Accelerating the Development of H2ICEs – VTO/DORMA Projects

Gurpreet Singh, Program Manager

Decarbonization of Off-Road, Rail, Marine, and Aviation (DORMA)






Motivation

- Many applications in the long-haul transportation, construction, and agriculture sectors will be difficult to electrify due to their power, range, and fueling needs
- H_2 fuel cell (H2FC) and H_2 internal combustion engine (H2ICE) powerplants have unique characteristics that give each technology advantages in specific applications
- H2ICEs can help promote a H_2 economy by creating early demand while production, infrastructure, material supply chains, and customer acceptance scale up

For additional information on the technical and techno-economic viability of H2ICEs see the February H2IQ Hour: **www.energy.gov/eere/fuelcells/2023-hydrogen-and-fuel-cell-technologies-office-webinar-archives**

Characteristic	H2ICE	H2FC
Efficiency*	+	+ +
Cooling needs*	0	- -
Emissions*	+	+ +
Durability*	-	- -
Robustness*	0	-
Noble metal consumption	0	- -
Fuel purity	+ +	- -
Fuel flexibility	+	- -
Upfront cost*	0	-
Cold start	0	-

* Current technology status compared with diesel baseline

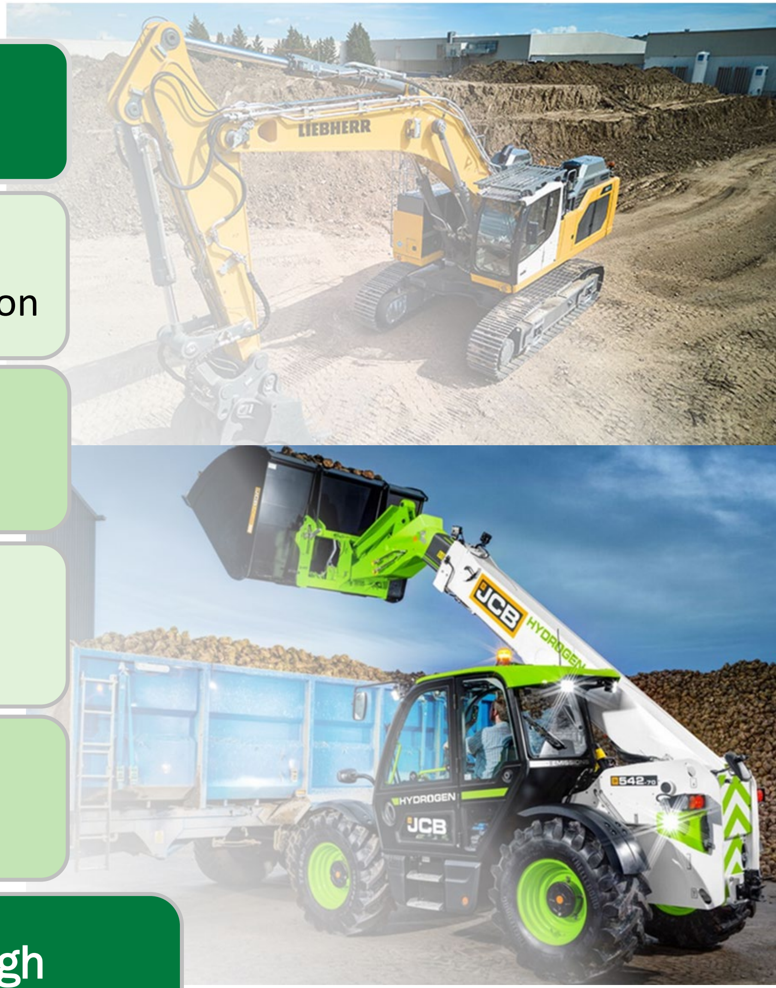
"Hydrogen combustion and hydrogen fuel cells are complementary… they thrive in the same ecosystem"

McKinsey & Co. 2021

The challenge

Vehicles for construction, agriculture, mining, and heavy transport are *tools*
– they need to serve their intended purpose

Key Attribute	Barriers or Knowledge Gaps
Power density	• Pre-ignition & knock • Fuel injection & mixture preparation
Range or duration	• Efficiency • Heat losses
Emissions	• Aftertreatment systems • Wall quenching behavior
Reliability & Durability	• Injection systems • Material compatibility • Lubrication (⇨ wall quenching)



VTO/DORMA projects address each of these areas through experiments and advanced computational design tools

