


# 2013 Hydrogen Compression, Storage, and Dispensing Cost Reduction Workshop Final Report

S. Ahmed and E. Sutherland

Proceedings from the Hydrogen Compression, Storage, and Dispensing Cost Reduction Workshop

Argonne National Laboratory
March 20–21, 2013

April 2013

Sponsored by:

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

U.S. Department of Energy,
Office of Energy Efficiency and Renewable Energy,
Fuel Cell Technologies Office

Organized and hosted by:

Argonne NATIONAL LABORATORY

Argonne National Laboratory

# Hydrogen Compression, Storage, and Dispensing Cost Reduction Workshop

Workshop held March 20–21, 2013
Argonne National Laboratory
9700 S. Cass Avenue
Argonne, IL 60439

Sponsored by:
U.S. Department of Energy – Fuel Cell Technologies Office (FCTO)

Organized and hosted by:
Argonne National Laboratory

**Lead Organizers**

Erika Sutherland, Fuel Cell Technologies Office, U.S. Department of Energy
Shabbir Ahmed, Argonne National Laboratory

**Organizing Committee**

Erika Sutherland, Fuel Cell Technologies Office, U.S. Department of Energy
George Parks, FuelScience LLC
Nico Bouwkamp, California Fuel Cell Partnership
Amgad Elgowainy, Argonne National Laboratory
Kristine Babick, Energetics Incorporated
Aaron Harris, Sandia National Laboratories
Shabbir Ahmed, Argonne National Laboratory

**Breakout Group Chairs**

Marianne Mintz, Argonne National Laboratory
Bob Boyd, Boyd Hydrogen LLC
Aaron Harris, Sandia National Laboratories
Amgad Elgowainy, Argonne National Laboratory
Shabbir Ahmed, Argonne National Laboratory

**Breakout Group Scribes**

Kristine Babick, Energetics Incorporated
Dylan Waugh, Energetics Incorporated
Scott Morgan, Energetics Incorporated

**This page intentionally left blank.**

# Contents

# Executive Summary

## Objective and Approach

The objective of the Hydrogen Compression, Storage, and Dispensing Cost Reduction Workshop was to share information and identify the research, development, and demonstration (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 that if resolved could lead to significant reductions in cost at the fueling station. These presentations were followed by a moderated discussion to further clarify and explore the issues. Workshop participants then participated in breakout sessions, during which they identified and discussed the key cost drivers, reliability issues, and high-impact RD&D activities to reduce the cost of hydrogen delivery at the forecourt. These identified issues and activities were disseminated to all workshop participants at the end of each breakout session.

Following are summaries of the discussions for each of the three topic areas, including highlights of the key cost drivers, reliability issues, and high-impact RD&D activities as identified by workshop participants.

## Compression Cost Reduction Opportunities

Hydrogen compressors currently used at fueling stations are generally either diaphragm or reciprocating compressors. Poor reliability continues to plague forecourt hydrogen compressors because current standards for their design assume prolonged operation at peak pressure. This operating regime is not representative of the operating conditions to which forecourt hydrogen compressors are exposed. The operating and maintenance cost of in-service compressors is exacerbated by the on/off cycling of the compressors resulting from a lack of station demand. The capital cost of the commercial hardware remains high due to low production volumes. Significant cost reductions can be achieved through high-volume production; panelists estimate that a 70% reduction in compressor capital cost is possible from a three-order-of-magnitude increase in production demand.

Identified activities to decrease the cost of hydrogen compression at the forecourt include research and development (R&D) to develop design standards and tests that accurately reflect operating conditions, development of high-temperature polymer and composites that are compatible with hydrogen, identification of high-strength metallic materials that are resistant to hydrogen embrittlement, improved compressor efficiency, and collection of compressor durability and reliability data to better understand the current mean time between failures and failure modes.

## Storage Cost Reduction Opportunities

The cost of on-site storage is determined by vessel requirements and durability. High-pressure stainless steel vessels are expensive due to the thickness necessary for containment and the manufacturing process requirements. Composite carbon fiber and steel vessels are a potential alternative. To become economically competitive with steel, lower-cost, high-strength carbon fiber and improved batch-to-batch carbon fiber quality are needed. In addition, composite vessels are constrained due to the lack of non-destructive tests for recertification and the 15-year service life, which is based on glass fiber degradation. R&D to better understand the effect of partial pressure cycles on composite tank life and the design of non-destructive tests for tank recertification is needed to extend the service life of carbon fiber composite tanks, which would lower the life cycle cost. Another low-cost alternative is a steel/concrete composite vessel that is projected to meet the U.S. Department of Energy's 2020 dollar per kilogram cost goal and is currently under development at Oak Ridge National Laboratory.

