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Assessment of Heavy-Duty Fueling Methods and Components

Cooperative Research and Development Final Report

CRADA Number: CRD-21-17844

NLR Technical Contact: Shaun Onorato

The National Laboratory of the Rockies is a national laboratory of the U.S. Department of Energy, Office of Critical Minerals and Energy Innovation, operated under Contract No. DE-AC36-08GO28308.

Technical Report
NLR/TP-5700-99088
February 2026

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Cooperative Research and Development Final Report

Report Date: December 3, 2025

In accordance with requirements set forth in the terms of the CRADA agreement, this document is the CRADA final report, including a list of subject inventions, to be forwarded to the DOE Office of Scientific and Technical Information as part of the commitment to the public to demonstrate results of federally funded research.

Parties to the Agreement: Chevron U.S.A. Inc and NextEnergy Center and UChicago Argonne, LLC

CRADA Number: CRD-21-17844

CRADA Title: Assessment of Heavy-Duty Fueling Methods and Components

Period of Performance: 2/2/2022 – 5/1/2025

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Sponsoring DOE Program Office(s):

Office of Energy Efficiency and Renewable Energy (EERE), Hydrogen and Fuel Cell Technologies Office

Joint Work Statement Funding Table showing DOE commitment:

Estimated Costs	NLR /ANL Shared Resources a/k/a Government In-Kind
Year 1	$1,881,000.00
Year 2	$1,430,400.00
TOTALS	$3,311,400.00

Executive Summary of CRADA Work:

Chevron, NLR, ANL, and NextEnergy partnered in the development of a comprehensive assessment of heavy-duty (HD) fuel cell electric vehicle fueling protocols. The project leveraged and built upon existing international heavy-duty (HD) fueling protocols and fueling component development activities to deliver component performance assessments, modeling tools and methods evaluations, techno-economic assessments of industry-selected protocol structures and experimental validations of the strategies performed at NLR's HD hydrogen fueling station.

CRADA benefit to DOE, Participant, and US Taxpayer:

- Assisted laboratory in achieving programmatic scope
- Added new capability to the laboratory's core competencies
- Enhanced the laboratory's core competencies
- Used the laboratory's core competencies
- Enhanced U.S. competitiveness by utilizing DOE developed intellectual property and/or capabilities

Summary of Research Results:

The intent of this CRADA was to evaluate and further develop fueling protocol for heavy-duty fuel cell electric vehicles. Heavy-duty fueling hardware and components were evaluated using EU-PRHYDE protocols and Society of Automotive Engineers (SAE) J2601/5 protocols for robustness and performance to help identify improvements needed and push industry towards standardization for refueling hardware designs. A TEA analysis was also used to further understand the effects of fueling protocols on fueling time, station cost, and TCO. In general, protocol parameters that improve the fueling performance will result in a relatively more expensive station.

Task 1: Coordination with domestic and international HD fueling protocol activities

In Task 1, NLR will participate as an external technical expert in appropriate work package groups within the Fuel Cells and Hydrogen Joint Undertaking (FCH-JU) Project for Research on Heavy-Duty Hydrogen Refueling Protocols (PRHYDE) project and relevant working groups through the International Organization for Standardization (ISO) Technical Committee (TC) 197 United States Technical Advisory Group (US TAG) and Society of Automotive Engineers (SAE) will leverage approaches in these two key working groups to inform the assessment completed in the other Tasks.

Task 1 Results:

NLR actively participated in Working Groups 5, 22, 24, and 38 and has remained a technical expert in all meetings and discussions pertaining to heavy-duty fueling protocols and communications development. NLR is an active member of the SAE J2601/5 Task Force. NLR performed and provided regular updates, presentations as well as sharing of results/data with all partners participating in applicable working groups and within this CRADA.

Task 2: Determine the Protocols and Fueling Methods to be Analyzed

In Task 2, NLR and project partners will determine the fueling protocol architectures, fueling methods, and associated communications protocols and requirements for data messaging. The source of fueling protocol architectures, fueling methods, and communication protocols will be those considered and developed within the working groups from Task 1.

Task 2 Results:

The selected fueling protocol architectures determined by NLR with input from industry and CRADA partners included the European Union Project for Research on Heavy-Duty Hydrogen Refueling Protocols (EU-PRHYDE) protocols and SAE J2601/5 protocols. These protocols are the most advanced in development and applicable to the fueling of heavy-duty fuel cell electric vehicles (FCEVs).

The SAE J2601/5 protocol is considered a normative fueling protocol and establishes high-flow fueling of compressed gaseous hydrogen at peak flow rates of 60 to 300 g/s, with compressed hydrogen storage system (CHSS) volume capacities between 248.6 and 7500 liters (L).