Overview

Key Current VTO-funded projects

- Dual-Fuel H_2 Combustion Research for Rail (FRA co-funding)
  CFD modeling at ANL, experiments at ORNL
  CRADA with Wabtec/Convergent Science Inc.
- Hardware-in-the-Loop (HIL) Toolkit
  Experiments and vehicle system modeling at ANL
- Engine Modeling of H_2 Direct Injection and Combustion
  CFD modeling at ANL, experiments at SNL & industry
  CRADAs under negotiation
- Fundamentals of H_2 Injection and Combustion (Aramco co-funding)
  Experiments and CFD modeling at SNL
- FY22 FOA Awards:
  - *Caterpillar Inc. - Transient-capable Hydrogen-hybrid for Off-Road. $3,270,995 (DOE)*
  - *Purdue University - High Energy-Efficient Hybrid Excavator Powered by Hydrogen Combustion Engine. $2,492,978 (DOE)*

Barriers addressed

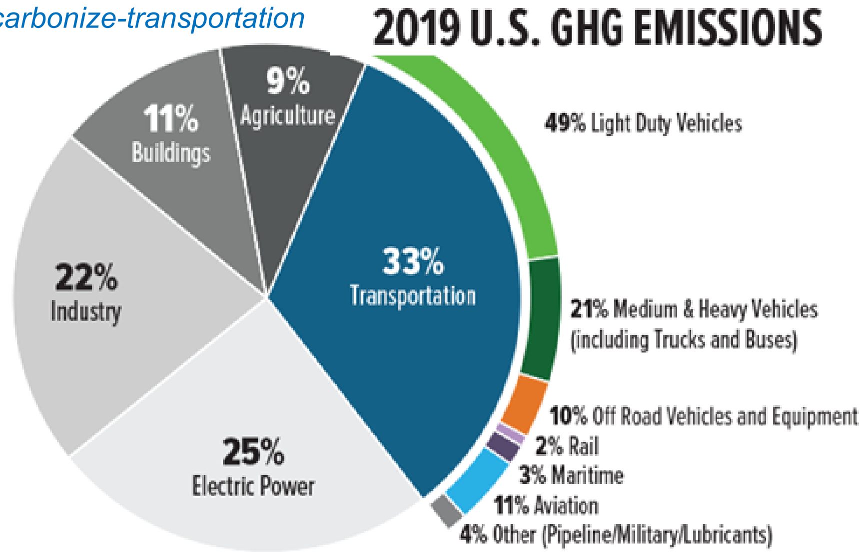
- Power density
- Range
- Emissions
- Reliability & Durability

Collaborative partners:

- ANL (PIs – Ameen, Biruduganti, Scarcelli)
- ORNL (PI – Edwards)
- SNL (PIs – Pickett, Srna)
- Aramco Services
- Borg-Warner
- Caterpillar
- Convergent Science
- Wabtec

Goal & Approach

https://www.epa.gov/greenvehicles/why-decarbonize-transportation



Goal

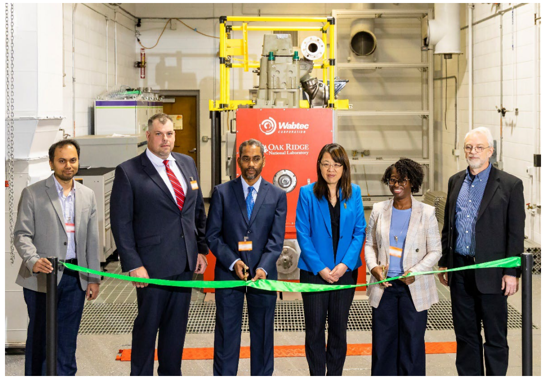
Fast decarbonization of off-road/rail/marine sectors:

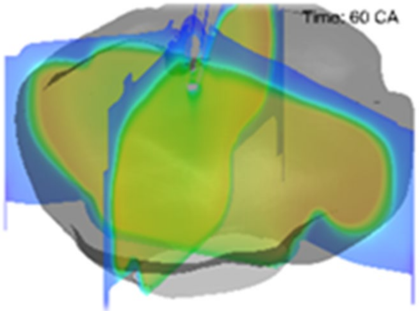
- Provide industry with knowledge and tools to decarbonize their applications by using H_2 as a low-carbon fuel
- 15% of transportation GHG emissions stem from off-road, rail, and marine. As other transportation sectors decarbonize this share will grow
- Additional synergies with heavy-duty on-road transportation

Approach

Lab-to-Lab and Lab-to-Industry collaborations combining modeling, engine experiments, advanced diagnostics, and industry-led RD&D projects.

