occurs due to weak attractive interactions known as "van der Waals" forces
- Is exothermic

Desorption…

- is the reversible removal of molecules from a surface
- is endothermic



CNG Cylinder   ANG Adsorbent

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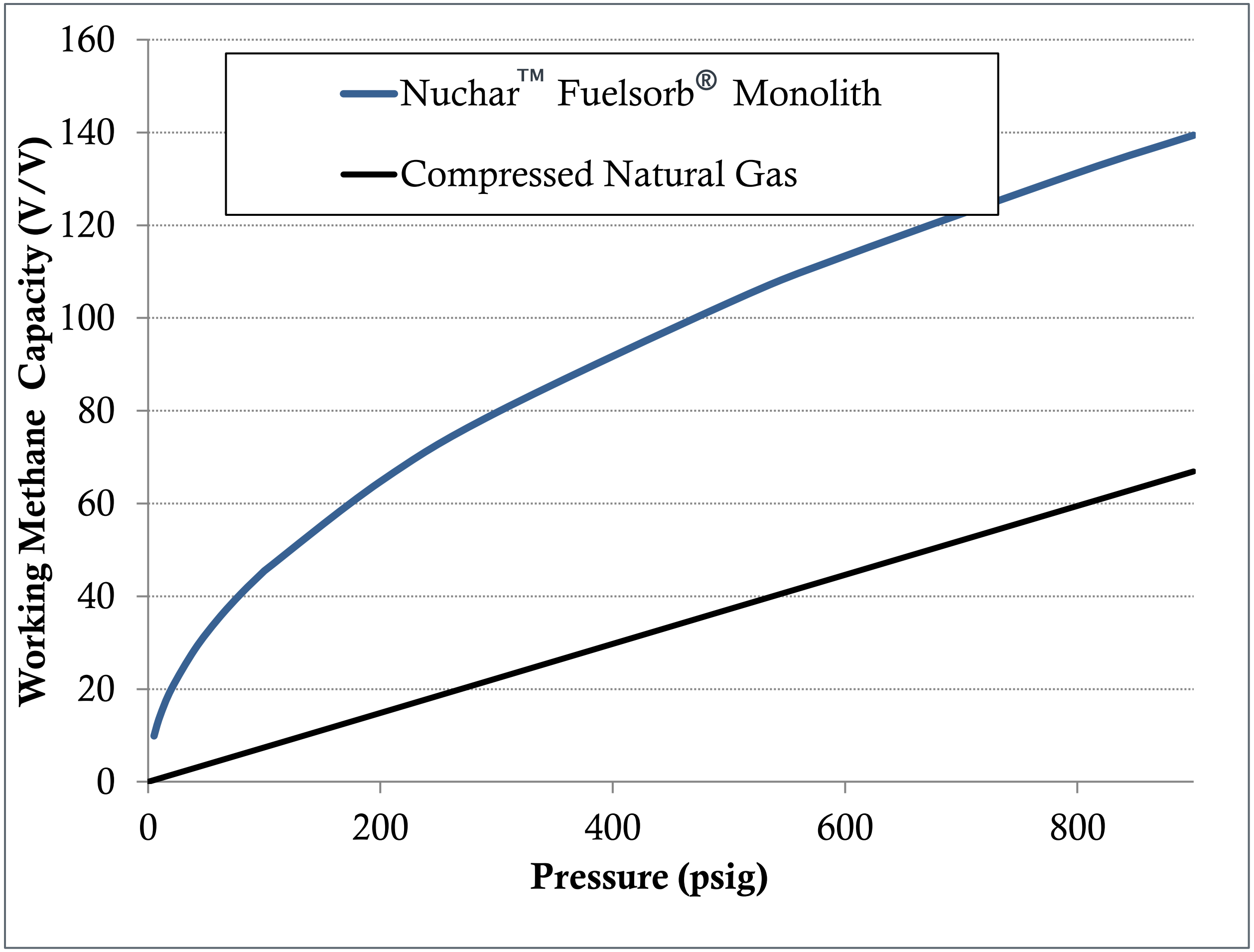
Why activated carbon for ANG?

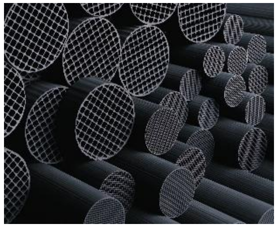
- Pore size distribution control (i.e. bimodal, multimodal, narrow, etc.)
- Performance vs cost
- Ability to create different forms, shapes and sizes



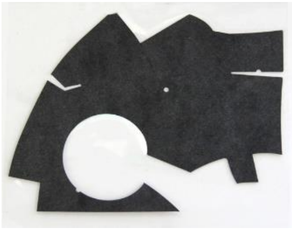

Pellets


Granular


Powder


Honeycombs


Monoliths


Carbon sheet

Patent pending

ANG bi-fuel Ford F-150 product offering

The plug-in hybrid adsorbed natural gas vehicle (PHANGV®)[2]

- Standard package Ford F-150 pickup.
- CNG prep includes hardened valves and seats.
- Flexible cylinder designs allow for a range of on-board natural gas storage (from 2 GGE to 8 GGE).
- Zero-weld cylinder arrays rest conveniently in tool box.
- Full warranty intact (QCM and QVM).
- Extended fuel range enabled by complete gasoline and on-board natural gas storage.