The EU-PRHYDE protocols are prescriptive and determine a pressure ramp rate strategy based on information about the storage tanks that is communicated to the station. There are four concepts included in the EU-PRHYDE fueling protocols, including T-static, T-initial, T-initial+, and T-throttle. The T-static protocol uses static vehicle information including the CHSS volume categories and thermophysical properties. The T-initial and T-initial+ protocols build upon the T-static protocol by using dynamic vehicle information, such as the fueling history and CHSS initial temperature at hot soak, respectively. The T-throttle protocol includes the T-initial+ data and adds the station component thermophysical properties at worst-case and soaked at ambient-temperature.

Task 3: HD Component Experimental Testing and Modeling

HD Fueling Component Hardware Evaluation

In Task 3, NextEnergy will provide a complete set of HD fueling components to NLR (a complete set comprises a breakaway, nozzle, and receptacle and hose) for fast flow evaluations. NLR will conduct flow testing with supplied components under fast flow conditions, pre-cooled hydrogen gas, and relevant HD fueling protocols (based on the output of Task 2) to evaluate performance and overall usability. The components will also be evaluated for nozzle freeze lock (within the limitations of NLR capabilities). The performance and usability evaluation will include the measurements of pressure drop, gas temperatures, surface temperature, and mass flow which will allow thermophysical characterization of the component assembly (i.e. thermal mass, thermal conductivity, and flow coefficient). Results and usability feedback will be provided to the project partners and component suppliers to help accelerate standardization activities under ISO TC 197-17268.

Pressure Drop and Freeze Lock Testing

In efforts to accelerate the standardization of nozzle and receptacle geometry under ISO/TC 197-17268, NLR will evaluate the nozzle assemblies provided by NextEnergy along with up to 2 additional nozzle/receptacle sets from other manufacturers. Each nozzle assembly will be evaluated over a series of defined pressure drop, freeze lock, and HD fueling protocol tests (agreed upon by NLR and the project partners). Under nozzle freeze evaluations, NLR will leverage existing capabilities to expose components to -40°C gas temperatures over the duration of a HD flow test (with a HD fueling protocol) and predefined test chamber conditions (temperature and humidity) to assess the effort required to disconnect the nozzle. Back-to- back freeze tests capabilities will be assessed based on research capabilities, with a goal of up to 2-3 tests per test condition. The results will be presented to project partners, individual component suppliers, and finally the relevant ISO working group(s) to drive the decision- making process for component geometry standardization.

Computation Fluid Dynamics

Using geometry obtained from the components and test data generated in Task 3, NLR will utilize Ansys Fluent to build a 3D Computational Fluid Dynamics (CFD) model of the HD fueling Nozzle, receptacle, and breakaway devices. The NLR team will leverage NLR's High-Performance Computer (HPC) to complete the 3D CFD analysis. Modeling results will be compared to the experimental data and reviewed with project partners.

Task 3 Results:

NextEnergy provided nozzle, breakaway, receptacle, and hose components to NLR for evaluation under heavy-duty fast flow hydrogen refueling conditions.

Table 1. Nozzles, receptacles, hoses, and breakaway sets used for protocol testing and equipment evaluation

	Supplier 1	Supplier 2	Supplier 3	Supplier 4	Supplier 5	Supplier 6
Nozzle	X	X	X	X		
Receptacle	X	X	X	X		
Hose					X	X
Breakaway	X	X				

For all fueling sets provided, filling events were performed to obtain characterization data for determining the set's overall flow coefficient and pressure drop. The figures below show representative data used to determine these characteristics.

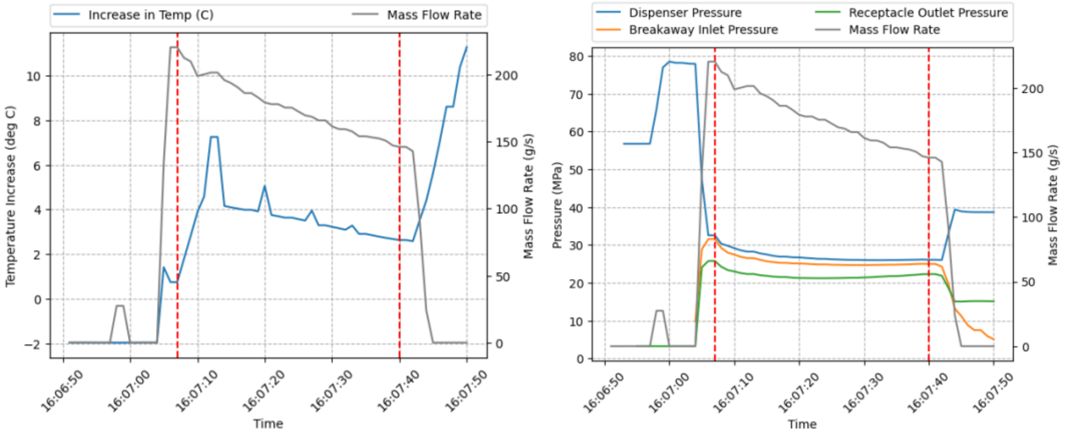


Figure 1. Representative pressure and temperature measurements during 30-second window of heavy-duty fill used to calculate pressure drop and resulting flow coefficient (Cv) for breakaway, hose, nozzle, and receptacle sets