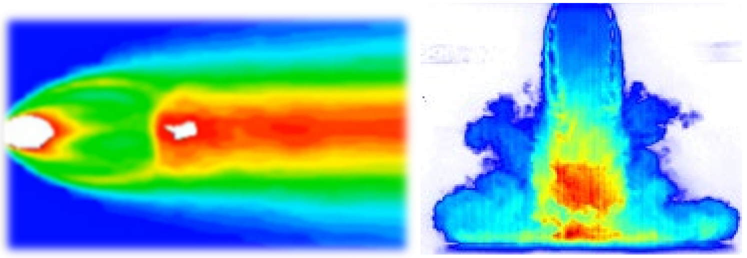
Joint ANL & ORNL project kick-off





Advanced CFD models and best practices

Engine research + engine data for model validation



X-ray & laser diagnostics

Technical Accomplishments: Single-cylinder locomotive engine installation (Wabtec H2ICE CRADA)

Wabtec single-cylinder research locomotive engine delivered and installed at ORNL

- **Based on Wabtec 12-cylinder EVO engine with production hardware**
  - 15.7-L displacement, 250-mm bore – not scaled
  - 375 hp at 995 rpm (production V12: 4500 hp at 995 rpm)
- **Wabtec service team assisted ORNL with engine rebuild using Tier 3 hardware**
  - Instrumented head & new power assembly (piston, liner, diesel injector, etc.)
  - Planning underway for new cam shaft and lower CR hardware
- **Dual-fuel port-injection intake system**
  - Adapted from existing Wabtec NG-diesel dual fuel engine design
- **Updated emissions bench and FTIR with mass-spectrometer (for H_2)**
  - AVL smoke meter and MicroSoot plus other options for PM measurement and characterizations

Wabtec single-cylinder locomotive research engine installed at NTRC

ORNL riggers placing engine in research facility at ORNL

Wabtec service team on-site at ORNL to assist with rebuild and train ORNL staff on engine service and maintenance

Dual-fuel intake with port injection system for hydrogen

OAK RIDGE National Laboratory

Wabtec CORPORATION

Technical Accomplishments: Establishing a new H_2 research facility

New facility being developed at ORNL's National Transportation Research Center to support LLCF research for locomotive applications

- **Major infrastructure upgrades are underway to support larger engine**
  - Dynamometer:
  - Electrical: Adding 1400A of 480V, 3-phase power
  - Facility water: Adding ~100 tons of cooling capacity
  - Air: New 3-stage compressor system to supply boost (1500 cfm @ 125 psi)
  - Fueling: New 2500-gal capacity diesel storage and delivery system
  - Hoisting: 3-ton jib crane to support engine service and maintenance

New dyno and controls installed in the laboratory

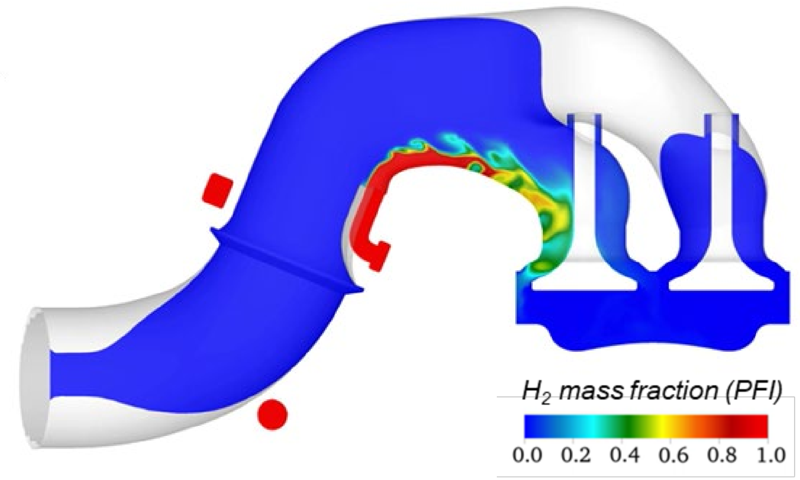
Lab being connected to existing 340-ton chiller to provide engine cooling and fluid conditioning

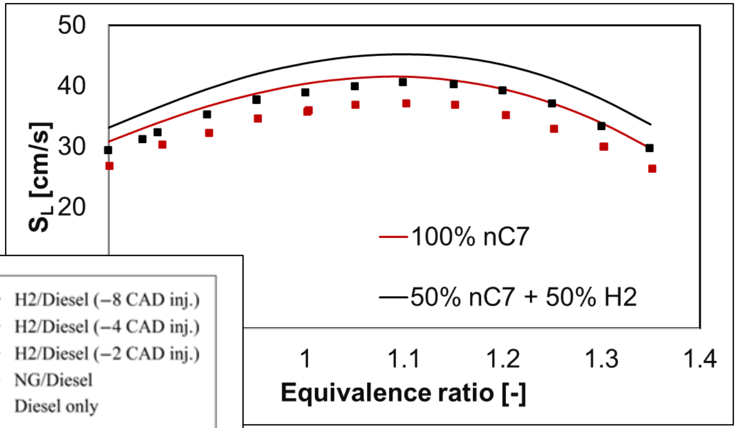
New 3-stage compressor system to provide boost pressure to the single-cylinder engine

