High-Throughput Hydrogen Fueling R&D at NREL

December H2IQ Hour Webinar
December 19, 2022

Shaun Onorato & Taichi Kuroki
National Renewable Energy Laboratory

DOE/Industry/Lab Partnership Achieves First-of-its-Kind Heavy Duty Fast Flow

Project Objectives

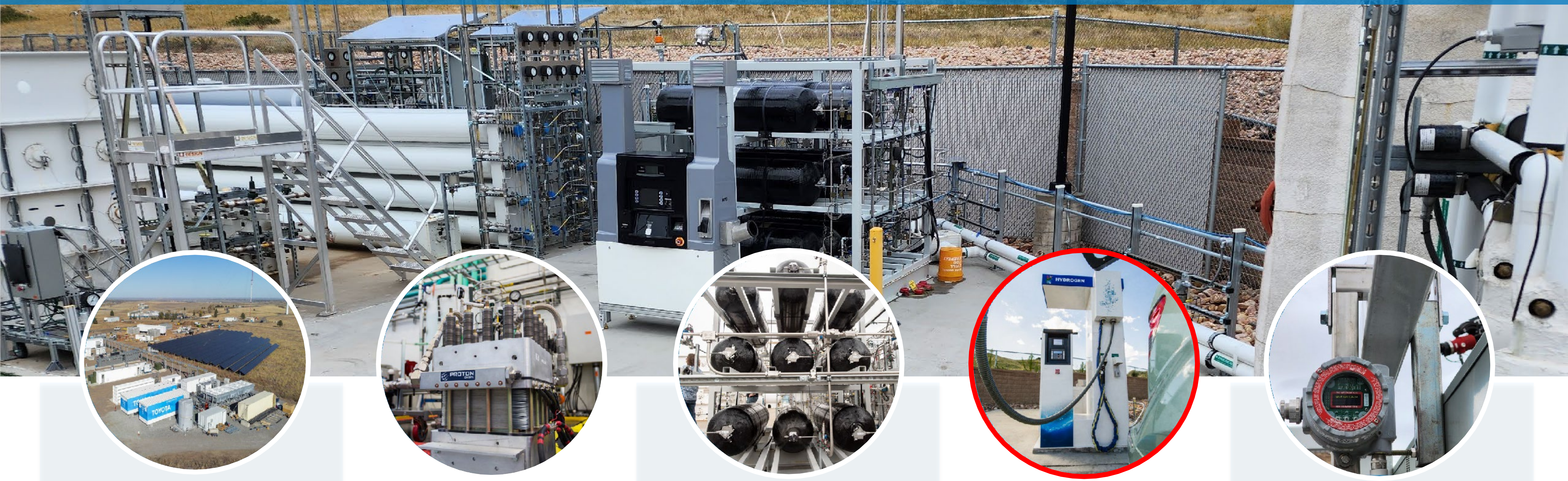
Heavy-duty research capabilities

Comprehensive high flow rate fueling models

Publicly available tools and data.

NREL Expansion Under the Innovating Hydrogen Stations Project

About NREL’s Hydrogen Infrastructure Research



Grid and Renewables Coupling

Electrolyzers as dispatchable loads in power systems, dynamic operations and integration with renewable production

Hydrogen Production

Full stack scale electrolyzer and BOP performance, system optimization when coupled to grid/renewables and end uses

Distribution and Storage

System scale distribution and storage challenges, vehicle and ground storage performance and modeling

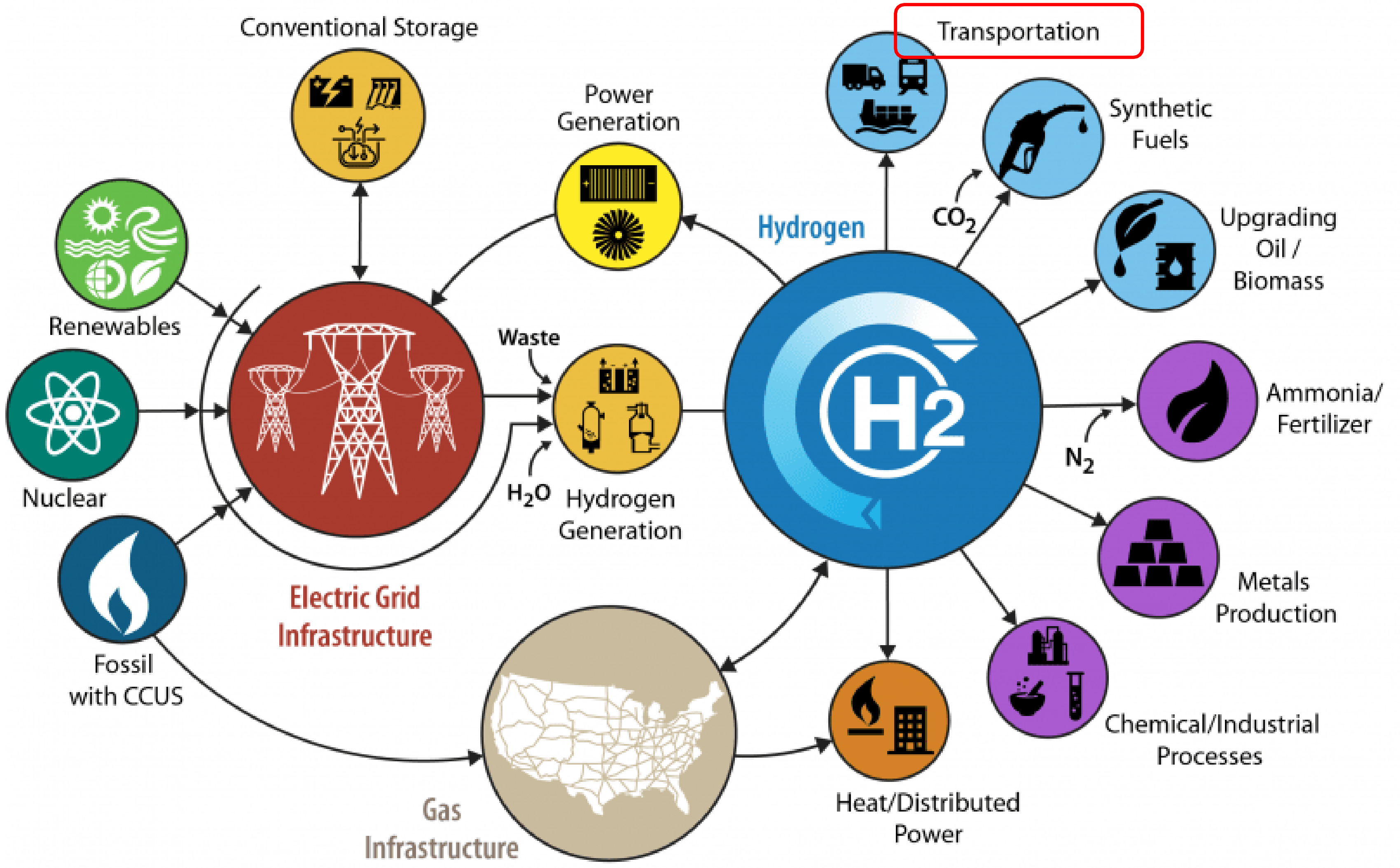
End Use Applications

Transportation applications, industrial applications, natural gas blending, renewable synthetic molecules

Safety and Sensors

Development and evaluation of safety and sensor systems, component failure characterization

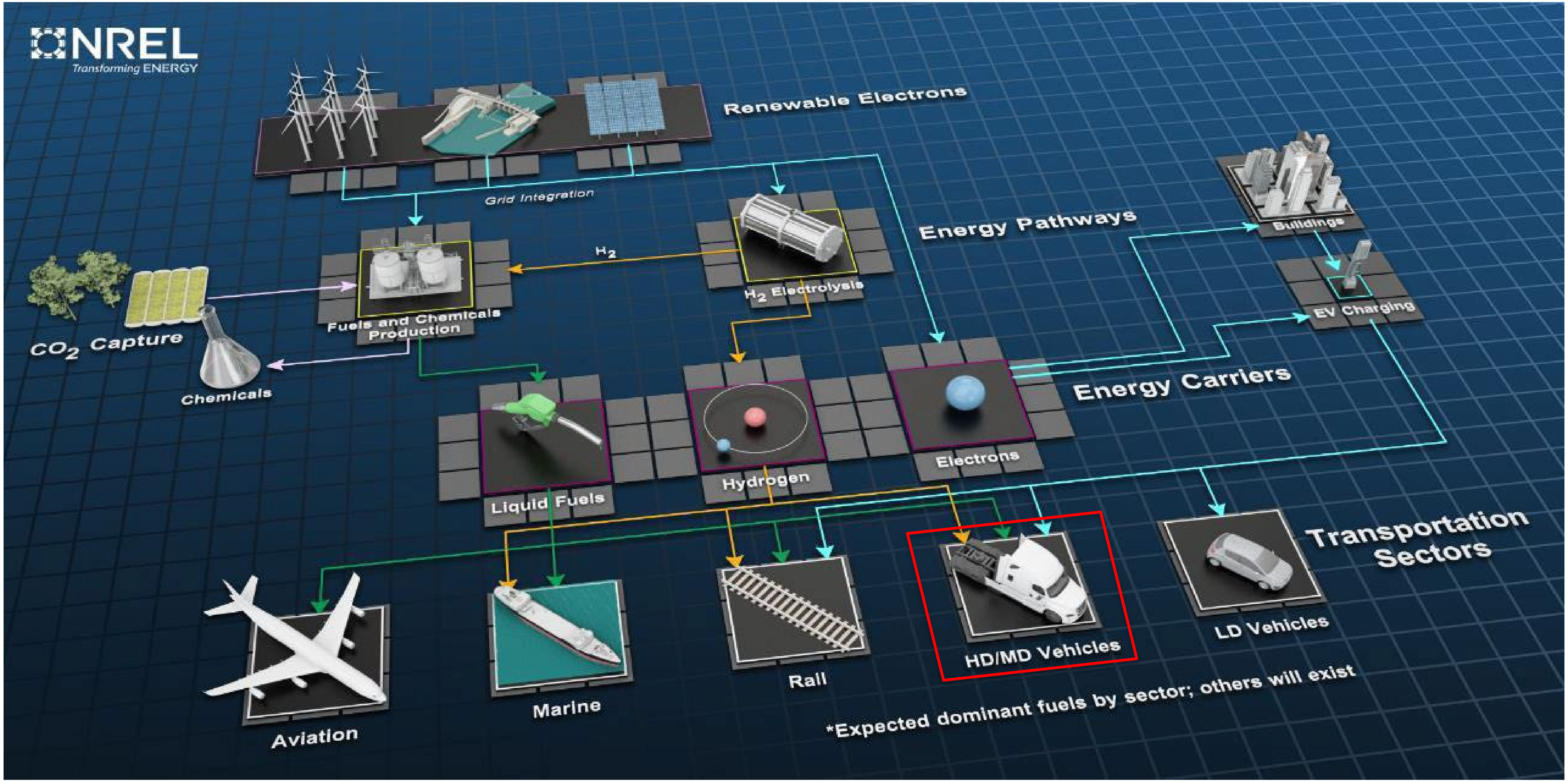
DOE's H2@SCALE Vision



https://www.energy.gov/eere/fuelcells/h2scale

DOE’s H2@SCALE Vision at NREL

NREL’s strategy for decarbonizing the transportation sector follows DOE’s H2@Scale vision



HD Fueling End Use Applications

Medium (MD) and heavy-duty (HD) hydrogen truck infrastructure R&D helps enable fast fueling and infrastructure for other emerging HD applications.

Photos: Toyota, Nikola, and Hyundai

Medium and Heavy-Duty Trucking

Focus Area

enables…

Photo: All American Marine Inc.

Marine & Port

Emerging Applications

Photo: Caterpillar

Mining & Industrial

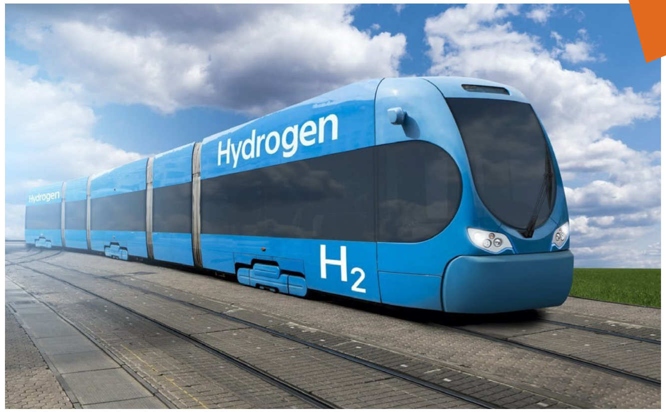


Photo: Global Railway Review

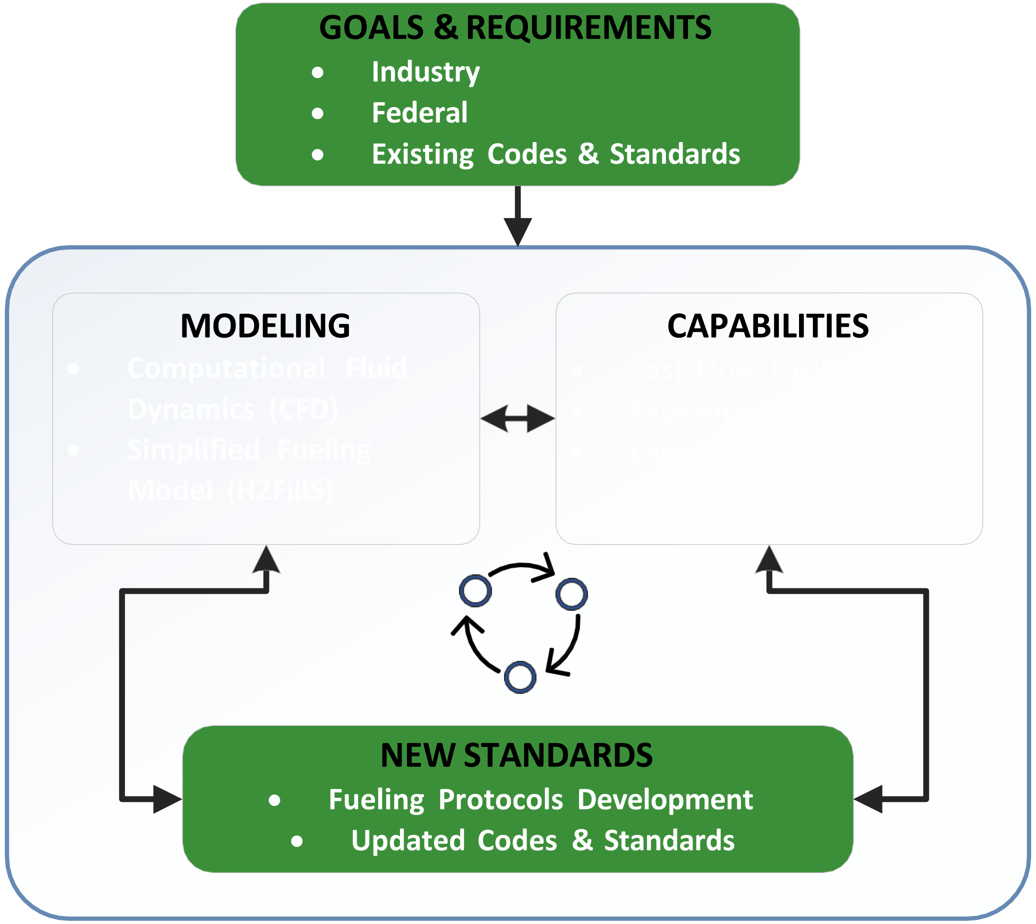
Freight & Passenger Rail

Photo: Airbus

Aviation

Fast Flow Hydrogen Fueling R&D

NREL's approach to fast flow hydrogen fueling R&D centered on:



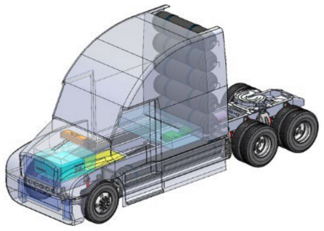


Table 1. Technical System Targets: Class 8 Long-Haul Tractor-Trailers (updated 10/31/19)

Characteristic	Units	Targets for Class 8 Tractor-Trailers	
		Interim (2030)	Ultimate[9]
Fuel Cell System Lifetime[1,2]	hours	25,000	30,000
Fuel Cell System Cost[1,3,4]	\$/kW	80	60
Fuel Cell Efficiency (peak)	%	68	72
Hydrogen Fill Rate	kg H_2/min	8	10
Storage System Cycle Life[5]	cycles	5,000	5,000
Pressurized Storage System Cycle Life[6]	cycles	11,000	11,000
Hydrogen Storage System Cost[4,7,8]	\$/kWh (\$/kg H_2 stored)	9 (300)	8 (266)

Source: https://www.hydrogen.energy.gov/pdfs/19006_hydrogen_class8_long_haul_truck_targets.pdf

NREL HD Research Capability Design

Heavy-Duty Hydrogen Fast Flow Facility

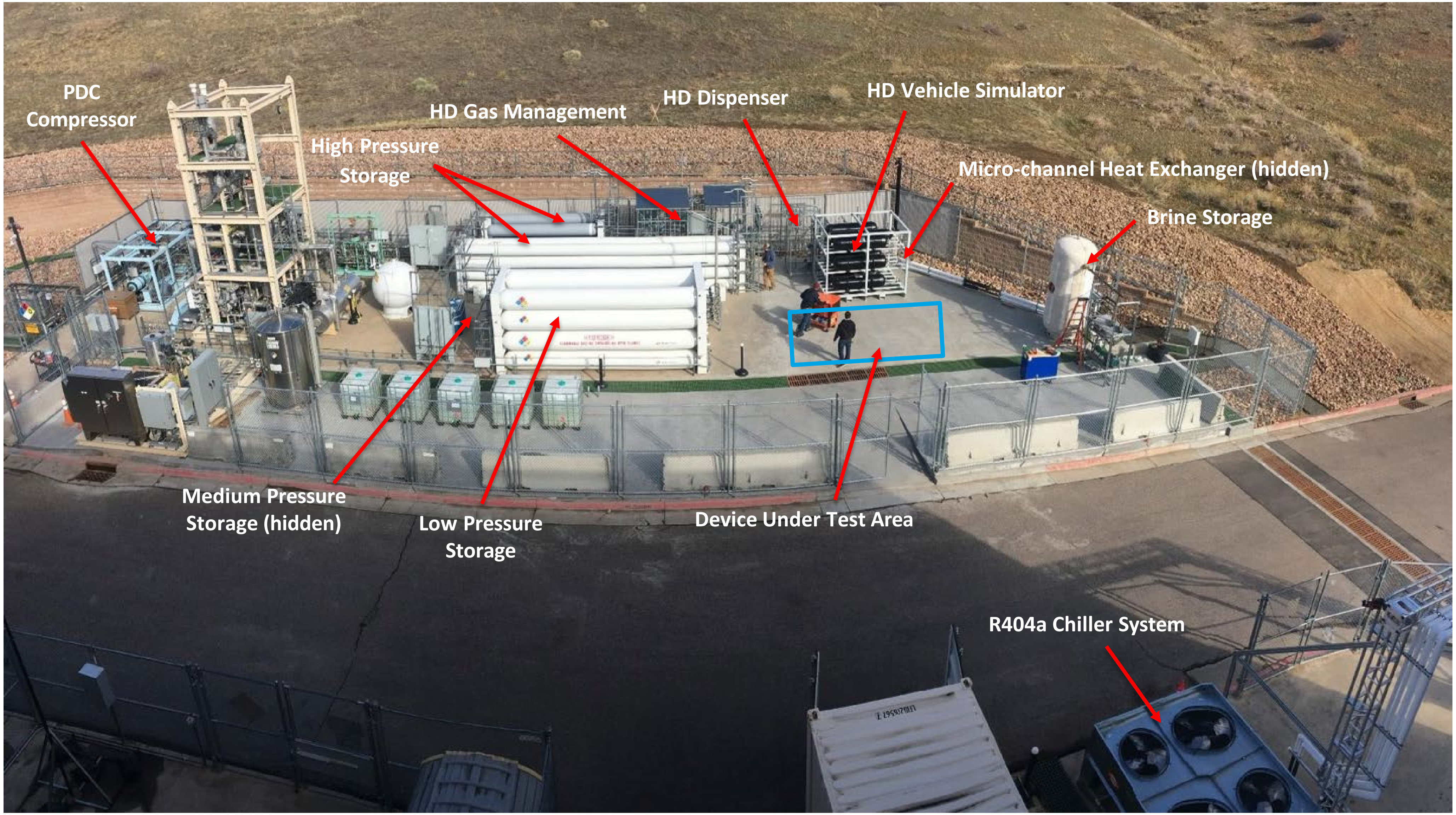
First-of-its-kind, experimental research capability for medium and heavy-duty fueling R&D

- Located: Energy Systems Integration Facility (ESIF)
  - Golden, Colorado, USA
- Leverages legacy light-duty station capabilities
- Fueling capability (gaseous): 70 MPa, -40°C precooling, 10 kg/min average (20 kg/min peak), and 80+ kg fill mass into a heavy-duty vehicle simulator.
- Operational: July 2022
- ~650 kg bulk gas storage (L, M, HP)
- Limited back-to-back fueling capability

√ **Enables HD fueling protocols, components, and hardware evaluations**

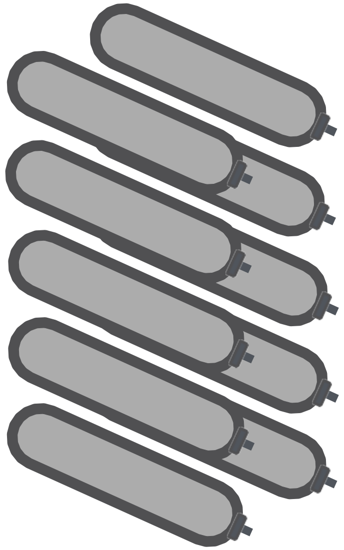
√ **Publicly available modeling tools and data for hydrogen infrastructure stakeholders**

Heavy-Duty Hydrogen Fast Flow Facility



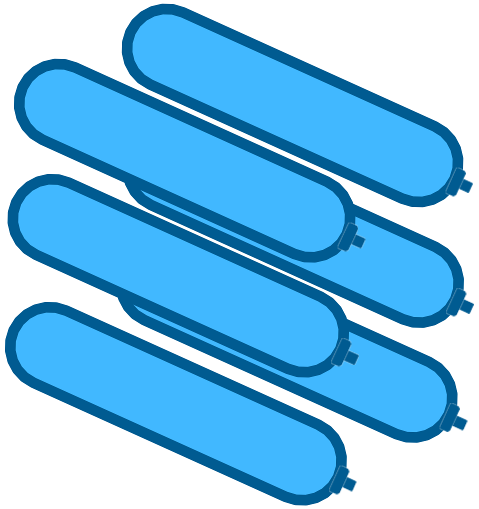
Pressurized Ground Storage for HD Fills

Low Pressure Storage



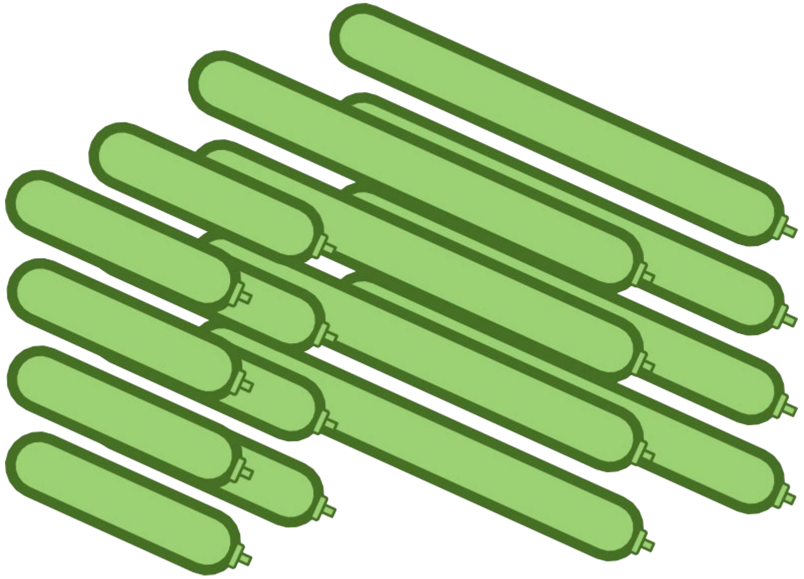
10X - 18 kg/tank
Type I
Total: 180 kgs

Medium Pressure Storage



6X - 13.5 kg/tank
Type I
Total: 81 kgs

High Pressure Storage



8X - 16 kg/tank
Type II
Total: 128 kgs

8X - 32 kg/tank
Type I
Total: 256 kgs

~650 kg total storage

Cascade approach:

- Low: 20.7 MPa (3,000 psig)
- Medium: 41.4 MPa (6,000 psig)
- High: 93 MPa (13,500 psig)

Demonstrated:

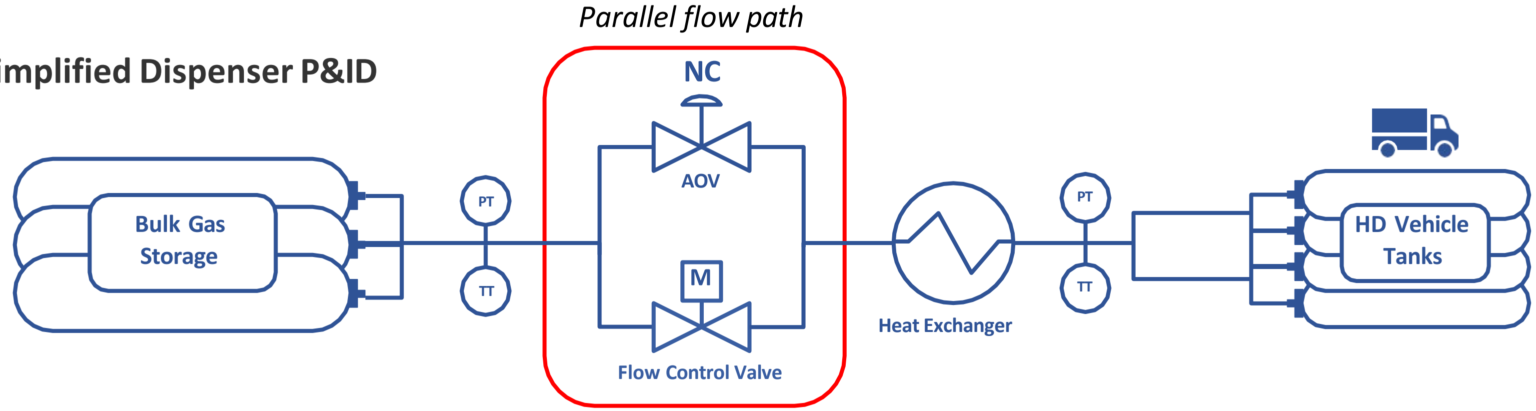
~80 kgs transfer using MP and HP storage (all HDVS tanks)

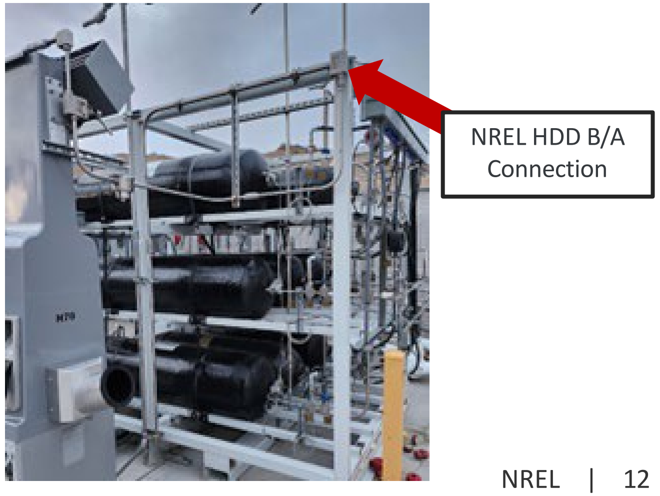
~60 kgs transfer using only HP into 7 Type IV tanks on HDVS

