Innovating Hydrogen Stations: Heavy-Duty Fueling

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DOE Hydrogen Program
2021 Annual Merit Review and Peer Evaluation Meeting

Project ID H2061

Project Goal

A research and industry partnership for an experimentally validated high flow rate fueling model and near-term hydrogen station innovations

- First-of-its-kind, experimental research capability for 10 kg/min, 60+ kg fueling
- Comprehensive high flow rate fueling models validated with experimental data
- Publicly available tools and data for the benefit of hydrogen station stakeholders

<u>**Three Key Aspects**</u>

Experimental Data

Computational Fluid Dynamics

Simplified Fluid Model H2FillS

Overview

Timeline and Budget

- Project start date: 8/1/19
- Project end date: 12/31/21
- Total project budget: $2.8M
  - Total recipient share: $1.4M
  - Total federal share: $1.4M
  - Total DOE funds spent*: $1.1M

    * As of 02/28/2021
- Related Projects Funded by HFTO:
  - HD Vehicle Simulator: $384k
  - EU PRHYDE Participation: $330k

Barriers

- 3.7 Hydrogen Safety, Codes and Standards
  - G. Insufficient Technical Data to Revise Standards
- 3.2 Hydrogen Delivery
  - I. Other Fueling Site/Terminal Operations
- Targets for Class 8 Tractor-Trailers
  - Hydrogen Fill Rate

Partners

- Project lead: NREL
- Partner organization(s): Air Liquide, Honda, Shell, Toyota

Relevance

Experimental Data

- Fast fill data into representative Medium- or Heavy-Duty storage systems (multiple tanks) is not available, likely doesn't exist
- October 31, 2019: DOE released Hydrogen Class 8 Long Haul Truck Targets

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**)

Station and Vehicle Research

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

Relevance

Modeling

- Flexible, fast, easy to use modeling tools are needed to accommodate options within the M/HD market
  - Long-haul, drayage, vans, etc.

- Need for detailed 3D modeling to avoid unsafe conditions during the filling process
  - Hot spots, stratification, etc.

Approach

Experimental Data

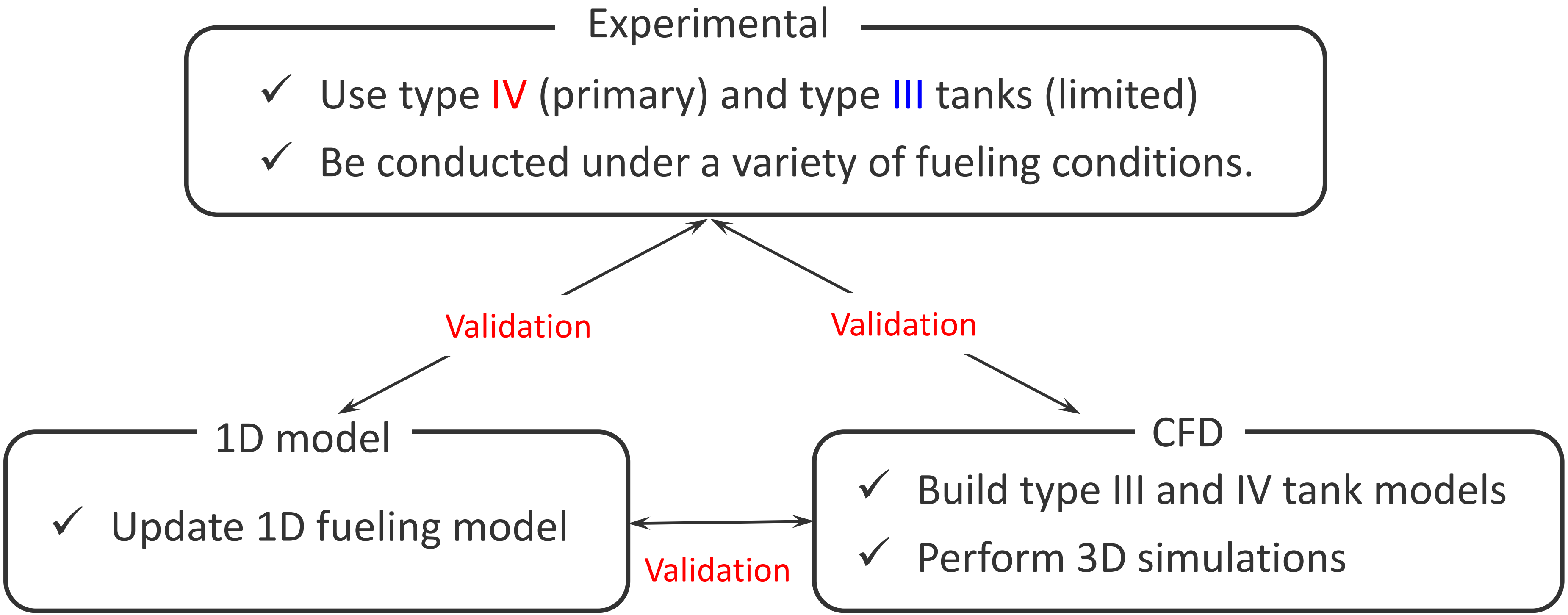
- Upgrade NREL's station to achieve HD fast fill
  - Compile lessons learned in design and commissioning
  - Build flexible HD vehicle simulator
- Execute comprehensive test program
  - Single tank, multiple tanks
  - Fast versus slow fills
  - Ambient temperature conditioning

