Advancing Hydrogen Dispenser Technology by Using Innovative Intelligent Networks

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Ivys Energy Solutions Inc.

2018 DOE Annual Merit Review

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Project ID: PD146

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Energy Solutions

www.ivysinc.com

Overview

Timeline

Project Start Date: June 2016

Project End Date: June 2019

- Second 6 month no-cost extension granted

Percent Complete – 54%

Budget

Total Funding
- DOE share: $1,999,947
- Contractor share: $620,600

Expenditure through 3/31/2018:
- DOE share: $801,249
- Contractor share: $381,789

Barriers Addressed (Delivery)

F. Other Fueling Site/Terminal Operations*

- Dispenser reliability and cost
  - 2020 MYRD&D Target: $60,000
- Cooling system reliability and cost
  - 2020 MYRD&D Target: $70,000
- Hydrogen metering accuracy
  - Commercial Target: <1.5%
- Robustness/cost of dispenser/vehicle communication hardware

Partners

Project Lead:
Ivys Energy Solutions, Inc.

Industry Collaborators:
Air Liquide Advanced Technologies U.S. (ALATUS)

Research Collaborators:
National Renewable Energy Laboratory (NREL)

International Partners:
Rheonik

** FCTO MYRDD Section 3.2: Hydrogen Delivery*

Relevance

Primary Objective:

Develop a robust, cost-effective system for dispensing and measuring hydrogen that further enables widespread commercialization of fuel cell vehicle technology

Technical Barriers Addressed	Project Activities
▪ Metering Accuracy over operating ranges of -40°C to 85°C / 2-60 grams per sec *Commercial Target: < 1.5%*	▪ Development of robust sensor hardware and algorithms that improve accuracy based on empirical testing and improved meter temperature measurement *Current Status: < 10%* *Project Target: < 4%*
▪ Robustness of IrDA Communication	▪ Develop, test and demonstrate the use of Dedicated Short Range Communication (DSRC) for use in vehicle refueling Project Target: Satisfy SAE J2799
▪ Dispenser Capital Cost *DOE 2020 Target: $60k Dispenser + $70k Cooling*	▪ Simplification and cost reduction of flow control and hydrogen pre-cooling systems *Current Status: >> $250k (Dispenser + Cooling)* *Project Target: <$150 k (Dispenser + Cooling)*

Approach

To be successful the deployment of new dispensing, metering and communication hardware must be:

- *<u>Safe</u>*
- Able to meet or exceed performance expectations
- Able to communicate SAE J2799 messages via DSRC
- Provide cost benefit over current state of the art

Therefore future actives include:

- Demonstrate ability for DSRC system to reliably communicate SAE J2799 messages using IEEE 1609 security architecture while ensuring nozzle to vehicle pairing
- Design and manufacture dispenser hardware to applicable codes / standards
- Validate prototype hardware to industry accepted refueling protocols at NREL's Hydrogen Infrastructure Testing & Research Facility
- Demonstrate technology in relevant environment at public hydrogen refueling station

IVYS Energy Solutions | RHEONIK THE CORIOLIS EXPERTS | NREL NATIONAL RENEWABLE ENERGY LABORATORY | Air Liquide

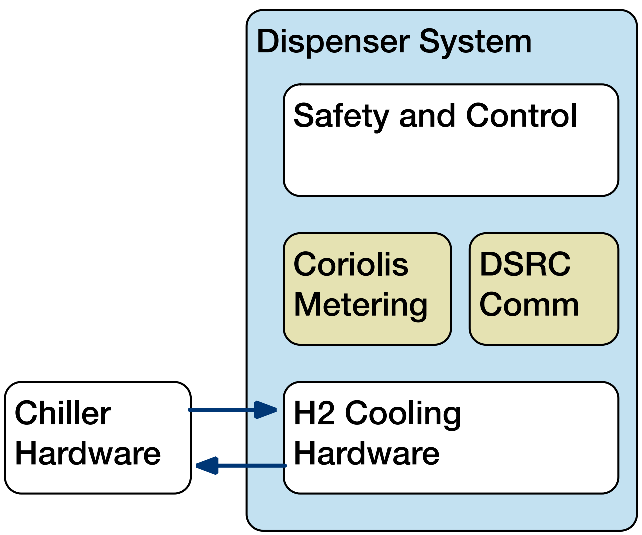
Any proposed future work is subject to change based on funding levels

Approach (2)

Integrated Approach including DSRC and Coriolis Technology

- DSRC, improved Coriolis meter, and dispenser system design all impact total cost
- DSRC hardware is low cost and leverages existing vehicle components
- Coriolis meter addresses fueling measurement accuracy requirement
- Close integration of meter with dispenser system is critical to realize bench-level meter accuracy in field applications
- Dispenser design will also include cost-optimized hydrogen safety system and cooling system designed to reduce system cost significantly.

Project Scope



Key Milestones & Deliverables

Phase 1	Bench verification of DSRC wireless communication performance (transmit SAE J2601 data) and advanced Coriolis meter accuracy (≤4%)
Phase 2	Test data for prototype dispenser at NREL HIRTF and Air Liquide LAX H2 refueling station, demonstrating performance to project targets.