Heavy-Duty Dispenser (HDD)

- 1” & ¾” OD – 20,000 psig rated stainless tubing and air-operated valves (AOV)
  - Largest commercially available hydrogen components when built
- Utilizes a parallel path flow control strategy comprised of:
  - 9/16” mechanical flow control valve (needle regulation type)
  - 9/16” open-close air-operated valve (AOV)
- Direct, hard-piped connection to HDVS (current configuration)
  - Twin ¾” 20,000 psig tubing connection acts as isolation from HDVS (reducing code setback distances from fire lanes)
  - Connection exists for breakaway mount for a nozzle assembly
- Full hydrogen recirculation capability - reduces cost, down time, storage size
  - HDVS acts as a “tube trailer delivery” per NFPA 2 code

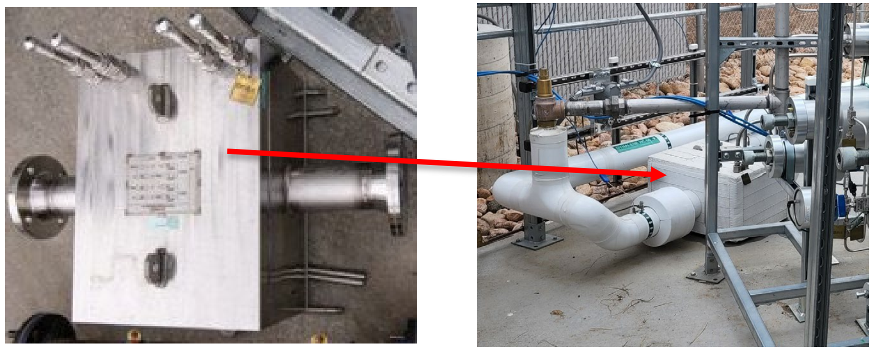
Simplified Dispenser P&ID





Heavy-Duty Pre-cooling System

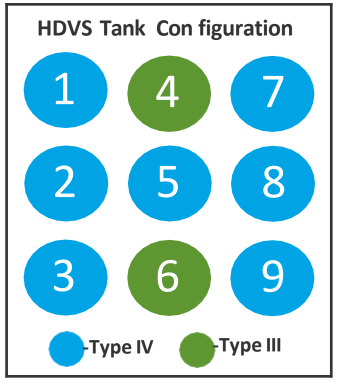
- Instantaneous pre-cooling of hydrogen gas from ambient to -40°C
  - Per SAE J2601
- Twin 30 HP chilling circuits chill brine system
- 1,200 gallon brine storage tank
  - Potassium formate - water-based heat transfer fluid/coolant
  - (-50°C to 218°C)
- Custom microchannel diffusion-bonded heat exchanger
  - 20 kg/min peak mass flow rate (gaseous)
  - Low rated pressure drop
  - 500 kW of heat load absorption



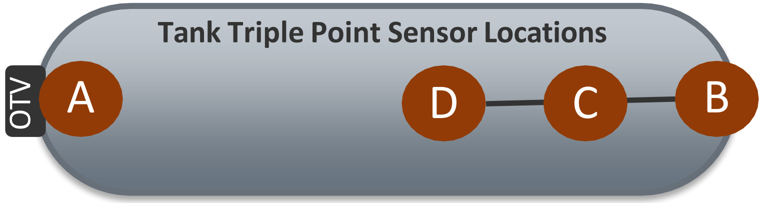
Microchannel Heat Exchanger

Heavy-Duty Vehicle Simulator (HDVS)

- <u>Simulates 1x Class 8 semi-truck</u>
- 9x tanks total (max 86 kg fill) - configurable
    - 7x Type IV tanks (60+ kg fill, 85°C rated)
    - 2x Type III tanks (20+ kg fill, 125°C rated)



- Utilizes automotive on-tank-valves (OTVs) with integrated bulk gas temp sensors and thermal pressure relief devices (TPRDs).
- Triple point sensors (2x) installed within each Type IV & III tanks.



NREL Heavy-Duty Vehicle Simulator (HDVS)

- Additional pressure transducers (PTs) installed at rear of tanks.
- Tank manifold instrumented and built for consistent inlet conditions.

Fast Flow Test Summary

HD Fast Flow Testing Achievements

Industry and DOE Target Metrics:

Mass	Mass Flow	Time	Pressure	Temperature	Vehicle
60-100kg	Average: 10 kg/min Peak: 20 kg/min	<10 minutes	70 MPa	-40 C	Within tank temperature & pressure limits

Major milestone fast flow tests completed:

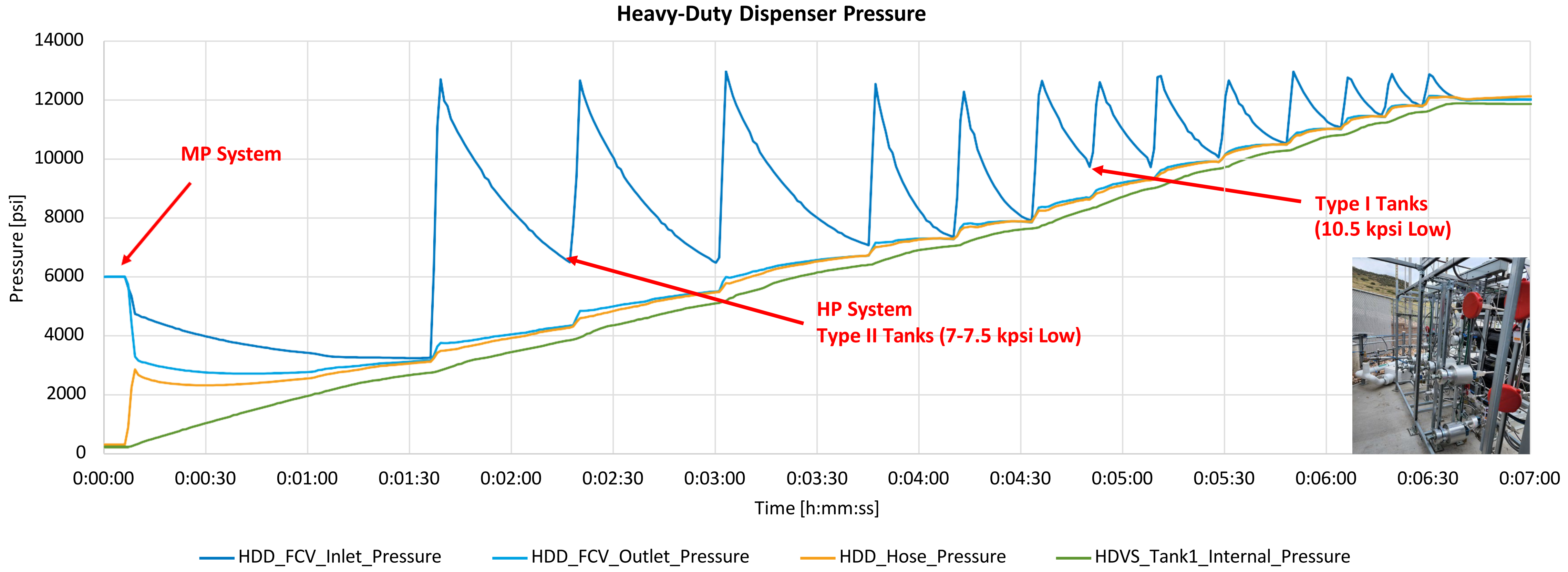
Date (mo./yr.)	Fill Mass (kg)	Time (mins)	Average Mass Flow Rate (Kg/min)	Peak Mass Flow Rate (Kg/min)	SOC (%)	Notes
08/2022	61.5	4.7	13.2	18.7	94%	Type IV Only (60 kgs)
10/2022	**82.3**	6.6	12.6	23	100%	Complete HDVS (>80 kgs)

Met all industry and DOE target metrics for fast-fill tests into the heavy-duty vehicle simulator

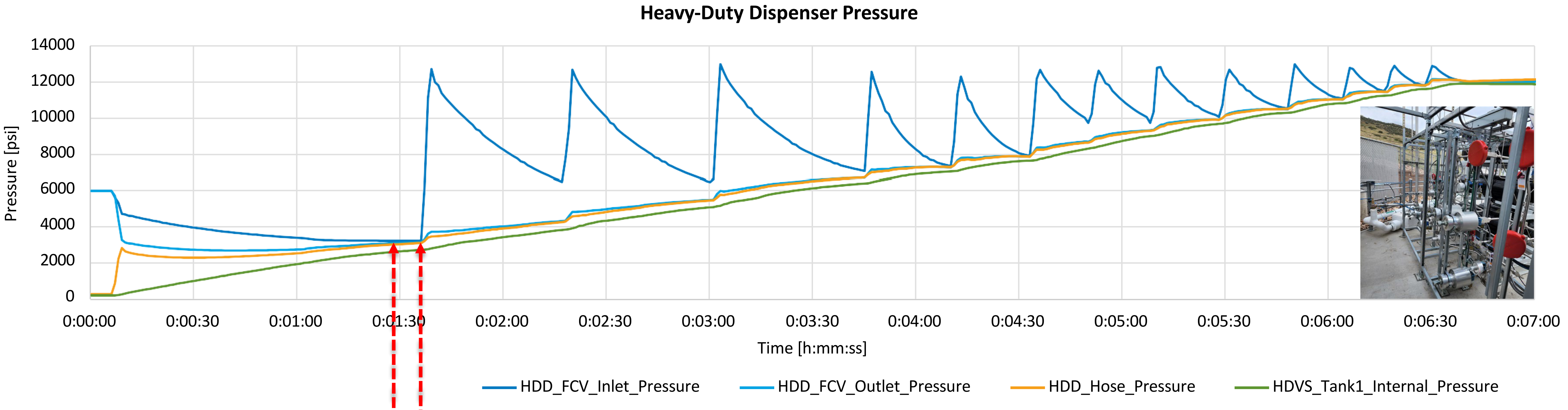
82.3 kg Flow Test – Experimental Results

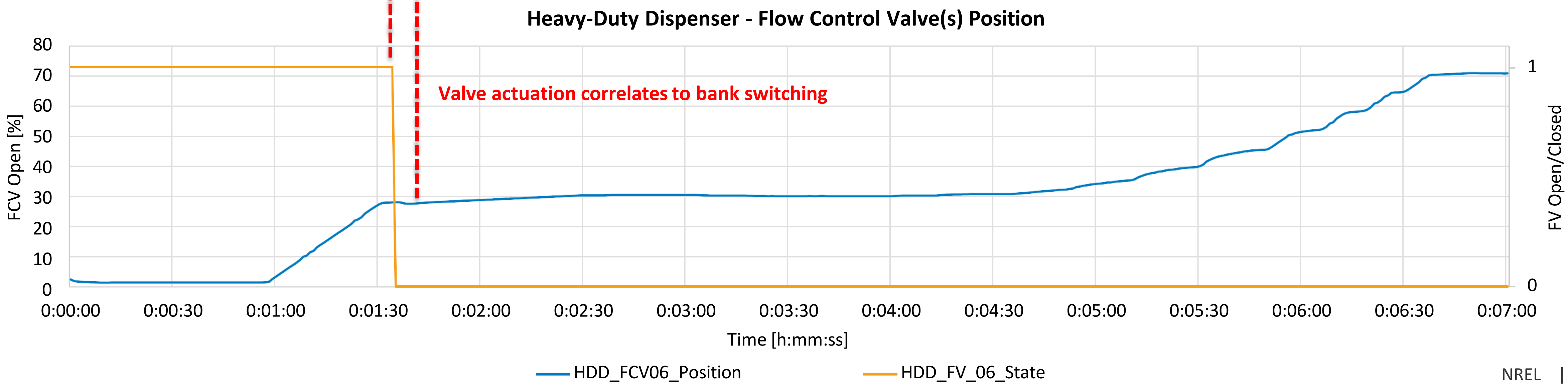
Date: 10/6/2022
Mass Transfer: 82.3
Time: 6 minutes 33 seconds (<10 minute target)
Average Mass Flow Rate: 12.57 kg/min (10 kg/min target)
Peak Mass Flow Rate: 23 kg/min (20 kg/min target)

Configuration: 9 tanks - Type IV and III
Starting/Ending Pressure : 1.52 MPa (220 psig)/ 83.4 MPa (12,100 psig)
APRR: 12.3 MPa/min (1,778 psig/min)
HDVS SOC: 100%
Ambient Temperature: 19°C

