
Advancing Hydrogen Dispenser Technology by Using Innovative Intelligent Networks

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Subcontractors:

- Air Liquide Advanced Technologies (US), Houston, TX
- Rheonik GmbH, Oldehausen, Germany
- National Renewable Energy Laboratory, Golden, CO

Project Start Date: June 1, 2016
Project End Date: June 30, 2019

Fiscal Year (FY) 2018 Objectives

- Improve reliability of vehicle-to-dispenser communication with the use of emerging connected-vehicle-to-infrastructure wireless communication technologies employed for Intelligent Transportation Systems, using the secure IEEE 1609 vehicle communications protocol.
- Achieve consistent 2% or better metering accuracy of the dispenser system through tight design control of flow dynamics and thermal response of the meter, as well as improved thermal mass flow regulation enabled by advanced fueling event notification.
- Reduce cost and complexity of dispenser hardware, such as hydrogen pre-cooling systems, via intelligent and predictive controls incorporating individual vehicle data, and, where possible, area-wide fleet data to allow more appropriately sized equipment.

Overall Objectives

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Technical Barriers

This project addresses the following technical barriers from the Hydrogen Delivery section of the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration (MYRDD) Plan¹:

(I) Other Fueling Site/Terminal Operations.

Technical Targets

This project will develop an SAE J2601-compliant dispenser system that aims to address reliability concerns with vehicle-to-dispenser communication, compliance with weights and measures standards for commercial fueling, and dispenser cost and complexity. Specifically, the project team will develop, test, and demonstrate dedicated short-range communication (DSRC) hardware for vehicle-to-station communication as opposed to the current infrared communication standard, as well as engineer a new high-accuracy Coriolis flow meter specifically designed to

¹ <https://www.energy.gov/eere/fuelcells/downloads/fuel-cell-technologies-office-multi-year-research-development-and-22>

maintain an accuracy of 4% or better in automotive hydrogen-refueling conditions. This meter will be integrated with the prototype dispenser in an optimized way to ensure that accuracy is maintained, enabling a pathway for NIST Handbook 44 compliance of dispenser systems. Lastly, the project will engineer and develop novel methods for hydrogen pre-cooling, flow control, and predictive control algorithms to decrease system complexity and cost. Technical targets are detailed in Table 1.

FY 2018 Accomplishments

- Successfully completed the first project go/no-go and passed into Budget Period 2 with updated budget proposal.
 - Tested improved hydrogen meter hardware to demonstrate $\leq 2\%$ accuracy of technology using hydraulic bench tests and SAE J2601 H70-T30-compliant refueling.
 - Completed bench testing of DSRC wireless system with over 1 million SAE J2799-compliant messages sent and capability of roadside unit (RSU) to support multiple nozzles.
 - Updated project budget allocation to reflect increased use of contract services to aid in design of innovative dispenser system and DSRC wireless communication.
- Froze the design of innovative dispenser in preparation for hardware build, which included:
 - Collaboration with project partners (National Renewable Energy Laboratory

- [NREL] and Air Liquide) to assess design hazards of dispenser, heat exchanger, and DSRC wireless communication using structured what-if method.
- Finite-element analysis (FEA) to assess ability of dispenser housing to withstand drive-off events.
- Completion of mechanical and electrical design package including process and instrumentation diagrams, wiring schematics, bill of materials, and assembly drawings for use by U.S.-based contract manufacturing/assembly house.
- Completion of mechanical design package of heat-exchanger system.
- Verification of component functional operating limits to design verification and reporting plan.
- Executed agreement with contract manufacturer for the build of dispenser and low-cost ASME heat exchanger with about 45% build completion to date.
- Executed agreement with contract software developer well-versed in DSRC implementation to develop full-scale prototype wireless communication system.
- Presented update on DSRC wireless communication and demonstration plan to the SAE Interface Task Force.

Table 1. Hydrogen Dispenser Targets Compared to Corresponding MYRDD Targets

| Category | Project Target | MYRDD | Project Status |
|------------------------|--|---------------------------------|---|
| Dispenser Capital Cost | \$150,000 at low volume | \$40,000 by 2020 at high volume | Less than \$200K at prototype stage |
| Communication Method | DSRC using IEEE 1609 protocols | N/A | Demonstrated capability at bench scale |
| Meter Accuracy | $\leq \pm 2\%$ accuracy at temperatures between -40° and 85° C and flow rates between 0.6 and 60 g/s | N/A | $\leq 2\%$ accuracy with 95% confidence |
| Cooling System Cost | \leq \$100,000 at low volume | \$70,000 by 2020 | In progress—will be determined after prototype is built |

INTRODUCTION

This project aims to improve early adoption of fuel cell electric vehicles (FCEVs) by addressing technical obstacles and high costs associated with SAE J2601/1-compliant hydrogen dispenser systems. The team will focus on three main areas: (1) robustness of vehicle-to-dispenser (SAE J2799) communication, (2) ability to comply with NIST Handbook 44, and (3) complexity of system design associated with hydrogen cooling and flow control. The team intends to address these issues by improving hydrogen-meter accuracy, replacing infrared communication with wireless technology used for vehicle-to-vehicle and vehicle-to-infrastructure communication, and implementing improved modeling and controls around thermal and flow management.

