Natural Gas Vehicle Technology Forum 2019

Salisbury, North Carolina

April 16–17, 2019

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.

Table of Contents

Table of Contents

Table of Contents

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Natural Gas Vehicle and Engine R&D Consortia Update

April 16, 2019

Background

Three agencies

- California Energy Commission
- Southcoast AQMD
- US DOE

came together to jointly fund projects with objectives of mutual technical interest

- Lowering the Total Cost of Ownership (TCO)
- Improving NG Engine and Vehicle Emissions
- Expanding NG Engine and Vehicle Availability

for the purpose of

- Larger technical impact
- Leveraging funding
- Coordinating research

Schedule/Timeline

RFP

- Issued September 20, 2018
- Due November 20, 2018

Evaluation

- Rankings/Scoring December 2018

Notifications

- Successful Offerors Notified February 14, 2019
- Unsuccessful Offerors Notified Via Email February 26, 2019

Announcement

- NREL Press Release and EERE News Alert (3/6/2019)
- Included in Michael Berube's remarks at the Work Truck Show (3/6/2019)

Agreements

- Expected between May and June 2019
- Kickoff meetings summer and fall 2019

Program Overview

Nine projects selected

- 24 proposals received
- Four focus on applied research
- Five focus on basic research

$36M total investment

- $20M in agency funding
  - DOE – $15M
  - CEC - $3.4M
  - SCAQMD - $1.7M
- $16M in matched funding

Partner Participation by Award

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

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

Projects Overview

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

Cummins, Inc. – Columbus, Indiana

Cummins Inc. will address natural gas engine emissions and efficiency improvements by developing a natural gas specific combustion design utilizing optimized in-cylinder charge motion and cooled exhaust gas recirculation (EGR). The engine will be integrated on a global heavy-duty base engine platform, enabling up to a 20 percent system cost reduction. The technical targets of the project include demonstrating a 10 percent improvement in cycle average and peak brake thermal efficiency over the current commercially available product; maintaining 0.02 g/bhp-hr NO_x capability with reduced aftertreatment cost; and demonstrating a diesel-like torque curve.

CNG Full Fills with a Complete Smart Fueling System

Gas Technology Institute – Des Plaines, Illinois

The Gas Technology Institute (GTI) and its partners will address total cost of ownership by developing and demonstrating a smart fueling system, including the full suite of necessary technologies to enable consistent full fills of natural gas vehicles. These technologies include a smart vehicle and dispenser, an advanced full fill algorithm and cost-effective gas pre-cooling using a near-isentropic free piston expander/compressor. This combination of technologies seeks to solve the technical challenges of dispensing uncertainty and heat of compression that results in natural gas vehicles being under-filled.

Downsized, Optimized, High Efficiency, Spark Ignited Natural Gas Engine

Gas Technology Institute – Des Plaines, Illinois

GTI and its partners will address natural gas engine and vehicle availability by developing a production intent, optimized, spark ignited natural gas engine demonstrating near-zero emissions and meeting EPA 2027MY greenhouse gas (GHG) targets in a Class 6 vocational vehicle.

Projects Overview

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

Michigan Technological University – Houghton, Michigan

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

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

Southwest Research Institute – San Antonio, Texas

Southwest Research Institute and Isuzu will address natural gas engine emissions and efficiency improvements and engine availability by developing and demonstrating a hybrid medium-duty truck using advanced natural gas spark-ignited engine. A pent-roof cylinder head version of a diesel engine will be developed for operation on natural gas and integrated into a medium-duty truck chassis. The pent-roof design will enable the use of elevated levels of EGR dilution to yield a high efficiency engine that can also meet future NO_X regulations. To further the vehicle level efficiency gains, a hybrid drivetrain system will be integrated into the truck as well to provide a demonstration of a highly optimized low GHG emission medium-duty truck.

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

Transient Plasma Systems, Inc. – Torrance, California

Transient Plasma Systems and Argonne National Laboratory will address natural gas emissions and efficiency improvements by developing a production intent prototype of a transient plasma ignition system to enable stable ignition of natural gas and air mixtures that challenge traditional spark plugs. This project will demonstrate the increase in combustion stability at high-pressure, high-exhaust gas recirculation conditions across a wider operating range relative to existing or future heavy-duty natural gas spark-ignition internal combustion engines.

Projects Overview

Plug-in Hybrid CNG Drayage Truck "PHET"

US Hybrid Corporation – Torrance, California

US Hybrid Corporation and its partners will address total cost of ownership by developing and demonstrating a fully integrated and optimized natural gas, plug-in hybrid class 8 vehicle utilizing the Cummins 9-liter near-zero emission engine, a commercialized parallel hybrid powertrain with 240hp rating and a 40kWh liquid-cooled high-power density lithium-ion battery pack. The project includes a 24-month demonstration in port drayage operations to quantify emission and performance improvements and will implement a GPS-based predictive geofencing hybrid control architectures to ensure zero emission operation at the port.

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

University of Alabama – Tuscaloosa, Alabama

The University of Alabama, in collaboration with an industrial partner, will address natural gas emissions and efficiency improvements by developing a laboratory scale proof-of-concept for a commercially viable high-efficiency natural gas dual fuel heavy-duty engine that will conform to current and future emissions standards. The strategies to achieve this include use of a high cetane oxygenated pilot fuel, spray-targeted reactivity stratification, variable valve actuation, and temperature-controlled exhaust gas recirculation.

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

University at Buffalo – Buffalo, New York

The University of Buffalo and its partners will address natural gas emissions and efficiency improvements by developing a novel aftertreatment system for future natural gas vehicles using palladium-based catalysts, which have shown the best activity for the oxidation of CH_4 at low temperatures.

Natural Gas as a Transportation Fuel – A Strategic Opportunity for U.S. Energy Security Enabled by Innovation and Advanced Technology

Dr. Robert Marlay, Ph.D., P.E.
Office of Energy Efficiency & Renewable Energy
U.S. Department of Energy

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Energy Efficiency & Renewable Energy Transportation R&D

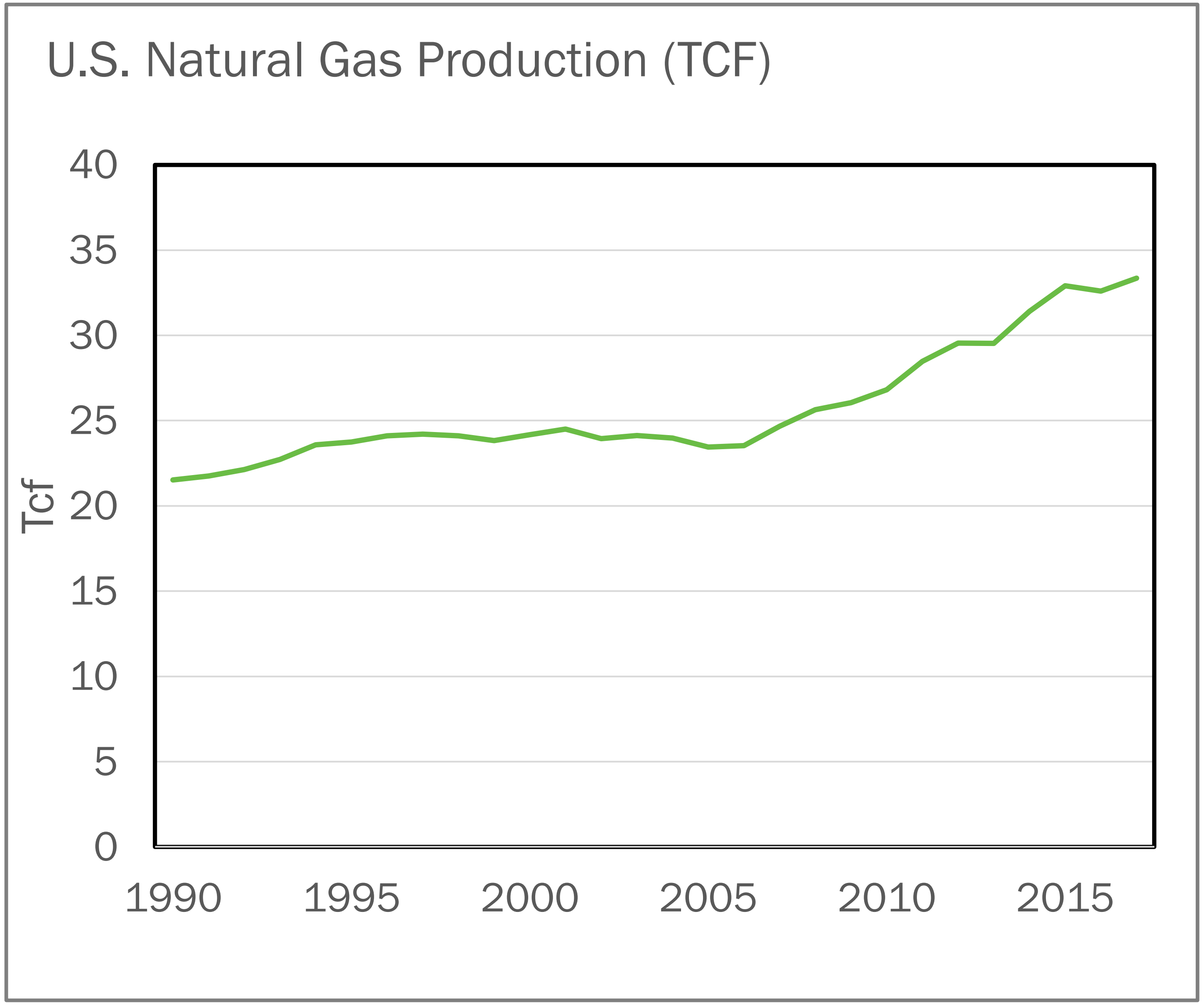
Natural Gas – Salient Features & Public Benefits

- Abundant Worldwide (Outside Cartel):
  - U.S., Russia, M. East, Hydrates
  - Potentials in South Asia, S. America
- National Security Benefits:
  - Domestic Resource, w/90-Year Supply
  - Greater Transp. Use Displaces Insecure Oil
- Economic Benefits (Comparatively Affordable):
  - Expanded Use Seen as and Economic Stimulus
  - Reduces Balance of Trade – Imported Oil
- Environmental Benefits:
  - Low Emissions Profile -- H_2O, CO_2
  - Meets Criterial Pollutant Stds., Low NOx, $PM_{2.5}$
- Climate Benefits:
  - Bridge Fuel to a Lower-Emissons Future
  - GHGs – 50% Less than Coal; 20% Less than Oil

Energy Efficiency & Renewable Energy Transportation R&D

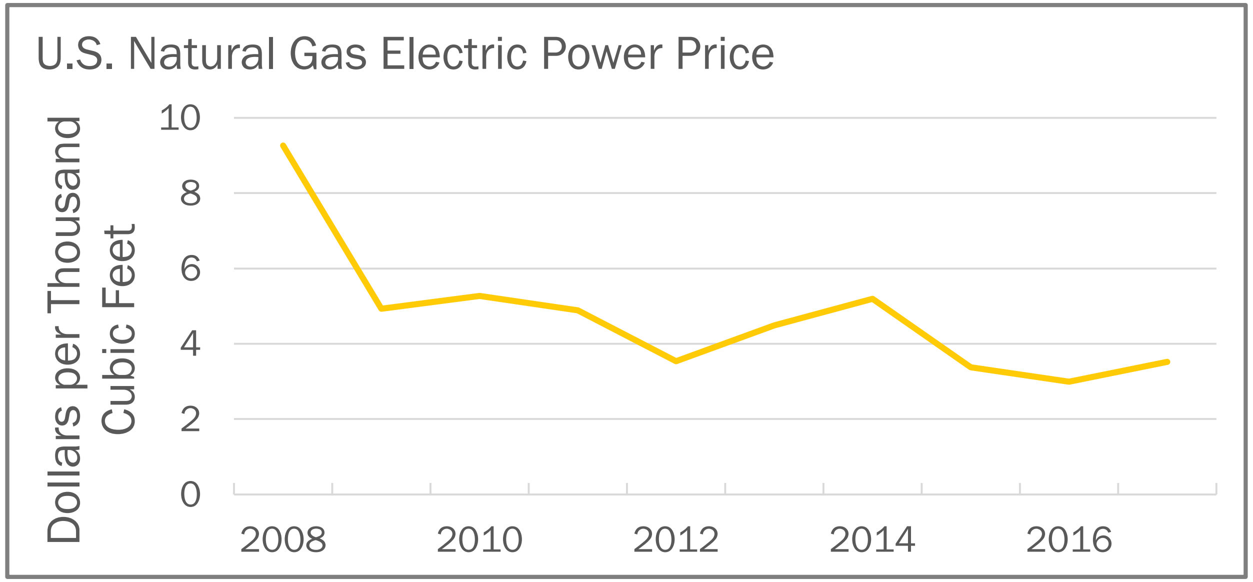
Natural Gas Production in the U.S.

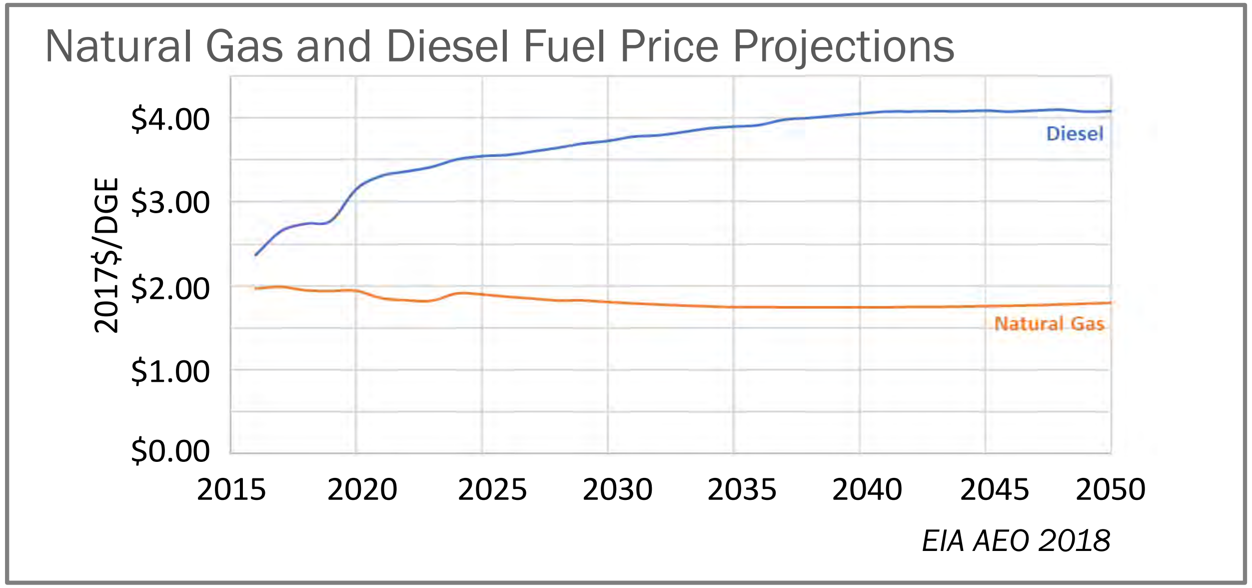
- **Natural Gas Production:**
  - U.S. Production on the Rise
  - Increased by 50% Since 1990
  - U.S. Now Leads Global Production
- **Fracking Revolution Enabled by DOE**
- **Polycrystalline Diamond Drill Bit:**
  - NREL -- Geothermal "Hot Rock" R&D
  - Los Alamos -- Diffusion Bonding of Diamond Surfaces on Steel
  - Sandia – Radical Cutting Surf. Design
- **Down-Hole Telemetry (DOE/FE R&D)**
- **3-D Seismic – Mathematical Algorithms**
  - DOE's High Energy Physics Program
- **Horizontal Drilling (DOE/FE)**



Natural Gas Prices Are Projected to be Competitive vs. Diesel

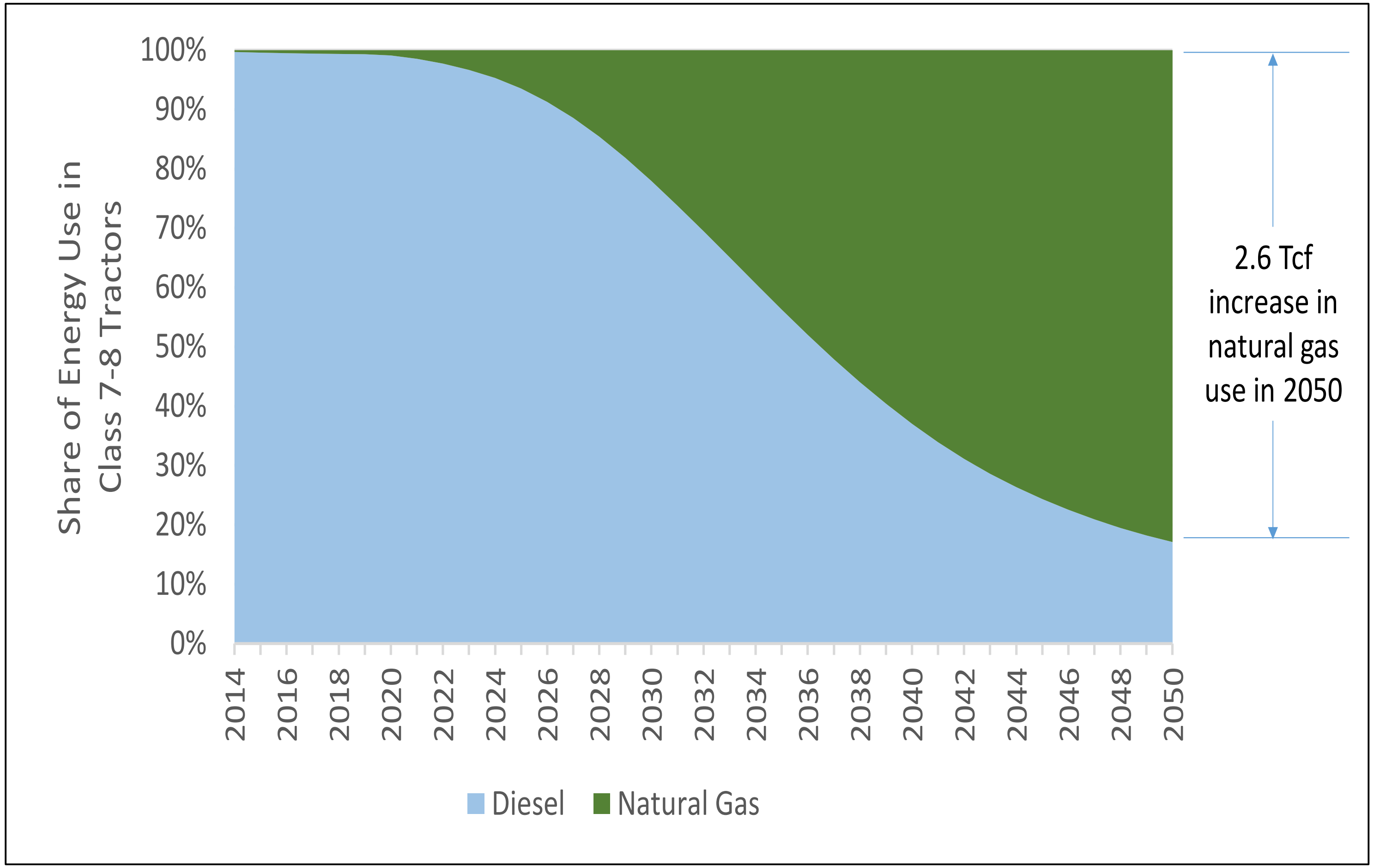
- **U.S. Natural Gas Prices:**
  - Fallen by More Than 50% over the Last 10 Years
  - Decoupled from World Oil
- **Advantages vs Diesel:**
  - Current Fuel Price Differentials of About ~$0.60/DGE
  - Bulk buyers ~$1.00/DGE
- **Long-Term Outlook:**
  - EIA Projects Retail Advantages
  - $1.00/DGE Diff. by 2025
  - $2.00/DGE Diff. by 2035 thru 2050





Potentially Significant National Benefits from A Shift to Natural Gas as a Transportation Fuel

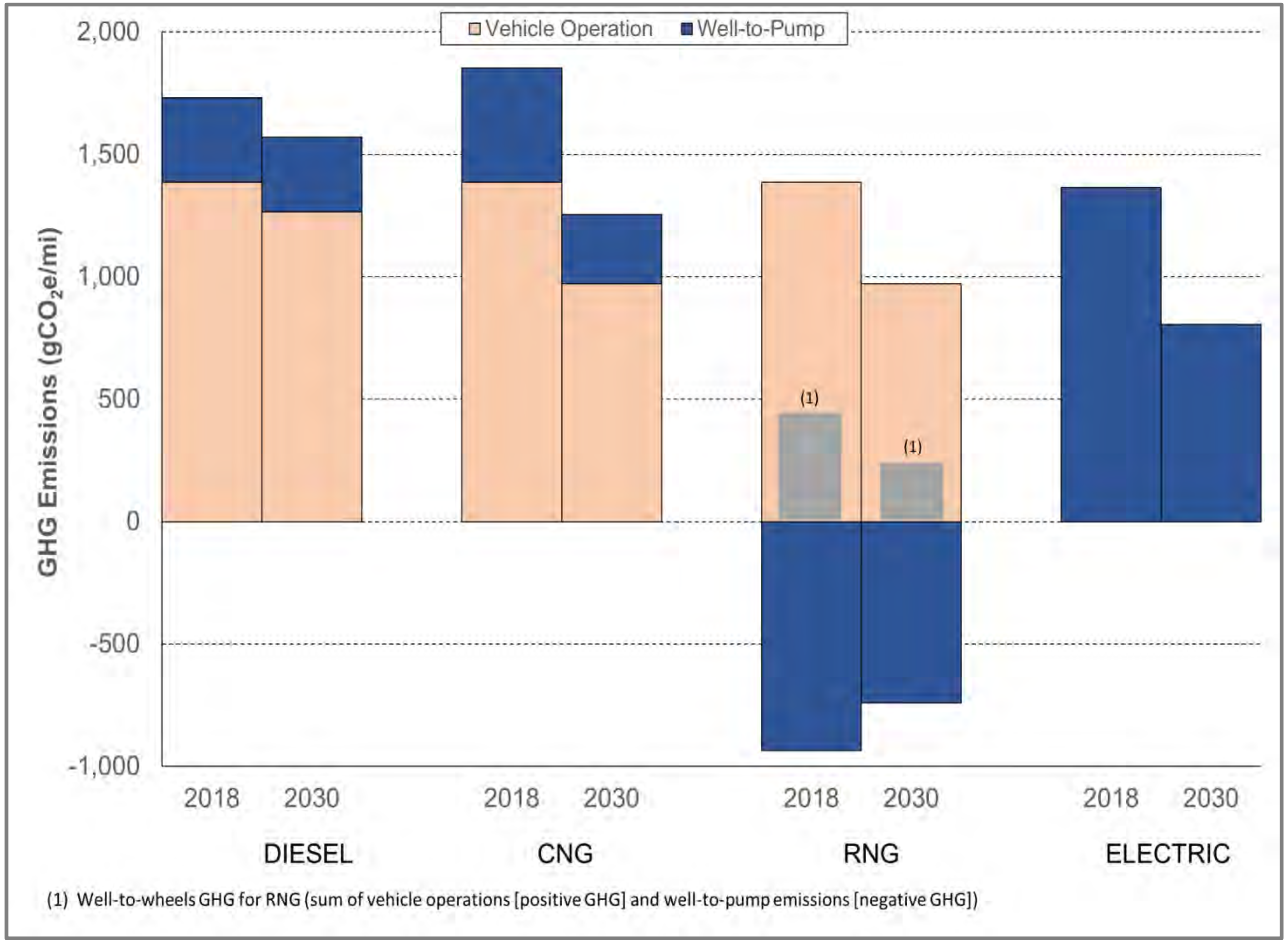
- **NGVs Could Capture Large Market Share by 2050**
- **If NGVs Displaced Diesel by 80%, the Result Would Be a 2.6 TCF Increase in Natural Gas Use in Transportation**
- **Using EIA Projections, this Could Result in:**
  - Enhanced Resiliency Against Oil-Related Econ. Disruptions
  - Significant User Fuel Savings
  - U.S. Economic Stimulus
  - Reduction in U.S. Balance of Oil-Trade by $80 Billion/Year



Potential Shares of Fuel Use by Class 8 Trucks Due to a Shift to Natural Gas

Greenhouse Gas Considerations

- **GHG Emissions:**
  - Full Fuel Cycle Includes Upstream E&P
- **Today:**
  - Natural Gas (CH_4) Burns w/20% Less GHGs than CH_2-Chains (Diesel), but NG Engine Efficiency is 15% Less
  - GHGs of NGVs & Diesel are Similar
- **Upstream Leakages:**
  - Methane Leakages from E&P and Distribution Adds to GHG Emissions
  - Ranges from 1.6% to 2.6% of Supply
- **Future:**
  - With NGV Engine Efficiency Gains & Continued Mitigation of E&P, NGVs Could Have 20% Less GHGs than Diesel
- **Electrics:**
  - May Have Even Less GHGs, if a Future Grid Were to be Partly De-Carbonized
- **Renewable Nat. Gas Vehicles (RNGVs):**
  - Could Have the Least (Net) GHGs

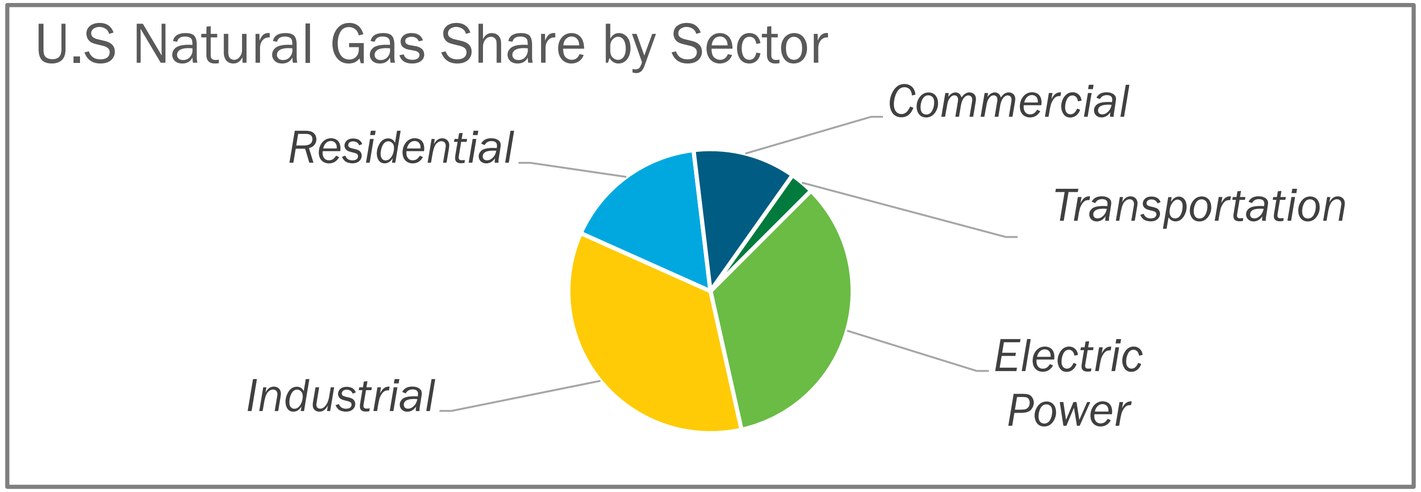


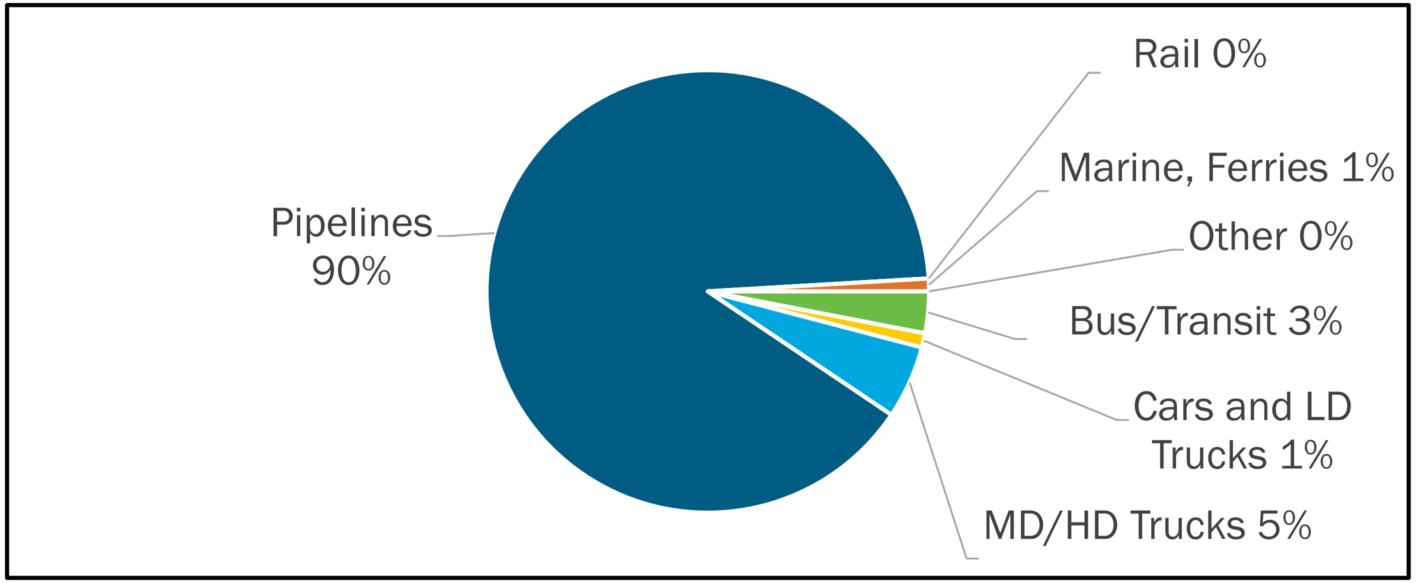
Comparisons of Greenhouse Gas Emissions (GHGs) for a Class 8 Truck Employing Various Powertrains and Fuel Types.

Energy Efficiency & Renewable Energy Transportation R&D

Minimal Use of N. Gas in Transportation, 2017

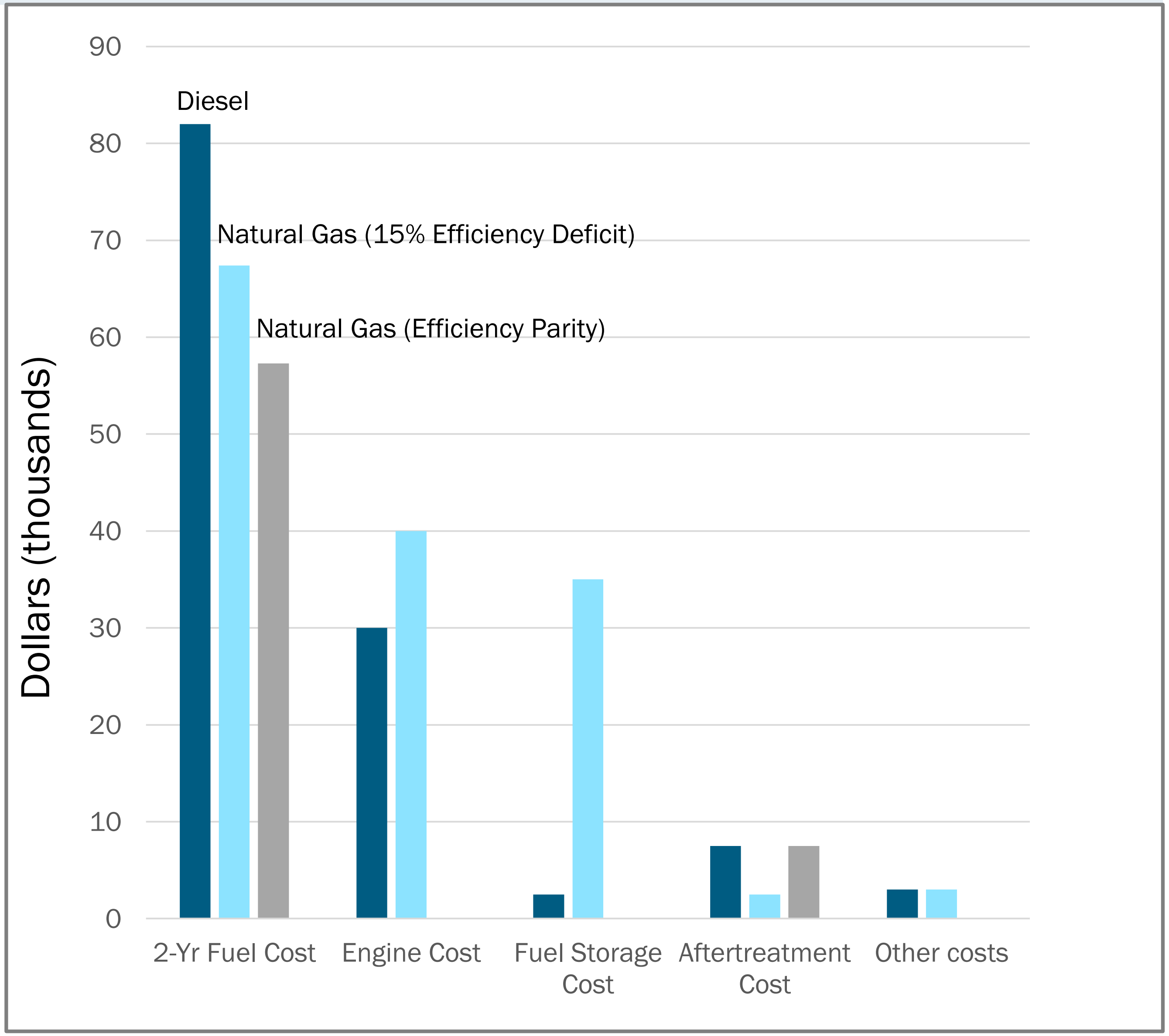
- Natural Gas End-Use:
  - Now About 30% of All U.S. Energy Use
  - Major Inroads Recently into Industry & Elec. Power
  - Full Displaced Coal in Res/Commercial Sectors
- Transportation – Last Hold-Out for Natural Gas
  - Small Amounts of N. Gas Used in Pipelines and Compressors
  - Less than 0.2% Used in Vehicles





What is Holding Back More Use of N. Gas?

- **Fixed Costs – NG vs Diesel:**
  - Fuel Storage ($35K vs $2.5K)
  - Engine ($40K vs $30K)
  - After treatment ($2.5K vs $7.5K)
- **Running Costs on 2-Year Payback ***
  - Fuel ($65K vs $82K)
  - Fuel at Efficiency Parity ($57K vs $82K)
  - Other Costs ($3K vs $3K)
- **Other Considerations:**
  - Fuel Price Uncertainties
  - Less Torque, Less range
  - Uncertain Refueling Access
  - New Training/Maintenance Programs



* Assumptions:
- 100,000 miles per year; Diesel truck fuel economy of 7.5 MPG
- Diesel fuel price of $3.15/gallon; CNG price of $2.18/GGE

Energy Efficiency & Renewable Energy Transportation R&D

R&D Strategy – Target #1 (Reduce Cost of Storage)

- **Fixed Costs – NG vs Diesel:**
  - Fuel Storage ($35K vs $2.5K)
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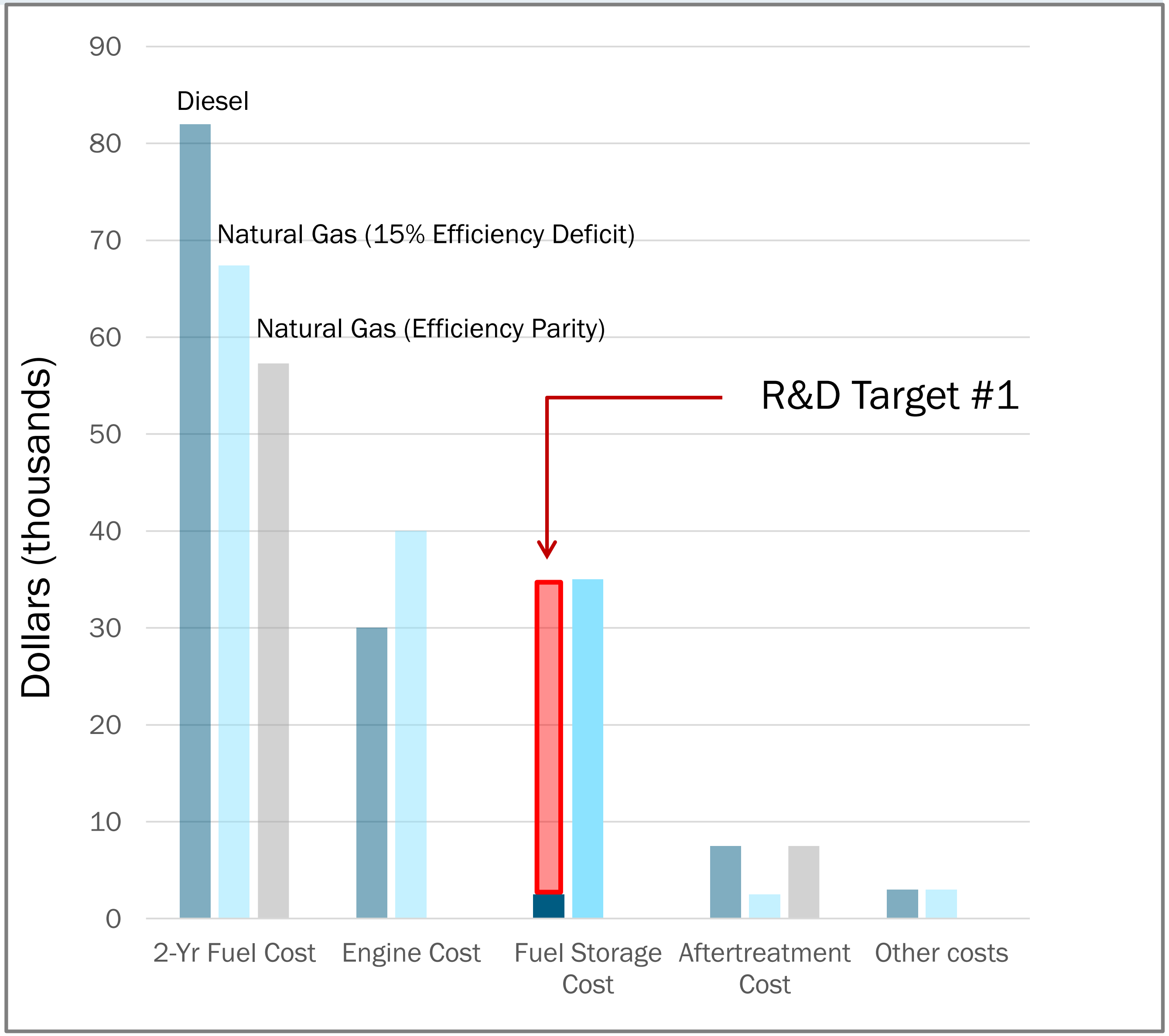

R&D Strategy – Target #2 (Power Train Efficiency)

- **Fixed Costs – NG vs Diesel:**
  - Fuel Storage ($35K vs $2.5K)
  - Engine ($40K vs $30K)
  - After treatment ($2.5K vs $7.5K)
- **Running Costs on 2-Year Payback ***
  - Fuel ($65K vs $82K)
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- **Other Considerations:**
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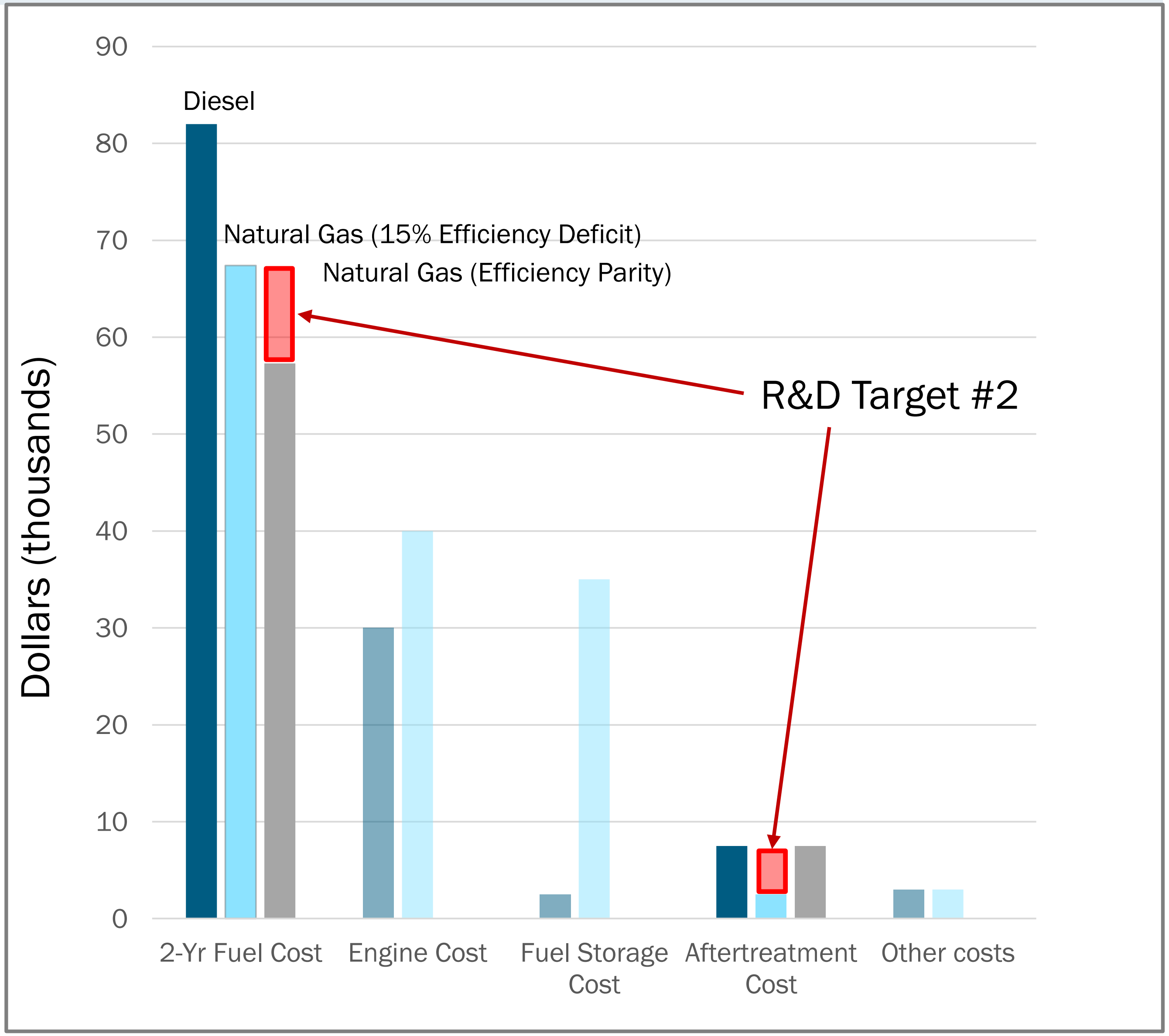
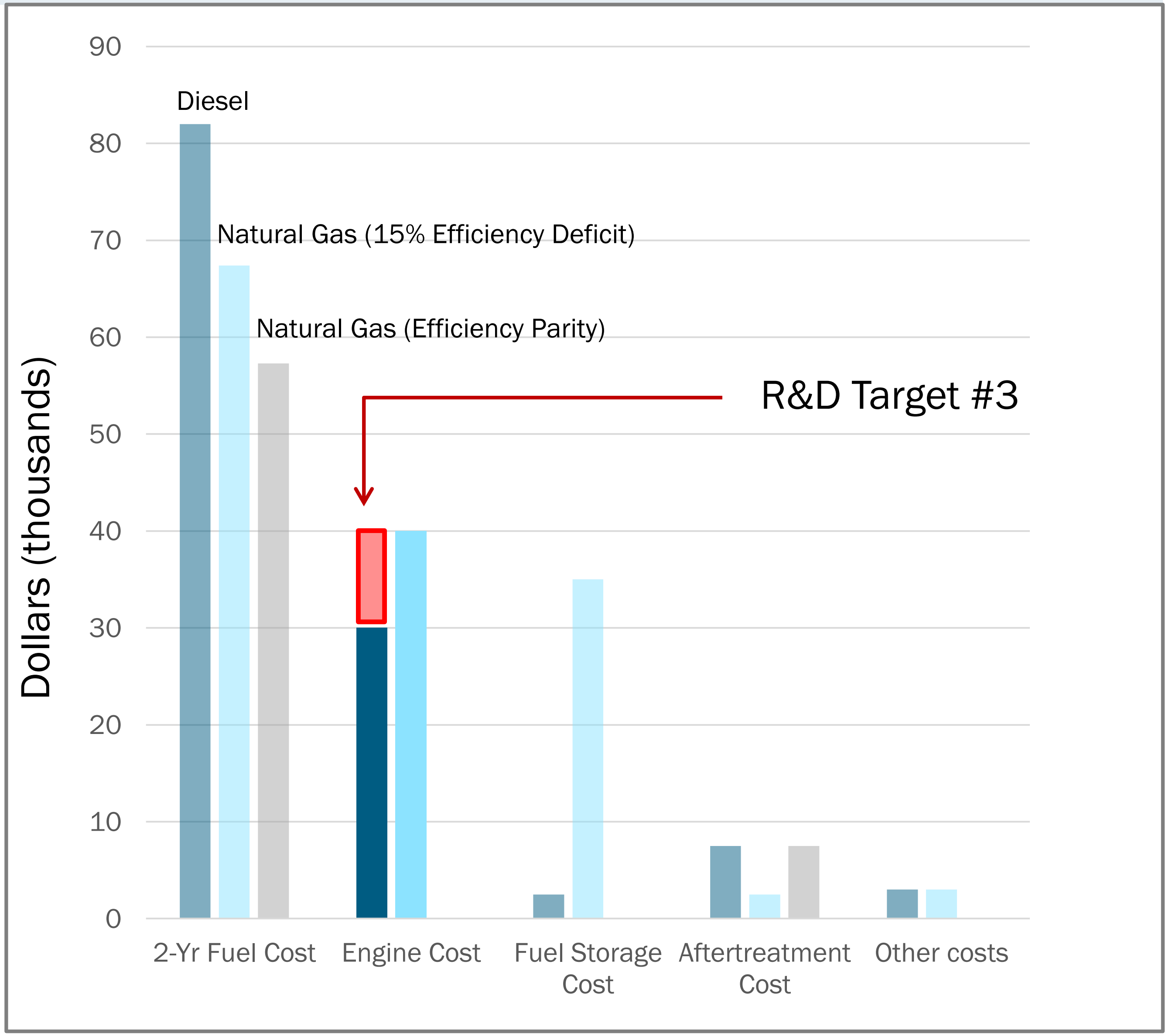
  - New Training/Maintenance Programs



R&D Strategy – Target #3 (Reduce Engine Cost)

- **Fixed Costs – NG vs Diesel:**
  - Fuel Storage ($35K vs $2.5K)
  - Engine ($40K vs $30K)
  - After treatment ($2.5K vs $7.5K)
- **Running Costs on 2-Year Payback ***
  - Fuel ($65K vs $82K)
  - Fuel at Efficiency Parity ($57K vs $82K)
  - Other Costs ($3K vs $3K)
- **Other Considerations:**
  - Fuel Price Uncertainties
  - Less Torque, Less range
  - Uncertain Refueling Access
  - New Training/Maintenance Programs



Summary – Cost-Reduction Strategies

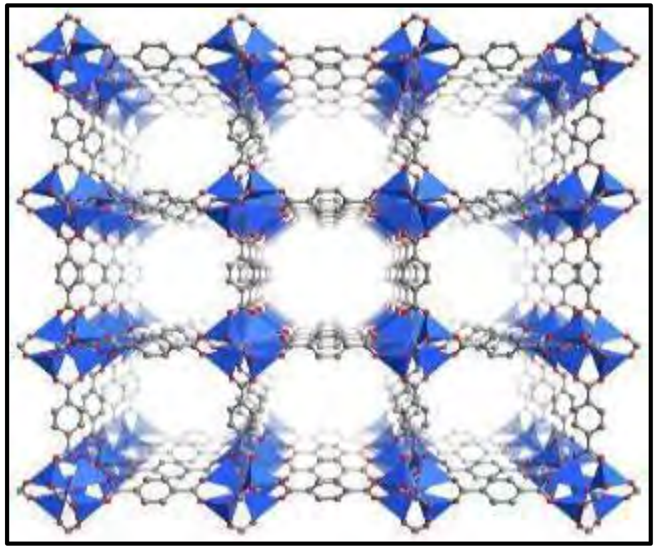
- **In View of the Uncertainties, the Cost-Reduction Goal Should Be:**
  - Ambitious & Robust
  - Say, Overall, $40K or More
- **Innovation & Advanced Tech. Could Close the Gap**
- **DOE R&D Would Focus on Key Cost-Reduction Pathways [Box]**
- **Coupled w/Information Sharing & Technical Support to Facilitate**
  - Efficient Market Functioning
  - Informed Tech. & Fuel Choices
- **Also, Policy Review of Potential Regulatory Barriers, Imbalances**

FOCUS AREAS FOR DOE RESEARCH

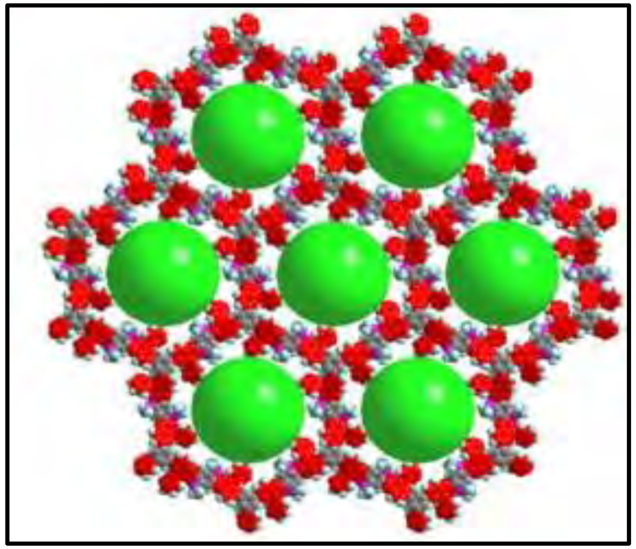
- Reduce Costs of On-Board Fuel Storage;
- Improve NG Engine Efficiency & Power, While Minimizing After-Treatment;
- Reduce Costs of Manufacture, Certification & Sale of NG Engines and Powertrains;
- Reduce Costs and Provide Innovative Options for Refueling Infrastructure and Natural Gas Vehicle Life-Cycle Maintenance; and
- Facilitate a Robust Manufacturing Supply Chain for U.S.-Based NG Equipment and Vehicles

N. Gas Storage in Solid State Media – Metal & Co-Valent Organic Frameworks (MOFs & COFs)

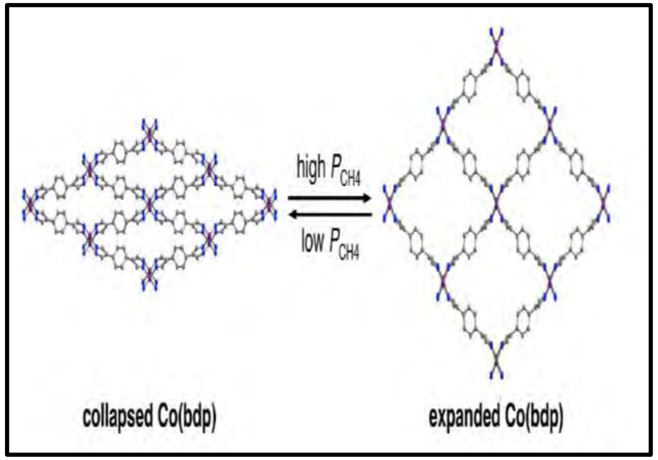
- **Hollow Molecular Structures**
  - Metallic Organic Frameworks
  - Co-Valent Org. Frameworks
  - Pore Size: "Low Nanometers"
  - Graphene or Borophene Sheets
  - Suitable for Storing (Gas) Substances of Like-Size
- **Large Surface Areas in Compact Volumes**
  - 2,000 to 5,000 m^2/g
  - Pressures: < 900 psi vs. 3,600
  - Some MOFs "collapsible" to Allow Nearly All Gas Out < 10 Bar
- **Cut Storage Costs by 75%**



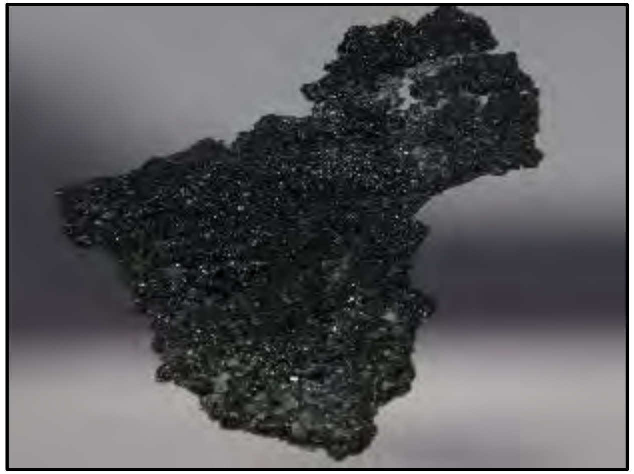
MOF-5



COF



MOF – Phase Change



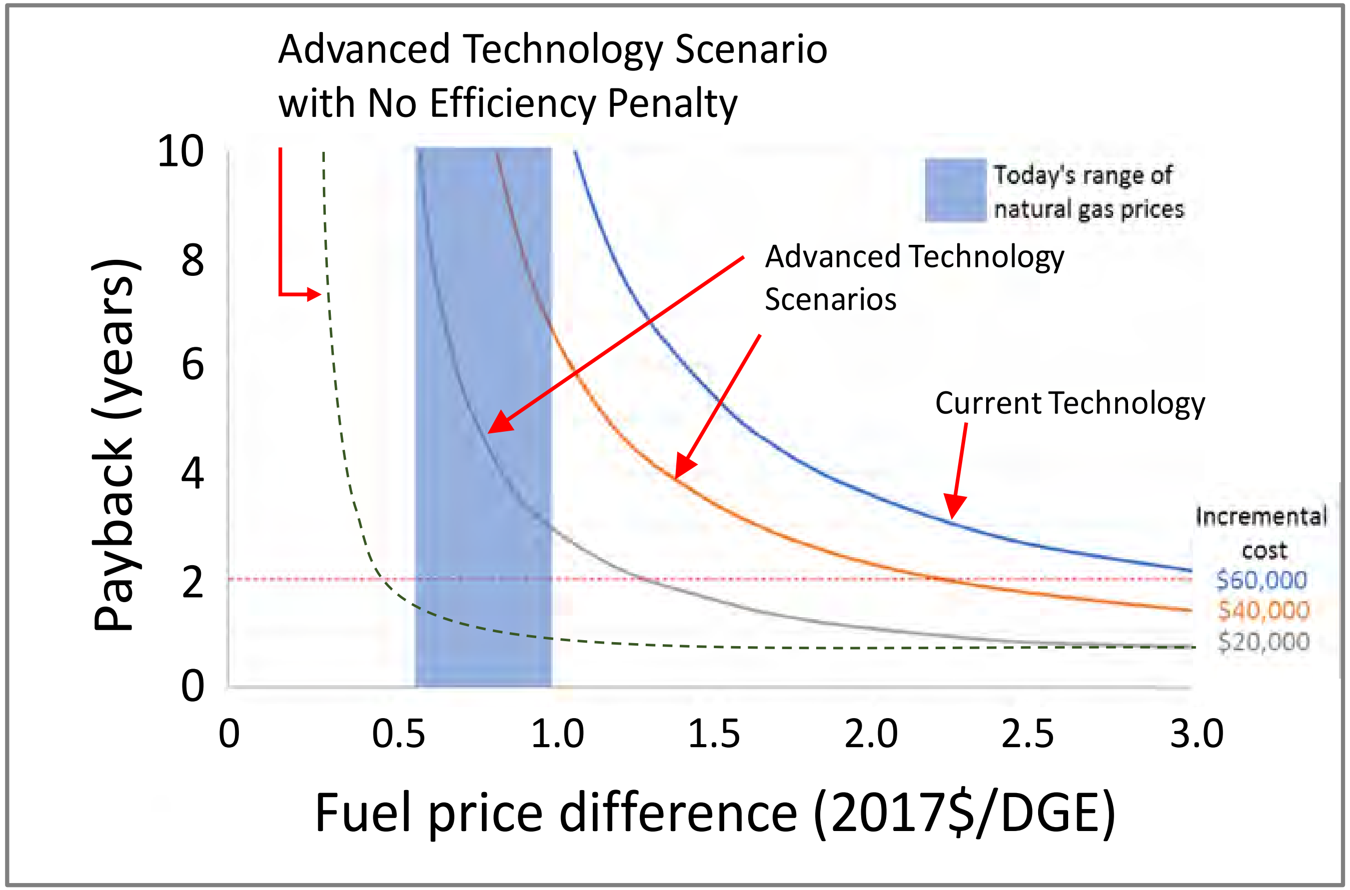
Borophene Sheets

Ongoing R&D Projects – If Successful, Could Lead to . . . .

