

# H2@Scale CRADA: CA Research Consort. (Ref. Station, Fueling Perf. Test Device, Station Cap Model)

PI: Sam Sprik (National Renewable Energy Laboratory)  
Presenters: Ethan Hecht (Sandia National Laboratories, Reference Stations), and Jacob Thorson (NREL, HD Station Performance Test Device)

WBS 8.6.2.1

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DOE Hydrogen Program  
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Project ID: H2041

# Project Goals

**The goal of this project is to advance hydrogen fueling infrastructure for heavy-duty vehicles via the continued research partnership between national laboratories, DOE, and California public agencies.**

- Three subproject goals are to:
  - Provide design considerations and risk analysis for heavy-duty hydrogen fueling stations
  - Design a test device to validate heavy duty stations' high-flow fueling capabilities
  - Develop a model to evaluate the dispensing capacity of heavy-duty hydrogen stations
- This cooperative work relates directly to California's transition to Zero Emission Trucks as spelled out in the California Air Resource Board's suite of regulations and Governor Gavin Newsom's zero-emission vehicle Executive Order N-79-20
- This project will provide tools and information that lead to more efficient design, acceptance, and commissioning of these larger capacity, higher flow rate stations serving heavy-duty applications

# Overview

## Timeline and Budget

- Project start date: 10/01/21
  - Project end date: 12/31/24
  - Total project budget: \$1,171k (\$65k In-Kind)
    - DOE share: \$1,056k
    - Cost share: \$50k
    - DOE funds spent\*: \$646k
    - Cost share funds spent\*: \$35k
- \* As of ~02/29/2024

## Barriers

Lack of information on operation and evaluation of high-flow infrastructure for heavy-duty hydrogen vehicles including:

- Infrastructure examples
- Tools to evaluate designs
- Test devices for performance

## Partners

- National Renewable Energy Laboratory (**NREL**): Sam Sprik (PI), Taichi Kuroki, Kazunori Nagasawa, Jacob Thorson
- Sandia National Laboratories (**SNL**): Ethan Hecht (Co-PI), Steven Wirydinata, Qi Guo
- Argonne National Laboratory (**ANL**): Amgad Elgowainy
- California Governor's Office of Business and Economic Development (**GO-Biz**): Gia Vacin
- California Air Resources Board (**CARB**): Andrew Martinez
- California Energy Commission (**CEC**): Esther Odufuwa
- South Coast Air Quality Management District (**South Coast AQMD**): Maryam Hajbabaei

# Relevance/Potential Impact

Leverages national lab capabilities at SNL, NREL, and ANL with collaboration and funding cost share from California agencies (CEC, South Coast AQMD, and GO-Biz) to enable the build-out of heavy-duty (HD) hydrogen fueling stations with large dispensing capacity and high flow rates by providing tools and information that lead to more efficient design, acceptance, and commissioning

- HD Reference Station
  - Facilitate understanding of technical and cost considerations, as well as identification and interpretation the latest applicable regulations, codes and standards for HD vehicle refueling infrastructure
- HD Station Test Device
  - Enable the rapid validation of heavy-duty stations' ability to meet new and existing fueling protocols by designing a high flow station testing device
- Station Capacity Model
  - Enabling improved station design via a better understanding of the station capacity under different conditions

# Approach: Tasks & Meetings

SNL led tasks (with guidance and review from ANL and NREL)

- Year 1: Report on reference station designs for HD vehicles – complete
- Year 2: Report on risk analysis of an HD vehicle fueling station – in progress

NREL led tasks (with guidance and review from ANL and SNL)

- Year 1: Beta version of model to evaluate HD hydrogen fueling station for high pressure onboard (70 MPa) and on-site production
- Year 2: Publicly available, executable model that can be used by H2@Scale community to evaluate HD hydrogen fueling station dispensing capacity based on the specified station equipment and the expected vehicle storage and demand profile
- Year 2: Report on design concepts for HD fueling performance test device

All:

- Year 2: CRADA final report – Project summary
- Regular monthly meetings with partners are used for task updates and project review

# Approach: Safety Planning and Culture

- **This project was not required to submit a safety plan to the Hydrogen Safety Panel (HSP)**
- Safety culture has been integrated into this project by:
  - The reference station designs and codes and standard review from this work informs stakeholders about the latest safety codes and standards, provides practical examples of implementation, and identifies potential issues that should be considered by the wider hydrogen community.
  - A thorough process hazard analysis (PHA) was conducted to evaluate the design and operation of the heavy-duty fueling performance test device. Outcomes have been documented for confirmation upon final design and fabrication.