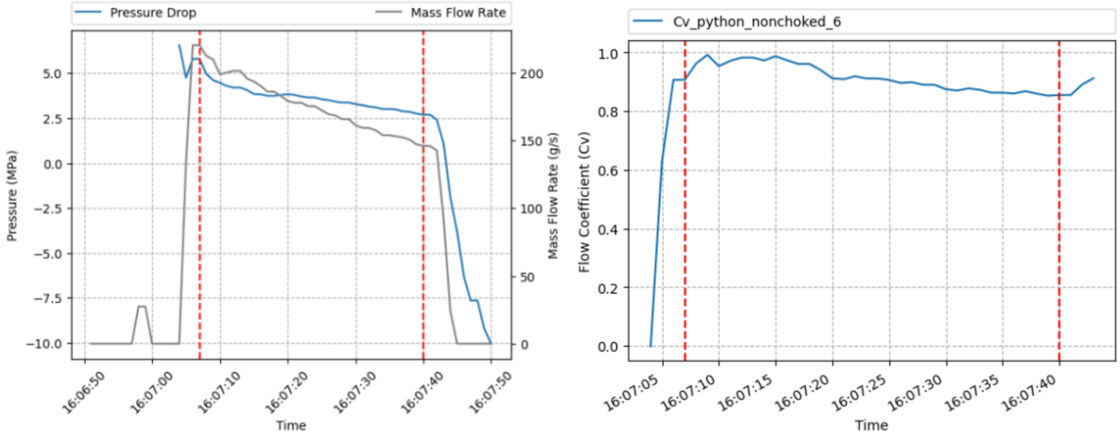


Figure 2. Pressure drop observed during 30-second window during heavy-duty fill. Resulting flow coefficient value is shown on the right for the breakaway, hose, nozzle, and receptacle set

A 3-D CFD analysis was performed on a single breakaway provided by NextEnergy based on the geometry information shared by the manufacturer.

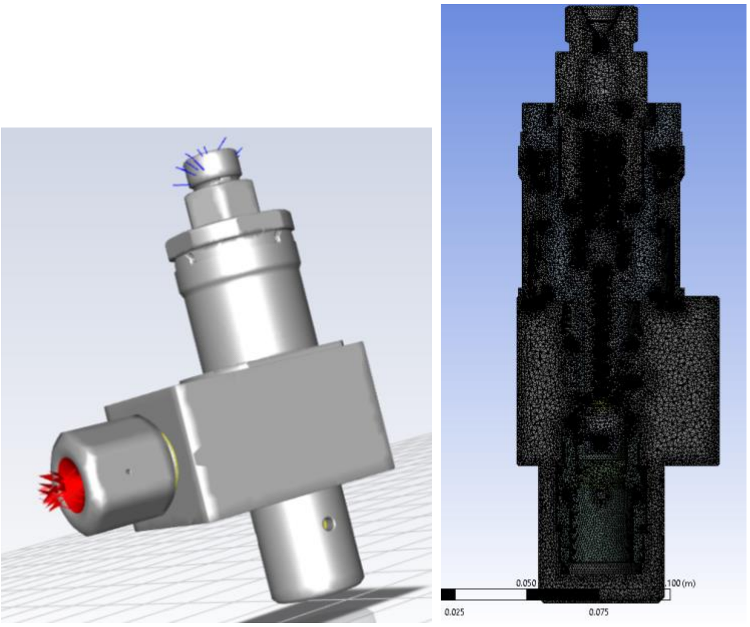


Figure 3. 3-D model and grid refinement for CFD analysis on breakway.

Simulation conditions for the 3-D CFD modeling were as follows:

Table 2. 3-D CFD modeling and simluation conditions

Condition	Set Point
Inlet Temperature	233.15 K
Inlet Mass Flow Rates	60, 120, 180, and 300 g/s
Inlet Pressures	15, 30, 50, 70 MPa
Outlet Pressure and Temperature	1 bar and 300 K
Simulation Run Time	30 seconds

Work remains in progress for the 3-D CFD simulation, modeling, and analysis in coordination with the breakaway manufacturer.

All component sets were subjected to several heavy-duty fueling events in various ambient conditions. All full-fill fueling events were based on FM300, T40, and 700-bar fueling standards, allowing all components to experience real-world fueling pressure and temperatures.

Components were also subjected to various simulated environmental conditions to assess freeze-lock performance in back-to-back fueling events. In Table 3, the environmental conditions provided by the test apparatus and chamber are detailed.

Table 3. Nozzle Freeze-lock test conditions for each component set

Condition	Dry Bulb Temperature (°C)	Relative Humidity (%)
HD ISO per 17286-2	30	93
LD ISO per 17268-1	15	90
Worst Case Light-Duty Test	35	75

Environmental conditions were maintained during a series of three consecutive, "back-to-back" T40 fueling events. A freeze-lock condition was determined when a nozzle took >30 seconds to disconnect from the receptacle after the fill. Time to disconnect, nozzle connection surface temperature, and external receptacle temperature data were recorded and distributed to each manufacturer.