- Larger N. Gas Engines, Ultra-low Emissions, and Near-Parity Efficiency with Diesel — Colorado State University, Cummins, and Woodward, Inc.
- New Classes of Catalysts for More Cost-effective After-treatment – University of Houston, CDTi, University of Virginia, and Oak Ridge National Lab.
- Knowledge for Achieving Low-temperature Mixed-Mode N. Gas Combustion for 10% Efficiency Improvement (from Lean Burn) – University of Minnesota, Carnegie Mellon, and Johnson Matthey
- Knowledge for Designing Pre-chamber Spark Ignition N. Gas Engines – Argonne National Lab, Oak Ridge National Lab, National Renewable Energy Lab, and Sandia National Laboratory
- Low Temperature Methane Oxidation (at 250°C) Using Pd/SSZ-13 Catalysts With High Si/Al Ratios – Pacific Northwest National Lab and Oak Ridge National Lab

Expected Outcomes – Risk Adjusted to Accommodate Uncertainties

- **Overall Goal:**
  - Seek 2-Year Payback Period
- **Broad-Based Strategy:**
  - Class 8, at 100,000+ Miles/y, and
  - Class 3-7, at 60,000 Miles/y
- **Natural Gas Price Difference**
  - Could be $2.00 or More DGE
  - Or ~$0.50 (Uncertain)
- **NGV Cost Premium & Goal:**
  - ~ Up to $60K for Class 8
  - Reduce by $20K to $40K
- **Expected Outcomes:**
  - Even w/Future NG Price Uncertainties
  - NGV Options Would be Competitive
- **Also of Note:**
  - Emissions Standards May Prompt Add'l N. Gas Use, if Technology is Ready



Estimated Payback Periods for Natural Gas Class 8 Trucks under Advanced Technology Scenarios

Summary

- **DOE's Remit is to Realize Pubic Benefits via:**
  - Research and Development
  - Addressing Barriers to Efficient Market Functioning
  - Sharing Information and Raising Awareness
- **DOE Has a Strategic Interests in:**
  - Expanded Use of Domestic Natural Gas as a Transportation Fuel
  - Diversifying Fuel Sources in Oil-Dominated End-Use Sectors
- **DOE's Investments are Trending Upward:**
  - $7M in FY17; $8.5M in FY18; and $20M in FY19
  - Aimed at Improving Performance, Reducing Costs, Creating New Technologies
- **Your Input and Feedback is Highly Valued**
- **Thank You for Your Attention!**

Back-Up Slides

Natural Gas Powered Turbines As Range-Extenders in Electric-Hybrid Trucks

- **Novel N. Gas Power Train Concepts**
  - Electric Drive w/Battery Storage
  - N. Gas Micro-Turbine w/Electric Generator
- **Potential Market Segments**
  - High Fuel Use, Frequent Stop & Go
  - Long-Haul and Refuse Trucks
- **Wrightspeed (Founder, Ian Wright):**
  - Micro-Turbine (300+ HP)
  - Generator (80 KW)
  - Cuts Fuel + Maint. Costs by 50%
- **Video Links**
  - https://www.wrightspeed.com/

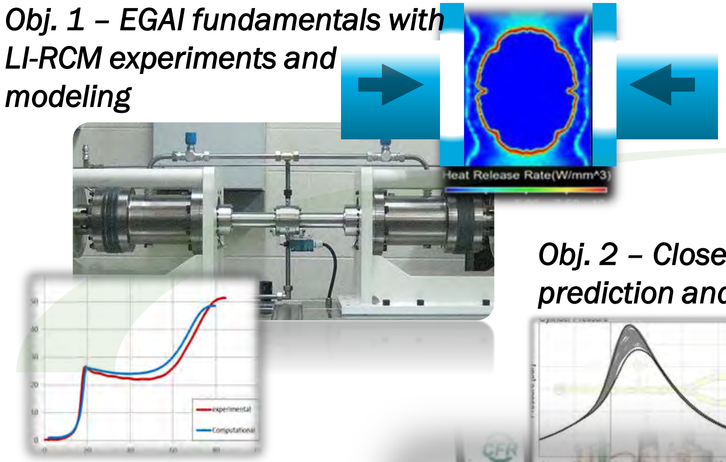
Expanding the Knock/Emissions/Misfire Limits for the Realization of Ultra-Low Emissions, High Efficiency Heavy Duty Natural Gas Engines

Key Participants: Colorado State University, Cummins Inc., and Woodward, Inc.

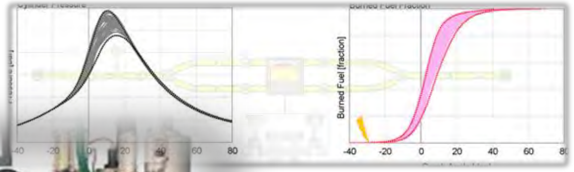
Goal: Demonstrate 44% peak torque efficiency for a 15L NG engine through improvements to engine geometries that enhance in-cylinder fluid dynamics and support advanced real-time control for near knock operation.

Technology Summary:

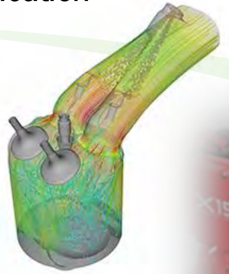
Obj. 1 – EGAI fundamentals with LI-RCM experiments and modeling



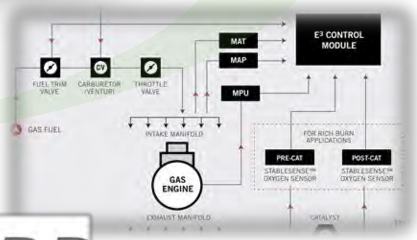
Obj. 2 – Closed cycle combustion engine prediction and validation with CFR testing



Obj. 3 – Computer aided single cylinder engine design and fabrication



Obj. 4 – Demonstration of 44% efficient 2.5 L single cylinder engine with real time control and controlled EGAI for variable fuel reactivity



Impact:

1. Improved understanding of NG EGAI and burn rates to support the development of physics based design tools
2. Identify pathway to “diesel-like” efficiencies for NG engines using an advanced controlled EGAI combustion mode

EERE Funds: $1,257,633 Cost Share: 20%

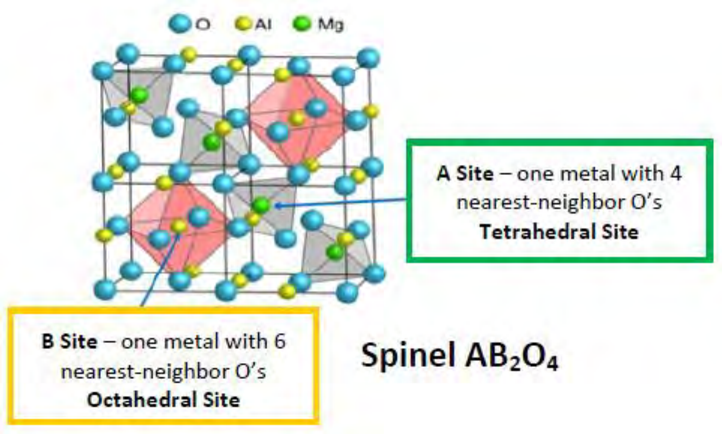
Reduced Precious Metal Catalysts for Methane and NO_x Emission Control of Natural Gas Vehicles

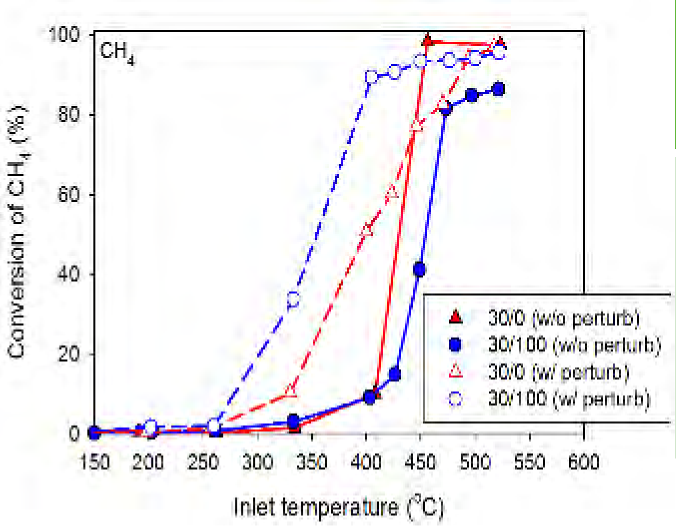
Project Team Members:

University of Houston, CDTi, University of Virginia, Oak Ridge National Laboratory

Project Goal:

Develop a new class of cost- and performance-effective Spinel-based catalysts with optimized composition and architecture for combined methane, non-methane hydrocarbons (NMHC), CO, and NOx conversion in emission control of vehicles fueled by natural gas in compressed or liquefied forms





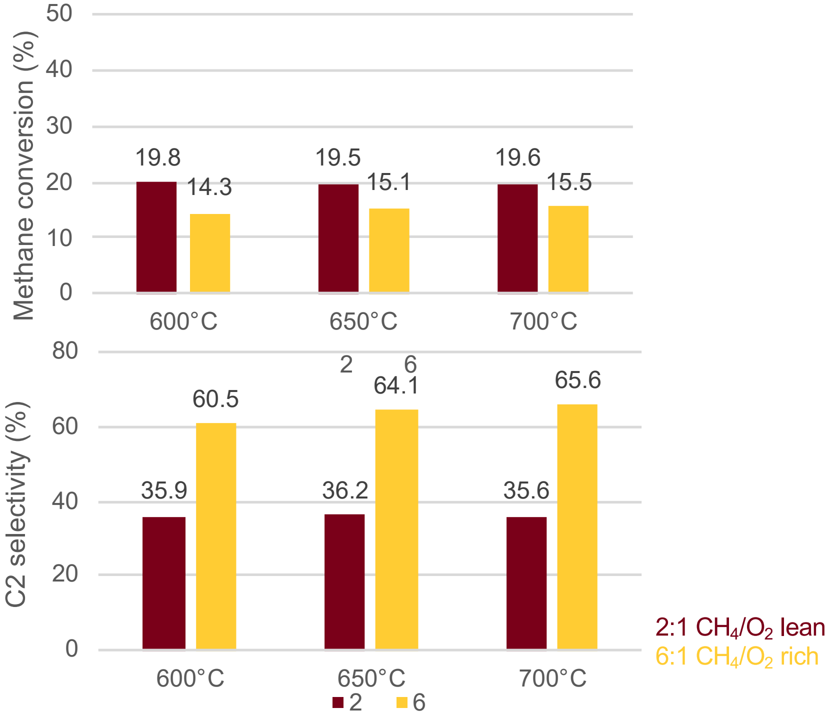
Material	**M-OC**	+	**HC-OC**	+	**N-RC**
	AB_2O_4/Al_2O_3		Pd + $CeO_2/ZrO_2/Al_2O_3$		Rh/Al_2O_3
Function(s)	Methane oxidation		HC + CO oxidation & oxygen storage/release		NO_x reduction

On-Demand Reactivity Enhancement to Enable Advanced Low Temperature Natural Gas Internal Combustion Engines (U. of Minnesota)

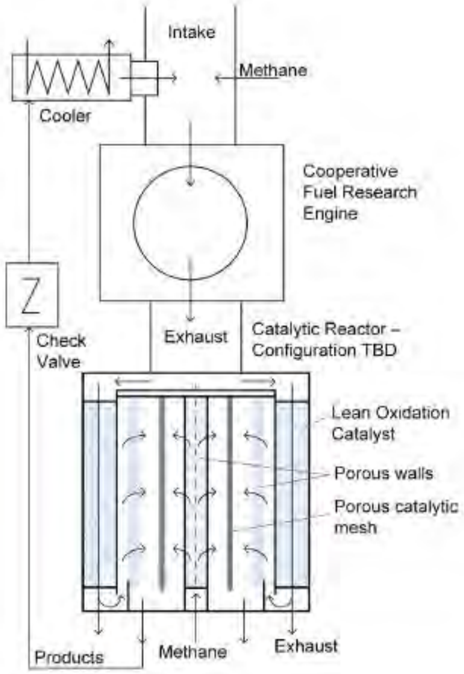
Objective: Demonstrate ≥10% improvement in indicated efficiency compared to data from a state-of-the-art lean-burn Natural Gas (NG) dedicated spark ignition (DSI) engine through 1-dimensional simulation of a multi-cylinder NG engine.

Approach: Modeling and experiments investigating oxidative coupling of methane (OCM) to produce C_2 molecules including acetylene, ethylene and ethane to enhance NG reactivity.

Results: Chosen OCM catalyst has suitable conversion and selectivity to C_2 products



Experimental Plan: Test novel engine-scale reactor using single-cylinder engine



UNIVERSITY OF MINNESOTA
Driven to Discover®

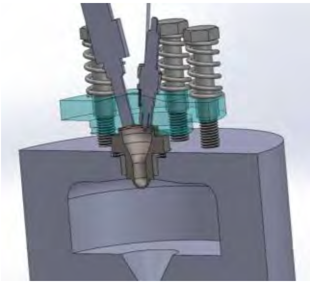
Carnegie Mellon University

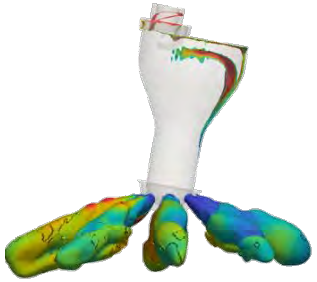
JM Johnson Matthey
Inspiring science, enhancing life

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

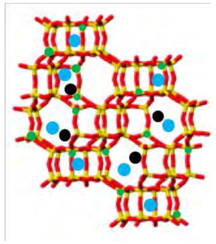
Argonne NATIONAL LABORATORY | NREL NATIONAL RENEWABLE ENERGY LABORATORY | OAK RIDGE National Laboratory | Sandia National Laboratories

- Early stage research focusing on pre-chamber spark-ignition (PCSI) and aftertreatment to achieve diesel-like efficiency in MD and HD natural gas engines by extending the lean dilution limit and/or EGR dilution limit, as well as shortening burn duration
- Integrated experiments and simulations to address barriers to market penetration of PCSI for MD/HD NG engines
  - 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
  - Limited ability to extend EGR and/or lean dilution limits at higher loads
  - Increased propensity for PCSI hot-spot pre-ignition at high loads relative to SI
  - Ineffective methane catalysts for the high engine-out unburned fuel concentrations coupled with low exhaust temperatures (<<400 °C) of high efficiency engines



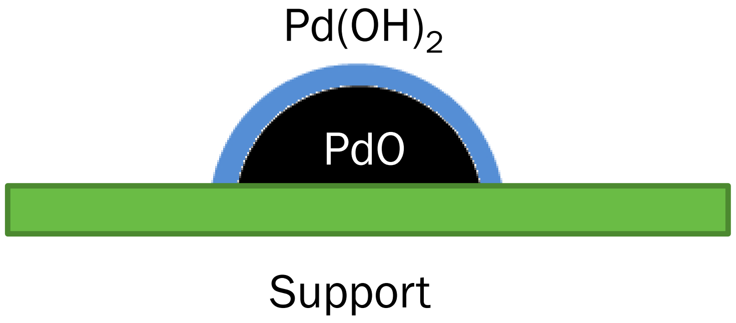


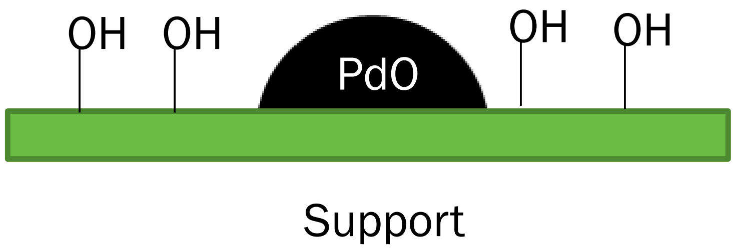
Mg-Pd/SSZ-13



Low Temperature Methane Oxidation Effort at PNNL (PI: Yong Wang)

- Methane oxidation activity on conventional Pd-based catalysts is limited by both the phase transformation of PdO and inhibition by water OHs.





Transformation of PdO to $Pd(OH)_2$

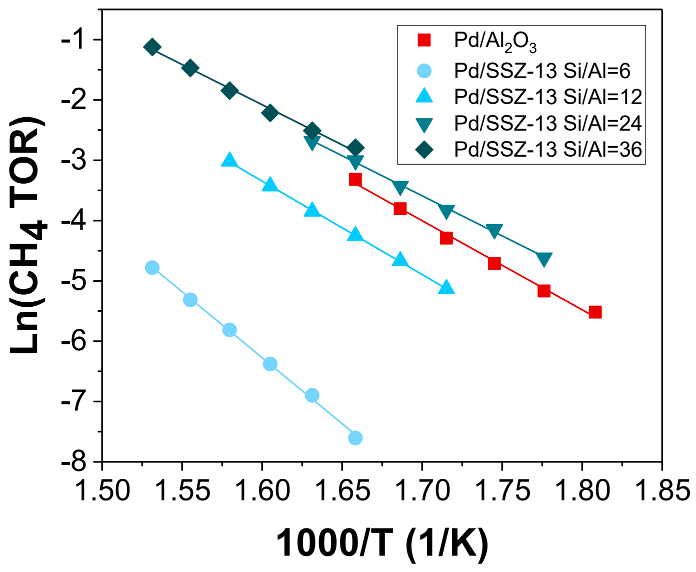
Burch, R.; Urbano, F. J.; Loader, P. K. *Appl. Catal., A* 1995, 123, 173−184.

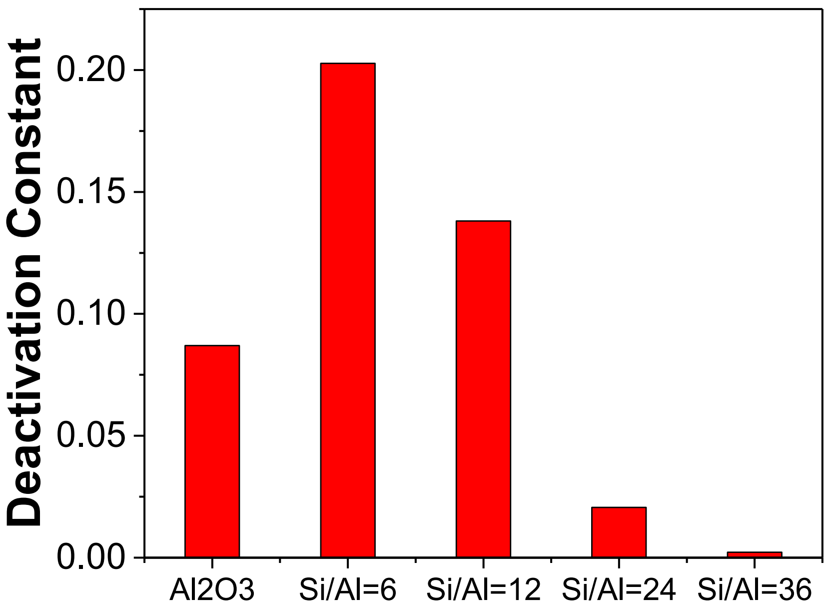
Accumulation of hydroxyl groups

Schwartz, W. R.; Ciuparu, D.; Pfefferle, L. D. *J. Phys. Chem. C* 2012, 116, 8587−8593

- To address these issues, we take the following approaches at PNNL (in close collaboration with ORNL):
  - Modification of the active phase, e.g., by single atom alloying, to stabilize the PdO phase and oxidation state of Pd while reducing the use of scarce precious Pd metal.
  - **Modification of the supports, e.g., by changing their hydrophobicity, to increase the tolerance to water/OHs.**

Pd/SSZ-13 Catalysts with High Si/Al Ratio Exhibited High Activity and Stability





Test Condition: 120 mg catalyst. Total flow 300 ml/min. Concentrations: 640 ppm CH_4, 14% O_2, 5% CO_2 and 2.5% H_2O, balanced with N_2.

- For Pd/SSZ-13 catalysts, catalyst activity (TOR) increases with increasing Si/Al ratio of the support.
- High Si/Al ratio apparently leads to better catalyst stability (H_2O resistance).
- Preliminary results with single atom alloy showed methane can be oxidized at about 250°C.

U.S. DEPARTMENT OF ENERGY

Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

Vehicle Technologies Office

Update on Recent NGV Initiatives

Dennis A. Smith, P.E.

National Clean Cities Director,

Technology Integration Manager

Clean Cities

U. S. Department of Energy

FY19 Commercial Trucks and Off-road Applications FOA # DE-FOA-0002044

Includes 6 topics ($16.5M) for Gaseous Fuel Research and Technology Integration for MD and HD Vehicles

- **Advanced Storage for Gaseous Fuels**
- **Waste to Energy (including renewable nat-gas)**
- **NGV Maintenance Cost Study**
- **CNG Tank Affordability**
- **Smart CNG Refueling**
- **Next Generation CNG Driver Info Systems**

~~Concept papers due March 29~~; Full Applications due May 15

https://www.grants.gov/web/grants/view-opportunity.html?oppId=313354

FY19 Advanced Vehicle Technologies Research
FOA # DE-FOA-0002014

Includes 5 Technology Integration topics ($17.5M) related to alt-fuels and new mobility services

- **Alternative Fuel Vehicles & Infrastructure for Resiliency and Emergency Preparedness**
- **New Mobility Services in Rural America**
- **Alternative Fuel proof-of-concept Demonstrations in new communities and fleets**
- **EV data collection**
- **Open topic – innovative ideas for AFVs & mobility**

Concept papers due May 1; Full Applications due June 19

https://www.grants.gov/web/grants/view-opportunity.html?oppId=314499

Nearly 100 Clean Cities coalitions with thousands of stakeholders, representing ~80% of U.S. population

Clean Cities U.S. Department of Energy — 25th Anniversary Since 1993

(CleanCities.Energy.gov)

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

Questions ??

Dennis A. Smith, P.E.
National Clean Cities Director,
Technology Integration Manager

Clean Cities
U. S. Department of Energy

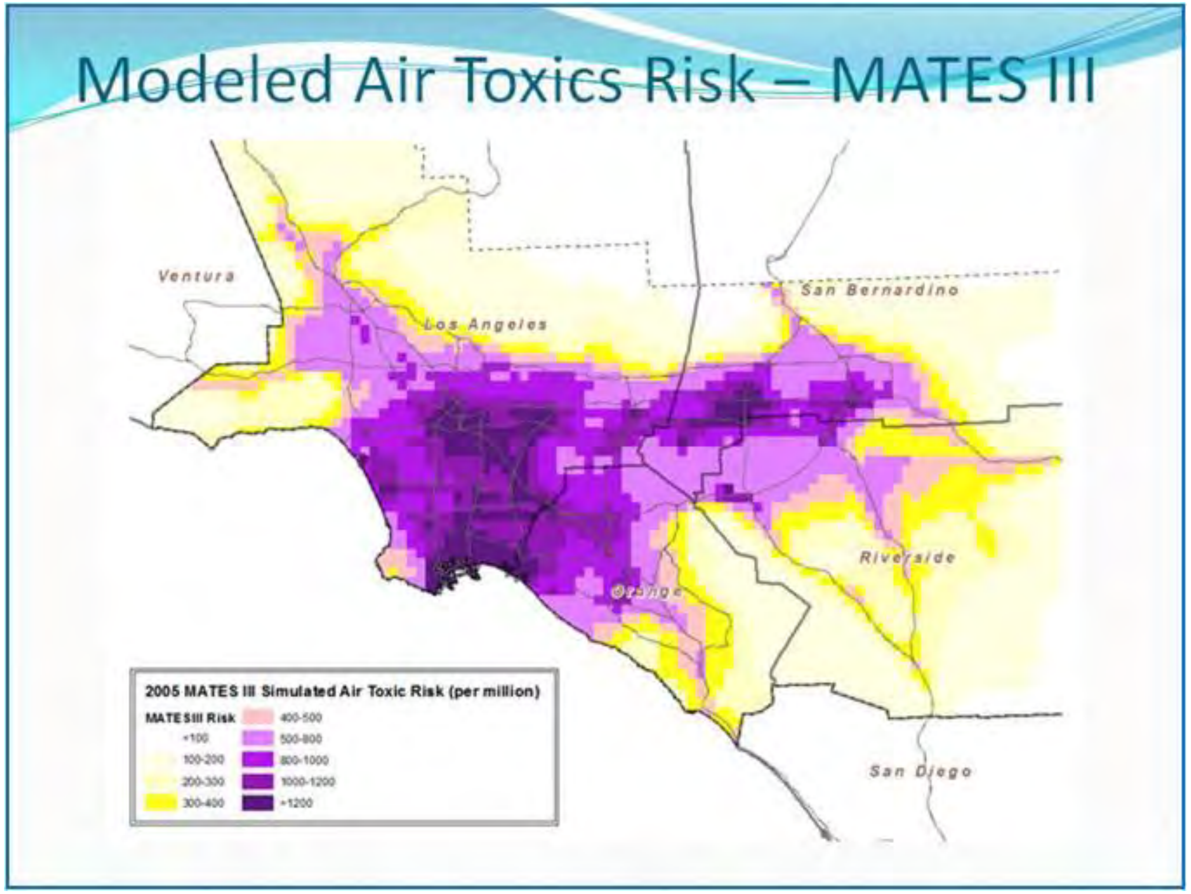
Natural Gas Vehicle Technology Forum
April 16, 2019

Naveen Berry, Assistant DEO, Office of Technology Advancement

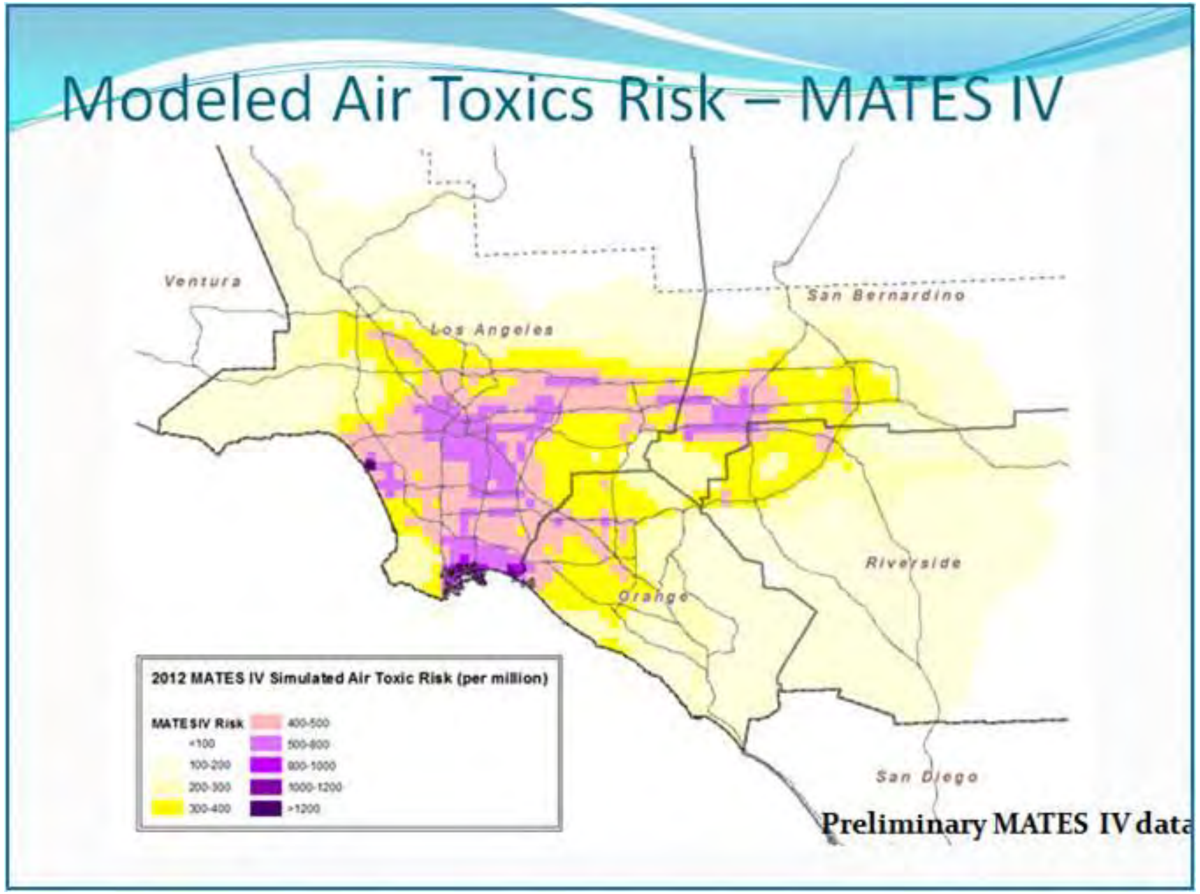
20 min increments

Cancer Risk Assessment – Diesel Exhaust

2005

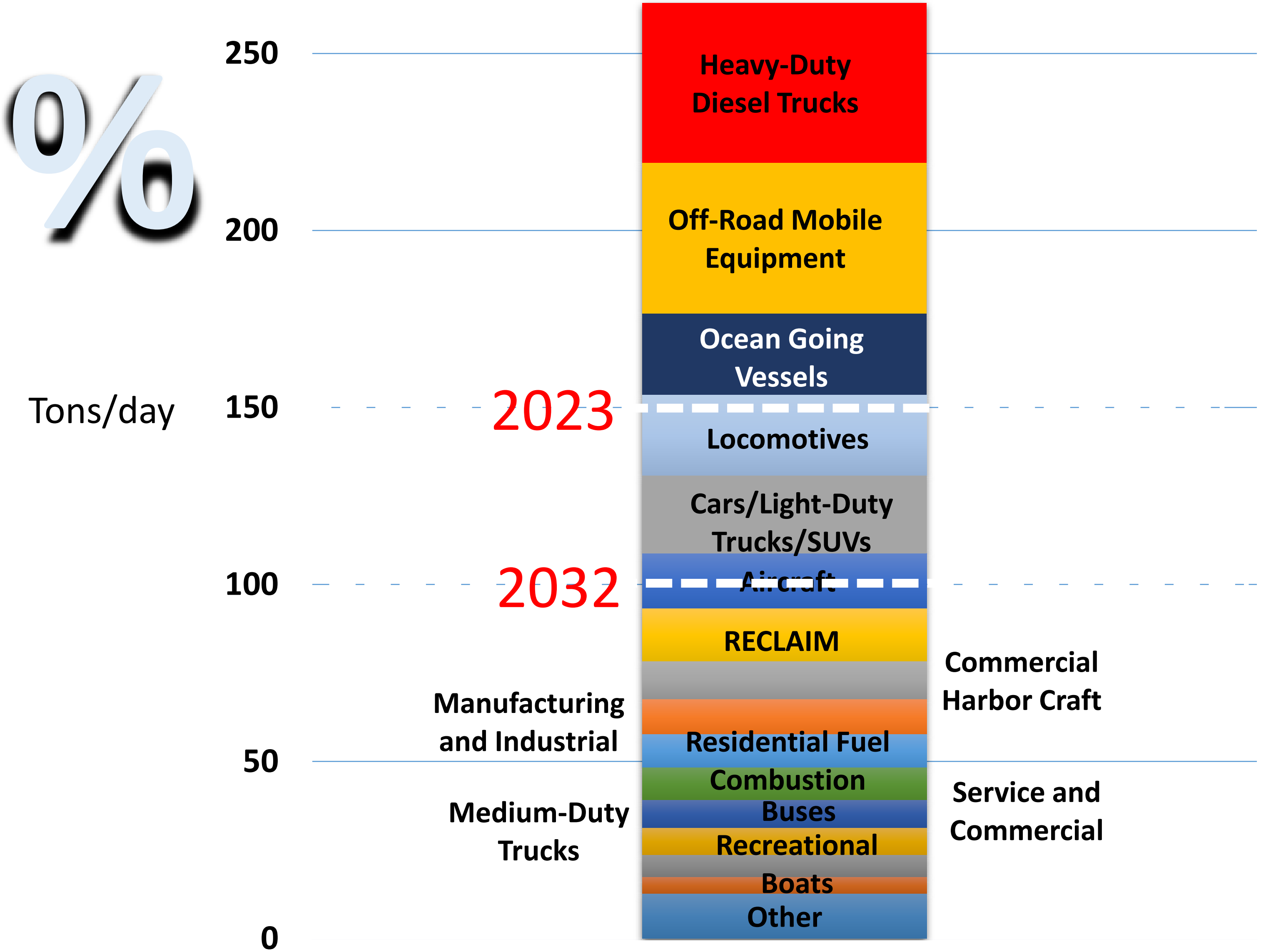


2012

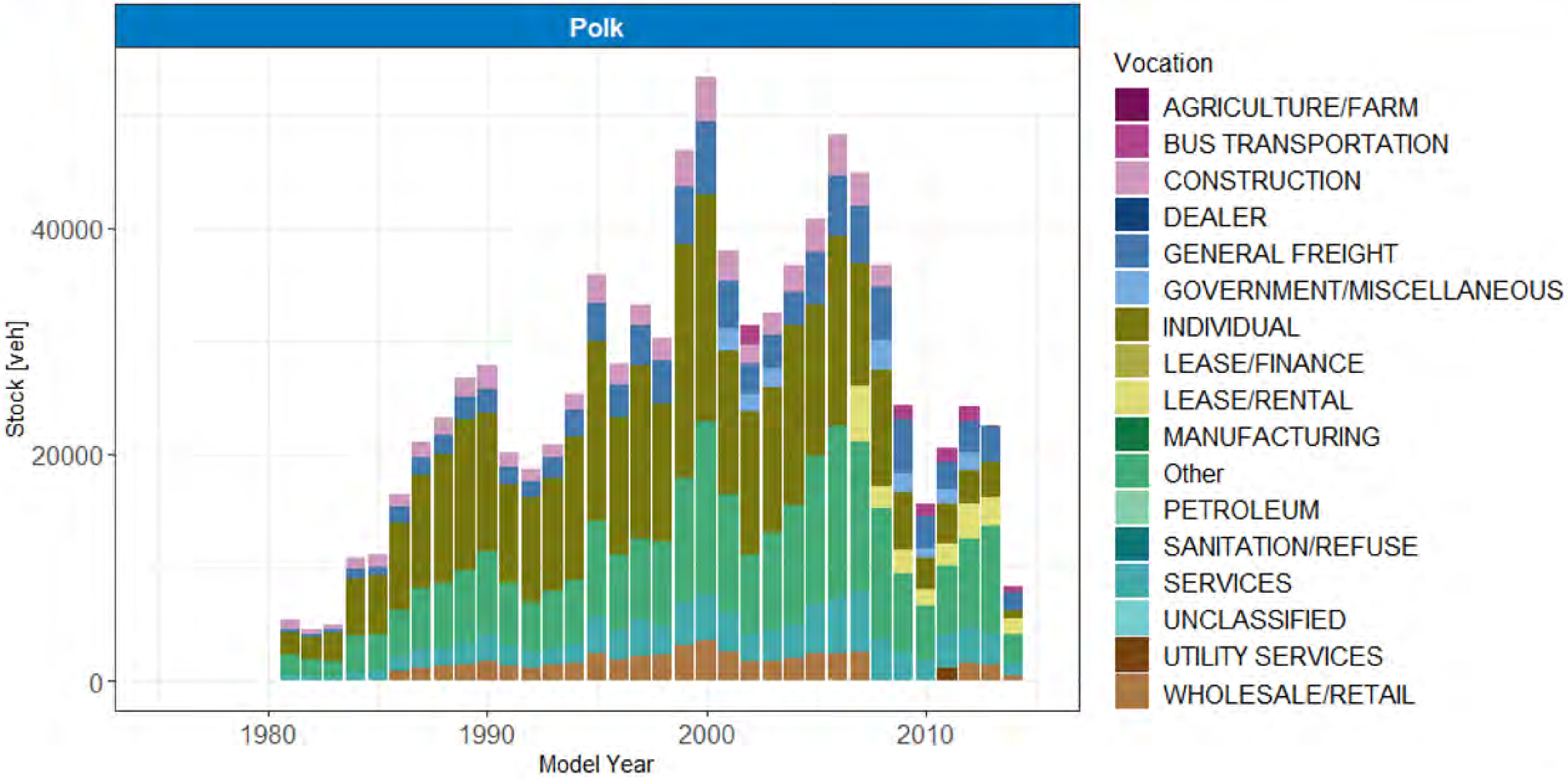


NOx Reductions Needed

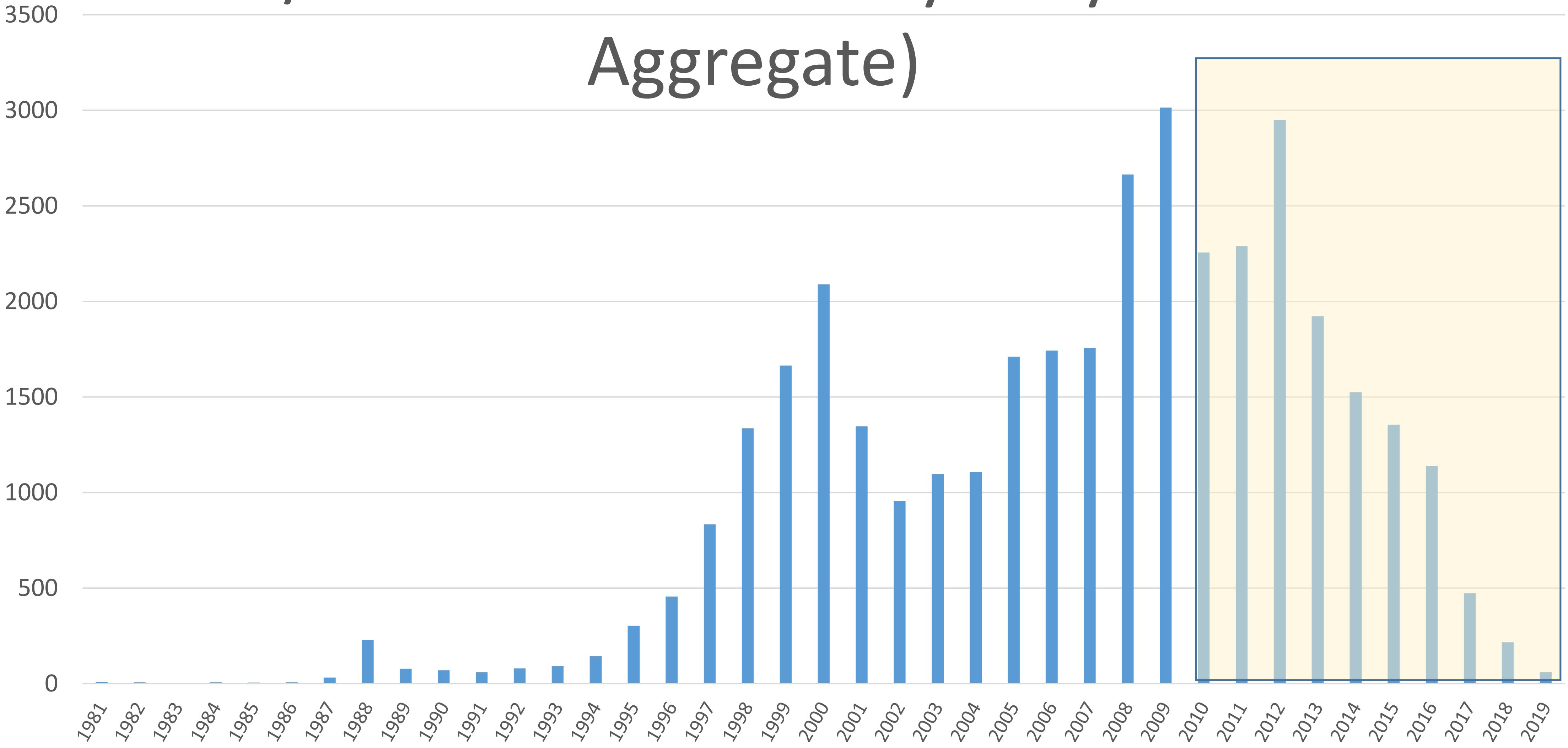
43-55%



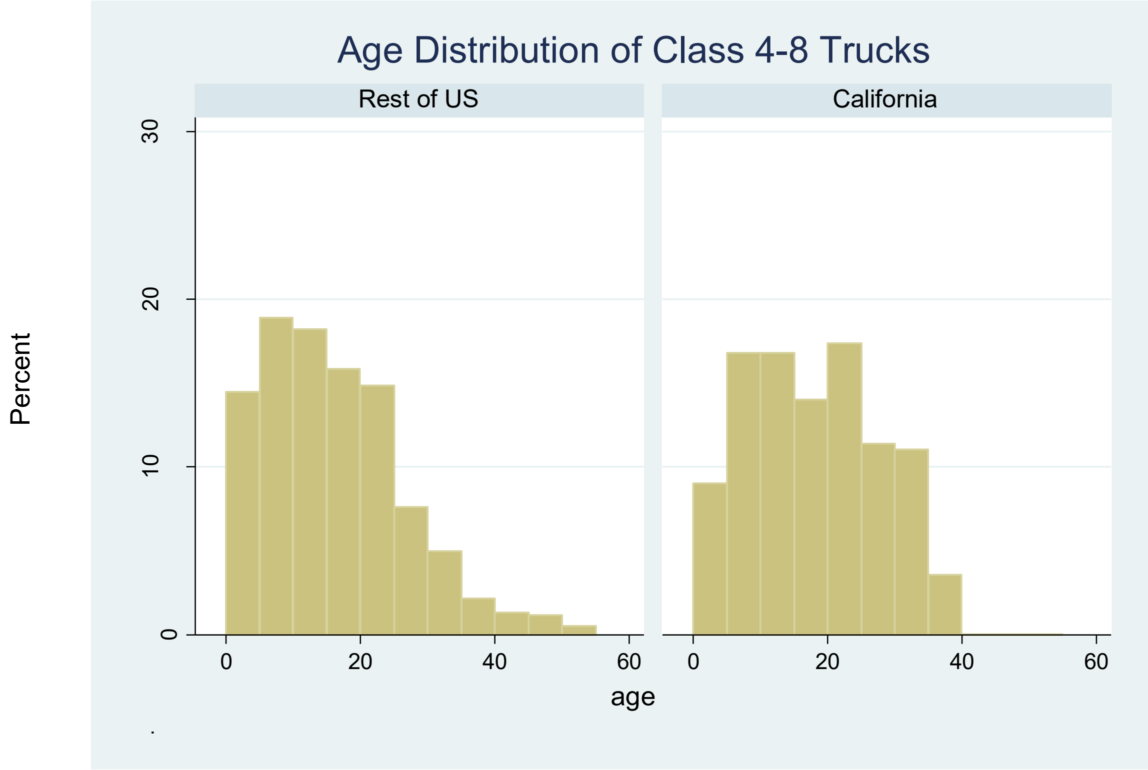
Polk California Vehicle Population Breakdown



IHS/Polk Data - CA Heavy Duty Trucks Aggregate)



Age Profile of Trucks by GVW



Population: 7,822,697
Average Age : 15.6

Population: 999,484
Average age: 17.5

Population: 3,576,389
Average Age : 14.4

Population: 393,204
Average Age : 16.5

Source: SCAQMD staff analysis of IHS/POLK data (data date: March 31, 2018).

Heavy-Duty Truck Usage National Data

Trucks Shipments – Increasing 1.4% per year

Table 2-1 Weight of Shipments by Transportation Mode: 2012, 2015, and 2045
(millions of tons)

	2012				2015				2045			
Millions of tons	Total	Domestic	Exports[1]	Imports[1]	Total	Domestic	Exports[1]	Imports[1]	Total	Domestic	Exports[1]	Imports[1]
Total	**16,896**	**14,901**	**864**	**1,130**	**17,978**	**15,983**	**920**	**1,075**	**25,346**	**20,940**	**2,202**	**2,204**
Truck	10,092	9,899	105	89	10,776	10,568	108	100	14,829	14,235	290	305
Rail	1,616	1,481	53	82	1,602	1,459	55	89	1,918	1,588	109	221
Water	884	502	68	313	884	544	95	246	1,100	609	190	301
Air, air & truck	10	2	4	4	10	2	4	5	37	4	16	18
Multiple modes & mail	1,311	309	596	406	1,346	324	615	407	2,962	431	1,521	1,010
Pipeline	2,942	2,672	37	233	3,326	3,056	43	226	4,468	4,058	73	338
Other & unknown	41	37	1	3	33	29	1	3	31	16	4	11

[1] Data do not include imports and exports that pass through the United States from a foreign origin to a foreign destination by any mode.

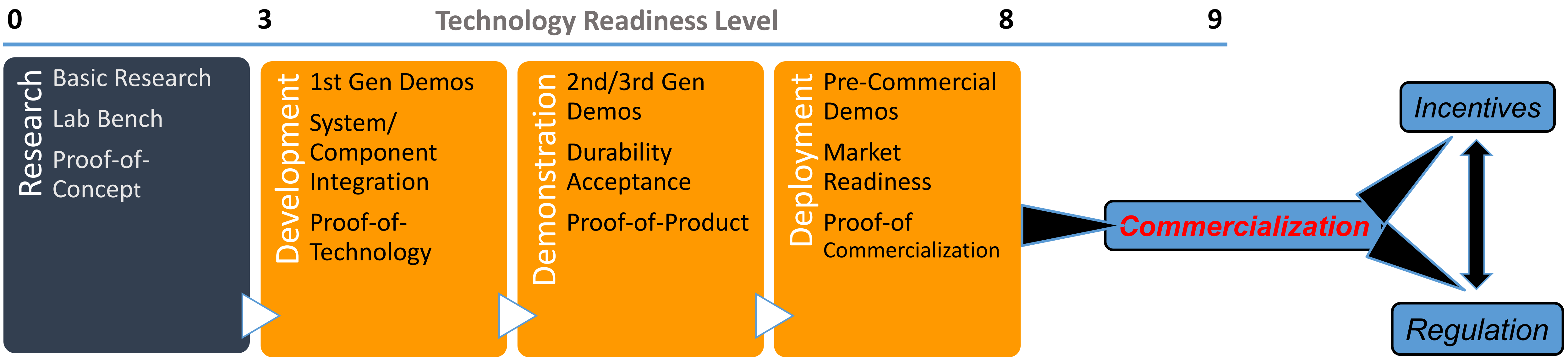
NOTES: Numbers may not add to totals due to rounding. The 2015 data are provisional estimates that are based on selected modal and economic trend data. All truck, rail, water, and pipeline movements that involve more than one mode, including exports and imports that change mode at international gateways, are included in multiple modes & mail to avoid double counting. Multiple modes and mail also includes some air movements. As a consequence, some totals in this table are less than other published sources.

SOURCE: U.S. Department of Transportation, Bureau of Transportation Statistics and Federal Highway Administration, Freight Analysis Framework, Version 4.3.1, 2017.

Pathways to Cleaner Air

- Near Term: Near-Zero NOx ICEs, Plug-in Hybrids
- Longer Term: Battery Electric and Hydrogen Fuel Cell

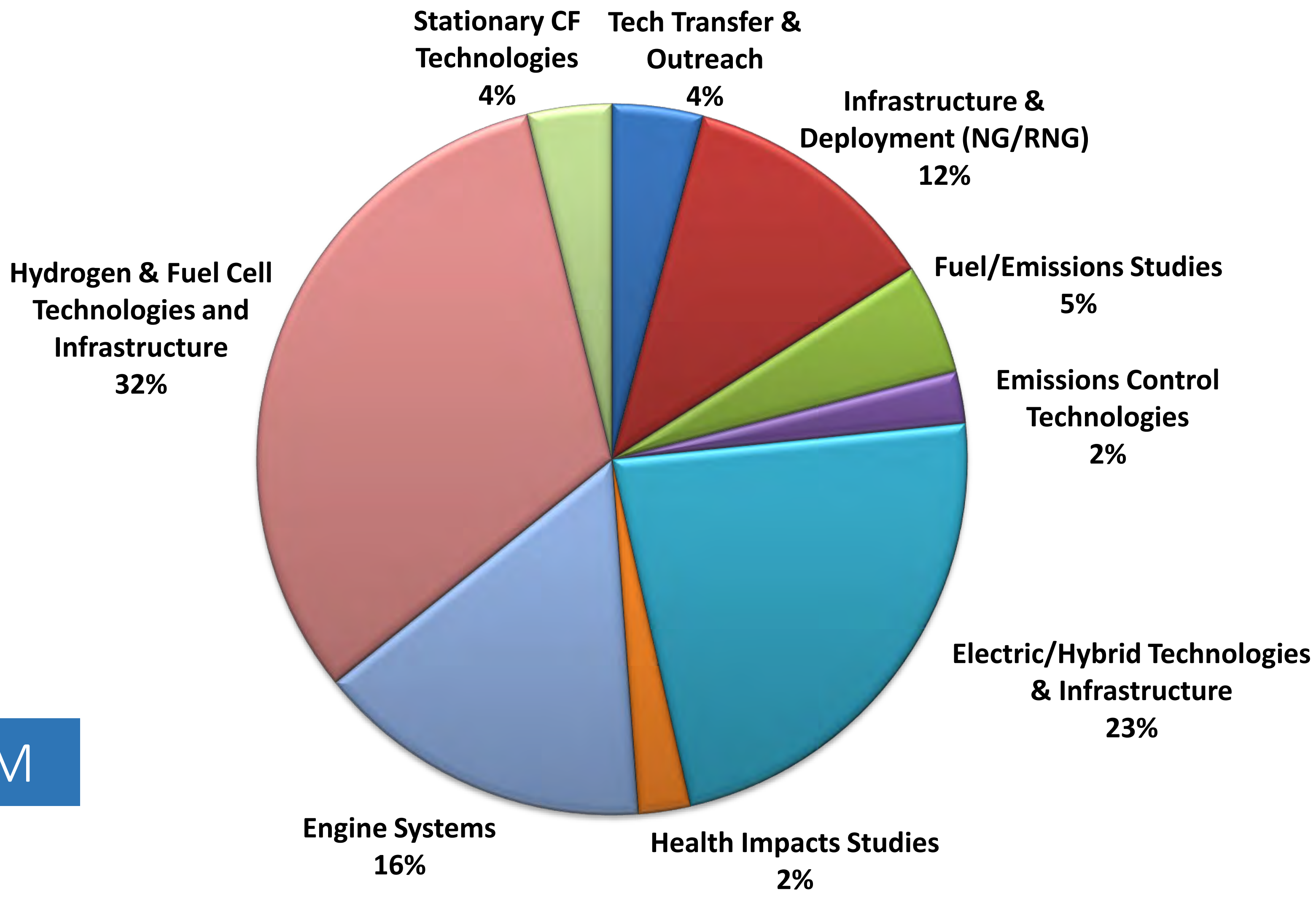
Technology Advancement



Clean Fuels Program-Core Technologies

- Hydrogen/Fuel Cell Technologies and Infrastructure
- Electric/Hybrid Technologies and Infrastructure
- Engine Systems/Technologies (ultra-low emission NG HDVs)
- Fueling Infrastructure and Deployment (NG/RNG)
- Fuels/Emissions Studies
- Stationary Clean Fuel Technologies
- Emission Control Technologies
- Health Impacts Studies
- Technology Assessment/Transfer and Outreach

Draft 2019 Plan Update



$16.9M

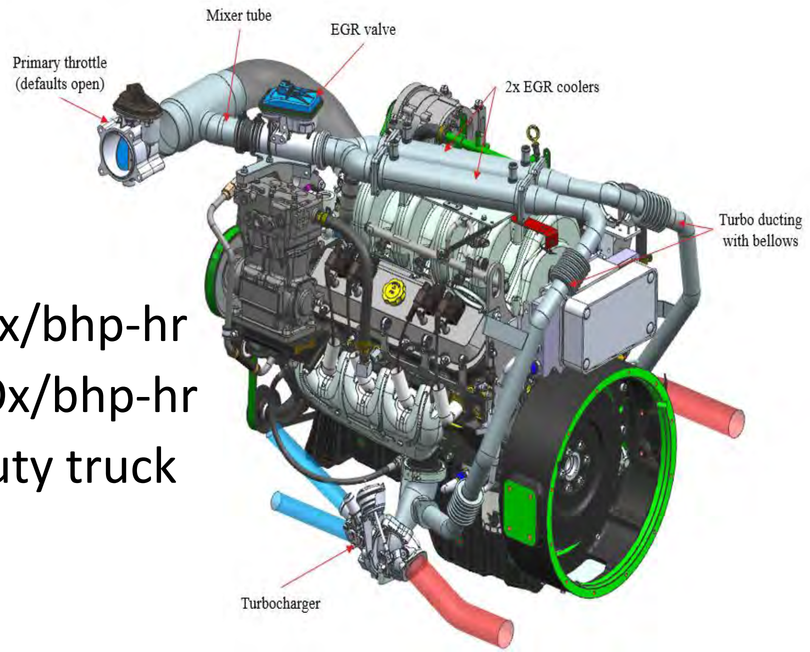
Key CNG Projects

In Production

- CWI: 9-liter (L9N) and 12-liter (ISX12N) certified at 0.02g-NOx/bhp-hr
- Commercialized in Class 7-8 trucks, including refuse trucks, and buses

2018 Department of Energy Solicitation through NREL

- Partnership with California Energy Commission & SoCalGas Company
- Nearly $27 million awarded
  - **Cummins:** 12L-15L CNG engine technology efficiency improvement
  - **US Hybrid:** Plug-in Parallel Hybrid Electric truck with L9N CNG/0.02g-NOx/bhp-hr
  - **GTI:** Production intent higher efficiency 5.4L CNG Isuzu Engine/0.02g-NOx/bhp-hr
  - **SwRI:** 5.4L CNG Isuzu engine integrated into a hybrid electric medium-duty truck



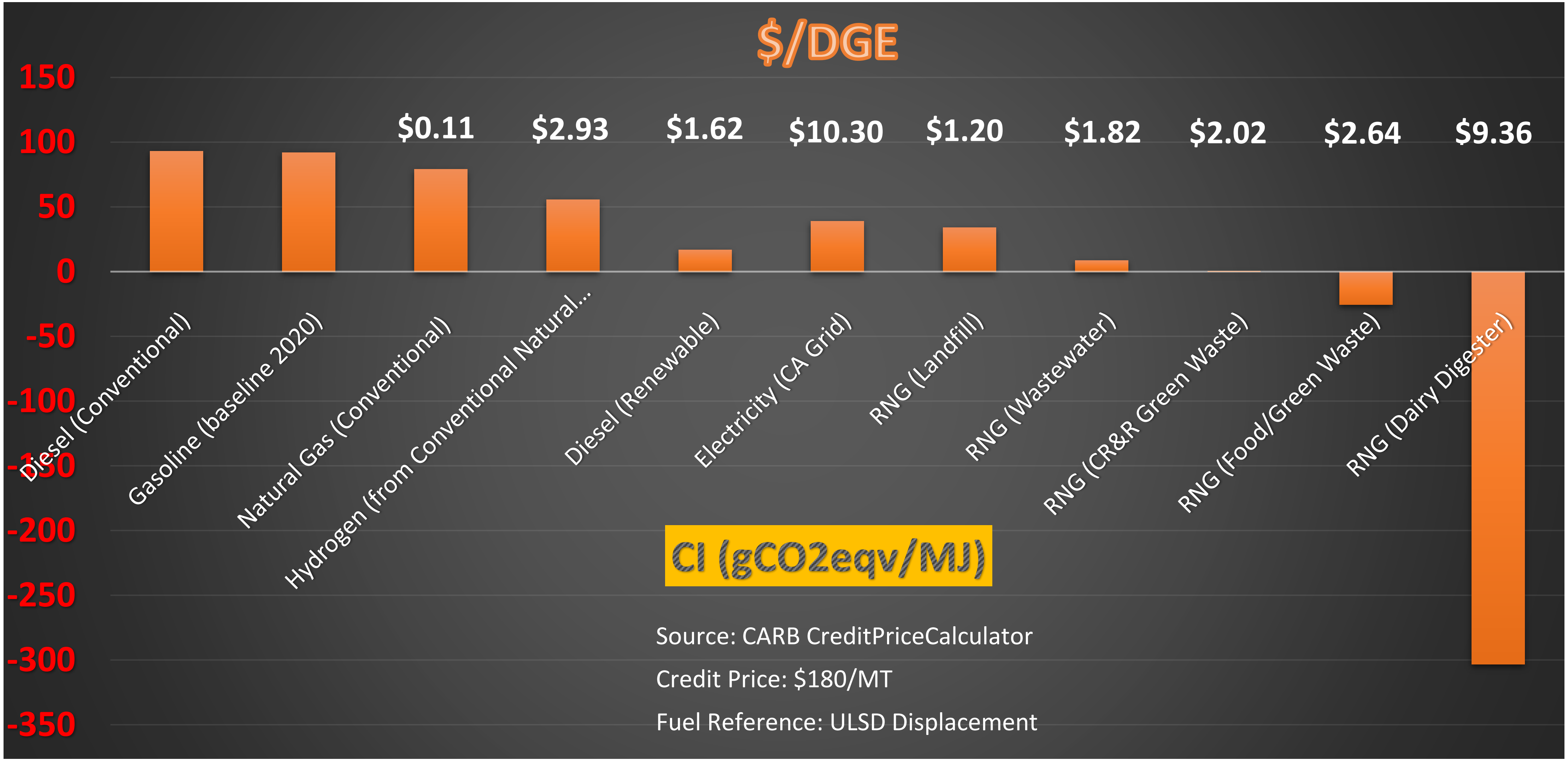
Local Production Renewable Fuels

CR&R Anaerobic Digestion of MSW to RNG

Kore Infrastructure Pyrolysis of Biomass to RNG and H_2

Rialto Bioenergy/Anaergia Anaerobic Digestion & Pyrolysis of MSW and Biosolids to RNG

LCFS Credit Transportation Fuels ($/DGE)



Incentives: Near Zero Engines/Vehicles

CWI L9N

$50 MM

587 Vehicles

- 228.3 tpy NOx

Agility's 366NG

$15.2 MM

175 Vehicles

- 18 tpy NOx

CWI ISX12N

$32.4 MM

383 Vehicles

- 173.8 tpy NOx

Takeaways

- Significant NOx reductions needed from mobile sector
- OEM engagement to scale up production and reduce costs
- Funding to accelerate commercialization
- Incentives to accelerate fleet turnover in CA
- Expanding local production and use of Renewable Fuels
- Supporting revised national heavy duty engine standard to push scalability and lower prices
- Partnerships with local, state and federal entities – key to success



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

Clean Cities
U. S. Department of Energy

Clean Cities Coalition Listening Sessions

“feedback from the front-lines”

U.S. Department of Energy Priorities

National Security

Economic Growth

Affordability for Businesses and Consumers

Reliability/Resiliency

Technical Portfolio

Light-, Medium-, and Heavy-Duty Vehicles


Energy Efficient Mobility Systems and Technologies

Alternative Fuel Infrastructure

Nearly 100 Clean Cities coalitions with thousands of stakeholders, representing ~80% of U.S. population

Clean Cities
U.S. Department of Energy

25th ANNIVERSARY Since 1993

(CleanCities.Energy.gov)

Technical and Problem Solving Assistance

Technical Response Service

TechnicalResponse@icfi.com

800-254-6735

- Capture lessons learned and best practices
- Address unforeseen permitting & safety issues
- Identify chronic vehicle or infrastructure field problems
- Incident investigations
- Inform future R&D with real world experiences

Every Clean Cities Coalition is a *Living Laboratory!*

- New technologies always have bugs and shortcomings when they are first introduced (some more serious than others).
- Coalition stakeholders have years of practical real-world field experience with alternative fuels and other advanced vehicle technologies. They know what has worked well and not so well.
- Feedback from listening sessions will help to identify technology gaps, lessons learned, and critical improvements that provide important feedback to the research program and inform future research needs (related to vehicles, infrastructure, and unforeseen end-use complications).