APPROACH

The team will design, develop, and deploy an advanced hydrogen dispenser that incorporates DSRC wireless communication and improved hydrogen-meter accuracy to a minimum of $\leq 4\%$. During the beginning phases of the project, demonstration of core technologies will occur at the bench level along with detailed system modeling. Testing will include wireless communication of refueling protocol messages using DSRC hardware and bench-scale demonstration of hydrogen-meter accuracy of at least 4% over varying temperatures, pressures, and flow conditions.

After bench validation, a prototype dispenser will be designed and manufactured for full-scale simulated-environment testing at the NREL Hydrogen Infrastructure Testing and Research Facility (HITRF). The goals of this phase are to validate compliance with SAE J2601/1 (2016), demonstrate hydrogen-meter accuracy of $\leq 4\%$ when integrated in a dispenser, and show wireless communication of refueling messages from a simulated vehicle to the dispenser control unit. Lastly, the prototype dispenser will be installed at an Air Liquide station for up to a 6-month test to validate the advanced communication, meter accuracy, and dispenser performance under real environmental operating conditions fueling FCEVs.

RESULTS

The team successfully demonstrated two key technologies as part of the first project go/no-go: (1) the wireless-to-vehicle communication, which uses DSRC wireless technology customized for this application to transmit SAE J2799 fueling messages, and (2) the hydrogen metering system, which provides highly accurate measurement of hydrogen mass delivered during vehicle fueling events with an accuracy of $\leq 4\%$. In addition to completing this major project milestone, the dispenser design was completed, 100% of components have been procured, and hardware build is about 45% completed.

To demonstrate the go/no-go goal of $\leq 4\%$ hydrogen flow accuracy, the team conducted more than 100 tests with a wide range of conditions. Led by Rheonik, these tests included hydraulic flow accuracy measurements and simulated refueling events in two separate SAE J2601 H70-T30 compliant dispensers. Twenty Coriolis mass flow meters were tested using Rheonik's standard hydraulic test by flowing water through each meter at 10, 8, 4, 2, and 0.2 kilograms per minute. The meter's digital-pulse output channel, typically used for sealed custody-transfer applications such as those in hydrogen refueling, was electronically recorded. Pulsed-flow measurements were then compared to a NIST-calibrated gravimetric device to calculate meter accuracy. As shown in Figure 1, the hydraulic test demonstrated $< 4\%$ accuracy when scaled for hydrogen (10:1 ratio).

Additional meter accuracy testing was performed under a number of SAE J2601 H70-T30 refueling events and validated using an EU metrology device used to measure hydrogen-meter accuracy for fielded systems. In total, 30 tests were performed to quantify meter accuracy over a varying range of pressures, flow rates, total mass dispensed, pre-cool temperatures, and meter placement relative to the heat exchanger (e.g., upstream or downstream). Results from these tests were analyzed using various statistical methods: moving range, one-way analysis of variance (ANOVA), and process capability. Results from these tests demonstrated repeatable accuracy of $\leq 2\%$ with 95% confidence over all conditions tested, as shown in Figure 2, and the capability of the meter to meet DOE's MYRDD target of $\leq 2\%$ meter accuracy. Additional tests that quantify zero-point shift, meter stability, and temperature effects further validate the meter's ability to maintain high accuracy in demanding hydrogen refueling applications.

| Test Flow Rate | Average % Error | Standard Deviation | Standard Error |
|-----------------|-----------------|--------------------|----------------|
| 10 kg/min | 0.044% | 0.054% | 0.01% |
| 8 kg/min | 0.038% | 0.073% | 0.02% |
| 4 kg/min | -0.017% | 0.079% | 0.02% |
| 2 kg/min | 0.011% | 0.108% | 0.02% |
| 0.20 kg/min | 0.033% | 0.108% | 0.02% |
| Overall Average | 0.022% | 0.032% | 0.01% |

