III.0 Hydrogen Delivery Sub-Program Overview

INTRODUCTION

The Hydrogen Delivery sub-program addresses all hydrogen transmission and distribution activities from the point of production to the point of dispensing. Research and development (R&D) activities address challenges to the widespread commercialization of hydrogen technologies in the near term through development of tube trailer and liquid tanker technologies as well as forecourt compressors, dispensers, and bulk storage; and in the mid- to long-term through development of pipeline and advanced delivery technologies. Technoeconomic analysis is used by the sub-program to identify cost, performance, and market barriers to commercial deployment of hydrogen technologies, and to inform program planning and portfolio development.

GOAL

The goal of this program is to reduce the costs associated with delivering hydrogen to a point at which its use as an energy carrier in fuel cell applications is competitive with alternative transportation and power generation technologies.

OBJECTIVES

The objective of the Hydrogen Delivery sub-program is to reduce the cost of hydrogen dispensed at the pump to a cost that is competitive on a cents-per-mile basis with fuels used in competing vehicle technologies. Based on current analysis, this translates to a hydrogen threshold cost of <$4/kg (produced, delivered, and dispensed, but untaxed) by 2020[1], apportioned to <$2/kg for delivery and dispensing[2]. The program plans to meet these objectives by developing low-cost, efficient, and safe technologies to deliver hydrogen from the point of production to the point of use in both stationary fuel cells and fuel cell electric vehicles. This objective applies to all of the possible delivery pathways. Key objectives for specific delivery components include the following.

- **Tube Trailers:** Reduce the cost of compressed gas delivery via tube trailer by increasing vessel pressure and lowering trailer cost on a per-kilogram-of-hydrogen-transported basis
- **Pipeline Technology:** Develop mitigation strategies for combined material fatigue and hydrogen embrittlement in steel pipelines; advance the development and acceptance of alternative composite pipe materials that can reduce installed pipeline costs; and develop lower-cost, higher-reliability compression technology for hydrogen transmission by pipeline
- **Liquid Delivery:** Reduce the capital and operating costs of hydrogen liquefiers and bulk liquid storage vessels
- **Forecourt Technologies:**
  - Compression: Develop lower-cost, higher-reliability hydrogen compression technology for terminal and forecourt applications
  - Storage: Develop lower capital cost off-board bulk storage technology
  - Dispensers: Improve the cost and accuracy of 700 bar dispensers
- **Analysis:** Conduct comprehensive analyses on near- and longer-term hydrogen delivery options to identify the advantages of each and areas for potential improvement

FISCAL YEAR (FY) 2015 TECHNOLOGY STATUS AND ACCOMPLISHMENTS

In FY 2015, the Hydrogen Delivery sub-program kicked off several new projects, held two Funding Opportunity Announcements (FOAs), participated in one workshop, and saw significant progress in research, development, and demonstration (RD&D) activities of existing projects. Significant accomplishments included the following.

[1] Hydrogen Threshold Cost Calculation, Program Record (Office of Fuel Cell Technologies) 11007, U.S. Department of Energy, 2012, http://www.hydrogen.energy.gov/pdfs/11007_h2_threshold_costs.pdf
[2] Hydrogen Production and Delivery Cost Apportionment, Program Record (Office of Fuel Cell Technologies) 12001, U.S. Department of Energy, 2012

- Updates to the Multi-Year Research, Development, and Demonstration (MYRDD) Plan now detail the technical and economic status of delivery technologies as of FY 2015. The updated plan includes revised 2020 and ultimate targets for technologies in the three most mature delivery pathways: gaseous tube trailer, liquid tanker, and pipeline.
- Two new FOAs and one lab call focused on hydrogen pipelines, as well as compression and dispensing technologies. Selections are expected to be announced by the end of 2015.
- One workshop was held to foster collaboration between industry, government, and the international community to identify the current challenges and RD&D needs of forecourt technologies to reduce costs and improve system reliability.
- The Hydrogen Fueling Infrastructure Research and Station Technology (H2FIRST) project published a report in April of 2015 on fueling station designs and costs. The project is a collaboration between Sandia National Laboratories (SNL) and the National Renewable Energy Laboratory (NREL).

Workshops

The Third International Workshop on Hydrogen Infrastructure and Transportation, organized by NEDO (New Energy and Industrial Technology Development Organization) of Japan, NOW (National Organisation for Hydrogen and Fuel Cell Technology) of Germany, and the DOE and hosted by Technova, Inc., was held in June of 2015 in Tokyo. The workshop included members of industry, academia, and government from Japan, Germany, the European Union (EU), Scandinavian countries, and the United States. Key takeaways from the workshop are summarized in Table 1.