U.S. DEPARTMENT OF ENERGY

Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

Interesting Feedback so far …..

Dennis A. Smith, P.E.

National Clean Cities Director,

Technology Integration Manager

Clean Cities

U. S. Department of Energy

Agility®
fuel solutions

The Many Faces of Agility

Chet Dawes – SVP Cylinders & Europe

About Agility

Agility Vision

Clean air everywhere
through sustainable transportation solutions

Agility Mission

Make a difference in the world by delivering the most innovative, cost effective clean transportation solutions

Inspire ingenuity and teamwork to design outstanding products backed by exceptional customer service

Partner with our customers to ensure their success

Nurture a values-based and results-driven culture to win in the marketplace

Agility Executive Overview

- Designer, developer, manufacturer and service provider of alternative energy systems and storage cylinders
- Solutions include Hydrogen, CNG, LNG, Electric and Propane
- **#1 market position**, first mover in rapidly expanding market
- ~500 employees, including ~70 Agility engineers and technicians
- **10 locations** worldwide
- Provided cylinders and/or fuel systems for **over 60,000 commercial vehicles**
- Aftermarket service network across North America
- Wholly-owned subsidiary of Hexagon Composites ASA (OSLO: HEX), which is 25% owned by Mitsui – strong profitability and capital resources

Medium & Heavy Duty Trucks, Bus, and Refuse

Heavy Duty

Medium Duty

Transit buses

Refuse trucks

Business Segments

Complete clean fuel solutions for medium- and heavy-duty commercial vehicles

Energy Storage & Delivery

- Modular fuel storage and delivery systems
- CNG, LNG and H_2
- Since 1996; Over **45,000 vehicles** on the road today

Compressed Gas Cylinders

- Largest manufacturer of Type 4 composite H_2 / CNG cylinders globally
- Origins in aerospace in 1963; 25 years making vehicle cylinders

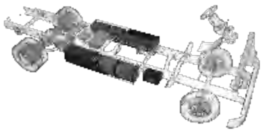
Powertrain Systems

- Complete certified fuel systems development (engine optional)
- Medium duty vehicle market: propane, CNG

EV Systems

- Launched in 2018
- Battery pack, BMS, drivetrain and systems integration for BEV medium and heavy duty vehicles

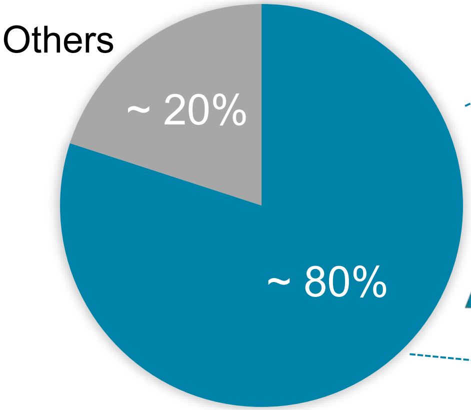
Product Competencies

	Energy Storage	Energy Mgmt	Powertrain Integration	Vehicle Integration	User Interface	
G-Mobility	 Methane or H2 Cylinders	 Agility Blue iQ	 Certified natural gas, LPG engines	 CNG/H2 Pack	 CNG / H2 Covers / Design for Service	 Fueling Interface
E-Mobility	 Lithium-Ion Cells	 BMS Controller	 Electric drivetrain integration	 Battery Pack	 Electric Covers / Design for Service	 Charging Interface

Complete system capabilities for energy storage, delivery and conversion

Strongly Positioned in North America

NG Fuel System & Cylinder NA Market Share



Bus

- DINA
- NEW FLYER
- GILLIG
- NOVA BUS
- ELDORADO REV GROUP

Refuse

- WM Waste Management
- Republic Services
- McNeilus
- Waste Connections
- Autocar
- CCC Crane Carrier Company

Truck OEMs & Fleets

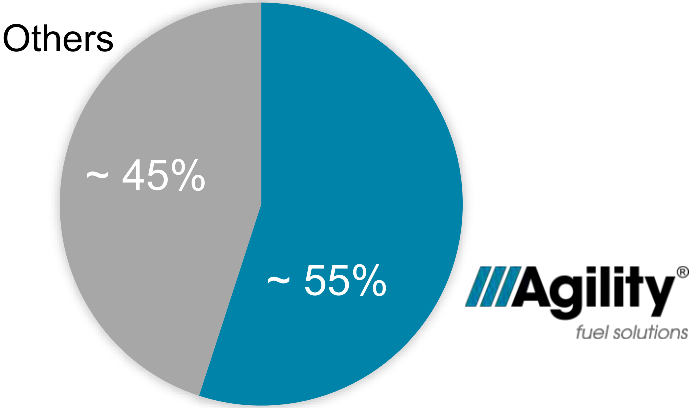
- Freightliner
- FedEx
- UPS
- Volvo
- Mack
- Penske
- Ryder
- Navistar
- Frito Lay
- Kwik Trip
- Anheuser-Busch
- Kenworth
- Peterbilt
- Chrysler
- GTM Grupo Transportes Monterrey

Representative customers, not all inclusive

Transit Bus System Leader in Europe

Agility fuel solutions

Transit Bus NG Fuel System Europe Market Share



Bus OEM Customers

MAN

SCANIA

IVECO

DAIMLER

SOR

SOLARIS

Representative customers, not all inclusive

Customer Care and Training

Installations
- On-site installation services
- Off-site installation available

Training
- Training for OEMs and end users
- Dealer training for maintenance and repair

Warranty
- 2 years of standard coverage
- Extended warranties available

Repairs
- Growing network of service providers
- Service centers strategically placed for quick and local service support

Aftermarket Parts
- OEM quality parts

Service
- Emergency breakdown service where local dealer isn't available
- Field service engineering and technical support available

Technical Publications
- Factory parts, operations, and service manuals developed for dealers and user.

Marketing Support
- Dealer and end-user education
- Co-marketing and presentations at conferences / expos / events
- Whitepapers

Agility's in-field capabilities and expertise have made us the go-to aftermarket service partner for OEMs and fleets

Hexagon Group

Hexagon Composites

Hexagon Ragasco

- Propane cylinders
  - Household
  - Catering
  - Leisure
  - Forklift

Mobile Pipeline

- CNG cylinders and solutions for bulk transport

Hexagon Purus

- CNG and hydrogen cylinders for light duty vehicles
- Hydrogen cylinders for transportation and storage

Agility Fuel Solutions

- Focus on medium & heavy duty vehicles
- CNG cylinders
- CNG fuel systems
- Hydrogen systems
- EV systems / packs
- Propane fuel systems
- CNG & propane engines

Technical Products Businesses

Hexagon Masterworks – specialized composite products

Digital Wave – testing technology

Who is Hexagon?

- Leading global manufacturer of composite pressure cylinders and systems for gas applications
- Headquartered in Aalesund, Norway
  - Modern production facilities in Germany, Norway and USA
  - Around 450 employees outside of Agility
- 2018 pro forma revenue of US$346 million
- Public company listed on Oslo Stock Exchange (HEX.OL)
  - Market cap of approx. US$764 million as of Apr 10, 2019

Renewable gas storage, distribution and fuel systems technology and solutions

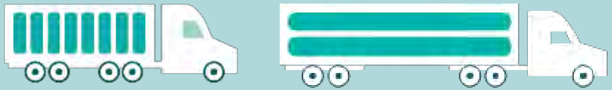
Agility Solutions Portfolio

Fuel & Energy sources

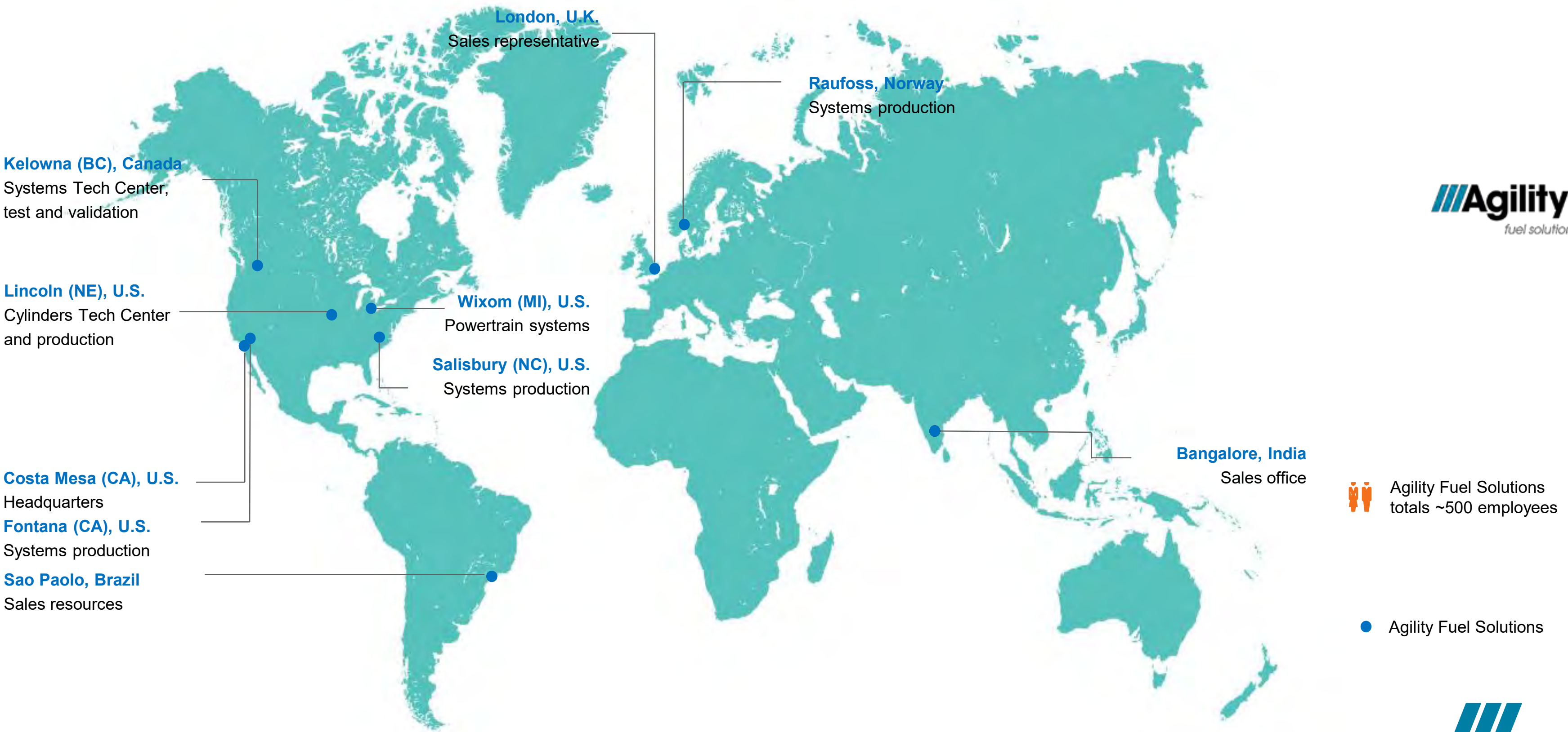
Automotive
Energy storage and conversion systems for heavy-duty trucks, refuse trucks and buses, medium-duty vehicles

CNG / LNG / Biogas
Propane
Hydrogen
Electricity

Hexagon Solutions Portfolio

	Fuel & Energy sources
Automotive Energy storage and conversion systems for heavy-duty trucks, refuse trucks and buses, medium-duty vehicles, light-duty vehicles 	CNG / LNG / Biogas Propane Hydrogen Electricity
Mobile Pipelines Storage and transportation cylinders and modules for off-pipeline applications 	CNG / Biogas Hydrogen
Marine & Rail Fuel and storage cylinders for marine and rail 	Hydrogen
Ground storage Cylinders for ground storage 	Hydrogen
Cylinders LPG cylinders for leisure activities, household and industrial applications 	LPG (propane / butane)

Agility Global Capabilities



Hexagon Global Capabilities

New Hexagon Composites Group totals ~950 employees

- Hexagon admin & production sites
- Hexagon sales offices / reps
- Agility Fuel Solutions

Agility Salisbury

Salisbury, NC
Agility's Newest Facility

World Class Fuel System Manufacturing

Agility® fuel solutions

Plant Information	
Location	**Salisbury, North Carolina, USA**
Products	• Bus systems • Refuse systems • Truck systems • Fuel Management Modules • Engine assembly / test • Full installations
Value Add	• Component fabrication • Painting • Assembly • Vehicle installation
Manufacturing Equipment	• CNC laser • CNC roll form • CNC press brake • CNC machining • Multi axis extrusion machine • Robotic tube bending • Automated paint shop • Installation
Quality Equipment	• Full quality lab • CMM • Paint color match
Footprint	200,000 Sq. Ft. / 18,580 Sq. M
Certifications	ISO 9000, ISO 14001; TS16949 in process

System Architecture
ProCab

Agility® fuel solutions

ProCab Assembly

- Multi Configurations
- 40 DGE – 175 DGE
- Planned Takt Time 1 hour
- Two cylinder to five cylinder systems
- BlueIQ and Standard

System Architecture
ProRail & LNG

ProRail
System Assembly

- Dedicated line used for multiple configurations
- 17 DGE – 60 DGE
- Planned Takt Time 32 minutes per station
- Integrated FMM’s
- BlueIQ and Standard

System Architecture
Roof Mount and Tailgate

Roof Mount and Tailgate System Assembly

- Roof Mount, Tailgate, Front of Body, Back of Bus, Under Body system assembly
- Planned takt time 1.1 hour per station
- Single cylinder to five cylinder systems

Manufacturing Capability
Machine & Fabrication

Agility® fuel solutions

Manufacturing Capability
Machine & Fabrication

Laser

De-burr

Brake Press

Roller

Mill

Multi-Axis Extrusion Machine

Manufacturing Capability
Machine & Fabrication

Mazak CNC

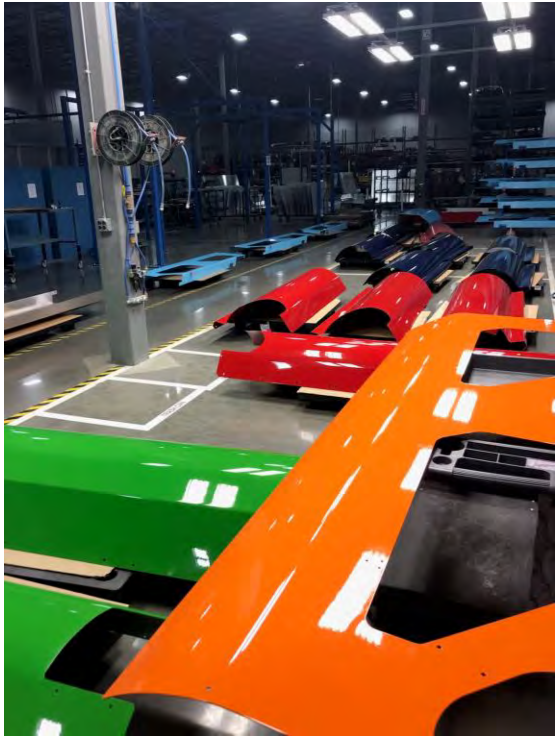
Robotic Tube Bender

Saw

Router

Paint System

- World class powder coat and wet spray paint
- Powder coat runs two shifts
- Wet spray runs one shift
- Using Volvo acceptance standards
- Color match of any OEM request
- Contract service as needed



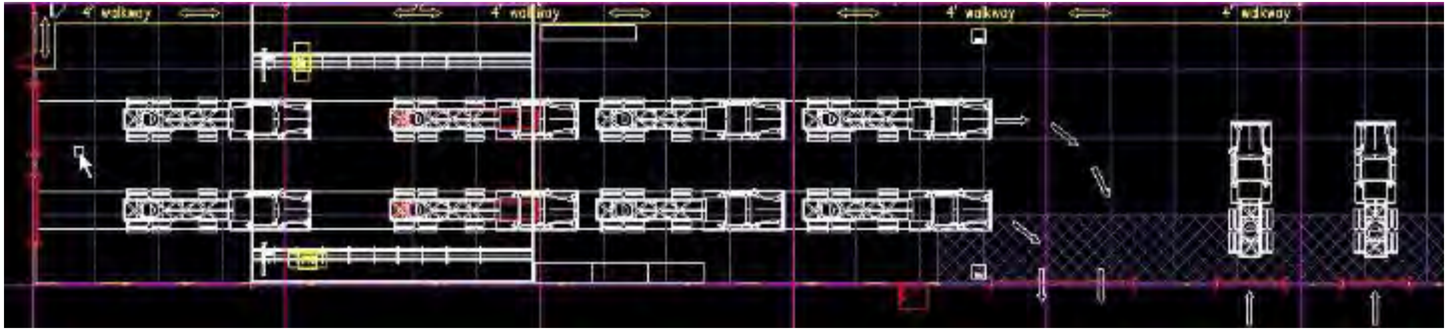
Assembly
Fuel Management Modules

- Multiple configurations
- Integrated and Remote Mount
- Hardware/software installed
- System leak check/verification
- BlueIQ and Standard

Powertrain Engine Assembly

- Multiple configurations
- Engine dressing from purchased long blocks
- End of line engine hot test

System Installation Capability



- BTC, SideMount, Dual Sidemount installs
- CNG fueling
- BlueIQ installations
- Final system pressure testing and tank inspection

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

End of Life Testing of CNG Fuel Containers

Lauren Lynch
Mechanical Engineer
NGVTF
April 16th, 2019

Agenda

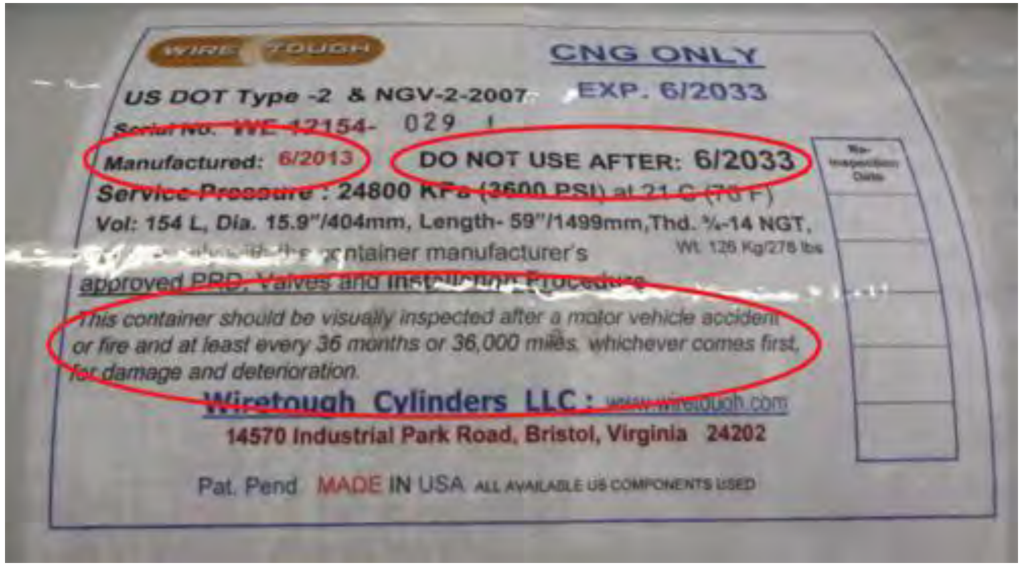
- Introduction
- Project Background
- Project Objective
  - Scope
  - Key Deliverables
- Project Update
- Next Steps
- Conclusion

Introduction

- Lauren Lynch
- National Renewable Energy Laboratory 2016-Present
  - Mechanical Engineer
  - Vehicle Technology Integration Group
- Cummins Emission Solutions 2011-2016
  - New Product Engineer/Program Leader
  - Emission Control Technologies

Project Background

- Vehicles are Outliving the Manufacturer's Defined Life for CNG Fuel Tanks
  - Safety Concerns??
  - Cost Concerns for Fleets??
  - Re-certification Potential??



Project Objectives

- Characterize the CNG fuel tank conditions at the end of their defined useful life.
- Determine how fuel tanks might fail under routine operating conditions after their end of life date.
- Characterize the remaining functional life.
- Recommend safety measures to address end of life issues.
- Provide guidance on tank inspection.

Project Scope

IN SCOPE:

- Type III CNG Tanks
- Type IV CNG Tanks
- CSA NGV2
- DOT 49 CFR
- ANSI
- ASME
- Used tanks

OUT OF SCOPE:

- Type I CNG Tanks
- Type II CNG Tanks
- New tanks
- Unused tanks

Key Deliverables

NREL Subcontractor Digital Wave Corporation Inc. of Centennial, Colorado with Selected as the Testing Lab on October 3rd, 2016

- Test plan
- Comparison of test results vs. the pre-test visual inspection results
- Comparison of test results to the specific tank design standards
- Overall comparison of Type III to Type IV tank results
- Assessment(s) on the end of life condition of the tanks, the risks associated with further use (as well as quantification of these risks)
- Recommendation of tests and inspections for tank re-certification
- Recommendation(s) on changes to relevant codes and standards
- Presentation of results and recommendation to NGV stakeholder group as identified by NREL

Project Update

EXECUTIVE SUMMARY Of SUBCONTRACT 1

- EOL performance testing of Type III & Type IV composite pressure cylinders.
  - Hydraulic Burst Testing
  - Notch Testing
  - Drop Testing
- Full service life tanks in bus service with the Los Angeles Metro Transit Agency.
- Modal Acoustic Emission (MAE) was utilized to assess the structural integrity of cylinders before and after testing.

Project Update

EXECUTIVE SUMMARY Of SUBCONTRACT 1

- 10 Type III & 10 Type IV CNG tanks were subjected to a hydraulic burst pressurization.
- 4 Type III & 4 Type IV CNG tanks were subjected to notch tolerance testing.
  - Both cylinder design types’ burst strength revealed that tanks at EOL still maintained strength performance within manufacturing requirements.

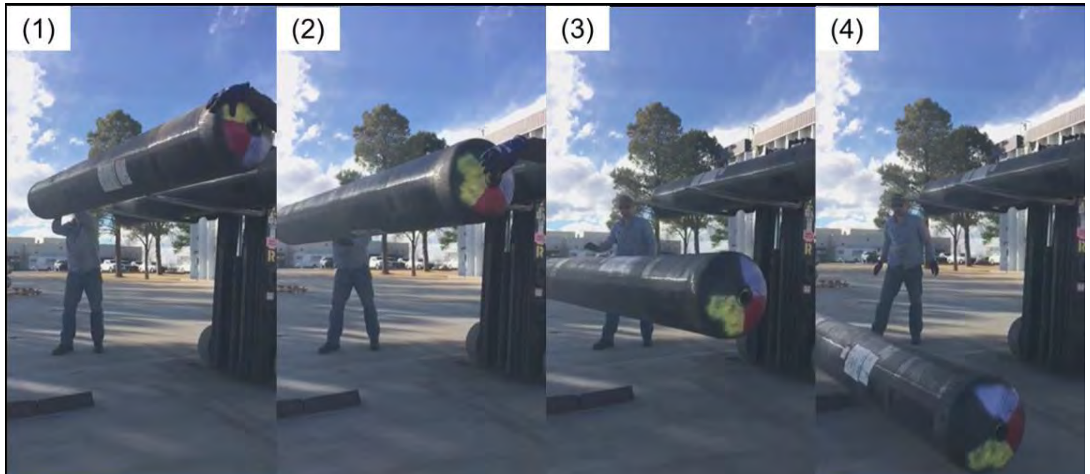
Axial and hoop oriented strain gages for burst testing

(a) short width, deeper depth notch and (b) longer width, shallower depth notch

Project Update

EXECUTIVE SUMMARY Of SUBCONTRACT 1

- 6 Type III & 6 Type IV CNG tanks were subjected to impact tolerance testing.
  - All 6 fatigue cycled vessels met the fatigue cycling requirement of ISO 11439.
  - 2 of the 4 *Type III* cylinders which were subjected to the localized impact test procedure met the min. manufacturing burst strength req.
  - 4 *Type IV* cylinders which were subjected to localized impact testing did not meet minimum required burst strength per NGV2 and 49 CFR 571.304.
- MAE waveforms indicated significant and localized damage to the locally impacted cylinders.



Time lapse of a Type IV cylinder being impacted onto steel angle iron.

Recommendations to Date

EXECUTIVE SUMMARY Of SUBCONTRACT 1

- An inspection procedure capable of detecting damaged cylinders that do not have visual indications of damage should be adopted to prevent in service failures which risk life and property.
- Cylinders involved in a motor vehicle accident should be inspected by a more rigorous method than visual inspection, as that procedure was found to be nonconservative.
- MAE testing identified all cylinders that had degraded strength performance, as well as cylinders which were structurally sound.

Next Steps

Continuation of characterizing the EOL performance of the composite CNG pressure tanks:

- Modal Acoustic Emission examination (non-destructive)
- Hydraulic fatigue cycle testing (physical)
  - One type 3 and one type 4 tank will be randomly selected after finishing the fatigue test protocol to be subjected to a gaseous leak test.

Conclusion

- Testing commenced March 2019
- Expected test completion date August 2019
- Final report due September 2019
  - Presentation of results

Questions

Lauren Lynch

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Evaluation of NGV Fuel System and Fuel Container Integrity Requirements

Lauren Lynch
Mechanical Engineer
NGVTF
April 16th, 2019

Agenda

- Introduction
- Project Background
- Project Objective
  - Scope
  - Key Deliverables
- Interactive Discussion
  - Commonly used standards/best practices
  - Key Concerns
- Next Steps
- Conclusion

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- Lauren Lynch
- National Renewable Energy Laboratory 2016-Present
  - Mechanical Engineer
  - Vehicle Technology Integration Group
- Cummins Emission Solutions 2011-2016
  - New Product Engineer/Program Leader
  - Emission Control Technologies

Project Background

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” & FMVSS 304 “Compressed Natural Gas Fuel Container Integrity”
  - Light-duty CNG vehicles
    - Passenger cars, multipurpose passenger vehicles, trucks, and buses
  - CNG Fuel Systems Only

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

Interactive Discussion

Common CNG standards/references:

- FMVSS No. 303
- FMVSS No. 304
- NGV 2
- CSA/ANSI NGV 6.1
- UN ECE R.110
- CMVSS No. 301.2

OTHERS??

Today’s Federal Standard

- CNG Fuel Container Integrity
  - Labels:
    - “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.
    - OTHERS?

Today’s Federal Standard

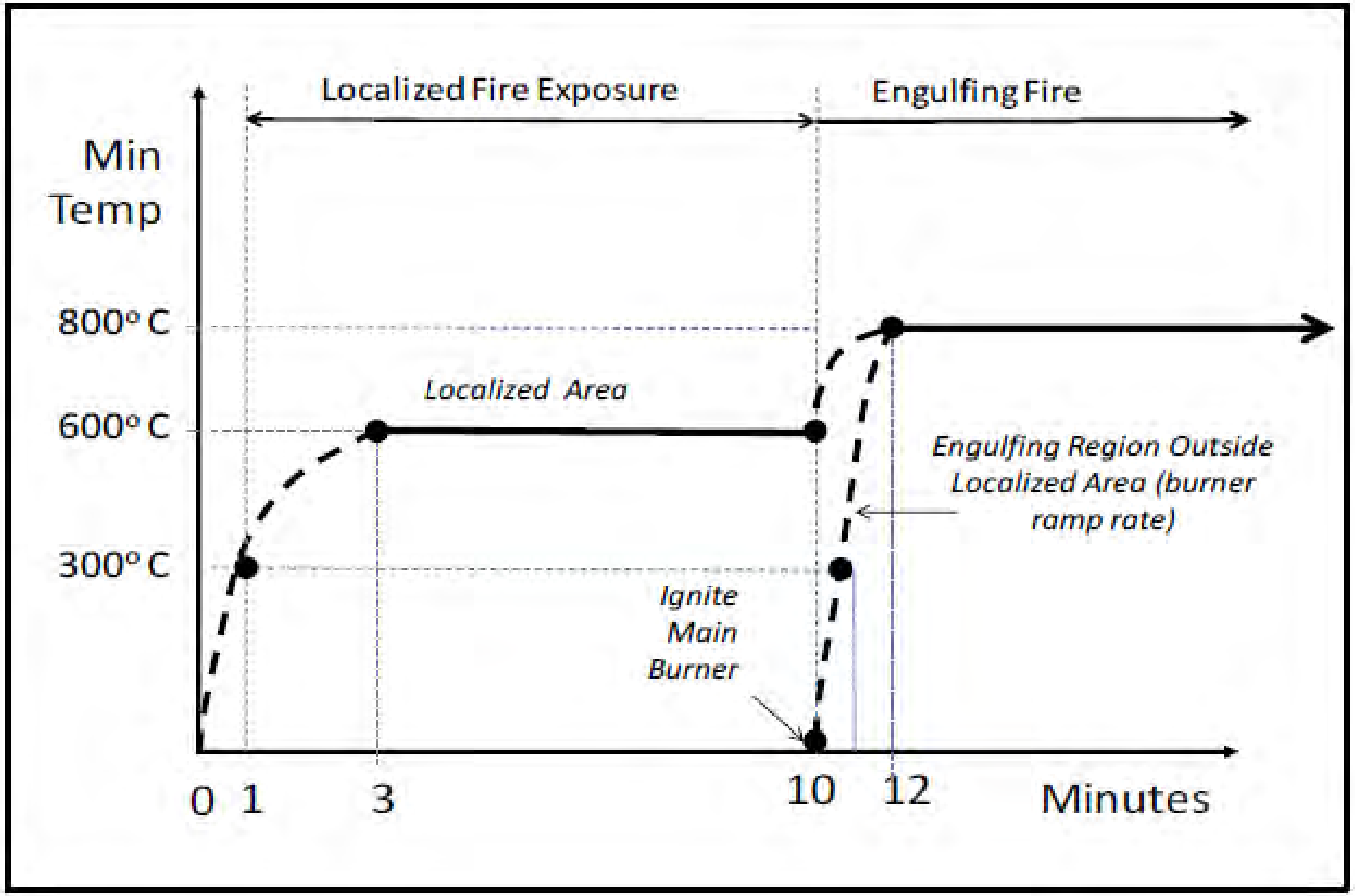
- CNG Fuel Container Integrity
  - Burst pressure of 2.25 x Service pressure for non-welded containers and 3.5 x Service pressure for welded containers.
  - Hydrostatic pressure testing of 13,000 cycles from service pressure to <10% of service pressure at ambient temperature. Then 5,000 cycles from 125% of the service pressure to <10% of service pressure at ambient temperature.

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.

GTR No. 13

GTR 13 Localized & Engulfing Fire Test



GTR No. 13 Phase 2

GTR 13 Localized & Engulfing Fire Test

- Studies show that the flame height effects the temperatures at end-boss and the top the of the cylinder in localized fire test of hydrogen fuel tanks.
  - Proposals to update GTR 13 (hydrogen fuel tank specification) to make the test more repeatable **and reproducible**
  - Standardize the fire source (LPG) by defining a precise flame height to achieve a specified temperature profile on a **standard metal** cylinder top side & end boss.
  - Derived from Japan Automobiles Research Institute (JARI) vehicle fire data.
- Reduces variation in testing laboratories.
- Reduces the influence of combustion of combustible materials.

- JARI aims for international agreement in June 2020 on measures to improve the **repeatability and reproducibility** of the localized fire test.

Today's Standards/Best Practices

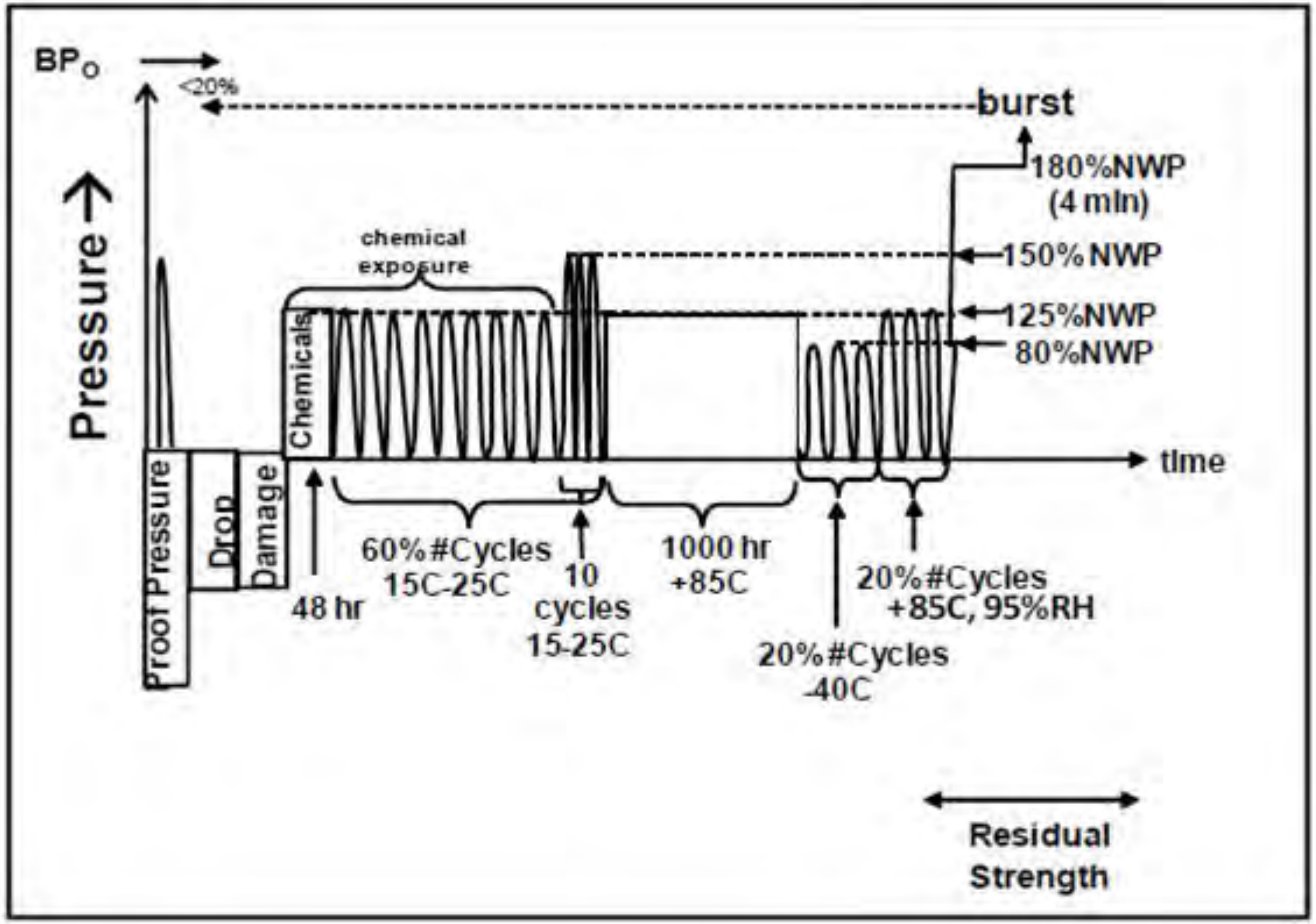
Chemical exposure, impact testing, drop testing, stress rupture and fueling to 150% & 180% of working pressure.

- NGV 2 – defines above as individual tests.
- GTR 13 – combines into one as cumulative exposure during lifetime of the container.

Thoughts??

GTR No. 13

Hydraulic Verification Test for Performance Durability



Today's Standards/Best Practices

- CNG Fuel Container Integrity
  - OTHERS??
    - Barrier crash testing??
    - Light-, medium-, and heavy-duty application differences??
    - CNG vs. LNG??

Today’s Standards/Best Practices

- 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.

Today's Standards/Best Practices

- CNG Fuel System Integrity
  - Barrier Crashes:
    - Frontal
    - Rear Moving
    - Lateral Moving
    - Moving Contoured
    - 100% service pressure w/N2

Today’s Standards/Best Practices

GTR 13 Fuel System Integrity Test

- Crash test for heavy-duty vehicles is not practical because vehicles are built to order and crash testing per single vehicle can be expensive.
  - UN inspired standard of installation and mounting requirements and a component level test.
  - *“All components and interconnecting piping and wiring should be securely installed or supported in the vehicle and located (or given protection) such that its components, piping, fittings, and valves are protected from damage due to contact with objects encountered during normal operation of the vehicle.”*
  - *“The mountings and supports shall withstand the following accelerations as static forces on the fully-filled hydrogen storage system:”*

- Concerns of a component standard being design restrictive.

Today's Standards/Best Practices

- CNG Fuel System Integrity
  - OTHERS??
    - Light-, medium-, and heavy-duty application differences??
    - CNG vs. LNG??

Summary of Key Concerns

Next Steps

- NREL will summarize the discussion
  - Fuel System Integrity Crash Test of Heavy-duty Vehicles
  - Fuel Container Integrity
    - Chem exposure, drop, impact/notch, stress rupture etc.
    - Stress rupture update
  - Fuel Container Fire Test
  - Key Concern
- Post summary to NGVTF website
- Share summary with NHTSA
- Follow-up on open questions

Questions

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APRIL 16, 2019

Codes and Standards Update

2019 Natural Gas Vehicle Technology Forum

Brent Hartman

Codes and Standards Update

1. About CSA Group
2. How Standards Work
3. CSA Group Alternative Energy Vehicle Program
4. Natural Gas Vehicles Codes and Standards
5. Codes, Standards, and New Technologies

CSA GROUP™


CSA GROUP
HOLDING THE FUTURE TO A HIGHER STANDARD
About CSA Group

About CSA Group

- Established in 1919
- Independent, not-for-profit
- Accredited by
  - Standards Council of Canada (SCC) in Canada; and
  - American National Standards Institute (ANSI) in the U.S.
- 3,000+ standards, codes & related products
- 1,800 employees
- Product testing, inspection & certification
- Offices around the world

Holding the Future to a Higher Standard

CSA GROUP

HOLDING THE FUTURE TO A HIGHER STANDARD

How Standards Work

How Standards Work

- Establish enforceable minimum safety requirements
- Practical and easy to implement
- Written in terms that are measurable or enforceable
- Have clear and readily understood language
- Avoid ambiguity – “shall”, “should” & “may”
- Provide maximum benefit to large segment of population
- Reflect the state of the art
- Voluntary until adopted into regulation
- Reviewed every 5 years (maximum)

Open.

Balanced Interests.

Due Process.

Consensus.

HOLDING THE FUTURE TO A HIGHER STANDARD

The People & Process

The People & Process

- Our 10,000 members serve as the technical experts
- We facilitate the process and indemnify our members
- A rigorous process ensures consistency and credibility
- Development stages include:
  - Notice of intent
  - Content development (drafts, meetings & deliberations)
  - Public consultation
  - Formal edit & approval
  - Publication
- Standards are living documents, open to revision

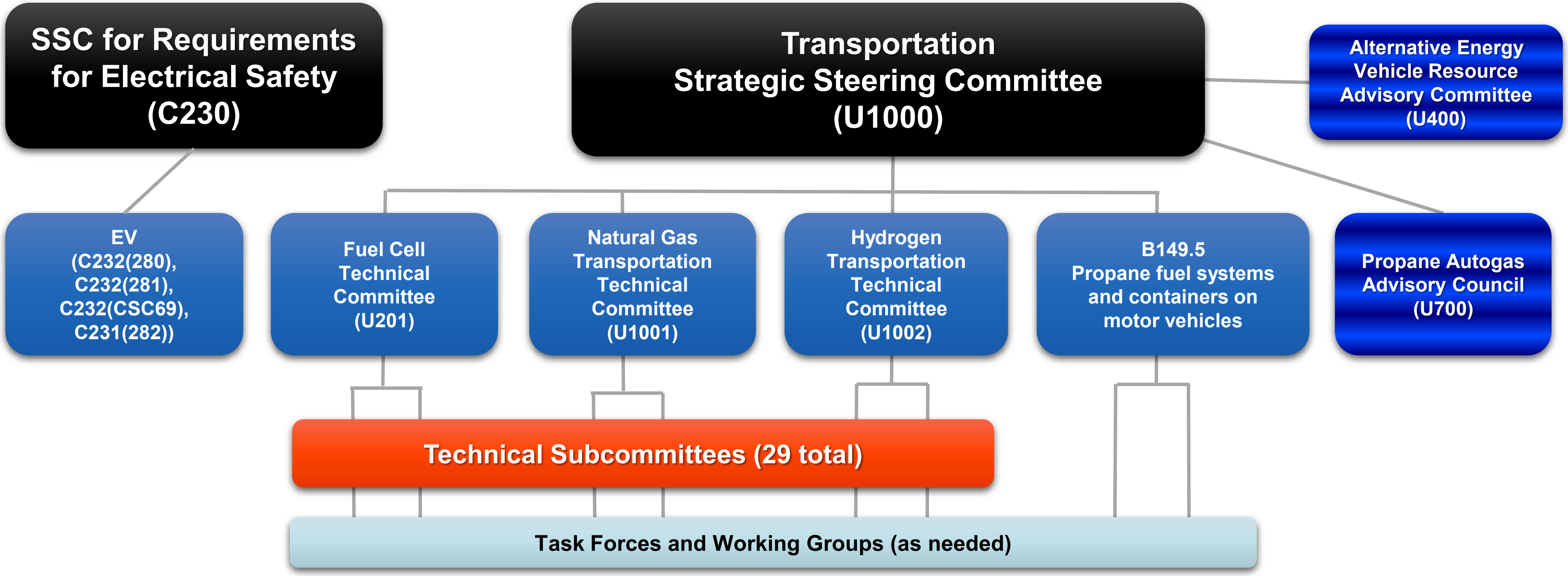
The standards development process on average takes 18 months

CSA Group's Alternative Energy Vehicles Program

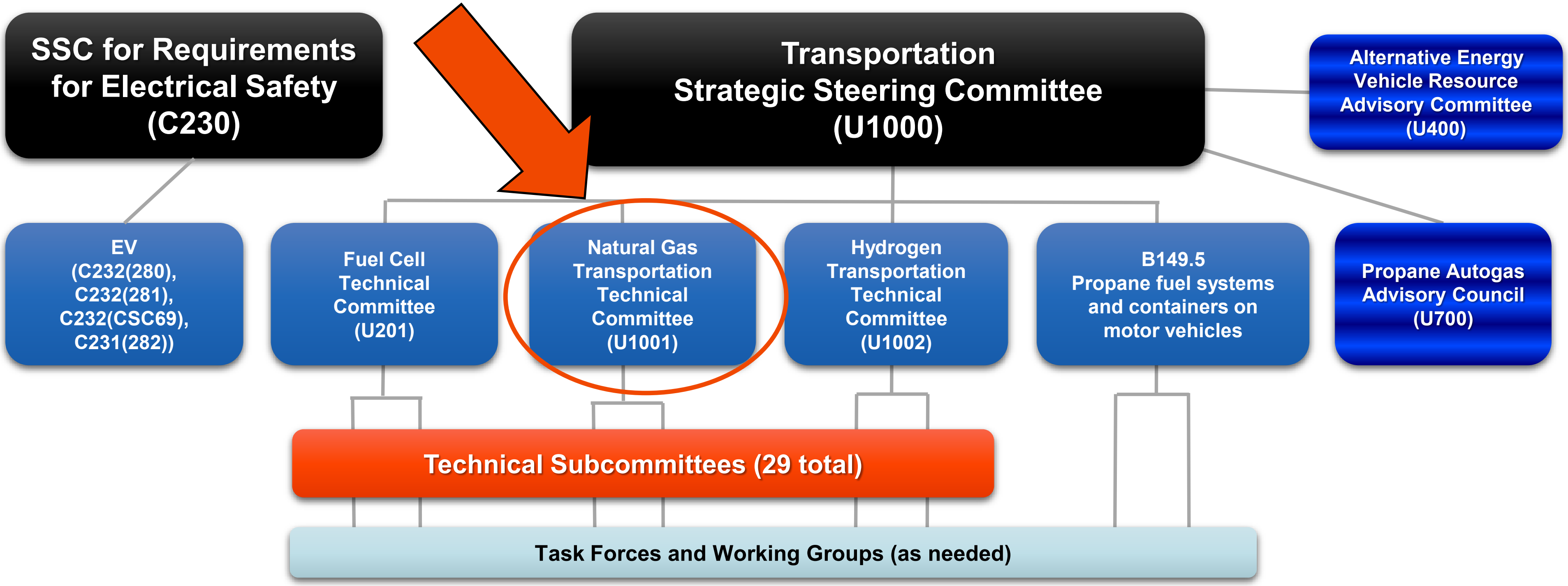
Alternative Energy Vehicles Standards Program

- Program Scope
  - Safety, performance, and installation of alternative energy vehicles, components, systems, and fueling stations
  - “Alternative energy”: CNG, LNG, Hydrogen, Propane, and Electric
  - “Vehicles”: current scope focuses on on-road, but there are exploration activities in marine, rail, and off-road
  - Initial activities started for connected and automated vehicles
- 72 Total Standards in the Portfolio
  - 38 NGV standards (CNG and LNG)
- Canadian and U.S. Presence
  - CNG and LNG standards are primarily binational (i.e., same standards apply in Canada and the U.S.)

Transportation Program Structure

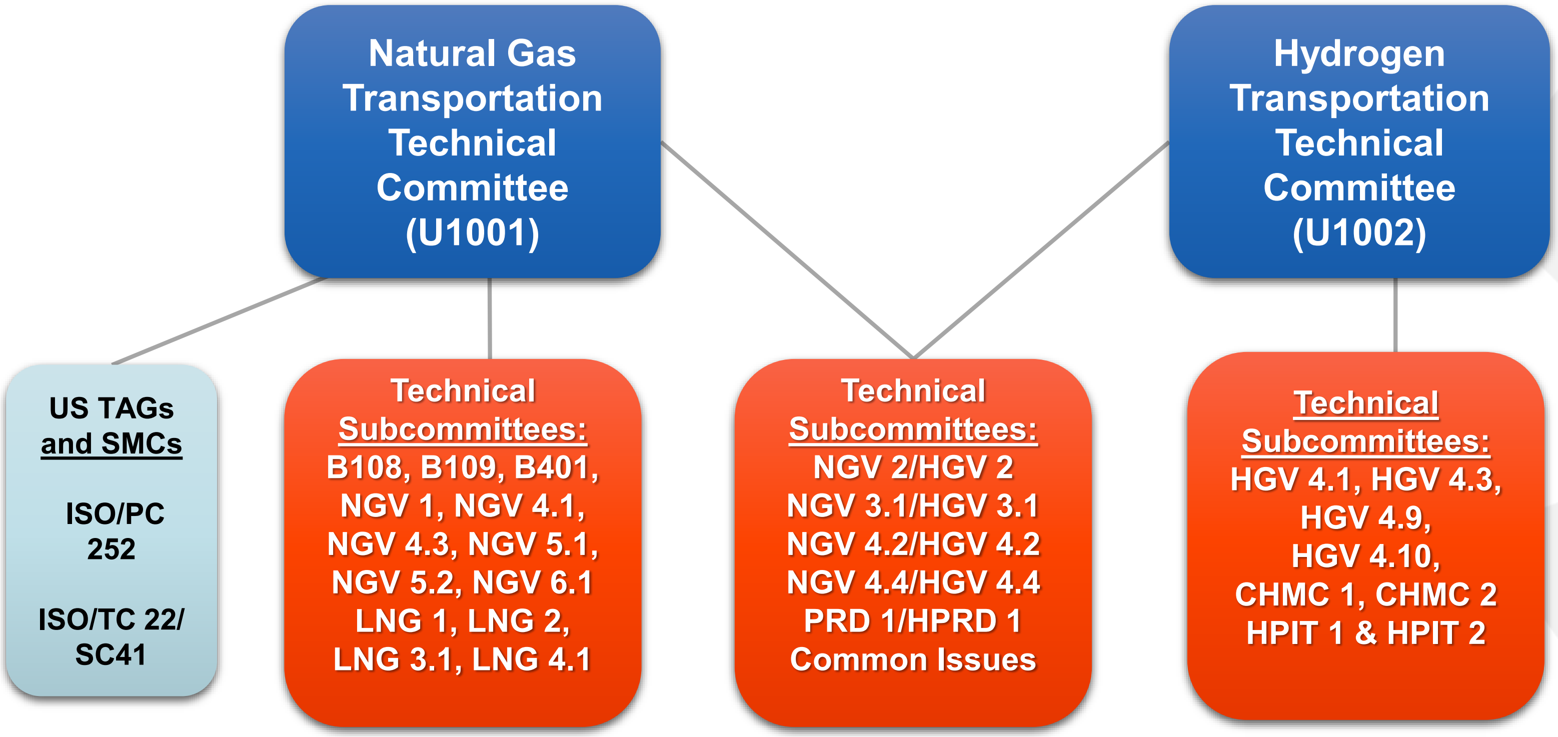


Transportation Program Structure



Transportation Program Structure

NATURAL GAS AND HYDROGEN TECHNICAL COMMITTEES



Scope of Natural Gas Transportation TC

To set forth standards for the design construction and maintenance of:

a) facilities designed to fuel CNG and LNG vehicles (on road and off road applications), this may also include railroad locomotives, and marine;

b) vehicle refuelling appliances (VRA) and residential fuelling appliances (RFA) for the fuelling of NGVs;

c) related components and equipment for CNG, or LNG fuelling facilities;

d) related components and equipment installed on vehicles operating on CNG or LNG; and

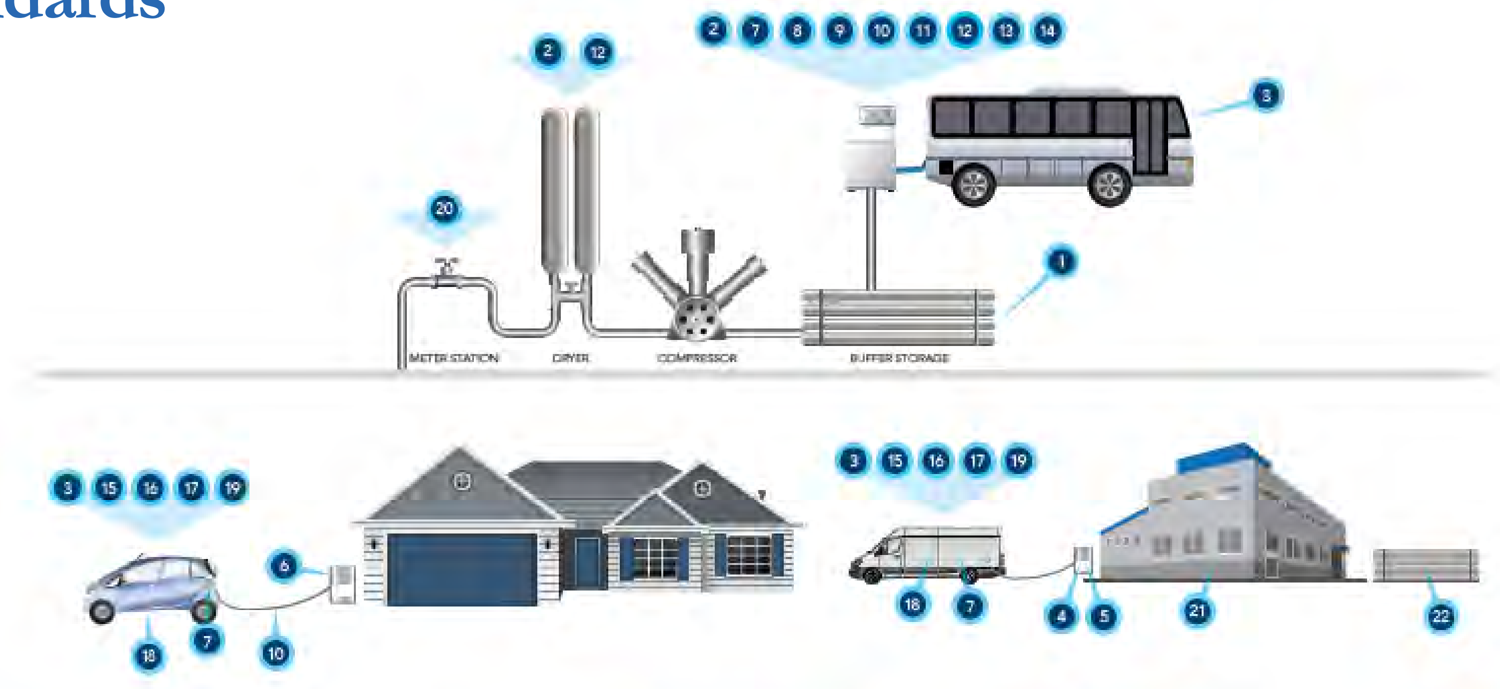
e) installation, servicing and repair of CNG, or LNG, vehicle fuel systems.