Project Targets

Metric	Current State-of-the-Art	Project Target	MYRD&D/FOA Target
Communication Method	Nozzle Infrared (IR)	DSRC - Wireless	Nozzle IR Alternative
Dispenser Capital Cost	\$250k to \$400k	\$150k (Low Vol.)	\$40,000 (2020, Hi Vol.)
Metering Accuracy -40°C to 85°C	Widely variable to >10%	≤2%	≤4%, Commercial Goal 1.5%

Approach (3)

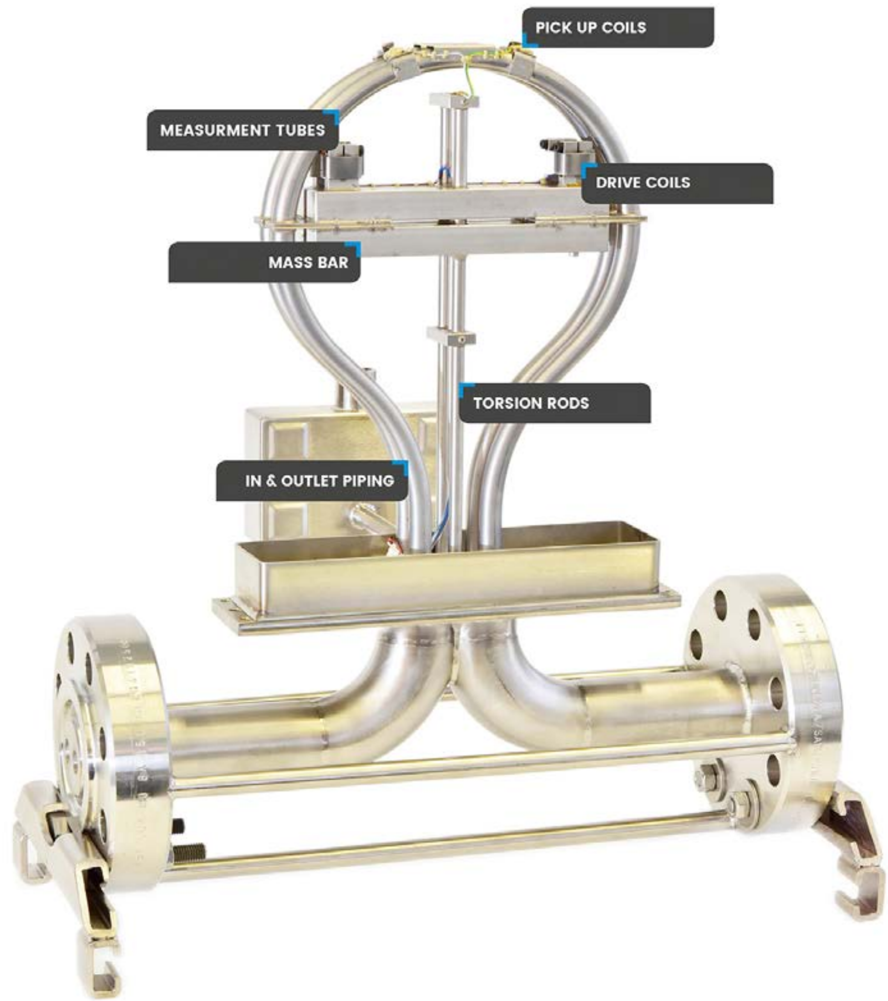
Core Technology: Coriolis Flow Meter

Advantages

- Widely used in hydrogen applications
- Accurate over large pressure, temperature, density and turndown ranges
- Project partner Rheonik is expert in the field, with unique technology

Challenges Being Addressed

- Component selection for improved sealing and reduced cost
- Modeling and measurement to address thermal impacts on meter hardware
- Development of robust temperature compensation algorithms to allow highest accuracy



Approach (4)

Core Technology: DSRC

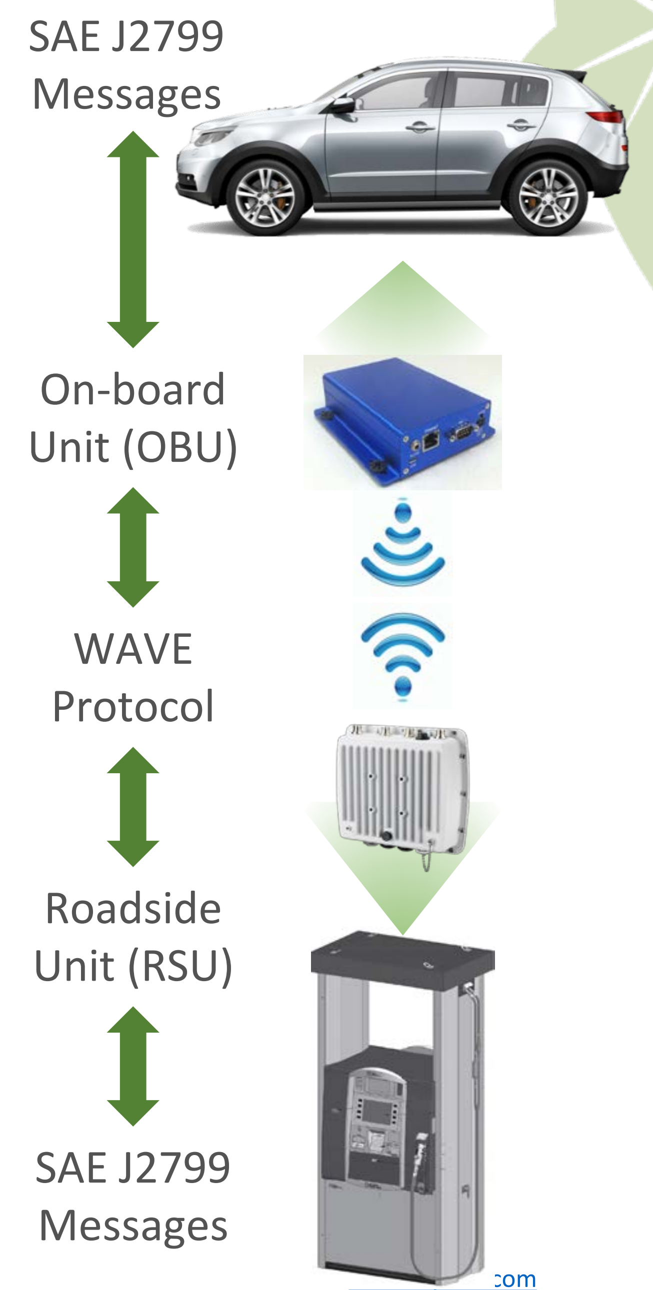
(Dedicated Short Range Wireless Communication)