Figure 1. Results of hydrogen-meter flow accuracy using hydraulic test method

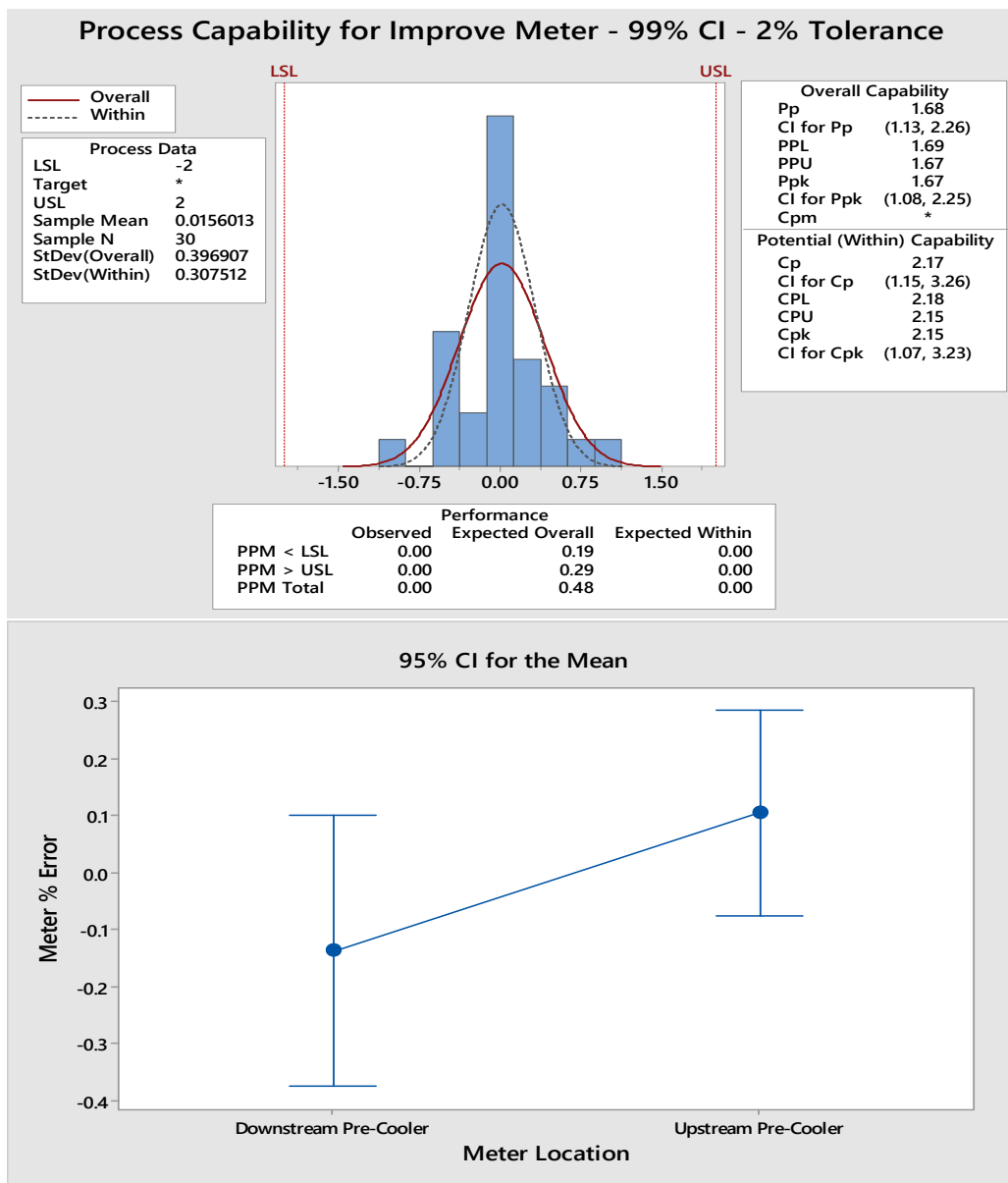


Figure 2. Results of hydrogen-meter accuracy in SAE J2601 H70-T30-compliant refueling