CSA GROUP™

Natural Gas Vehicle Standards

PUBLISHED BY CSA GROUP

- Key Recent Publications
  - NGV 2 – January 2019
  - B401 – December 2018
  - B108 – October 2018
  - NGV 4.1 – February 2018
  - NGV 4.3 – January 2018

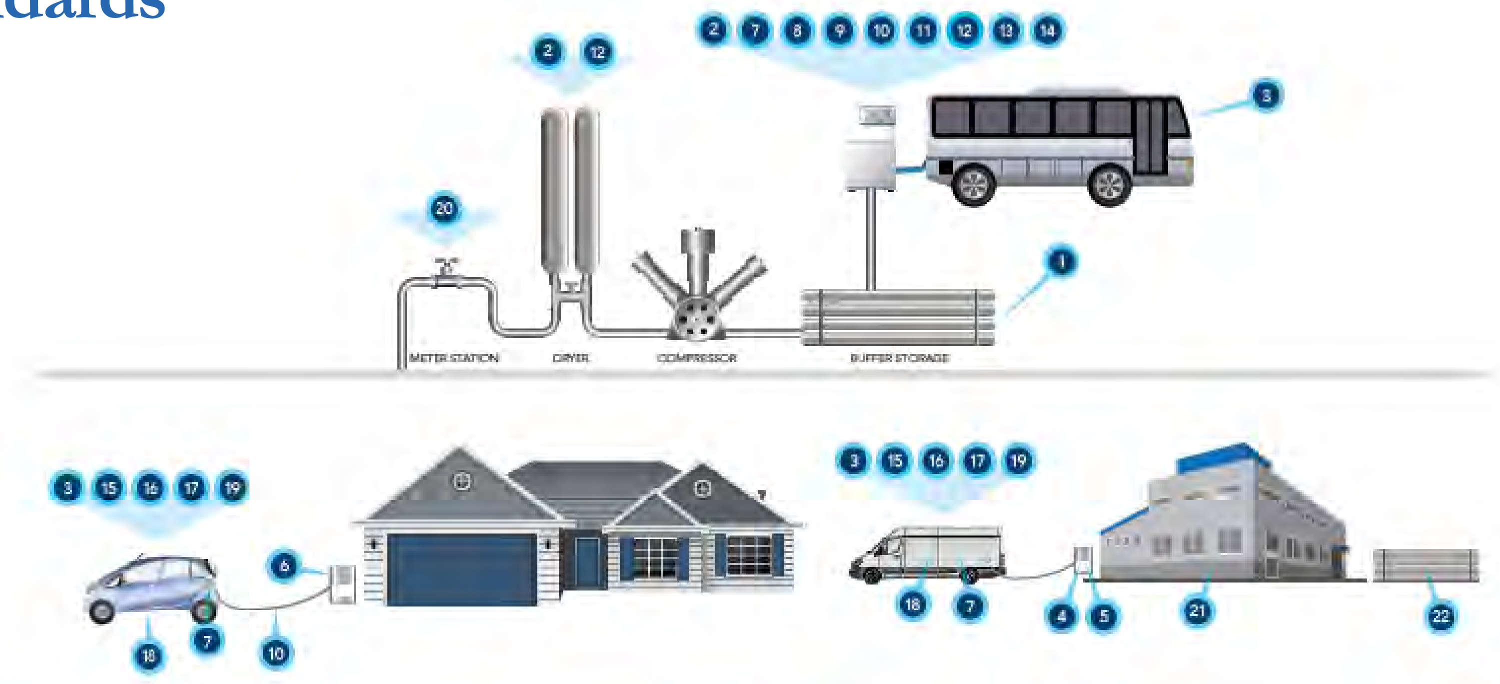


1. **CSA B51 PART 3**
   Compressed Natural Gas and Hydrogen Refueling Station Pressure Piping Systems and Ground Storage Vessels
2. **CSA B108**
   Natural Gas Fueling Stations Installation Code
3. **CSA B109**
   Natural Gas for Vehicle Installation Code, Part 1
4. **NGV 5.2**
   Vehicle Fuelling Appliances (VFA)
5. **B149.1**
   Natural Gas and Propane Installation Code
6. **NGV 5.1**
   Residential Fuelling Appliances (RFA)
7. **NGV 1**
   Compressed Natural Gas Vehicle (NGV) Fueling Connection Devices
8. **NGV 4.1**
   NGV Dispensing Systems
9. **CSA 12.52 / NGV 4.2**
   Hoses for Natural Gas Dispensing Systems
10. **NGV 4.3**
    Temperature Compensation Systems for Compressed Natural Gas Vehicle Fueling Stations
11. **CSA 12.54 / NGV 4.4**
    Breakaway Devices for Natural Gas Dispensing Hoses and Systems
12. **CSA 12.56 / NGV 4.6**
    Manually Operated Valves for Natural Gas Dispensing Systems
13. **NGV 4.7** *PENDING*
    Automatic Valves for Natural Gas Dispensing Systems
14. **CSA 12.8 / NGV 4.8**
    Natural Gas Vehicle Fueling Station Reciprocating Compressor Guidelines
15. **CSA NGV 2**
    Compressed Natural Gas Vehicle Fuel Containers
16. **CSA B51 PART 2**
    High Pressure Cylinders for the On-Board Storage of Natural Gas and Hydrogen as Fuels for Automotive Vehicles
17. **CSA 12.3 / NGV 3.1**
    Fuel System Components for Compressed Natural Gas Powered Vehicles
18. **NGV 6.1**
    CNG Fuel Storage And Delivery Systems for Road Vehicles
19. **CSA PRD 1**
    Pressure Relief Devices for Natural Gas Vehicle (NGV) Fuel Containers
20. **CSA Z662**
    Oil & Gas Pipeline Systems
21. **B401**
    Vehicle Maintenance Facilities Code
22. **SPE 2.1**
    Best Practices for Defueling, Decommissioning, and Disposal of Compressed Natural Gas Vehicle Fuel Containers and Liquefied Natural Gas Vehicle Fuel Tanks

Natural Gas Vehicle Standards

PUBLISHED BY CSA GROUP

- Current Projects
  - NGV 3.1 *CNG Vehicle Components*
  - PRD 1 *Pressure Relief Devices*



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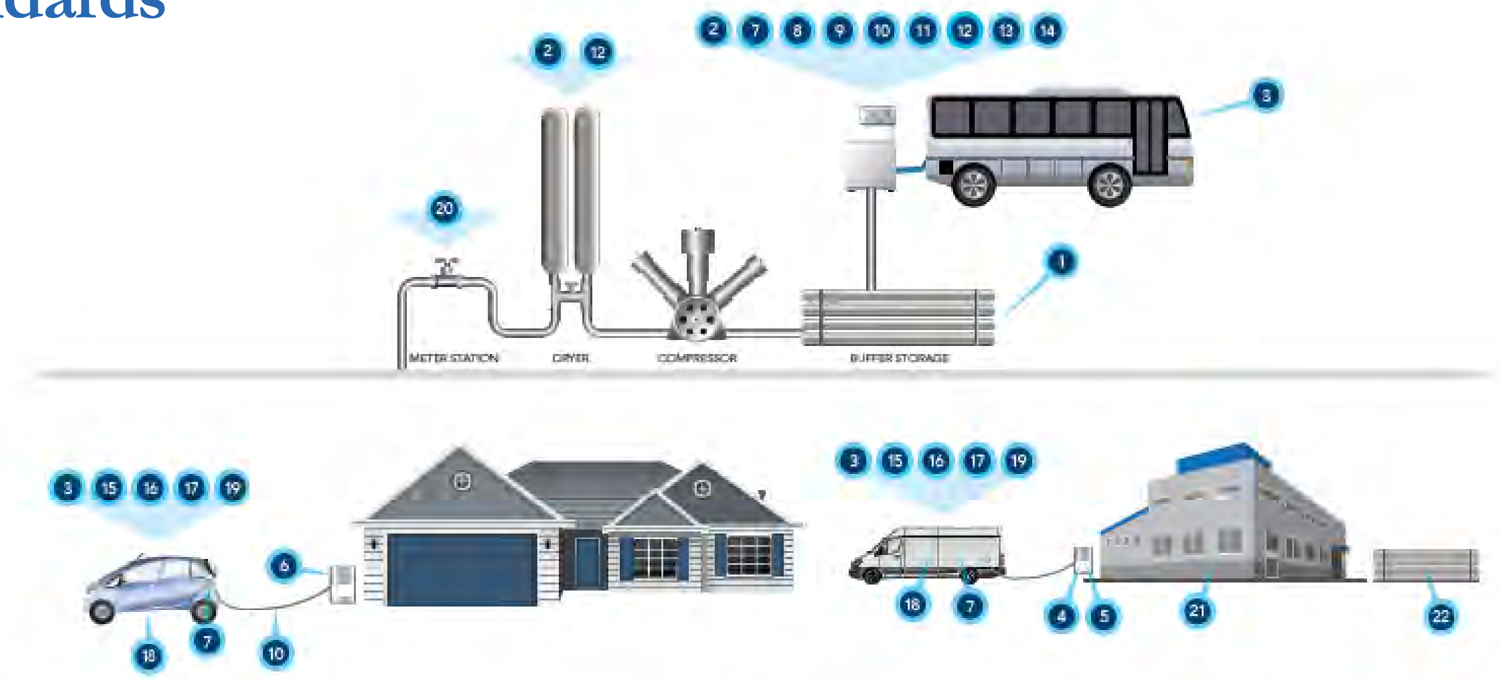
Natural Gas Vehicle Standards

PUBLISHED BY CSA GROUP

- Upcoming Projects
  - NGV 4.3 *Temperature Compensation Systems*
  - NGV 4.4 *Breakaway Devices*
  - NGV 4.6 *Manual Valves*
  - NGV 4.7 *Automatic Valves*
  - NGV 4.8 *Station Compressors*
  - LNG 3.20 *Vehicle Hoses*
  - LNG 4.2 *Station Hoses*
  - LNG 4.4 *Breakaways*



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Canada

CSA GROUP™

Key Developments & Upcoming Meetings

- CSA/ANSI NGV 6.1 CNG Fuel Systems
  - Referenced in NFPA 2-2019
  - All CNG Engine Fuel Systems must be either NGV 6.1 or Section 16.3 of NFPA 52
- B401 NGV Maintenance Facilities
  - Proposed for reference in NFPA 30A and International Fire Code
  - Proposals to incorporate B401 methodologies into U.S. Code
- ISO/TC 22/SC 41 – 2019 Plenary Week
  - Plenary week to be conducted at CSA offices in Cleveland, OH
- CSA Group's Annual General Meeting (June 17-20)
  - 100th Anniversary Celebration and Meetings in Ottawa, Ontario
  - Transportation Strategic Steering Committee – June 19
  - Natural Gas Transportation Technical Committee – June 20

Codes, Standards, and New Technologies

Supporting Innovation & Expanded Markets

- Conformable CNG Containers
  - Added coverage in CSA/ANSI NGV 2:2019
- Adsorbed Natural Gas
  - CSA has developed interim requirements for containers and fueling appliances
  - The interim requirements will ultimately be the basis of national standards
- Mobile Fueling
  - Developing coverage for CSA B108
- Marine Working Group
  - CSA has established a Working Group identifying gaps and priorities in codes and standards for the use of natural gas in the marine industry

Helping bring products to market.

Harmonization

- State and Provincial Alignment
  - Support uniform code adoption of latest editions
- North American
  - Binational Standards → National Codes
  - Mexico & Tri-national Standards
- International
  - ISO participation and adoption (TC 22/SC 41, TC 58, PC 252)
    - 2019 Plenary in Cleveland
  - UN ECE R110

Harmonization enhances global trade opportunities.

Leveraging Standards

- Reference and Adoption
  - Standards can be referenced in Model Codes
  - Model Codes can be adopted by Authorities Having Jurisdiction
- Testing, Inspection, and Certification
  - CSA Group Laboratories in Cleveland, OH and Langley, BC have testing capabilities for vehicles and fueling equipment.
- Training
  - CNG Fuel System Inspector – Online and In-Person
  - Defueling, Decommissioning, and Disposal of CNG Containers – Online
- Personnel Certification
  - ANSI-accredited CNG fuel system inspector exam

Get your products tested, inspected, and certified for safety, compliance, and global market access.

Get Involved

- Codes and Standards play a critical role in safety, innovation, and market access.
- Membership is free.
- Most meetings are conducted virtually.
- Follow us on CSA Group's Communities of Interest:
  - https://community.csagroup.org/community/alternative-energy-vehicles

Have an impact.

Connect with experts.

Build your experience.

Have your say.

Questions?

Thank you.

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NGVAMERICA

Natural Gas Vehicles for America

NGV TF: Incident Investigation

Tim Standke, Director of Technology & Development

About NGVAmerica

NGVAmerica is the national organization dedicated to the development of a growing, profitable, and sustainable marketplace for vehicles powered by natural gas and biomethane and for promoting the use of more natural gas in transportation... trucks, trash, transit, and even off-road uses like HHP marine, rail, and construction/mining applications.

200+

NGVAmerica represents 200+ companies, LDCs, fleets, OEMS, environmental and government organizations.

NGVAMERICA

NGVAmerica Members

Ford
Applied LNG
South Jersey Gas
KinetrexEnergy
Clean Energy
UPS
Southern Company Gas
AGA American Gas Association
ONE Gas
DTE Energy
American Public Gas Association
UGI Energy to do more
noble energy
Southwest Gas
Kwik Trip Natural Gas
Penske
Momentum Fuel Technologies
ATA
NW Natural
Sempra Energy for every day life!
Blue Bird
Chart Innovation. Experience. Performance.
FortisBC
Piedmont Natural Gas
Westport Fuel Systems
TECO Energy
WM Waste Management
Daimler Trucks
ANG American Natural Gas
FCA Fiat Chrysler Automobiles
Frito Lay Good fun!
Luxfer Gas Cylinders
Hexagon Lincoln
Agility fuel solutions
PSE Puget Sound Energy
Vectren Live Smart
Ryder
Metropolitan Utilities District
spire formerly The Laclede Group
ampCNG
Cummins Westport
Volvo Trucks
Worthington Industries
Catalina Composites Division of Catalina Cylinders, Inc.
TruStar Energy CNG
GAIN Clean Fuel
ANGI
CenterPoint Energy
Black Hills Energy Improving life with energy
Trillium CNG
Net Lease Capital Advisors An Investment Banking Approach to Real Estate Transactions

Incident Investigations and Root Cause Analysis

Working Group Mission:

The Technology & Development Committee leads NGV incident investigations. This effort involves collaboration with the National Highway Traffic Safety Administration (NHTSA), industry representatives and national laboratories. The main goal of this Work Group is to ***educate the industry of the root cause of incidents*** involving natural gas vehicles, and ***ensure that proper codes and standards are in place*** to reduce the risk of occurrence in the future.

Manual Shut Off Valve

There have been five incidents involving valves that have blown out. One incident injured an inspector.

The inspector was limit checking the valve when the open stop mechanism failed. Gas pressure subsequently blew the handle from the valve injuring the inspector and discharging fuel.

Manual Shut Off Valve

Mankato, MN, Nov 14, 2018 - Allstate Peterbilt Truck Stop

Courtesy of:

"The Mankato Free Press"

http://www.mankatofreepress.com/news/local_news/two-injured-in-peterbilt-natural-gas-explosion/article_1295e7dc-e843-11e8-866a-73d8ff3eea4a.html

Manual Shut Off Valve

Mankato, MN, Nov 14, 2018 - Allstate Peterbilt Truck Stop

After a technician completed a high pressure filter service on a refuse truck, he opened manual high pressure shut-off valve. The open stop mechanism failed injuring the technician's hand and vented natural gas.

The facility was evacuated, except for one person. When the gas found an open ignition source, it ignited injuring the individual.

Manual Shut Off Valve

NHTSA Recall Notices

Recall Number

(18E-111): Luxfer (Equipment)

(18V-858): McNeilus (Vehicle)

(19V-146): A-1 Auto Electric (Vehicle)

Please Visit the NHTSA website:

https://www.nhtsa.gov/recalls?gclid=Cj0KCQjwtMvlBRDmARIsAEoQ8zS5wBiWVpPv2kZ446czYQhzV7uZ90zlNZUcCbTCqQp5wwJ9t7OzZNoaAlScEALw_wcB&gclsrc=aw.ds

- Select, “VEHICLE” in *Safety Issues & Recalls*
- Then select, “search by NHTSA ID” under *Check your vehicle safety*
- Then, enter the “Recall Number” (e.g. 18E-111)

Manual Shut Off Valve

NGV 3.1 to include Torque Testing for Valves

NGV 3.1 has already taken steps to address this particular failure mode. A new test to evaluate over-torqueing of valve handles has been defined and is expected to be included in the new release of NGV 3.1, currently in process.

PRD Damaged by Freezing Water

Colchester, VT, Nov 28, 2018 – J&B Truck Center

Courtesy of:

"NBCUniversal"

https://www.necn.com/news/new-england/-Industrial-Fire-at-Vermont-Truck-Maintenance-Company-Draws-Large-Response-501452221.html

PRD Damaged by Freezing

Colchester, VT, Nov 28, 2018 – J&B Truck Center

A thawing, ice damaged PRD activated after the truck was brought inside the J&B Truck Center. The truck center was properly evacuated. Leaking fuel eventually found an ignition source, ignited and created a blaze that consumed much of the facility.

J&B Truck Center was not an NGV Service prepared facility.

PRD Damaged by Freezing

Cold Weather Bulletin

NGVAmerica has re-issued it's *Cold Weather Notice* which advises this condition.

NGVAMERICA

https://www.ngvamerica.org/wp-content/uploads/2018/03/Technology-Bulletin_ColdWeatherPRD.pdf

Refuse Truck Load Fires

Kansas City, KS (12/7/18)

Courtesy of: “NGT News”
https://ngtnews.com/cng-truck-fire-under-investigation-in-kansas-city-kan?utm_medium=email&utm_source=LNH+12-11-2018&utm_campaign=+Latest+News+Headlines

Fall River, MA (12/10/18)

Courtesy of: “The Herald News”
https://www.heraldnews.com/news/20181211/recycling-truck-catches-fire-in-fall-river-damaging-nearby-homes-and-vehicles

Tank Rupture

Bakersfield, CA, Nov 28, 2018: Billowton Valero Station

Courtesy of:

“Bakersfield Now, KBAK Fox58”

https://bakersfieldnow.com/news/local/crash-causes-explosion-but-no-fire-chp-said

Tank Rupture

Bakersfield, CA, Nov 28, 2018: Billowton Valero Station

A class 8 truck was filling at the Billowton gas station when an explosion brought down the service station. The driver filling the vehicle received injuries and the station canopy collapsed.

NGVAMERICA

Natural Gas Vehicles for America

Thank you…

Questions?

Cummins Westport
The Natural Choice

2018/19 NG Products

Yemane Gessesse

April 17, 2019

Cummins is Celebrating 100 Years Anniversary in 2019

5 Business Units

190+ Countries

60,000+ Employees

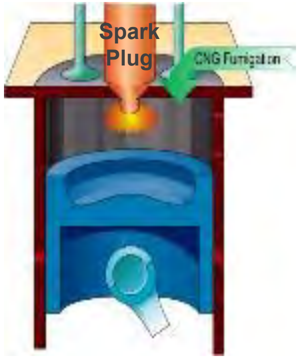
Cummins Natural Gas Products

- Cummins Started Working on On-Highway Natural Gas Engines in the 1980s
- There were limited business opportunities in that space at the time
- Cummins and Westport established the Cummins-Westport (CWI) Joint Venture in 2001
- CWI started the production of Natural Gas engines with the release of C Gas Plus (8.3L) and B Gas Plus (5.9L) Engines

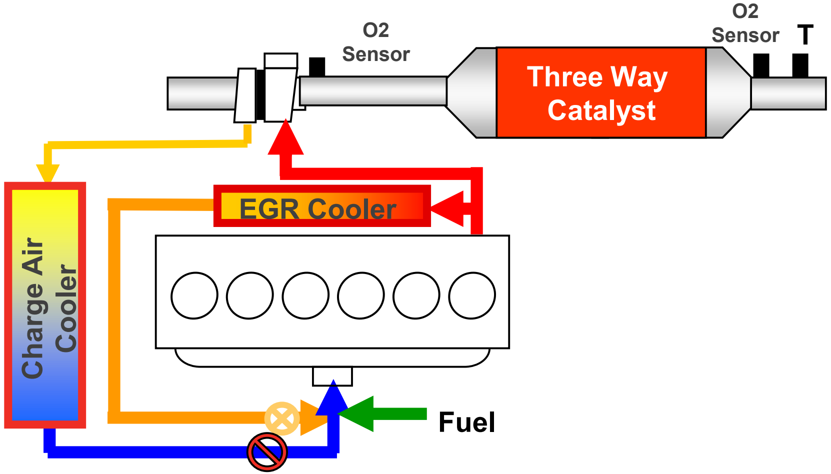
Cummins Westport Products

- CWI Natural Gas Engines
  - 8.3L replaced by 8.9L in 2007
  - 11.9L released in 2013
  - 5.9L replaced by 6.7L in 2016
- Predominant presence in North America
  - EPA and CARB compliant
- Some global presence
  - Europe, South America, India and China

Cummins Westport 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

Progressive Emission Regulations

- NO_x and PM have come down significantly (optional low NOx is at the Near Zero value of 0.02 gm)
- The next set of regulations have focused on CO_2
- Natural Gas engines are suited to meet GHG requirements better because of the inherent molecular structure of Methane

  - **Diesel - C:H ratio ~ 1:2**
  - **Methane - C:H ratio = 1:4**

Move to Zero … new for 2018

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

CNG LNG RNG

ISX12N™

L9N™

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

B6.7N™

Certified to Optional Low NOx
0.1g/bhp-hr

Westport

Cummins Westport Engine Manufacturing

- Medium size engines manufactured at RMEP in Rocky Mount, North Carolina
  - 6.7L and 8.9L engines
- Large size engine manufactured at JEP in Jamestown, New York
  - 11.9L engine

Why Cummins Westport Natural Gas Engines?

Environmental Leadership
- Lowest NOx
- 50 - 90% Below EPA Standard
- RNG => negative carbon intensity

Move to Zero

Energy Security
- Abundant Fuel
- Extensive network
- Renewable

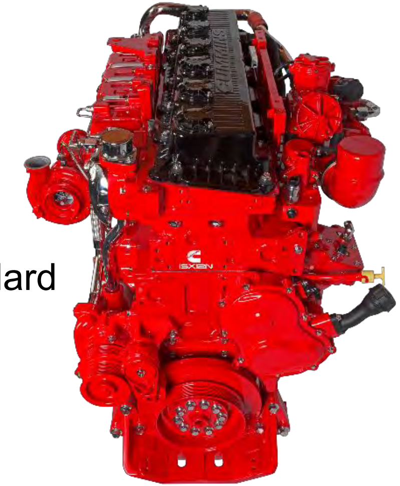
Economic Advantage
- Mature technology
- Affordable
- Ready Now

Westport

2018/2019 Changes	ISX12N™	L9N™	B6.7N™
Emission Certification	EPA/CARB Optional Near Zero 0.02 g NOx	EPA/CARB Optional Near Zero 0.02 g NOx	EPA/CARB Optional Low NOx 0.1 g NOx
NOx Reduction to 2017 EPA	90%	90%	50%
OBD	YES (2019)	YES	YES
CCV	YES	YES	YES
TWC	• Increase in size • One piece design • Mid bed O2/Temp Sensor • OEM Harness	• Same size as '17 ISL G NZ • One piece design • Mid bed O2/Temp Sensor • OEM Harness	• Same size as '17 ISB6.7 G • One piece design • Mid bed O2/Temp Sensor • OEM Harness
Product Changes	• New fuel system improves performance and reduces parts content • On-engine electric CCV filter with 2 CCP sensors • CM2380 ECM • 500 kbaud datalink • New wiring harness • New Ignition Control Module	• Steel Pistons • New Liners • Improved Ring Pack • New Valve Seat Material • New Oil Cooler • Improved Piston Cooling • Additional crankcase pressure sensor • New CM2380 ECM • 500 kbaud datalink • New wiring harness • New Ignition Control Module	• Additional crankcase pressure sensor • New CM2380 ECM • 500 kbaud datalink • New wiring harness • New Ignition Control Module

ISX12N™

- **Key Product Attributes**
  - 4 cycle, spark ignited, in-line 6 cylinder, turbocharged, CAC
  - Displacement – 11.9 litres (726.2 cu in)
  - Certified to CARB Optional Near Zero (ultra-low) NO_x 0.02g Standard
  - **Exceeds 2017 EPA GHG requirements (good until 2021)**
  - **2018 On-Board Diagnostics (OBD lite)**
  - **2019 On-Board Diagnostics (OBD)**
  - 100% natural gas engine
  - Engine braking
  - **Peak rating: 400 hp, 1450 lb-ft**
  - Maintenance-free Three-Way Catalyst Aftertreatment
  - **Up to 80,000 lb. GVW**



CNG LNG RNG

Westport

L9N™

- **Key Product Attributes**
  - 4 cycle, spark ignited, in-line 6 cylinder, turbocharged, CAC
  - Displacement - 8.9 Litre (540 cu. in.)
  - Certified to CARB Optional Near Zero (ultra-low) NO_x 0.02g Standard
  - **Exceeds 2017 EPA GHG requirements (good beyond 2027)**
  - **2018 On-Board Diagnostics (OBD)**
  - 100% natural gas engine
  - **Peak rating: 320 hp, 1000 lb-ft**
  - Maintenance-free Three-Way Catalyst aftertreatment
  - **Up to 66,000 lb. GVW**

B6.7N™

- **Key Product Attributes**
  - 4 cycle, spark ignited, in-line 6 cylinder, turbocharged, CAC
  - Displacement – 6.7 litres (408.9 cu in)
  - Certified to CARB Optional Low NOx 0.1g Standard
    - Evaluating the need for Near Zero NO_x 0.02g engine
  - **Exceeds 2017 EPA GHG requirements (good beyond 2027*)**
  - **2018 On-Board Diagnostics (OBD)**
  - 100% natural gas engine
  - **Peak rating: 240 hp, 560 lb-ft**
  - Maintenance-free Three-Way Catalyst aftertreatment
  - Automatic Transmissions
  - **Up to 33,000 lb. GVW**

CNG LNG RNG

*** With the release of 260HP**

Westport

Questions

NATURAL GAS RAILROAD LOCOMOTIVES AND HARBOR CRAFT

JERRY WIENS

Based on economic LNG availability in the ports, at scale, and a strong combination of regulations and incentives for NOx reduction.

- Let's take advantage of low-priced gas to maintain progress on NOx reduction.
- CNG/LCNG options
- RNG availability can support demonstrations now
- Clean Air Act mandates progress towards healthful AQ
- Expiration of MOU between Class 1 RRs and AQMD/ARB

NOx history

- Discovery by UCLA Prof. Bush – late 60s
- Early controls for HC and CO increased NOx
- TWC/unleaded gasoline/VSAD – late 70s
- AFTP ...FFVs
- HD truck demonstration – early 80s
- SIP – suit by C. Gladstein, CCA – mid 90s
- Carl Moyer Program – late 90s – optional low-NOx standards for SIP credit - $120 million per year to save $billions in potentially withheld gas tax funds

We now have taken heavy-duty *on-road* engines from diesels at over 5 grams NOx (last century) to competitive natural gas engines at “near-zero” levels

- Cert to lowest optional level of 0.02 g/BHP-hr, 90% below regulated levels
- NZ … vs zero tailpipe!
  - GNA “Game changer”
- And they do the job!

Can NG benefits be achieved by adapting larger *off-road* diesel engines?

- Dual fuel and Reactivity Controlled Compression Ignition (RCCI) are important research topics to get higher efficiency and lower NOx.

Large diesel engines are both highly efficient and high NOx producers.

- Most railroad and harbor craft engines produce high NOx levels, some over 10 grams.
- They typically are rebuilt several times with new or refurbished cylinder kits.

As the NOx emission inventory from LD vehicles declines, HD trucks and buses grow to dominate what remains.

As HD *on-road* vehicle NOx emissions decline, HD *off-road* becomes a bigger part of what remains.

- SCAQMD inventory for 2019 shows off-road equipment and locomotives at 54 and 17 NOx tons per day respectively, compared to 87 for HD trucks.

The Ports, their tenants, and harbor craft operators are *committed* to major NOx reduction; *and* they recognize the importance of near-zero emission options *that do the job*.

Harbor craft and rail locomotives often utilize a limited selection of common diesel engines that are rebuilt multiple times during their life.

- Opportunity for upfit at rebuild time.

Recent LNG (dual-fuel) locomotives have not been particularly low NOx

- Florida East Coast locomotives; 4 plus 2 LNG tenders that appear to be transport units on flat beds, pulling a very long train.

Railroad acceptance depends on low-priced LNG availability, rail tankers, and interoperable tender cars.

- 2017 AAR specifications for LNG tenders to supply ≤ 165 psi “GNG” to locomotives
- Need approval for LNG tenders to supply cryogen or high-pressure natural gas to HPDI locomotives
- Kits to convert tankers to serve as tenders?

Metrorail and Amtrak domicile in California, and are acquiring Charger locomotives built by Siemens in Sacramento.

- These use Cummins QSK-95 diesel engines that can be adapted to HPDI 2.0.
- Boron (Clean Energy -Total) has rail on site
- Topock (ALT) would need siding
  - Both need rail loading facility
  - Both currently supply renewable LNG by truck tanker to south coast.

Sempra, Shell, and FortisBC ready to supply tanker loads

- West coast ports

International market development

- Yamal, Sabetta
- Persian Gulf investing in US LNG facilities

Switch engines are often the oldest and dirtiest.

- They can be upfit for dual fuel, challenge for low NOx emissions.
- Switch operation is ideal for hybridizing, with low average power use.
- Potential for California manufacture of upfit components.

Dual fuel engines *may be* developed to extremely low NOx emission levels with higher efficiency using RCCI.

- “Dual fuel” vs HPDI
- Dual fuel may also accelerate railroad interest if capable of diesel-only operation.
- Both are revertable

Solid oxide fuel cells coupled with a gas turbine and fueled by natural gas promise extremely low NOx levels with very high efficiency.

- Tier 5 – Tier 6??
- SOFC/GT hybrids could operate with low-sulfur diesel, but require added reformers.
- Stationary application

Success in regional California operation and LNG availability at scale can interest the Class I railroads

- It will be decades before rail and marine reach the goal of zero emission well to wheels!
- ARB petition for Tier 5 (0.2 g/bhp-hr)

Develop dual fuel engines

- CA universities with OEM partners
- 2-stroke medium speed
- 4-stroke medium speed
- Upfit on rebuild
  - Diesel reversion capable
  - Opportunity for CA labor or cylinder kit production?
- Special pilot fuels (DME or mixed ethers), RCCI
- Intermediate NOx emission levels?

Develop dedicated engines

- HPDI 2.0
  - Can be upfit
  - No change to diesel combustion system, can revert
- Medium speed
  - Existing Westport HPDI work with Progress Rail
    - Not low NOx!
    - Focus on low-NOx
- High speed
  - CAT C-175 - 1800 rpm - EMD F125 Metrolink
  - Cummins QSK-95 – 1800 rpm - Siemens SC-44 Charger, Sacramento
- Tier 4, 5, 6

Develop SOFC/GT power units

- Resolve power density issues
  - Go with current tech?
  - First advance tech?
- Focus on gas turbine development
  - Full power?
- Hybrid switch engines
  - Retrofit old loco to prove
    - Low power, under a MW + available batteries
  - Design new switch hybrid
    - FC
    - Turbine
    - Batteries
    - Fuel storage
    - Cooling system
    - Port LNG fueling
- Line haul
  - Power density?
  - Throttle response
  - LNG supply infrastructure?

Develop fueling infrastructure

- LNG/RLNG from CA sources
- Rail tenders
  - Cryogenic hoses and connectors
  - Equipment to convert tanker to tender
- Rail loading facilities
- Waterside delivery
  - OGV adoption
  - ECA
  - Costa Azul (Shell and Sempra)
  - Vancouver (FortisBC)

Demonstrate locomotives

- CA
  - Passenger rail
    - Metrolink
    - Amtrak California
  - Switchers
    - Hybrid
    - $$ to replace old tired, or not?
- 49 States and Canada
  - When low-cost LNG arrives at the Ports
- Mexico
  - PV 327 CNG transit buses

Any errors are mine, and this presentation does not represent adopted policy

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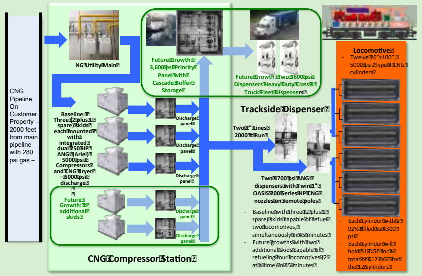
SUSTAINABLE TRANSPORTATION

Leading the Decarbonizing of the Rail and Marine Markets with Innovative, Cost-Efficient, and Sustainable Renewable Natural Gas & Hybrid Solutions

"The bottom line for railroads: Without operational and technological innovation, railroads could see their competitiveness erode over a larger share of their traffic base…In short, there's no shortage of technological alternatives for railroads to consider and eventually pursue – and they're running out of road with current diesel-locomotive technology and time against fast-moving trucking rivals." – Jason Kuehn, Vice President, Oliver Wyman, Forbes – September 26, 2017

OptiFuel Systems LLC

Design, Production, Sales, Leasing, and Refueling of Tier 5 and Near Zero Natural Gas Hybrid Locomotives and Inland Work Boats

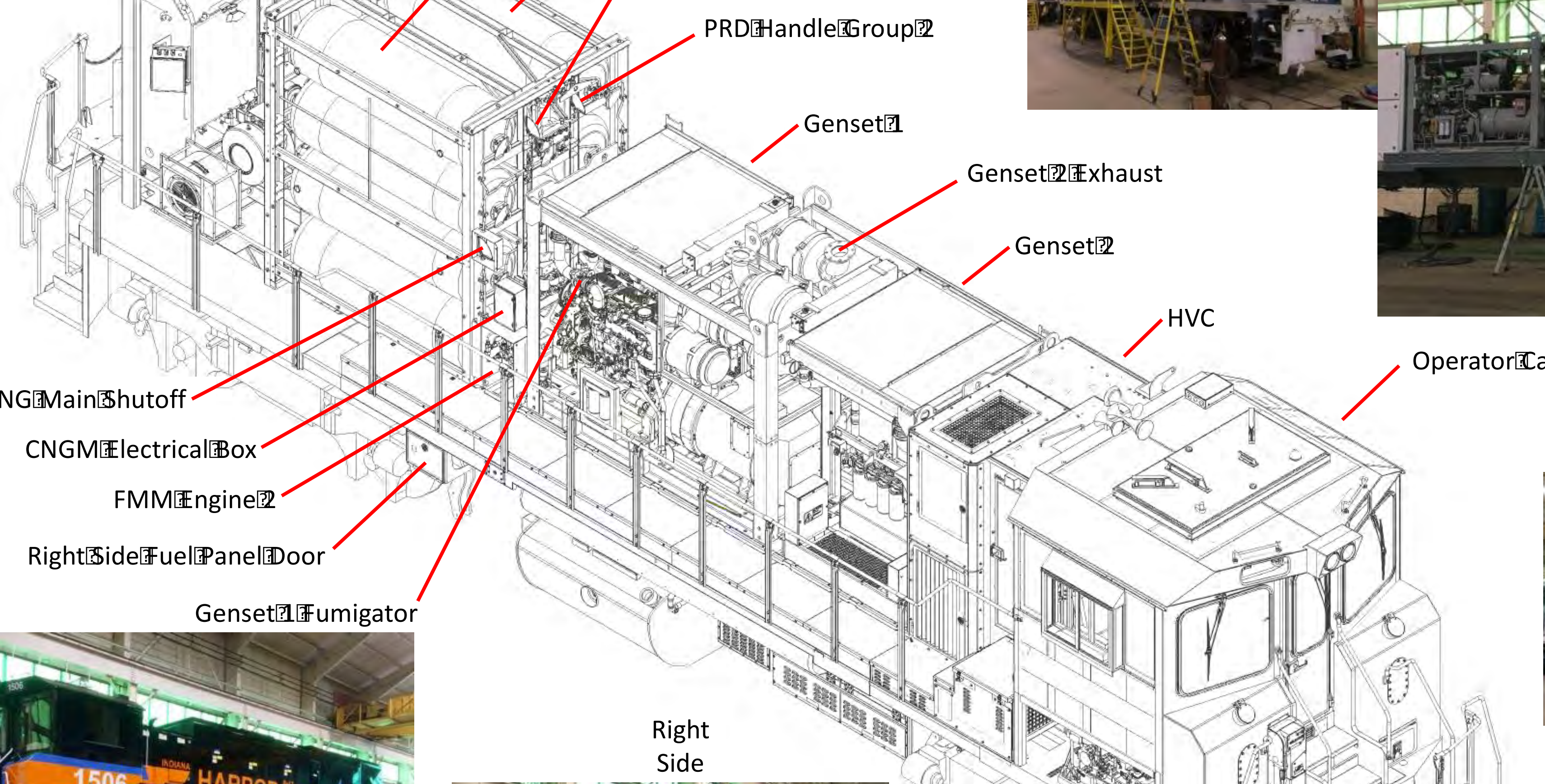
Markets Potential	Locomotives for Rail Customers Around the World	Towboats, Tugboats, & Ferries for the U.S. Inland Waterways and Ports	CNG / RNG / LNG Refueling for Rail and Marine	Asset Leasing
Products				
Product Description	• 800 to 4,400 Hp Near Zero and Zero Emissions Natural Gas Hybrid Locomotives • CNG/RNG tenders	• 1,500 to 6,000 Hp CNG/RNG/LNG Natural Gas Hybrid Towboats, Tugboats, and Ferries • CNG/RNG/LNG Tender Barges	• Design and Install Natural Gas Fueling stations • Stationary and Mobile Natural Gas Refueling	• Leasing locomotives and tow & tug boats
Business Alliances	• Cummins • Railpower • BAE Systems	• Cummins • BAE Systems	• ANGI	

CNG: Reduce OpEx, Increase Market Competitiveness & Meet Sustainability Goals

- OptiFuel Systems LLC, is a four-year-old systems integration company focusing on developing natural gas (NG) and hybrid heavy horsepower systems, onboard NG storage systems, and NG refueling systems for the rail and marine markets
- Over the last 4 years, OptiFuel developed, tested and produced the locomotive engine, CNG power conversion systems, the on-board CNG storage systems, and the CNG refueling station that allows locomotives at Indiana Harbor Belt Railroad (IHB) to operate on CNG – all approved by FRA
- IHB pays less than $0.70 Diesel Gallon Equivalent (DGE) for the CNG – they pay around $2.40 for their diesel fuel

OptiFuel Testing In Dyno Cell, Preparing For EPA Certification

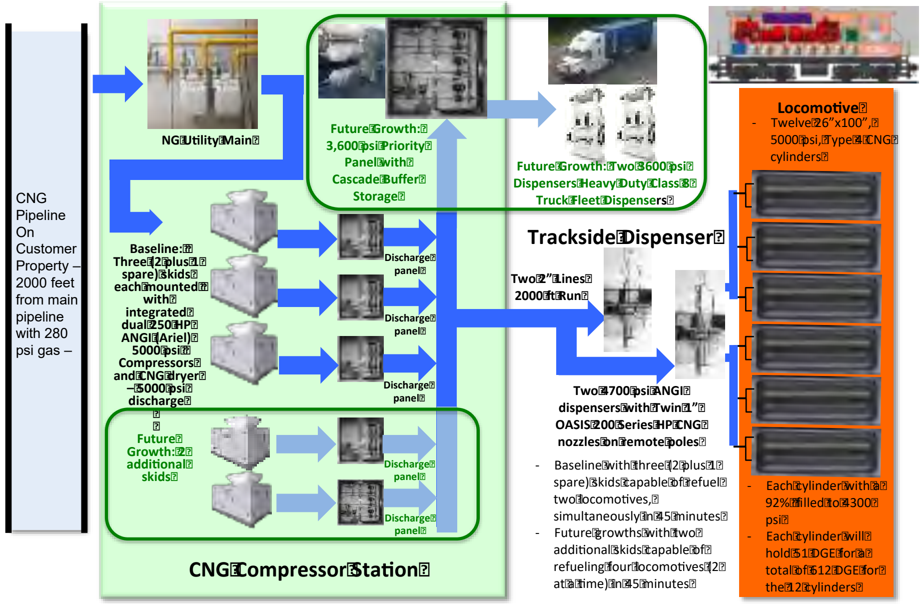
Location of CNG Components and Final Assembly

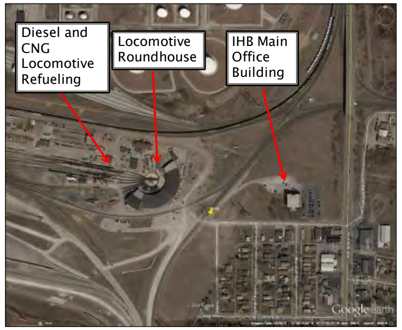


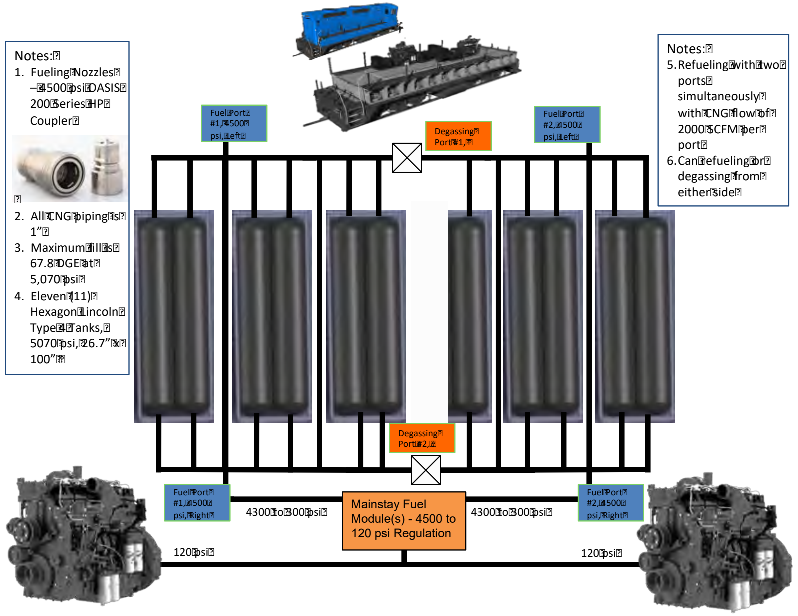
Right
Side

Current IHB CNG Refueling Equipment Supports Two Locomotives At A Time And Can Refuel Both In 30 to 45 Minutes – The First Of Its Kind In The World

- The 11, 5000 psi CNG cylinders providing 700 DGE, refueling equipment standard ANGI, ANGI CNG dispensers modified
- The dispensing is automatic and will work on either side
- Just snap the 1" inch nozzle on the CNG hose on the refueling port, push the start button and the rest is automatic until the CNG cylinders are full
- The ID tag on the locomotive connects to the refusing dispenser thru dynamics RF communications
- Filling is monitoring in real-time in the cab and in the IHB office with a full SCADA design







Broad Political Support for Funding to Eliminate Diesel Emissions in Urban Areas & Non-attainment Areas

OptiFuel Systems

- **In 2012, the International Agency for Research on Cancer (IARC) of the World Health Organization classified diesel exhaust as "carcinogenic to humans." The heaviest and most prolonged exposures, such as railroad workers, have been found to have higher lung cancer death rates and may cause tumors in the bladder**
- Peer-reviewed studies have found that there are significant diesel exposure disparities by race and income among residents living in close proximity to most of the major railyards
  - U.S. EPA's *Draft EJ 2020 Action Agenda5* (Action Agenda) identifies air pollution from freight-related hubs (like seaports and railyards) as an important national issue
- As of September 2016, there are over 1,000 railyards in the U.S. located in densely populated, urban areas classified as particulate matter and ozone EPA defined "nonattainment" areas
- Over 119 million people (nearly 40% of the U.S. population) living in these nonattainment areas are experiencing acute and chronic adverse health outcomes, including exacerbation of respiratory and cardiovascular disease

Green Gas Emissions	1990	2005	2013	2014	2015	2016	2017
N_2O Emissions (MMT CO_2 Equivalent)							
Medium & Heavy Duty Trucks, Buses (5 million in use)	0.2	0.3	0.4	0.4	0.4	0.4	0.4
Locomotives (39,000 in use)	0.3	0.4	0.4	0.4	0.4	0.3	0.3
Ratio of **N_2O** Emissions per Locomotives vs. Trucks & Buses	**192**	**96**	**128**	**128**	**128**	**171**	**171**
C_2O Emissions (MMT CO_2 Equivalent)							
Medium & Heavy Duty Trucks, Buses (5 million in use)	198	371	365	378	387	393	393
Locomotives (39,000 in use)	35.5	45.5	40	41.6	39.9	36.7	37.9
Ratio of **C_2O** Emissions per Locomotives vs. Trucks & Buses	**23**	**16**	**14**	**14**	**12**	**12**	**12**

Transportation Activities Accounted For The Largest Portion (29 Percent) Of Total U.S. Greenhouse Gas Emissions In 2017 And Still Growing

- All of the transportation modalities are focused on decarbonizing their fuel **except freight rail**
  - Cars and light/medium duty-cycle trucks in production put out zero emissions with hybrid electric drive
  - Class 8 trucks are going to go to zero or near zero emissions with CNG/RNG or hybrid electric drive
  - Airlines are going to more efficient jet engine and smaller, high efficient planes that can use renewable jet biofuel
  - The marine market is moving rapidly to LNG
- **In 2018, Class 1 railroads bought 4,284,478,689 gallons of diesel fuel,** yet, rail is the only transportation modality that is doing very little to reduce ozone and SMOG emission in urban areas and reducing Green House Gas emissions causing climate changes

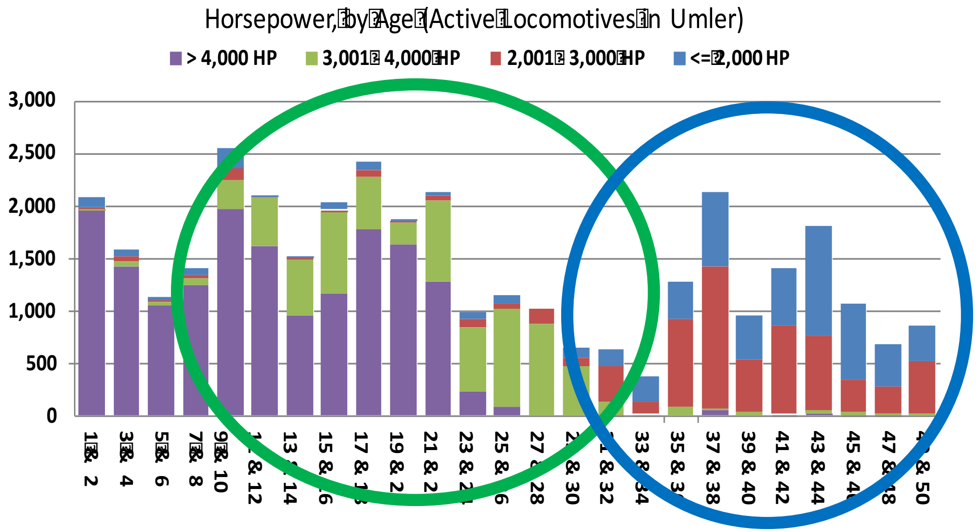
Umler Chart Create in FY2016 and Adjusted to 2018

The Class 1/2/3 Railroads Believe That the 39,000 Locomotives in the US Fleet Are Clean Enough With Average Emissions Level of Tier 0/1 – No Need to Reduce Emissions Any More

Their rational:

- They just build a small number of Tier 4 locomotives (1000 or even less) in 2015 to 2019 – they have done enough
- Class 1 railroads believe that none of the federal, state, or local regulators are really pushing for a Tier 5 standard

EMISSION TIER	YEARS	NUMBER of LOCOMOTIVES Per TIER	EMISSIONS
4	>FY 2014	1,000 or less	NOx -1.3 g/bhp-hr, PM- 0.03 g/bhp-hr
3	FY 2012 - 2014	3,300	NOx - 5.5 g/bhp-hr, PM - 0.1 g/bhp-hr
2	FY 2005 - 2011	6,200	NOx - 5.5 g/bhp-hr, PM - 0.2 g/bhp-hr
1/ 0	FY 1993 - 2004	11,000	NOx -7.4/8 g/bhp-hr, PM - 0.22 g/bhp-hr
Pre - 0	<FY 1993	17,500	NOx - 17.4 g/bhp-hr, PM - 0.44 g/bhp-hr



Umler Chart Create in FY2016 and Adjusted to 2018

The Port Of Long Beach Air Emissions Inventory Report: Approximately 90% Of The Rail Locomotive Emissions Are Attributed To Line Haul Emissions, And The Remaining Emissions Are From Switching Operations

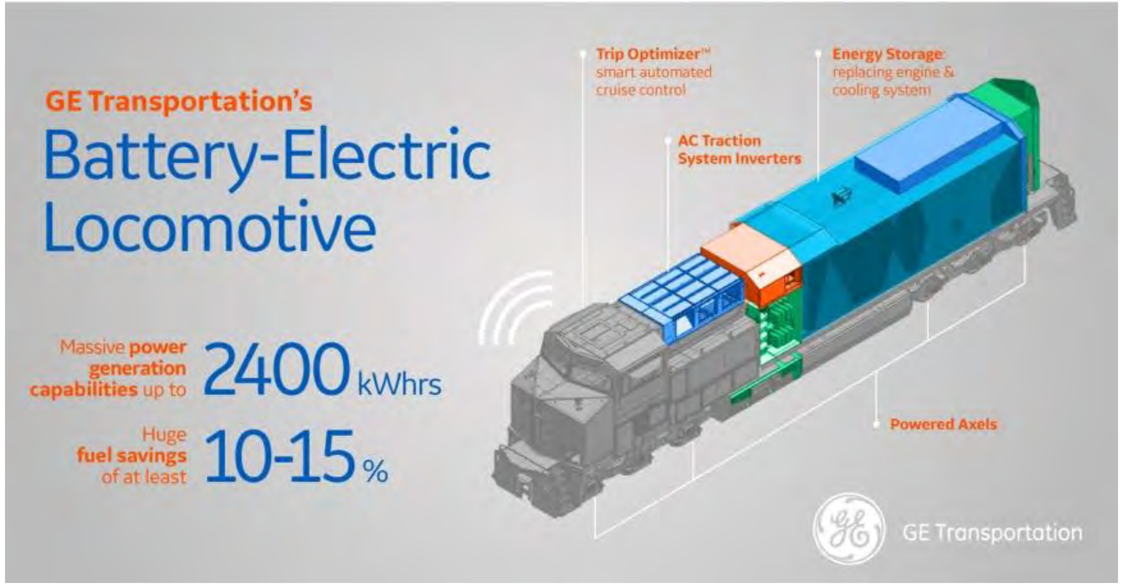
- On April 13, 2017, CARB petitions EPA to adopt more stringent Tier 5 emission standards for locomotives based on the table below
- It will be very hard to get to Tier 5 with 100% diesel – development cost in the hundreds of millions even if would work
  - Heavy EGR, heavy PM filter approach by Progress Rail and Wabtec to get to Tier 4 reducing fuel economy compared to Tier 3 and require more maintenance – reached the limit using heavy EGR
  - SCR approach by Cummins to get to Tier 4 is more efficient and has fuel economy better than Tier 3, but requires Diesel Exhaust Fluid (DEF)
- Conversations with Cummins – just adding additional DEF will NOT reach Tier 5 standards on 100% diesel rail engines

Tier Level	Year of Manufactured	NOx		PM		GHG		HC		Proposed Effective Date
		Standard (g/bhp-hr)	Percent Control	Standard (g/bhp-hr)	Percent Control	Standard (g/bhp-hr)	Percent Control	Standard (g/bhp-hr)	Percent Control	
2++	2005 - 2011	1.3	90	0.03	95	NA	0	0.14	85	2023
3+	2012 - 2014	1.3	90	0.03	95	NA	0	0.14	85	2023
4+	2015 - 2024	0.3	99	<0.01	99	NA	0	0.05	95	2023
5	2025	0.2	99+	<0.01	99	NA	10 -25%	0.02	98	2025
		With capability for zero-emission operation in designated areas.								

1. ARB, Technology Assessment: Freight Locomotives, 2016.
2. Compared with uncontrolled baseline, reflects percent control over line haul baseline for illustrative purposes; ARB staff assumed older pre-Tier 0 line haul and switch locomotives would be able to emit up to the Tier 0 PM emission standards, based on American Association of Railroads in-use emission testing (required to comply with U.S. EPA in-use emission testing requirements) for older switch locomotives with EMD 645 engines.

California: Focusing On Long Range Solutions That Will Not Achieve 2025 Tier 5 Goals

- California seems to have walked around with the idea a pushing a Tier 5
- California has decided to fund a demonstrate with a Tier 0/1 diesel line haul locomotive combined with a battery powered line haul locomotive – the locomotive is essentially a “battery tender” - for switching operations in a port
  - The 2,400 kW batteries storage system can operate for full power for less than 30 minutes
- **However, that approach uses more fuel to move the consist, not less, and will increase emissions outside the port in line haul operations**
- If California desires Tier 5 in 2025, it needs to provide seed funding to demonstrate to the railroads viable solutions that can realistically achieve these emissions goals

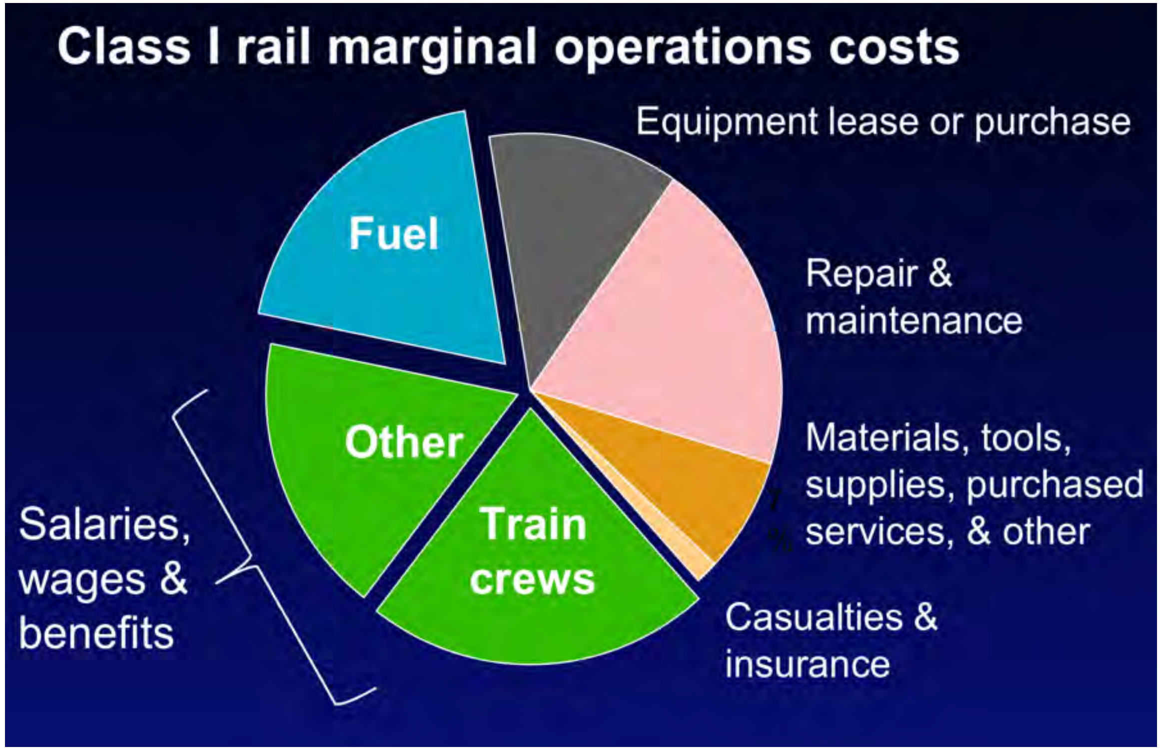


The Class 1 Line Haul Railroads Have NO Interest to Reduce Fuel Cost or Develop New Technology, Especially Emissions Solutions

- In 2018, Class 1 railroads bought 4,284,478,68 gallons of diesel fuel (555 Bcf of natural gas) at an average cost of $2.38 per diesel gallon
- **Diesel Fuel Surcharge: railroads have effectively insulated their financial results from fluctuations of the diesel market, and have gone a step further by profiting from their surcharges – all while challenges to the STB or in Class Action have been overturned**
  - Surcharges have prevented Wall Street from demanding substantial fuel OpEx reductions
  - With the Surcharge, the average cost of diesel is around $1.75
  - As a result, the Class 1s have no interest in reducing fuel cost
- The culture of Class 1 railroads is minimize technology and change – focus on what has always worked
- The Class 1s have no problem with tenders but will not own them - also want longer range with tenders between refueling (Chicago to LA, 6,500 gallons per locomotive)
- The Class I railroads will not to spend CAPEX to convert to natural gas – refueling equipment or tenders must be recovered in the cost of the fuel
- **The Class 1s will not provide an funds to test any new equipment, even if the testing is free**

Need A System Approach, A Low Carbon Intensive Fuel, And Demonstration Testing To Get To A Tier 5 Or Better Solution

- To get the railroads to buy in, need a system solution that will reduce overall operating cost by 50% even with the Fuel Surcharge
- Fortunately:
  - The technology already exists to reduce fuel cost by 50% or more and reduce harmful emissions to almost zero – a future requirement to operate in urban areas
  - The technology already exist to eliminate the crew in the cab, the largest operating cost - the big issue will be the labor negotiations and regulatory authorities
  - The use of tenders reduces refueling labor by 70% to 90% and allows a train to go 5,000 to 6,000 miles between swapping tenders
- **It will require leadership with all of the stake owners who want to see Tier 5 or better locomotives – the Class 1s will not provide that**
- **It will take 30 to 36 months to prove that existing off-the-shelf solutions, as outlined in this presentation, are low risk**



The Class I Railroads Will Expect To See A 30% To 60% Reduction In Fuel Cost Before Taking The Risk Of Converting To Natural Gas

- Additional cost savings can be achieved by reducing the number of refueling stops, having higher average velocity, having fewer environmental problems, and containing maintenance issues

2018 Fuel Statistics	BNSF Fuel Statistics for 2018	UP Fuel Statistics for 2018	CSX Fuel Statistics for 2018	NS Fuel Statistics for 2018	KCS Fuel Statistics for 2018	CN Fuel Statistics for 2018	CP Fuel Statistics for 2018	2018 Total
Total Gallons of Diesel	**1,475,000,000**	**1,068,000,000**	**424,000,000**	**471,769,000**	**134,900,000**	**448,000,000**	**248,000,000**	**4,284,478,689**
Cost per Gallon	$2.21	$2.29	$2.28	$2.18	$2.30	$3.26	$2.72	$2.38
Total Fuel Cost Diesel	$3,259,750,000	$2,445,720,000	$960,000,000	$1,028,454,240	$310,270,000	$1,460,480,000	$674,560,000	$10,185,388,657
Percentage Reduction for Hybrid Approach	20%	20%	20%	20%	20%	20%	20%	20%
% Natural Gas Substitution	83%	83%	83%	83%	83%	83%	83%	83%
DGE equivalent of CNG/RNG	$1.25	$1.25	$1.25	$$1.25	$1.25	$1.25	$1.25	$1.25
Total Fuel Cost With NG	$1,667,576,000	$1,219,057,920	$483,393,920	$531,437,217	$154,163,280	$570,465,280	$297,580,160	$4,941,330,169
Annual Total Fuel Savings	**$ 1,592,174,000**	**$ 1,226,662,080**	**$ 476,606,080**	**$497,017,023**	**$156,106,280**	**$890,014,720**	**$376,979,840**	**$5,244,058,488**
% Reduction of Fuel Cost	**49%**	**50%**	**50%**	**48%**	**50%**	**61%**	**56%**	**51%**

Why Electric Batteries and Hydrogen Will Not Be Used for Line Haul Locomotives

- It is true that using batteries produce no emissions, battery charging requires electrical power production that is principally made from coal or natural gas, and that production has a 2 to 6 time carbon intensity (124.1) than CNG from the pipeline or RNG – see CARB Table for California below
- **Currently, commercial battery packs cost around $180 per kWh, so a 5,000 diesel gallon equivalent (DGE) battery storage tender (1 DGE equal 40.7 kWh of energy) would cost over $40 million, would require replacement in 10 years, and would require a 200 MW power source to refuel in 1 hour**
- Hydrogen power fuel cells produce no emissions except water, however, hydrogen production is made from natural gas, and that production has a 2 to 6 time carbon intensity than CNG from the pipeline, and cost about $17 to $22 a gallon diesel equivalent
- Technology to produce enough hydrogen from wind or sun energy for use in rail transportation is decades away, and there are no large capacity hydrogen refueling stations
- **It would take five to six tenders of hydrogen to provide the same energy as a single CNG tender**

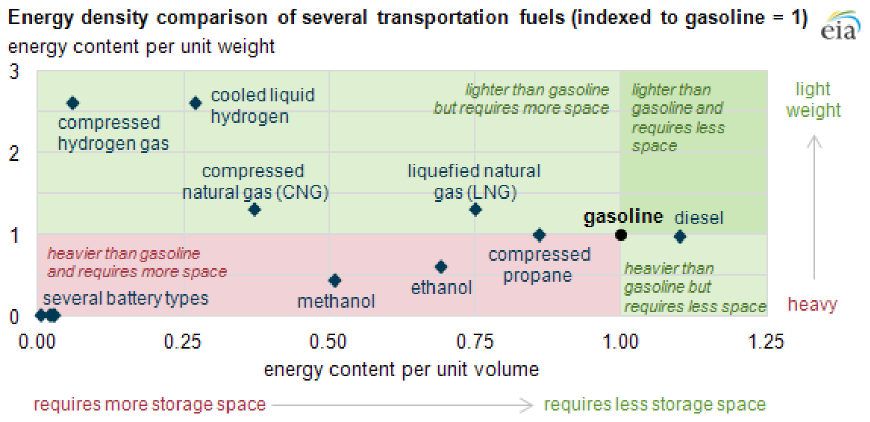
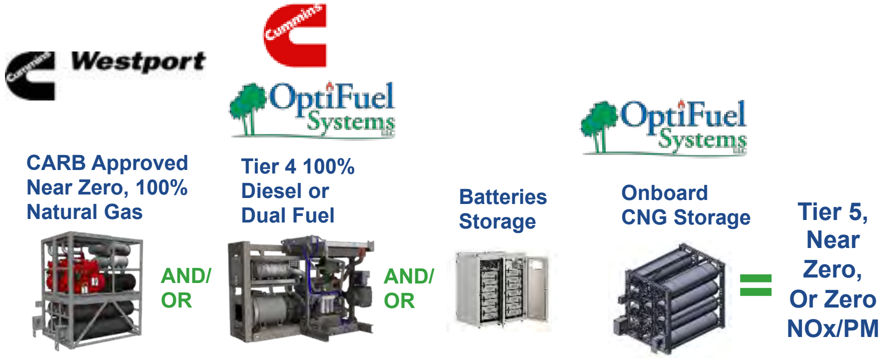


Table 7. CARB Carbon Intensity Lookup Table for Diesel and Fuels that Substitute for Diesel.