Results from the testing were shared with the relevant ISO standards working groups. The 17268-2 document was informed by these results to make critical decisions on standardized geometry needed to advance the document to the next stage of standard development.

Task 4: Define Reference / Boundary Conditions and Performance Targets

In Task 4, NLR will define all the conditions and parameters under which subsequent analysis will be conducted in the project by defining the types of medium-duty (MD)/HD vehicles and their duty cycles, a reference or baseline Compressed Hydrogen Storage System (CHSS) for each vehicle, reference station designs, the range of boundary conditions to be analyzed, the range of fueling conditions to be analyzed, and the fueling performance targets.

NLR will ultimately match the number of scenarios explored with available resources on the project weighing the complexity of a given scenario with available labor and computational power to carry out the analysis in Task 7.

Task 4 Results:

Class 8 vehicles – specifically long-haul sleeper semitrucks and short-haul tractors – were evaluated in the TEA/TCO framework consisting of Hydrogen Filling Simulation (H2FillS) [1], HDRSAM [2], and T3CO [3]. The Transportation Annual Technology Baseline (ATB) was also used to provide technological improvements for future analysis years. Both the EU-PRHYDE protocols and SAE J2601/5 protocols were used to demonstrate the influence of fueling protocols on station design.

Further station and analysis parameters can be viewed at the publicly available data site (https://hero.nlr.gov/app/hd-fueling).

Task 5: Determine the Control Parameters for Each Fueling Protocol

In Task 5, NLR will leverage NLR's H2FillS fueling model and the CFD model from Task 3 to determine a set of control parameters based on the fueling protocol architecture and associated boundary conditions determined in Task 2. To do this, NLR will enhance the H2FillS model to facilitate batch processing and automated calculations of the control parameters for each fueling protocol and set of boundary conditions considered.

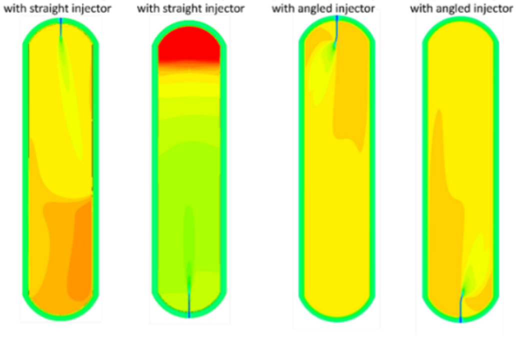
Task 5 Results:

NLR's H2FillS model was updated to feature improved modeling heavy-duty truck fueling with applicable protocols. Newer versions accommodate ambient temperature fueling capabilities, defueling scenarios, enhanced computation speed, and ability to run the model for high-flow fueling simulations (e.g., heavy-duty fueling).

CFD simulations were performed to evaluate tank fueling performance with utilization of straight vs. angled on-tank valve injectors in both vertical and horizontal tank orientations. Results helped identify potential temperature hotspots observed in the tank during high-flow fueling simulations.


(a) Horizontal tank with straight


(b) Horizontal tank with angled injector


(c) Downward filling with straight injector

(d) Upward filling with straight injector

(e) Downward filling with angled injector

(f) Upward filling with angled injector

Figure 4. CFD simulations evaluating tank temperature performance during high-flow fueling events. Tanks were oriented both vertically and horizontally and paired with both straight and angled on-tank valve injectors

The maximum temperature in the straight injector tanks is significantly different depending on the filling direction/tank orientation with the upward filling scenario identified as the least effective. The maximum temperature for the tanks with angled injectors is almost the same regardless of the filling direction/tank orientation.

CFD modeling of breakaway components is also being completed at the manufacturing partner's request. Those results are still pending.

Task 6: Develop and Integrate a Suite of Modeling Tools for the Total Cost of Ownership (TCO) Assessment

In Task 6, NLR will build the tools needed to conduct the technoeconomic assessment (TEA) in Task 7. NLR will leverage its existing tools by combing the relevant models in the following way: H2FillS will be combined with NLR's internal hydrogen station design model (referred from here as H2FillSHDStation), T3CO will calculate the total cost of ownership. NLR will create a wrapper program such that the two combined models can seamlessly interface with each other. NLR will program the proposed fueling protocols into the H2FillS-HDStation model. NLR will derive station component cost for the T3CO model from ANL's HDRSAM. NLR will conduct a literature review to determine if there are already developed CHSS cost formulas which can be used in the H2FillS-HDStation model.

In Task 6, ANL will be responsible for updates to HDRSAM based on feedback on the cost of station components from the project partners. ANL will support the HDRSAM integration into other NLR models being used as part of the project. ANL will complete the necessary modifications to HDRSAM and will assist in interpreting and reporting the refueling cost component from the HDRSAM model.