[1]Ford's Qualified Vehicle Modifier program for non-standard upfits
[2]PHANGV® is a registered trademark of ANGP

Key components for low pressure ANG natural gas vehicle systems

- ✓ System integrator — ANGP
- ✓ Engine Calibrator (QCM) — Badillo Engineering, LLC
- ✓ Vehicle Outfitter (QVM) — ALTECH-ECO CORPORATION
- ✓ Shape-specific activated carbon monoliths — ingevity

- ✓ Low pressure natural gas tanks — WORTHINGTON INDUSTRIES

- ✓ Off-board natural gas fueling appliances — snam

On-Road testing: Technology Validation

Headquarter driver pilot program to quantify cost savings, CO_2 reduction and technology

	SC		NV	CA
	Actual	Annual*	Annual**	Annual**
Miles driven	3,389	12,000	12,000	12,000
Fueling Cycles	101	357	357	357
Fuel savings	$254	$946	$1,401	$1,705
Reduced emitted CO2 (lbs)	>700	>2,600	>2,600	>2,600
Displaced Gasoline (gal)	171	600	600	600

Additional NG utility annual revenue per commercial business
GA - $656.9 PA - $913.3 TX - $534.5

If 10% of NG commercial users own an ANG bi-fuel vehicle: GA - $8 MM PA - $22 MM TX - $17 MM

If 10% of NG residents own an ANG bi-fuel vehicle: GA - $362 MM PA - $428 MM TX - $751 MM

*Assumes 18.0 mpg
**Price differences from EIA August 2019 data

On-Road testing: Natural Gas Range

ANG bi-fuel F-150 has similar fuel economy to conventional F-150 and ~70-80 miles of range

	ANG Bi-fuel F-150		Gasoline F-150	
Topography	Rocky	Flat	Rocky	Flat
Total Range (miles)	451.7	493.7	-	-
Bi-fuel Fuel Economy (mpg)	17.6	18.1	17.7	18.0
NG Fuel Economy (mpg)*	19.9	20.3	-	-
Actual NG Range (miles)	73.2	77.1	-	-

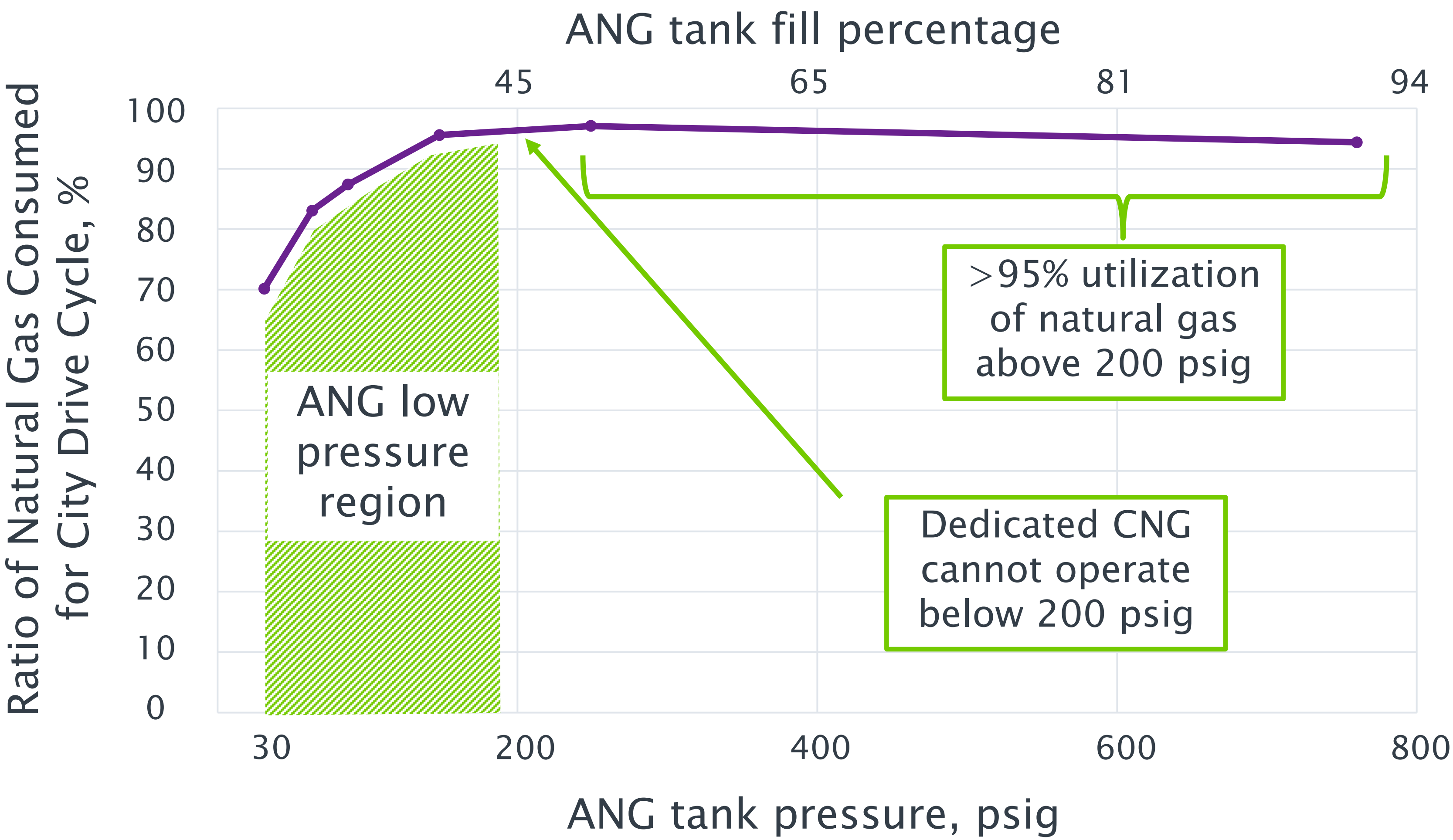
- Fuel economy equivalent to standard F-150 despite ~400 lb wt increase of ANG system
- Engine more efficient when fueled by NG
- Plan to replicate yearly