Fuel	Pathway Description	Carbon Intensity Values (gCO_2e/MJ)		
		Direct Emissions	Land Use or Other Indirect Effect	Total
Diesel	ULSD – based on the average crude oil delivered to California refineries and average California refinery efficiencies	94.71	0	94.71
Compressed Natural Gas and RNG	California NG via pipeline; compressed in CA	67.70	0	67.70
	North American NG delivered via pipeline; compressed in CA	68.00	0	68.00
	Landfill gas (bio-methane) cleaned up to pipeline quality NG; compressed in CA	11.26	0	11.26
	Digester Biogas to CNG	-303 to 13.45	0	-303 to 13.45
Electricity	California average electricity mix	124.10	0	124.10
	California marginal electricity mix of natural gas and renewable energy sources	104.71	0	104. 71
Hydrogen	Compressed H_2 from central reforming of NG (includes liquefaction and re-gasification steps)	142.20	0	142.20
	Liquid H_2 from central reforming of NG	133.00	0	133.00
	Compressed H_2 from central reforming of NG (no liquefaction and re-gasification steps)	98.80	0	98.80
	Compressed H_2 from on-site reforming of NG	98.30	0	98.30
	Compressed H_2 from on-site reforming with renewable feedstocks	76.10	0	76.10

Hybrid Power Definition From Wikipedia: "Hybrid Power Are Combinations Between Different Technologies To Produce Power"

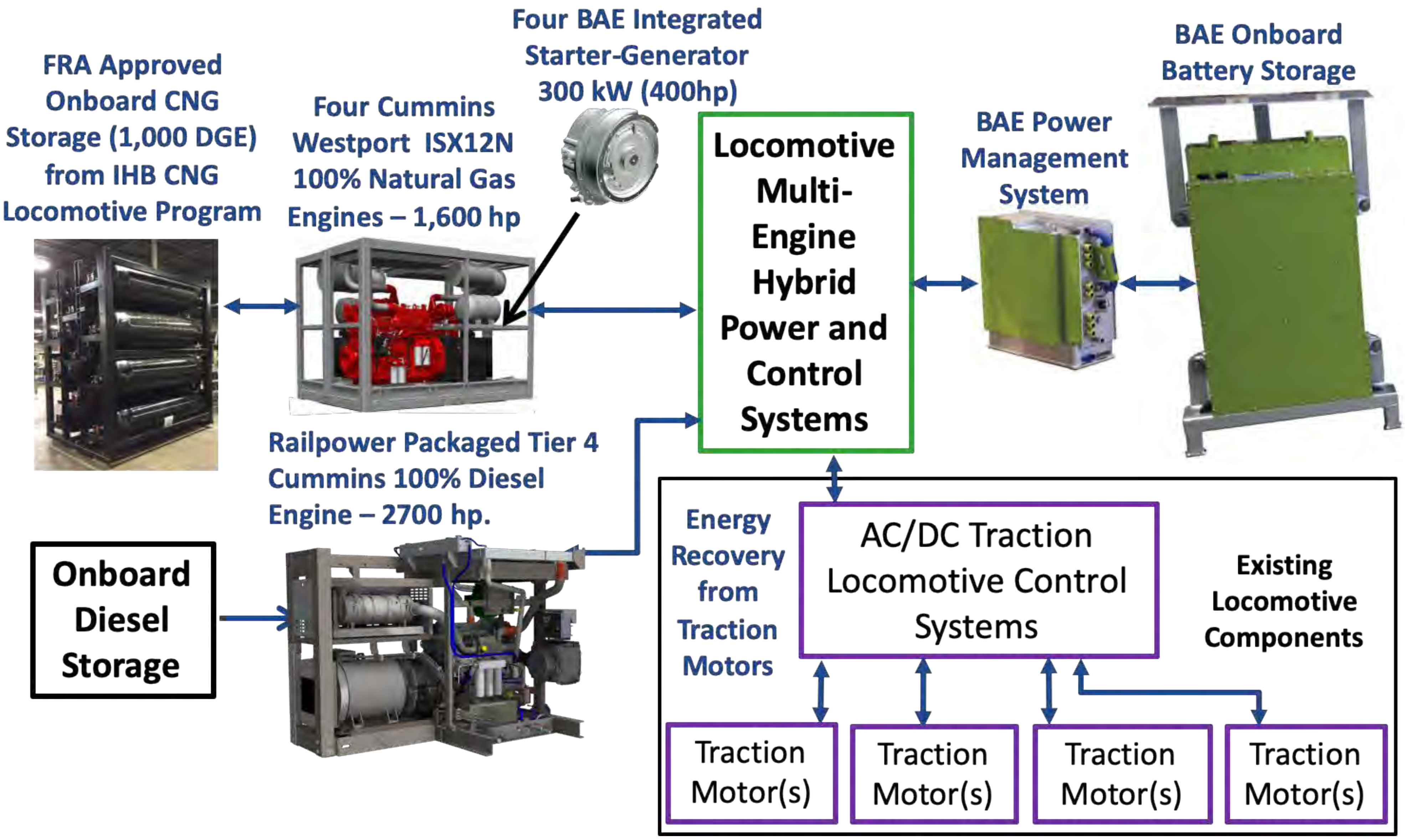
- By combining a Tier 4 diesel with one or more existing Near Zero, CARB approved, 100% natural gas engines and an onboard CNG storage system, the natural gas hybrid locomotive can meet or exceed the proposed Tier 5 standard
  - Run on Idle and Notches 1 to 3/4/5 on 100% natural gas, then use a 100% diesel engine, dual fuel engine and/or battery storage to provide remaining power in Notches 4/5 up to 8 - the lower notches are essentially Near Zero emissions and the higher notches are Tier 5



Tier Level	Year of Manufacture	NOx Standard (g/bhp-hr)	PM Standard (g/bhp-hr)	GHG Standard (g/bhp-hr)	HC Standard (g/bhp-hr)	Proposed Effective Date
4+	2015 - 2024	0.3	<0.01	NA	0.05	2023
5	2025	**0.2**	**<0.01**	NA	0.02	2025
		With capability for zero-emission operation in designated areas.				

Tier Level	Model	NOx – Steady Standard (g/bhp-hr)	PM – Steady State Standard (g/bhp-hr)	GHG - Steady Standard (g/bhp-hr)	NMHC - Steady Standard (g/bhp-hr)	Available Effective Date
NEAR ZERO	ISX12N 400 hp	**0.00** (Steady State)	**0.00** (Steady State)	**CO_2 – 429** **CO – 0.21** **CH_4 – 0.16**	**0.00** (Steady State)	2018
4 Line Haul	QSK60 2800 hp	**0.80**	**0.01**	**CO – 0.1**	**0.02**	2017

In Power Engineering, The Term 'Hybrid' Describes A Combined Power And Energy Storage System



The 100% Diesel, Tier 4 Engine, QSK60, Is Only Used on Notches 4 to 8 Where it is Very Clean - At Idle and Notch 1 to 3, Its Emissions Are Much Higher

4300 HP LINE HAUL LOCOMOTIVE - Quad ISX12N and Tier 4 QSK60 Engines	Total Annual Hours With ESS System	NOx g/bhp-hr	PM g/bhp-hr	CO g/bhp-hr	NMHC g/bhp-hr
Normal Idle	764	0.00	0.00	0.21	0.00
Dynamic Brake	0.00	0.00	0.00	0.00	0.00
Notch 1	491	0.00	0.00	0.21	0.01
Notch 2	491	0.00	0.00	0.21	0.01
Notch 3	393	0.00	0.00	0.21	0.01
Notch 4	333	0.04	0.00	0.19	0.00
Notch 5	287	0.15	0.00	0.14	0.00
Notch 6	295	0.15	0.00	0.13	0.00
Notch 7	227	0.13	0.00	0.14	0.00
Notch 8	1,225	0.09	0.00	0.14	0.01
EPA DUTY CYCLE WEIGHTED		0.05	0.00	0.18	0.01

Model	NOx – Steady Standard (g/bhp-hr)	PM – Steady State (g/bhp-hr)
ISX12 N 400 hp	0.00 (Steady State)	0.00 (Steady State)
QSK60 2800 hp	0.80	0.01

Tier Level	Model	NOx – Notch Standard (g/bhp-hr)	PM – Notch Standard (g/bhp-hr)	GHG - Notch Standard (g/bhp-hr)	NMHC - Steady Standard (g/bhp-hr)
NEAR ZERO	ISX12N 400 Hp	0	0	CO_2 – 429 CO – 0.21	0.01
4 Line Haul Notch 4	QSK60 2800 Hp	0.2	0	0.1	0
4 Line Haul Notch 5	QSK60 2800 Hp	0.25	0	0.1	0
4 Line Haul Notch 6	QSK60 2800 Hp	0.21	0	0.1	0
4 Line Haul Notch 7	QSK60 2800 Hp	0.19	0	0.1	0
4 Line Haul Notch 8	QSK60 2800 Hp	0.15	0	0.1	0.01

Annual Engine Performance Parameters	Engine #1 HP ISX12N	Engine #2 HP ISX12N	Engine #3 HP ISX12N	Engine #4 HP ISX12N	Engine #4 HP ISX12N
Total Annual Hours	4,506	3,251	2,759	1,225	2,366
Percentage Annual Hours	100.00%	72.15%	61.24%	27.18%	52.52%
Total Rated Hp	400	400	400	400	2,700
Avg. Annual Hp	228	228	228	228	1,090
Load Factor Percentage	57%	57%	57%	57%	40%
Avg. Annual Engine Running Hours	2,935	2,935	2,935	2,935	2,366
Avg. Annual Engine Running Percentage	65%	65%	65%	65%	53%

A Natural Gas Hybrid Approach Can Be Used For Switching, Line Haul, and Passenger Using the Appropriate EPA Duty Cycles

Near Zero Emissions 1,600 hp. Switcher

- 1,600 hp Switcher Locomotive
- **NOx/PM:0.00 g/bhp-hr** at all notches in Near Zero Mode
- Provides NEAR ZERO & ZERO-emission track-miles locomotives for use in railyards with battery system
- **100% CNG/RNG** powered
- 1,000 DGE of CNG/RNG onboard

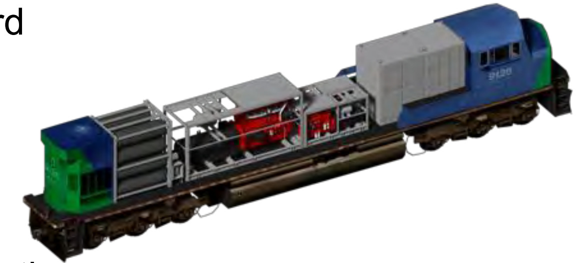
Tier 5+ Emissions for 3300 hp. Line Haul / Transit

- 3,300 hp Line Haul / Transit Tier 5 Locomotive
- Using natural gas to reach Tier 5 – **NOx:0.199 g/bhp-hr, PM:0.00**
- Horsepower weighted and duty cycle weighted fuel per gallon usage is **77% CNG/RNG and 23% diesel** with a 50% Idle Reduction System
- 5,000 gallons of diesel and 1,000 DGE of CNG/RNG onboard

Near Zero Emissions 2,000 hp. Switcher

- 2,000 hp Switcher Locomotive
- Using natural gas to reach Tier 5 – **NOx/PM:0.00 g/bhp-hr**
- Provides NEAR ZERO & ZERO-emission track-miles locomotives for use in railyards with battery system
- **100% CNG/RNG** powered
- 1,000 DGE of CNG/RNG onboard

Tier 5+ Emissions for 4,300 hp. Line Haul



- 4,300 hp Line Haul Tier 5 Locomotive
- Using natural gas to reach Tier 5 – **NOx:0.06 g/bhp-hr, PM:0.00**
- Horsepower weighted and duty cycle weighted fuel per gallon usage is **84% CNG/RNG and 16% diesel** with a 50% Idle Reduction System
- 5,000 gallons of diesel and 1,000 DGE of CNG/RNG onboard

Powered CNG/RNG Tender Using Four ISX12N Near Zero Engines to Provide Another 1,600 Hp of Addition Tractive Effort

- The use of CNG/RNG tenders will require less refueling stops, less equipment, less people, increasing overall system velocity, lower dwell time, and reduce environmental concerns with potential liability and cost issues
- The railroads will not have to worry about maintenance, repairs or refueling of the CNG/RNG tenders and they can return partially filled tenders

- Non-Powered CNG/RNG tender holds a MAXIMUM of 13,500 DGE
  - Can be interfaced to two 4,200 Hp Tier 5 OptiFuel locomotives, two Tier 3 SD70AC locomotives or two Tier 3 ES44AC locomotives, all running with dual fuel

- 1,600 Hp. **POWERED** CNG/RNG tender holds a MAXIMUM of 9,000 DGE
  - Near Zero Emissions, 100% CNG/RNG engines provide 1,600 Hp to power 4 axles with AC traction motor
  - Can be interfaced to one or more locomotives supporting wired and wireless distributed power

Powered Tenders Eliminate 25% of Locomotives & Associated Maintenance and Refueling Expense

- An eight locomotive consist can be replaced with six natural gas locomotives and six powered tenders
  - Total horsepower is the same but the tractive effort increases with twice the number of powered axes
  - The stored fuel is increased by 225%, providing longer ranges and less refueling time

- A four locomotive consist can be replaced with three natural gas locomotives and powered tenders, reducing fuel cost by over 50%
  - The operational concept can be used with existing Tier 3 SD70AC / ES44AC dual fuel locomotives or new OptiFuel Tier 5 locomotives
  - Can be interfaced to one or more locomotives supporting wired and wireless distributed power

Even With Existing Tier 3 Equipment With a Duel Fuel Kit, Using a Powered CNG Tender Can Go Cross Country Before Refueling

- Tier 5 OptiFuel Hybrid
  - NOx-0.06 g/bhp-hr, PM-0.00 g/bhp-hr

4,300 Hp Tier 5
83% Substitution

1,600 Hp Near Zero

5,000 Diesel,
1,000 DGE CNG/RNG

9,000 DGE CNG/RNG

2.5 gal/miles =

- Blended Cost - $1.40
- NOx-0.09 g/bhp-hr, PM-0.00 g/bhp-hr
- Dual Fuel Range – 6,726 miles

- Tier 3 EMD SD70AC Dual Fuel
  - NOx-5.5 g/bhp-hr, PM-0.10 g/bhp-hr

4,400 Hp Tier 3
60% Substitution

1,600 Hp Near Zero

5,000 Diesel

9,000 DGE CNG/RNG

2.5 gal/miles =

- Blended Cost - $1.59
- NOx-4.02 g/bhp-hr, PM-0.07 g/bhp-hr
- Dual Fuel Range – 5,114 miles

- Tier 3 GE ES44AC Dual Fuel
  - NOx-5.5 g/bhp-hr, PM-0.10 g/bhp-hr

4,400 Hp Tier 3
60% Substitution

1,600 Hp Near Zero

5,000 Diesel

9,000 DGE CNG/RNG

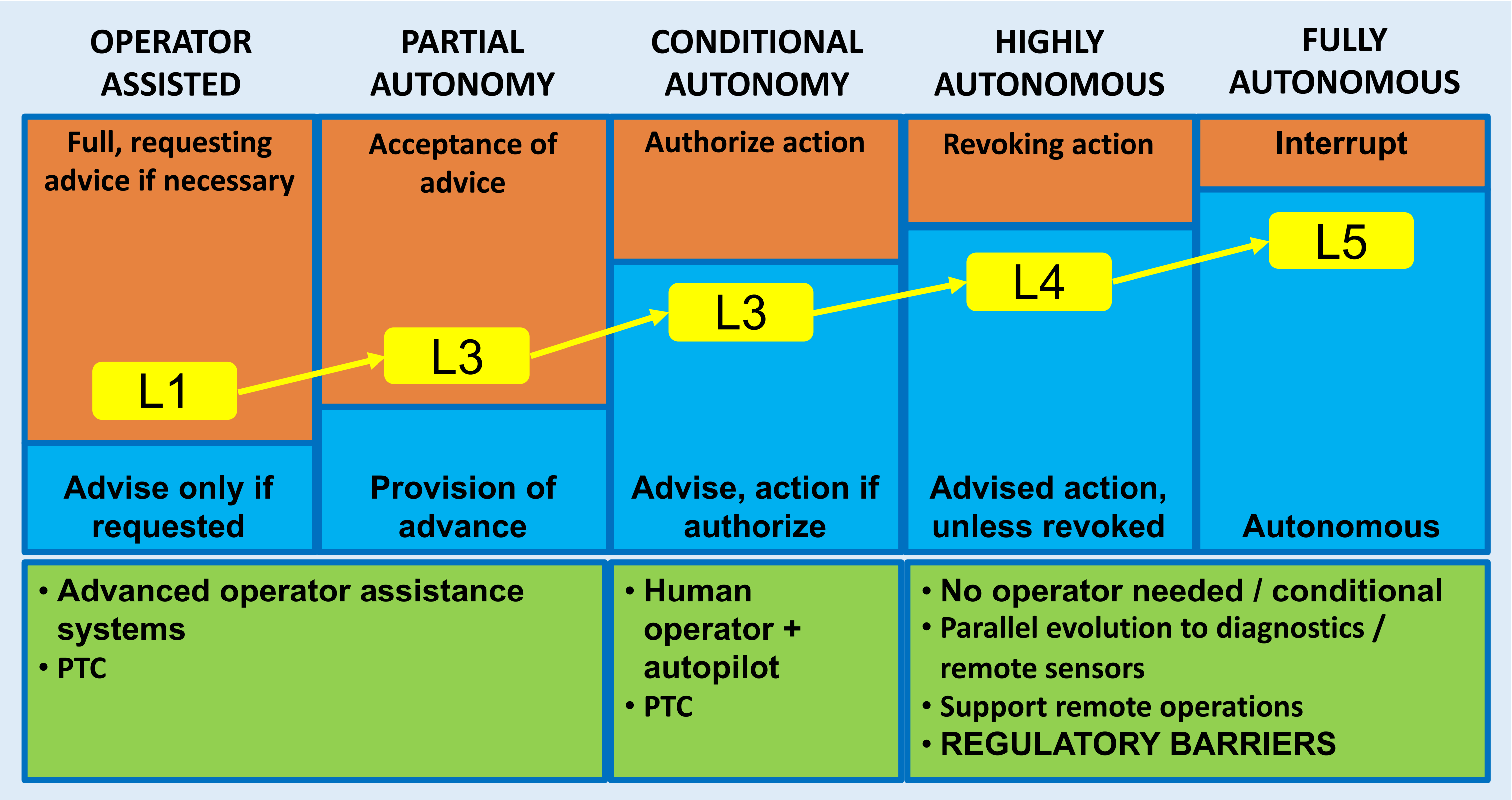
3.8 gal/miles =

- Blended Cost - $1.59
- NOx-4.02 g/bhp-hr, PM-0.07 g/bhp-hr
- Dual Fuel Range – 3,230 miles

NOTE: Diesel Gallon - $2.43 , CNG DGE - $1.25 , BNSF/NS gal/mi. Figures

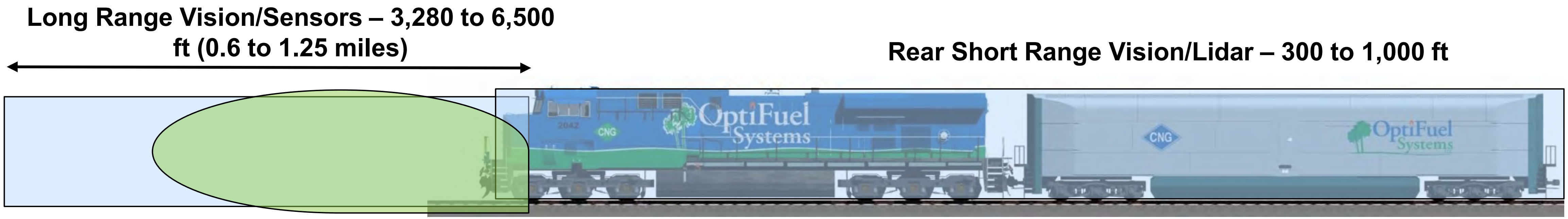
With PTC Soon in Place, Only Integrating Obstacle Detection Systems is Needed to Test and Verify L4 Autonomy

- Integrate obstacle detection system required on locomotives looking down the tracks, around the locomotives, and at fixed sites at grade crossing
- With real-time communications directly between the locomotive to the next obstacle detection grade crossing system provides autonomous monitoring of potential people, cars, trucks, or animal at the crossings, allowing the consist to safely operate with maximum velocity
- The benefits of L4/L5 autonomy is higher system safety, less potential legal cost, higher system velocity, reduced labor cost, and ability to operate locomotives remotely from fixed geographic locations with regular shift assignments



No Technology Development Required to Integrate Obstacle Detection (people, animal, vehicles, etc) on Locomotives Looking Down the Tracks, Around the Locomotives, and at Grade Crossing

- Citing preliminary Federal Railroad Administration (FRA) statistics, U.S. crossing collisions in 2018 rose 4.3%



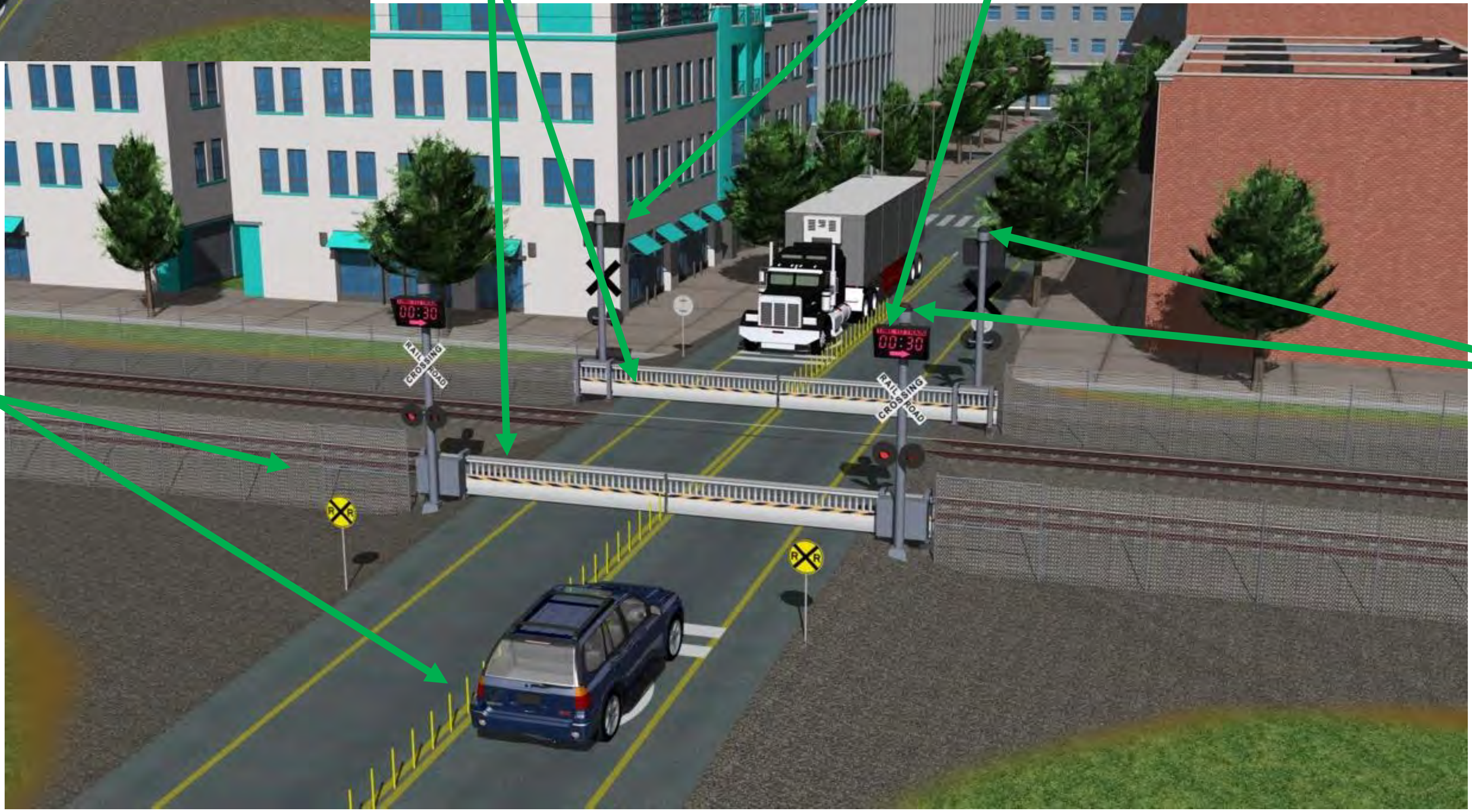
Note: 60 mph is 88 ft/s; 60 seconds to travel 5280 ft or 1 mile

Real-time Vehicle and Personnel Monitoring Systems at the Grade Crossing With Real-Time Communications to the Locomotive

European style sliding gates open and close quickly and have higher reliability – not affected by heavy winds

Provides real-time status to pedestrians and car/truck drivers when the train will arrive at the gate and when it will be passed

Vehicle and pedestrian barriers to reduce accidental crossing while the train is near the gates



Four 360 degree sensors/visions system on each pole and all four image streams are processed and blended into one stream, then send back up to the track to the locomotive for additional processing and integration into the collision detection system – all in real-time

The Future is Now With Affordable, Near Zero Emissions, Autonomous Trains That Can Operate In Urban Areas

- Supports the use of frequent, faster, shorter trains that operate with lower fuel and labor cost in order to increase market shares from trucking

Obstacle Detection System Can Detect People a Mile Away

Cost the Same as Tier 4 Diesel Locomotive

Multi-Engine Hybrid Power Reduces Fuel Usage by 20% to 40%
- Only Requires Yearly Maintenance
- Can Operate With Partial Power if One Engine Fails
- Cost Less Than Single Big Engine

1,200 hp Powered CNG Tender With 3 Axle Trucks With AC Traction Has Zero Emissions

Using CNG:
- Cost is $1.25 a Diesel Gallon Equivalent (DGE)
- The Cost Includes the Cost of the CNG Tenders and All CNG Refueling Equipment
- Can Operate With CNG or Renewable Natural Gas (RNG)

4,300 hp Line Haul Natural Gas Hybrid Locomotive Has Near Zero Emissions – 5,500 hp Total with Locomotive and Powered Tender

9,000 DGE of CNG on the Tender provide a Range of 5,000 to 6,500 Miles Before Refueling – 1 hour to Refueling CNG Tender

1,000 DGE of CNG on the Locomotive and 5,000 gallons of Diesel

Modern High Speed Engine Compared to Medium Speed Engines:
- 20% lower in cost
- 70% smaller on size
- Almost all markets except rail have gone to high speed engines

Technology Exist to Automate the Refueling and Car Coupling, Eliminating Labor Cost

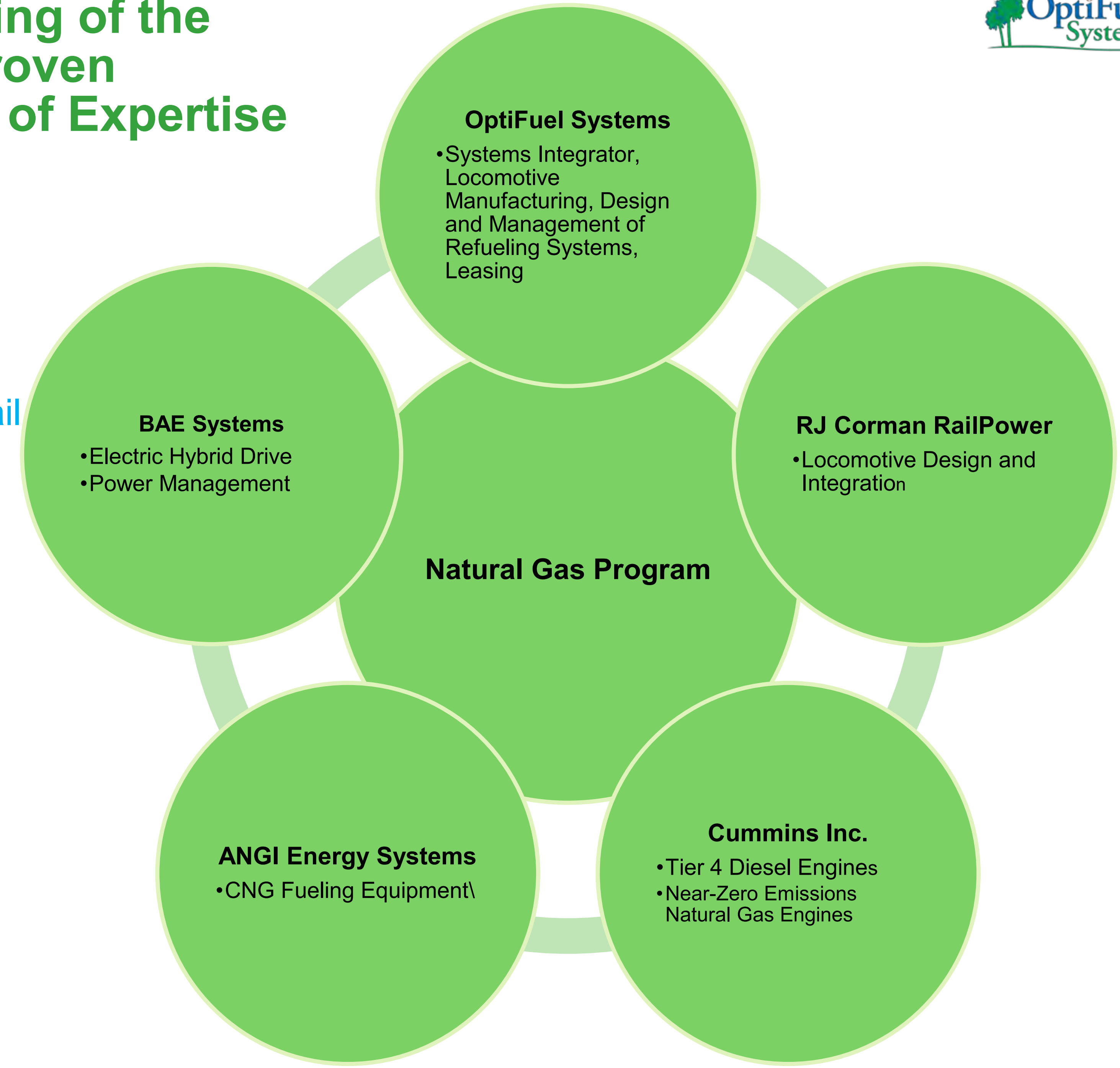
The Railroads Can Convert to CNG At No Cost and Save 50% of Their Fuel Cost – No Capex for Refueling Equipment or CNG Tenders

OptiFuel: No CAPEX Program for Natural Gas as the Primary Fuel to Reduce Fuel Cost by 50%

- During the last 12 months, a group of industry companies, led by OptiFuel, have analyzed the US Class 1/2/3 railroads market, with it's 39,000 locomotives, at a macro basis – the results are:
  - There is no technology development required and the processes are all in place
  - The US Class 1 railroads can reduce their operating ratio by 3% to 5% by converting their existing Tier 3 locomotives to dual fuel and/or by leasing new Tier 5 CNG/RNG locomotives
  - Class I railroads do not need to add additional CAPEX to convert to natural gas, the OptiFuel team has put together a US-wide program to provide 60, 250,000 DGE CNG/RNG refueling stations and 3,000 CNG/RNG powered and unpowered tenders
  - Over the last 11 years, the Class 1 railroads have bought diesel at an average of $2.42 per gallon
  - The railroads will only be required to pay $1.25 DGE: the fueling equipment and tender CAPEX will be recovered in the $1.25 DGE CNG cost
- **The macro results of the study can be scaled to down to the micro level to a single Class 1 railroad and it's unique network, with the same low risk approach and the same financial results**

OptiFuel's Team Consisting of the Most Experienced and Proven Companies in Their Area of Expertise

- OptiFuel Systems LLC
  - WWW.optifuelsystems.com
- RJ Corman Railpower
  - www.rjcorman.com/companies/railpower-locomotives
- Cummins Inc.
  - www.cummins.com
- ANGI Energy Systems Inc
  - www.angienergy.com
- BAE Systems
  - www.hybridrive.com



Macro Keys to Natural Gas are: 1) Use CNG/RNG and 2) Pool of Refueling Stations and Tenders – All Requiring No CAPEX to the Railroads

- Macro level results for all Class 1/2/3 railroads
  - To save railroads at least a $1.00 a diesel gallon equivalent (DGE) of natural gas, the natural gas needs to be sold to them at an average of $1.25 per DGE, including commodity cost, transportation, compressing, refueling equipment and tender CAPEX, operations, maintenance, and profit
  - Create a pool of 3,000 CNG/RNG tenders, each holding 8,000 (Powered) or 13,000 (standard) DGE of CNG/RNG, around the U.S., eliminating any upfront cost by the railroads
  - Create a pool of 60 CNG fueling stations around the U.S., each capable of fueling 260,000 DGE of CNG/RNG daily, eliminating any upfront cost by the railroads
  - The maximum cost for refueling equipment and tenders for all Class 1 railroads in the U.S. is estimated to be $8.41 billion – **NO CAPEX REQUIRED BY THE RAILROADS**
    - 60 250,000 DGE CNG/RNG refueling stations @ $46 million each - $2.760 billion
    - 3000 CNG/RNG powered and unpowered tenders @ $1.8 million - $5.4 billion
    - CNG/RNG mobile refueling equipment and bulk transport equipment - $250 million
- The fueling equipment and tender CAPEX (refueling stations, tenders, misc. equipment) will be recovered in the cost of a $1.25 DGE of natural gas – the CAPEX cost part is $0.20 a DGE ($0.07 for refueling stations and $0.13 for the tenders)

CNG Expense Breakdown – Diesel Gallon Equivalent (DGE)

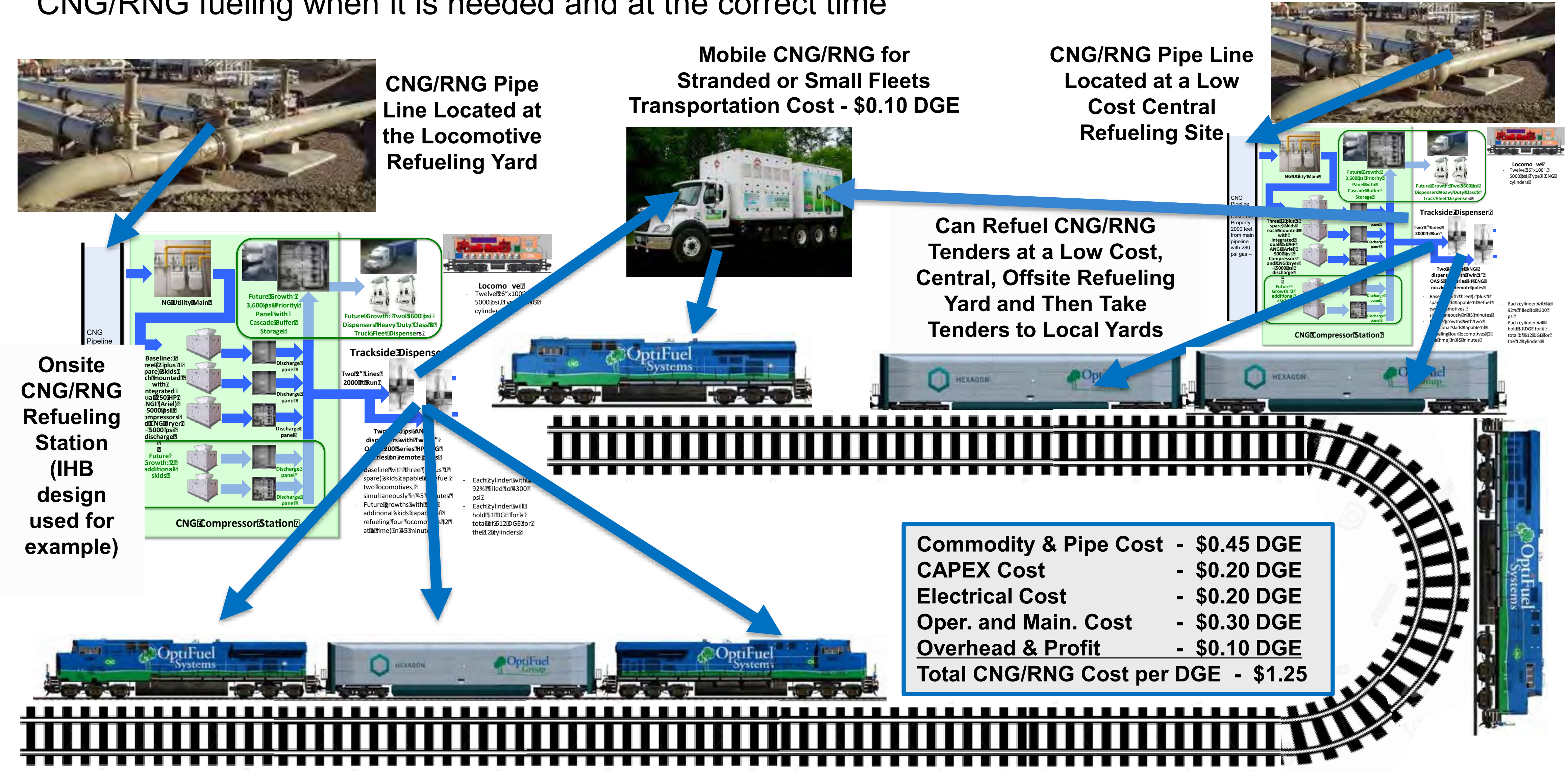
- PSR priority on reducing cost, on-schedule operations, better fuel efficiency and standard routes and segments, strong support for our strategy to convert CSX to natural gas

Commodity & Pipe Cost	**-**	**$0.45 DGE**
CAPEX Cost	**-**	**$0.20 DGE**
Electrical Cost	**-**	**$0.20 DGE**
Oper. and Main. Cost	**-**	**$0.30 DGE**
Overhead & Profit	**-**	**$0.10 DGE**
Total CNG/RNG Cost per DGE	**-**	**$1.25**

- **Commodity Cost**
  - This cost of $0.45 is based on current cost of $3.00 per MBTU plus pipe line transportation cost
  - Any cost above that basic cost can be recovered with a CSX fuel surcharge cost, same as current diesel surcharge cost
- **CAPEX Cost**
  - This is a FIXED COST of $0.20 to recover the OptiFuel CAPEX of CNG/RNG refueling stations and tenders
  - The $0.20 cost is based on a recovery period of 20 years with 8% interest
- **Electric Cost**
  - This is the estimated electric cost to run a 260,000 DGE per day refueling station with eleven 1,200 hp 4-stage CNG compressors
- **Operation and Maintenance Cost**
  - Operation cost is $0.15
  - The maintenance cost of $0.15 is put into a reserve to replace parts and maintenance cost over the 30 year life period of the refueling equipment, tenders and mobile refueling equipment
- **Overhead & Profit**
  - Standard rate for installing and managing CNG stations is $0.10 to $0.20 per DGE

Multiple Options to Refuel Locomotives and Tenders

- Precision schedules and optimized segments allow OptiFuel to strategically provide CNG/RNG fueling when it is needed and at the correct time



Commodity & Pipe Cost	-	$0.45 DGE
CAPEX Cost	-	$0.20 DGE
Electrical Cost	-	$0.20 DGE
Oper. and Main. Cost	-	$0.30 DGE
Overhead & Profit	-	$0.10 DGE
Total CNG/RNG Cost per DGE	-	$1.25

NOTE: THE $0.20 CAPEX COST INCLUDES RECOVERING THE COST OF REFUELING STATIONS, TENDERS, AND MISCELLANEOUS SUPPORT EQUIPMENT OVER A 10 YEAR PERIOD

No CAPEX CNG/RNG Refueling Stations – $0.20 CAPEX Cost of Each DGE and Stations are Scalable

- Refueling technologies are off-the-shelf and have been used in thousands of stations operating in all climates with great success at fill rates greater than 90%
- Systems are robust with proven safety records spanning decades of operation
- **The CNG/RNG refueling stations are identical to the IHB CNG/RNG refueling station, except can scaled up to refueling 260,000 DGE a day, and support refueling 4 tracks at the same time**

No CAPEX Mobile Refueling Equipment – $0.20 CAPEX Cost of Each DGE

- CNG/RNG bulk transport equipment, small skid mounted refueling stations, and other miscellaneous refueling equipment for small fleets and stranded equipment around the U.S
- CSX will not have to worry about maintenance, repairs or refueling of the CNG/RNG tenders

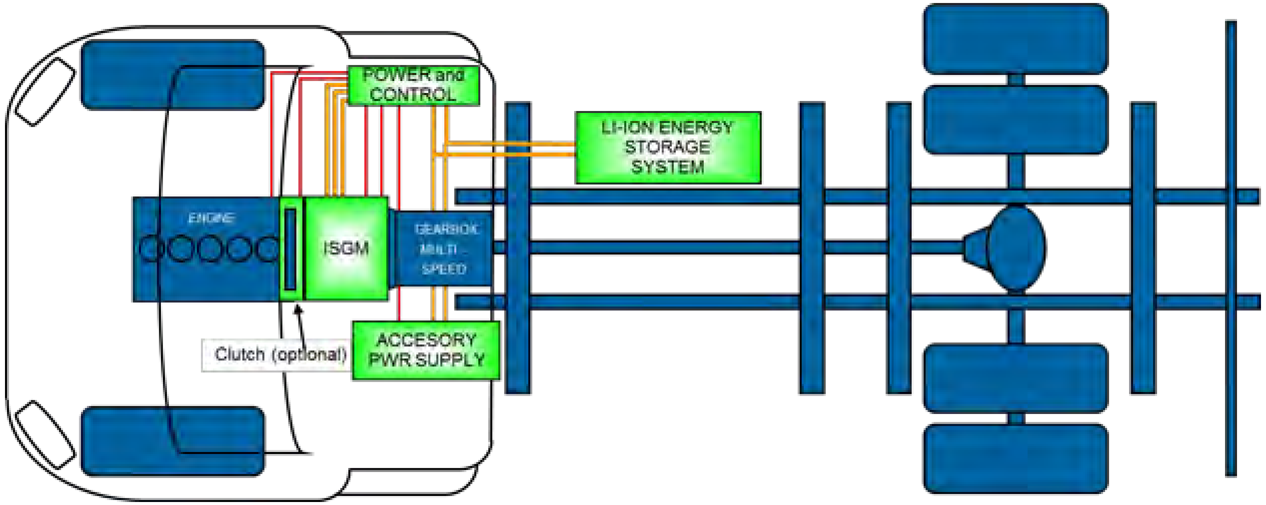


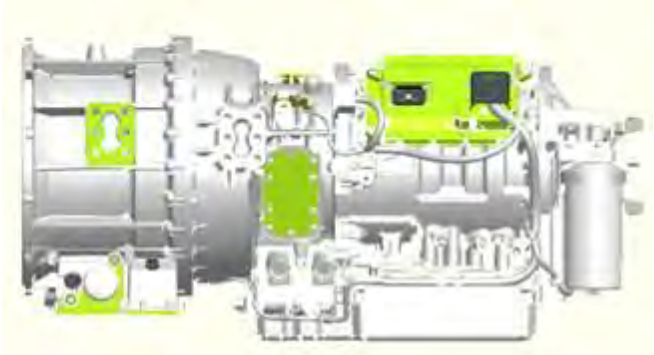


Other Near Zero or Zero Emission Mobility Systems Using the ISX12N and Hybrid Drive Components

The Hybrid Integrated Drive Unit (IDU) Boost the Driveline Power by Up to 100 kW / ~135 Hp for the 30% of the Class 8 Trucks That Need More Than 400 Hp Going Cross Country

- **Near Zero emission Class 8 truck with 535 Hp of total power and 750 miles between CNG refueling**
- The IDU works with a battery pack, a 400 Hp ISX12N Near Zero natural gas engine, and transmission to boost the driveline power by up to 100 kW / ~135 Hp to augment power from the ISX12-N to achieve desired transient performance go up hills and mountains with heavier loads
  - Power management Integrated Starter, Motor, Generator (ISG) architecture with energy storage system (ESS) added
  - ISG mounted between engine and transmission
  - Multi-Speed gearbox (automatic transmission with torque converter)
  - Small sealed battery pack for under vehicle environment (submersion, dirt, debris…)
  - *Optional Isolation clutch between ISG and the engine*
    - Electric accessories to support engine-off modes
- System is right-sized and right-priced for long haul Class 8 trucks – cleaner than an electric truck with RNG





The Larger Sea Crossing Ships Companies Are Already Building LNG Powered Ships, But No Affordable Tier 4/5 Natural Gas Engines for the Coastal and Inland Market

- All new boats operating in the U.S. waterways must have EPA Tier 4 engines to be licensed by the Coast Guard
  - Tier 4 regulations apply to *newly-built* marine diesel engines with displacements less than 30 liters per cylinder installed on all vessels flagged or registered in the United States
- Ship builders are already building new ocean-going vessels that are powered with LNG using very large micro-pilot dual fuel engines (>10,000 Hp, $1 million or more) from Wartsila
- Offshore rigs and associated working boats are shifting to natural gas due to ever-tightening federal air quality regulations
- Companies are already gearing up to spend hundreds of millions on LNG production and fueling facilities to serve U.S. inland marine industry
- Large dual fuel engines being used by the new 300 ft. LNG powered workboats in the Gulf are too large and too expensive for use by the towboat and tugboat industry in the U.S. inland waterways

Only Need Three Hull Sizes, Two Engine Sizes, and Use Standard Subcomponents to Reduce Production Cost for the CNG/RNG/LNG Powered Tug and Tow Boats

- Current standardized towboat / tugboats approach for coastal and inland marine markets
  - 2,300 Hp: Small Hull 78' x 30' x 11' - Powered by twin Tier 4 Cummins Tier 4 QSK19 Dual Fuel and two Near Zero ISX12N - abt $4 million each new
  - 3,050 Hp: Medium Hull 90' x 34' x 11' - Powered by triple Cummins Tier 4 QSK19 Dual Fuel and two Near Zero ISX12N - abt $8 million each new
  - 4,600 Hp: Large Hull 120' x 40' x 11' - Powered by four Cummins Tier 4 QSK19 Dual Fuel and four Near Zero ISX12N - abt $12 million each new

Small Hull – 2,300 Hp

Medium Hull – 3,050 Hp

Large Hull – 4,600 Hp

Tender Barge – 90,000 Gal of LNG

Bunker Barges – 600,000 Gal of LNG

The Marine Market Is Perfect For Dual Fuel Due To The Large Amount Of Fuel Used

- There are over 5,000 tugboats, towboats (push boats), and working boats in harbors, in inland waterways, and off-shore on the Gulf Coast
  - A majority of them are 30 to 50 years old and will need to be replaced over the next 10 years with multiple 19 to 50 liter engines
  - Depending on size, towboats can consume from 15,000 to 90,000 gallons of diesel fuel every 14 days – a perfect market for LNG and dual fuel
  - New tug and tow boats designs are 1,500 hp to 6,000 hp with multi–engines, hybrid, electric drive configurations

TOWBOAT Configurations With Cummins QSK19DF and ISX12N Engines	Cost of Diesel Fuel for Original EMD Engine(s) Configuration Running a Full Year (8,760 Hours at 90% Power, $3.30 per Gallon of Diesel)	Cost of Dual Fuel with Cummins Engine Configurations Running a Full Year (8,760 Hours at 90% Power, $3.30 per gallon of Diesel, $1.60 DGE LNG, 70% Substitution)	Annual Fuel Savings Running on Dual Fuel (70% Substitution) Instead of Original EMD Engines	Estimated Delta Cost of Dual Fuel System Including LNG Storage	Payback Period in Years
Triple QSK19DF and Twin QSX12N – 2,300 Hp	$3,800,389	$2,024,955	$1,775,434	$1,100,000	0.62
Triple QSK19DF and Twin QSX12N – 3,050 hp	$7,667,064	$4,085,229	$3,581,836	$1,550,000	0.43
Four QSK19DF and Four QSX12N– 4,600	$5,111,376	$2,723,486	$2,387,890	$1,450,000	0.61

Advancements in CNG Full Fills

April 2019

Ted Barnes, P.E.

Discussion

- Background on Full Fills
- Path for Development
- Recent Past Modeling and Testing
- Current Research
- Next Steps

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

FOR A BETTER ECONOMY AND A BETTER ENVIRONMENT

SUPPLY ▶ CONVERSION ▶ DELIVERY ▶ UTILIZATION

RESEARCH & DEVELOPMENT

PROGRAM MANAGEMENT

TECHNICAL/ ANALYTICAL

CONSULTING

TRAINING

COMMERCIALIZATION

360+ EMPLOYEES

World-class piloting facilities headquartered in Chicago area

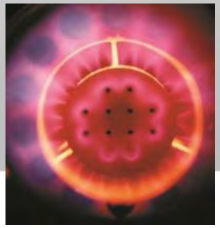
GTI Technology Expertise

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

U.S. Office Locations

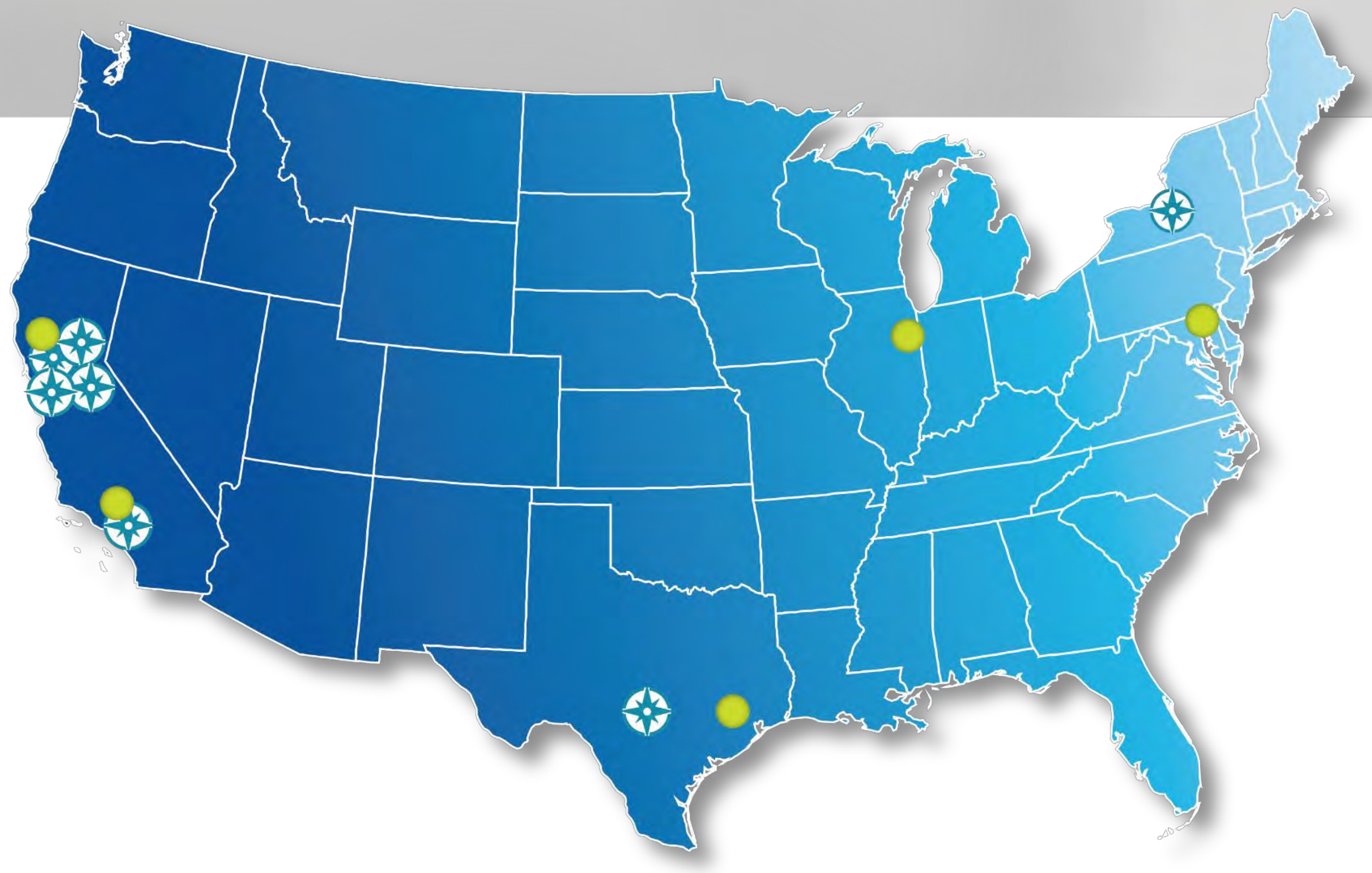
GTI Office Locations

- 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



Background – Full Fills

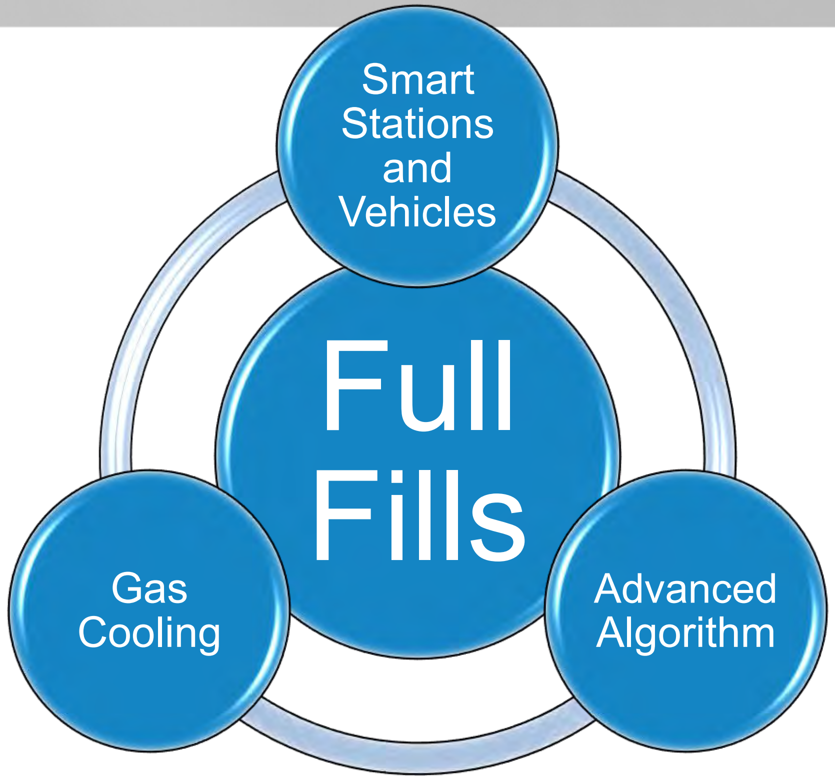
- A **Full Fill** is the amount of gas required to fill a CNG vessel to 3600 psig at 70 F
- Underfilling is when less than a full fill is supplied to the vehicle
  - **20% to 30% underfilling** can easily be experienced
- Underfilling is caused by a combination of factors including:
  - Heat of compression
  - Hardware pressure limits (Vessel and Dispenser)
  - Station design (Storage Capacity and hydraulic losses)
  - Dispenser algorithms are conservative
  - High initial gas temperature
  - Gas compositions vary

Why are Full Fills and Smart Stations Important?