TABLE 1. Key Issues Discussed at Third International Workshop on Hydrogen Infrastructure and Transportation

Fueling	Germany has one operational device that validates station performance. The United States is expected to have such a device completed (Hydrogen Station Equipment Performance device, HySTEP) by the end of 2015.
Hydrogen Quality	The technical, cost, and time requirements of hydrogen quality monitoring remain common concerns. In the United States, water, carbon monoxide, hydrocarbons, and particulates are the primary contaminants of concern.
Metering	Japan and Germany are both considering interim regulations for station metering to allow the technology to evolve, similar to the approach that has been adopted in California. In FY 2015, the German Clean Energy Partnership will also validate a meter with an uncertainty of <1.5% at high pressures.
Hardware	The United States, Germany, and Norway all collect data on the failure rates and modes of station equipment. While compressors have shown significant improvement in the past year, fuel cooling requirements are now a concern. Germany and the EU's Joint Research Centre are studying the impacts of initial tank temperature on the need for pre-cooling.

Publications

In FY 2015, the H2FIRST project published a report that describes the designs and costs of hydrogen stations that are expected to be viable in the near term. The report includes detailed piping and instrumentation diagrams (P&IDs), bills of material, and layouts for five stations (Table 2). The report additionally describes the impact of several key variables (station utilization rate, capacity, number of hoses, and supply method) on capital costs, levelized costs of hydrogen, and station footprint. These analyses are used to provide recommendations for future research on station components, codes and standards, and business practices. The project completed much of its analysis using the Hydrogen Refueling Station Analysis Model (HRSAM), which was created at Argonne National Laboratory (ANL) in FY 2015. HRSAM allows a user to determine the levelized cost of hydrogen dispensing for a given fueling station design and projected utilization rate.

TABLE 2. Station Designs Detailed in H2FIRST Reference Station Design Report

Delivery Method	Daily Capacity (kg)	Target Market	Site Type	Installed Capital Cost ($K)	Fuel Cost ($/kg)
Gaseous	300	High Use	Gas station or greenfield	$1,265	$6.03
Gaseous	200	Low Use		$1,179	$5.83
Gaseous	100	Intermittent		$1,098	$13.28
Liquid	300	High Use	Greenfield	$2,007	[a]
Future Liquid	300	High Use		$1,551	$7.46

[a] This station type was not available in HRSAM as of this analysis and fuel cost could not be estimated. It has been included in the current version of the model.

Key conclusions from this report are as follows.

- Standardization of key station components (e.g., chillers and cryogenic pumps) would lower station costs by eliminating non-recurring engineering costs, driving manufacturing volume, and allowing interchangeability of parts.
- Liquid stations could benefit from the development of underground storage that lowers setback distances, as well as high pressure pumps and evaporators that eliminate the need for compressors and heat exchangers at high-use stations.
- Technically robust modeling of the setback distances necessary at liquid stations could significantly improve the viability of these stations, especially in urban settings.
- Business practices that could improve station viability include contracts with fleets of fuel cell vehicles, a reduction in the chilling at the station to enable customers to accept longer-duration fills for a lower cost, and the use of mobile refuelers to meet the rapidly changing demand in the near-term market.

FY 2015 Funding

The Fuel Cell Technologies Office (FCTO) Incubator FOA selections were announced in FY 2015, and the Hydrogen Delivery Technologies (DE-FOA-0000821) FOA selections are expected to be announced by the end of 2015. The Incubator FOA sought research on game-changing technologies that could reach FCTO targets but were under-represented in the program's MYRDD Plan targets and/or research portfolio. The Delivery Incubator Award selection was Gas Technology Institute for a feasibility analysis of thermal compression technologies that can pressurize hydrogen to 700 bar at hydrogen fueling stations in a cost-effective, reliable way.

During FY 2015, progress was made by existing projects in several key areas.

Tube Trailers and Bulk Storage

Significant cost reduction at the forecourt can be achieved through the use of high pressure tube trailers and low cost onsite storage. Increases in the capacity of high pressure tube trailers will lower the costs of delivery in the near term and improve station logistics. This year the following two projects have contributed to the cost reduction of the gaseous hydrogen delivery pathway.