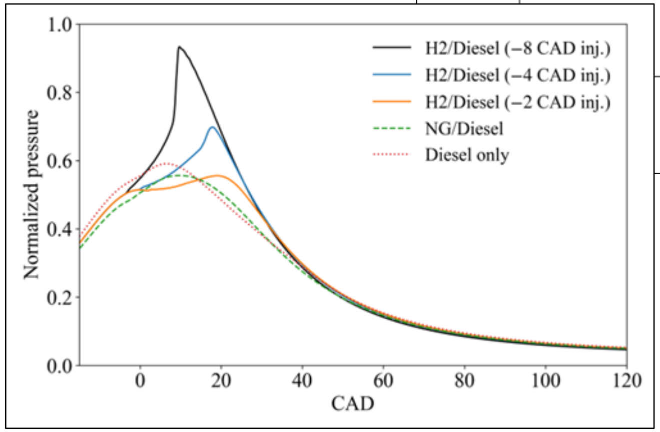
Technical Accomplishments (Dual-Fuel Wabtec CRADA)

Detailed modeling of H_2 port fuel injection (PFI) and mixing processes in a rail engine

- Higher H_2 injection rates leads to a more balanced H_2 mass flow through the two intake valves
- Early PFI timing leads to H_2 build-up in intake port
- Late PFI leads to more homogenous in-cylinder mixture







** Experimental data from Commandini et al (IJHE, 2019)*

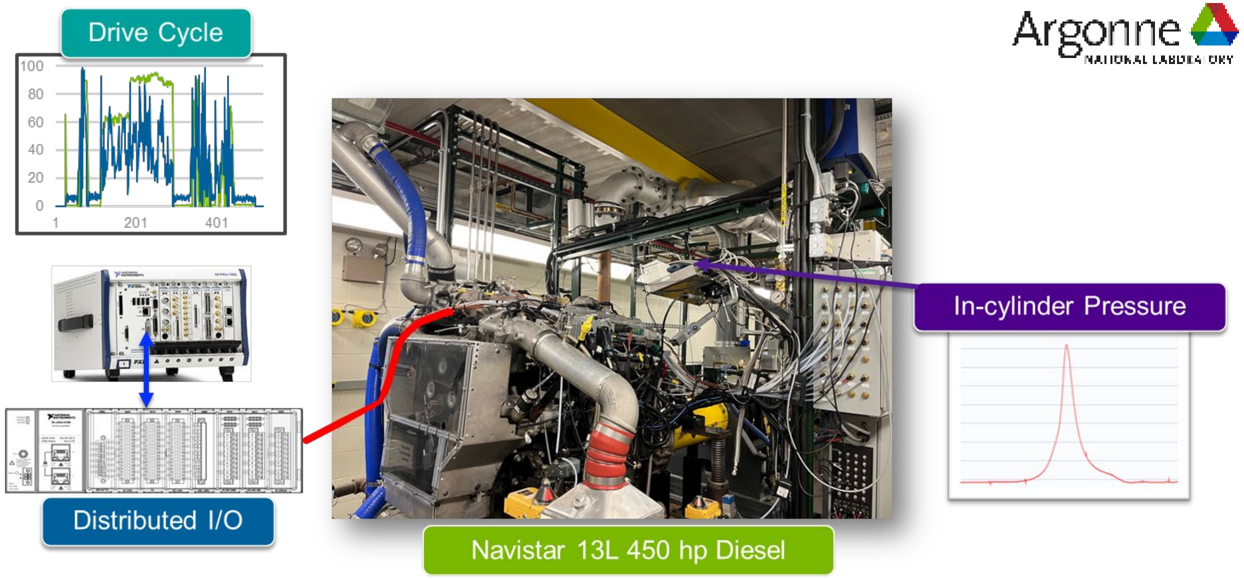
Detailed modeling of H_2 PFI on combustion rates for Diesel/H_2 Dual-Fuel Combustion

