III.0 Hydrogen Delivery Program Overview

INTRODUCTION

The Hydrogen Delivery program addresses all hydrogen 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 compression technologies. Techno-economic analysis is used by the 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[1]

The objective of the Hydrogen Delivery 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 competing vehicle technologies. Based on current analysis, this translates to a hydrogen threshold cost of $2–$4 per gallon gasoline equivalent (gge) (produced, delivered and dispensed, but untaxed) by 2020[2], apportioned to $1-$2/gge for delivery only[3]. The program plans meet these objectives by developing low-cost, efficient, and safe technologies for delivering hydrogen from the point of production to the point of use, including stationary fuel cells and fuel cell electric vehicles. This objective applies to all of the possible delivery pathways. Interim and ultimate targets for various delivery components have been updated in the *Fuel Cell Technologies Program Multi-Year Research, Development, and Demonstration Plan (MYRD&D Plan)*.[4] Key objectives for specific delivery components include:

- **Tube Trailers:** Reduce the cost of compressed gas delivery via tube trailer by increasing vessel capacity and lowering trailer cost on a per-kilogram-of-hydrogen-transported basis.
- **Pipeline Technology:** Develop mitigation strategies for combined material fatigue and hydrogen-induced 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: Quantify and improve the safety and durability of 700 bar dispenser hose and nozzle assemblies.
- **Analysis:** Conduct comprehensive analyses on potential near- and longer-term hydrogen delivery options, comparing the relative advantages of each and examining possible transition scenarios between the two timeframes.

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[1] Note: Targets and milestones were recently revised; therefore, individual project progress reports may reference prior targets.

[2] *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.

[3] *Hydrogen Production and Delivery Cost Apportionment*, Program Record (Office of Fuel Cell Technologies) 12001, U.S. Department of Energy, 2012.

[4] *Fuel Cell Technologies Program Multi-Year Research, Development, and Demonstration Plan* (MYRD&D Plan), Delivery Chapter, July, 2013, http://www1.eere.energy.gov/hydrogenandfuelcells/mypp/pdfs/delivery.pdf.

FISCAL YEAR (FY) 2013 STATUS AND PROGRESS

In FY 2013 the Hydrogen Delivery program focused on identifying the research, development and demonstration (RD&D) needs for materials and components for forecourt technologies to reduce capital costs and improve system reliability. In support of this effort two workshops were held to discuss the current status and challenges in these areas. The first workshop, *Polymer and Composite Materials Used in Hydrogen Service*, was held as a joint workshop with the Safety, Codes and Standards program.[5] Discussion centered on the knowledge gaps and data needed for the durable use of polymers and composite materials in high-pressure hydrogen service under the demanding duty cycles associated with 700 bar hydrogen fuel cell electric vehicle refueling; and on enabling lower-cost, higher-performance systems through attention to these knowledge gaps and revision of codes and standards. The participants identified material knowledge gaps in six key areas. The topical areas identified are shown in Table 1.

TABLE 1. Six key areas for RD&D were discussed for the reliable use of polymer and composite materials in high pressure hydrogen service at the workshop.

Polymer and Composite RD&D Areas Identified
Thermal performance of polymers at service conditions and impact of thermal excursions
Evaluation and minimization of gas permeation and absorption into polymers
Polymer performance characterization tests considering significant material variability
Characterization and performance of seals and o-rings
Liner buckling in pressure systems
Low-cost composite material systems

The second workshop, *Compression, Storage and Dispensing Cost Reduction*, was held at Argonne National Laboratory in March 2013. At this workshop information was shared by participants in order to identify the RD&D needs in the areas of compression, storage, and dispensing to enable cost reduction of hydrogen fuel at fueling stations (forecourt). The workshop was divided into sessions for three topic areas—compression, storage, and other forecourt issues. For each topic area, a panel of experts discussed the status of relevant technologies and identified the key issues and challenges in that topic area. The panel presentations were followed by a moderated discussion and breakout sessions to further clarify and explore the issues. Workshop participants discussed the key cost drivers, reliability issues, and high-impact RD&D activities to reduce the cost of hydrogen delivery at the forecourt. Following the workshop a report was issued along with a request for information (RFI) for public feedback.[6] The key areas discussed during the workshop and identified in the report are summarized in Tables 2-4. In addition to feedback on the workshop report, the RFI also solicited information on the current status of liquefaction technologies.