Task 6 Results:

This project assessed the HD fueling protocols by developing and integrating a suite of tools to understand the effects that the protocol architectures, fueling methods, and associated boundary conditions have on the station design, the vehicle design, the associated costs, the functional safety requirements, and the holistic implications of these on the TCO for the HD high-flow fueling of MD/HD fuel cell electric vehicles FCEVs with 70- megapascal (MPa) storage systems. Figure 5 shows the structure for combining the National Laboratory of the Rockies' (NLR's) Hydrogen Filling Simulation (H2FillS™) software, Argonne National Laboratory's Heavy-Duty Refueling Station Analysis Model (HDRSAM), and NLR's Transportation Technology Total Cost of Ownership (T3CO) tool to determine the effect of fueling protocols on the TCO. H2FillS provides fueling tables to HDRSAM, which designs the station and calculates the levelized station cost. The station's levelized cost is passed to T3CO to determine the TCO.

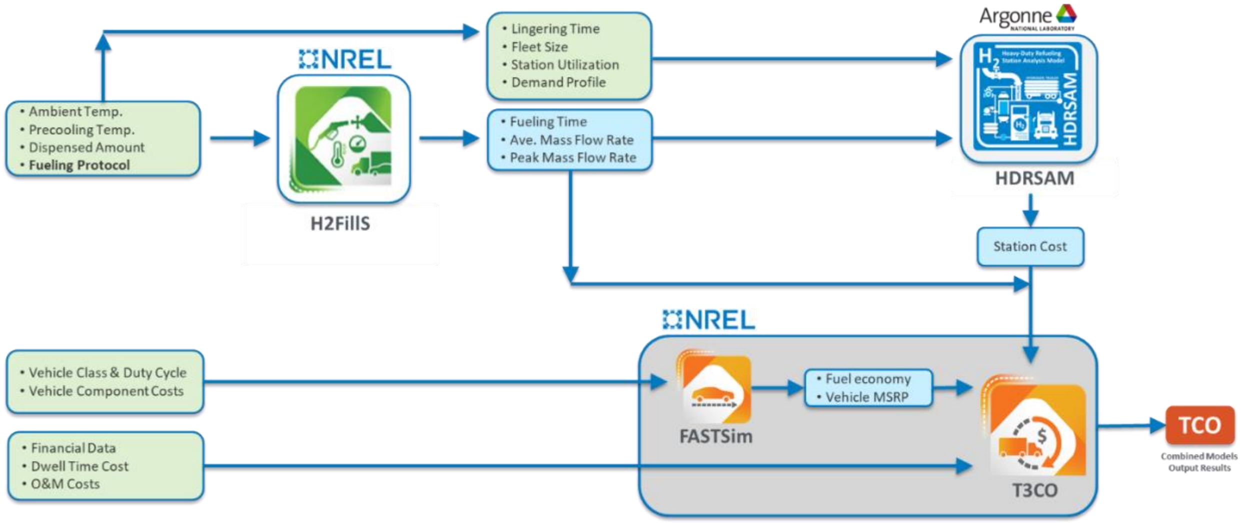


Figure 5. Structure for combining the analysis models from NLR and Argonne National Laboratory. Illustration by Shaun Onorato, NLR

In lieu of a wrapper, a website was created to visualize TEA/TCO data created with this suite of models for the CRADA under this Task. The website can be viewed here.

ANL was able to consistently provide the most up-to-date version of HDRSAM to the NLR team throughout the duration of the CRADA.

Task 7: Conduct Comprehensive TEA Based TCO Analysis

In Task 7, NLR will conduct a comparative TEA to come up with a TCO analysis that will focus on assessing and understanding the effects that different fueling protocol architectures, fueling methods, and associated boundary conditions have on station design and associated costs, class 8 truck vehicle design and associated costs, functional safety requirements, and the holistic implications of these on the TCO for HD high flow fueling of MD/HD FCVs with 70 MPa storage systems.

Sensitivity Analysis with Combined Model Structure

NLR will perform sensitivity analyses on station configurations based on various demand profiles that can be achieved using different vehicle fueling protocols. The fueling protocols may enable different station throughputs and will be reflected in the levelized dispensed price of hydrogen at the station. The station costing will be updated from industry input to reflect the current state of the technology. The provided analysis will inform how station throughput and capacity may depend on fueling protocol selection. Depending on the station design and protocol selection, the levelized dispensed price of hydrogen will inform which scenario will result in the lowest cost option.

ANL will serve in an advisory role in Task 7. Monitoring the TCO progress and providing feedback to NLR based on their expertise in this space.

Task 7 Results:

HD FCEV fueling protocols were incorporated into the H2FillS-HDRSAM-T3CO model framework to analyze the effects of fueling protocols on fueling time, station cost, and the TCO. The HDRSAM analysis showed that the compressor for gas-supplied stations and the pump for liquid-supplied stations contributed the largest portion of the station cost. The effect of protocols on the station cost was noticeable at high ambient and precooling temperatures, which necessitated additional hoses, booster compressors, and chillers.