Mt. Mitchell, NC – 6,300 ft elevation

*Based on NG Miles driven and amount of NG fill

ANG bi-fuel natural gas consumption

At low pressure engine remains powered with natural gas



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EPA tailpipe emissions

Roush Industries evaluated tailpipe emission differences between ANG and conventional gasoline 2019 F150 4x4 SuperCab

SuperCrew (White, 8.5' bed)	EPA Reqs (g/miles)	Gasoline ICE			ANG bi-fuel ICE		
		FTP75	HWFET	US06	FTP75	HWFET	US06
PM	0.01	0.003	0.007	0.005	0.002	0.001	0.0037
N_2O	0.01	0.003	0.002	0.003	0.003	0.005	0.004
CH_4	-	0.014	0.003	0.014	0.149	0.014	0.129
CO_2	-	482	340	528	394	274	427
Total GHG_{eq}		483	341	529	398	276	431

- ❑ Greenhouse Gas reduction between 18 - 19%
- ❑ PM reduction between 26 – 86%

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We are focused on developing purpose-built, low-pressure refueling appliances

Existing compressors available for market entry; modified to operate at ANG pressures (<1,000 psi)

Single Vehicle

Multi-Vehicle

NGVT focused on identifying and testing a second-generation system to meet ANG design targets

- Low up-front cost: <$2,500
- 10+ year service life
- Total cost of ownership <$1.00/GGE
- Reliable and low maintenance
- Lower energy consumption
- **GTI project (5 appliances; 4 manufacturers)**

ANG enables low cost private refueling

Repurposed CNG home refueling appliances meet total cost of ownership ARPA-E target (<$1.00/GGE) while fueling faster with reduced maintenance

Appliance	ANG Energy Savings* (%)	Fleet Maintenance Savings** (%)	ANG Average Fueling Rate Increase (%)	Total Cost of Ownership ($/GGE)
FMQ (New)	33%	18%	13%	$0.89
FMQ (Used)	53%	45%	63%	$1.02
Phill (Cubogas)	40%	26%	35%	$1.87
Appliance H	40%	45%	42%	$0.78
Appliance G	29%	37%	24%	$0.92

- Demo pilots include FMQ.
- TCO costs are variable with use.
- Lower costs expected for ANG dedicated appliance.

*$0.12/kwh,

**Daily fueling cycle of 5 GGE, 325 days/year (92.5 miles of daily range on natural gas; ~30,000 miles/yr; 18.5 mpg)

Where does ANG fit in the vehicle market?