- The TITAN™V XL40 trailer was developed and deployed in compressed natural gas service. These trailers can transport about 890 kg of hydrogen payload at 250 bar. Additionally, the liners in TITAN™ tanks were determined to be resilient to deep pressure cycles. The tanks were subject to rapid depressurization cycles after saturation with hydrogen to ensure that the liners would retain their integrity. (Hexagon Lincoln)
- A prototype 90 kg steel/concrete composite vessel (SCCV), which exceeded the DOE 2015 cost target for stationary storage, was built. The inner steel layer was certified by American Society of Mechanical Engineers (ASME) for 430-bar service after a burst test. The vessel is now being cycled in hydrogen to test its resistance to fatigue. (Oak Ridge National Laboratory [ORNL])

Pipeline Technologies

Pipelines are an attractive delivery pathway for large market scenarios. Advances in both pipeline compression and fiber reinforced polymer pipelines continue to improve the economics of the scenario, while work on hydrogen embrittlement of steel continues to improve the understanding of the performance of traditional pipeline materials for hydrogen pipeline transmission and distribution network.

- The inclusion of fiber-reinforced composite pipeline with a 50-year design life in the ASME B31.12 code was approved by the Code Committee and is now being considered by the Standards Committee. Burst testing and leak testing were completed on dry wrap thermoplastic piping with embedded monitoring and communication cables. The piping had a significantly greater burst strength than manufacturer specifications and an acceptable leak rate. (Savannah River National Laboratory)
- Fatigue analysis showed that, at modest stress ratios (R = 0.5), hydrogen pipeline thickness may not have to exceed that of a natural gas line to ensure 50-year life. The analysis was based on triplicate measurements of hydrogen assisted fatigue crack growth completed on X52 steel. Fatigue measurements were also completed on regions of friction stir welds in X52 steel. Additionally, data from FY 2014 measurements of hydrogen assisted fatigue crack

growth in the base metal, fusion zone, and heat-affected zones of girth welds in X65 pipeline steel were modified to account for crack closure effects. (SNL)

Forecourt Technologies

Forecourt technologies, in particular compression and onsite storage, are a key area of focus for the program. Efforts in this area aim to improve the reliability and reduce the cost of the technologies.

- A 30-cell, 82 cm^2 electrochemical hydrogen compressor stack has been demonstrated to compress 2 lb/d to 4,500 psig for over 200 h. The stack is utilizing cooling fins to improve its current density, and thereby lower capital cost. Additionally, a 185 cm^2 stack has now been compressing hydrogen to 3,000 psi for over 16,000 continuous hours, indicating strong reliability. The project is now concluding and will identify opportunities to transfer its technology to industry and government. (FuelCell Energy)
- HRSAM was developed and made publicly available. The model estimates the costs of station equipment based on recent vendor data and allows users to simulate gaseous stations, along with near-term and futuristic liquid stations. By the end of 2015, a modified version of the Hydrogen Delivery Scenario Analysis Model (HDSAM) will also be made publicly available. The model will incorporate recent cost data from vendors and from applications to the California Energy Commission and will include the ability to simulate varying annual station utilization rates, near-term and futuristic liquid hydrogen stations, and impacts of market penetration on component costs. (ANL)
- A novel dispensing hose material developed through a Small Business Innovation Research project was shown to meet cost and durability requirements, and a ceramer was developed to bind the material to nozzles. The hose material was tested for solvent resistance and abrasion resistance, and the ceramer was tested for compressive strength at a range of temperatures (-60°C–300°C) as well as shear strength. In the coming year, the hose durability, lifetime, and impact on hydrogen quality will be further characterized by measuring the pull-out strength of fittings crimped with the novel ceramer, hydrostatic strength, burst pressure in cyclic loading, and response to hydraulic pulse, as well as conducting dynamic mechanical analysis and evolved gas analysis. (NanoSonic)
- Pressure testing has been successfully completed on a prototype of a 765-liter, 875-bar cylinder being developed for forecourt storage of hydrogen. These cylinders are being developed by wrapping Type I vessels with high-strength steel wire. Finite element modeling has been completed to guide the design of future cylinders, and a significant literature review has been conducted to assess the impacts of hydrogen on fatigue crack growth at the conditions these vessels will experience (e.g., cycle frequency). The fracture analysis being completed aims to enable the vessels to be certified by the ASME Boiler and Pressure Vessel Code. In the coming year, an additional burst test will be completed on a short prototype, and equipment will be developed to enable wire-winding of the full-length vessels. (Wiretough)
- ORNL is optimizing the design of their 430-bar SCCV to enable low-cost 875-bar underground storage at stations. In FY 2015, high-strength steels and hydrogen permeation barrier materials with sufficient strength for use in these vessels have been identified. Additionally, an initial set of optimized vessel designs has been developed. In the coming year, the welding process for the high-strength steels will be assessed, the concrete reinforcement technology will be improved to lower cost, vessel design will be further optimized, and sensor technologies for the monitoring of vessel health will be evaluated. Vendor quotes will then be obtained for a prototype design. (ORNL)