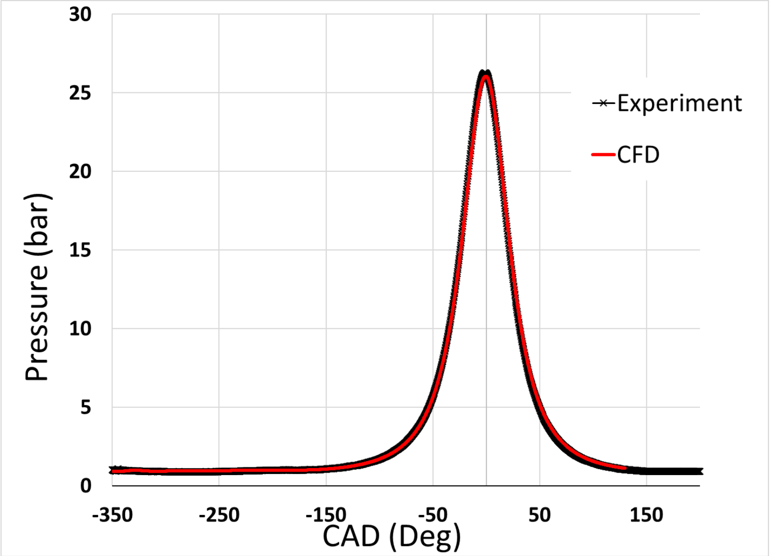
- Reduced C3 mechanism (87 species, 392 reactions) demonstrated good sensitivity to H_2/Diesel ratio on ignition delay and flame speed predictions
- H_2/Diesel operation shows faster combustion rates as compared to Diesel-only and Diesel/NG
- Diesel injection timing provides a strong controlling mechanism for pressure rise rate

Technical Accomplishments (other projects)

Hardware-in-the-Loop (HIL) Toolkit for H_2 Off-road and Marine:

- Upgraded H_2 Capacity:
  - 5000 slpm (0.45 kg/m)
- Recommissioned Heavy Duty Engine Test Cell for Transient Operation
- Demonstrated Transient Cycle With Navistar Heavy Duty Engine