In general, protocol performance parameters that reduce fueling rates, and therefore necessitate additional dispensers,, are expected to result in relatively more expensive stations. The demand profile showed a negligible effect on the liquid station but up to $1/kg higher for a single 10-hour demand profile compared to the double 5-hour demand profile in the gaseous-storage station. This is mainly because the liquid station is oversized due to a lack of real-world market data regarding cryogenic pumps, which remains a topic for future work.

Incorporating the station cost also showed sensitivity to lingering time, in which increasing the lingering time from 5 to 10 minutes could increase the station cost by up to $3/kg due to the increase in the required number of hoses and the associated capital cost increase. The TCO analysis showed that the fuel price, which incorporated both the station cost and the hydrogen delivered to the station, contributed one of the largest fractions to the TCO. The fuel price could influence the TCO by approximately $0.40 per mile.

The cost of vehicle technologies (e.g., fuel cell, storage) also had a large effect on the TCO. Cost reductions, such as those achievable by research, development, and economies of scale might reduce the TCO by approximately $0.75-$0.90 per mile.

Last, improving the fuel economy from the conservative trajectory to the advanced trajectory might reduce the TCO by approximately $0.65-$0.85 per mile. The protocol selection, however, had a smaller effect on the TCO, at less than $0.10 per mile in many scenarios. The filling process, station design, and vehicle characteristics all play an important role in developing effective protocols for fueling HD FCEVs, and will guide future fueling protocol development.

Task 8: Integrate a Communication System to Facilitate Fueling Protocol Testing

In Task 8, NLR will analyze and implement the communication protocol from deliverable 2.3 at NLR's hydrogen station and with NLR's vehicle simulator. If a wireless communication protocol cannot be implemented, NLR will implement a communication system that emulates these requirements and can exchange the required data messages the fueling protocol requires - this will be a hard-wired system.

Task 8 Results:

NLR implemented the Shell Techworks HyConnect Advanced Communications System, which is a proof-of-concept hydrogen-vehicle-to-dispenser-communications system capable of bidirectional data transfer. It is SAE J2799 compliant and has compatibility for SAE J2601/5 and EU PRHYDE fueling protocols. NLR successfully completed the baseline evaluations of the HyConnect near-field communication (NFC), Wi-Fi and Ethernet-APL communications methods over a sequence of SAE J2601/5 fueling events with only unidirectional data transfer.

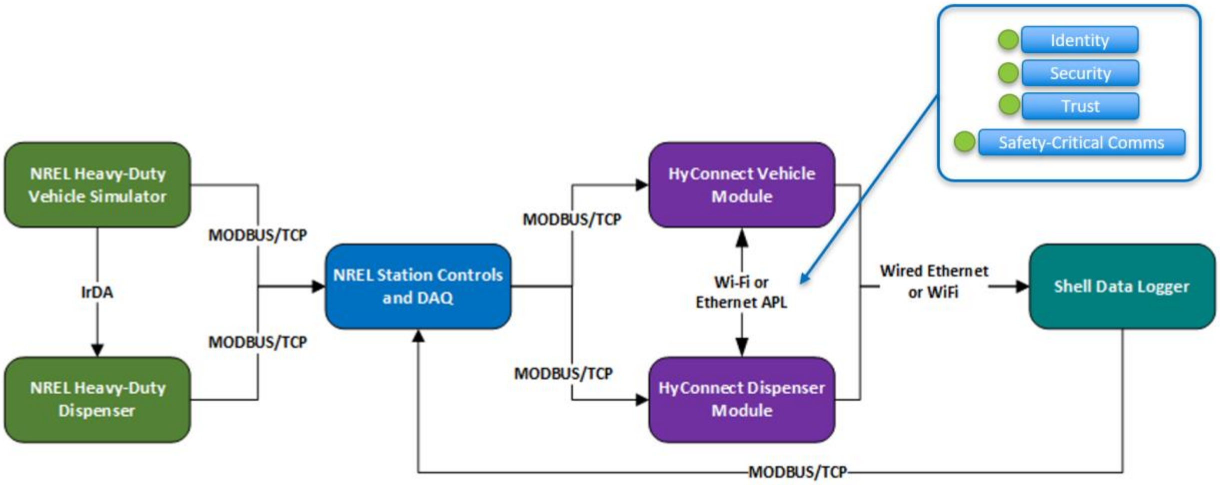


Figure 6. Overview and block diagram of the NLR and Shell HyConnect Communication System integration

The HyConnect test system interacts directly with the NLR heavy-duty vehicle simulator and heavy-duty dispenser through NLR's modbus/TCP network. HyConnect units also transmitted optional data fields in addition to SAE J2799. Static and dynamic data captured by the HyConnect dispenser and vehicle modules were compared against the data transmitted by the NLR system to confirm consistency (i.e., identifying any data loss, lag, or inaccuracies).