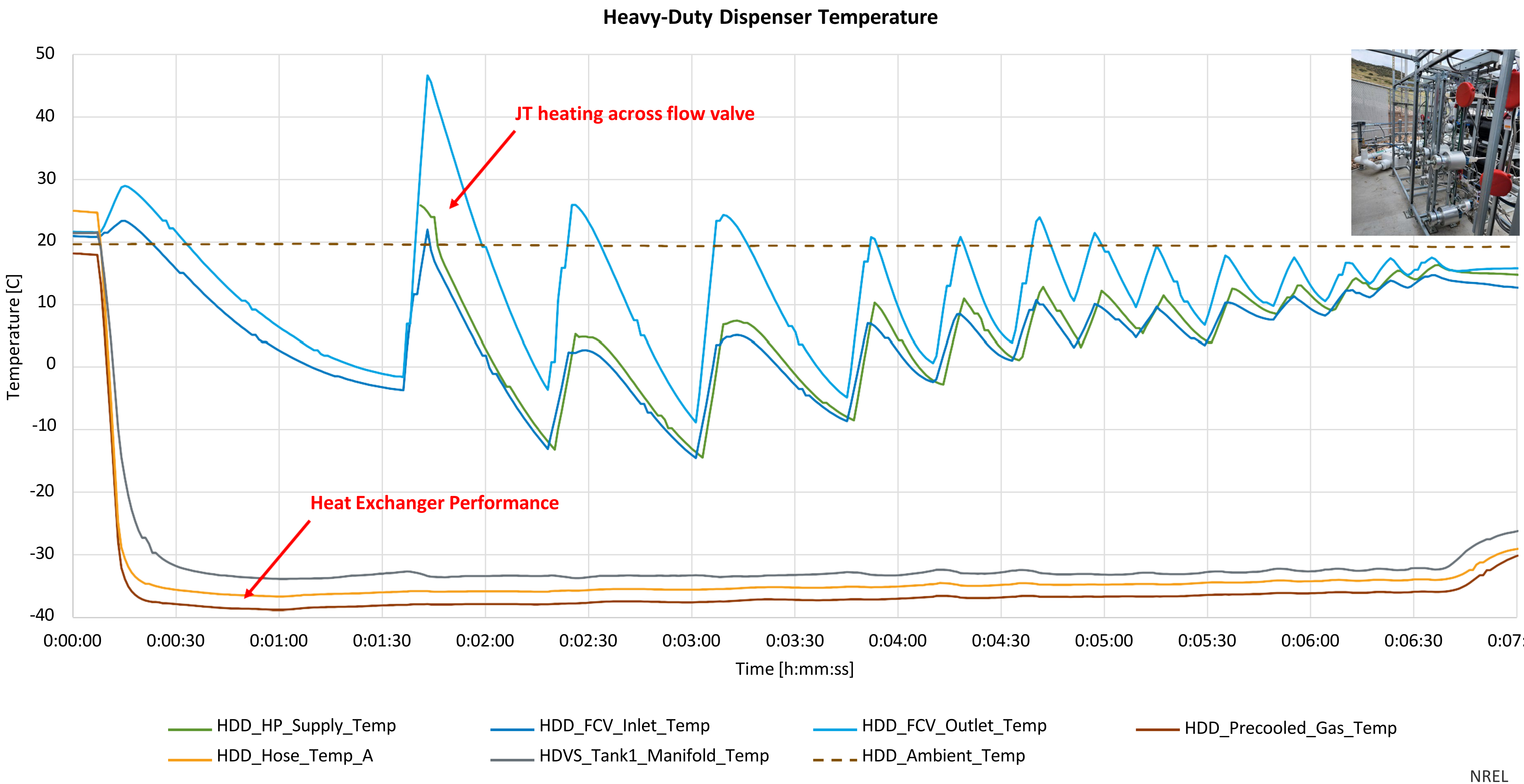


Flow Control Valve Actuation

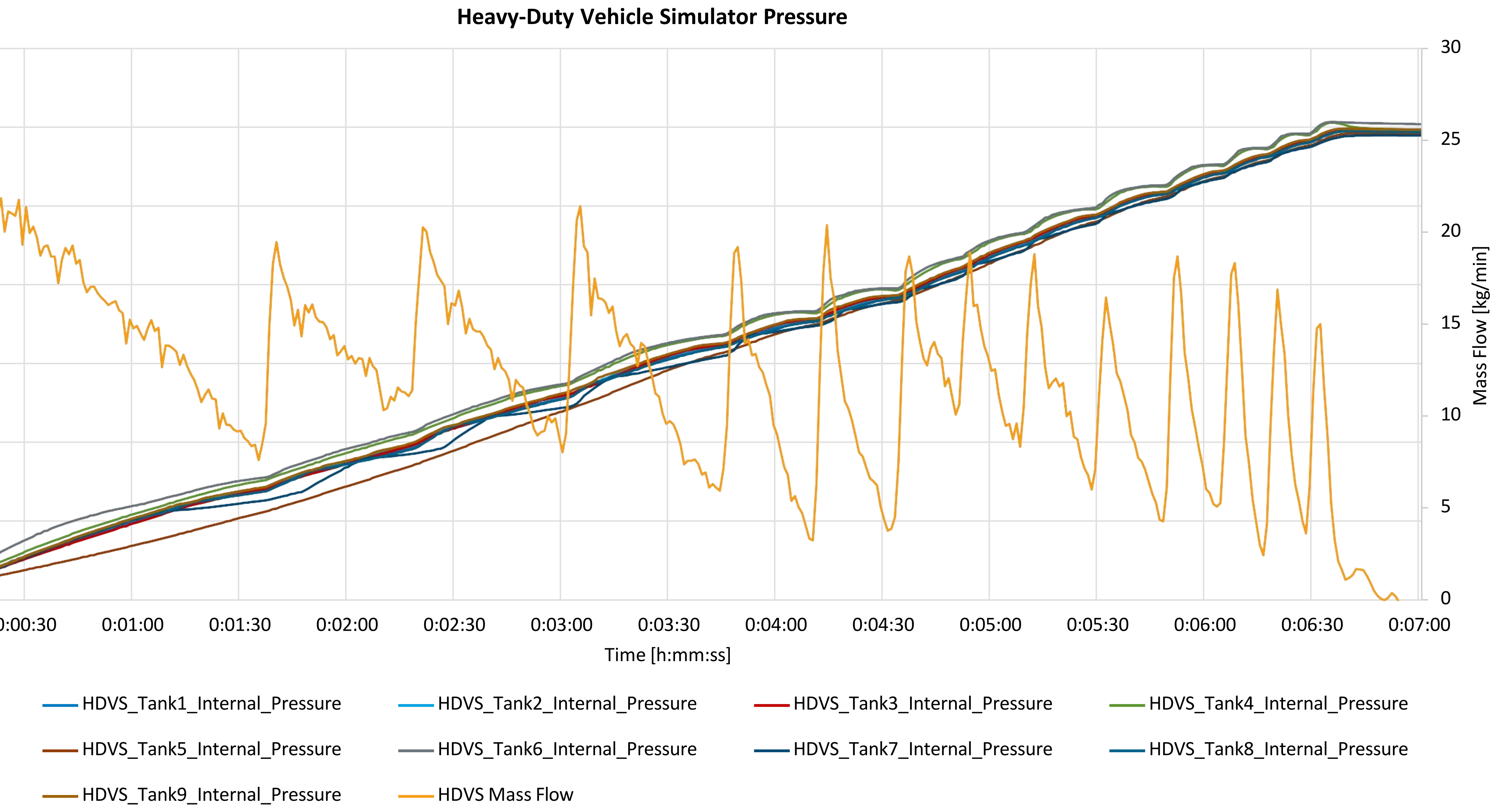


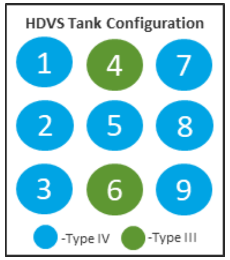


Heavy-Duty Dispenser Temperature

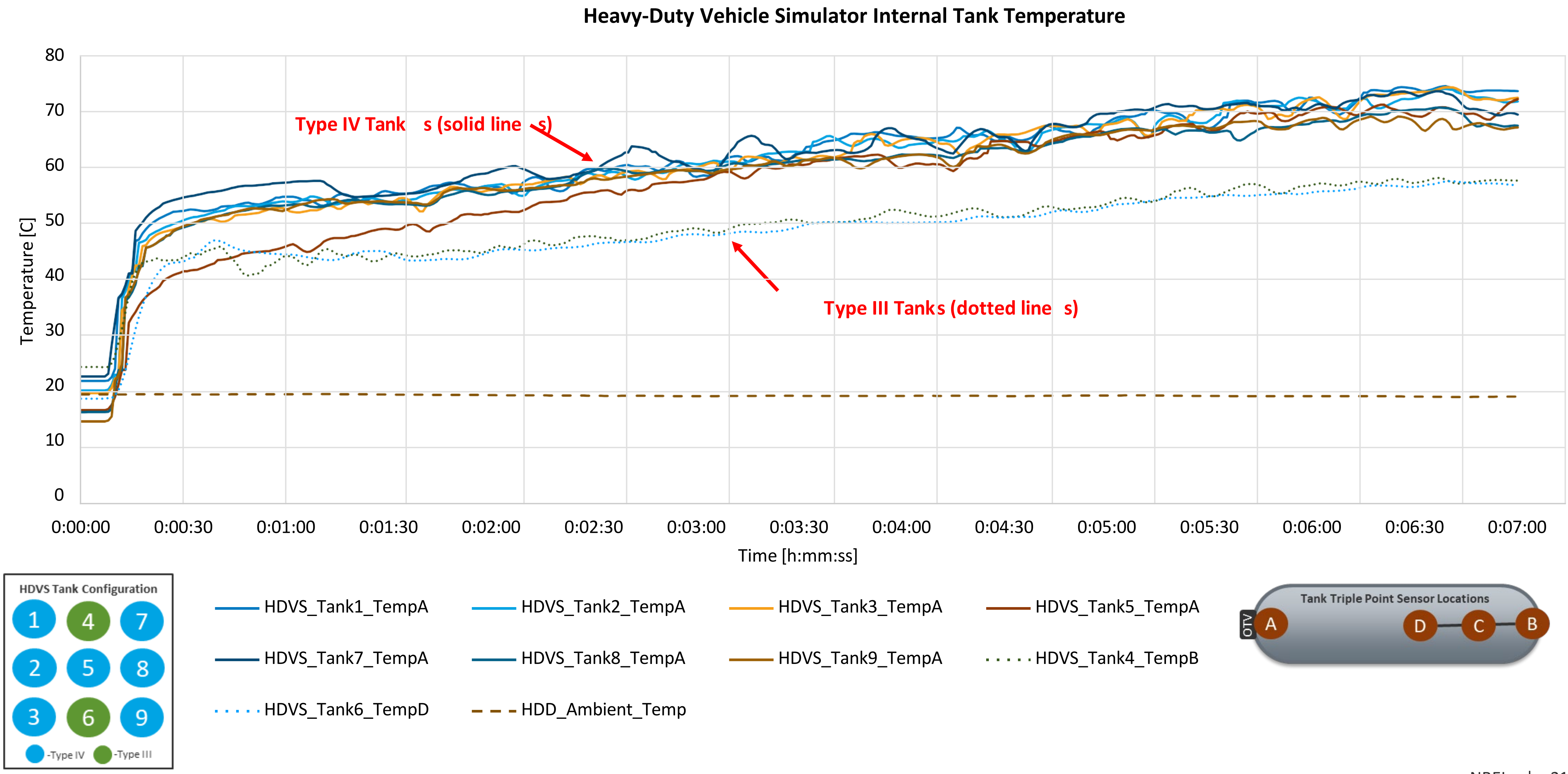


Heavy-Duty Vehicle Simulator Pressure and Mass Flow

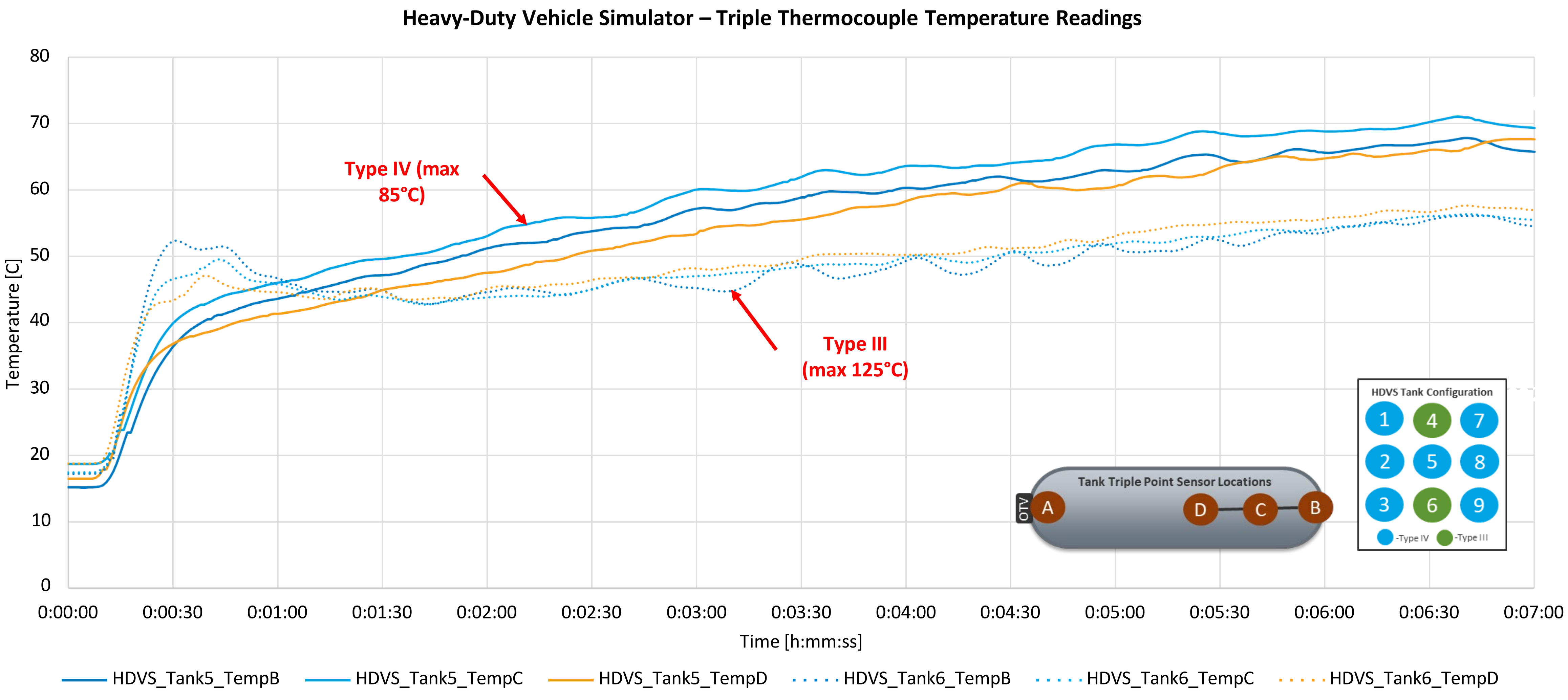




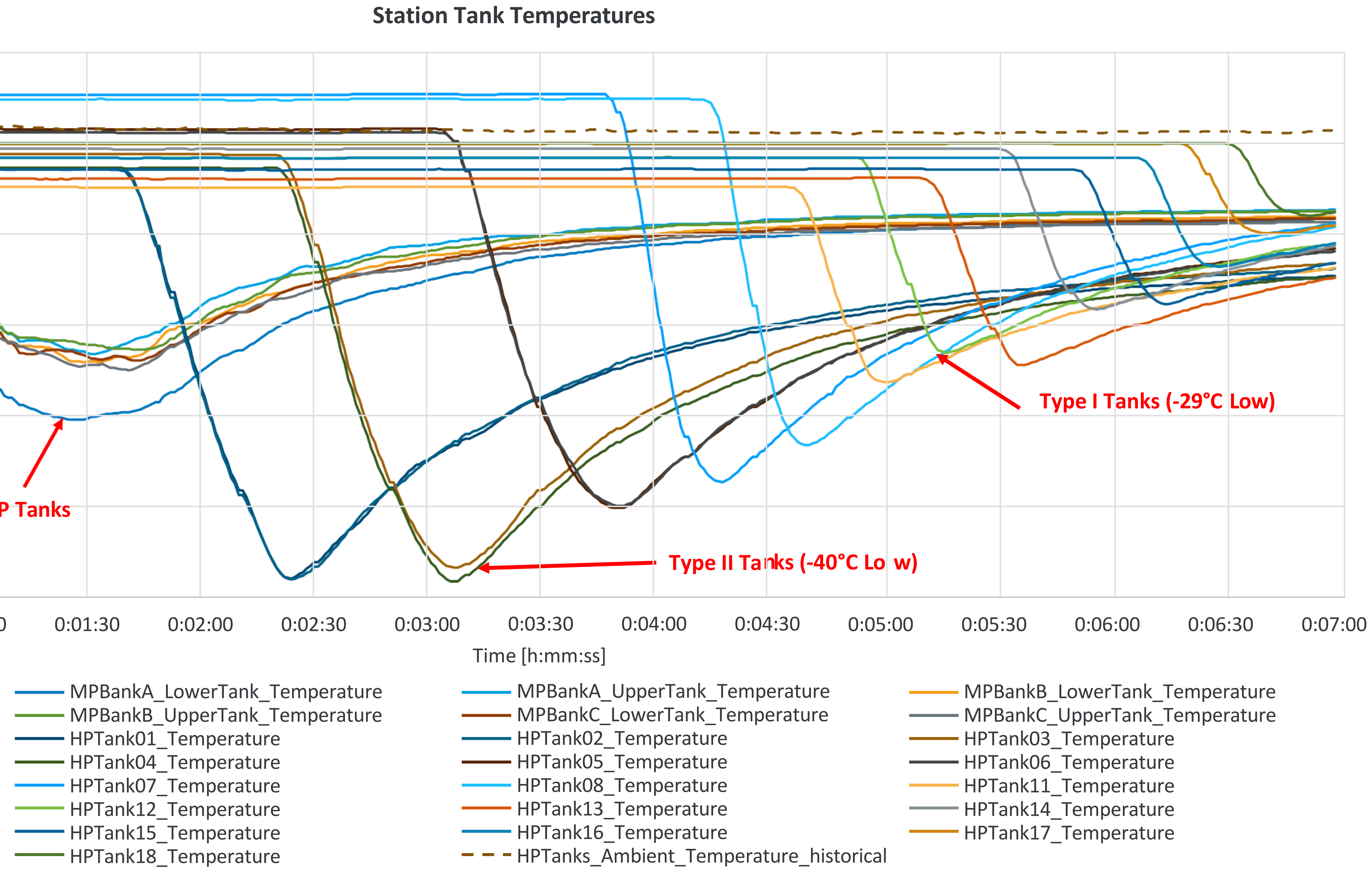
Heavy-Duty Vehicle Simulator Internal Tanks Temperatures



Heavy-Duty Vehicle Simulator Triple Point Temperature Sensors

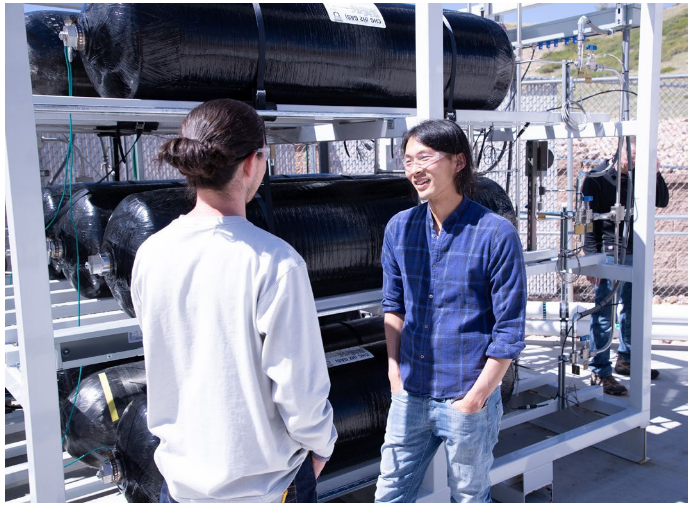


Hydrogen Station Storage Tank Temperatures



Engineering Challenges

- Bank switching strategies from bulk gas storage tanks
  - Somewhat unique to the NREL research facility
- Implementation of multiple sensors required within vehicle tanks to accurately observe internal tank conditions.
  - Pressure and multiple temperature measurements
  - Reliability of OTV readings
- Flow control valve actuation times result in major lag during dynamic processes
  - Potential limiting factor for implementation of new fueling protocols.
- Accuracy of mass flow readings for fast flow testing
  - Required for implementation of fueling protocols
  - NREL to implement a meter when received (current supply chain constraints)