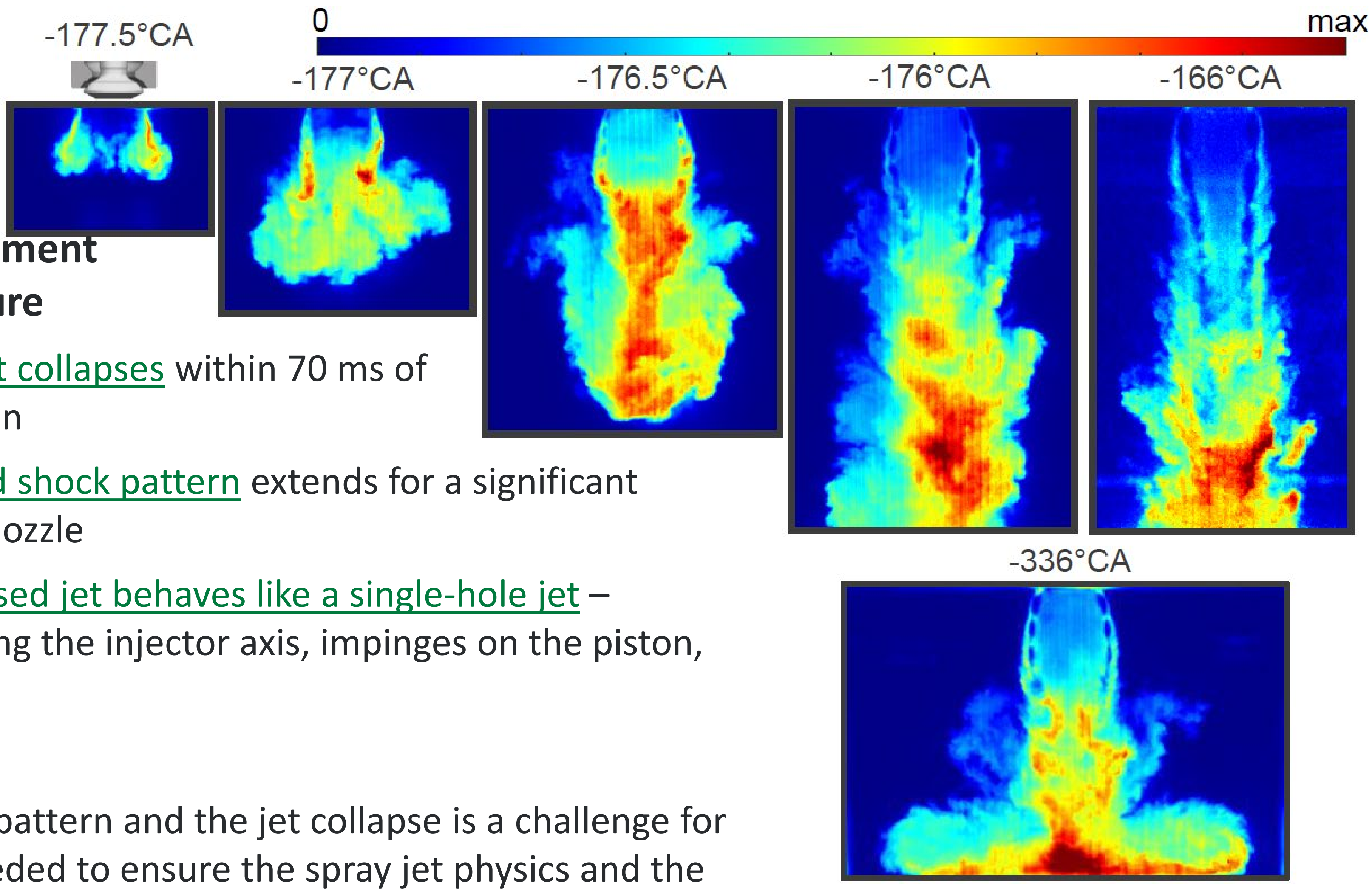




CFD Modeling of Direct Injection and Combustion in H_2 Engines:

- Built engine CFD case setup based on Sandia optical Heavy Duty engine geometry
- Matched experimental in-cylinder pressure data for motored condition before injection

Injection fundamentals: Imaging of the early H_2 jet evolution reveals a collapsed jet with significant internal shock structure



The jet pattern is impacted by the injector needle movement and the shock structure

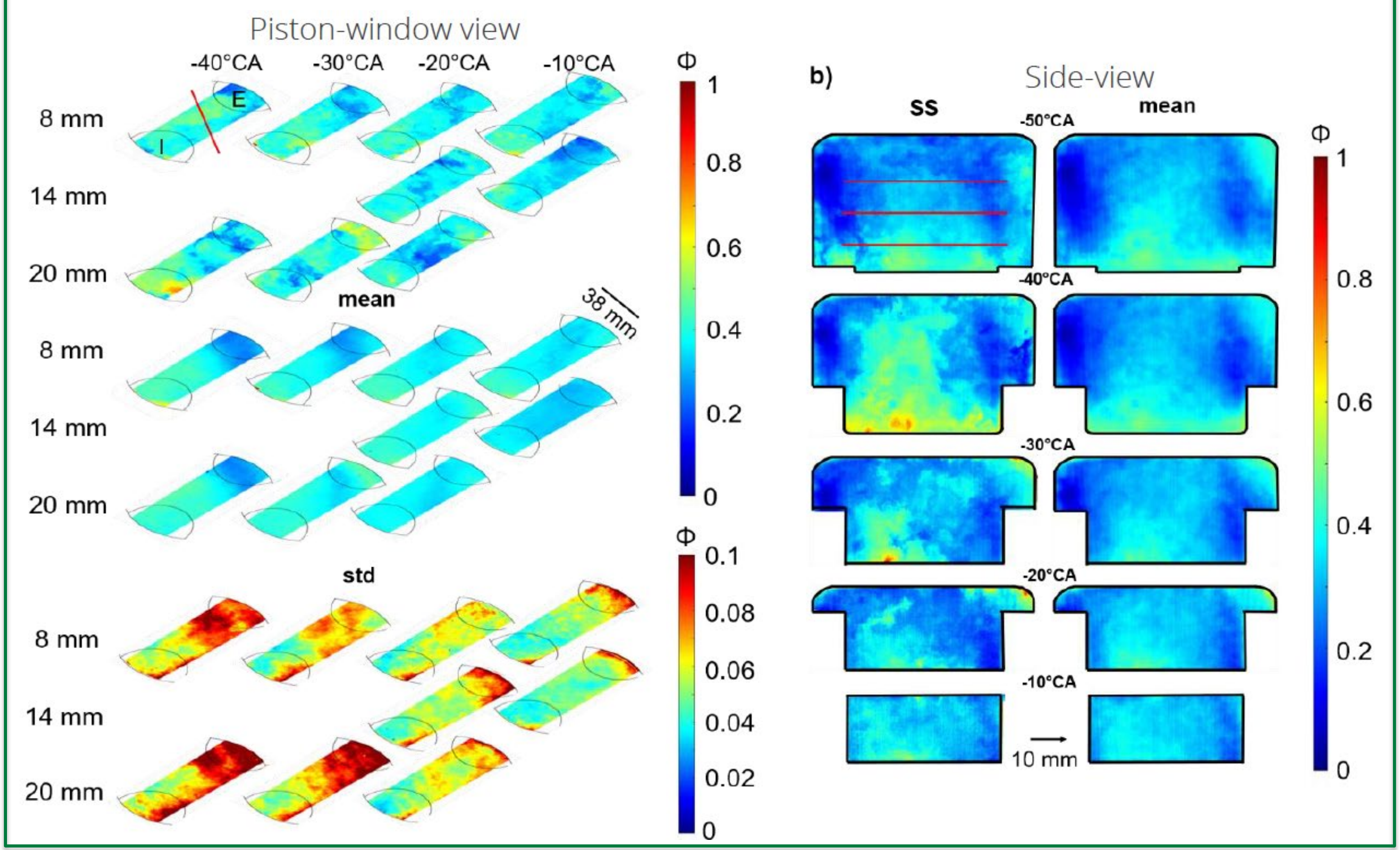
- The hollow-cone jet collapses within 70 ms of the start-of-injection
- An under-expanded shock pattern extends for a significant distance from the nozzle
- Globally, the collapsed jet behaves like a single-hole jet – fuel penetrates along the injector axis, impinges on the piston, and recirculates