# Approach: HD Reference Station Development

## 1. Publish report on HD reference station designs

- Stations that can provide 700 bar, 10 kg/min
  - Electrolyzer supplied
  - Liquid hydrogen supplied
    - » Using low-pressure vaporizer and compressor
    - » Using liquid pump and high-pressure vaporizer
- Footprint of different station concepts, based on codes and standards
- Cost considerations for different station concepts

## 2. Publish report on applicability and gaps for codes & standards and HD station risk

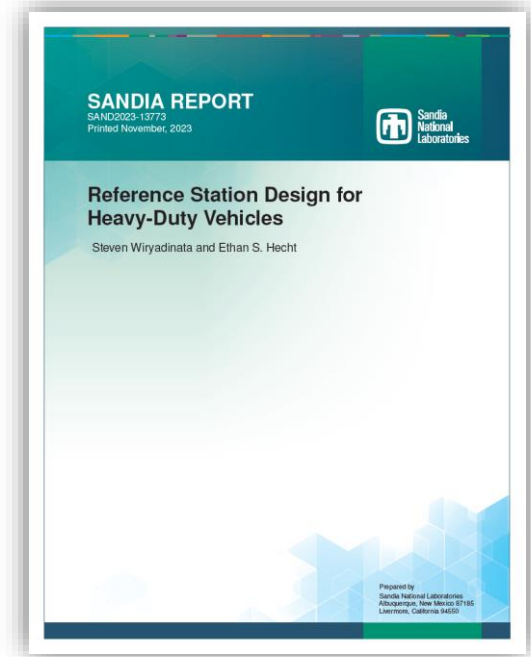
- Review codes & standards and assess where there are limitations in volume or flowrate associated with HD infrastructure
- Understand the relative risk of heavy-duty vs light-duty infrastructure

- **Provide current technical and cost information for several HD station concepts so that interested parties can develop advanced technologies and solutions for refueling HD vehicles**
- **Help stakeholders identify and interpret the latest applicable regulations, codes and standards and understand the risk associated with this technology**

# Accomplishments and Progress: HD Reference Station Development

Finalized HD reference station designs and published report with:

- 5 station configuration concepts
  - On-demand electrolysis provided H<sub>2</sub>
  - Off-peak electrolysis provided H<sub>2</sub>
  - LH<sub>2</sub> delivered with small amount of compression and large cascade dispensing system
  - LH<sub>2</sub> delivered with large amount of compression and small buffer dispensing system
  - LH<sub>2</sub> delivered with cryopump dispensing system
- 3D renderings of station concepts
- Power utilization profiles
- Operating and capital costs