TABLE 2. Key Compression Challenges Discussed

	Issue	Relevant Activities
Compression	Lack of identified metallic materials for use in high-pressure hydrogen environments.	Standardize testing and qualification of metallic materials for use in high-pressure hydrogen environments, distinguishing between materials with high-fatigue cycle life and those without.
		Create metallic testing protocols that represent the use condition.
	Dynamic compressor seals have limited life in high-pressure hydrogen compressors due to thermal limitations of the seals (approximately 200°F).	Develop new polymer materials suitable for hydrogen in high-pressure and high-temperature applications (300°–400°F).
	Current compressor designs have low efficiencies and high capital and operating costs.	Develop innovative compression technologies.
		Target improved hydraulic efficiencies for current technology.
	The mean time between failures of the compressors in 700 bar hydrogen service is not well documented due to the lack of stations and historical data.	Continue to collect and analyze data from new and existing stations.

[5] The "Polymer and Composite Materials Used in Hydrogen Service" Workshop Proceedings are available here: http://www1.eere.energy.gov/hydrogenandfuelcells/mtg_poly_comp_materials.html

[6] The "Compression, Storage and Dispensing Cost Reduction" Workshop Proceedings are available here: http://www1.eere.energy.gov/hydrogenandfuelcells/wkshp_hydrogen_csd.html

TABLE 3. Stationary Storage Challenges Discussed

	Issue	Relevant Activities
Storage	Codes and standards are too conservative with regard to setback distances for both liquid and gaseous storage, resulting in a larger than necessary storage footprint and increased cost.	Determine why the current setback distances in the United States are twice those in Europe.
		Perform testing and analysis to find methods to reduce distances and work with the National Fire Protection Association to update the codes accordingly.
		Perform necessary analysis, testing, and demonstration to understand the feasibility and safety of underground storage at the forecourt.
	The cost of the carbon fiber used in high-pressure composite tanks is too high.	Develop low-cost carbon fiber for use in high-pressure applications.
		Improve batch-to-batch consistency of existing carbon fiber.
		Expand the supplier base for carbon fiber.
	The cycle life of carbon fiber tanks, particularly under partial cycles, is undefined.	Model and verify through testing tank life under typical station load conditions; in particular, quantify the life under both deep and shallow pressure cycles.
		Understand the failure modes associated with the decompression of saturated polymeric materials.
		Design non-destructive test methods for carbon fiber tanks to allow recertification and extend their service life beyond 15 years.
	The usable storage pressure is limited by component availability.	Initiate an R&D activity in the United States similar to the European Union's Smart Valve program to increase the usable storage pressure by developing high-pressure valves, fittings, and other balance of plant components.
	Focused development of hydrogen stations at existing gasoline stations limits the real estate available for installing storage to meet the current code requirements for setback distance.	Evaluate the feasibility of dedicated hydrogen filling stations (such as at large department stores/retail sites).