Approach

Modeling

- H2FillS:
  - Upgrade with newly obtained validation data
  - Publicly available thermo/fluid modeling tool
- CFD:
  - Aim for specific scenarios of concern
  - Leverage NREL's HPC

Approach



CFD simulations and experiments are conducted to make the 1D model reliable.

Accomplishments and Progress

Experimental Data

Design*

High pressure ground storage

- Requires increase of high-pressure capacity ~300-kg + existing 90-kg hp + existing 80-kg medium-pressure

Pre-cooling system

- Modeling shows 300+ hp chiller needed for back-to-back fueling at T40
- System will leverage thermal storage for single fills

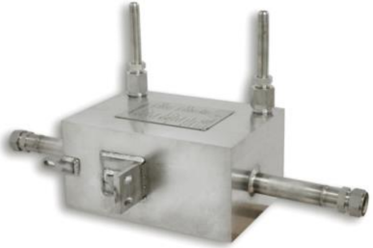
HD dispenser

- Hard tube connection from station to vehicle with “hooks” in place if nozzle, hose, breakaway, flow meter, filter become available

BoP upgrades

- Minimum upgrades are needed to ¾” tubing, 1” is safer choice

60 horsepower chiller at NREL’s site



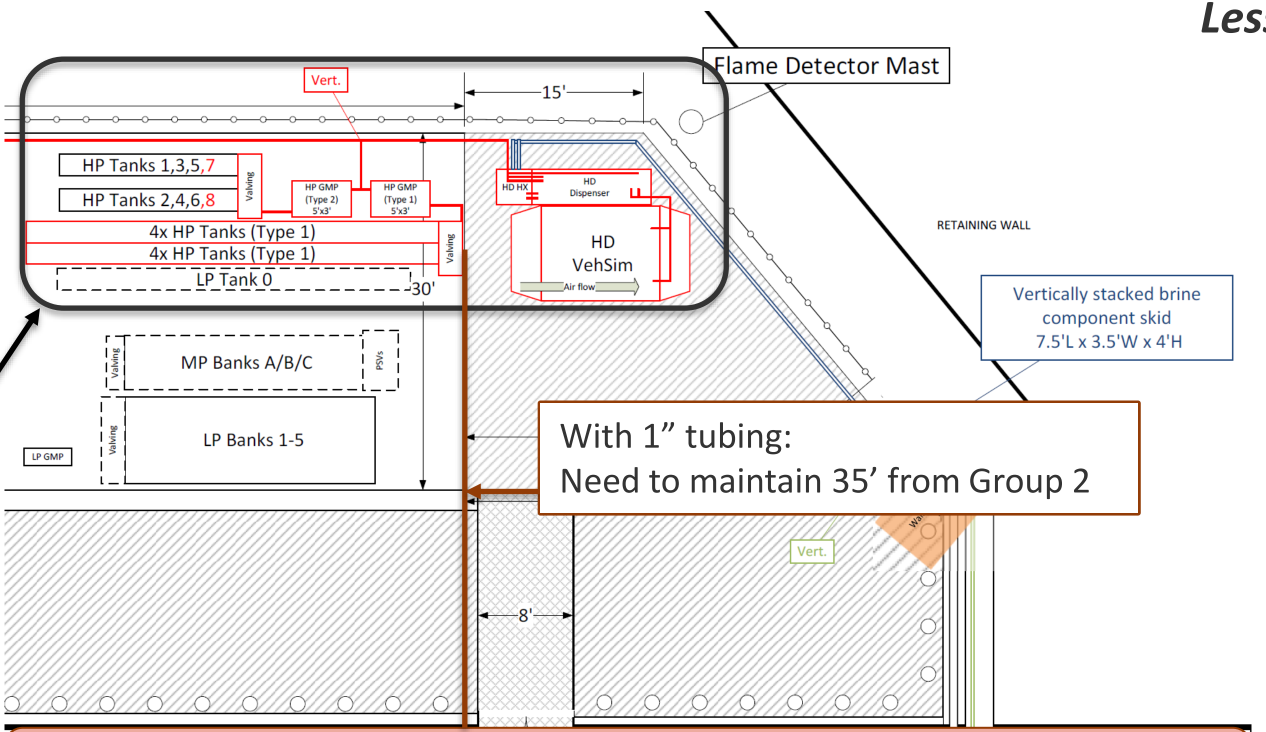
VPE Microchannel Heat Exchanger

*More details found in technical backup slides

Accomplishments and Progress

Experimental Data

Lessons Learned



Heavy-duty Station Upgrades

With 1" tubing:
Need to maintain 35' from Group 2

Group 2: Road/Fire Lane

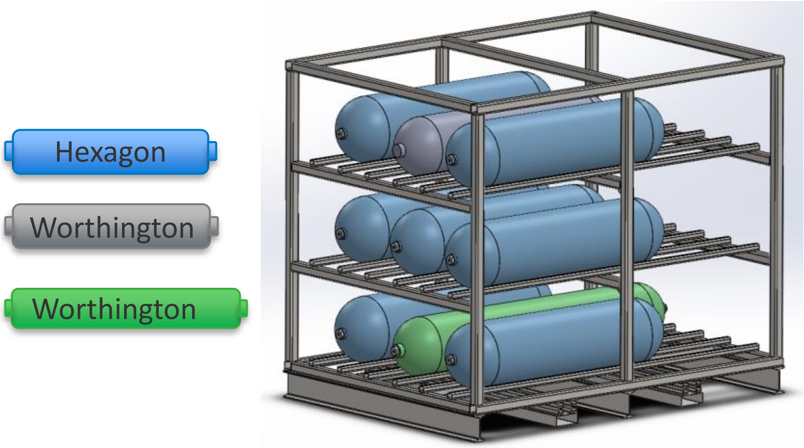
Accomplishments and Progress

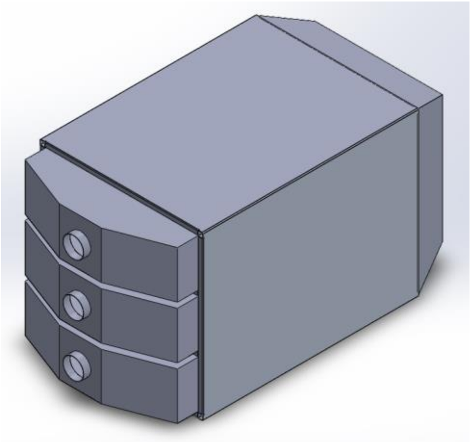
Experimental Data

Vehicle Simulator

Design and Build Progress:

- 7 Type IV tanks (60+ kg fill), 2 Type III
- 9 tanks (80+ kg fill), Any configuration (HV isolation)
- Thermal chambers for ambient conditioning
- Highly instrumented tanks -> thermocouple trees