Advantages

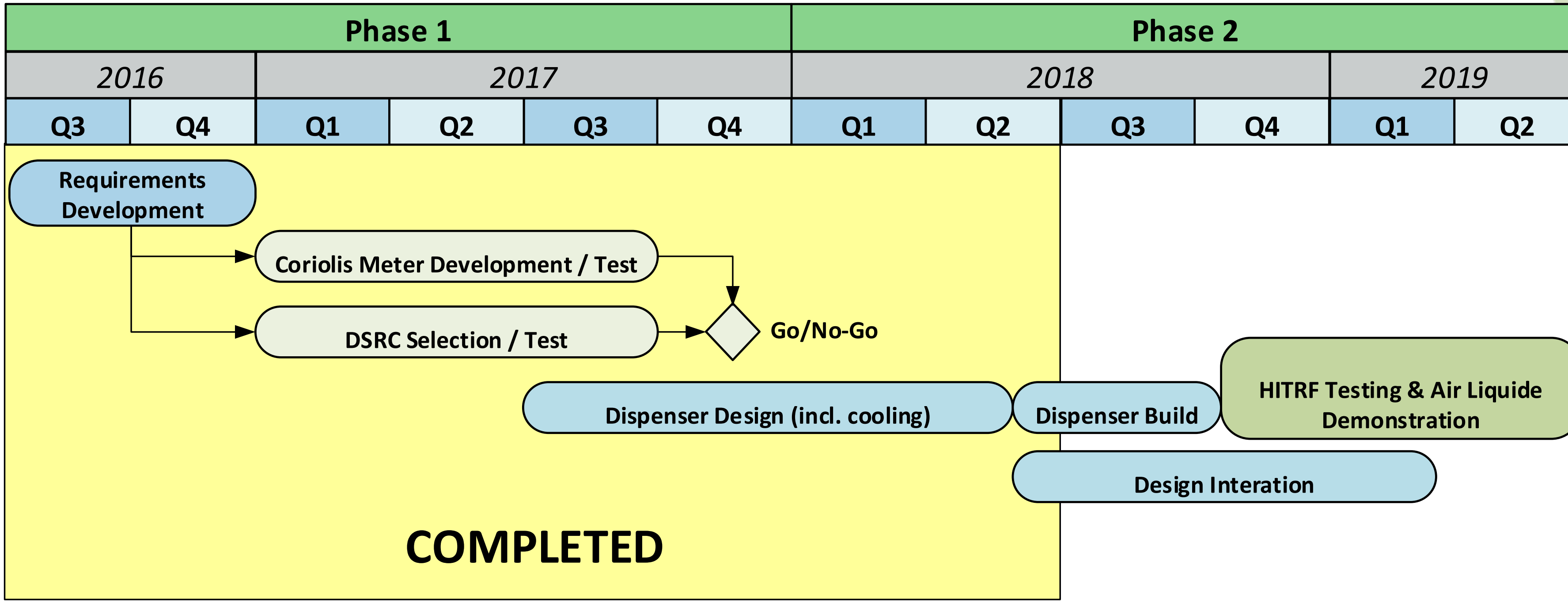
- Existing technology that is commercially available
- Robust – no hardware for user to damage
- Established security protocols (IEEE 1609 & SAE J2735)
- One RSU for whole station / multiple nozzles
- On board units are plug and play
- Very low latency (5-10 ms)

Challenges

- Developing applications to transmit SAE J2799 messages via DSRC
- Handshake – ensure nozzle is paired to vehicle
- Standards development for new communication protocol (SAE J2799 & SAE J2735)



Schedule Summary



Phase 1: Core Technology Bench Test, Dispenser Design and Build - COMPLETE

Phase 2: Field Testing (NREL HITRF, Air Liquide Commercial Station)

- Schedule reflects second 6 month no-cost extension
- System design overlaps with bench testing of key technologies
- Phase 2 allows for testing of prototype dispenser up to TRL 7 (field testing)