TABLE 4. Other Forecourt Issues Discussed

	Issue	Relevant Activities
Other Forecourt Issues	The optimal relationship between compressor throughput and compression ratio versus the storage pressure and volume to meet demand while minimizing cost is not well understood.	Statistical analysis to determine short-, mid-, and long-term station demand profiles.
		Optimize the cost trade-offs between compression and storage to meet short-, mid-, and long-term demand profiles at minimal cost.
	No devices exist that can test the quantity, quality, and performance of hydrogen delivery stations.	Develop devices that can test the rate and temperature at which hydrogen is delivered to a vehicle, the total mass of hydrogen delivered, and the quality of hydrogen delivered.
	Existing hydrogen flow meters are costly and only accurate to within 4% at the delivery conditions, while the existing standard requires 1-2% accuracy.	Develop a low-cost, high-accuracy hydrogen flow meter for measurement of hydrogen vehicle dispensing at 700 bar.
	Currently there are no welding standards for high-pressure applications.	Determine hydrogen embrittlement phenomena in traditional and friction stir welds.
		Engage ASME Section 12 to develop a clear and consistent inspection standard for high-pressure hydrogen welds.
	Current applicable code requires containerized storage to have explosion vents but does not indicate a test or qualification method for those vents. Containerized storage can also reduce station footprint and cost.	Develop explosion vent test standards and test methodology that would allow for containerized solutions, including underground storage.
		Develop modularized storage designs to reduce footprint at stations.
	Low-volume production, a small supplier base, and low equipment utilization leads to high costs.	Determine ways to better optimize station designs at early market, when there is low utilization.
		Develop better tools to forecast refueling demand over time.
		Develop small (<150 kg per day) modular station designs that can be moved and replaced with larger permanent stations as the market expands.
		Promote competition among the supplier base.
	Dispenser hose reliability is unknown and leads to frequent replacement.	Create and perform a test protocol that will determine the performance and degradation of dispenser hoses under application conditions and develop improved designs.

In FY 2013 the Hydrogen Delivery program released two new records (#12021 and #12022) to document the cost status of hydrogen delivery technologies for transport and distribution from central production facilities at an average cost of $4.00/kg, shown in Figure 1, and for compression, storage, and dispensing at forecourt production sites at an average of $2.45/kg.

A Small Business Innovation Research (SBIR) topic on hoses for hydrogen dispensing at 700 bar was also released and a Phase I award made to Nanosonic Inc. The project objective is to develop a low-cost hose for dispensing hydrogen which can operated reliably for more than 25,000 fuelings under the temperature and pressure cycles (-40°C and 875 bar) experienced during fueling of 700-bar tanks according to the SAE International Standard J2601 2010 fast-fill protocol. A second SBIR topic has also been released in collaboration with Office of Science on polymer and composite sealing materials for high-pressure hydrogen applications in order to address the poor reliability of polymer and composite seals in hydrogen applications identified at the workshops.

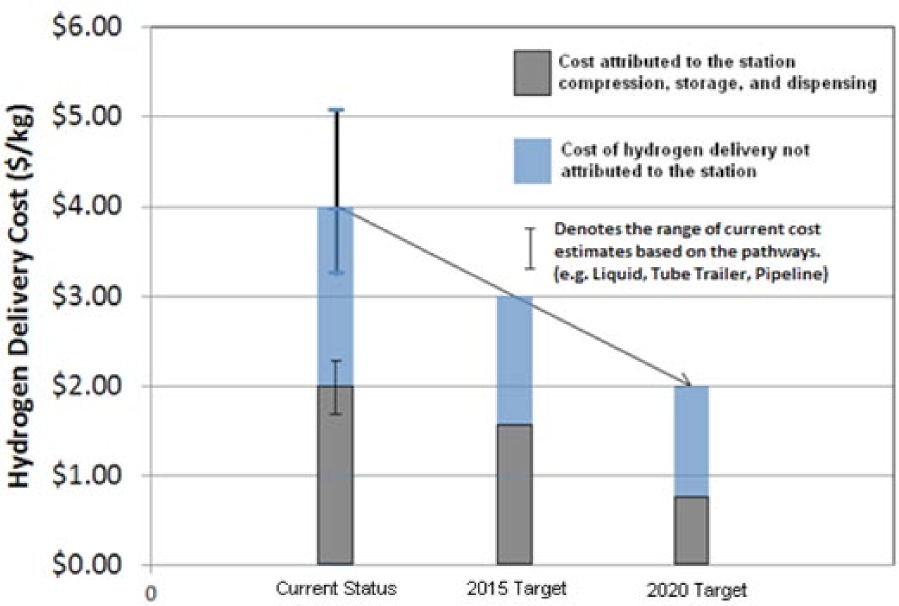


FIGURE 1. The average hydrogen delivery cost status based on nine 700 bar delivery scenarios including pipeline, tube trailer, and liquid delivery and 2015 and 2020 delivery targets are shown in the graph by the sum of the grey and the blue bars. The grey bars indicate the cost of the compression storage and dispensing at the fueling station. Data for these is available in the MYRD&D Plan and Record #12021 and Record #12022.