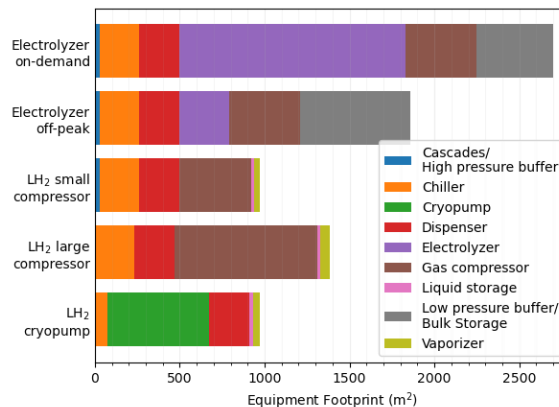
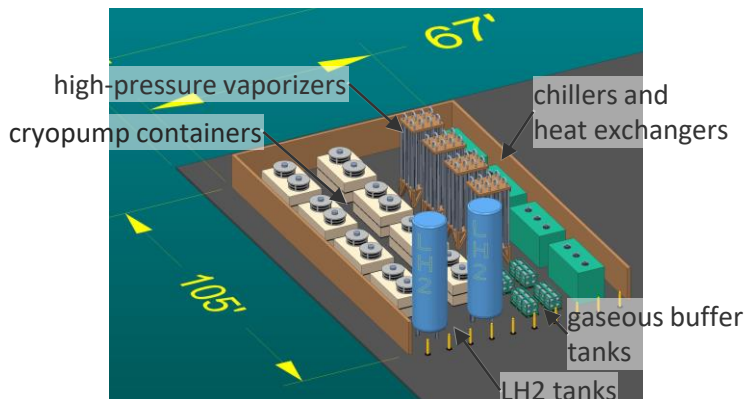
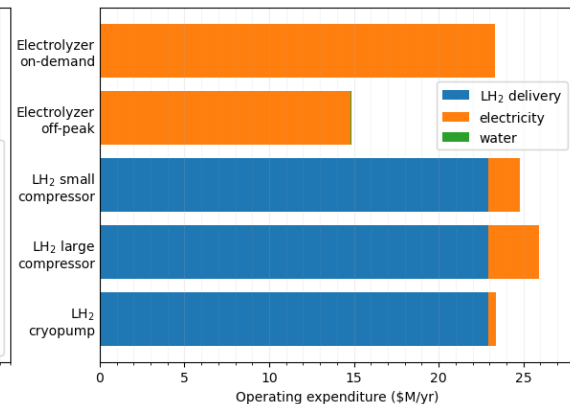
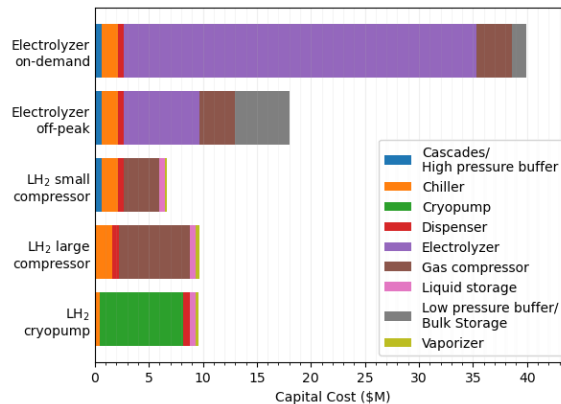




# Accomplishments and Progress: HD Reference Station Development

LH<sub>2</sub> delivered station with a cryopump is promising technology

- Relatively low capital and operational costs
- Small footprint
- Lowered delivered LH<sub>2</sub> costs would improve economics
- Higher flowrate and reliable cryopumps will help enable these types of stations



# Accomplishments and Progress: Codes & Standards review and Risk Analysis

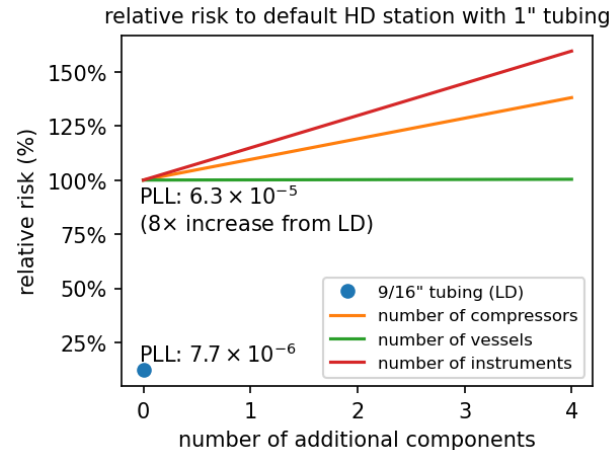
Codes and Standards review identified some potential issues:

- NFPA 2 (applies to stations/infrastructure but not vehicles)
  - MD/HD stations more likely to have bulk (and larger bulk) storage than LD stations
  - Setback distances defined for Bulk GH2 (Chapter 7) and Bulk LH2 (Chapter 8)
    - Bulk GH2 systems: > 5000 scf (12kg)
    - Bulk LH2 systems: >39.7 gal (11kg), but setbacks not specified for > 75,000 gal (~20,000 kg), *which may be needed for HD*
    - Distances are a (linear) function of pipe diameter, which *will increase for HD stations*
  - Dispensers (Chapter 10) “shall use a standard, approved fueling protocol”
    - *HD protocols are still being developed*
  - Guidance in Chapter 13 for onsite generation – systems from 36 -100 kg/hr; > 100kg/hr should follow nationally recognized standards
    - *Onsite production for HD vehicles may require larger production rates*
- SAE J2600 (Compressed Hydrogen Surface Vehicle Fueling Connection Devices)
  - *Specifications for hardware for HD vehicles needed*
- SAE J2601-5 (High-Flow Prescriptive Fueling Protocols for Gaseous Hydrogen Powered Medium and Heavy-Duty Vehicles)
  - Published in Feb 2023 as Technical Information Report, not yet an *approved fueling protocol, but can* be used by authority having jurisdiction to help with approval



# Accomplishments and Progress: Codes & Standards review and Risk Analysis

- Using HyRAM+ to perform relative risk analyses
- HD stations will require larger tubing
  - Increasing tubing from 9/16" (typical LD) to 1" (typical HD) increases risk by 8x
- HD stations will require more components
  - Vessels have low leak rates, therefore adding additional vessels **does not** increase risk significantly
  - Compressors and instruments have high leak rates; additional compression or instrumentation **will increase risk**
  - Increasing cascade storage size is likely lower risk than increasing compression capabilities



# Approach: HD Station Performance Test Device

Design a heavy-duty hydrogen station equipment performance test device (HD HyStEP) that will be capable of rapidly verifying that fueling stations meet the high-flow rate requirements of J2601-5 and future fueling protocols for heavy-duty vehicles.

1. Leverage feedback from the current HyStEP users and standards committee members to identify key metrics for an HD HyStEP device that is capable of high-flow fueling (i.e., 300 g/s peak and > 100 kg).
2. Develop draft P&ID, controls documents, and other relevant documents for the HD HyStEP.
3. Conduct a thorough safety review via a process hazard analysis (PHA) to identify and address risks.
4. Incorporate findings from the PHA to finalize the design.
5. Deliver a report including the documents that may be used by a 3<sup>rd</sup> party to fabricate a future HD HyStEP device.

## Original HyStEP Device



Photos by Dennis Schroeder, NREL 35188, 35179, and 35180

# Accomplishments and Progress: HD Station Performance Test Device

- Gathered feedback regarding the existing HyStEP device and the requirements for future HD fueling was gathered from key stakeholders including operators of current HyStEP device and members of relevant standard committees
  - Key design specifications that came from these discussions include:
    - Variable total CHSS volume *and* largest individual tank volume
    - Adjustable restrictiveness to match vehicle piping
    - Capability to utilize various fueling connections (H70-HF, H70-LF, H35-HF,...)
    - Ability to vent some tanks while others are used for fueling for back-to-back testing
    - Requirement to travel without inert purging
    - Inclusion of active vent control to optimize blowdown rate
- A rigorous PHA was conducted to evaluate the preliminary HD HyStEP design documents.
  - The PHA consisted of >100 person hours of analysis by a team of subject matter experts (SMEs)
  - Findings from this PHA were documented and this documentation will be included with the full design package