Vehicle-to-dispenser wireless communication was validated at the bench scale, successfully demonstrating DSRC’s capability to send SAE J2799 messages using commercially available hardware. Validation included

development of custom message generation and transmitting applications to send and receive J2799 messages. The onboard unit (OBU) application was designed to read and transmit randomly generated, simulated fueling event messages from a source file. Each message was encoded into a network packet (or payload) and broadcasted by the OBU (vehicle) using WAVE protocols through IEEE 1609 [1] stacks and IEEE 802.11p [2] radios on designated channels. Packets were then received by a corresponding RSU (dispenser), decoded back to ASCII formats, and transmitted to a desktop computer. Each message included a randomly generated set of SAE J2799 string to simulate refueling events, which included randomly varying protocol version, tank volume, pressure, temperature, and fueling commands. Additional information such as message timestamp, send/receive latency, and a unique identifier were also added to each packet. Two other parameters were varied during the test: distance between the OBU and RSU, and the number of messages transmitted per second. For most testing, the distance was about 1.5 meters, as shown in Figure 3; for longer-distance tests, the separation was increased to more than 20 meters, with a wall in between each radio. Message transmission frequency was varied from a low end of 10 messages per second (per requirements in SAE J2799) to a high end of 300 messages per second to simulate multiple simultaneous refueling events.

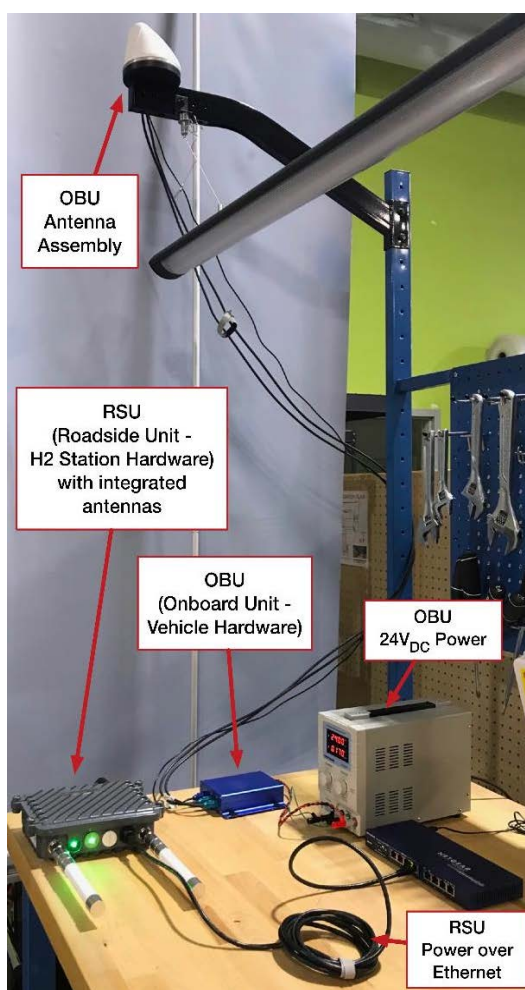


Figure 3. DSRC vehicle-to-dispenser wireless communication test apparatus

Results of the DSRC vehicle-to-dispenser bench testing are summarized in Table 2. In total, 117 individual tests were performed, amounting to more than 1 million messages exchanged, or the equivalent of more than 160 complete refueling events. Over all of these tests, a total of 127 messages (0.01%) were missed with a maximum delay of less than 300 ms; however, all the messages successfully received showed zero errors and

complete cyclic redundancy checks (CRCs) when compared bit by bit over the entire test set. Testing results far exceeded requirements specified in SAE J2799, thus allowing completion of this go/no-go milestone.

Table 2. Summary of DSRC Vehicle-to-Dispenser Communication Bench Testing Results

| Test | # of Tests / # of Messages per Test | Message Send Period (ms) | Missed Messages / Total Messages | Longest Delay between Messages (ms) |
|---|--|--------------------------------|---|---|
| 5-Minute Refueling – Set 1 | 31 / 6,000 | 100 | 31 / 186,000 | 300 |
| 5-Minute Refueling – Set 2 | 30 / 6,000 | 100 | 1 / 180,000 | 200 |
| High-Data-Rate Test 100 Hz | 10 / 6,000 | 10 | 0 / 60,000 | 10 |
| High-Data-Rate Test 300 Hz | 10 / 6,000 | 3.3 | 7 / 60,000 | 19 |
| 70,000-Message Data Set 10 Hz | 1 / 70,000 | 100 | 13 / 70,000 | 300 |
| Long-Distance Test 50 Hz (distance >20 m through wall) | 1 / 6,000 | 20 | 1 / 6,000 | 40 |
| Long-Distance Test 300 Hz (distance >20 m through wall) | 1 / 74,000 | 3.3 | 48 / 74,000 | 54 |
| Halt and Abort Tests (1 message per 100 has FC=Halt; 1 message per 100 has FC=Abort) | 3 / 65,000 | 4 | 13 | 24 |
| Transmission Pause Tests (insert 1 sec pause every 6K messages) | 30 / 6,000 | 4 | 13 | 31 |
| <i>Summary</i> | <i>117 tests / 1,011,000 total messages</i> | <i>3.3–100</i> | <i>127 / 1,011,000</i> | <i>Max. 300</i> |
| <i>Go/No-Go Requirements</i> | <i>Min. 5 tests / Min. 30,000 total messages</i> | <i>100 or faster</i> | <i>N/A (Message content error rate = 0)</i> | <i>500 or less</i> |
| <i>Result</i> | <i>Pass</i> | <i>Pass</i> | <i>Pass</i> | <i>Pass</i> |