- Improve vehicle range, weight, and/or cost by reducing unused storage volume
  - **Range** is critical for long haul applications
  - **Reduced weight** of fuel system enables additional cargo capacity
  - **Reduced vehicle cost** can increase NGV adoption
- Improve NGV experience by providing **consistent** full fills
  - **Dependable** fueling experience and range
- Increase NGV adoption
  - Reduced GHG emissions
  - Significantly reduced NOx

Smart CNG Fueling

Development Path



Full Fills

- Allow for **reduced storage needs** and improved customer experience with more **consistent** fueling

- Advanced Algorithm
  - Fueling algorithm must **safely** and effectively utilize information to achieve accurate fill
- Smart stations and smart vehicles
  - Station and vehicle must **communicate** to improve dispensing accuracy
- Gas cooling
  - Cooling is required to overcome heat of compression and give a **dependable full fill**

Advanced Algorithm Testing

- GTI created a dynamic CNG station simulation to test full fill algorithms, validated with limited testing
- Simulation runs hundreds of fill cases
  - Ambient temp: -40 to 140 F
  - Tank temp: -30 to +30 F from ambient
  - Starting tank pressure: 0 to 3000 psi
  - Tank volume: 1 to 300 GGE
  - Pure methane and high ethane gas compositions
- Algorithms with and without communication were tested for accuracy

Algorithm
Typical Station Pressure Target

- State of the art systems indirectly measures tank **pressure at the dispenser** and **ambient temperature** to determine full fill target pressure
- Accomplished by calculating settled pressure at ambient temperature assuming average natural gas, then uses a simple formula or **table to determine target pressure** after heat of compression
- Dispenser fills to heat of compression target pressure, maximum pressure limit, or until flow from supply drops below ~ 1 Gas Gallon Equivalent (GGE) per minute
- Another method is mass-based systems
  – Estimate empty volume and calculate mass needed for full fill

Algorithm
Issues Identifying Initial State and Target

- Real gas equation: PV=ZnRT
- **None of above variables are known directly**
- Pressure is measured indirectly and depends on vehicle design
- Temperature can vary significantly from ambient
  - Hot case: Vehicle left in sun can be significantly hotter than ambient
  - Cold case: Continuous operation can cause significant temperature drop in CNG cylinder as fuel is consumed (i.e. isentropic cooling)
- Gas composition of the incoming vehicle and station are unknown
- Methane content of natural gas can range from ~75% to ~100%
- Volume can be estimated using “huff step”, but variables above impact accuracy

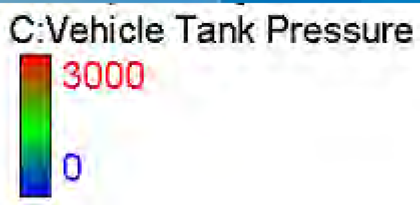
Algorithm with Communications
Advanced Algorithm

- Real gas equation: $PV=ZnRT$
- Improve characterization of variables above using passive or active communication
- Pressure can be directly measured using existing sensor on-board vehicle
- Temperature can be directly measured, but has some risk due to uneven gas mixing during fill (i.e. stratification)
- Gas composition is likely not practical to measure, but molecular weight and/or energy content can be measured at dispenser for gas being added to vessel
- Volume is relatively constant and can be transmitted by car and verified by dispenser
- Modeled using Matlab Simulink
- Not looking to replicate hydrogen industry

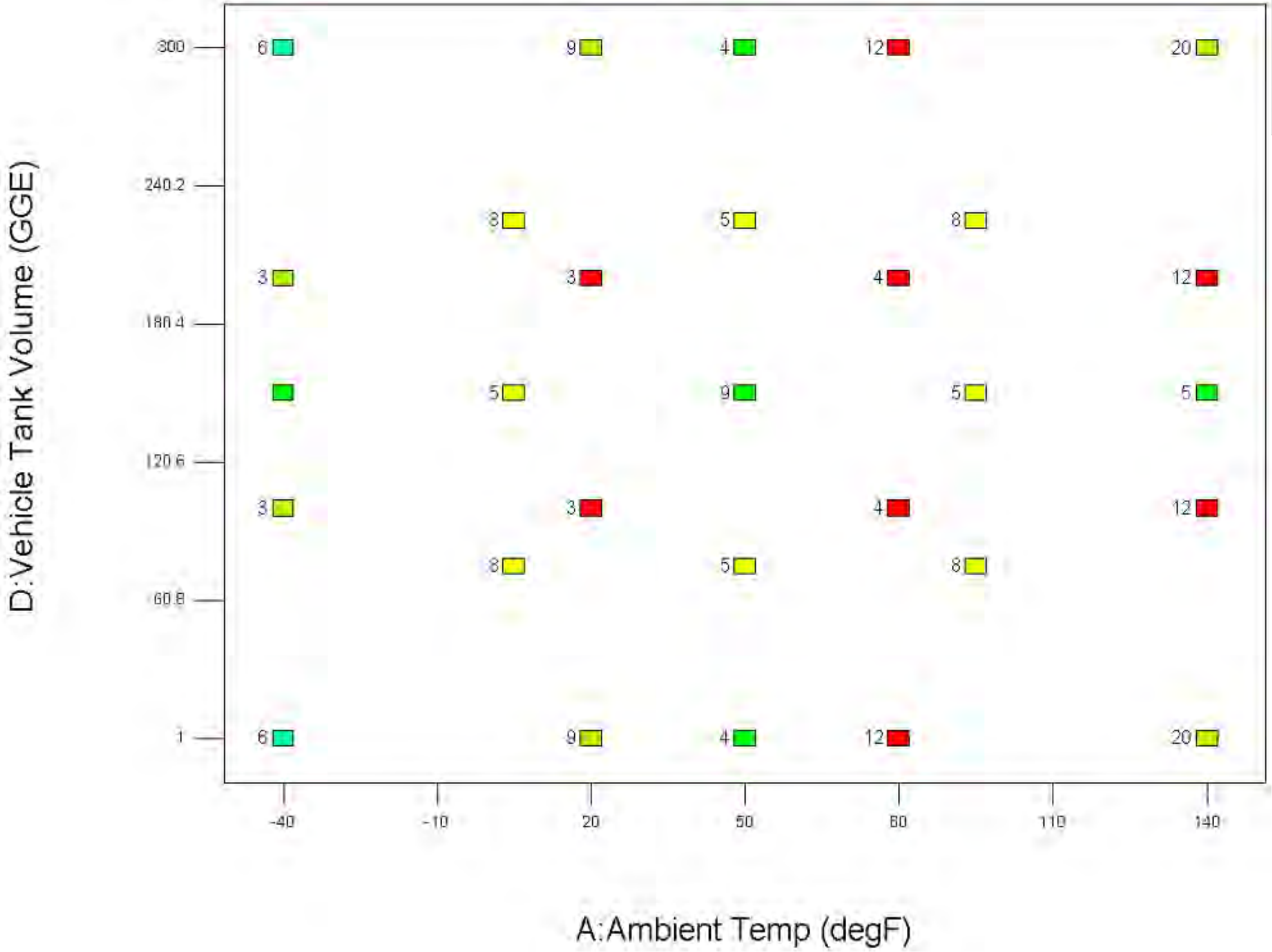
Algorithm with Communications Design of Experiment

- Design of Experiment (DoE) is used evaluate the cause and effect relationship between input variables and results
- In this case, station and vehicle starting conditions are the input and fullness of a fill is the output
- Primary input variables are:
  - Ambient temperature (-40 to 140 F)
  - Vehicle tank temp variation from ambient (-30 to 30 F) (cold and hot cases)
  - Vehicle starting pressure (0 to 3000 psig)
  - Vehicle volume (1 to 300 GGE)
- DoE designs test matrix using input variables

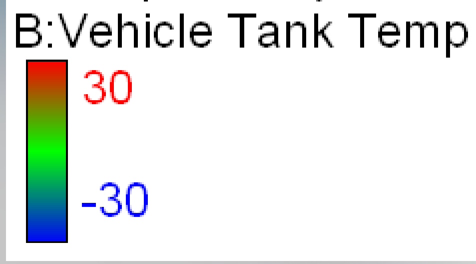
Algorithm with Communications Design of Experiment



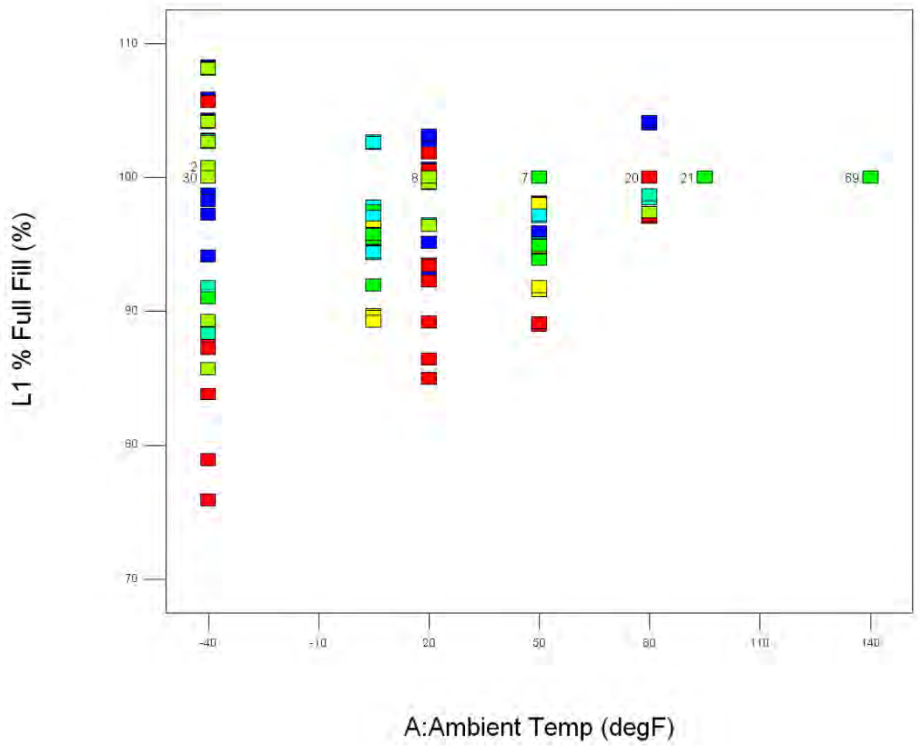
- Inputs result in 273 design points
- Matlab Simulink runs each case through simulation and records results for each dispenser algorithm
- Image: Example of test point distribution

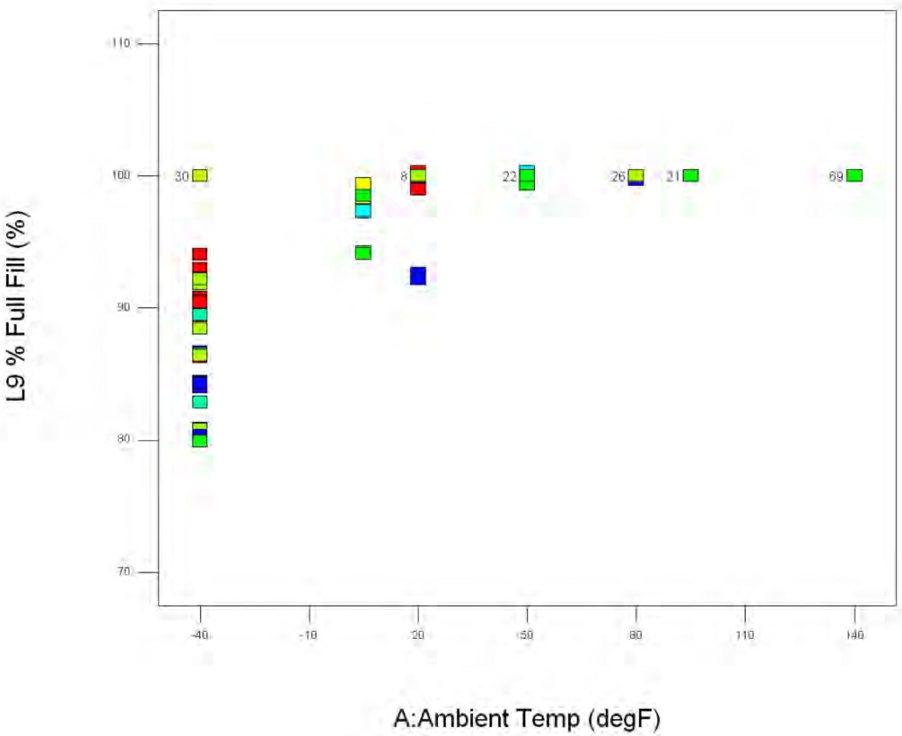


Algorithm with Communications
Current vs. Conservative PT



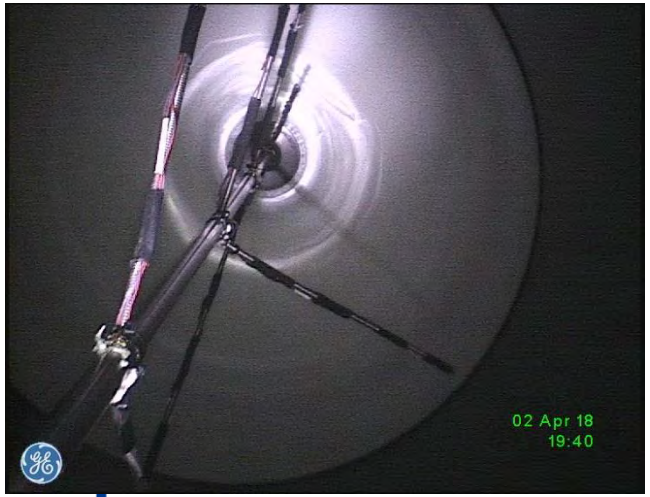
- Existing filling algorithm compared to conservative algorithm using communications

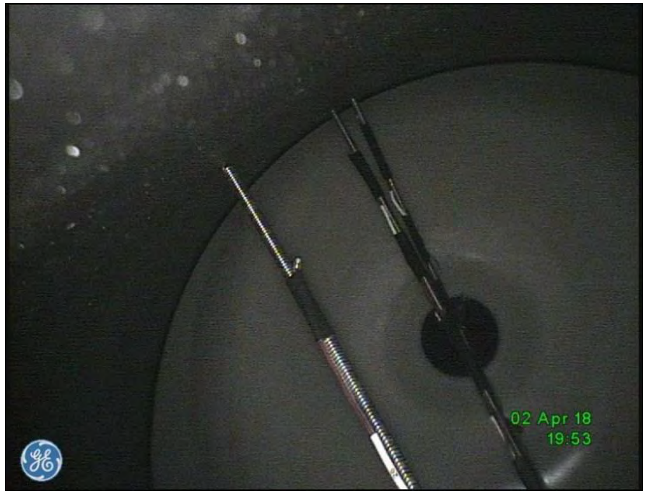




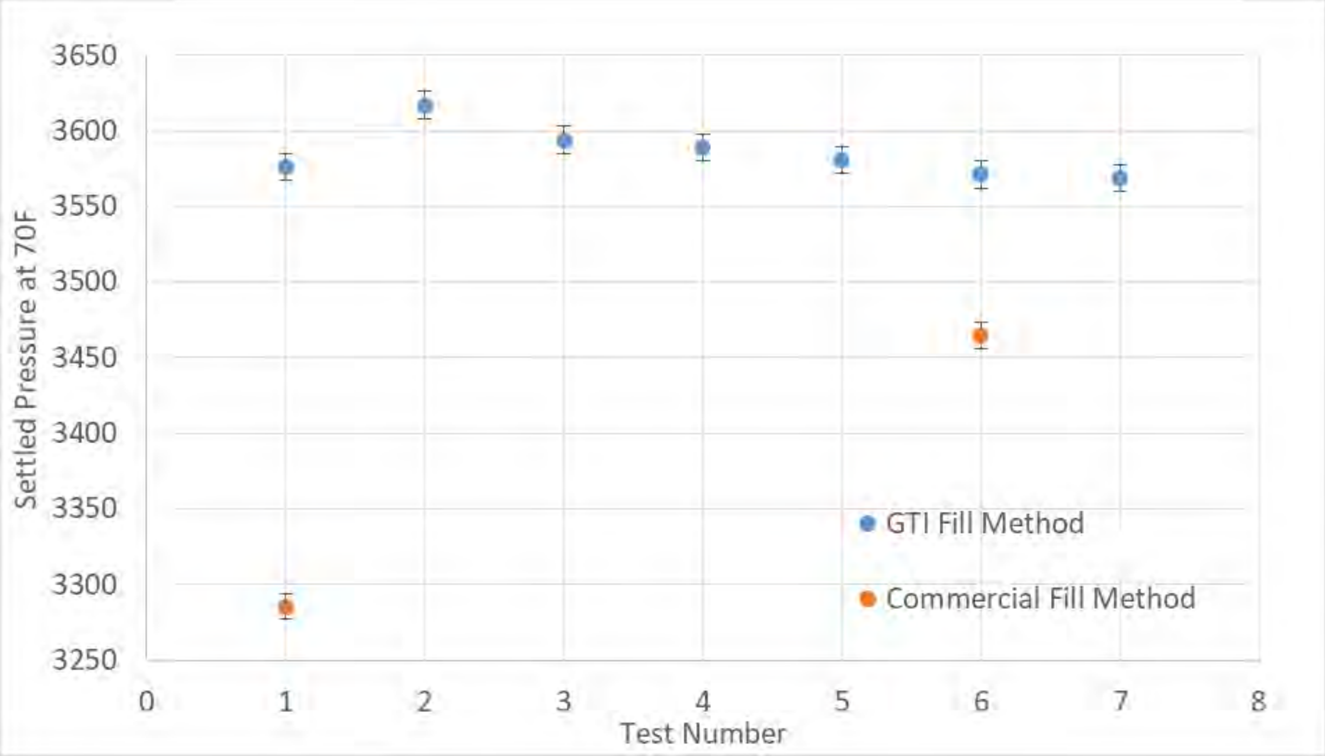
Algorithm with Communications Physical Testing

- GTI worked with ANGI and Agility to test and validate CNG fueling
- Compared performance of current fills and advanced algorithms
- GTI validated simulation
- GTI tested communications and improved filling algorithm performance using variety of CNG cylinders





Algorithm with Communications Physical Testing

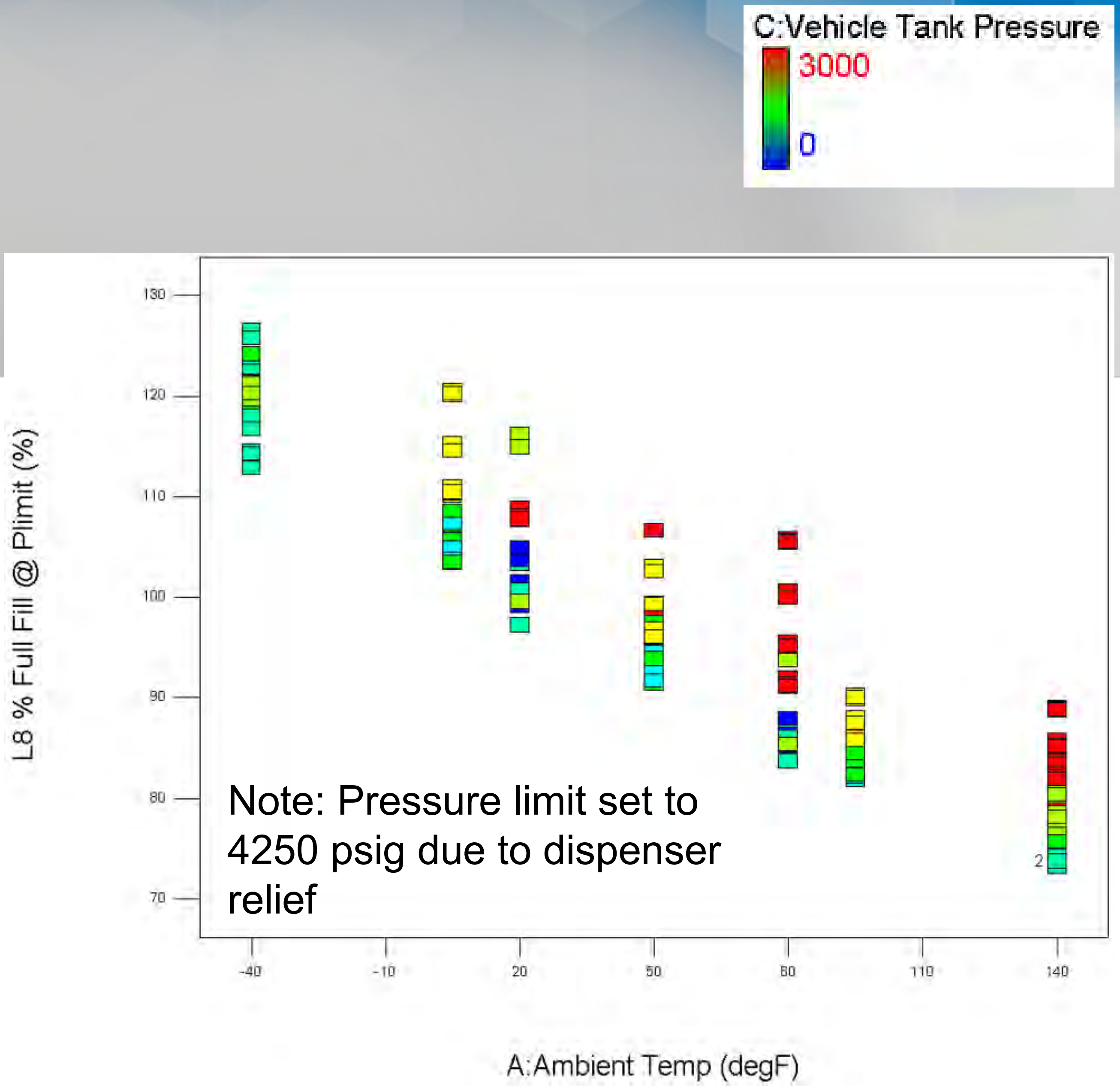


GTI Dispenser Full Fill Testing

	Initial Conditions				Settled Conditions					End of Fill			% Full		
	Tamb	TE 1	TE 2	P	Tamb	TE 1	TE 2	P	GGE Disp	TE 1	TE 2	P	Rated D	Settled D	% Full
5	62	78.6	80.3	423	55.5	64.3	63.7	2797	7.568	125.1	122.2	3510	13.015	10.969	84.3
5	56.5	56.3	56.1	1158	57	66.6	68.6	2913	5.281	108.1	205.3	3520	13.015	11.221	86.2
5	50.9	62.3	63.4	2210	79.6	85.3	83.8	3434.4	2.429	101	103.8	3740	13.015	12.04	92.5
5	67.5	69.7	69.8	180.3	62.7	68	67.2	2955.5	8.176	124	121	3750	13.015	11.338	87.1
5	64.9	63.8	63.2	2133	68	68.9	69.8	3051	2.31	101	98.7	3530	13.015	11.547	88.7

Precooling
Heat of Compression

- Design of Experiment also used to evaluate when it is possible to get a full fill, regardless of algorithm
- Above 20F, a full fill starts to become impossible under certain situations
- Above 50F, it is essentially impossible using current CNG station technology
- Station design and tank type will impact these results slightly

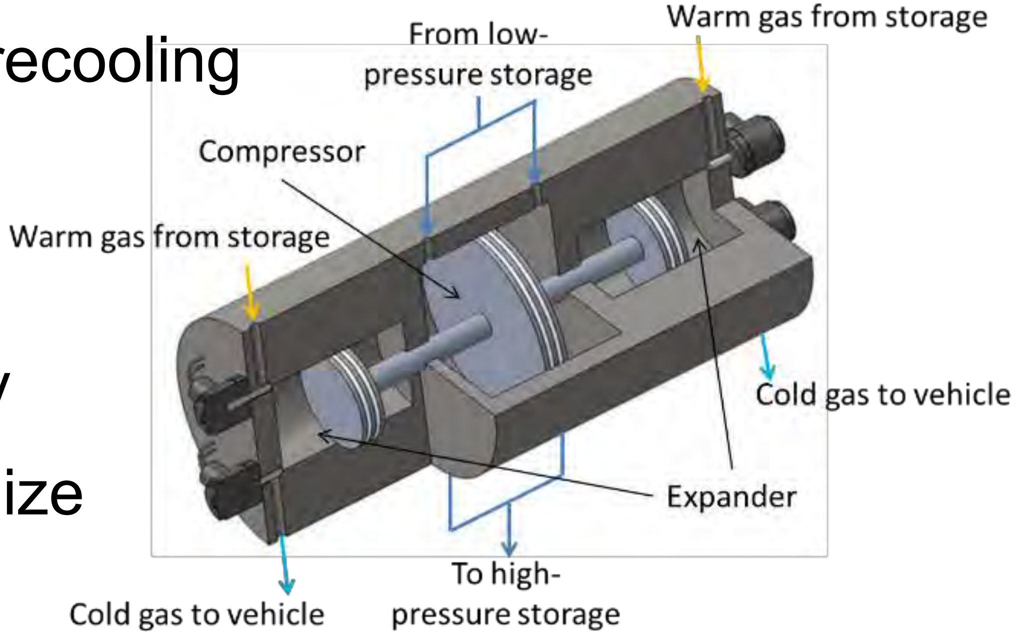


Summary of Past Work

- A dynamic filling simulation was developed in Matlab Simulink
- The current state of the art fueling method was compared to communication filling algorithms
- Design of Experiment was used to evaluate system properties and fill performance
- Limited physical testing was performed to validate model and algorithm
- Gas conditioning techniques are currently being investigated to improve full fills

Next Steps

- Continue development and testing of communications and algorithm
- Perform more testing at "commercial" locations
  - Deploy advanced fueling stations at controlled locations including algorithm, communications, and precooling
- Discussions on Communication Standards
  - Initial efforts have begun with CSA
- Continue development of precooling technology
  - Expander technology testing at GTI to optimize efficiency and cost



Other considerations

- Develop standard for CNG communication
  - Commit to communication method
  - Ensure safe, secure and accurate data transmission
- Develop standard for dispenser algorithm
  - With and without communication
  - Makes dispenser certification easier
  - Moves risk away from manufacturers
  - Improves safety

Thank you!!!

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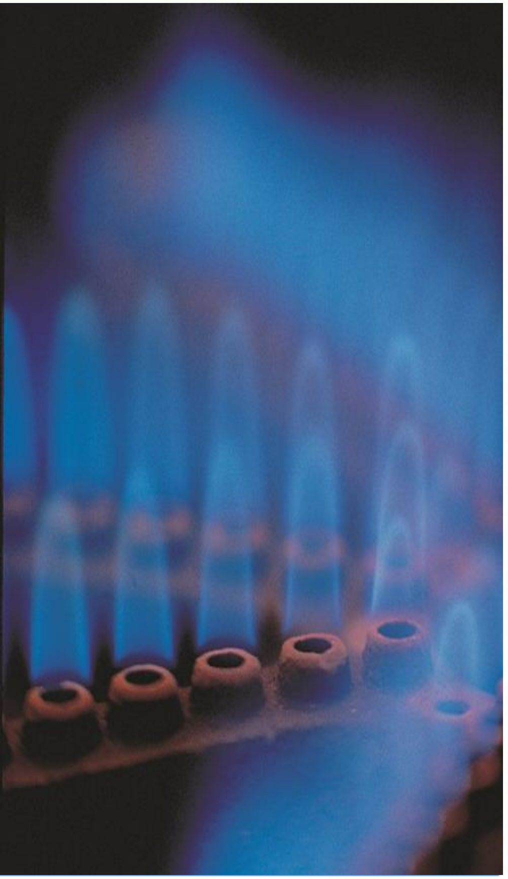
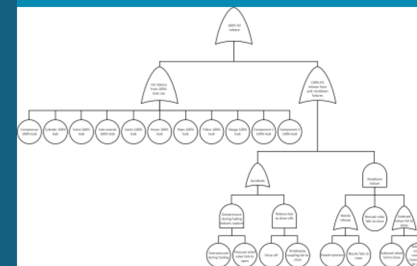
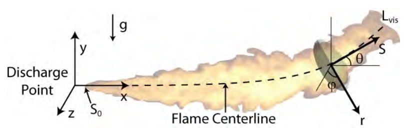


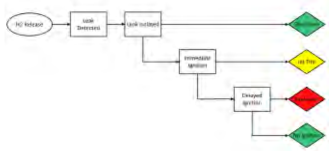


gti®

Overview and Development of Alternative Fuels Risk Assessment Models (AltRAM)







HyRAM HYDROGEN RISK ASSESSMENT MODELS

PRESENTED BY

Brian Ehrhart

Project Team: Myra Blaylock, Alice Muna

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SAND2019-3945 C

Introduction to Risk Assessment

Risk takes both **likelihood** and **consequence** into account

Likelihood measures how often or how probable an event is

- Frequency (events per year)
- Probability

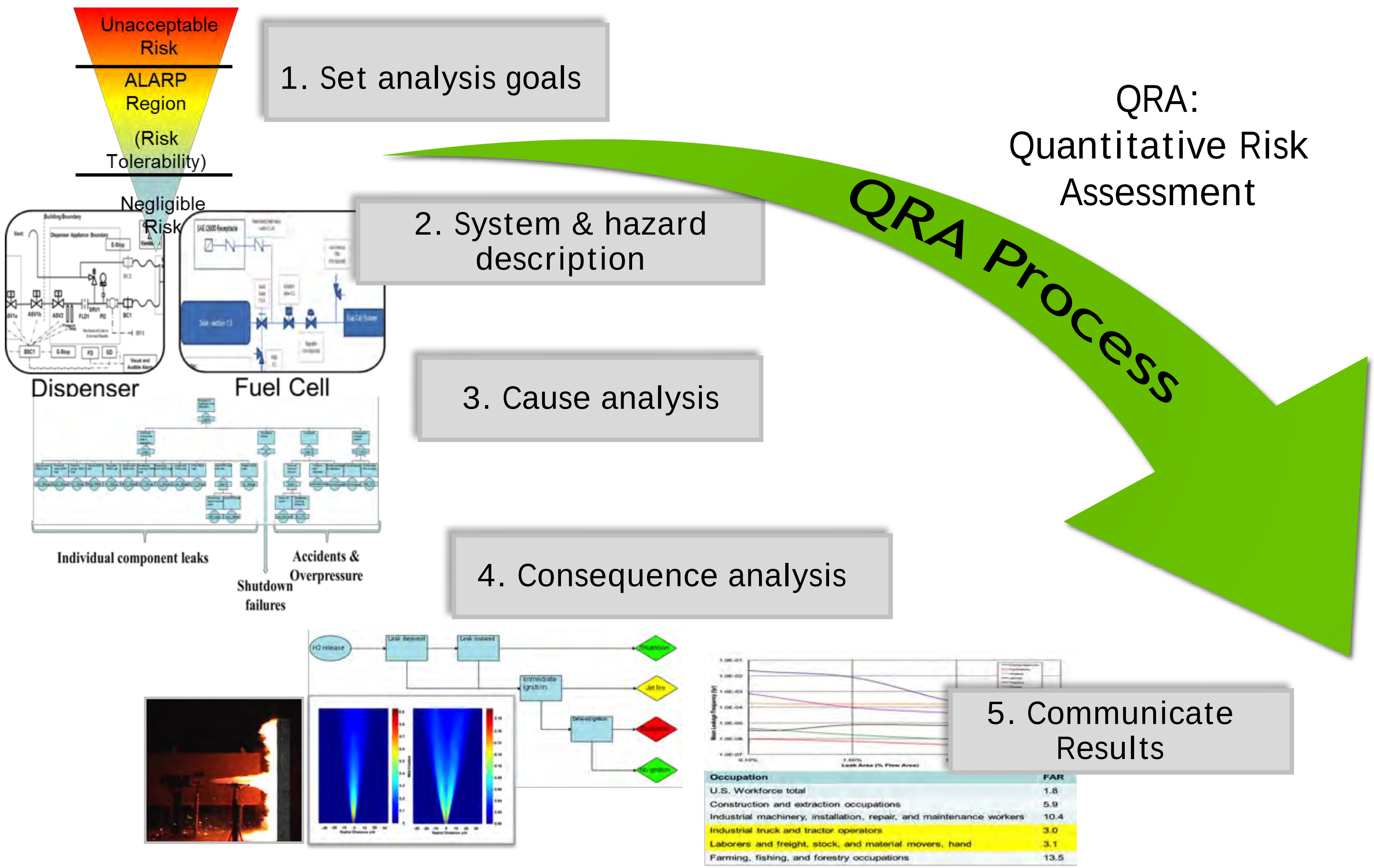
Consequence measures the effects of some event occurring

- Heat flux or overpressure
- Fatalities/injuries
- Economic losses

So the event with the highest risk may not be the most or least likely, and it may not be the worst or best case outcome

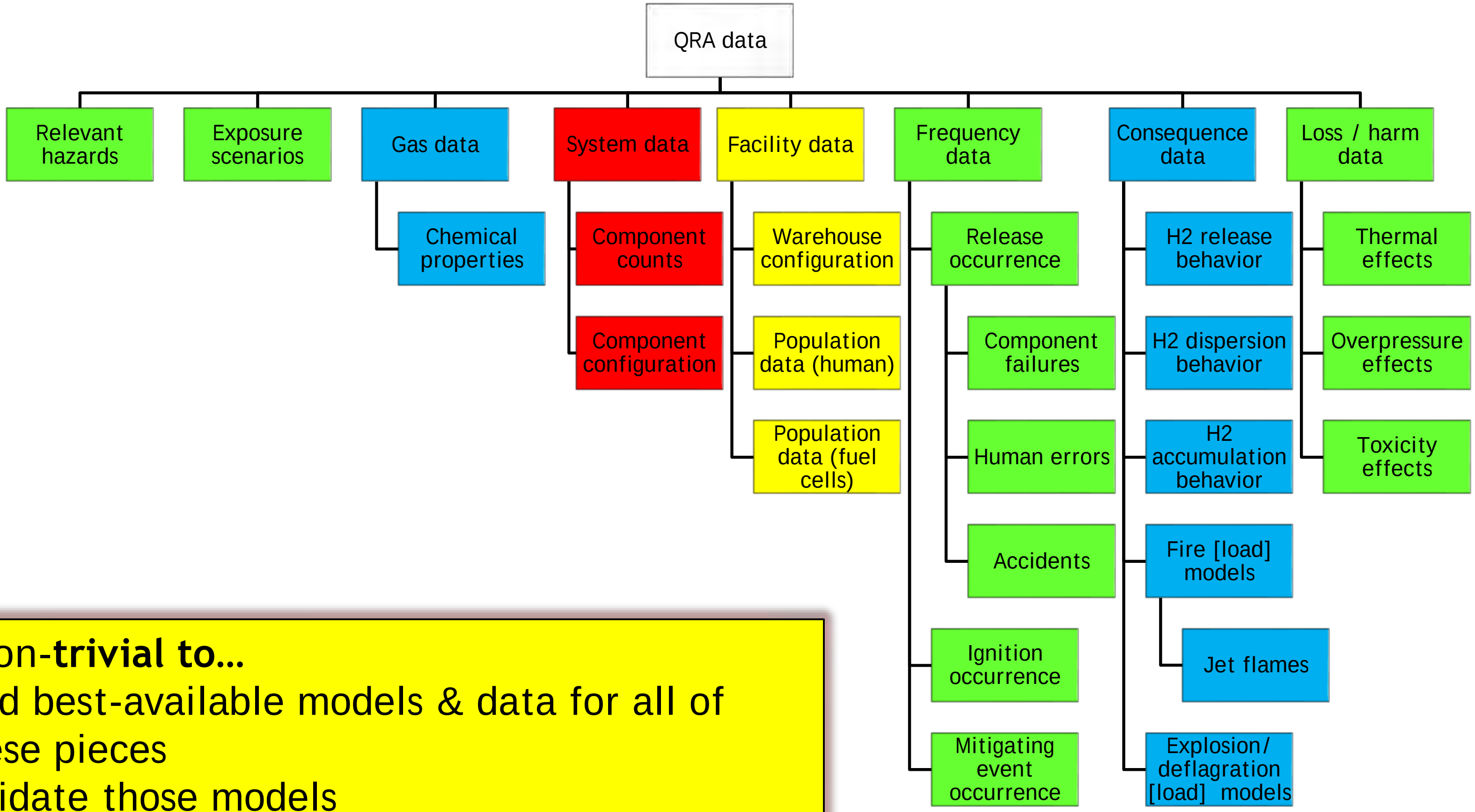
- Instead, some combination of the two

Building a Scientific Platform for Alternative Fuels QRA



Occupation	FAR
U.S. Workforce total	1.8
Construction and extraction occupations	5.9
Industrial machinery, installation, repair, and maintenance workers	10.4
Industrial truck and tractor operators	3.0
Laborers and freight, stock, and material movers, hand	3.1
Farming, fishing, and forestry occupations	13.5

Challenge: A quality QRA incorporates a large body of information from different areas



It is non-**trivial to…**

- Find best-available models & data for all of these pieces
- Validate those models
- And combine those all into a single framework

HyRAM: Making hydrogen safety science accessible through integrated tools

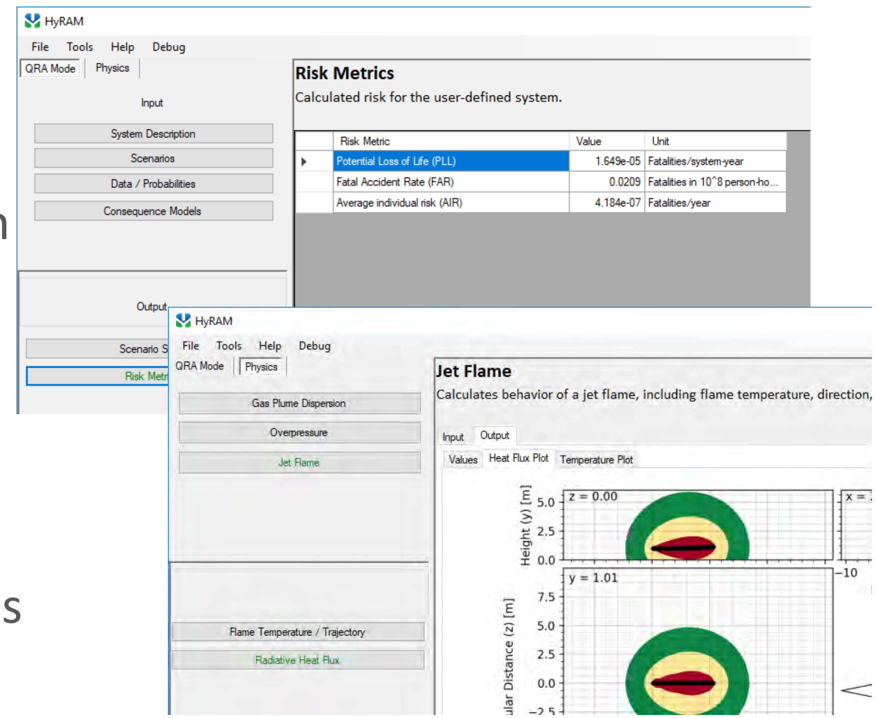
First-of-its-kind integration platform for state-of-the-art hydrogen safety models & data - **built to put the R&D into the hands of industry safety experts**

Core functionality:

- Quantitative risk assessment (QRA) methodology
- Frequency & probability data for hydrogen component failures
- Fast-running models of hydrogen gas and flame behaviors

Key features:

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



Major Elements of HyRAM Software: Physics Mode

Physics models

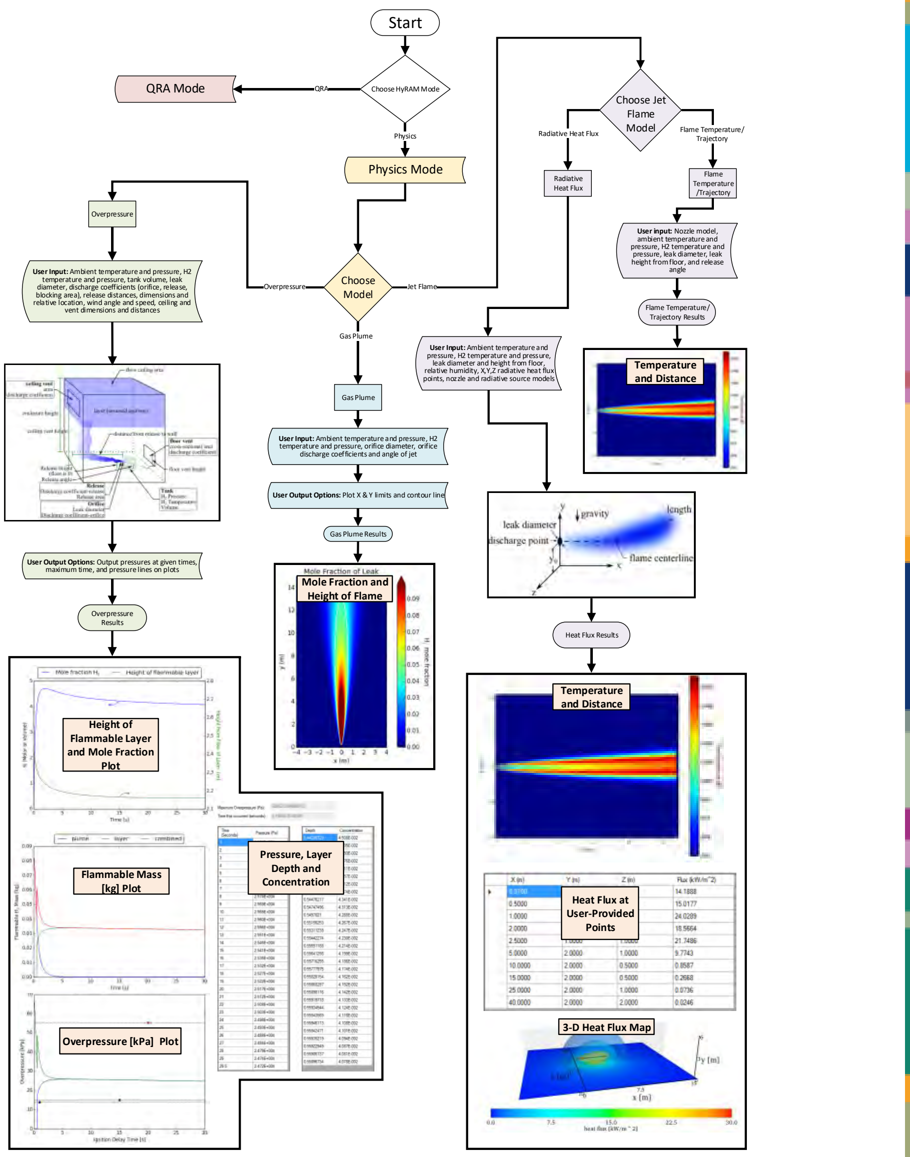
Properties of Hydrogen
Unignited releases: Orifice flow; Notional nozzles; Gas jet/plume; Accumulation in enclosures
Ignited releases: Jet flames; overpressures in enclosures

Software Language

Python for Modules
C# for GUI

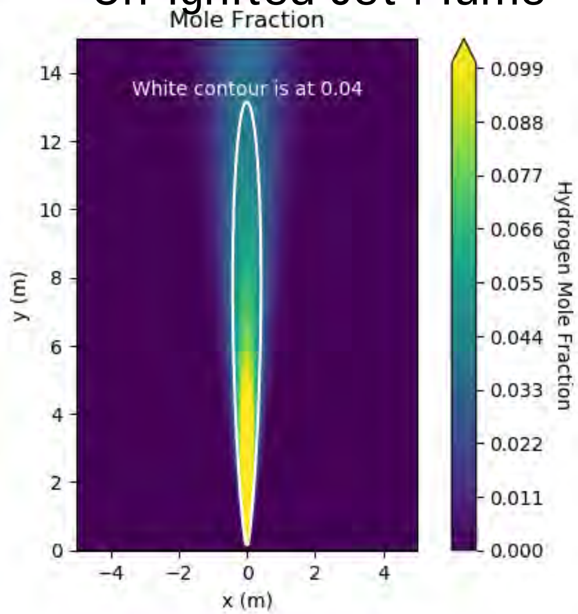
Documentation

Algorithm report (SAND2017-2998)
User guide (SAND2018-0749)

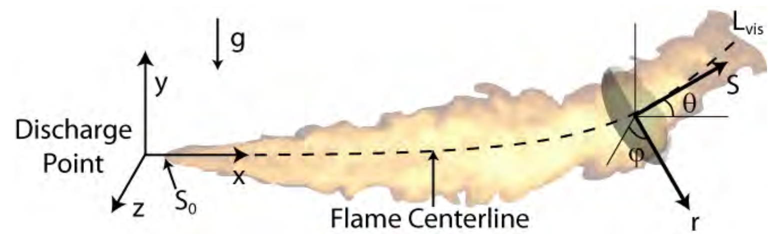


HyRAM Physics Models

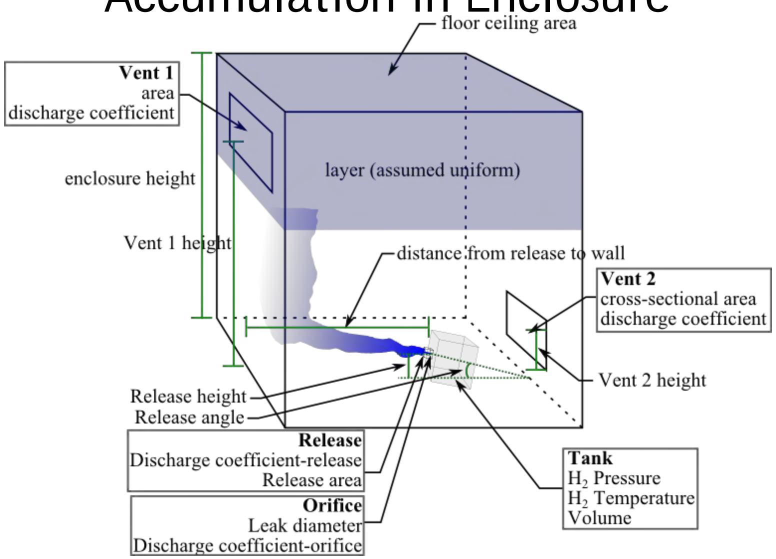
Un-ignited Jet Plume



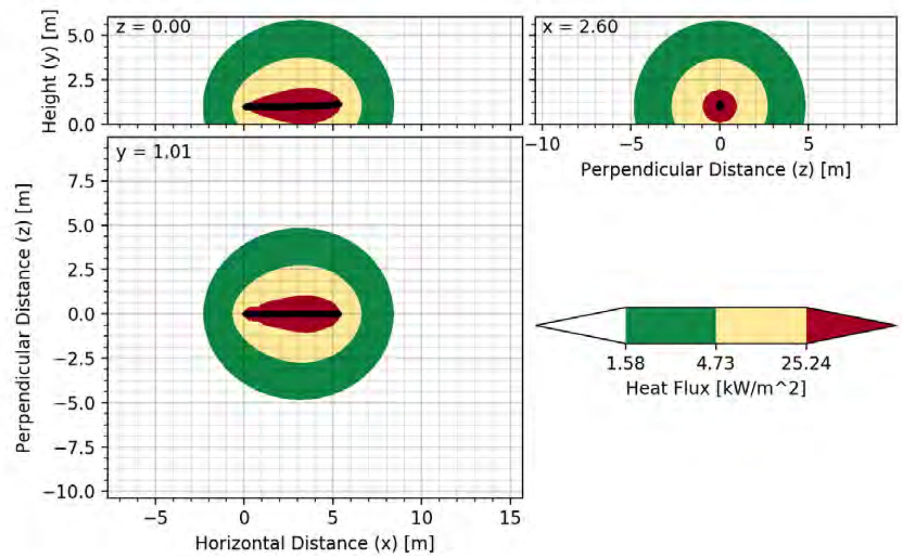
Jet Flame Temperature



Accumulation in Enclosure



Jet Flame Heat Flux



Benefits of Reduced-Order Models

Short run-time

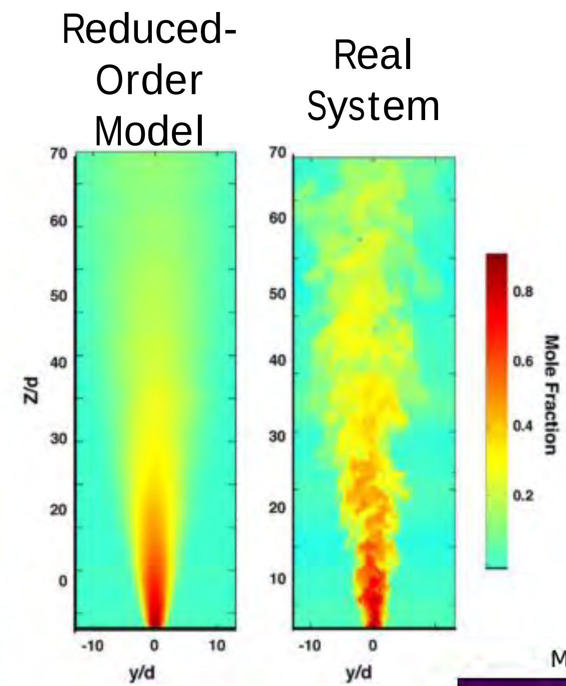
Modeling expert not required

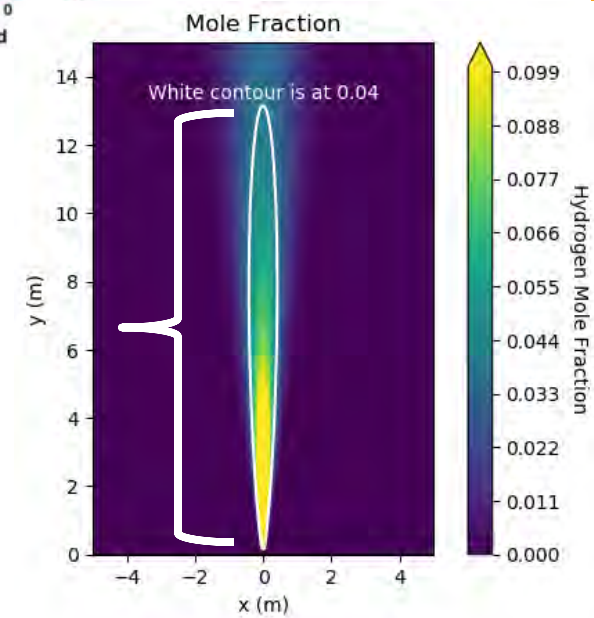
Useful for quantification

- If a hydrogen leak occurs, how far away does the hazard get?

Useful for comparisons

- What is the effect on safety is a system size is reduced?



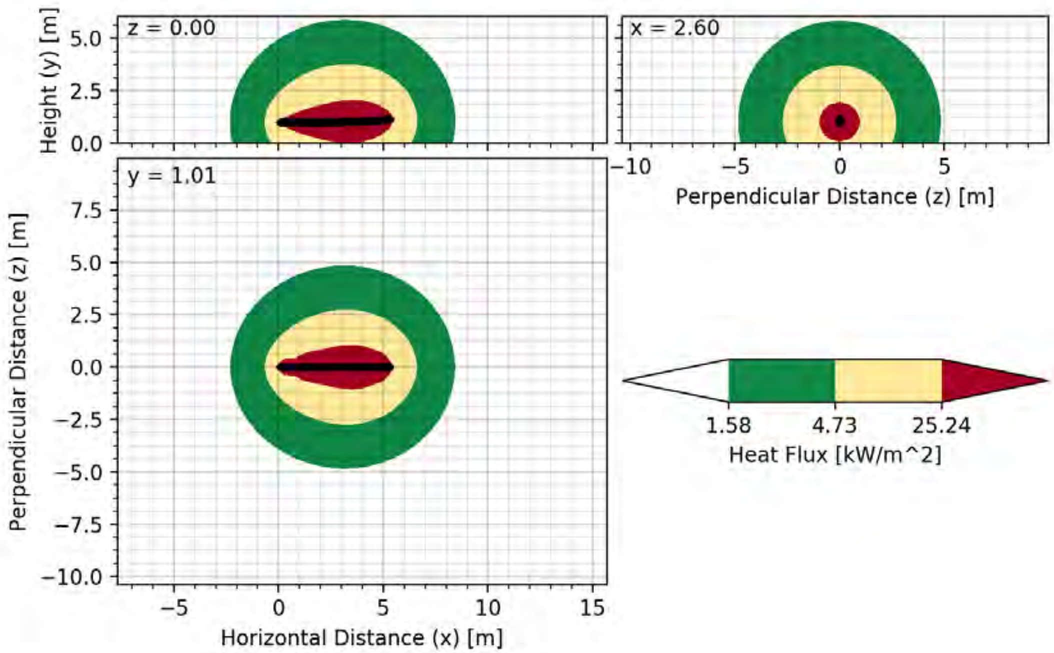


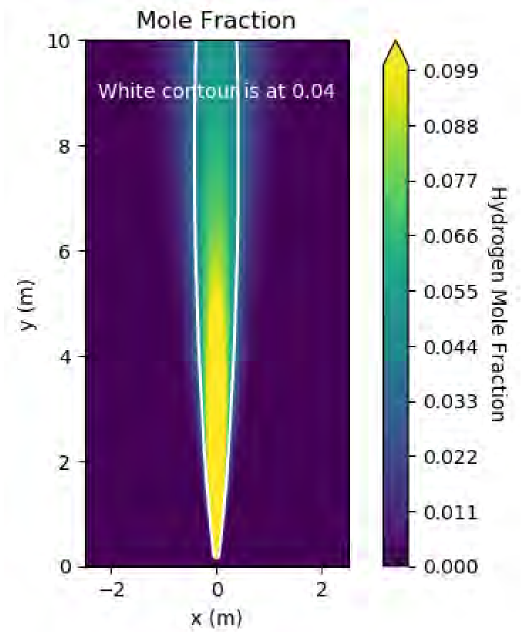
Example Physics Calculations

How far away is a safe distance from a jet flame?

How far away does a flammable concentration of gas reach?

What gets farther: a smaller leak from a high pressure system, or a larger leak from a lower pressure system?