During FY 2013 progress was made in several key areas including:

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 on-site storage. Higher pressure tube trailers at the forecourt can move the gaseous compression upstream to the tube trailer terminals where economies of scale can reduce the cost of the compression. This year the following two projects have contributed to the cost reduction of the gaseous hydrogen delivery pathway.

- The TITAN™ module and TITAN™V integrated semitrailer configuration for hydrogen delivery were successfully extended to the TITAN™V Magnum configuration—increasing 3,600 psi hydrogen capacity to 800 kg (30% increase relative to the baseline TITAN™ module). Figure 2 shows the TITAN™V Magnum and the arrangement of large and small tanks within. (Hexagon Lincoln)
- The effectiveness of novel hydrogen mitigation technology to prevent hydrogen entering the structural steel layer was successfully demonstrated for concrete composite vessels designed for bulk hydrogen storage at 860 bar. A

FIGURE 2. The Hexagon Lincoln TITAN™V Magnum Composite Tube Trailer

more than 95% reduction in hydrogen uptake in the outer carbon steel layers was achieved when compared to the baseline case without using the mitigation technology. (Oak Ridge National Laboratory)

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 our understanding of the performance of traditional pipeline materials in use in a hydrogen pipeline transmission and distribution network.

- A preliminary fatigue design curve for fiber-reinforced polymer pipelines was developed over the expanded pressure range of 750 to 3,000 psig. Data from this curve is necessary for the inclusion of fiber-reinforced polymer pipeline in ASME B31.12. A report documenting the findings will be submitted to ASME. (Savannah River National Laboratory)
- Reliable fatigue crack growth (da/dN vs ΔK) relationships were measured for pipeline steel in hydrogen environments. The crack growth rates were measured for the X65 weld heat-affected zone in 3,000 psi (21 MPa) hydrogen gas. These results show that the weld heat-affected zone is not more susceptible to hydrogen-accelerated fatigue crack growth compared to the base metal. These results are encouraging for the use of steel pipelines in hydrogen applications. (Sandia National Laboratories)
- Completed initial validation testing of single-stage oil-free centrifugal compressor system was performed in air and in helium at 60,000 rpm. Results confirmed a single-stage compression ratio of 1.10 and thermal stability. (Mohawk Innovative Technologies)