The team completed the design and component verification of the prototype intelligent dispenser system, which integrates DSRC vehicle-to-dispenser communication, high-accuracy hydrogen metering, and lower-cost hydrogen dispensing equipment for testing at NREL’s HITRF. Design activities included developing manufacturing-ready assembly drawings for mechanical and electrical systems, bill of material, hazard analysis, and FEA analysis. A major piece of this activity was the detailed hazard analysis led by Ivys with support from NREL and Air Liquide. More than 150 man-hours were spent assessing the design using a combination SWIFT/PHA analysis technique, covering various hazards associated with mechanical, electrical, fire, explosion, software, and operator error. Risks identified from this analysis have been mitigated by various design changes implemented before freezing the design. Local manufacturers with expertise in high-pressure gas-system assembly and hazardous-area electrical systems have since begun assembly of the prototype dispenser, which is 45% complete.

Lastly, Ivys presented the proposed DSRC wireless-communication method, testing, and results during the SAE Interface Task Force meeting held on June 6, 2018, in Torrance, California. This SAE team oversees the development and approval of various standards governed by SAE, including fueling protocols, nozzle

requirements, and communication protocols used in hydrogen systems. The presentation was well received by various automotive original equipment manufacturers (OEMs) and station providers, and feedback was used to update existing design and verification plans. An additional white paper was provided to three automotive OEMs to help begin internal discussion and to provide further feedback. The project team hopes that with cooperation from the industry, this project can assist in providing initial test data for use by the industry to influence long-term viability and acceptance of wireless vehicle-to-dispenser communication protocols.

CONCLUSIONS AND UPCOMING ACTIVITIES

In the second year of this project, significant progress was made to validate key technologies, far surpassing the requirements of the go/no-go and demonstrating the ability to meet DOE's MYRDD long-term targets. The dispenser-system design and hazard analysis have been completed, and the design was frozen before beginning build of the prototype dispenser system for testing in early 2019 at NREL's HITRF. Future planned activities include:

- Complete build of dispenser hardware that integrates high-accuracy hydrogen flow metering technology, improved variable-orifice flow control and wireless vehicle-to-dispenser communication.
- Complete a low-cost heat-exchanger system including initial factory testing and ASME certification.
- Install and validate prototype dispenser for compliance to SAE J2601/1 at NREL's HITRF.
 - Demonstrate $\leq 4\%$ accuracy of flow measurement during simulated filling events.
 - Demonstrate $\leq 2.5\%$ accuracy of flow measurement in secondary bench testing using hydrogen-meter qualification equipment at NREL at pressures up to 700 bar, flow rates up to at least 30 grams per second, and ambient hydrogen temperature.
 - Demonstrate transmission of SAE J2601/1 refueling messages from a simulated vehicle to the dispenser control unit per the requirements of SAE J2799.
- Install and validate prototype dispenser under real environmental operating conditions with FCEVs including the following:
 - Demonstrate $\leq 4\%$ hydrogen metering accuracy with a stretch goal of $\leq 2\%$ using the Hydrogen Field Standard dispenser accuracy verification.
 - Demonstrate successful wireless connection from FCEV to prototype dispenser and exchange of refueling event data using DSRC wireless communication.

FY 2018 PUBLICATIONS/PRESENTATIONS

1. Bryan Gordon, "Alternatives to IrDA using Dedicated Short Range Communication (DSRC)," SAE Interface Task Force Conference, 6 June 2018, Honda R&D Americas Inc, Torrance, CA.
2. Bryan Gordon, "Summary of Alternatives to IrDA using Dedicated Short Range Communication (DSRC)," Honda R&D Americas Inc., 19 June 2018.
3. Chris O'Brien, Bryan Gordon, and Darryl Pollica, "Advancing Hydrogen Dispenser Technology by Using Innovative Intelligent Networks," presented at the 2018 DOE Annual Merit Review and Peer Evaluation Meeting, Washington D.C., June 2018.

REFERENCES

1. IEEE 1609 series of standards define security and communication stacks (e.g., MAC and PHY layers) used by DSRC hardware.
2. IEEE 802.11p defines wireless-communication protocols.