Major Elements of HyRAM Software: QRA Mode

QRA Methodology

Risk metrics calculations: FAR, PLL, AIR

Scenario models & frequency

Release frequency

Harm models

Generic Freq. & Prob. data

Ignition probabilities

Component leak frequencies (9 types)

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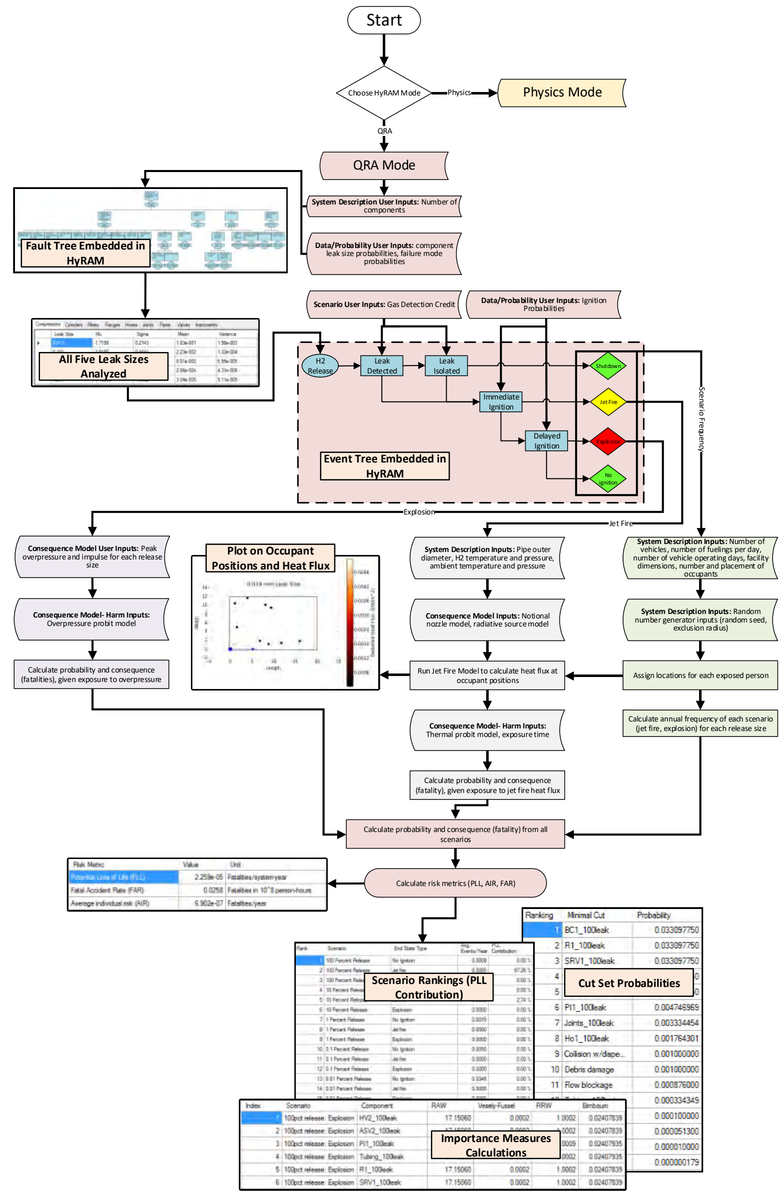
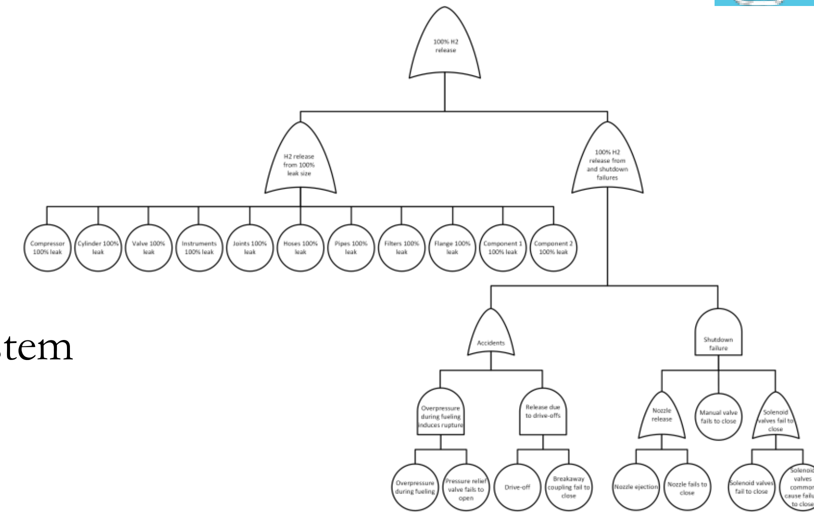


HyRAM QRA Analysis



Fault Trees

- Calculate frequency of different size leaks
- Considers random leaks from equipment in system
- Considers fueling dispenser leak

Event sequence diagram

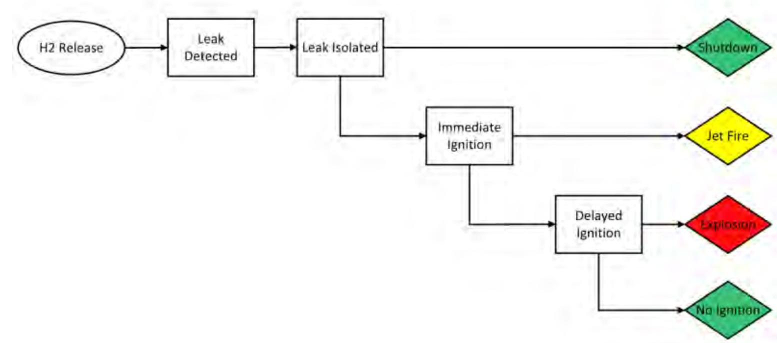
- Considers probability of outcome for each leak size
- Probability of ignition

Consequence

- For ignited releases, calculates harm (fatalities) for each ignited release

Overall Risk

- Combines all of the above to overall risk metric



Example QRA Calculation

What has a lower risk, a system with welded pipe or fittings?

What has a lower risk, fewer people closer to the system, or more people further away from the system?

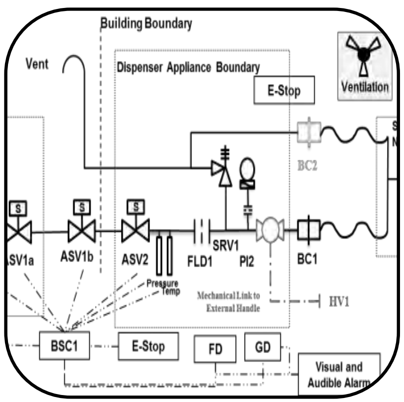
What system component is driving overall risk?

What is the setback distance away from the system to achieve overall risk below a threshold?

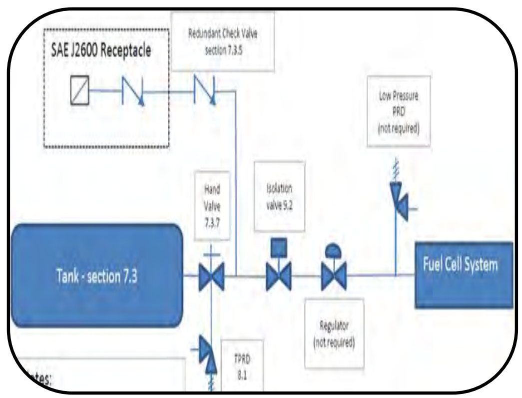
HyRAM QRA Basis

Focused on a gaseous hydrogen dispenser fueling forklifts located in a warehouse

Analysis can be altered for generic fueling stations, but applicability is limited beyond that scope

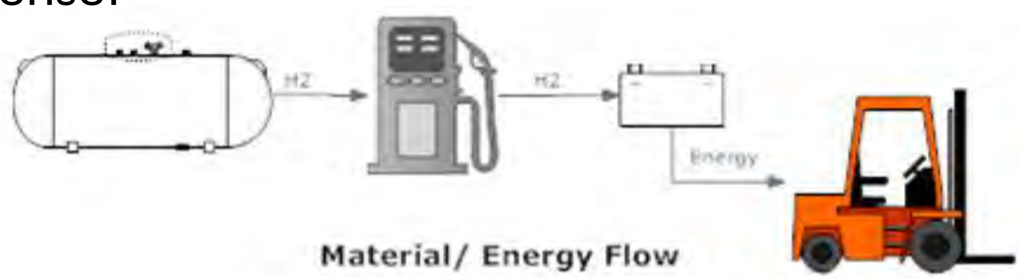


Dispenser



Fuel Cell

Vehicle

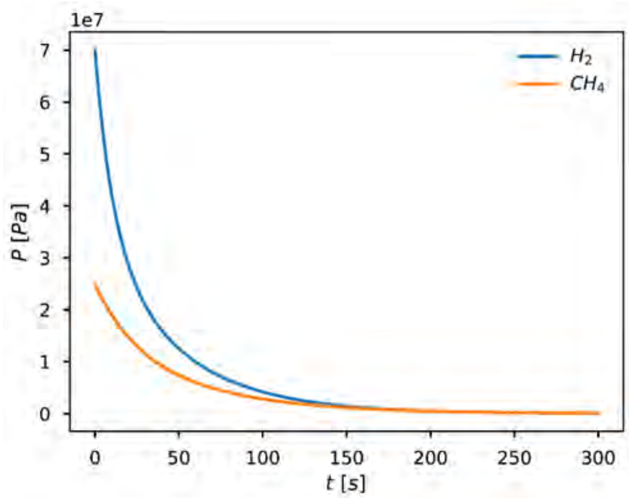


Incorporation of Alternative Fuels

Analysis **beyond hydrogen**

Customization of the components, failure modes and accidents, will allow for the risk analysis of alternative fuels (CNG, LNG, propane) ***with the addition of the appropriate physics/behavior models***

Component release frequencies, failure frequencies, accident frequencies, ignition probabilities and gas detection probabilities would all have to be calculated



Current Status of Alternative Fuels Risk Assessment Models (AltRAM)

Gas plume:

- Implemented in code, not yet validated
- Will be validated Summer 2019

Cold plume:

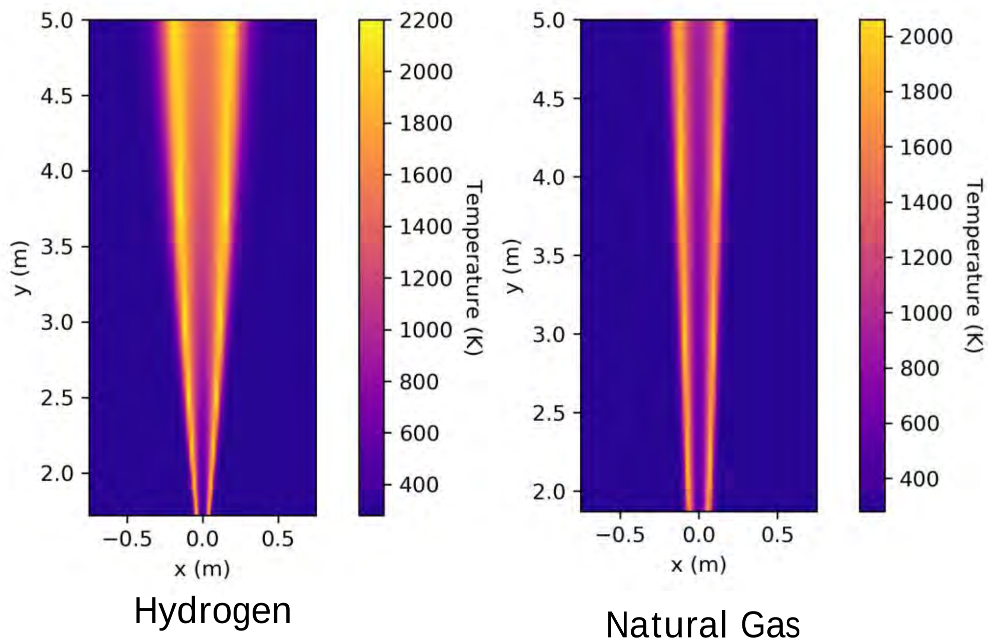
- Implemented and validated

Jet fire:

- Implemented in code, not yet validated
- Will be validated Summer 2019

All models still need to be implemented in GUI

Physics models need to be incorporated with QRA models



Selection of Base QRA Scenario

Can be extended beyond base scenario, but more difficult

Possible scenarios:

- Vehicle in repair garage
- Vehicle in parking structure
- Forklifts in warehouse
- Refueling station (indoor or outdoor)

Which scenario should be the focus first? We want to hear from you!

Brian Ehrhart bdehrha@sandia.gov

Example Necessary Information for Base Scenario

Depending on specified base scenario, need some specific information for QRA

Number of components

- Valves
- Dispensers
- Length of tubing
- Compressors
- Sensors
- Tanks/cylinders

Condition of natural gas in system

- Temperature
- Pressure

Pipe size

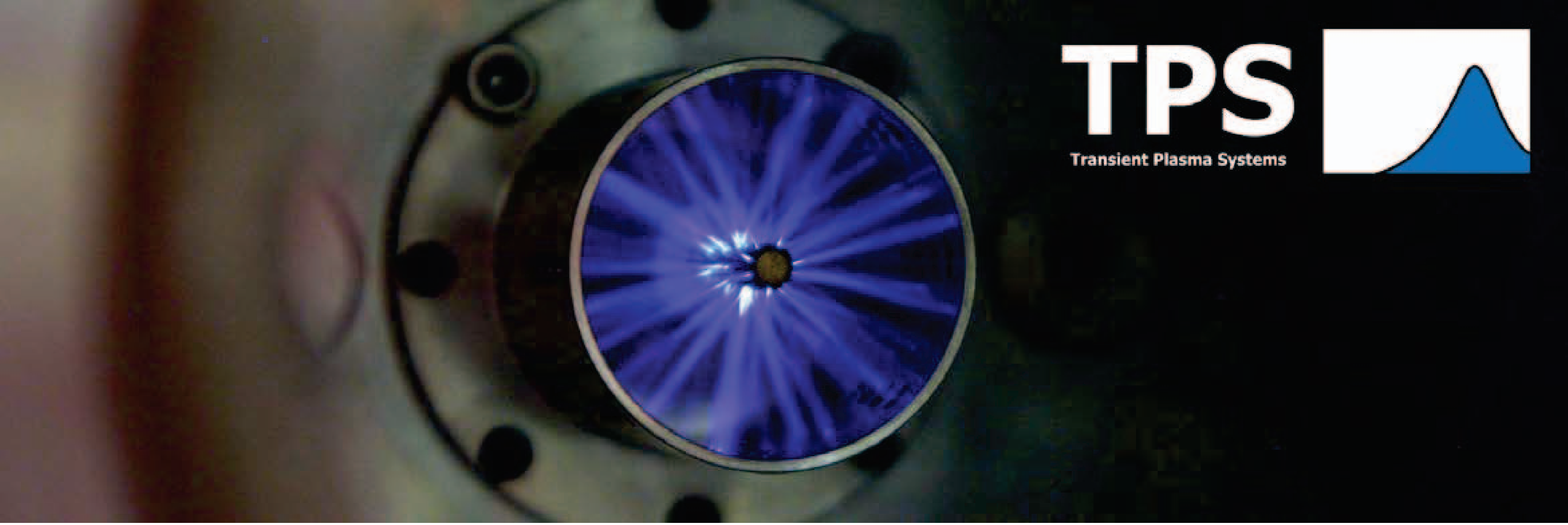
- Diameter
- Wall thickness

Will depend on specific base scenario selected

Thank you!

Questions? Feedback?

Brian Ehrhart bdehrha@sandia.gov



Transient Plasma Ignition System for Natural Gas Engines

CEC PIR-16-024

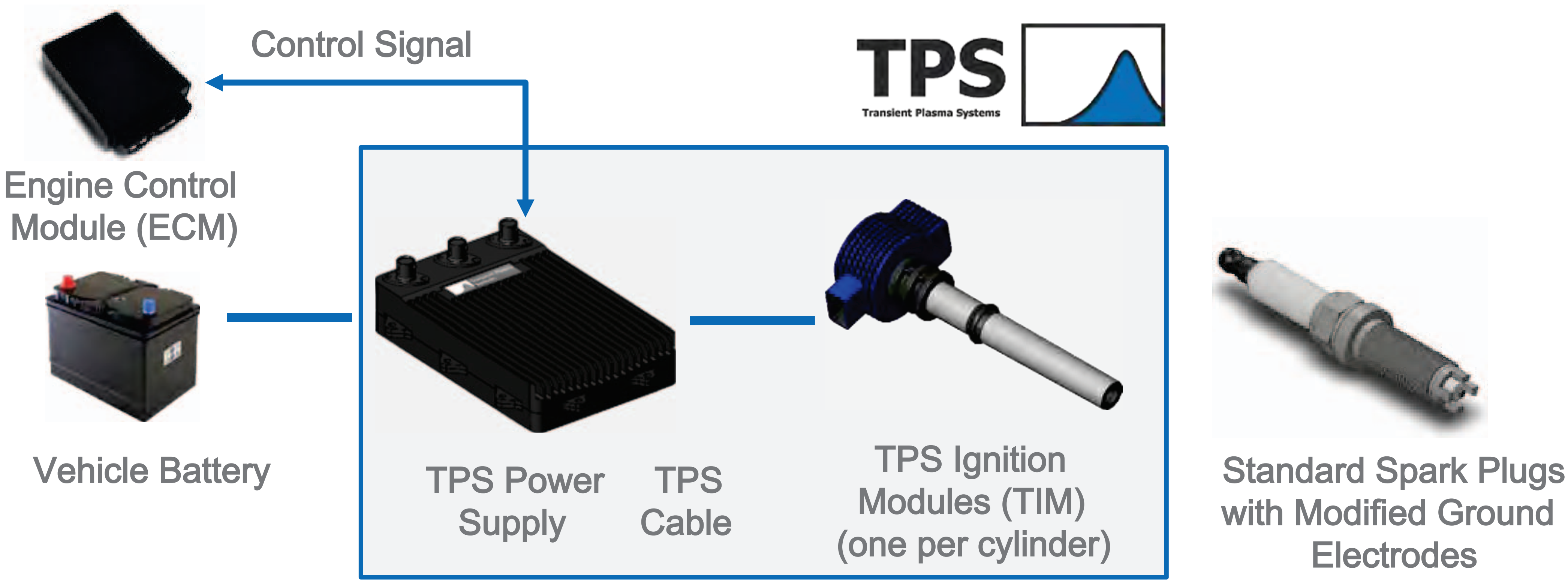
Natural Gas Vehicle Technology Forum
April 2019, Salisbury, NC

www.transientplasmasystems.com

TPS ignition approach is based on nanosecond pulses

- Fundamentally different physics from other plasma ignition systems
- TPS focused on OEM performance demonstrations from 2014-2019
- Completed $8.5M Series A funding Jan. 2019 for technology development

Production TPS ignition system concept (not current status):

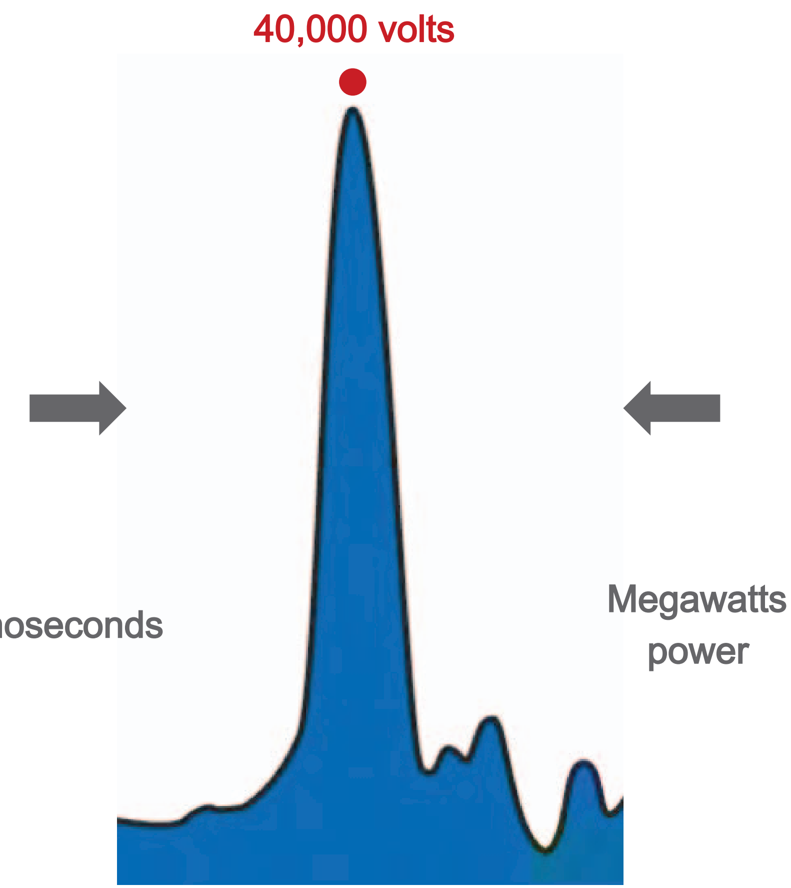


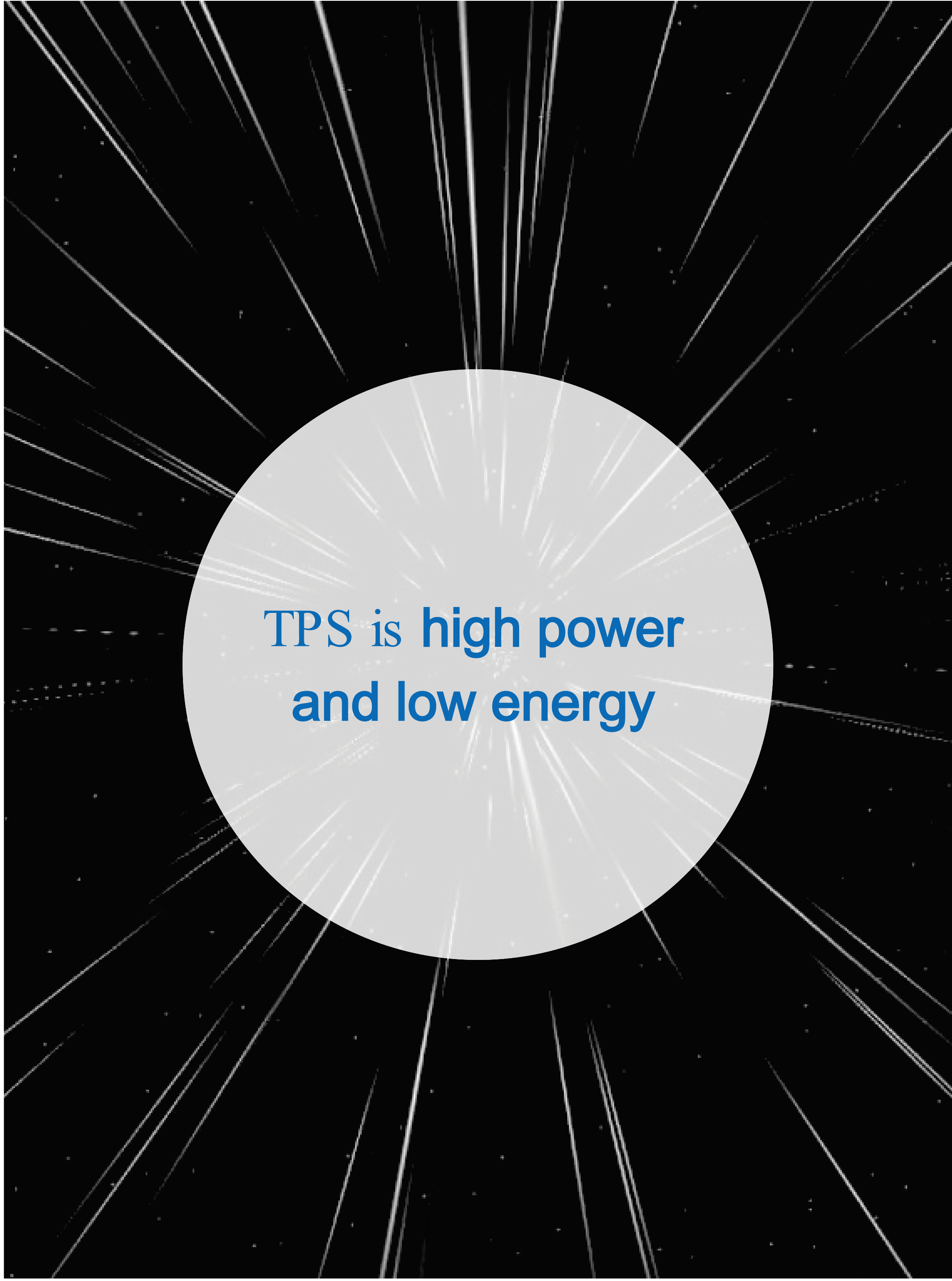
Demonstration of Natural Gas Ignition

TPS
Transient Plasma Systems

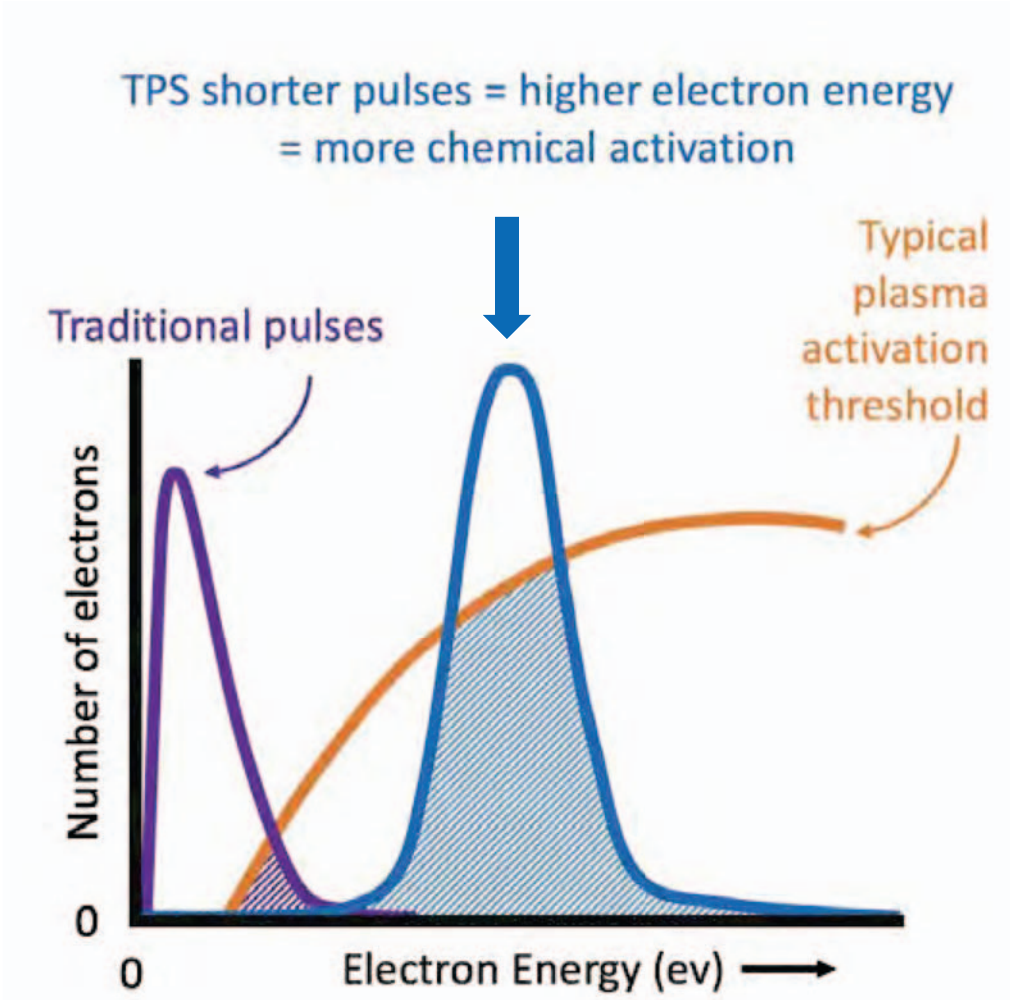
TPS is ultra-fast pulses;

4 million times faster than the blink of an eye

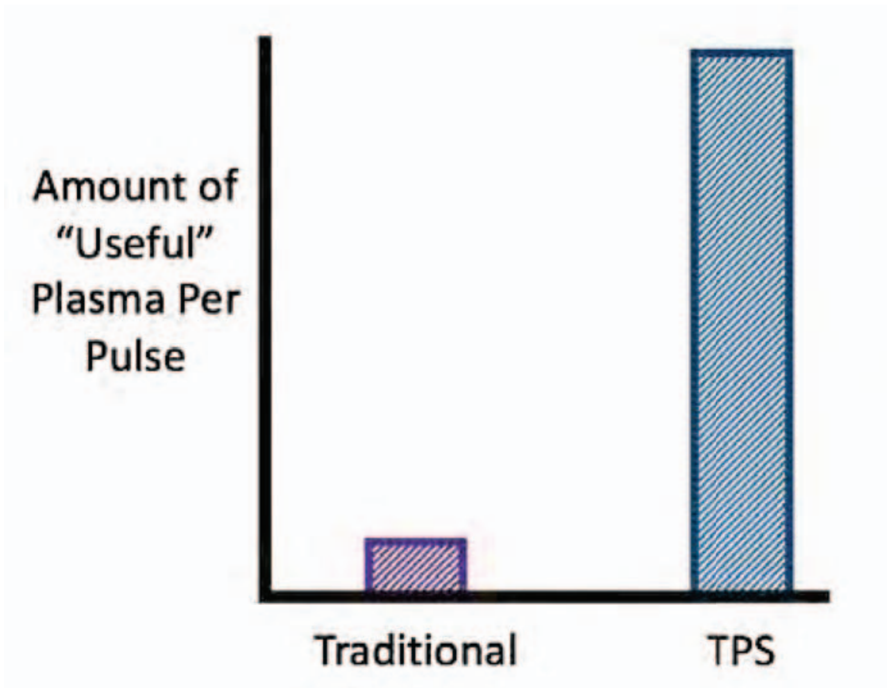




Short pulses make more effective plasma

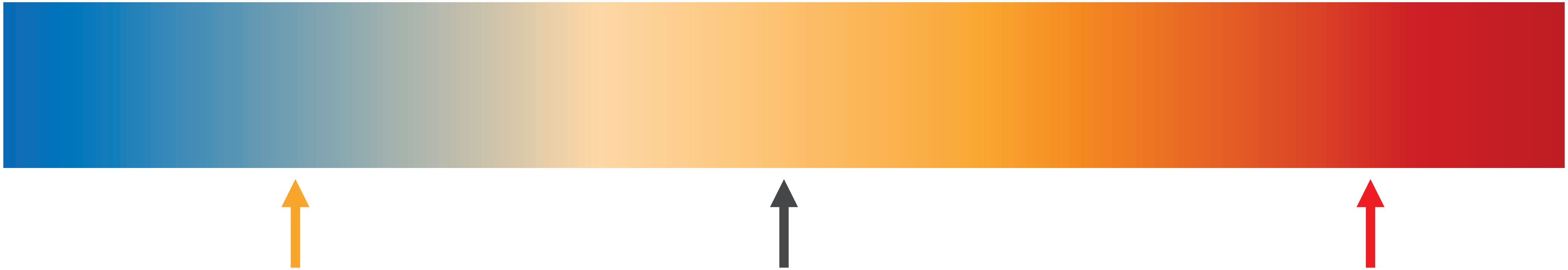


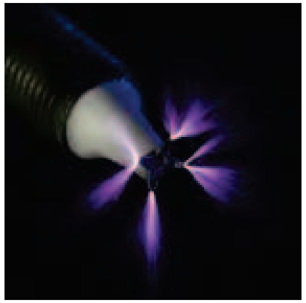
TPS uses nanosecond pulsed power to unlock previously inaccessible capabilities of plasma



Transient Plasma vs Other Plasmas

Gas Temp. During Ignition Discharge



Nanosecond Pulses (TPS)	RF Corona Discharges	High-Energy Spark, Microwave Plasmas, Plasma Jet
		

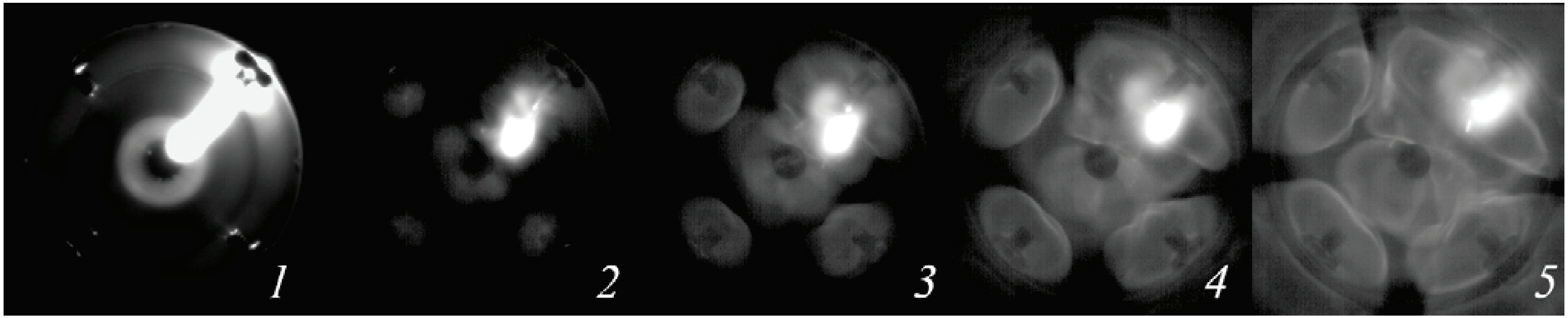
Combustion enhancement due to two features

Enhanced Chemistry

- Electrons collide with the gas producing chemically reactive species which catalyze the combustion process, enhancing ignition and stabilizing lean burn combustion

Volumetric Impact

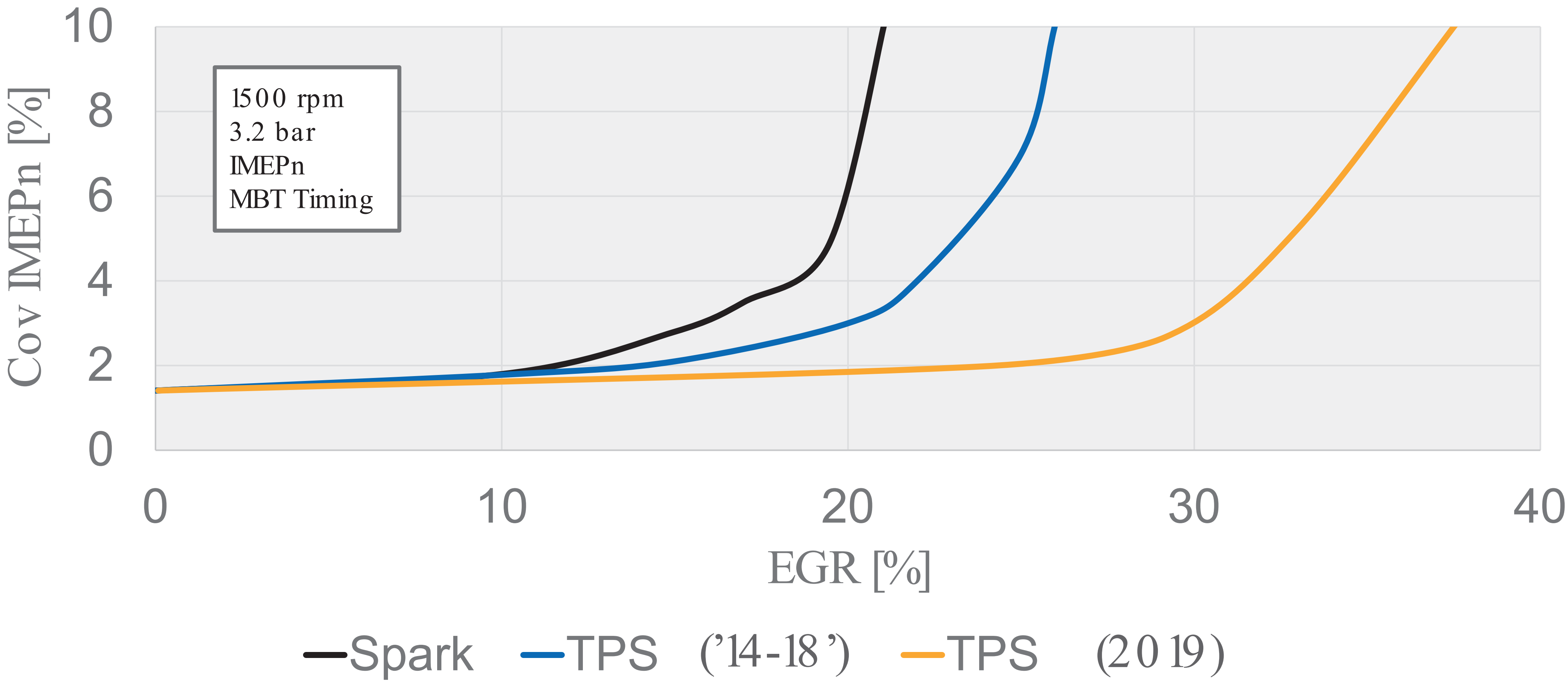
- Spatial distribution of plasma enables a single transient plasma discharge to impact a large volume and develop multiple flame kernels



- Regardless of discharge mode (a spark can be seen in figure 1 that occurs AFTER the transient plasma discharge), the benefits of transient plasma ignition are achieved through the fast-rising pulse

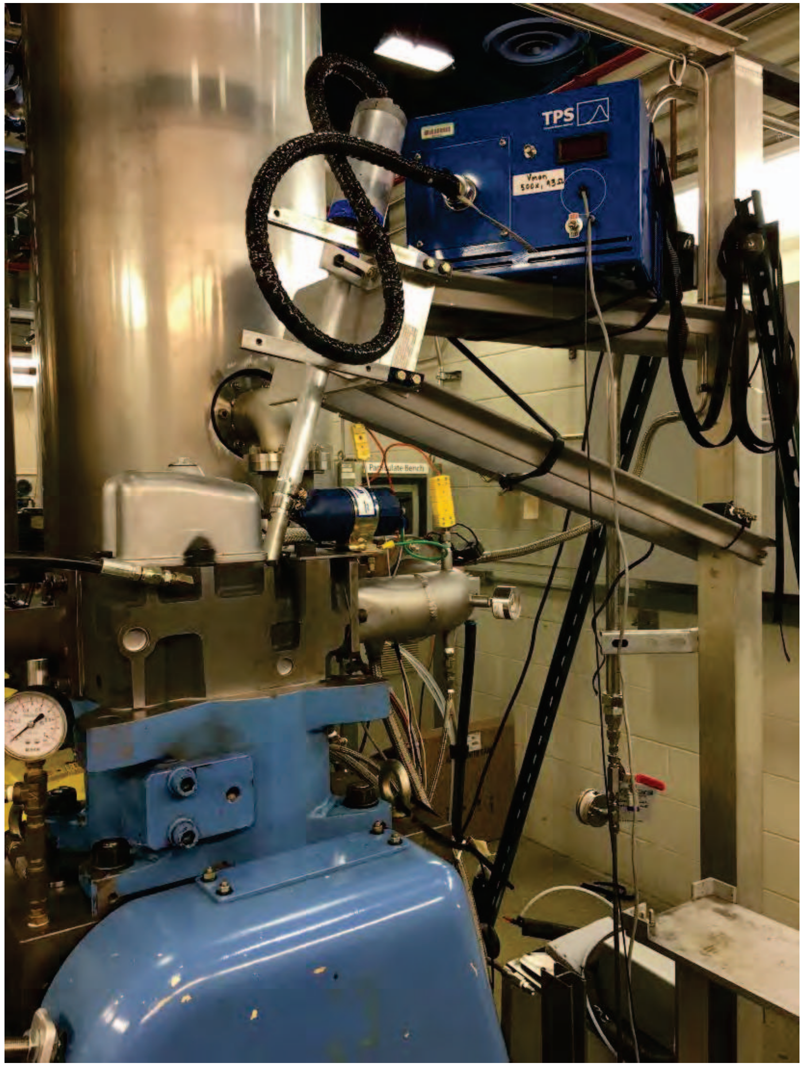
Dilution Extension in an Engine

Ford Single-Cylinder Engine @ANL
Test: Dilution with EGR
Results: **More than 35% dilution** with EGR
Demonstrated significant gains with newest 2019 TPS system

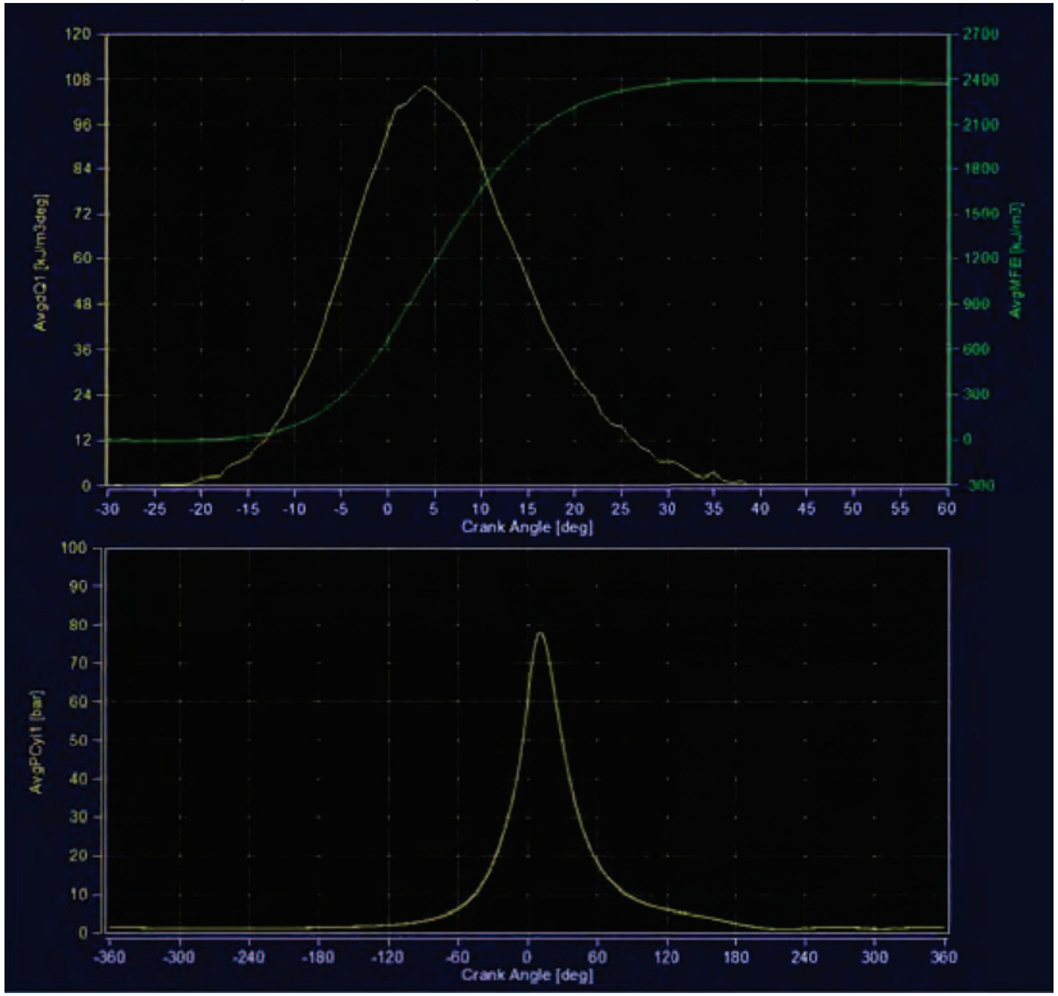


Lean Stability in a Natural Gas Engine Testing

Speed	BMEP	EQR	FCE/BTE	CO_2	O_2	THC	NOx	CO	CoV IMEP	TPS Settings			
RPM	bar	ϕ	%	%	%	g/kW-hr	g/kW-hr	g/kW-hr	%	Volts	% Energy	#Pulses	Gap (mm)
1200	9.79	0.56	37.03	6.22	10.27	10.05	4.43	2.43	2.96	15KV	51	20	0.5 mm



1200RPM;EQR0.56; IT:31BTDC



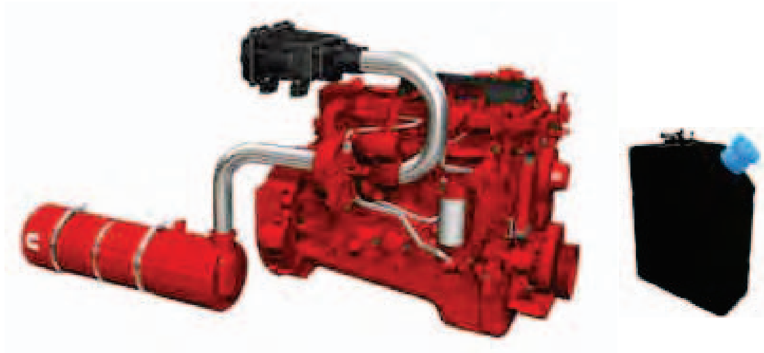
Immediate Market: Natural Gas

- The ignition temperature of natural gas is much higher than diesel (580°C versus 210°C), making it difficult to achieve stable combustion

- There are currently two main alternatives

1) Dual-fuel

- Burst of diesel fuel increases the temperature so that natural gas will ignite
- Requires expensive exhaust gas after-treatment and frequent fluid replacement



2) High-energy ignition source

- Requires 10x the spark energy to ignite the natural gas, causing the spark plugs to erode quickly thereby increasing expensive maintenance cycles
- Requires reduced engine pressure for ignition, decreasing fuel efficiency, power, and range

Status of Ignition System Development

Dilution extension	Complete
High-load/pressure	Complete
High-RPM	Complete
Multi-cylinder system	In Progress
Extended spark plug lifetime	In Progress
Production ready (size/cost)	In Progress

Non-Confidential TPS Active Ignition Projects

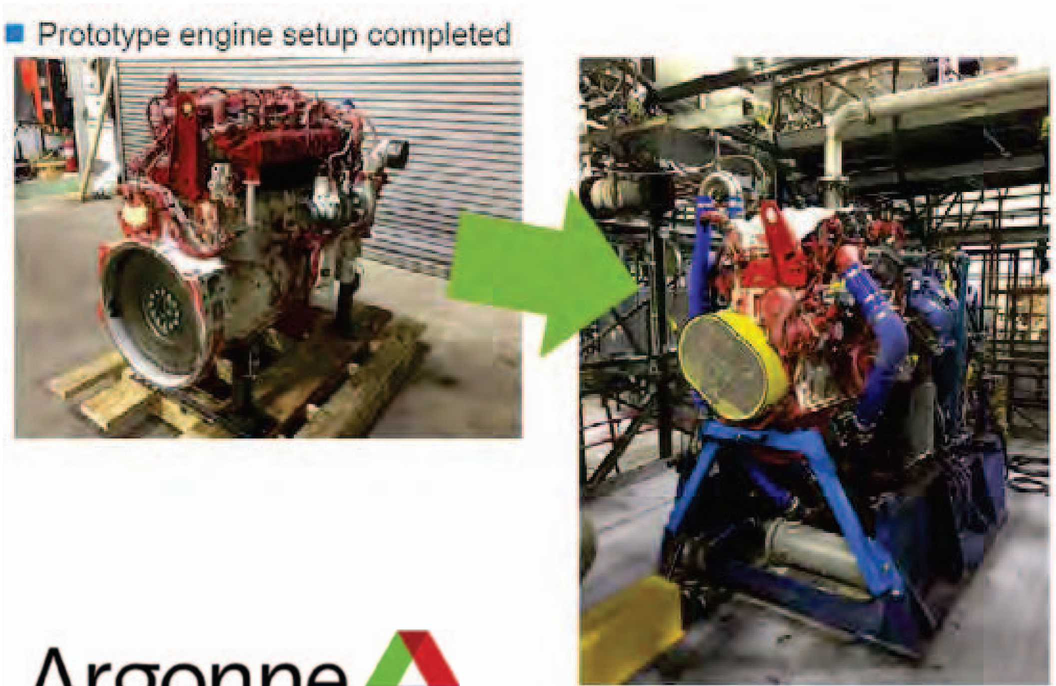
TPS Transient Plasma Systems

Funding	Primary Goal	Partners
KV	Venture capital: commercialization	TPS
State of California Energy Commission; SoCalGas, Sempra Energy utility	Lab grade multi-cylinder system	Cummins; Westport; Argonne National Laboratory
U.S. Department of Energy	Spark breakdown avoidance	Argonne National Laboratory
NREL National Renewable Energy Laboratory	Multi-cylinder miniaturization (just awarded)	Argonne National Laboratory

CEC Engine Test on Cummins Westport Engine

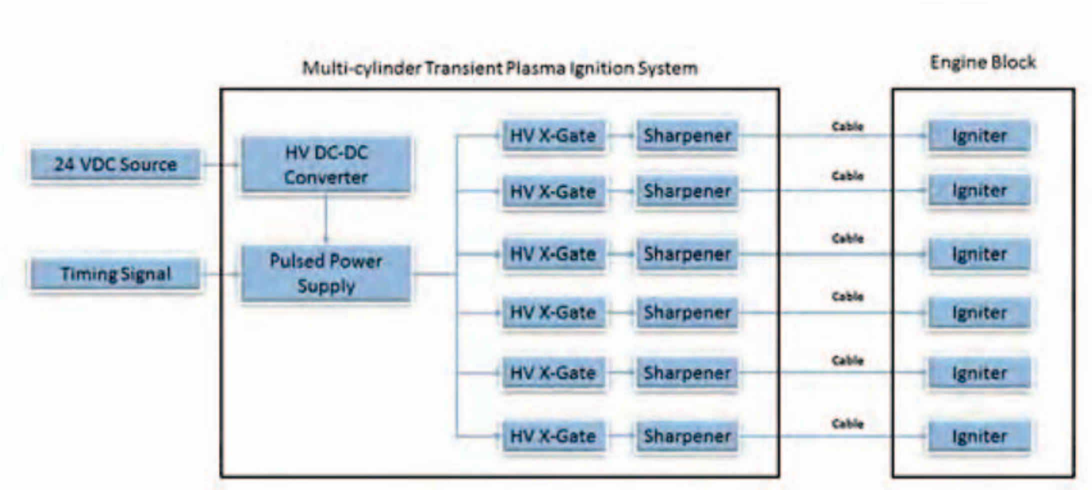
- Cummins Westport ISX12 N natural gas engine is a larger-displacement natural gas engine suitable for a variety of heavy-duty vehicles, including regional-haul truck/tractor, vocational, and refuse applications

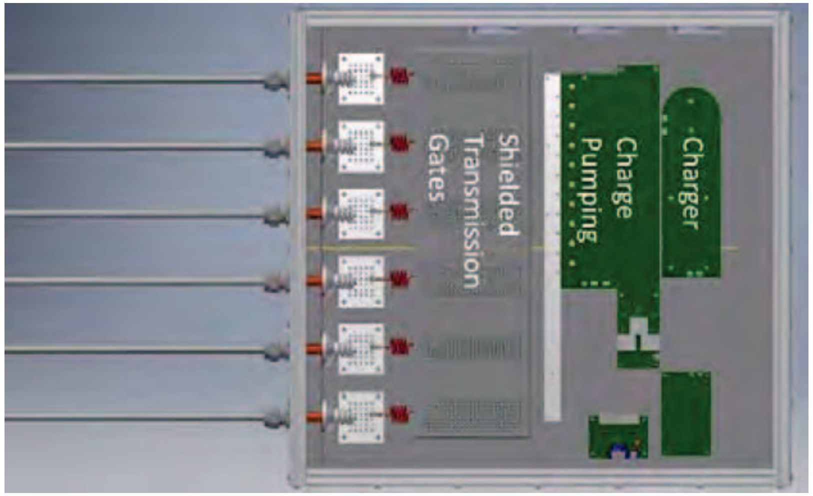
- TPS will perform a multi-cylinder engine test on this engine at Argonne National Labs



Milestone	Deliverable	Estimated Date of Completion
Task 5 Engine Testing & Performance Validation at ANL	Engine Test Stand Operational	11/1/2018
Task 5 Engine Testing & Performance Validation at ANL	Baseline Data	12/1/2018
Task 5 Engine Testing & Performance Validation at ANL	TPS System Data	04/30/2019
Project Close-out Review @ SoCalGas	Successful Project Close-Out Review	06/1/2019

Status of Engine Test Preparation





Approach: Solid-state transmission gating switches have been developed to gate each channel to provide cylinder-cylinder isolation and pulse steering.