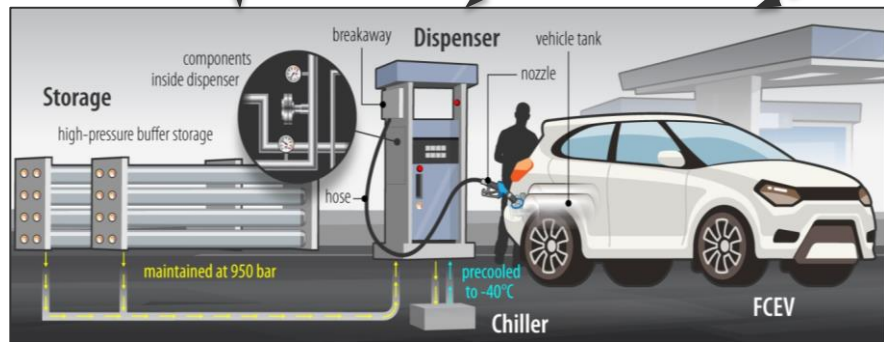


# Approach: Hydrogen Station Capacity Model

HyCap can create flexible station configurations to determine station capacity.



These three production/delivery capabilities can be added to the core configuration



## Core configuration

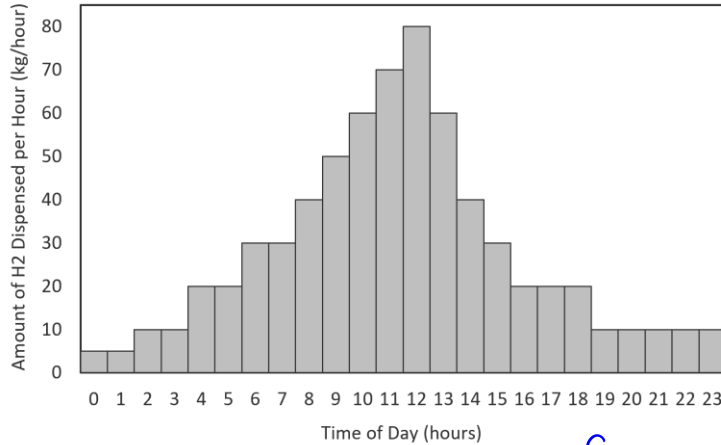
- Ground storage system(s)
- Compressor(s)
- Dispenser(s)
- HD, MD or LD vehicle

The capacity model will be programmed to address any type of conventional hydrogen fueling station.

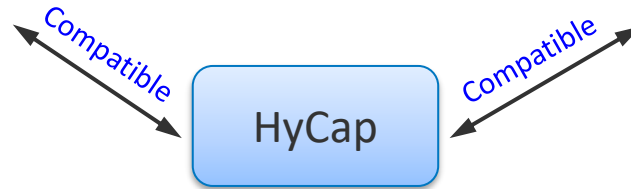
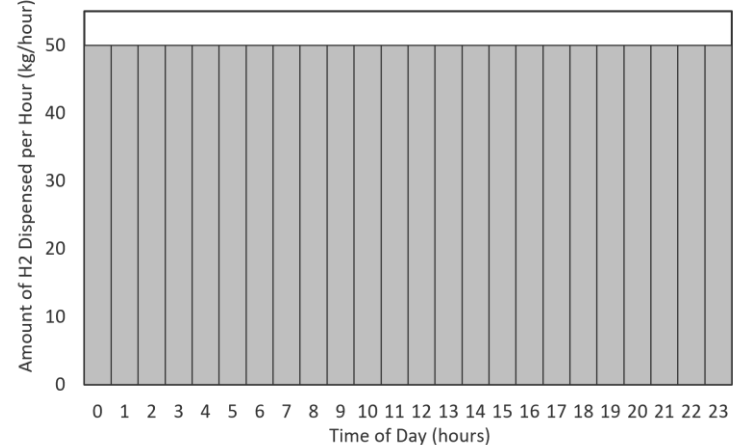
# Approach: Hydrogen Station Capacity Model

A customizable demand profile can be used to evaluate station capacity requirements.

(a) Time-dependent profile



(b) Flat profile



- The capacity model will be programmed to handle any hourly demand profile because the expected number of vehicles coming to HD stations depends on the location.