Milestones

Note: *All Milestone dates adjusted to reflect contract extension*

Date	Milestone #	Milestone	% Complete
4/17	M10.0	Program safety plan complete	100%
5/17	M1.0	Functional requirements and test plan documentation	100%
8/17	M2.3	Complete bench verification of DSCR communication	100%
10/17	M3.2	Bench testing of Coriolis meter to demonstrate ≤ 4% accuracy	100%
10/17	M3.5	Go / No-Go: Bench Verification of DSCR and Coriolis Meter	100%
5/18	M3.8	Prototype dispenser system design freeze and safety review	100%
10/18	M4.0	Prototype dispenser procurement, assembly and manufacturing testing	40%

Milestone Status as of 5/2018

Milestones

Note: *All Milestone dates adjusted to reflect contract extension*

Date	Milestone #	Milestone	% Complete
1/18	M5.0	Vehicle Simulator & HITRF station upgrades complete	50%
11/18	M6.2	Prototype dispenser installation at NREL complete	10%
2/19	M6.5	Passed simulated environment testing of dispenser system	0%
4/19	M7.1	Dispenser integration at demonstration HRS site complete	10%
4/19	M7.2	Vehicle upgrade to support DSRC communication complete	0%
4/19	M7.3a	First live refueling event	0%
6/19	M7.3b	Successful test of system in relevant environment	0%
4/17	M10.0	Program safety plan complete	100%

Milestone Status as of 5/2018

Accomplishments & Progress

Completion of H2 Meter Bench Test:

- Demonstrated ≤ 2% hydrogen meter accuracy in bench and relevant applications
- Continued testing at NREL's HITRF facility

Completion of DSRC Bench Test:

- Simulated 127 refueling events with over 1 million SAE J2799 compliant messages
- Demonstrated Roadside Unit capability to support multiple nozzles

Completion of Go/No-Go

- Successful completion of Go/No-Go
- Increased cost share from Rheonik to demonstrate meter capability

Dispenser Design Freeze:

- Completed mechanical and electrical design
- Completed detailed hazard analysis using SWIFT/PHA techniques with NREL and Air Liquide support
- Begun procurement and build of prototype dispenser system

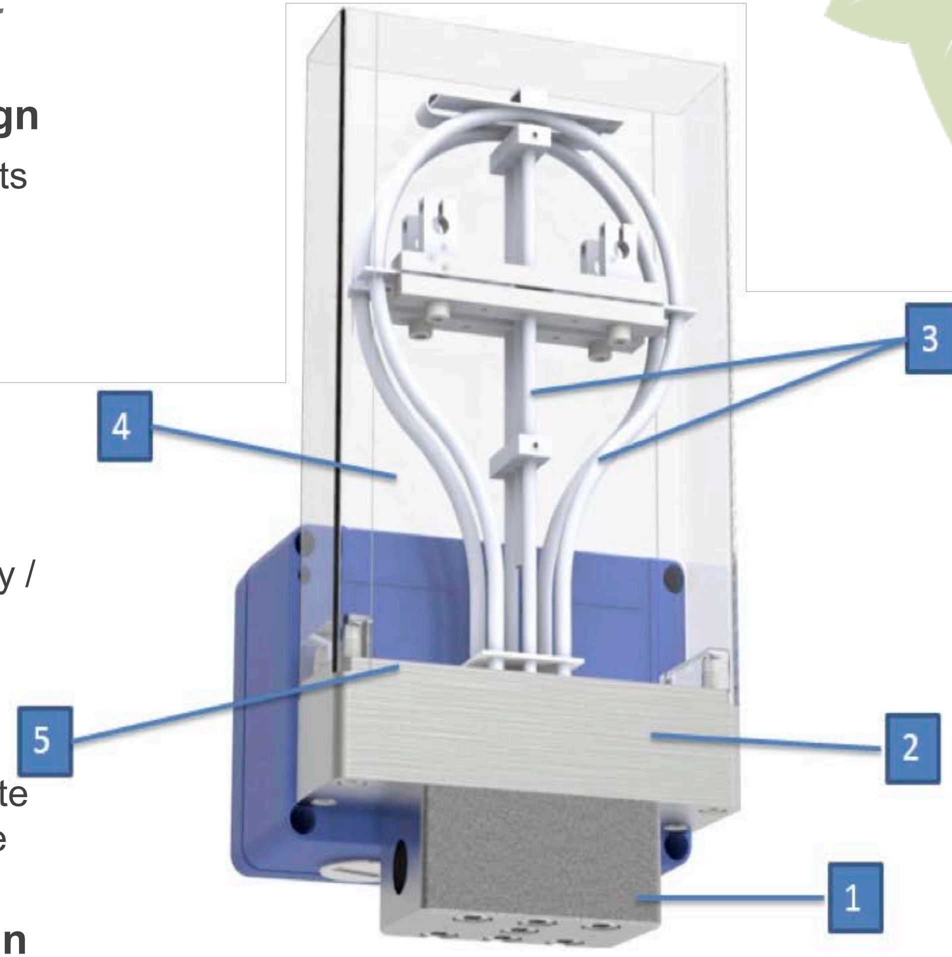
Status as of 5/2018

Accomplishments & Progress

Hydrogen Meter Development

Testing results informed new meter design

1. New “Mono-block” design tube reduces impacts of temperature changes & decreases flow turbulence
2. Two temperature measurements added to optimize software temperature compensation
3. Addition of two temperature measurement devices strategically located within the omega tube and housing
4. Argon / N2 housing purge to eliminate humidity / condensation impacts
5. Replacement of PTFE seal with FVQM
6. **Improved manufacturing processes
7. **Improved algorithms that actively compensate flow reading based on pressure & temperature