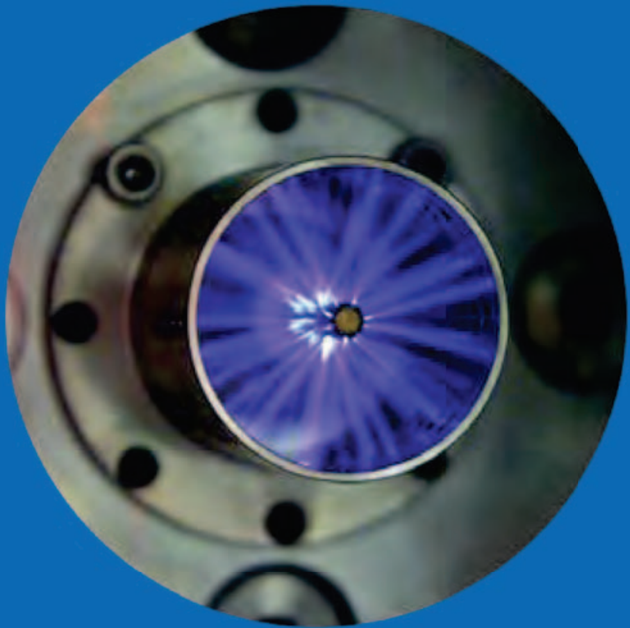
Prototype system is currently undergoing bench-top testing. Two cylinder channel operation has been tested. Full six cylinder validation will take place in April

- Engine testing at ANL in April 2019

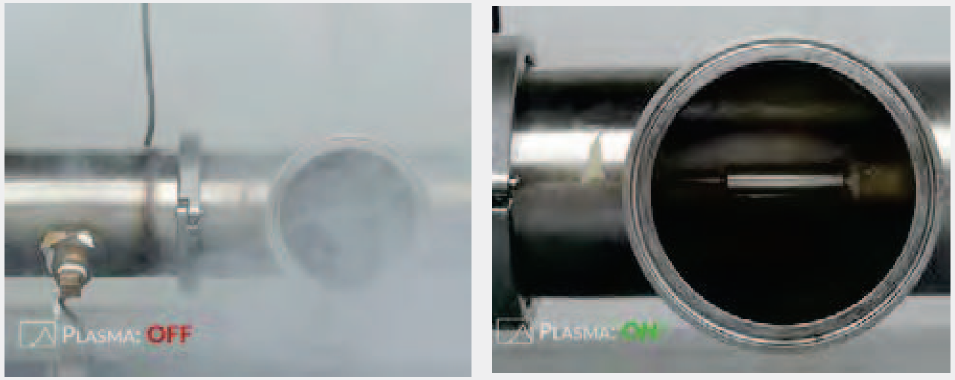
Another Application: Emissions Aftertreatment

Emissions Reduction Application

> 80% reduction in regulated emissions possible with <5% engine power

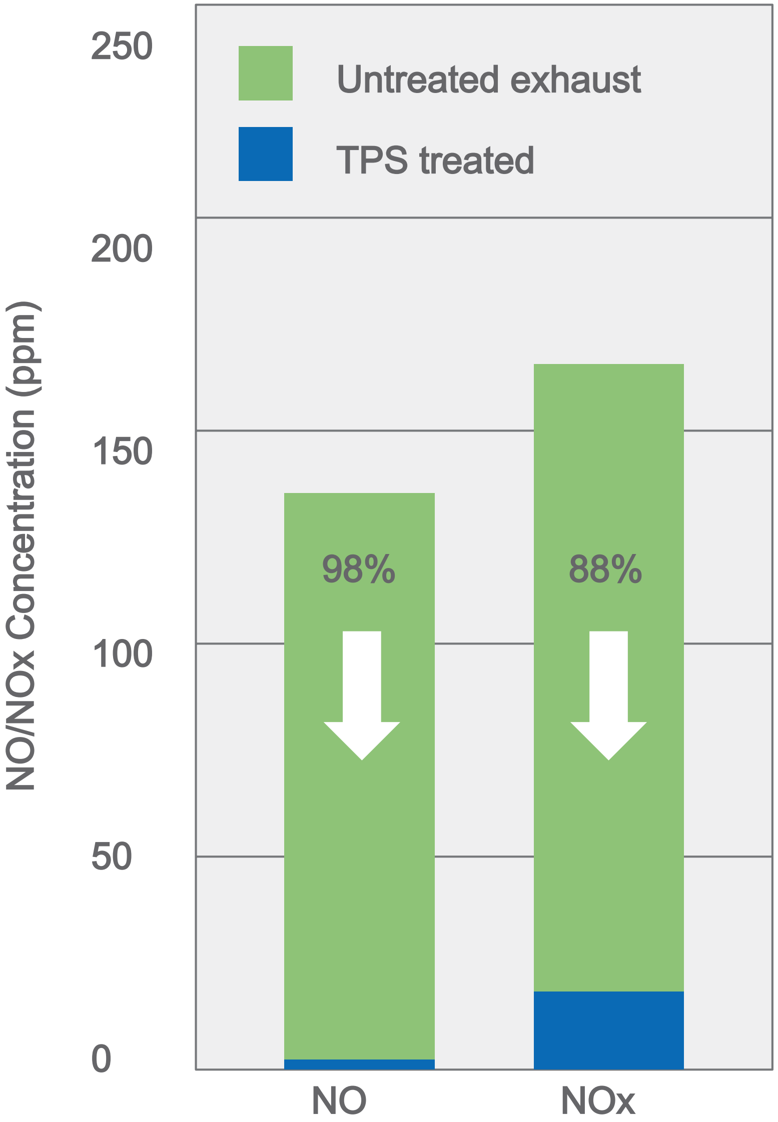


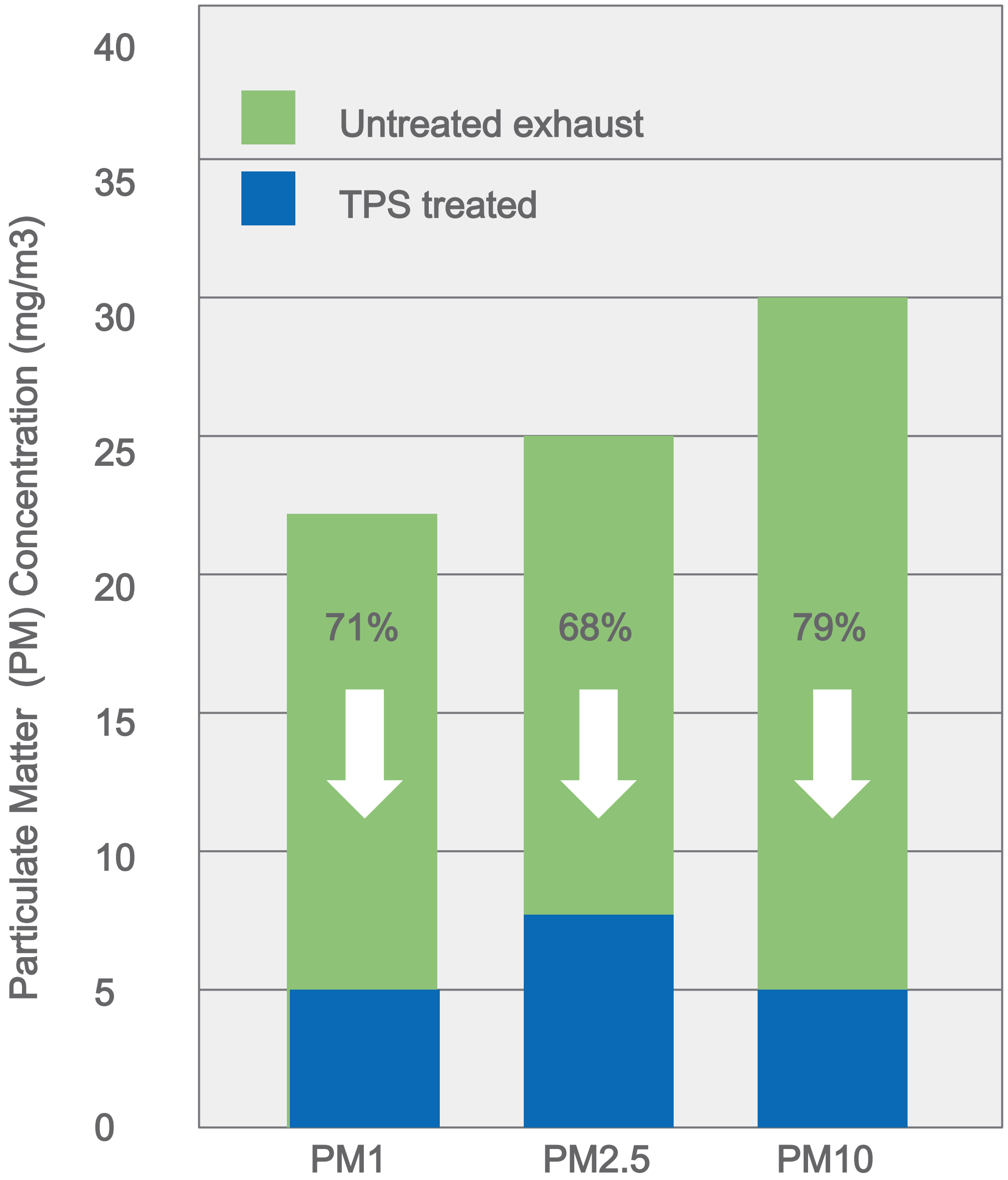
Without TPS



- Cold start capability
- Extends life of catalyst
- Operational cost savings
- Any fuel
- Allows existing engines to meet new emissions standards
- Application to stationary generators, off-highway and on-highway vehicles, and even charbroilers (restaurants)

Results treating Diesel Exhaust





Summary

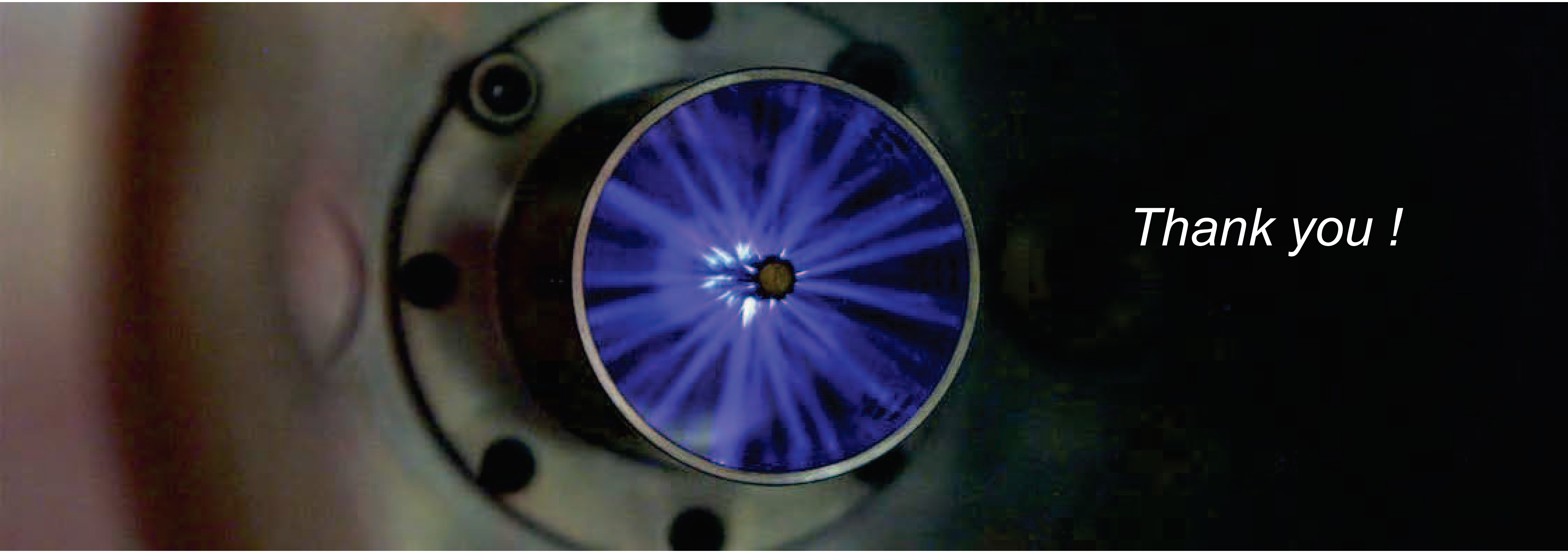
To date transient plasma ignition has:

- Demonstrated a lean ignition limit lower than a fuel/air equivalence ratio (φ) of 0.50 [1];
- Demonstrated high-pressure ignition in engines and static cells >20 bar BMEP equivalent [2];
- Demonstrated stable (COV_{IMEP} <5%) ignition at EGR dilution levels up to 35% [3]

- A prototype multi-cylinder system is being developed and tested on a Cummins Westport engine in 2019
- Additional application to emissions treatment is being explored

[1] M. Sjöberg, W. Zeng, D. Singleton, J. Sanders and M. Gundersen, "Combined Effects of Multi-Pulse Transient Plasma Ignition and Intake Heating on Lean Limits of Well-Mixed E85 DISI Engine Operation," *SAE Int. J. Engines* pp. 7(4):1781-1801, 2014.
[2] Y. Lin, D. Singleton, J. Sanders, A. Kuthi and M. Gundersen, "Experimental study of pulsed corona discharge in air at high pressures," in *Bulletin of the American Physical Society*, Austin, 2012.
[3] M. Sjoberg and W. Zeng, "Combined Effects of Fuel and Dilution Type on Efficiency Gains of Lean Well-Mixed DISI Engine Operation with Enhanced Ignition and Intake HEating for Enabling Mixed-Mode Combustion," *SAE Int. J. Engines* pp. 9(2):750-767, 2016.

TPS
Transient Plasma Systems



- Solutions to time -critical problems
- Superior technology
- Strong barriers to entry
- Experienced team
- Platform technology

Dan Singleton, CEO

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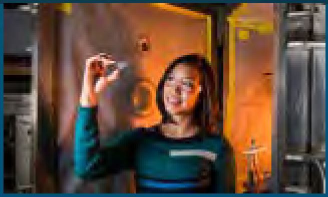
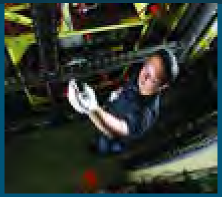
1751 Torrance Blvd, Torrance, CA 90501

Modeling of Ventilation Strategies for CNG Vehicles





PRESENTED BY

Myra Blaylock

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SAND2019-4309 C

Acknowledgements

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Brian Ehrhart, Alice Muna, Chris LaFleur – Risk Assessment Team
Rad Bozinoski , Ethan Hecht – Leak modeling and model validation

VTO Technology Integration: Dennis Smith and Mark Smith

Overview

Motivation: Inform Safety Codes & Standards

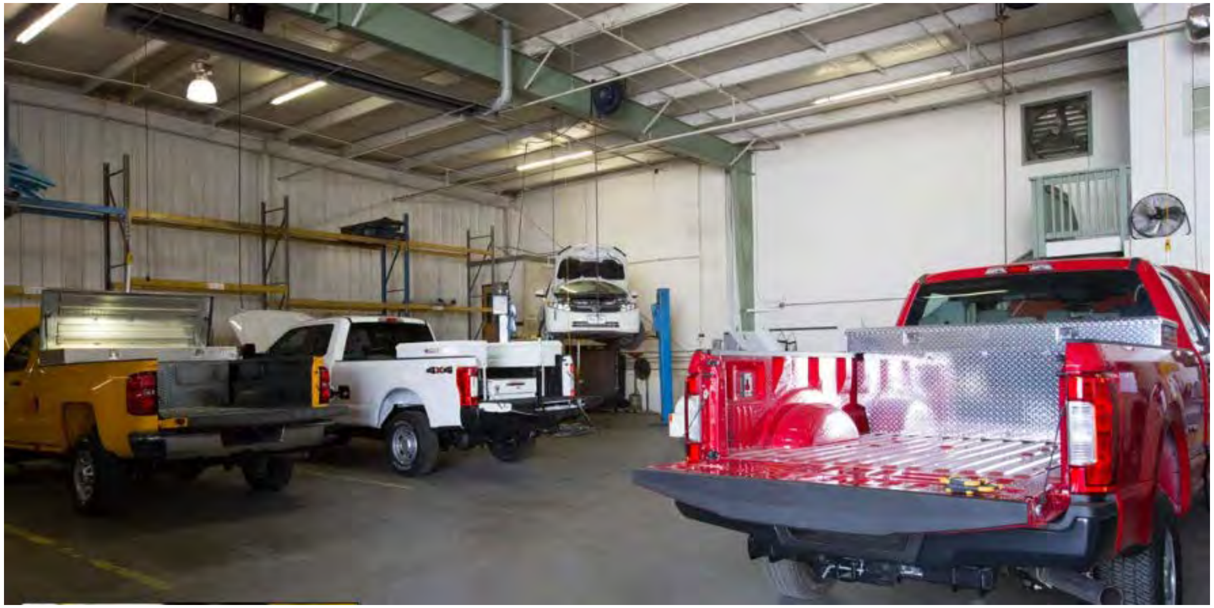
Computational Fluid Dynamics (CFD) Modeling of a CH_4 leak in a garage

Previously looked at different leak sizes, CNG vs LNG

Papers and video at: altfuels.sandia.gov

Current work: Effect of ventilation on same leak

Building off of same study for a H_2 car



Picture source:
Kelly & Melendez, 2017

Light Duty Vehicle Maintenance Garages: Garage Layout

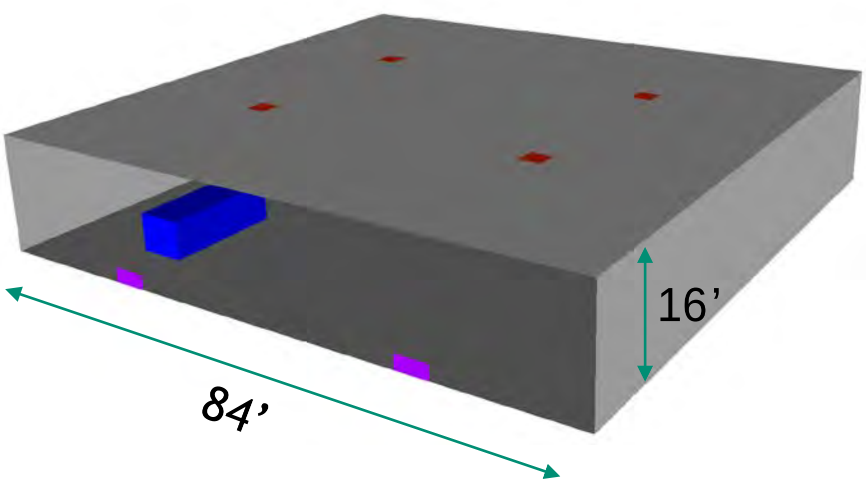
12 bays with aisle – medium/large size facility

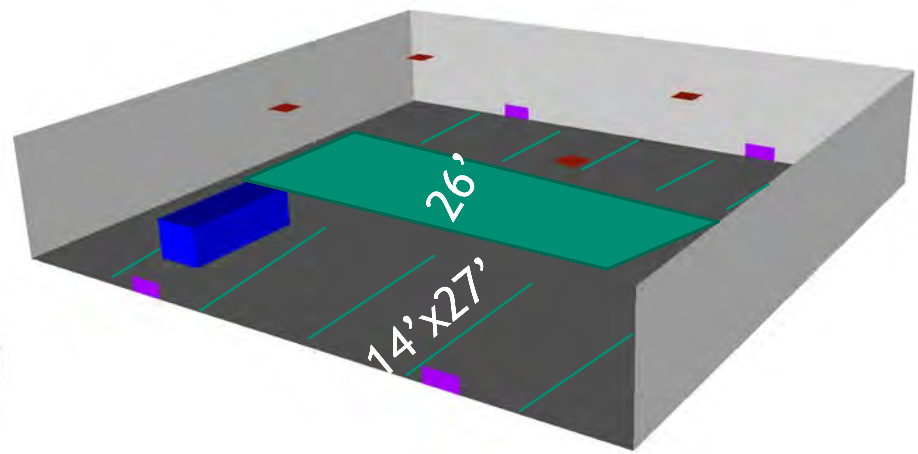
4 floor inflow vents

4 ceiling outflow vents

No other equipment

Item	Width	Length	Height
Vents in	4.5’	--	2’
Vents out	3’	3’	--
Car	6’	16’	5’

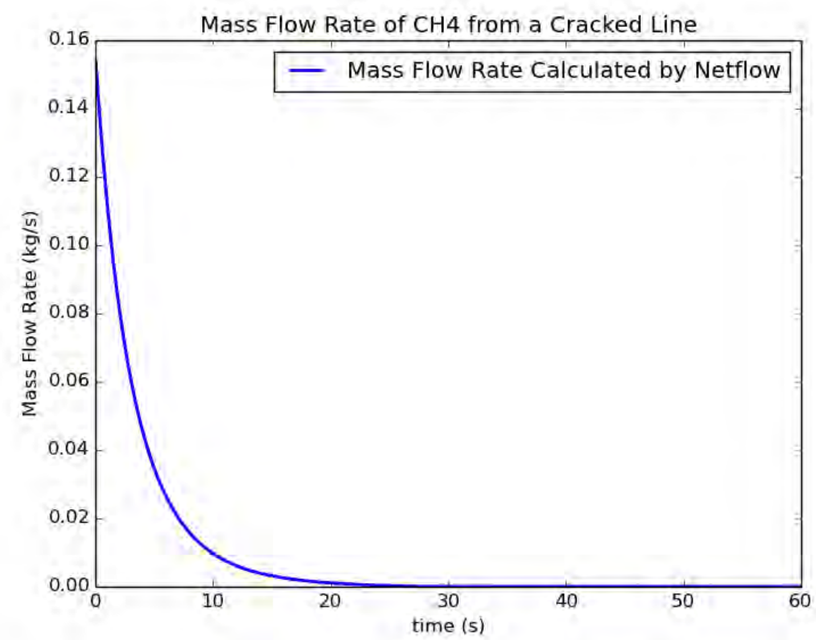




Leak Description

Likely light duty vehicle leak from a cracked line.

- 3.3 liters @ 248 bar;
- Size of hole is 3% by area of 1.27 cm ID tubing



Vehicle on jack 2' off floor, leak is downward

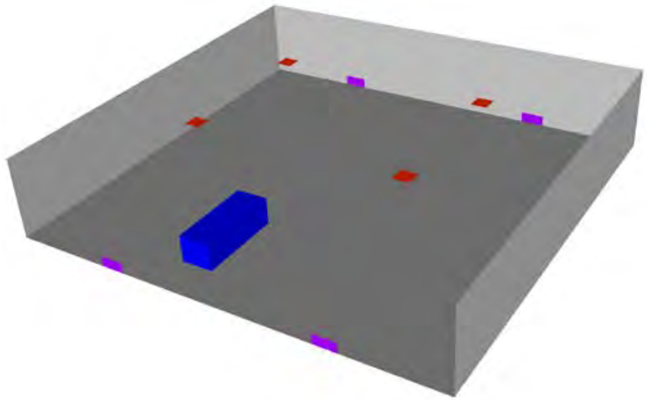
Gas in the flammable range: 5-15% by volume

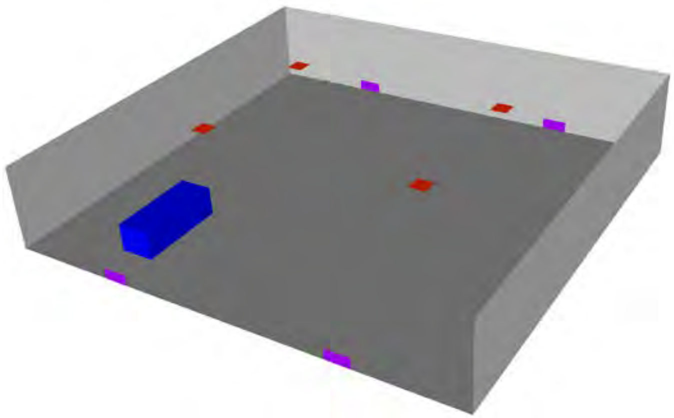
Integrated over the volume to get flammable mass.

Ventilation

Five ventilation scenarios

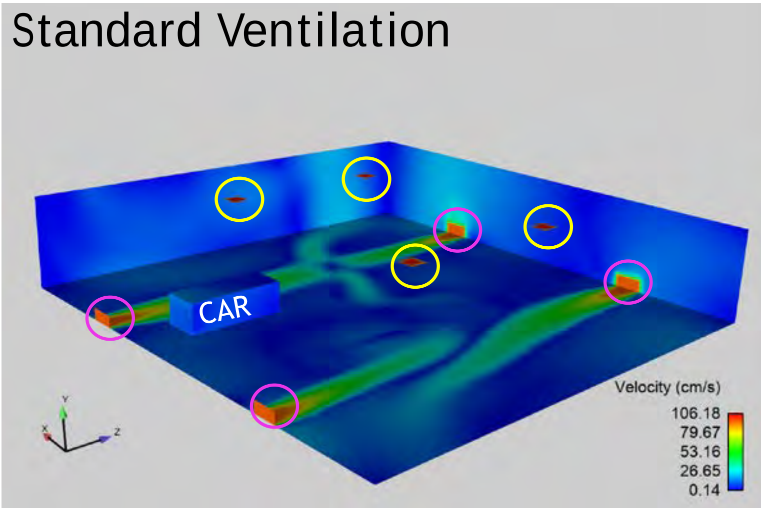
1. No ventilation
2. Standard ventilation: leak away from inflow
3. Standard ventilation: leak near inflow
4. Box fan continuously going
5. Box fan starting at same time as the leak
   - Note: 1&5 start at 0 sec. 2-4 start at 600 sec



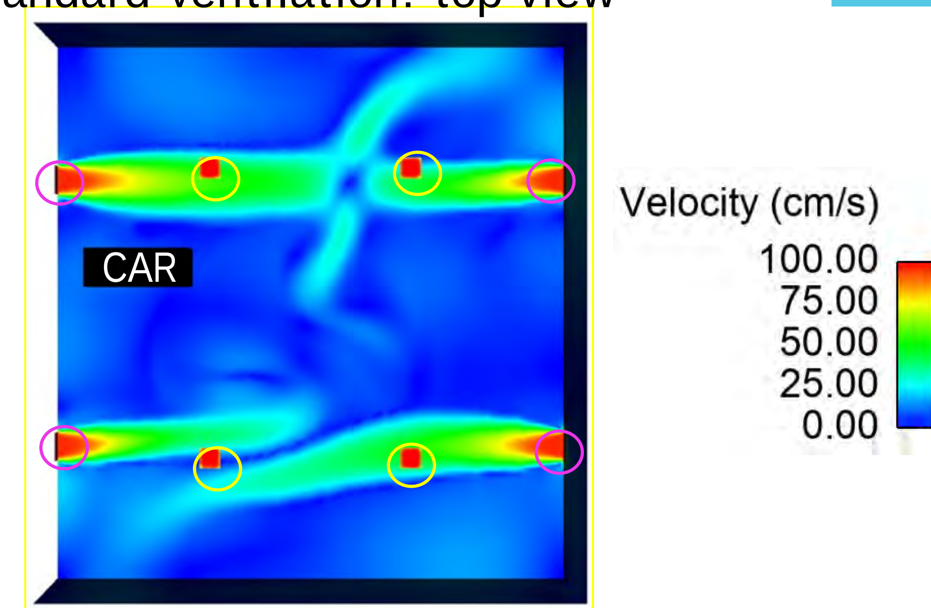


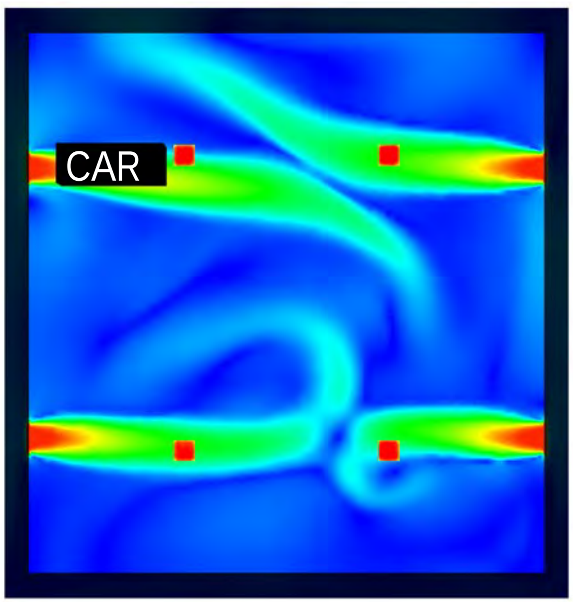
Code Requirements	Regulation equation	Vent velocity $\left[\frac{cm}{s}\right]$
NFPA 30A 7.3.6.7: H_2 repair facility 1 cfm/ft^2	$\frac{\dot{V}}{A_{floor}} = 1\frac{ft^3}{min * ft^2}$	94.8
IFC 2311.8: 1 cfm per 12 ft^3	5 air flow changes per hour	125.9
Standard repair facility 0.75 cfm/ft^2	$\frac{\dot{V}}{A_{floor}} = 0.75\frac{ft^3}{min * ft^2}$	71.1
Box fan	N/A	300.0

Garage Ventilation

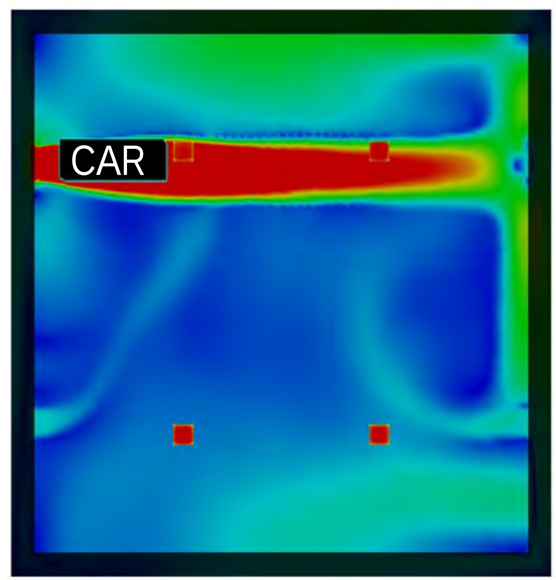


Standard Ventilation: top view





Standard Ventilation: leak near inflow

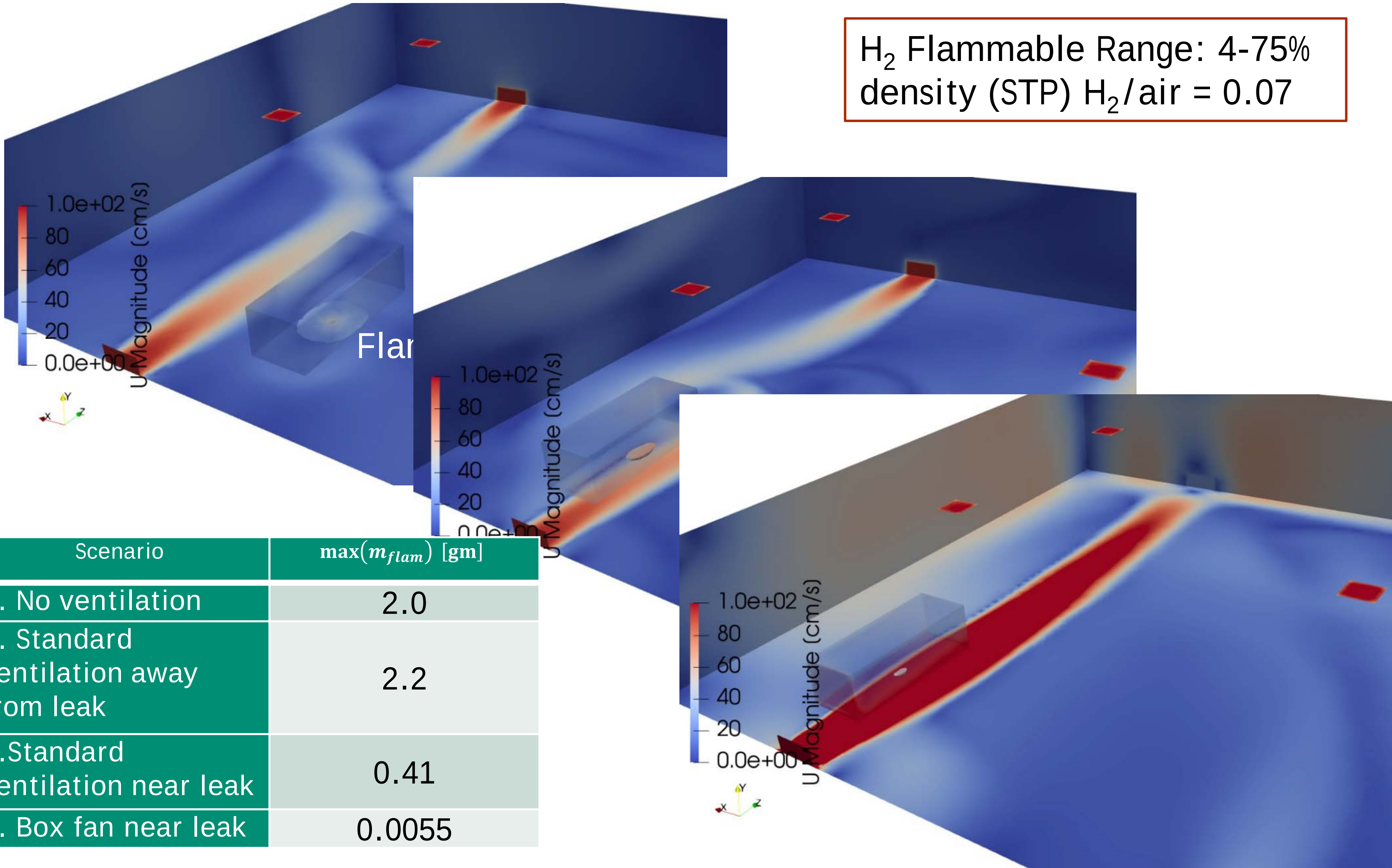


Box Fan Ventilation

Hydrogen Fuel Cell Car

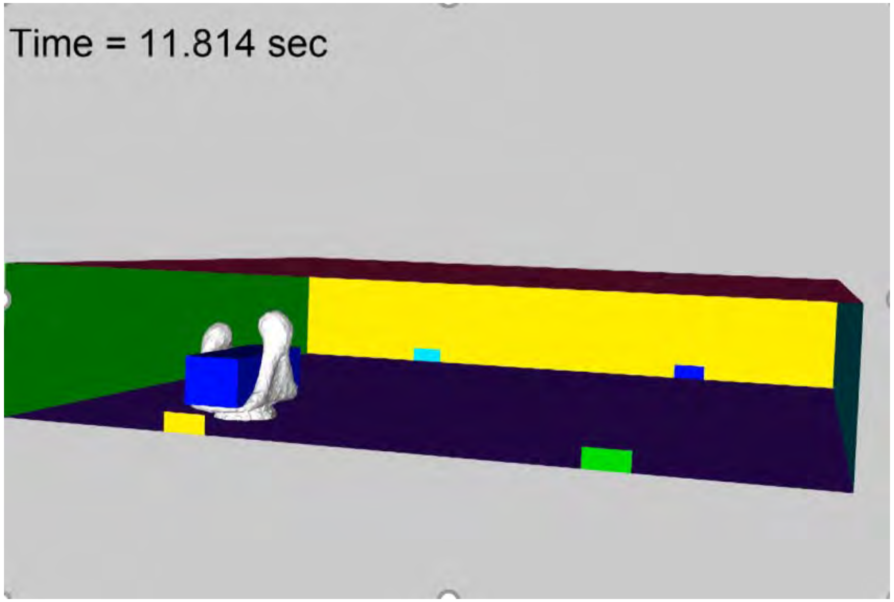
Less flammable mass when closer to ventilation or with more ventilation.

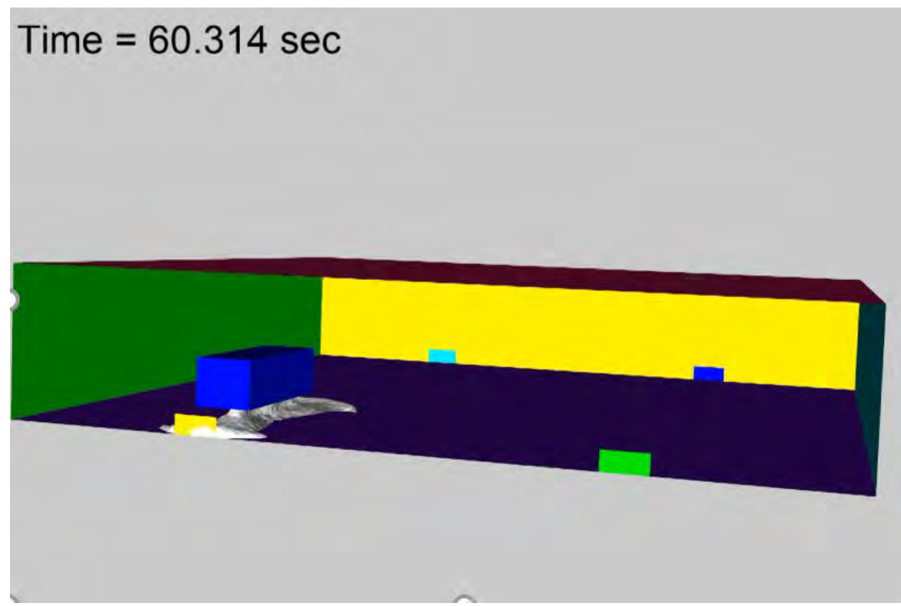
H_2 Flammable Range: 4-75%
density (STP) H_2/air = 0.07



Scenario	$\max(m_{flam})$ [gm]
1. No ventilation	2.0
2. Standard ventilation away from leak	2.2
3.Standard ventilation near leak	0.41
4. Box fan near leak	0.0055

CNG Leak: No Ventilation

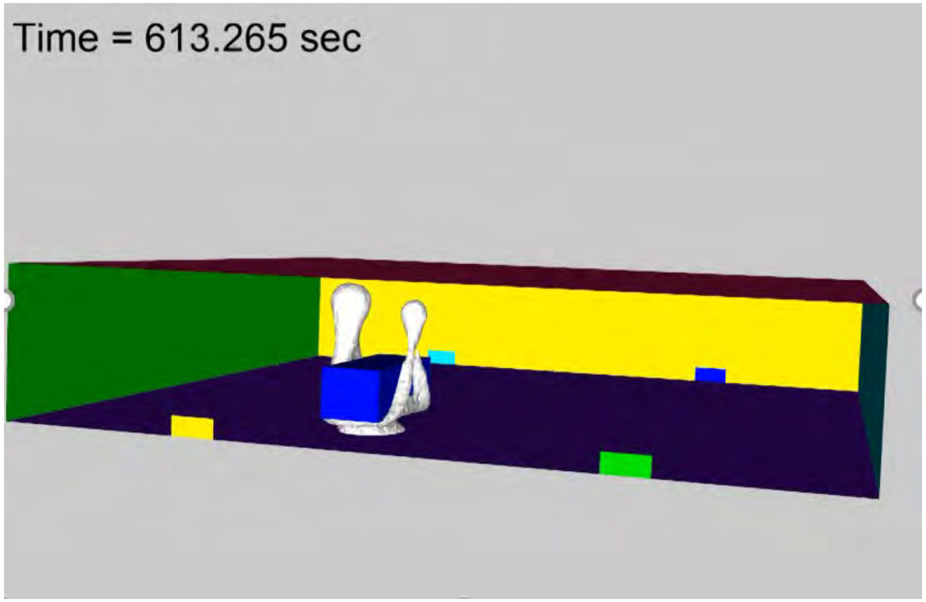


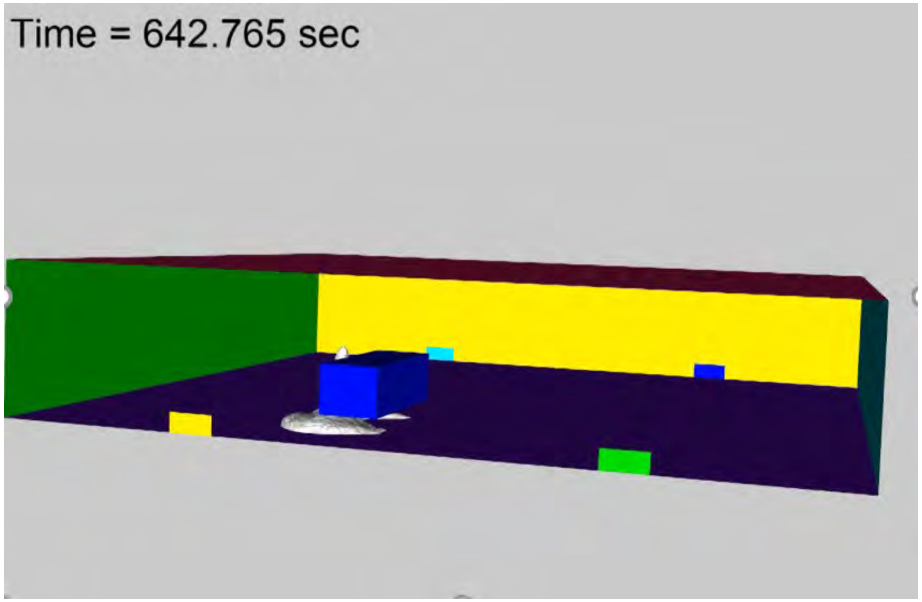


Maximum Flammable Mass: 140 gm

Time for dissipation: 138 sec

Standard ventilation with leak away from inflow ventilation



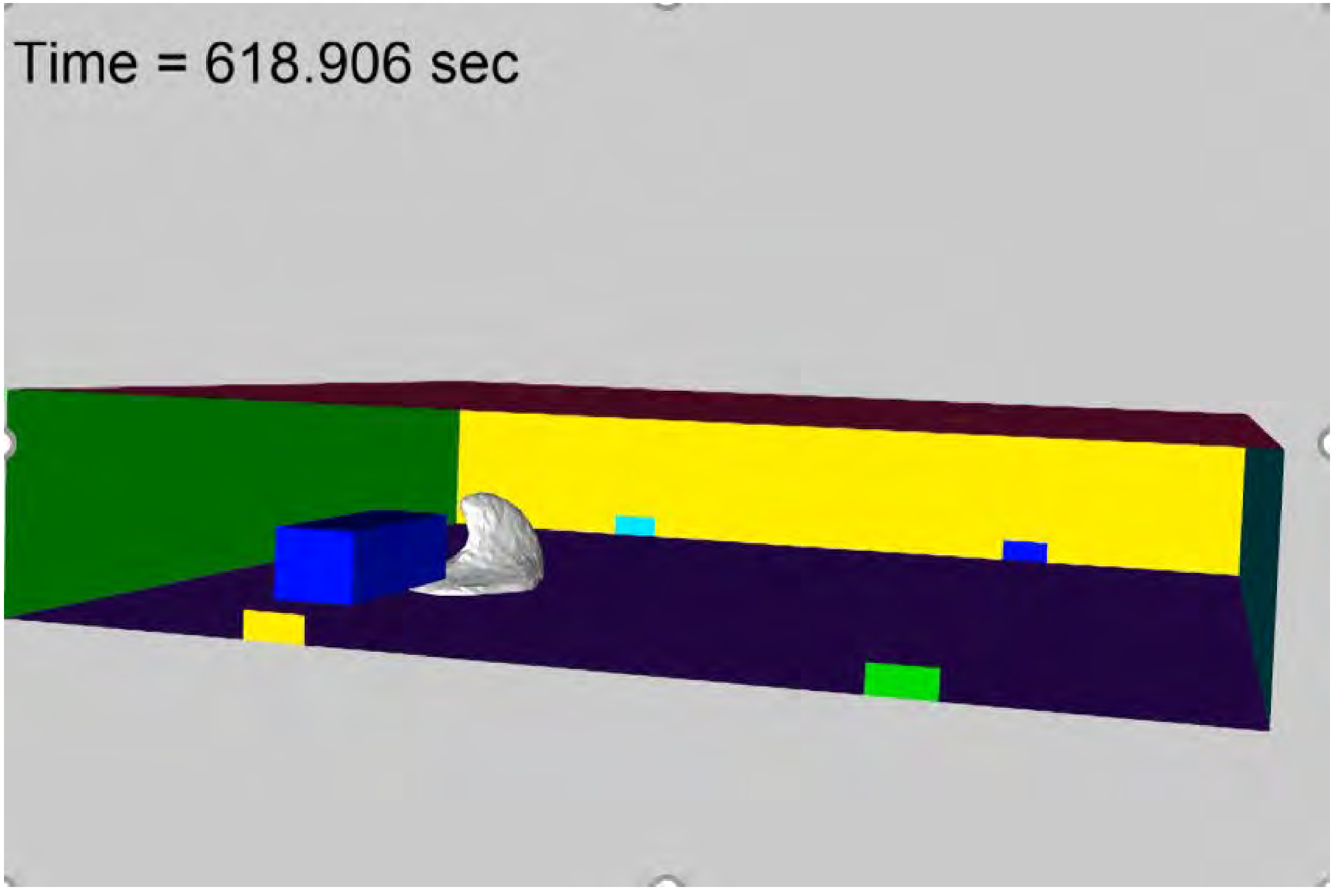


Maximum Flammable Mass: 130 gm

Time for dissipation: 103 sec

Simulation has run for 600 sec before leak

Standard ventilation with leak near inflow ventilation

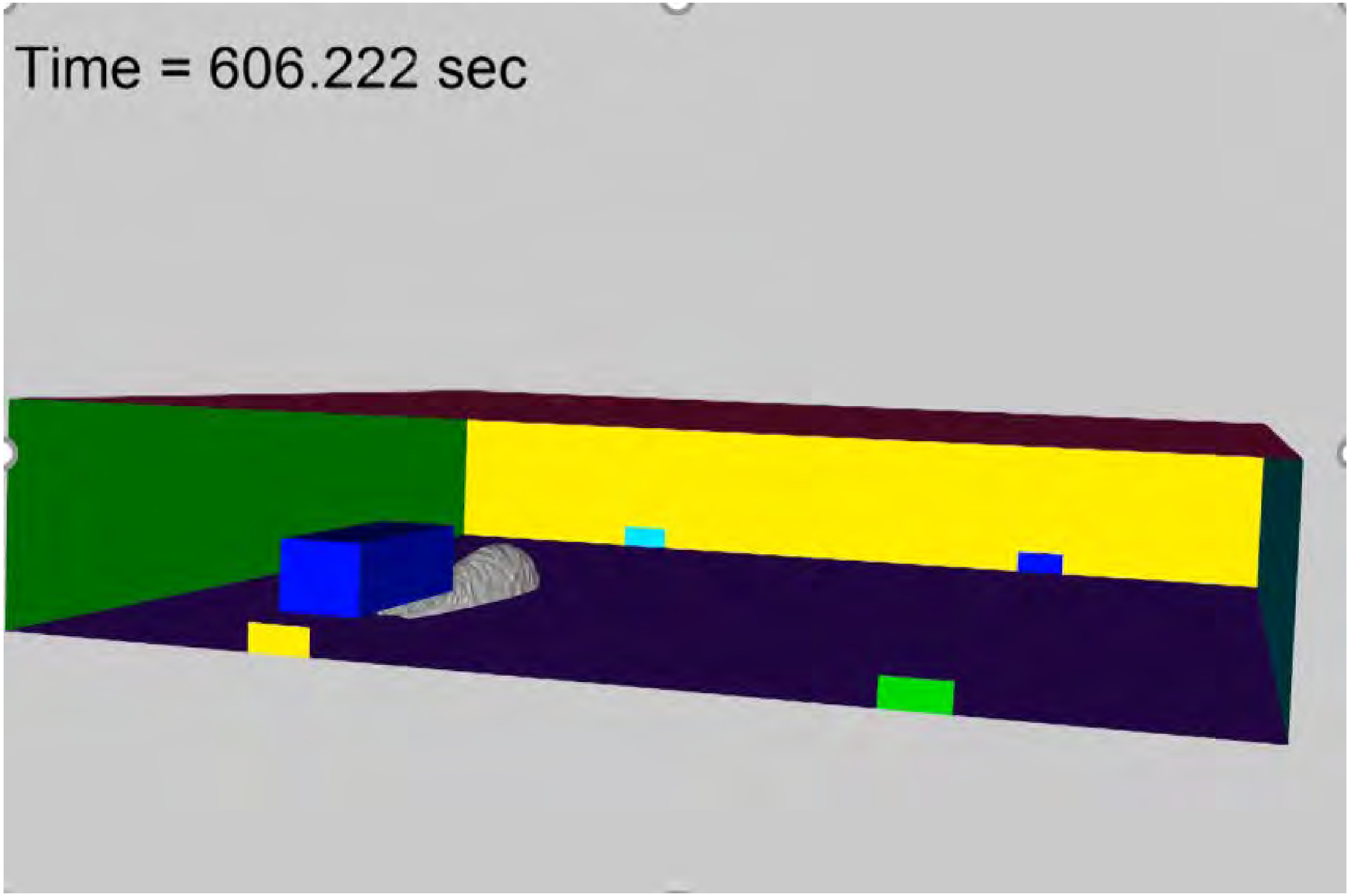


Maximum Flammable Mass: 240 gm

Time for dissipation: 33 sec

Simulation has run for 600 sec before leak

Box fan near leak – continuously going



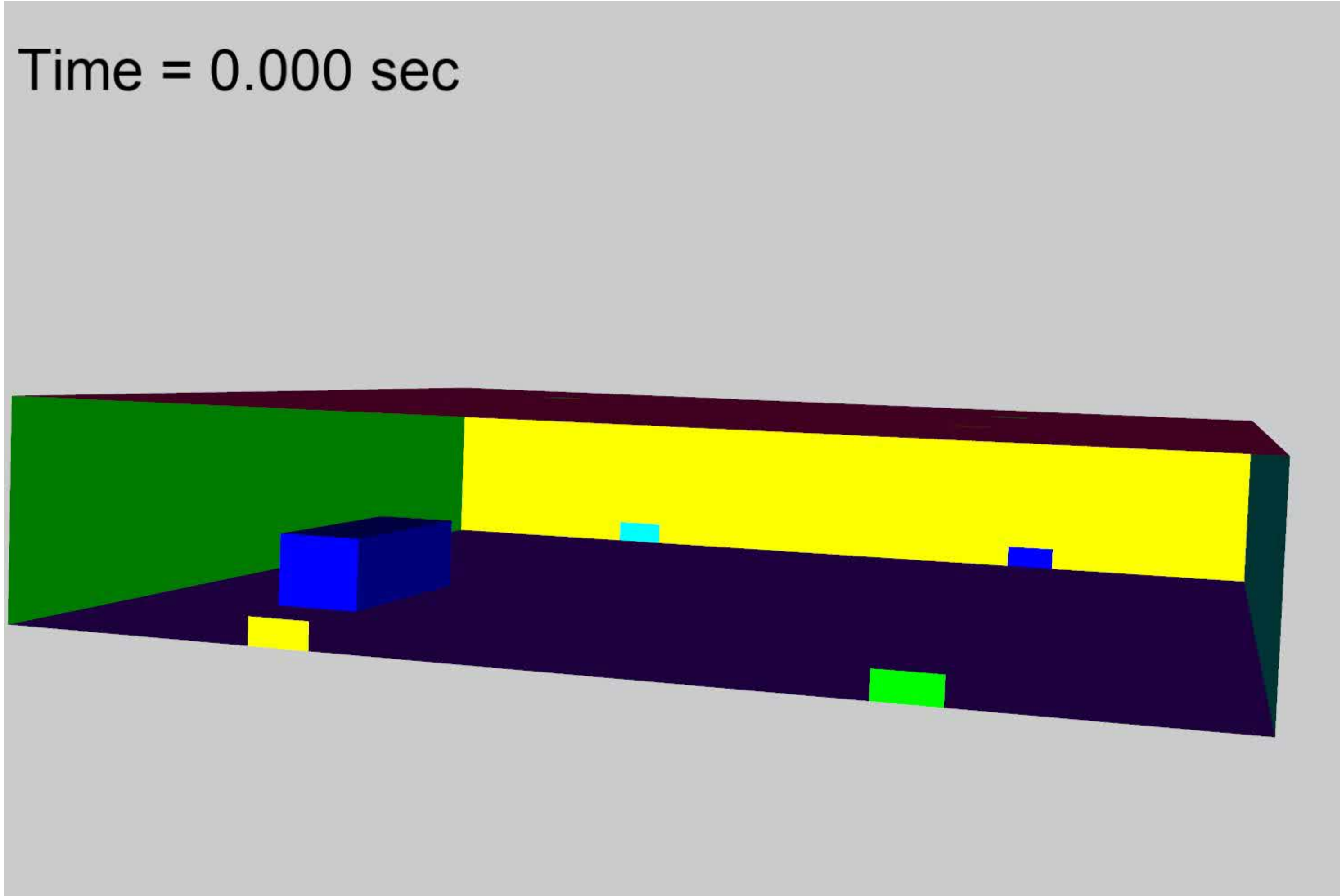
Maximum Flammable Mass: 140 gm

Time for dissipation: 27 sec

Simulation has run 600 sec before leak

30 fps

Box fan near leak – starting with “sensor”

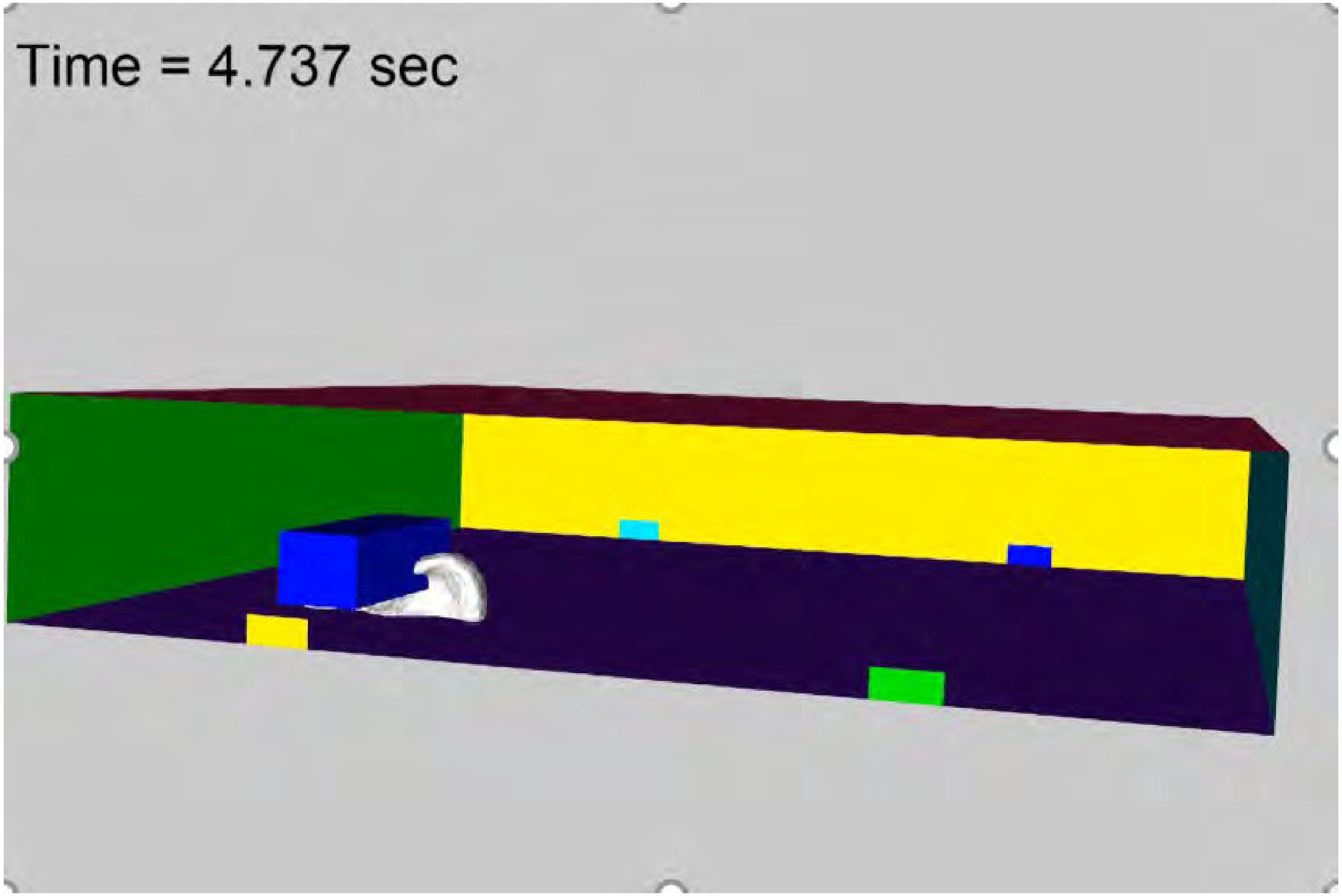


Maximum Flammable Mass: 174 gm

Time for dissipation: 27 sec

30 fps

Box fan near leak – starting with "sensor"

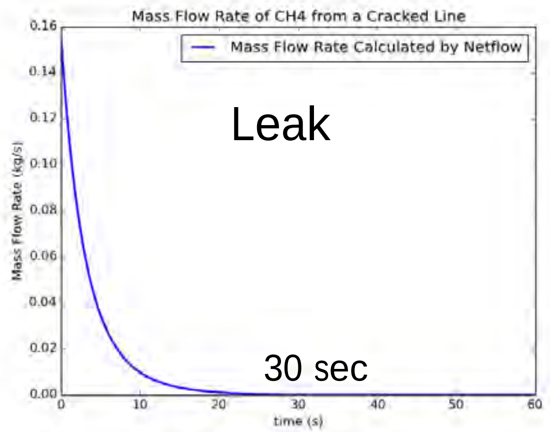


Maximum Flammable Mass: 174 gm

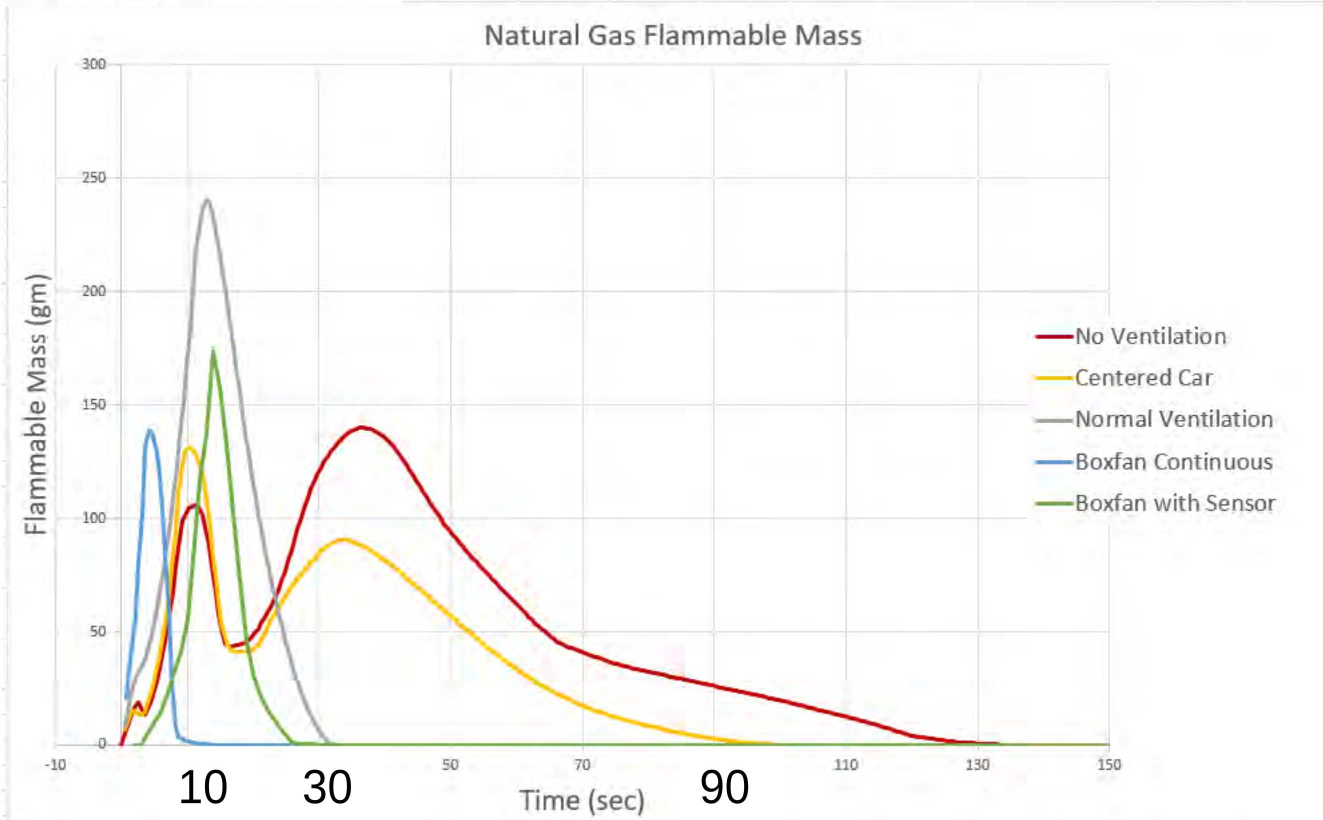
Time for dissipation: 27 sec

4 fps

Ventilation Comparisons



	Maximum Flammable Mass	Time for Dissipation
No ventilation	140 gm	138 sec
Away from inlet	130 gm	103 sec
Near inlet	240 gm	33 sec
Box fan –continuous	140 gm	27* sec / 10 sec
Box fan - sensor	174 gm	27 sec



Conclusions

Ventilation location and amount has an effect on amount and duration of flammable mass.

Can comply with codes and possibly not reduce risk.

Easy, non-structural changes (i.e. box fan with critical placement) might be effective.

Some CNG releases can produce flammable mass that is more dense than air (for a short time).

CNG results are different from hydrogen fuel cell vehicle simulations.

Thank you!

Questions? Feedback?

Thank You

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