Another significant barrier to low-cost on-site hydrogen storage is the large setback distances required by facility codes and standards. The early stations are expected to be deployed in urban environments where real estate is at a premium. Requiring larger than necessary setback distances from wall openings (e.g., gas station windows) at best significantly increases the station cost and at worse precludes station placement in these settings. Necessary activities include research to determine ideal minimal setback distances and development of underground and containerized storage to reduce cost. Analysis of other alternatives such as installing hydrogen refueling stations at retail stores or the use of high-pressure tube trailers in a "swap and drop" scenario could identify lower-cost alternatives to the traditional station design of co-locating facilities at existing gasoline refueling sites. Cost savings could also be obtained by maximizing the use of high-pressure storage through development of the necessary balance of plant components and standardization of storage vessel capacity to increase production volumes and lower cost.

## Other Forecourt Issues Cost Reduction Opportunities

Key opportunities for cost reduction outside of compression and storage were identified in hydrogen dispensing and through analysis work to optimize station designs. Hydrogen metering requires further development to meet the required 1-2% system accuracy while also lowering costs. Other recommendations included development of high-pressure welding standards and hardware to measure the quantity and quality of the hydrogen as well as the performance of the refueling station during vehicle fills.

Opportunities to reduce cost through station optimization include analysis to establish the expected demand profiles for early and mature market demands, allowing for optimization of station design for both the near and long terms. Once these profiles are established, an analysis of the trade-off between compressor throughput and on-site storage capacity to meet station demand could be performed to optimize station design for both performance and cost. Another analysis activity identified was work to quantify the cost effects of different fueling protocols in order to provide input to code development.

# Workshop Objectives and Organization

The Hydrogen Compression, Storage, and Dispensing Cost Reduction Workshop was held at Argonne National Laboratory (ANL) on March 20–21, 2013, and featured 36 participants representing industry, government, and national laboratories with expertise in the relevant fields. The objective of the workshop was to identify the research, development, and demonstration (RD&D) needs in the areas of compression, storage, and dispensing (CSD) to enable cost reduction of hydrogen fuel at fueling stations (forecourt).

The workshop began with an introductory session that featured a discussion of workshop logistics and objectives followed by a presentation on issues and barriers to fuel cell electric vehicle (FCEV) deployment.

The interactive segment of the workshop followed, featuring sessions on three topic areas—Compression, Storage, and Other Forecourt Issues. Each session started with a panel of plenary speakers who highlighted the key technologies and other issues relevant to that session's topic area that are responsible for the current high cost of hydrogen delivery. These presentations were followed by a moderated discussion to clarify and further explore the issues.

After each session's plenary presentations and panel discussion, workshop participants divided into three breakout groups. These breakout groups identified and discussed key issues and activities for each of the three topic areas to reduce cost at the forecourt. Each breakout group reported its findings to all of the workshop participants after each breakout session.

# Introductory Session

In the introductory session (Agenda in Appendix C), **Dr. Ed Daniels**, Associate Laboratory Director (Energy Engineering and Systems Analysis) at ANL, welcomed workshop participants, highlighted ANL's many contributions to the Hydrogen and Fuel Cells Program, and reiterated the importance of cost reduction in commercializing emerging technologies. **Dr. Sunita Satyapal**, Director of the U.S. Department of Energy's (DOE's) Fuel Cell Technologies Office (FCTO), started the workshop proceedings with an overview of the Office. She noted that the rapid progress of fuel cell technology is demonstrated by the large number of patents recently issued in the field. Dr. Satyapal highlighted recent fuel cell technology developments, including the demonstration of the world's first tri-generation station, research and development (R&D) progress resulting in an 80% reduction in the cost of polymer electrolyte membrane (PEM) fuel cells since 2002, and the doubling of PEM fuel cell durability since 2006. She also discussed DOE cost targets and stated that compression and storage are the largest contributors to the cost of hydrogen refueling at the station. **Ms. Erika Sutherland**, Hydrogen Delivery Technology Development Manager, served as facilitator, providing the logistics for the meeting, introducing the speakers and panelists and organizing the breakout sessions.

**Bill Elrick** (California Fuel Cell Partnership) then discussed the California FCEV market. He noted that the state plan calls for 1.5 million zero emission vehicles (ZEVs) by 2025 in order to meet California's 2050 greenhouse gas reduction goals. Mr. Elrick remarked that original equipment manufacturers (OEMs) have made large investments to deploy ZEVs, but several are delaying the deployment of FCEVs due to the lack of a refueling infrastructure. He noted that the California Road Map for the deployment of FCEVs states that a minimum of 68 fueling stations are needed to develop a coverage based station network, and that 100 stations are needed to initiate an integrated, self-sustaining system.