Meter test results inform dispenser design

- Thermal and pressure integration of meter into dispenser
- Dispenser control will integrate active meter feedback on measurement conditions

Accomplishments & Progress

Hydrogen Meter Development

Hydraulic Bench Testing

Test Method:

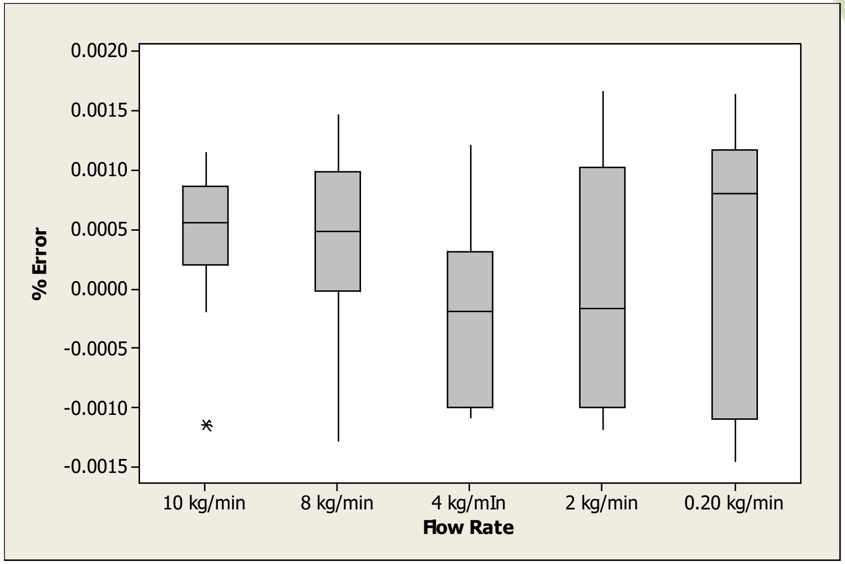
- Validates mono-block design that reduces turbulence and improved manufacturing processes (1, 6)
- 20 meters/transmitter systems tested totaling 400 sample points
- Simulated flow rates ranging from 0.2 kg/min to 10 kg/min using water

***Analysis*:**

- Standard Deviation and Standard Error to determine hydraulic accuracy of meter
- Box Plot to determine variance of accuracy vs. flow rate

Results:

✓ < 0.4% Accuracy water (<4% Hydrogen) over all flow ranges



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%
0.2 kg/min	0.033%	0.108%	0.02%
Overall	0.022%	0.032%	0.01%

Accomplishments & Progress

Hydrogen Meter Development

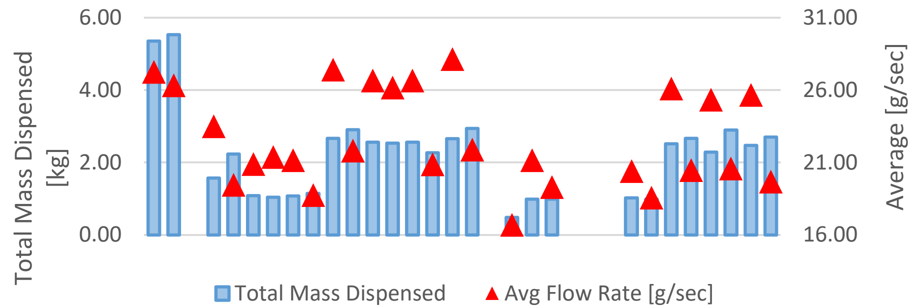
SAE J2601 T Class Testing

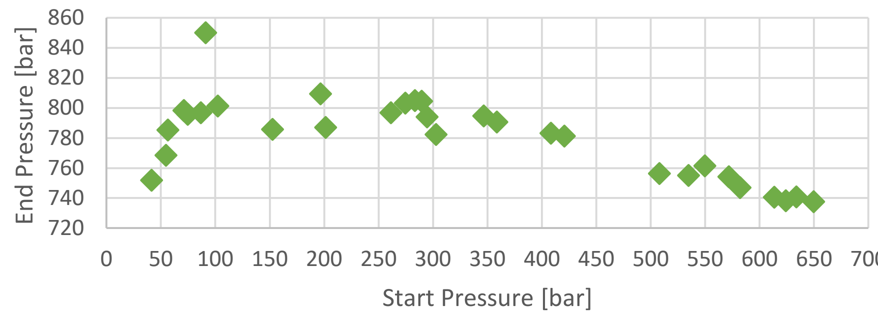
Test Method:

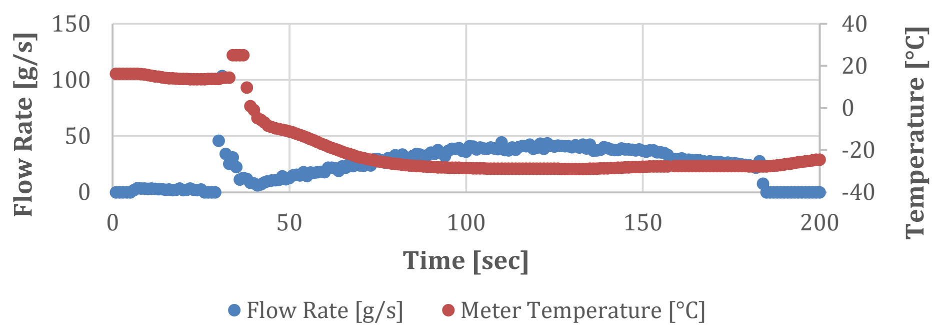
- Validates optimization of algorithms with temperature compensation and inert gas purge housing (2,3,4,7)
- 30 SAE J2601-T30 Compliant Dispensing
- Variables: flow rate, supply temperature, start pressure, end pressure, mass dispensed, average flow rate
- Comparison of performance pre/post HX to validate FVQM seals (5)

***Analysis*:**

- EU Gravimetric measurement apparatus intended for station qualification with Accuracy of +/- 0.1%
- Zero point stability & Vibration analysis
- Various statistical analysis including I-MR and Process capability analysis to determine meter accuracy performance







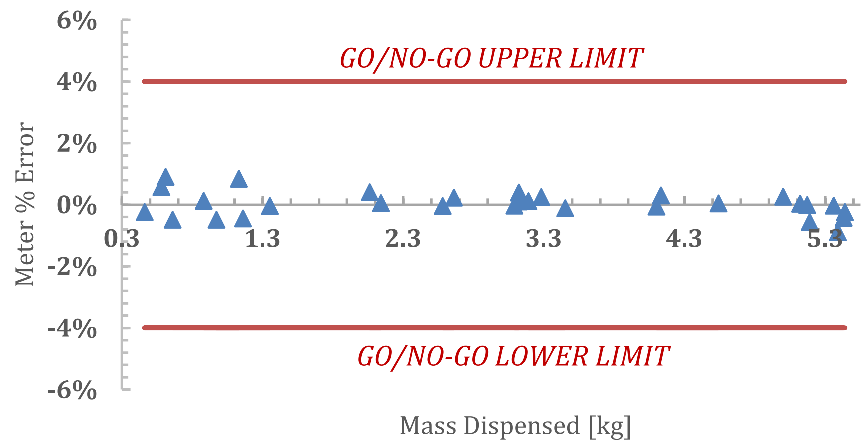
Accomplishments & Progress

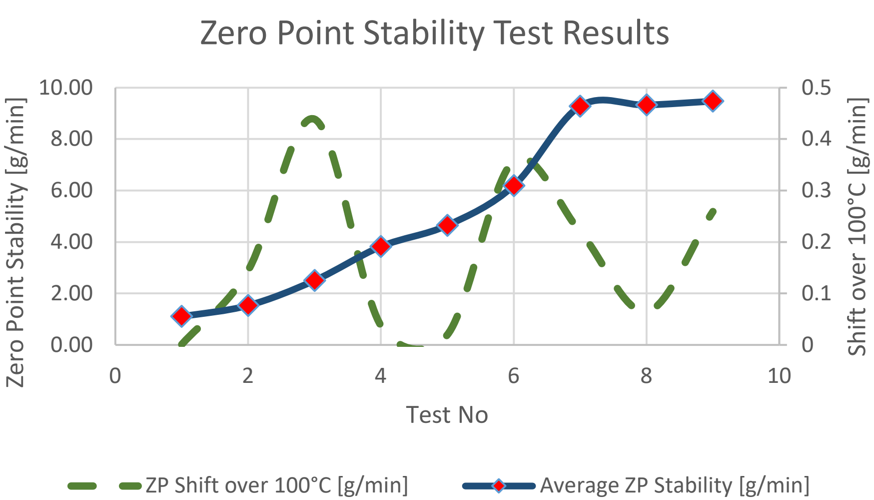
Hydrogen Meter Development

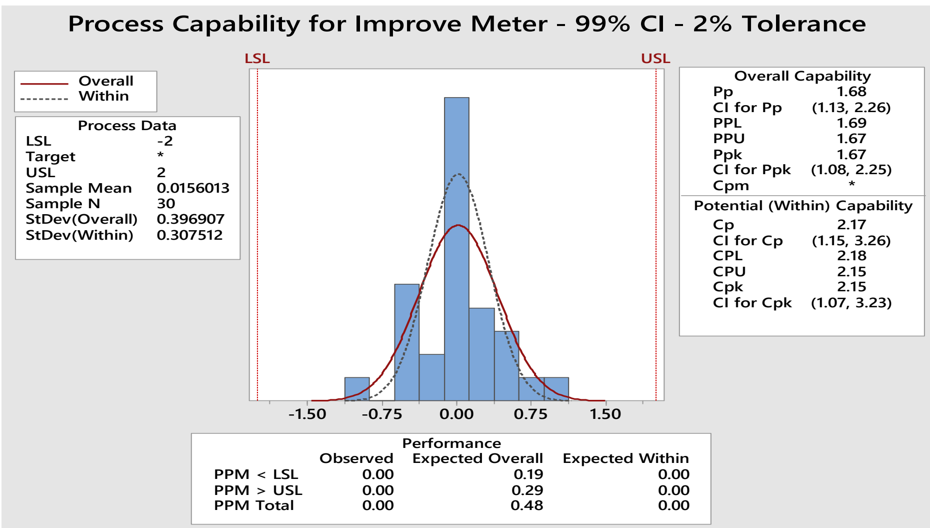
SAE J2601 T Class Testing

Results:

- ✓ Demonstrated meter accuracy better than 4% overall with 95% confidence interval
- ✓ Testing indicates meter is capable of +/- 2% accuracy with 99% confidence
- ✓ No significant difference in meter performance due to location or pressure





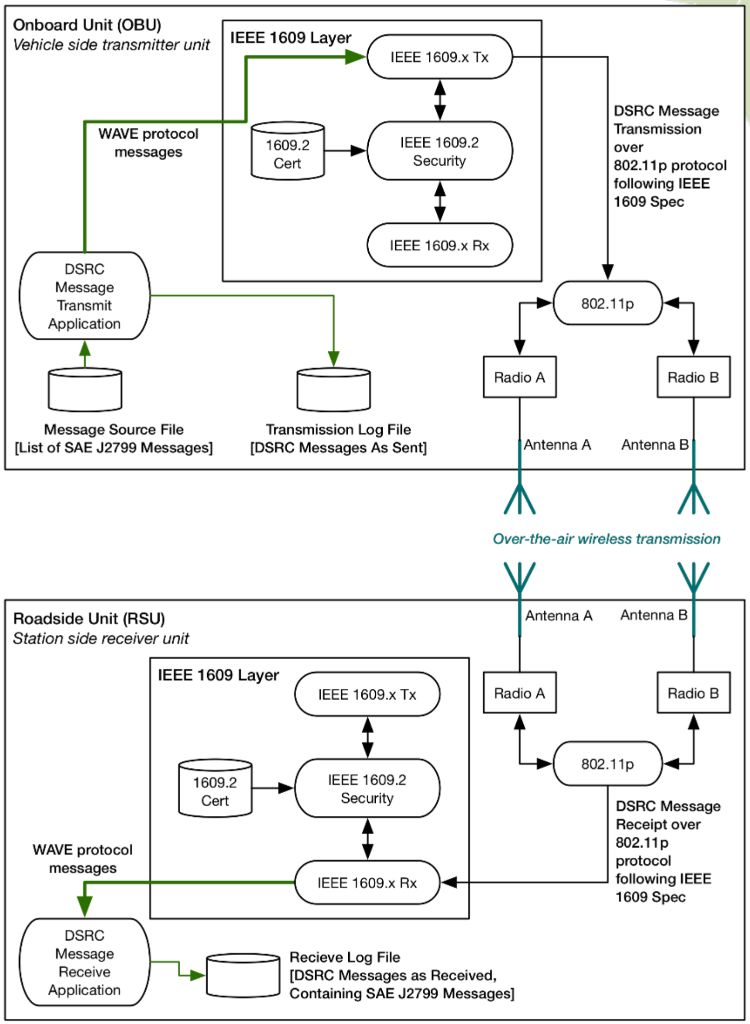


Accomplishments & Progress

DSRC Communication

Benefits of DSRC vs. IrDA

1. Easily interfaces with existing PLC hardware using TCP/IP protocols
2. Dedicated radio frequency bands to prevent interference
3. Very low latency (5-10 ms)
4. Reduced frequency of dropped or incomplete message sets
5. Option for long distance communication
6. One RSU (station receiver) capable of handling multiple nozzles simultaneously



Test Method:

- Develop test apparatus using commercially available hardware
- Randomly generate H35/H70 fill messages
- Bit comparison of sent vs. received message sets and latency measurement