NREL HD Modeling & Computational Fluid Dynamics

Overview of Hydrogen Fueling Models

<u>Modeling work</u>

- 1-dimensional hydrogen filling simulation (H2FillS) model
- 3-dimensional computational fluid dynamics (CFD) model

These models are physics-based thermal fluid models to evaluate the changes in hydrogen temperature, pressure, and mass in fueling system components during the fueling process.

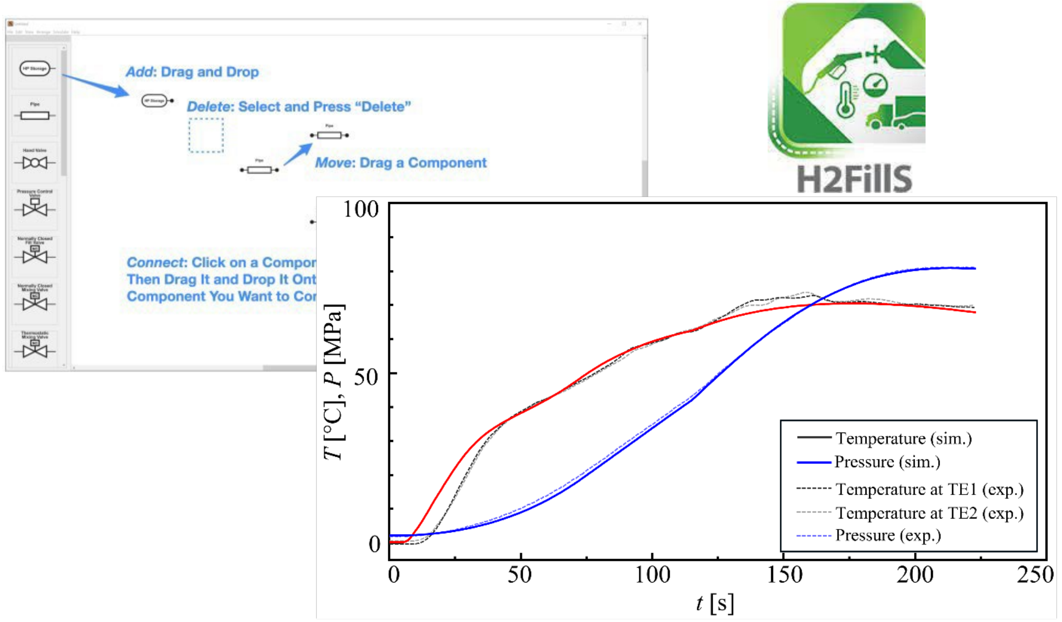
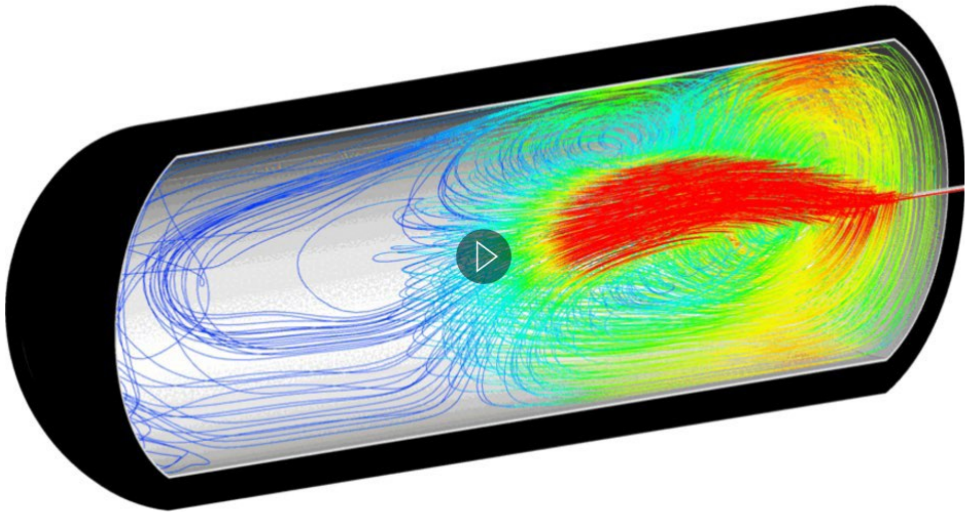


Fig. H2FillS’ GUI and simulation result



CFD - Stream lines of hydrogen flow

- H2FillS is openly available to the public: https://www.nrel.gov/hydrogen/h2fills.html
- The current version is specifically for light-duty fueling
- We have upgraded H2FIllS for heavy-duty fueling (HD-H2FillS), and the upgraded model will be distributed to the public early next year.

Hydrogen Filling Simulation (H2FIllS)

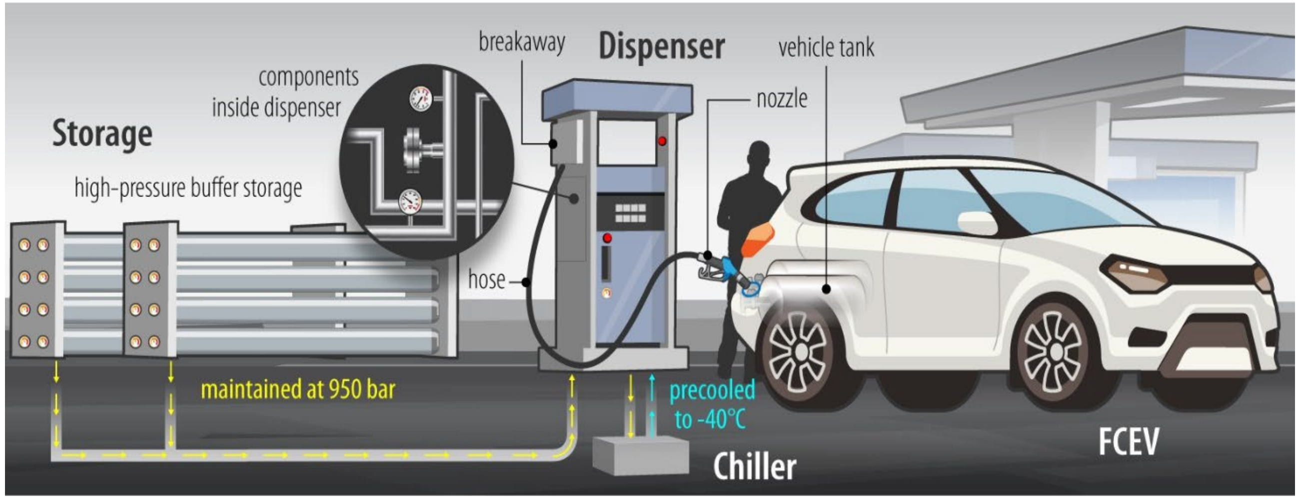


Fig. Hydrogen fueling station

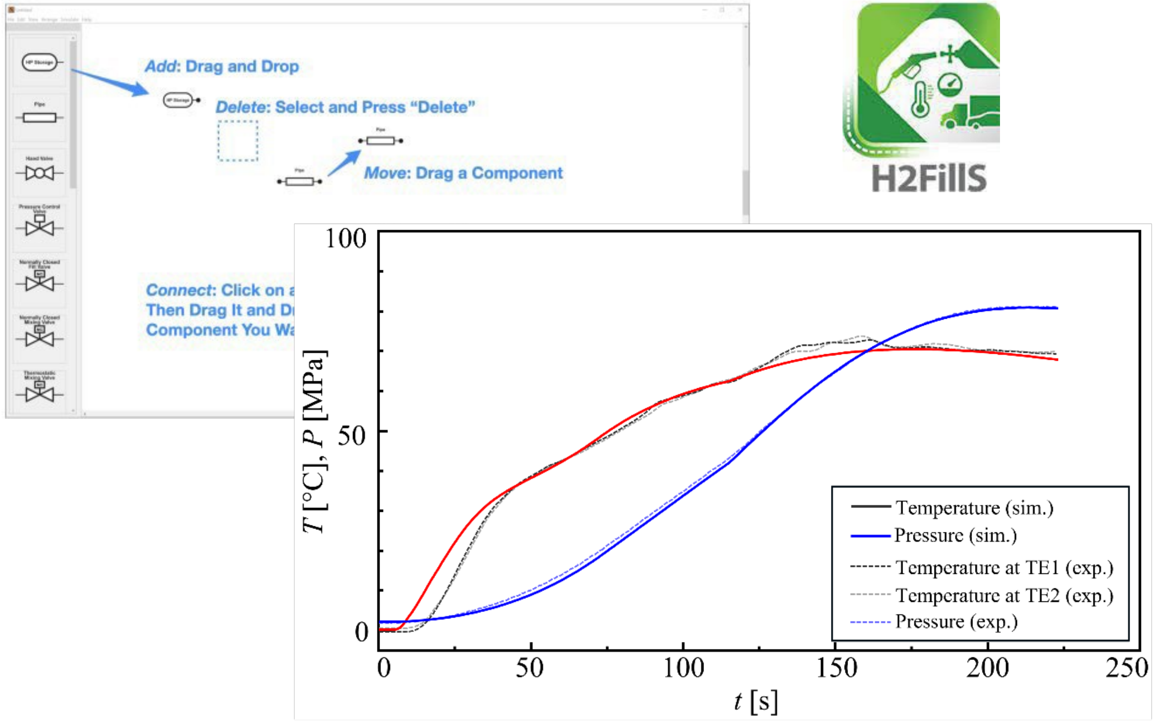


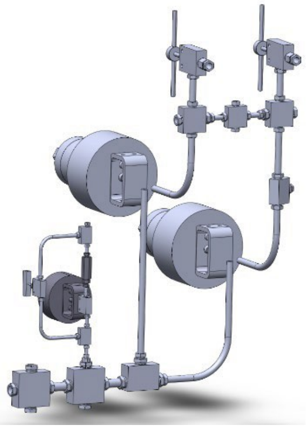
Fig. H2FillS' GUI and simulation result

- H2FillS simulates the real-world fueling process from the high-pressure storage system to the vehicle CHSS.