Accomplishments and Progress

Experimental Data

All major equipment installed, commissioning in-progress

Build Progress

Crane lifting new high-pressure ground storage into place

Gas Management Panels

HD Vehicle Simulator & Brine Storage

HD Vehicle Simulator & HP Storage

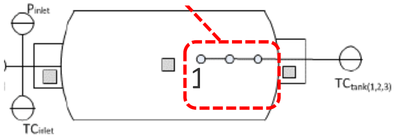
Accomplishments and Progress

CFD

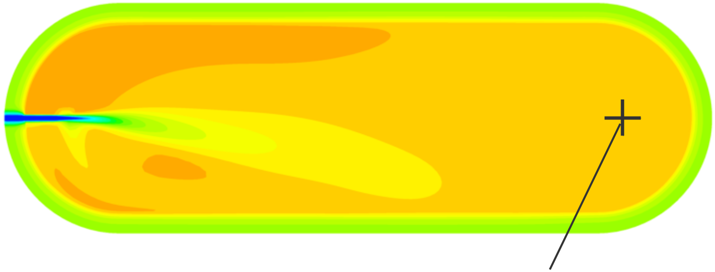
Integration with HPC

- Completed 6 full fills on NREL HPC
  - 3 different tanks modeled
    - 36 L, 116 L, 244 L (HDVS)
  - Two simulations per tank
- ***Validation in-progress***
  - Early results indicate CFD is matching experimental data and H2FillS closely

Thermocouples



Temp. measurement positions



Temp. evaluation position in CFD

Accomplishments and Progress

CFD

Slow Fill

Select scenario: evaluating stratification and severity

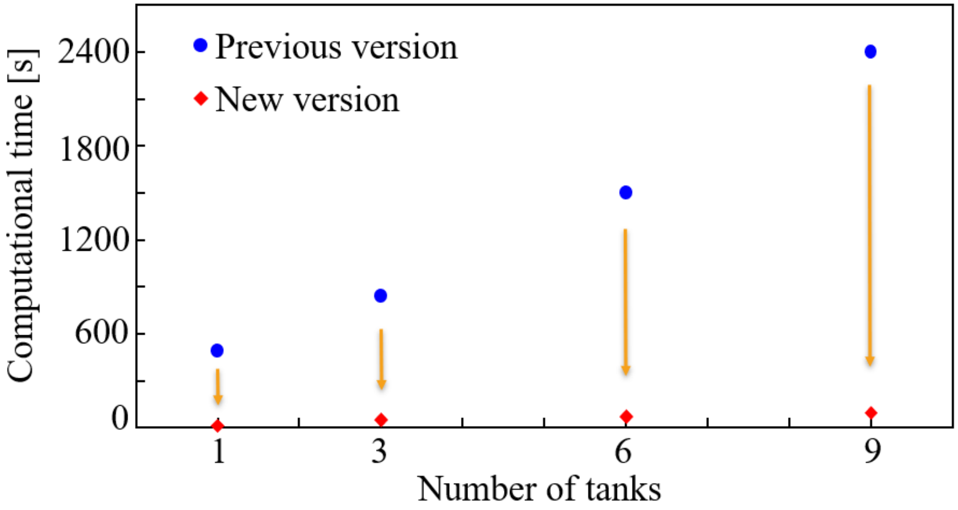
Fueling conditions

- APRR = 3.8 MPa/min - T_{soak} = 40.0°C

- T_{amb} = 40.0°C - T_{fuel_ave} = -37.0°C

Accomplishments and Progress

H2FillS



Speed Improvements

# of tanks	Computational time [s] Previous	New
1	490	12
3	840	49
6	1500	68
9	2400	95

New version is **20 to 40 times faster** than the previous.

Previous Version:

- Slower computational speed
  - single tank matched real fill time
  - e.g., 8 min fill = 8 min model run

New Version:

- Significantly improved computational speed
  - single tank far faster than real time
  - e.g., 8 min fill = **12 second** model run
- Multi-tank hits very fast metrics

Accomplishments and Progress:
Response to Previous Year Reviewers' Comments

This project was not reviewed last year.

Collaboration and Coordination

- **Industry:** Air Liquide, Honda, Shell, Toyota
  - Monthly updates on progress
  - Provide feedback on technical approach
- **International Japan:** Kyushu University
  - Continued collaboration on H2FillS
- **International EU:** IHS team joined EU PRHYDE project as a technical expert
  - Received additional funding from HFTO to participate
  - Dedicated test days with NREL's hardware system, multiple tank data is of value to the group

Source: https://prhyde.eu/

PRHYDE is a European based project, funded by the FCH2 JU under the Horizon 2020 programme, looking at the current and future developments needed for refuelling medium and heavy duty hydrogen vehicles, predominantly road vehicles, but also other applications such as rail and maritime.