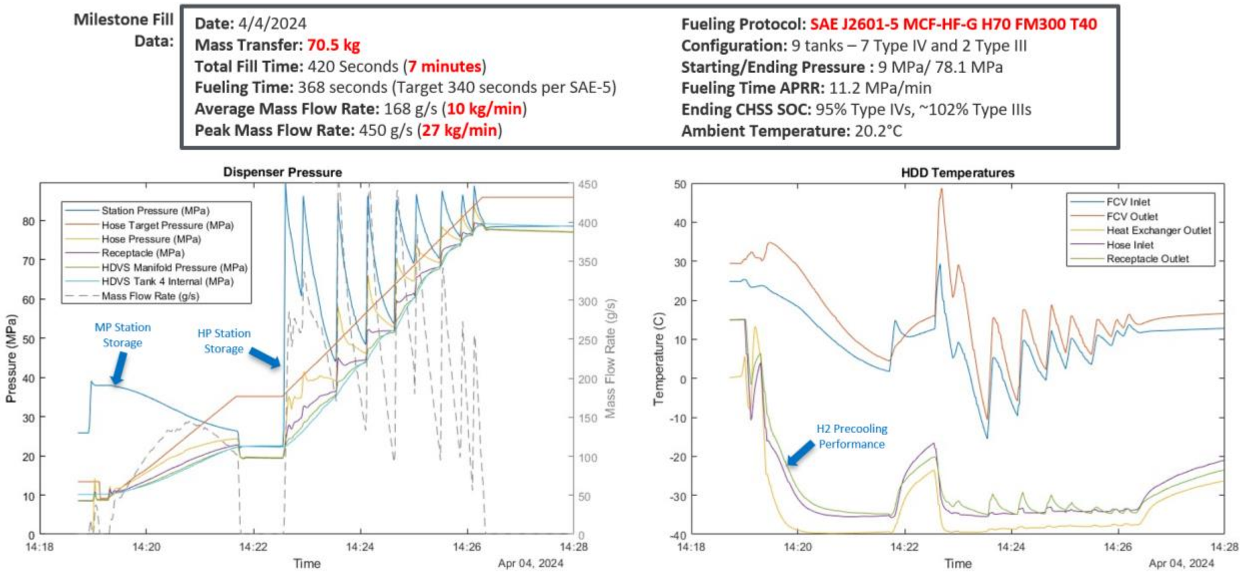
Work completed under this Task informed International Organization for Standardization (ISO) 19885-2, Part 2: Definition of communications between the vehicle and dispenser control systems.

Task 9: Fueling Protocol and HD Fueling Component Testing at NLR's HITRF

In Task 9, NLR will integrate a fueling architecture and method at their hydrogen station for a proof-of-concept test. Real world condition testing will be conducted by NLR. Testing will be conducted under as wide a variety of conditions (ambient temperature, pre-cooling, initial conditions, etc.) as practical. Results from Task 3 will inform any additional fueling component testing and NLR will conduct them during this Task. NLR plans on the tests including an additional assessment of nozzle freeze-on under back-to-back fueling events, an assessment of the maximum real-world pressure drop under the highest expected flow rates, and an assessment of the component ergonomics, including weight, ease of connect/disconnect, and touch temperature after cold gas exposure.

Task 9 Results:

NLR was able to implement the SAE J2601/5 protocols into its research dispenser capabilities for high-flow fueling evaluation. The model was implemented into an NLR-developed validator tool and further transferred into a C++ coding architecture for compatibility with NLR's programmable logic controllers (PLCs), control logic, and data-communication infrastructure. Additional evaluation is required for advanced fueling protocol concepts (i.e., pressure taper (P_{taper}) and minimum final pressure (P_{Tfinal_min})). Figure 7 demonstrates example results of a full fueling event following the SAE J2061/5 protocol.



Milestone Fill Data:

Date: 4/4/2024
Mass Transfer: **70.5 kg**
Total Fill Time: 420 Seconds (**7 minutes**)
Fueling Time: 368 seconds (Target 340 seconds per SAE-5)
Average Mass Flow Rate: 168 g/s (**10 kg/min**)
Peak Mass Flow Rate: 450 g/s (**27 kg/min**)
Fueling Protocol: **SAE J2601-5 MCF-HF-G H70 FM300 T40**
Configuration: 9 tanks – 7 Type IV and 2 Type III
Starting/Ending Pressure : 9 MPa/ 78.1 MPa
Fueling Time APRR: 11.2 MPa/min
Ending CHSS SOC: 95% Type IVs, ~102% Type IIIs
Ambient Temperature: 20.2°C

Figure 7. Full fueling event metrics following the SAE J2601/5 protocol

Pressure drop calculation across hardware components provided under this CRADA were evaluated. Results help industry partners identify design constraints and future improvements that can be made to prototype hardware for standardization. Example results from this Task 9 are shown below in Figure 8.