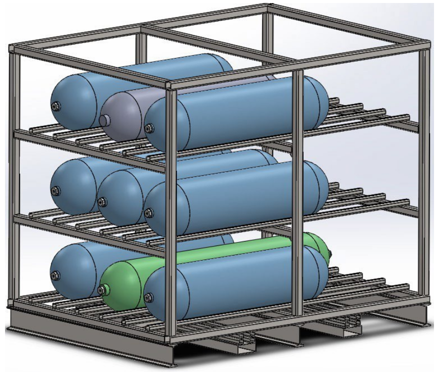
Advantage: Enables station and vehicle design optimization through individual component's influence on fueling performance (i.e. change in temperature and pressure, and pre-cooling system impacts on vehicle CHSS).

Disadvantage: Cannot simulate temperature distributions within components (i.e. in vehicle tanks). *CFD is needed*.

Fueling Experiment for Model Validation



HD dispenser (HDD)



HD vehicle simulator (HDVS)

Set specifications

Set specifications

H2FillS

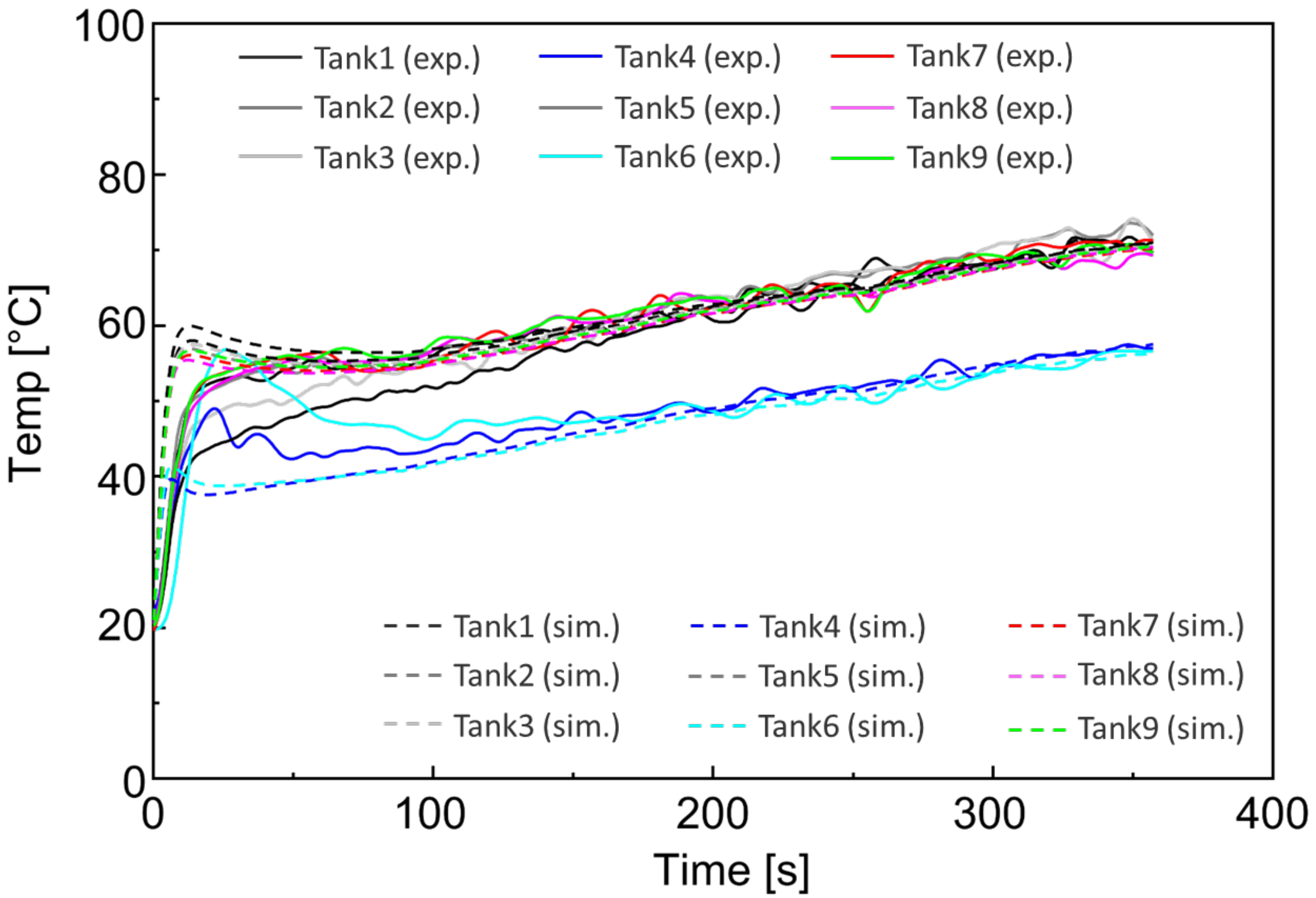
Set test conditions

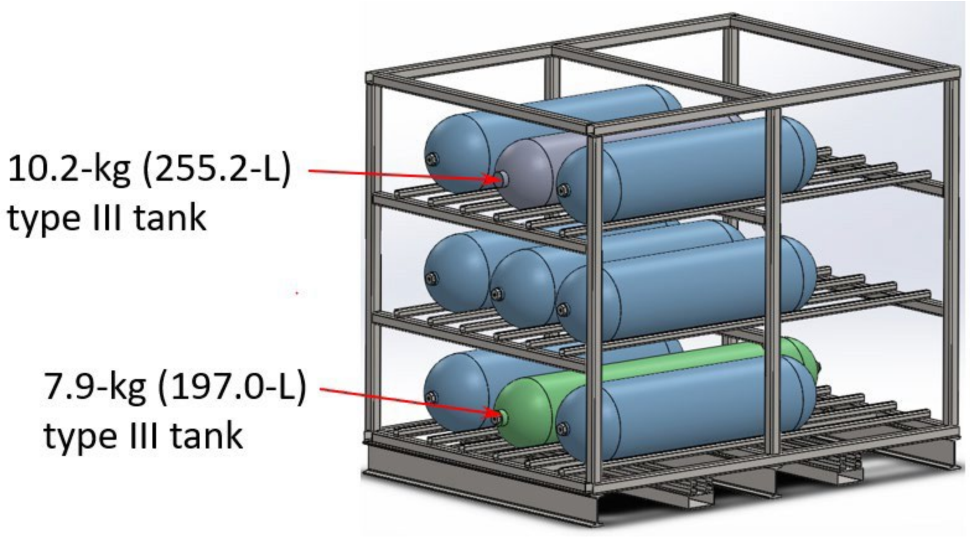
Fill conditions

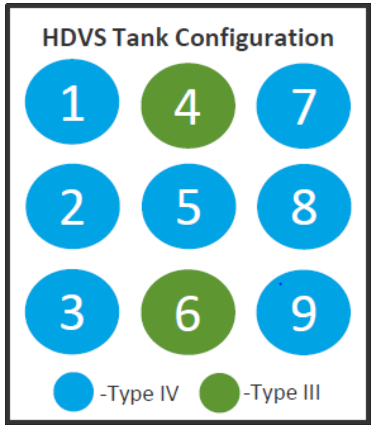
Name	Value
Ambient temp	23.0°C
HDVS size	86.8 kg
HDVS initial gas press	1.7 MPa
HDVS ending gas press	76.2 MPa
Fill time	360 s
Corresponding pressure ramp rate	12.4 MPa/min
Time-averaged mass flow	13.1 kg/min
Peak mass flow rate	23.2 kg/min

- Set the specifications of NREL's HD dispenser (HDD) and vehicle simulator (HDVS).
- Set the test conditions to the model in the table and then ran a simulation.

Comparison of HDVS Tank Gas Temperatures

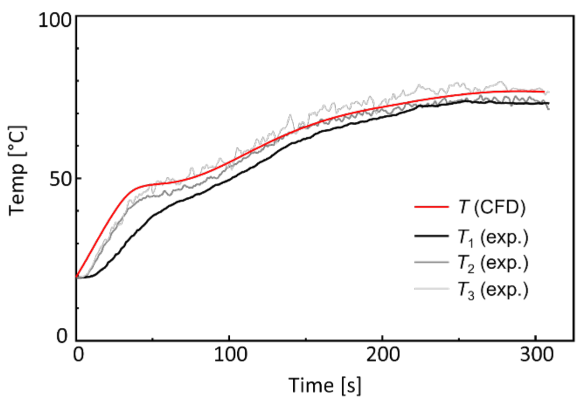


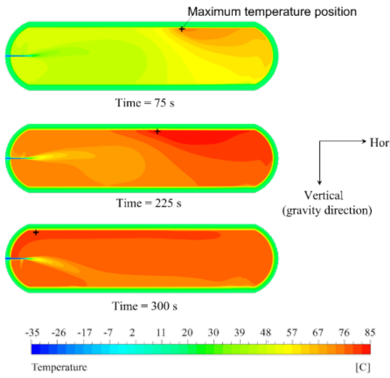


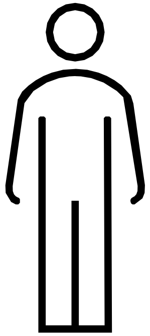


- The difference between the simulated and experimental values is large at the beginning of the fill, but the difference decreases towards the end of the fill.

Computational Fluid Dynamics (CFD)







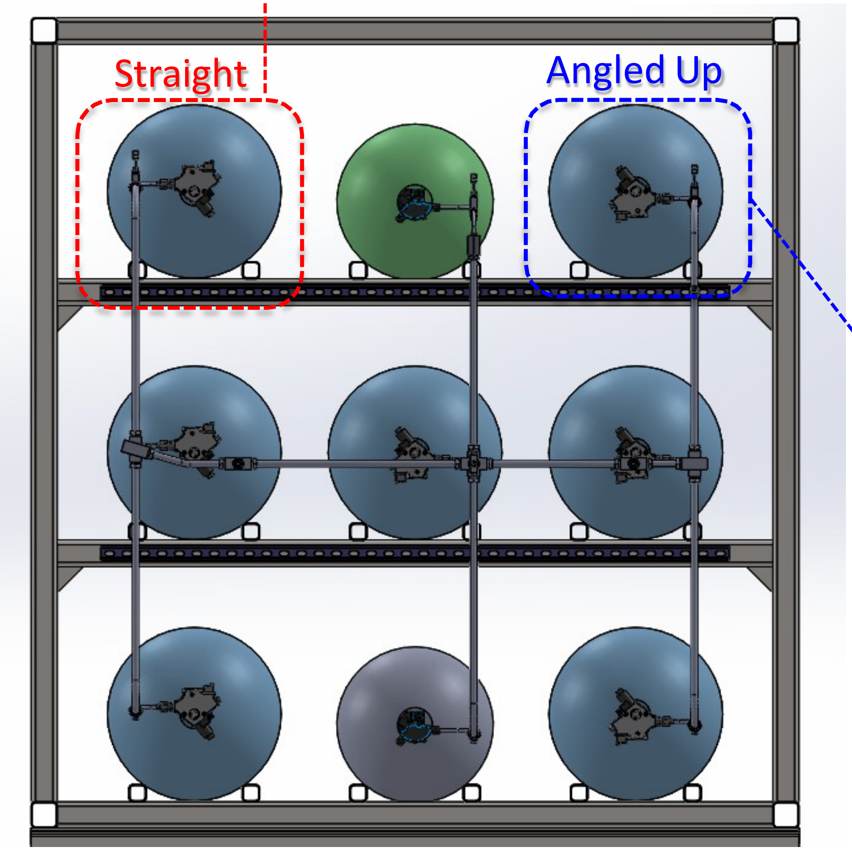
Access to HPC with ANSYS Fluent

Fig. NREL's High Performance Computer (HPC)

- CFD modeling work allows us to simulate thermal and flow fields inside/outside components.
  - This capability makes up for H2FillS' primary disadvantage.
- 3D CFD simulations are computationally expensive, CFD modeling work leverages NREL's high performance computer system (HPC) - super computer.