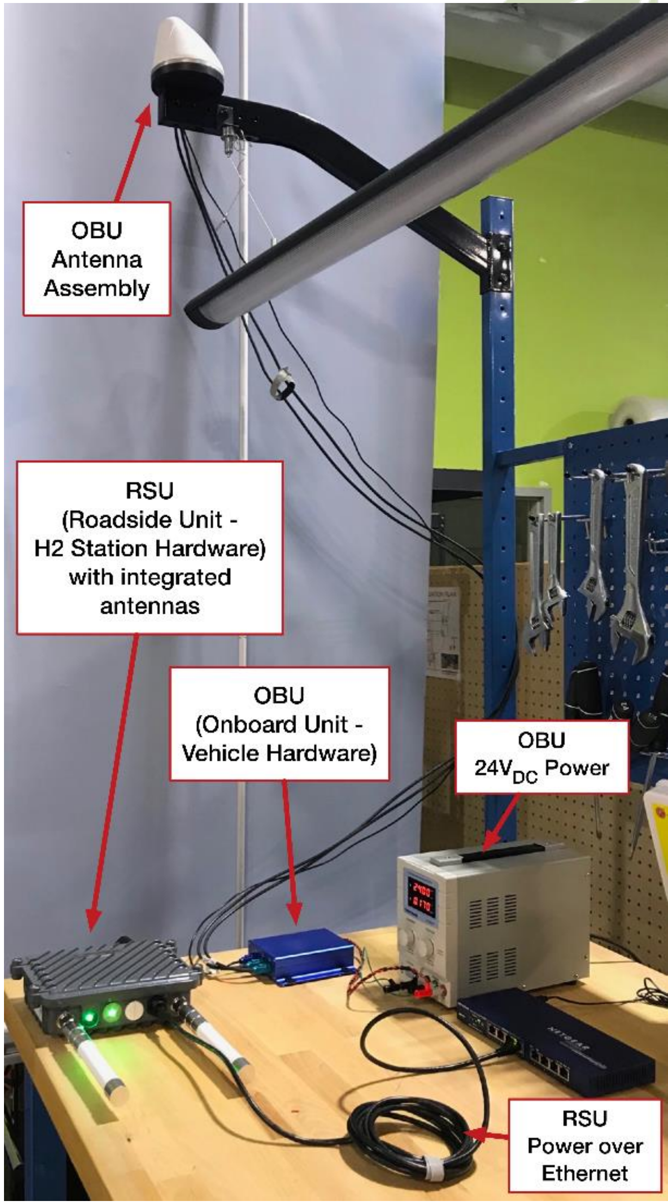
Accomplishments & Progress

DSRC Communication

Results:

- ✓ 1 million refueling simulated messages
- ✓ Zero incomplete messages
- ✓ Longest delay within 500ms requirement from SAE J2799
- ✓ RSU demonstrated 12 simultaneous refueling events
- ✓ No noticeable interference from other wireless sources (several hundred present when tested)

Test	Total Messages	Send Interval	Dropped Message %	Longest Delay between Message
Normal Refueling	436,000	100 ms	0.01%	300ms
High Speed	120,000	3.3 to 10ms	< 0.006%	10-19ms
Long Distance	80,000	3.3 to 20ms	0.061%	54ms
Other	375,000	4ms	0.07%	31ms
TOTAL	**1,011,000**	**3.3 to 100ms**	**0.01%**	**< 300ms**



Collaboration

Ivys Energy Solutions Inc. – Contract Lead

Air Liquide Advanced Technologies U.S. (ALATUS)

- *Demonstration site*
- *H2 expertise*
- *Retail style hydrogen dispenser enclosure with point of sale*

National Renewable Energy Laboratory (NREL)

- *Hydrogen Infrastructure Testing & Research Facility – used to validate dispenser to SAE J2601/1 (2014) prior to demonstration*
- *Facilities, personnel and equipment to validate hydrogen meter accuracy*
- *Vehicle simulator hardware used in equipment validation*

Rheonik

- *Leader in area of high accuracy mass flow measurement*
- *Design, manufacturing & validation of high accuracy meter*
- *Aiding in system integration of meter*
- *Providing two meters for test and integration*

Remaining Challenges & Barriers

1. **Adapt and Maintain Project Schedule**
   - Second 6 month no-cost extension granted due to increased time for dispenser design and installation of hardware at test sites
2. **DSRC Communication – test in new application**
   - Utilize IrDA as primary communication method during fueling – DSRC as secondary
   - Employ DSRC factory software which includes IEEE 1609 and WAVE protocols
3. **Installation of dispenser hardware for demonstration**
   - Continue planning for integration at NREL HITRF facility and AL demonstration site
   - Investigate alternative Air Liquide demonstration sites that offer rapid path to siting and installation

Proposed Future Work
FY 2018 & FY 2019 (Phase 2)

Prototype Dispenser System Procurement and Build

- Complete procurement of all balance of plant parts
- Source contract manufacturer with capabilities to build high pressure hydrogen hardware per required industry standards
- Successfully complete build of dispenser system and heat exchanger

Installation & Test of Prototype Dispenser to SAE J2601/1

- Complete training and safety review for dispenser hardware
- Validate DSRC hardware in simulated vehicle environment at NREL
- Complete partnership with vehicle OEM
- Validate hydrogen meter accuracy

Installation & Test of Dispenser in Relevant Environment

- Install hardware at Air Liquide demonstration site
- Training and safety review of hardware at demonstration site
- Successfully refuel vehicle using DSRC communication

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

Summary

Objective	Develop a robust system for dispensing and measuring hydrogen that further enables widespread commercialization of fuel cell vehicle technology
Relevance	Development of robust sensor algorithms combined with better understanding of meter operation in H2 filling applications can improve accuracy. Replacing IrDA communication with IEEE compliant DSRC systems can offer a robust and cost effective alternative to current state of the art Simplification of flow control and hydrogen pre-cooling systems can reduce overall hydrogen dispenser station costs
Approach	Demonstrate ability for DSRC to reliably communicate SAE J2799 messages using IEEE 1609 security architecture while ensuring nozzle to vehicle pairing Design and manufacturing of dispenser hardware to applicable codes / standards Validate prototype hardware to industry accepted refueling protocols at NREL's Hydrogen Infrastructure Testing & Research Facility Partner with automotive OEM to enable successful demonstration of communication method at demonstration site
Accomplishments	Completed DSRC bench testing to validate capability to meet SAE J2799 requirements Completed H2 meter bench testing validating meter accuracy < 4% in H70 refueling applications Froze dispenser design with updated from hazard analysis
Collaborations	Strong team with extensive knowledge in hydrogen system design, hydrogen refueling and hydrogen meter technology