Remaining Challenges and Barriers

- Commissioning of the new HD station and vehicle simulator will present a fair number of challenges and lessons learned
  - First of its kind hardware testing
  - Need to have high degree of confidence in controls before fast fill can be achieved

- The IHS team was able to make great progress through the COVID-19 pandemic, however, there are site restrictions in place that can slow technical progress

Proposed Future Work

- Carry out experimental test program at NREL's facility
- Use experimental data to validate CFD and H2FillS models
- Report test data and modeling validation to public
- Release new version of H2FillS

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

Summary

Goals:

- First-of-its-kind, experimental research capability for 10 kg/min, 60+ kg fueling
- Comprehensive high flow rate fueling models validated with experimental data
- Publicly available tools and data for the benefit of hydrogen station stakeholders

Progress:

- All major equipment installed, commissioning on-going
- A total of 6 Computational Fluid Dynamic fills have been completed on NREL's HPC
- H2FillS is in the process of being upgraded for HD applications including improvements in computational speed with multiple tank scenarios

Thank You

www.nrel.gov

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NREL Transforming ENERGY

Technical Backup and Additional Information

Technology Transfer Activities

- NREL has a license agreement with Kyushu University and continues to improve the H2FillS model – a new version of H2FillS will be released at the end of the project

- The experimental data generated within this project is expected to have a significant impact on the understanding of fast fills on vehicle systems within the medium- and heavy-duty market

Progress toward DOE Targets or Milestones

- The main target this project is pursuing is the ultimate target for Hydrogen Fill Rate as set in Table 1 of DOE's program record titled, "Hydrogen Class 8 Long Haul Truck Targets"

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Special Recognitions and Awards