CFD Modeling Work

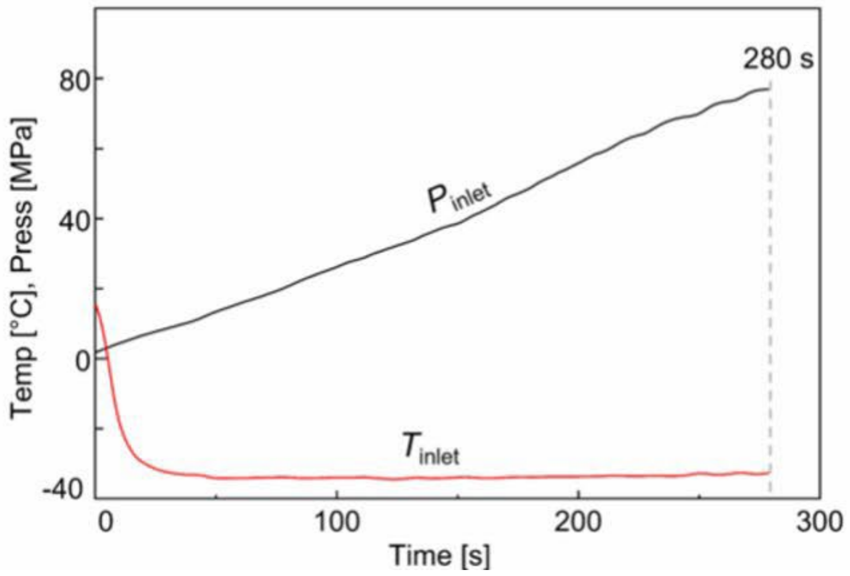
- Ran fast-fill CFD simulations with 9.8 kg type IV tanks that are installed in NREL's HDVS
  - The injector shapes in the two tanks are different, so the NREL team evaluated the impact of the injector shapes on the hydrogen temperatures.

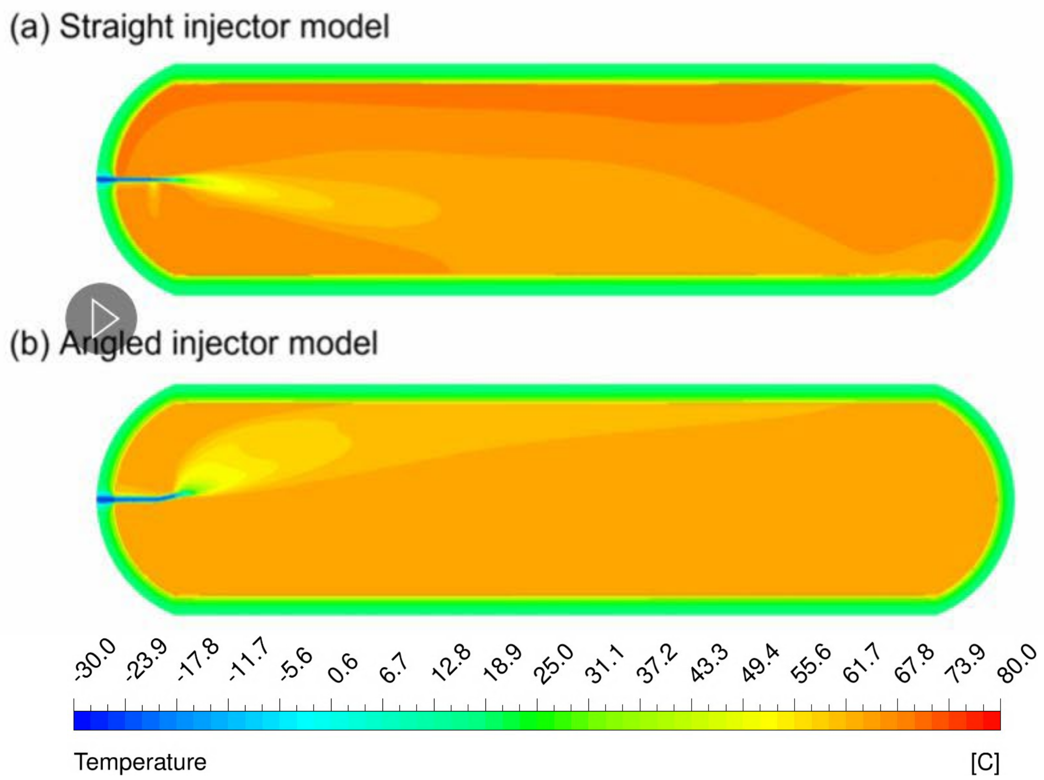


(a) Straight injector model
- Inner diameter: 5.4 mm

(B) Angled injector model
- Inner diameter: 5.4 mm
- Angle: 12 deg.

Thermal Fields during Fueling Process





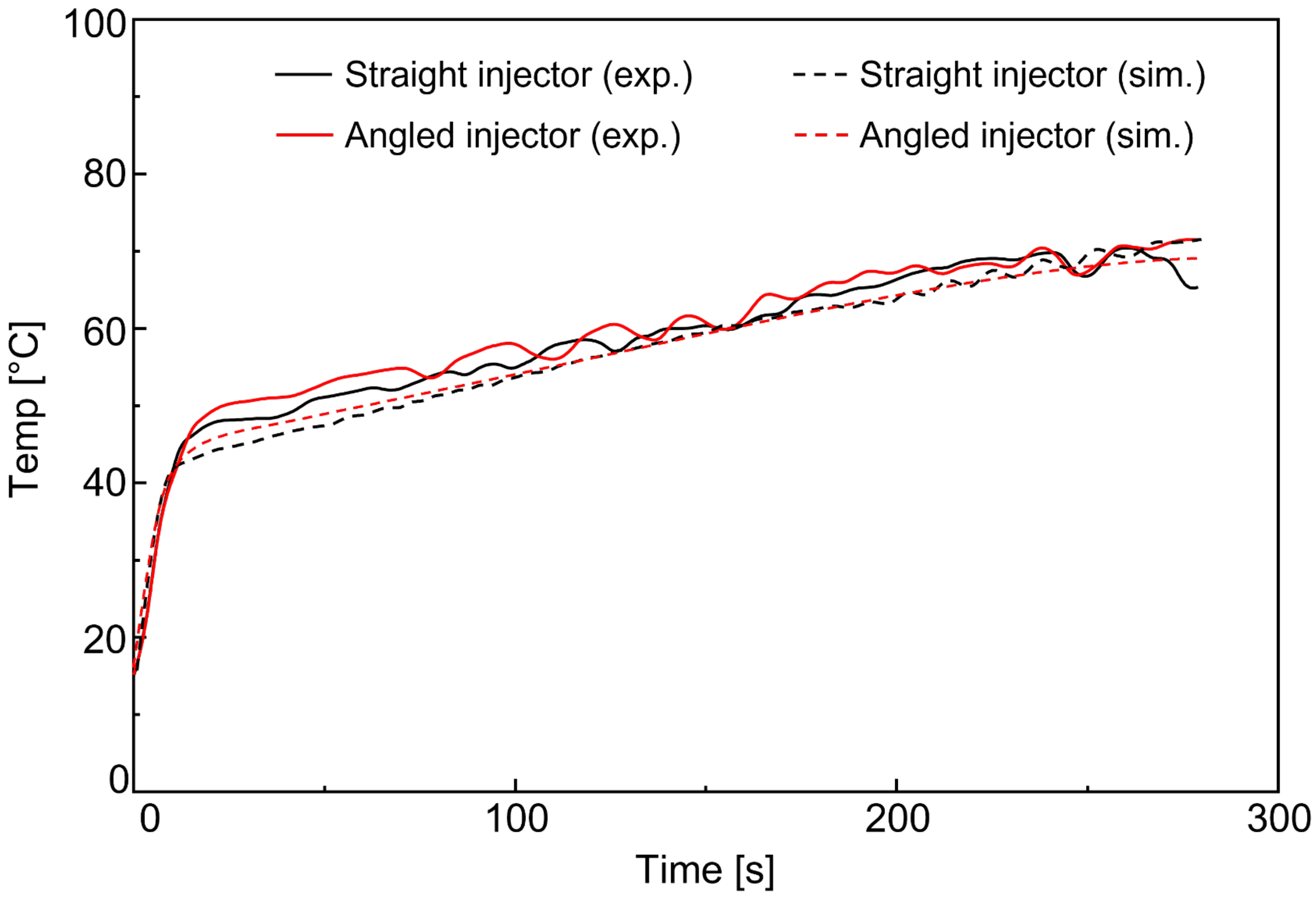
Straight injector model

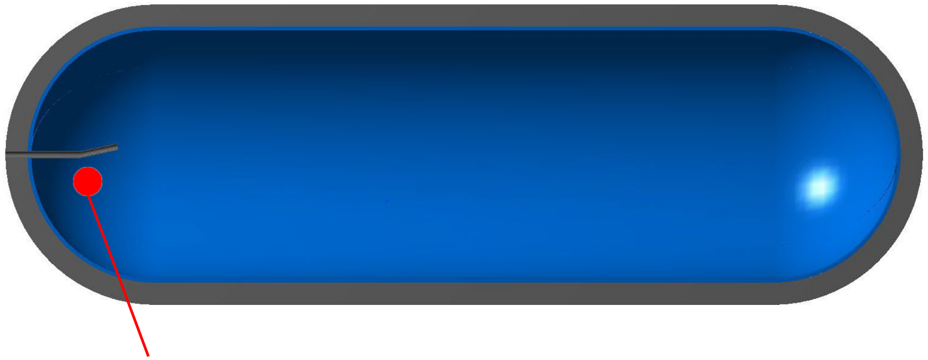
- There are large temperature gradients at the beginning of the fill, and hot spots can be found on the upper surface of the liner.

Angled injector model

- The thermal field is uniform throughout the entire fill.

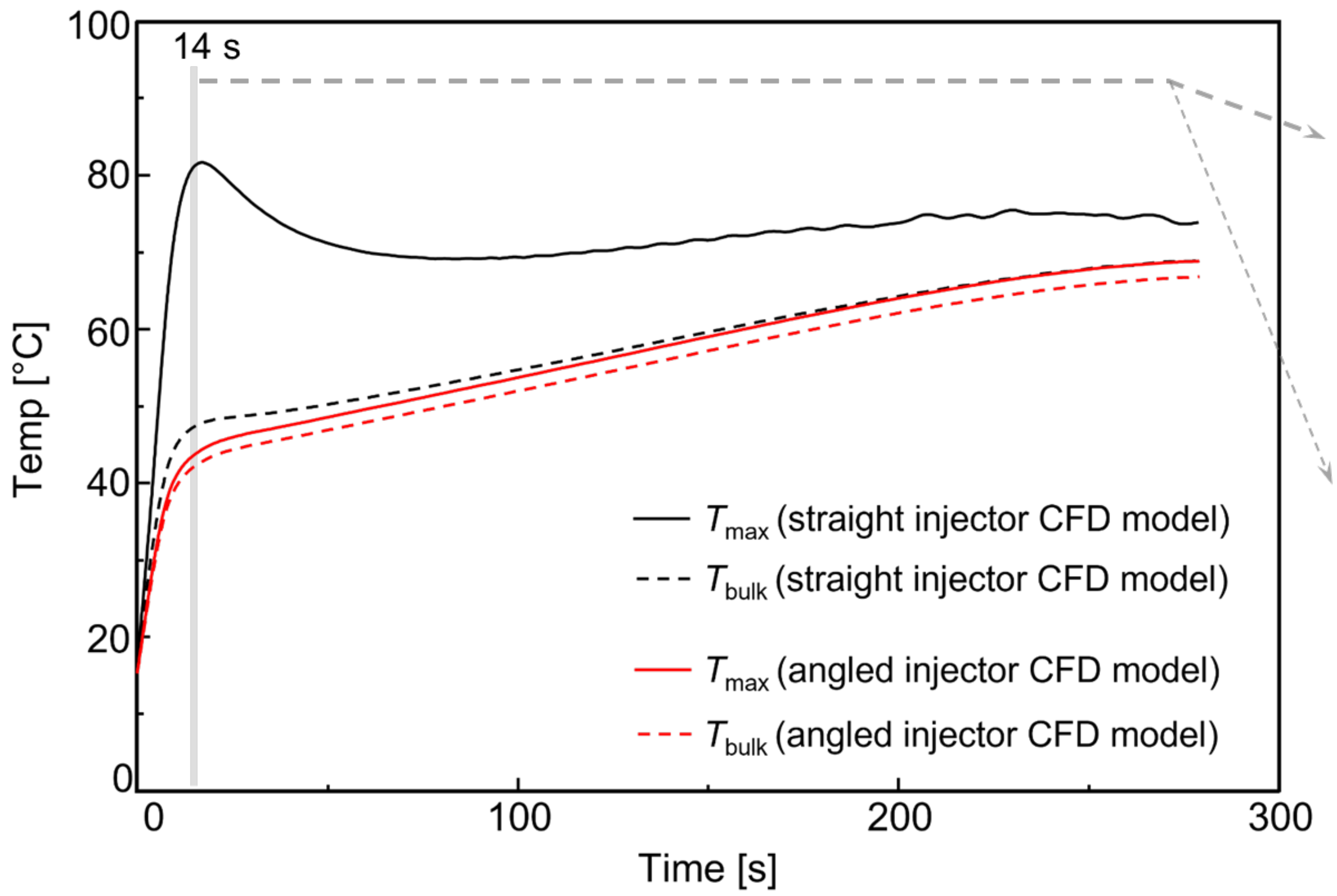
Comparison of CFD and Experiment

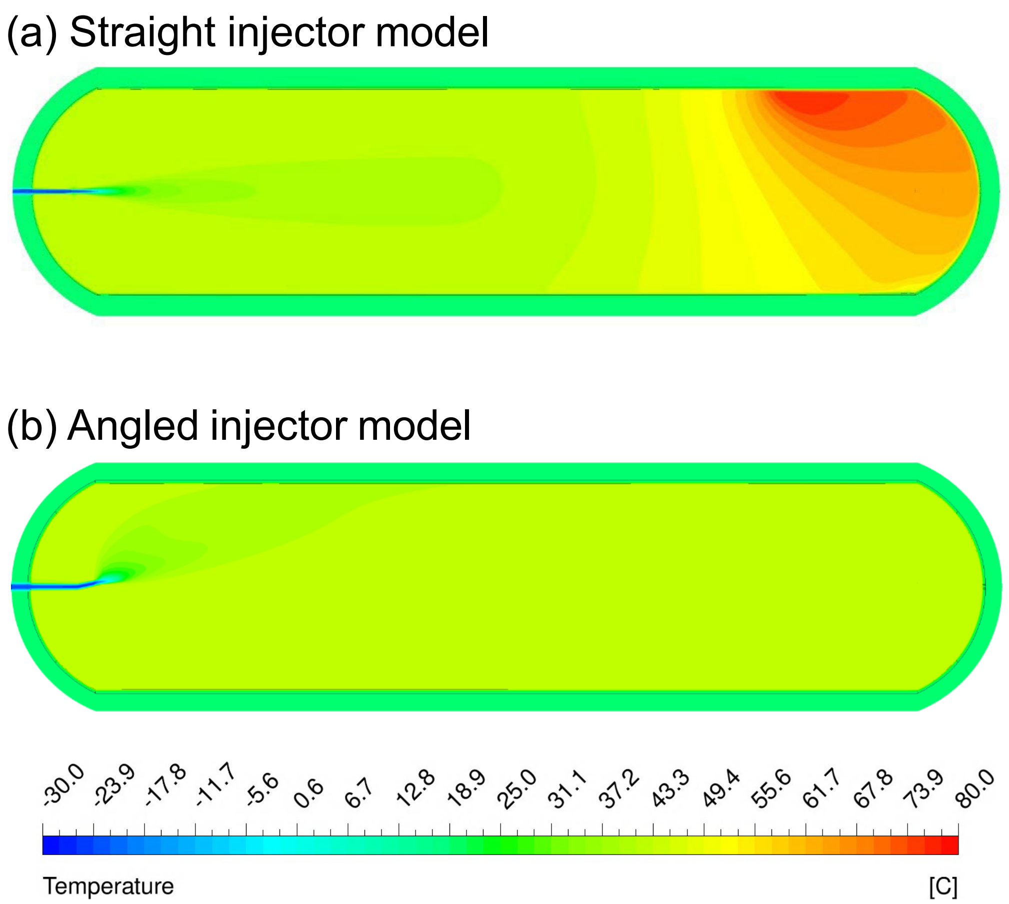




Both simulation results match the experiment data, but the influence of hot spots cannot be found in the experimental and simulation data of the straight injector tank.