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Large light-duty vehicles (LDV) have limited alternative fuel solutions

Alternative fuels focused on small LDV and medium-/heavy-duty vehicles

Yet ~60 percent of U.S. vehicle sales are large LDVs

Example vehicles

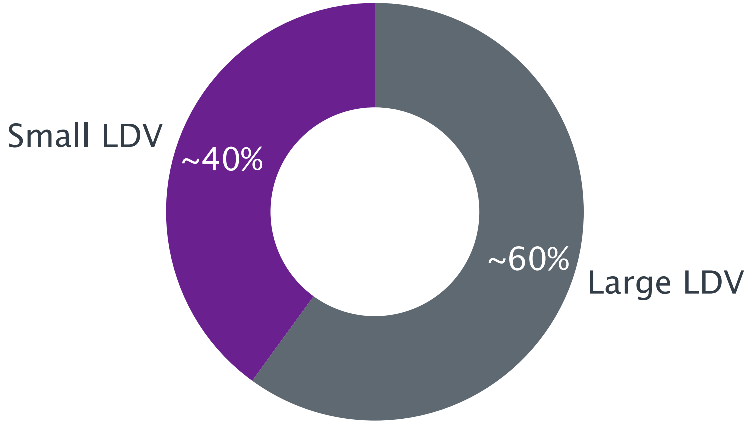
Hybrid (HEV + PHEV)

Electric Vehicle (EV)

Compressed Natural Gas (CNG)

U.S. new car sales by size*

n = 17m vehicles



- Top 3 selling vehicles in 2016 were pick-ups
- 6 out of top 10 were not sedans

Source: IHS data as of September 2017

* Small LDV defined as sedans; large LDV defined as pick-ups, vans, SUVs and crossovers

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North American market activity

California

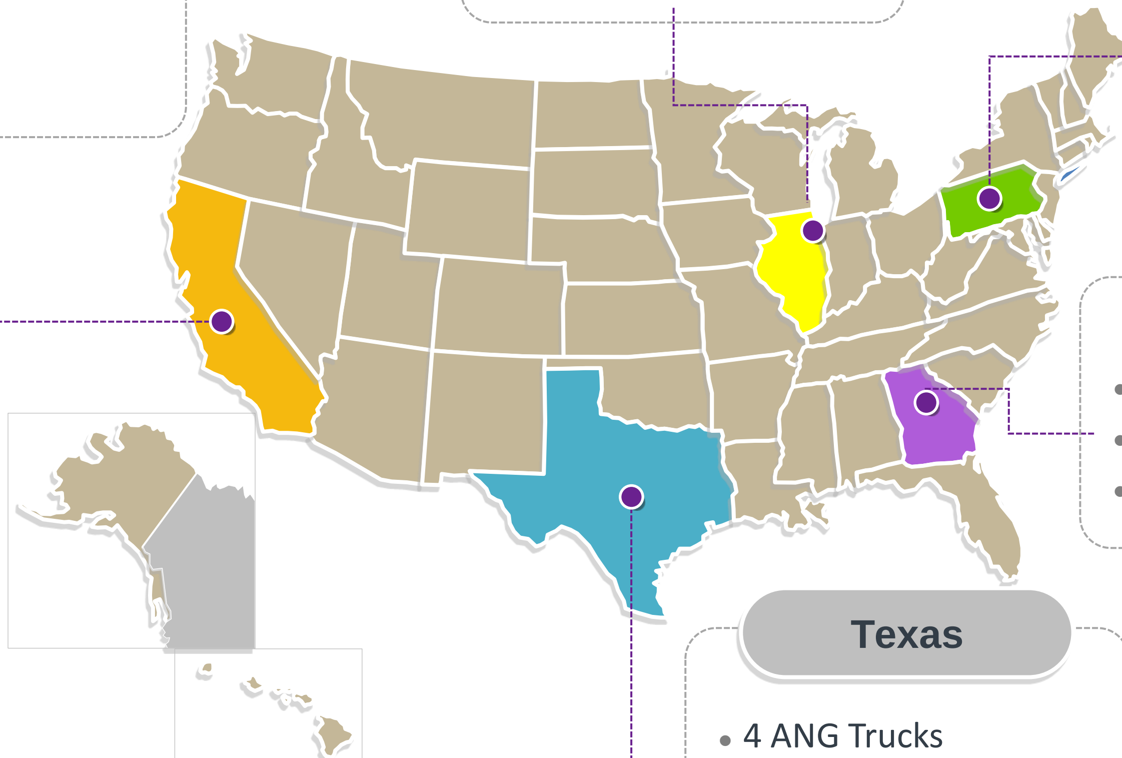
- 4 ANG Trucks
- 2 HRA's
- Los Angeles

Illinois

- 2 ANG Trucks
- 1 HRA's
- Chicago

Pennsylvania

- 5 ANG Trucks
- 3 HRA's
- Pittsburg/Philadelphia



Georgia

- 2 ANG Trucks
- 1 HRA
- Atlanta

Texas

- 4 ANG Trucks
- 2 HRA's
- Houston

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Thank you

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Thank You

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