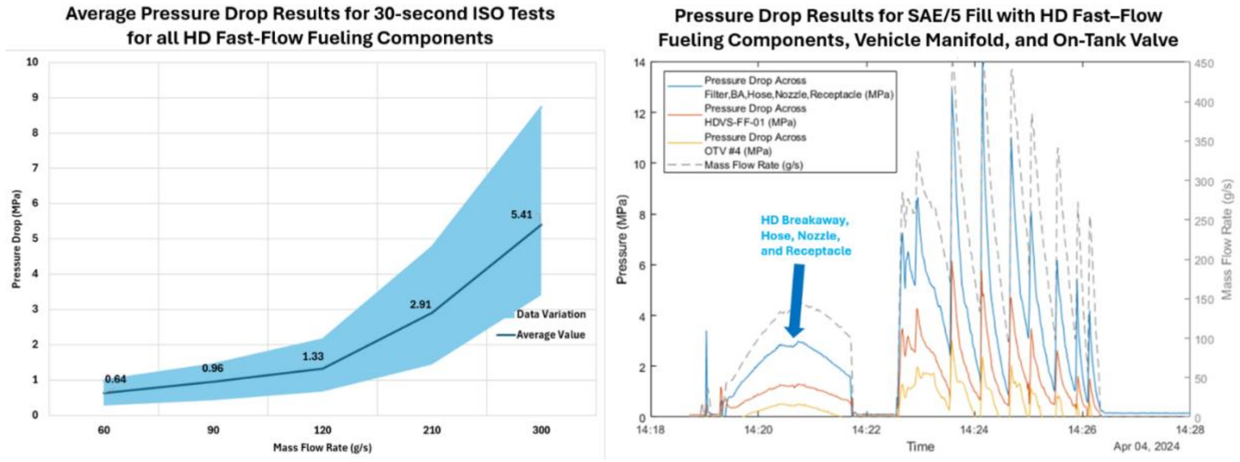


Figure 8. Pressure drop evaluation during SAE J2601/5 fueling event

Future work under a follow-on CRADA will include the implementation and evaluation of the EU PRHYDE protocol as well as other protocols including the Rapid Transfer Rate – Heavy Flow Protocol (RTR-HFP) and Japan Petroleum Energy Center (JPEC)] Dual Nozzle.

Issues encountered include limitations to the set pressure ramp rate (PRR) corridor. Modifications to the corridor limits were suggested and evaluated by NLR. Pre-cooling also remains a challenge for high-flow gaseous hydrogen fueling applications.

Flow control strategy has major limitations with most commercially available control valves. New larger valves with improvements to dynamic response, reliability, and lower cost are needed for appropriate high-flow performance and repeatability. Cascade fueling requires a balance of being able to transfer sufficient mass and maintain a pressure differential for flow rates to achieve the appropriate state of change (SOC). A new, fast-acting flow control valve has been installed in NLR's research dispenser and is currently undergoing characterization to perform protocol testing in future iterations of this work.

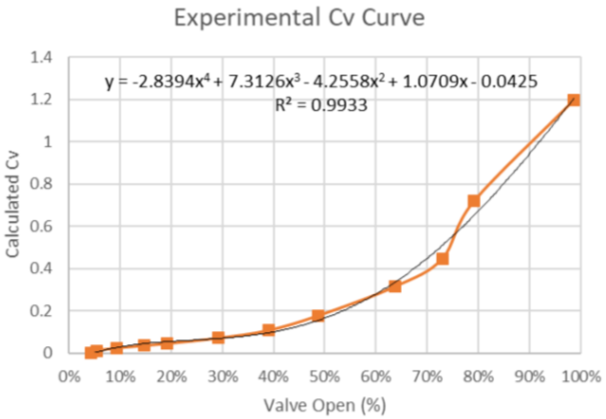


Figure 9. New, air-operated flow control valve characterization and experimental flow coefficient curve fit

Further results and information for Task 9 and for the HD Fueling Methods CRADA will be published in a technical report document in the near term.

Task 10: Project Report/CRADA Final Report

In Task 10, NLR will write and publish a comprehensive report summarizing findings, conclusions, and documenting analysis and testing procedures. The report will follow the format of the required CRADA final report (Preparation and submission in accordance with Article X) and will be reviewed and approved (via email confirmation from technical leads) by ANL, Chevron, and NextEnergy.

Task 10 Results:

This report serves to meet the requirements for the CRADA Final Report with preparation and submission in accordance with the agreement’s Article X.

A report titled “Assessment of Heavy-Duty Fueling Methods and Components – Modeling and Analysis” is currently in the publication process and will be made available to the public. This report captures all TEA/TCO and CFD modeling Tasks of this CRADA.

Future reports documenting the hardware analysis, evaluation, testing, and lessons learned will also be published via technical report once all evaluations are completed.

References:

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Subject Inventions Listing:

None.

ROI#:

None.