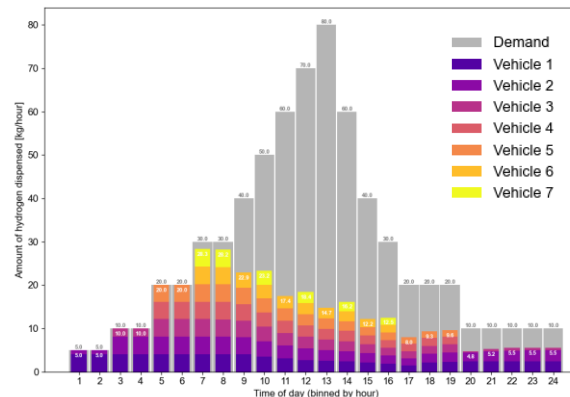
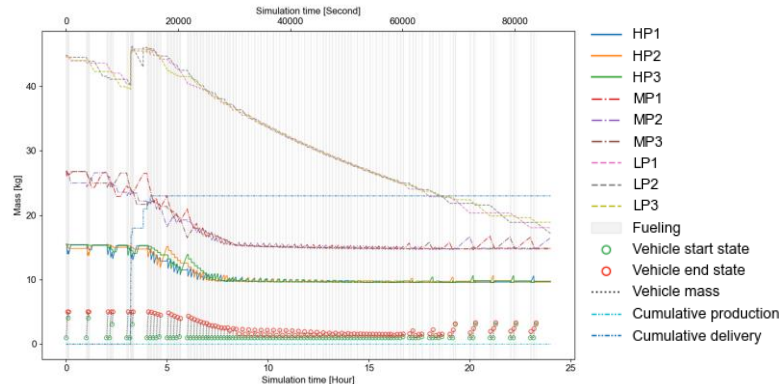
# Approach: Hydrogen Station Capacity Model

## User-Defined Parameters

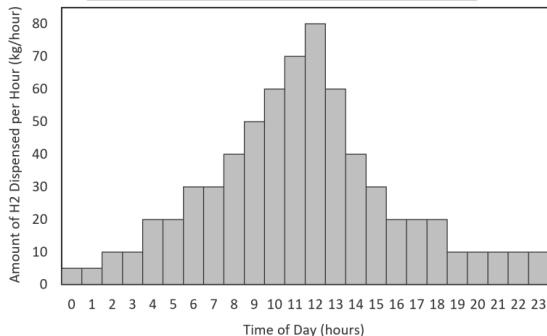
Deliver/Production		
Scenario	input	On-site production
Gas delivery	input	200 kg
	input	3 #/day
	input	6 #
	input	35 MPa
	input	1 kg/s
	input	3600 s
Liquid delivery	input	5 kg/s
On-site production	input	60 kgh
	input	20 MPa
Control	input	90 %
Gaseous/Liquid Storage		
High-pressure (HP) gaseous storage	input	Yes
	input	2
	input	0.33 m3
	input	45 MPa
	input	90 MPa
Medium-pressure (MP) gaseous storage	input	Yes
	input	2
	input	1 m3
	input	0 MPa
	input	40 MPa
Low-pressure (LP) gaseous storage	input	Yes
	input	2
	input	3 m3
	input	2.8 MPa
	input	24 MPa
Liquid storage	input	1
	input	100 #
	input	60 kgh
	input	60 kgh
	input	30 MPa

The model functionalities were tested and verified, and the web-based model is under development, with planned public release in 2024.