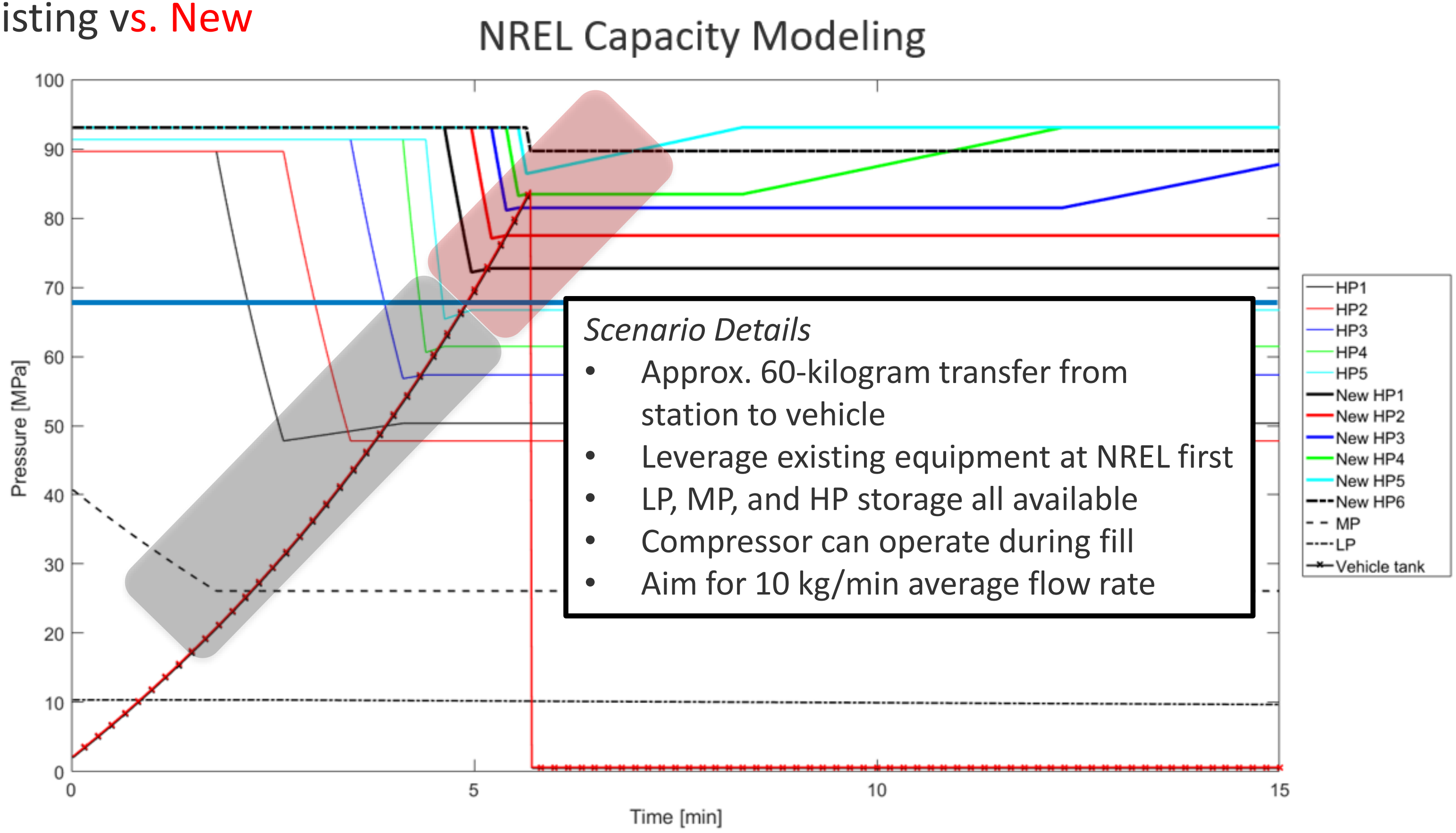
None

Publications and Presentations

T. Kuroki, K. Nagasawa, M. Peters, D. Leighton, J. Kurtz, N. Sakoda, M. Monde, Y. Takata. Forthcoming. "Thermodynamic Modeling of Hydrogen Fueling Process from High Pressure Storage Tanks to Vehicle Tank."

High-pressure Ground Storage for a Single HD Fill

*Existing vs. New



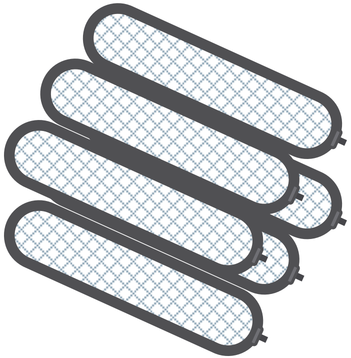
Scenario Details

- Approx. 60-kilogram transfer from station to vehicle
- Leverage existing equipment at NREL first
- LP, MP, and HP storage all available
- Compressor can operate during fill