BUDGET

The FY 2015 appropriation provided $20 million for the Hydrogen Production and Delivery program, with approximately $9.8 million provided for Delivery RD&D. The estimated budget breakdown for Delivery in FY 2015 and FY 2016 is shown in Figure 1. The budget request for Hydrogen Production and Delivery in FY 2015 is $23.6 million, with $11.6 million planned for Delivery RD&D, with an emphasis on improving reliability and reducing costs of near-term technologies, such as dispensers and forecourt storage, and developing technologies for longer-term pathways, such as liquefaction.

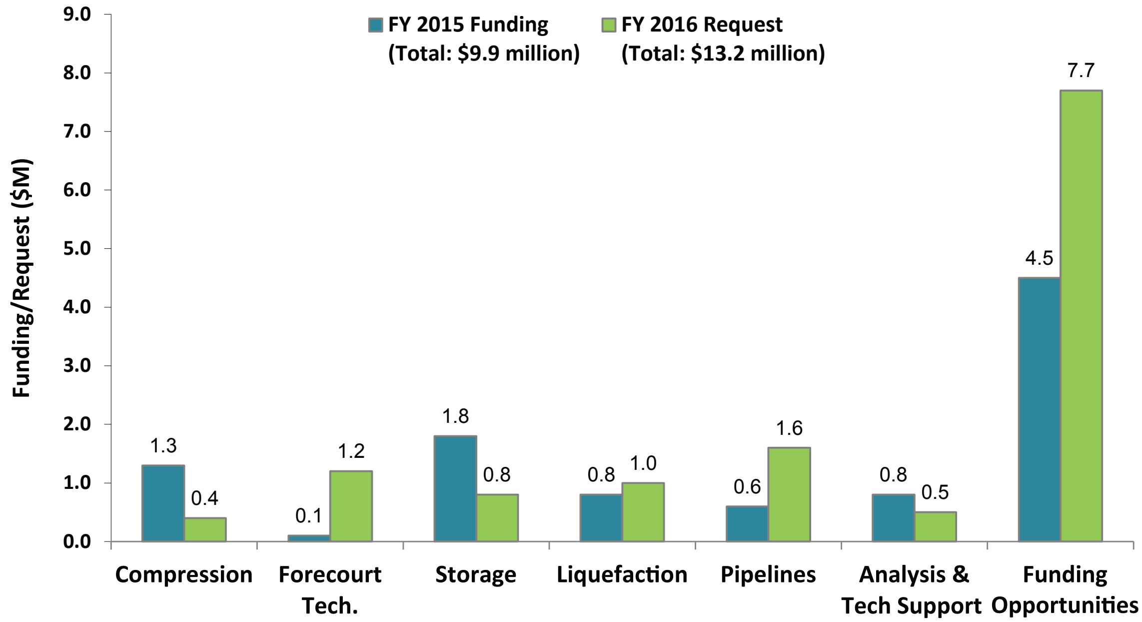

FIGURE 1. Hydrogen Delivery R&D Funding. Subject to appropriations, project go/no-go decisions, and competitive selections. Exact amounts will be determined based on research and development progress in each area and the relative merit and applicability of projects competitively selected through planned funding opportunity announcements.

FY 2016 PLANS

In FY 2016, the Hydrogen Delivery sub-program will focus on several key efforts, including the following.

1. Award and kick off a project to develop a low-cost hydrogen dispenser that can reliably complete communications-based fills with less than 4% error
2. Kick off two projects to develop higher efficiency hydrogen liquefaction technologies to achieve a figure of merit of 0.35 or better
3. Focus on lowering the cost of storage at the refueling station through the completion of two projects on stationary storage (ORNL and Wiretough)
4. Continue to address near-term forecourt R&D needs through the H2FIRST project, including analysis on the cost of onsite production and modular station designs (NREL and SNL)

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