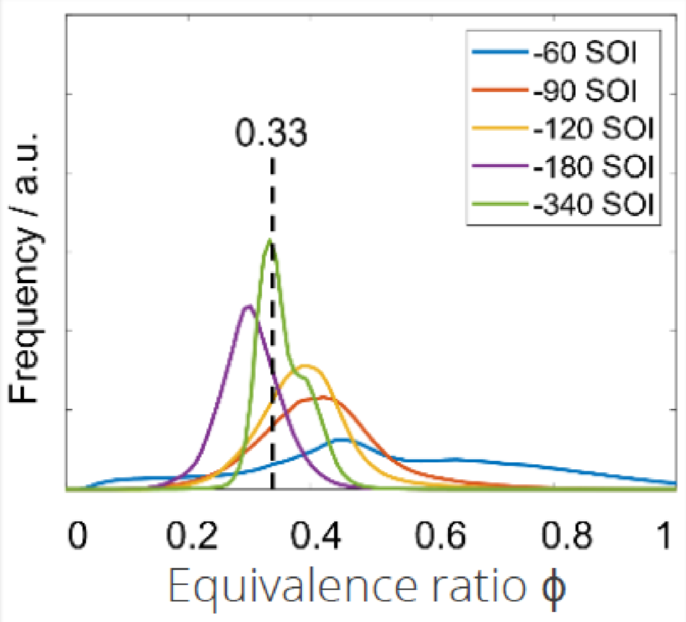
Impact

Reproducing the shock pattern and the jet collapse is a challenge for CFD. These data are needed to ensure the spray jet physics and the subsequent mixing are correctly captured

In-cylinder mixing data base provides quantitative, 3-d information about the H_2-air mixture formation, including detailed statistics

Sample dataset for a single operating condition: SOI = -120°CA, P_{inj} = 40 bar





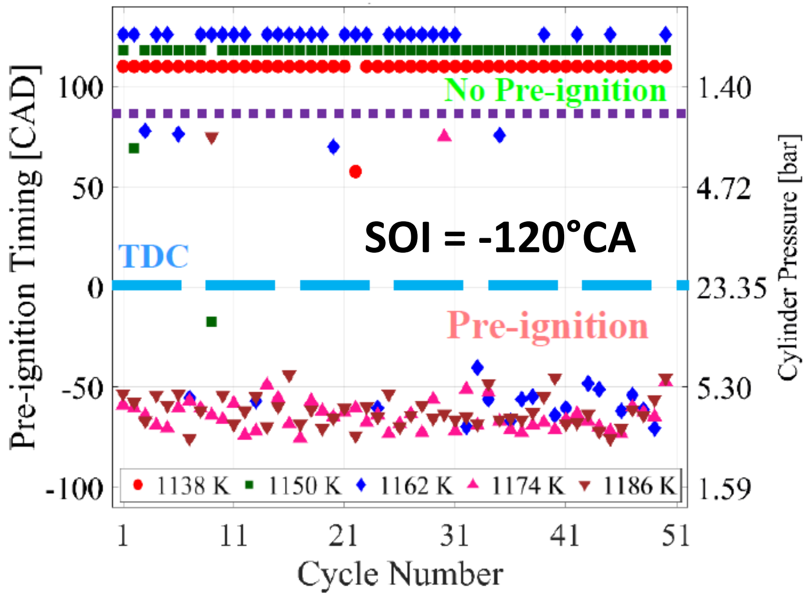
Impact

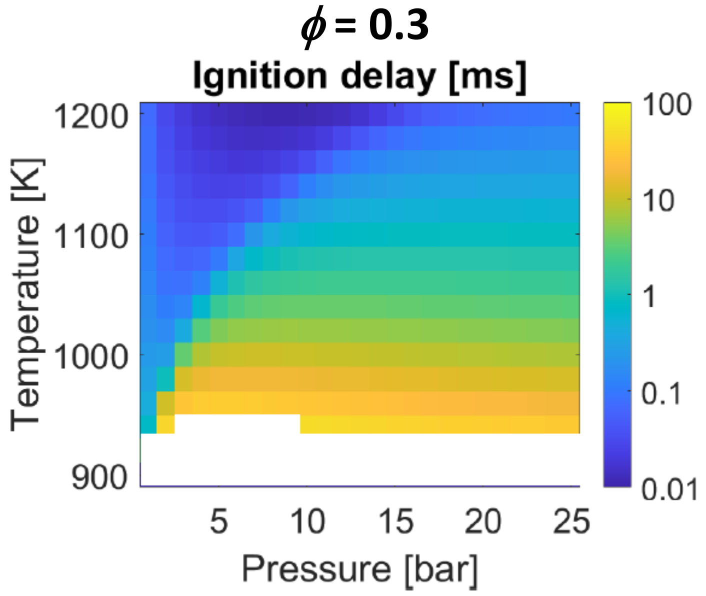
- Detailed data enables full validation of CFD mixing predictions through time of spark
- Statistics support 0-d models such as those used in GT-Power