- Aim for 10 kg/min average flow rate

High-pressure Ground Storage for a Single HD Fill

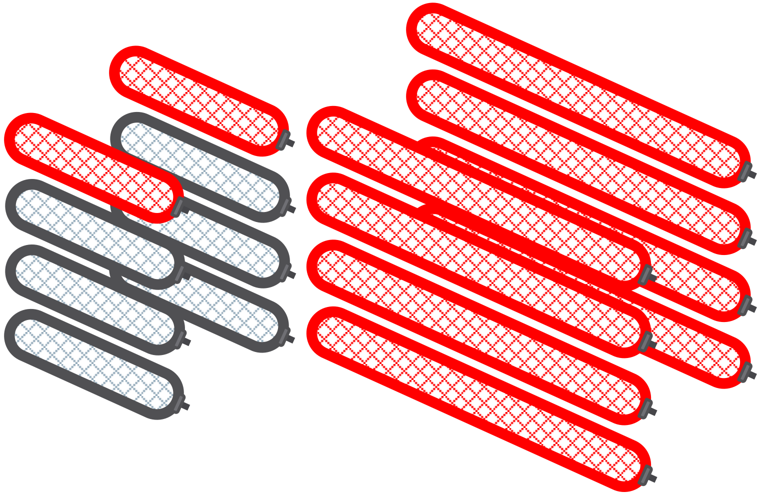
*Existing vs. New

MP Storage



13.5 kg each x 6
81 kilograms total

HP Storage



16 kg each x 8
128 kilograms total

32 kg each x 8
256 kilograms total

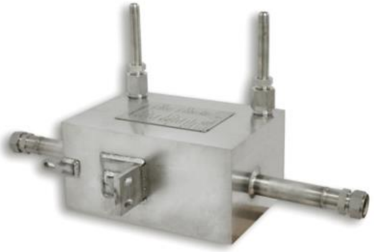
Quick Summary

- Disclaimer: there are many ways to fill a FCEV
- For a GH2 gaseous cascade setup, with a 60+ kilogram transfer at ~10 kg/min average flow rate our modeling shows that you need:
- **~80 kilograms at 40 MPa**
- **~380 kilograms at 90 MPa**

This doesn't include back-to-back filling!