Forecourt Technologies

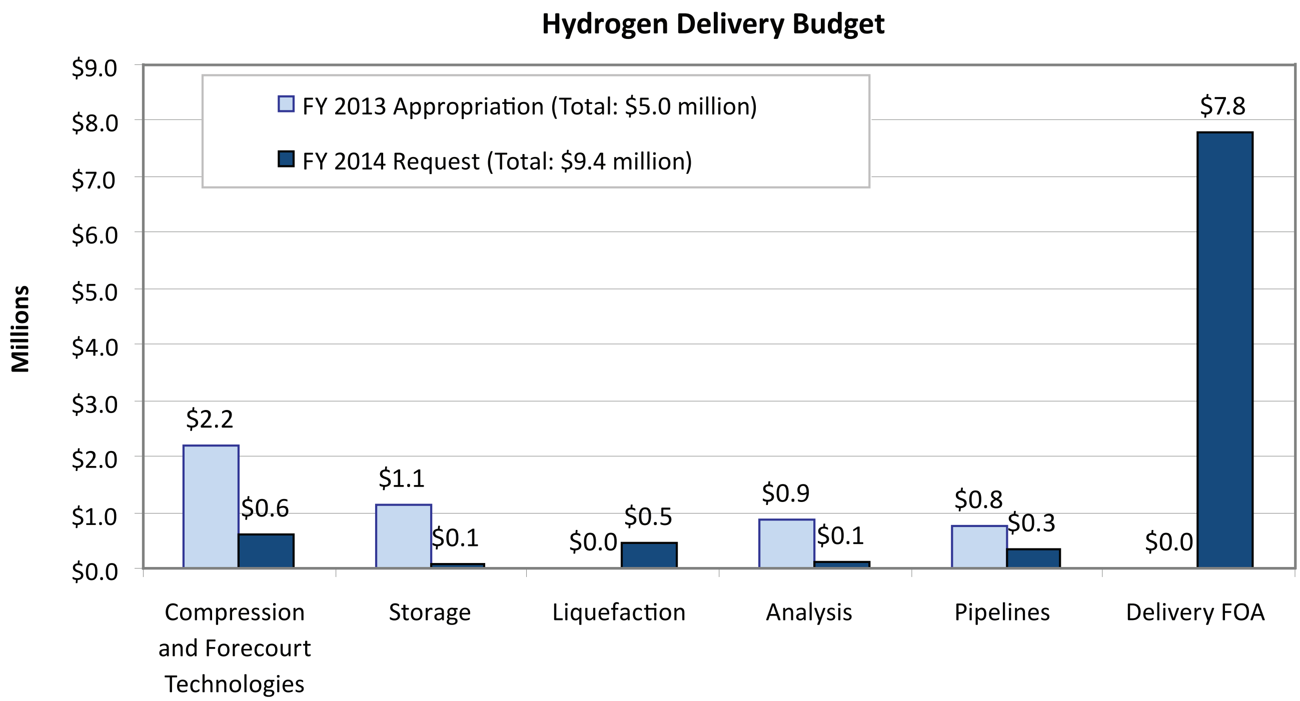
Forecourt technologies, in particular compression and onsite storage are a key area of focus for the program. Efforts in this area are focused on improving the reliability and reducing the cost of the technologies.

- Achieved 50% decrease in single production unit cost of an electrochemical compressor through reducing the cell part count by half, achieving a threefold increase in the current density and twofold increase in the cell active area to increase the production rate while lowering the total cells per stack. (Fuel Cell Energy)
- Performed analysis to show that high-pressure tube trailers delivering hydrogen at 350 bar can decrease the station cost by 20% when used for initial vehicle fill. (Argonne National Laboratory)

- Constructed a research cryo-compressed hydrogen delivery station. Results from testing will provide data on the footprint, efficiency, through-put and other valuable performance metrics. (Lawrence Livermore National Laboratory)

BUDGET

The FY 2013 appropriation provided $5.0 million for the Hydrogen Delivery program. The request for Production and Delivery in FY 2014 is $21 million, of which $9.4 million is planned for Delivery, with an emphasis on reducing near-term technology costs, increasing tube trailer capacity, and lowering the cost of pipeline delivery pathways.



FOA – Funding Opportunity Announcement

FY 2014 PLANS

In FY 2014, the Hydrogen Delivery program will focus on several key efforts:

1. *Expanding the portfolios focus on forecourt and near term technologies.* To this end the program plans to release a funding opportunity for new RD&D projects for advanced technologies in the area of compression, storage, and dispensing. The program also plans to award a new SBIR project to address polymer and composite materials for durable high-pressure hydrogen seals to improve the reliability of forecourt technologies for 700 bar hydrogen dispensing. Additionally the program will be leveraging work in the Technology Validation program to facilitate a multi-laboratory effort in the 700 bar forecourt delivery technology.
2. *Identifying the key areas for hydrogen transport and distribution* through a workshop focused on RD&D needs for the transportation and distribution of hydrogen.
3. *Improving the analysis of hydrogen delivery pathways.* The completion of an independent panel review report on the current status of compression storage and dispensing technologies is expected in FY 2014. The results of this report will be used to revise and release an updated version of HDSAM. The updated version will also include an updated cryo-compressed hydrogen delivery scenario based on technology evaluation performed by Lawrence Livermore National Laboratory.

4. *Validation of cost reduction of forecourt delivery* through the completion of consolidation algorithms which will allow for significantly lower cost of compression at the forecourt when combined with high-pressure tube trailer delivery and the construction and testing of a steel-concrete composite vessel to verify the technology's performance and cost.

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