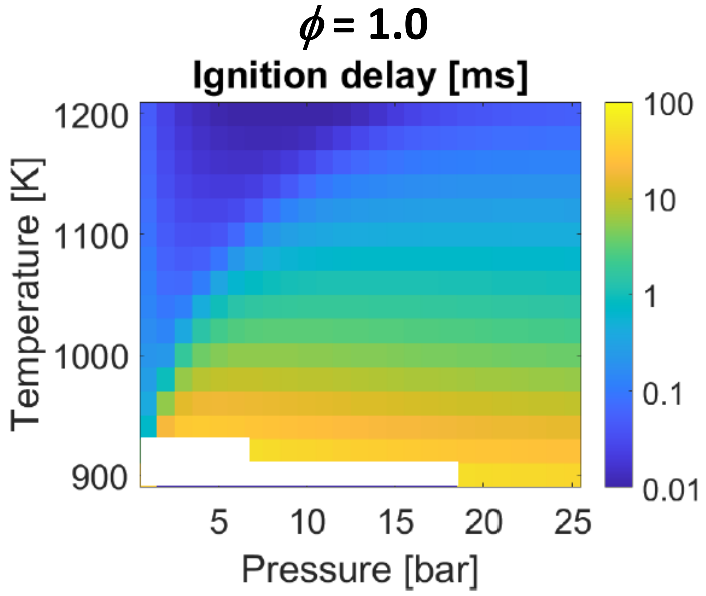
Pre-ignition of H_2 shows clustered pre-ignition events away from TDC

Pre-ignition typically occurs during the compression stroke before -50°CA or during expansion after 60°CA – *not when the pressure is high near TDC*

- Early pre-ignition timing is governed by mixing – the time it takes for fuel to reach a hot spot
- Pre-ignition variability is attributed to mixing variability – as visualized by imaging studies







Counterintuitively, simulations show ignition delay ***increases*** with pressure

Impact

Late injection can effectively mitigate pre-ignition, provided that mixing is sufficiently fast

Remaining Challenges and Future Work

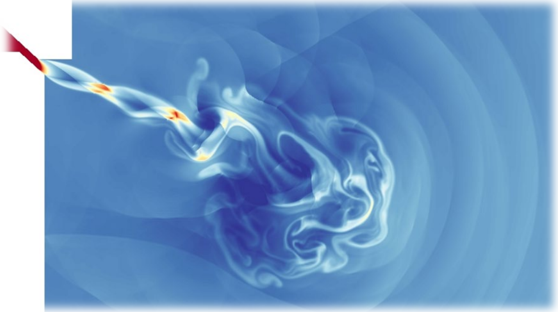
Any proposed future work is subject to change based on funding levels

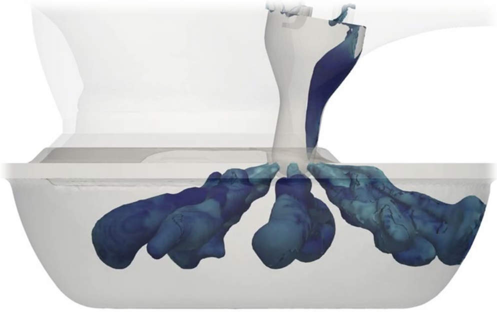
H2ICEs are both transitional and long-term technology solutions

H2ICEs can provide for a smooth, continuous transition as H2 supply and infrastructure develops

For some applications H2ICEs can be a preferred long-term solution

- **Continue work on factors limiting H_2 engine development, deployment, and acceptance:**
  - Power density
  - Range and duration
  - Emissions
  - Reliability and durability





- **New aftertreatment projects being started to control H2ICE emissions (NO_x).**

- **Key deliverables from all projects:**
  - Deeper understanding of the design and operational limits of various H2ICE technologies to guide technology selection
  - Knowledge and understanding of physical/chemical processes needed to guide technology development
  - Predictive computational design tools to enable engine optimization
  - Full-scale H2ICE development and demonstration