HD Pre-cooling System

- Direct cooling to -35°C from 35°C ambient would require a 360 HP chiller
- Because the project does not require back-to-back fills, thermal storage is an option:
  - Brine thermal storage allows reduction to a 60 HP off-the-shelf chiller
- Custom microchannel diffusion-bonded heat exchanger
  - Working with Vacuum Process Engineering (VPE) on custom design



HD Dispenser

- Cannot currently source any common components for a heavy-duty dispenser
  - Nozzle
  - Hose
  - Breakaway
  - Flow meter
- For our testing, we are going to hard pipe into a vehicle simulator, however, we have left the “hooks” in place to test components as they become available
- Multiple efforts on-going in this space, links below

DOE link: https://www.energy.gov/nepa/downloads/cx-101809-high-pressure-high-flow-rate-dispenser-and-nozzle-assembly-heavy-duty
MOU link: https://www.ccjdigital.com/stakeholders-form-group-to-develop-test-hydrogen-fueling-hardware-for-hd-trucks/

Balance-of-Plant Upgrades

Pressure Drop Calculation

- Underestimate: no bends, 7,000 psig line pressure
- Reduction to 500 psid (from 1,500 psid) reduces required tanks by five
- 1” tubing also enables 20 kg/min flow rates to handle non-uniform mass flow rate during fill

Differential Pressure Estimates [psid]	3/4", 20ksi			1", 20ksi		
	10 kg/min	15 kg/min	20 kg/min	10 kg/min	15 kg/min	20 kg/min
	537	1,008	2,239	198	387	804

FY21 Testing and Simulation – Objectives of Varying Parameters

Parameter	Experiments	3D CFD	H2FillS
APRR	• **Demonstrate fueling @ 10 kg/min ave** • Understand the effect of APRR on BGT and GT distribution	• **Understand the effect of APRR on BGT & GT distribution** • **Determine delta between BGT and GT_maximum.**	• **Validation** of BGT under wide variety of APRR • **Validation** of P, T from storage to tank inlet
T_{fuel}	• Understand the effect of T_{fuel} on BGT and GT distribution	• **Understand the effect of T_{fuel} on BGT & GT distribution** • Determine delta between BGT and GT_maximum.	• **Validation** of BGT under wide variety of T_{fuel} • **Validation** of P, T from storage to tank inlet
T_{soak}	• Understand the effect of T_{soak} on BGT and GT distribution	• **Understand the effect of T_{soak} on BGT & GT distribution** • Determine delta between BGT and GT_maximum.	• **Validation** of BGT under wide variety of T_{soak}
Defueling	• Part of the process after each fill	• Determine GT distribution • Accurately calculate BGT	• **Validation** of BGT under variety of defueling rates
Inlet Nozzle	• Understand the effect of nozzle direction on BGT and GT distribution	• **Understand the effect of nozzle direction on BGT & GT distribution** • Determine delta between BGT and GT_maximum.	• **Validation** of BGT under different nozzle directions
Tank Type	• Understand the effect of tank type on BGT & GT distribution	• **Understand the effect of tank type on BGT & GT distribution** • Determine delta between BGT and GT_maximum.	• **Validation** of BGT under different tank types

FY21 Testing and Simulation – Fueling Conditions for Model Validation

Parameter	3D CFD / Experiments *	H2FillS
APRR (MPa/min)	28*, 20**, 13***, 7, 2 • *10kg/min for 30 kg*, 45 kg**, 70 kg*** CHSS*	3D runs + All experiments
T_{fuel} (°C)	T40 (-36), T30 (-28), T20 (-20), T10 (-10), TA (Ambient)	3D runs + All experiments
T_{soak} (°C)	50 to -30 *(function of APRR and T_{fuel} from H2FillS)*	3D runs + All experiments
Defueling	Fast, slow	3D runs + All experiments
Inlet Nozzle	Angled Up, Straight	3D runs + All experiments
Tank Type	Type IV (*primary*), Type III (*limited*)	3D runs + All experiments
GT Max	< 85 °C (all experiments) and > 85 °C (limited # CFD)	3D runs + > 85 °C
# Sims	~ 24	~ 55

** Note: This table does not include all experimental conditions – only those that will be compared with CFD*