Maximum and Bulk Average Gas Temperatures





- The straight injector causes a large difference in the maximum and bulk average gas temperatures.
- The angled injector mixes the hydrogen well; therefore, the difference in the maximum and bulk average gas temperatures is small.

Current & Future HD Projects

HD Dispenser & Nozzle Assembly Project

Heavy-Duty Dispenser and Nozzle Assembly Development

- Develop retail focused HD dispenser and nozzle assembly (nozzle, receptacle, hose, and breakaway) capable of fueling heavy-duty (HD) vehicles.
- Test and demonstration of the system at NREL's HD R&D facility under real-world conditions.
- Targeting ≤100 kg fueling in 10 minutes at a nominal pressure of 70 MPa .
  - Utilizes SAE J2601 category D or other advanced HD fueling protocol.
  - IRdA communications

Project Partners

- Electricore Inc.
- Bennett Pump Company
- WEH Technologies Inc.
- Quong & Associates Inc.

Images: 2022 DOE AMR Electricore Slides

HD Fueling Methods Research Project

Industry lead assessment of HD fueling protocols (70 MPa), HD station architectures, functional safety requirements, and the implications of these on the total cost of station ownership (TCO).

- Provide industry stakeholders with key supporting information for selection and implementation of iterations of HD fueling protocols.
  - Leverage NREL's new HD research station capabilities.
- HD fueling components testing and evaluation.
- Techno-economic assessments (TEA) and Total Cost of Ownership (TCO) of HD fueling infrastructure and industry selected strategies.
  - Leverage existing models and tools for the development of the TEA and TCO methods.
- Explore advanced communications strategies (beyond IRdA).

HD Refueling Hardware

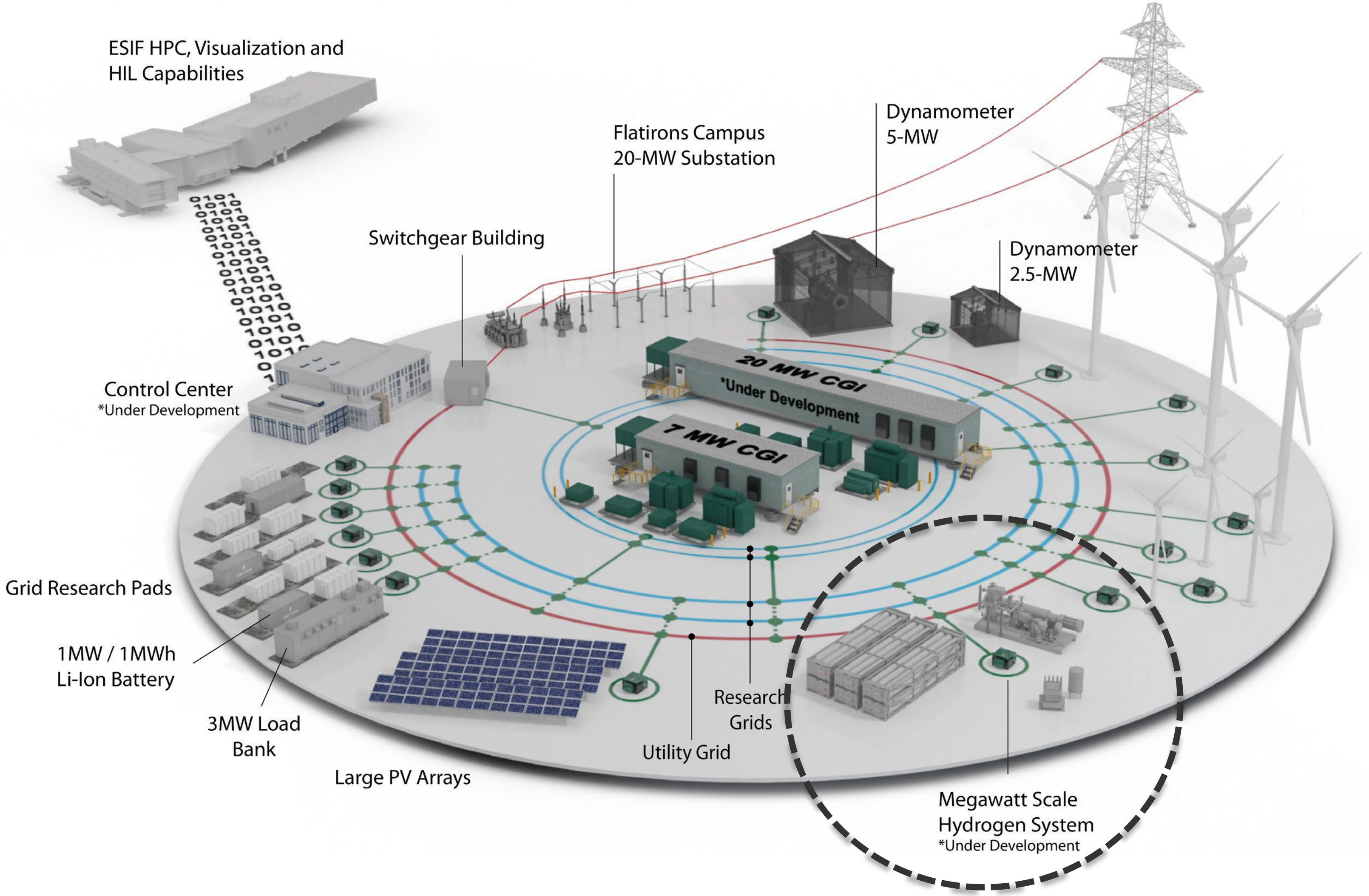
Partners

Chevron
NEXTENERGY
Air Liquide
nel
Argonne NATIONAL LABORATORY
HYUNDAI
TOYOTA
NIKOLA
H_2 PRHYDE Protocol for heavy-duty Hydrogen refuelling

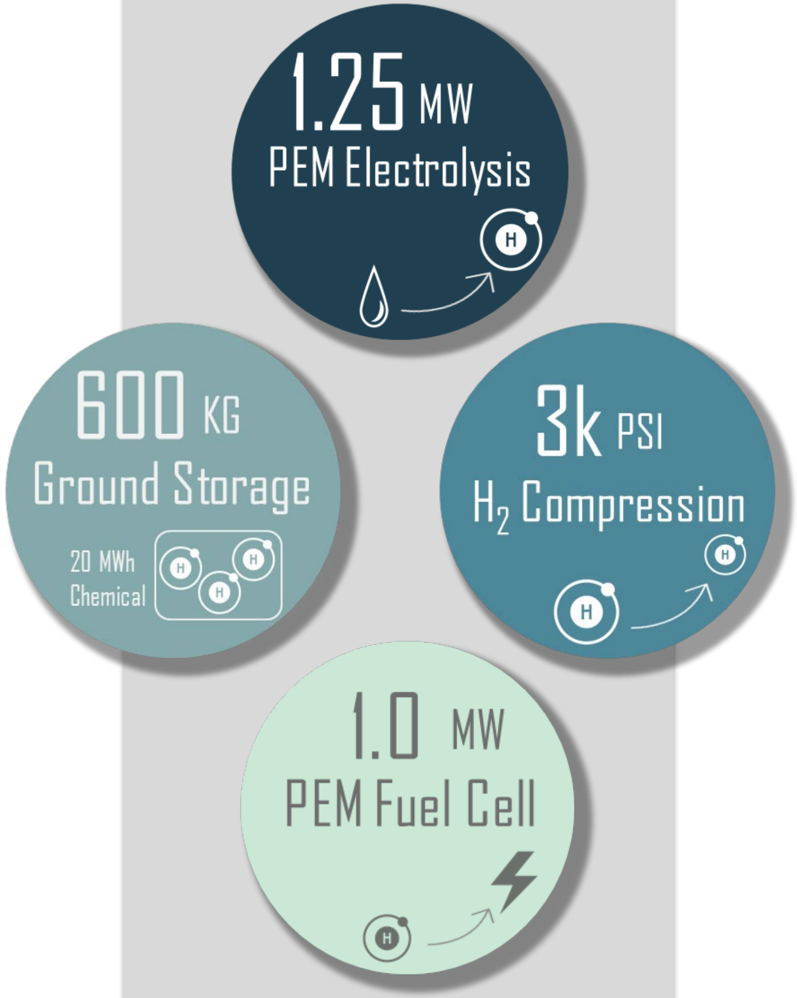
Advanced Research on Integrated Energy Systems (ARIES)

Science of Scaling Hydrogen Systems

- Research platform that can match the complexity of the modern energy system and conduct integrated research to support the development of groundbreaking new energy technologies.



Integrated Megawatt Scale Hydrogen System



Future Work Summary

Future Work

Hardware:

- Performing additional fast flow tests to generate data for model validation.
- Evaluate advance fueling protocols with industry supplied HD component sets.
  - Includes nozzle assemblies and HD dispensers
  - PRHYDE, SAE, NEDO, and others
- Inform SAE and ISO working groups for fueling protocol standardization.

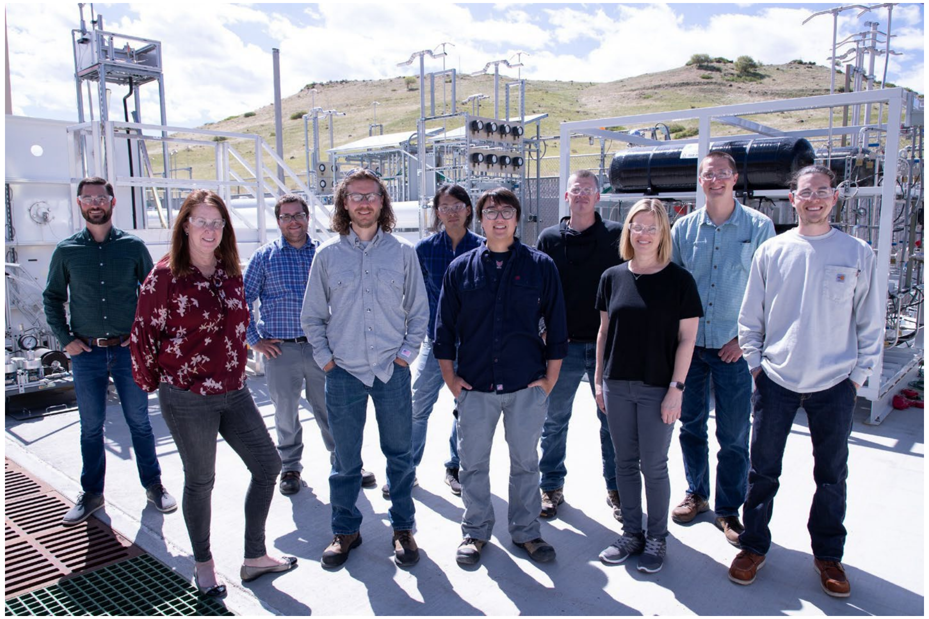
Modeling:

- Validate HD-H2FillS against HD fueling data and release the sophisticated model to the public.
- Assist SAE and ISO in development of HD fueling protocols.
- Expand modeling capabilities to liquid H2, marine, and aviation spaces.
- Perform techno-economic assessments (TEA) and Total Cost of Ownership (TCO) for HD infrastructure based on hardware work, modeling, and industry feedback.

NREL Test Matrix for HD Fueling Protocols & Hardware

	Hardware			
Tests	NREL HDD/ Station	Industry HD Dispenser	HD Hardware Set 1	HD Hardware Set 2
Baseline Performance Evaluations	Complete	Winter 2023	Winter 2023	Winter 2023
Implement Fueling Protocols	Winter 2022/3	Winter 2023	N/A	N/A
Fueling Protocols Evaluations	Winter/ Spring 2023	Winter/ Spring 2023	Winter 2023	Winter/ Spring 2023

Note: Planned activity dates may change based on various project challenges and constraints.



Team (left to right): Shaun Onorato, Sarah Mills, Owen Smith, Matthew Ruple, Taichi Kuroki, Jeffrey Mohr, Josh Martin, Katie Hurst, Daniel Leighton, & Spencer Gilleon

Not Shown: Phil Clark, Tavis Hanna, Sara Havig, Athanasia Kendl, Marc Mann, Nathan Mitchell, Jennifer Kurtz, Kazunori Nagasawa, Keith Wipke, and many others!

Thank You

www.nrel.gov

NREL Transforming ENERGY