## Outputs from HyCap



## User-Defined Demand Profile



# Accomplishments and Progress: Response to Previous Year Reviewers' Comments

- **Comment:** “The project could address the question of whether the performance capability model, which is trained on compressed hydrogen storage configurations, will also work for liquid hydrogen (LH2) storage configurations.”
  - **Response:** The HyCap model has been validated on various configurations of light- and heavy-duty fueling events. Although these experiments have not, to date, been supplied by liquid storage, we believe that the thermodynamic models have been proven to accurately capture both temperature and pressure effects on hydrogen flow.
- **Comment:** “The differences between H2FAST, [HDRSAM], HyCap, and HySCapE should be better explained to measure new progress from already existing models.”
  - **Response:** HyCap and HySCapE differ because HyCap is thermodynamically-based model with more accurate temperature modeling. HySCapE was developed for light-duty, whereas HyCap is designed to handle heavy-duty (high flow) fueling as well as light-duty. H2FAST and HDRSAM differ from HyCap, because HyCap is focused on the technical viability of a station design to meet demand based on storage and compression equipment, whereas H2FAST and HDRSAM are focused on cost implications of HD station design and operation.
- **Comment:** “The project has no Accomplishments and Progress on risk analysis and gaps with codes and standards (C&S), which were Year 2 deliverables.”
  - **Response:** The year 2 analysis started after the previous AMR presentation was made and has been included as a part of the HD reference station effort this year.
- **Comment:** “There is a lack of involvement, even anonymous, from the industry.”
  - **Response:** Project members have conducted meetings with several industry stakeholders to support subtask activities. These have included feedback on station equipment to inform the HD Station Design and demand profiles seen at stations for heavy duty fueling.

# Collaboration and Coordination

<b>NREL</b>	Lead the development of the HD station fueling capacity model and the design concepts for station performance test device
<b>SNL</b>	Lead the HD reference station designs and risk analysis
<b>ANL</b>	Provide guidance and review of station design concepts

**GO-Biz – California Governor’s Office of Business and Economic Development**

**CARB – California Air Resources Board**

**CEC – California Energy Commission**

**South Coast AQMD – South Coast Air Quality Management District**

Provide guidance, review, feedback and stakeholder engagement



# DEIA/Community Benefits Plans and Activities

- This project did not have a Diversity, Equity, Inclusion, and Accessibility (DEIA) plan or Community Benefits Plan (CBP).

# Remaining Challenges and Barriers

- Releasing a report on codes & standards applicability and gaps and relative risk assessment of HD infrastructure
- Completing beta-testing with the project partners and releasing the HyCap model through the web user interface
- Selecting a default demand profile that is applicable to heavy-duty fueling
- Identifying other temperatures and pressures that are of interest to vehicle and/or station manufacturers to inform future HD station performance test device concepts

# Proposed Future Work

<u>Task Name</u>	<u>Future Deliverables</u>
<b>HD Reference Station Design</b>	<ul style="list-style-type: none"><li>• FY24 – Develop and report on quantitative risk assessments and how codes and standards apply to HD stations</li></ul>
<b>HD Station Test Device Design</b>	<ul style="list-style-type: none"><li>• FY24 – Evaluate alternative designs for different fueling technologies, e.g., LH2, and publish finalized design documents in a comprehensive report.</li></ul>
<b>HD Station Capacity Tool</b>	<ul style="list-style-type: none"><li>• FY24 – Finalize station capacity model with additions of pipeline delivery options</li></ul>
<b>Overall Project</b>	<ul style="list-style-type: none"><li>• FY24 – Summarize project outcomes in a final CRADA Report</li></ul>

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

# Summary

## **Relevance:**

- Enables the build-out of heavy-duty (HD) hydrogen fueling stations with large dispensing capacity and high flow rates servicing HD hydrogen trucks, e.g., class 8 trucks in long haul applications

## **Approach:**

- Develop reports on reference station designs for HD vehicles and risk analysis of HD vehicle fueling stations
- Build a hydrogen station capacity (HyCap) model for HD hydrogen stations that works for LD also
- Develop a high-flow station performance test device concept for others to use in production of test device

## **Accomplishments and Progress:**

- Published report on HD reference stations
- Completed review of codes & standards and assessed gaps and applicability for HD infrastructure
- Initiated relative risk assessment of HD infrastructure
- Developed design documents for a HD station performance test device
- Conducted a safety review of the preliminary HD station performance device design
- Added compressed gas and liquid delivery capabilities to the HyCap model

## **Future Work:**

- Publish report on codes & standards applicability and gaps and relative risk assessment of HD infrastructure
- Develop HyCap model for gaseous pipeline delivery to station and make available to public
- Publish test device designs that would measure HD station fueling performance

# Thank You

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[www.nrel.gov](http://www.nrel.gov)

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