Mr. Elrick also identified various challenges and issues in the deployment of FCEVs and their refueling infrastructure in California, such as the lack of standardized components and procedures. He noted that current hydrogen refueling systems require a large footprint, which translates to space constraints and higher real estate costs. Moreover, he stated, the main stakeholders are supported by industrial hydrogen demand and are not as familiar with retail applications, which are the model for hydrogen FCEVs. Mr. Elrick suggested that the federal government demonstrate greater long-term engagement and commitment, which would promote the development of a long-term, shared vision on FCEVs.

# Compression

## Compression Presentations

**John Cornish** (EPC): Mr. Cornish acknowledged that the market for compressors in hydrogen refueling stations is continuing to evolve and that the industry needs more data on the effects of high compression ratios on capital and maintenance costs. He noted that the current hydrogen distribution system tends to overlook localized production opportunities and that there is a tremendous opportunity for developing affordable hydrogen refueling stations.

**Matt Weaver** (PDC Machines): Mr. Weaver noted that PDC Machines manufactures triple diaphragm gas compressors used in the hydrogen refueling and high-pressure storage industry. He stated that diaphragm technology is appropriate for high-pressure hydrogen mobility applications because of its leak-tight and zero-contamination properties. He also said that PDC manufactures high-pressure hydrogen dispensers in accordance with OEM guidelines and industry practices, and that the company supports hazard and operability, safety integrity level, and other safety protocols.

Mr. Weaver shared that PDC manufactures for industries involved in on-site hydrogen generation; high-pressure storage; and high-pressure trans-fill for rapid filling for automotive, bus, and forklift refueling applications. He noted that all of these applications are extremely price sensitive and that the industry has started to standardize in order to mitigate the high costs, but that there is much work to be done. He stated that some other means of controlling costs are being addressed by engineering analysis throughout the United States, such as real-time data monitoring of operating sites, material analysis, and failure mode analysis of refueling stations.

Mr. Weaver remarked that diaphragm compressor technology has proven very effective for hydrogen refueling applications due to its high throughput, low power consumption, and low cooling requirements compared to other technologies. He detailed challenges to the technology, including the volatility of raw material (stainless steel) prices, initial capital costs, and more frequent maintenance intervals from the on/off cycling of the compressors due to low station demand. He described the need for R&D for standard station design and long-term cost analysis. Mr. Weaver stated that analysis shows the possibility of a 70% reduction in capital expenditures if demand increases by three orders of magnitude.

**Pinakin Patel** (FuelCell Energy): Mr. Patel described how electrochemical hydrogen compressor (EHC) technology is being developed to increase reliability and lower the cost of hydrogen compression. He noted that the feasibility of reaching DOE's pressure target of 12,000 pounds per square inch (psi) has been demonstrated in a single-stage EHC cell, and that hydrogen capacity of up to about 1 pound per day has been reached in a short stack. He also noted that durability of the EHC cell architecture has been demonstrated at over 8,000 hours at 3,000 psi, and that efficiency has been demonstrated at 6-12 kilowatt hours per kilogram (kWh/kg) from <30 to 3,000 psi.

Mr. Patel remarked that some of the technology challenges facing these compressors include creep of cell materials under the high compressive loads and increased resistance and power requirements; hydrogen back-diffusion, which reduces efficiency; and temperature tolerance of the seals. He said that key RD&D opportunities lie in cell active area and stack scale-up, higher (>1,000 milliamperes per square centimeter) current density operation, and higher-strength and lower-cost materials of construction. He stated that these developments will increase capacity and significantly reduce capital cost. Moreover, Mr. Patel noted, robust and low-cost thermal management, water management and packaging, and longer-term endurance testing are needed.

**Greg Walti** (Haskel International): Mr. Walti noted that Haskel has been involved in generating high-pressure hydrogen compressors for several decades in laboratory, industrial, and automotive refueling applications around the world. He mentioned that during this time, the company has observed that each region's automotive refueling applications have unique material requirements and flow expectations, and that these variations force compressor manufacturers to design, procure, and construct distinct units for their Asian, European, and North American clients. He stated that the variation of units in these three regions has a direct impact on unit costs, limits the cost benefits of part standardization and volume purchasing, and increases overhead costs. He explained that the primary drivers for this variation appear to stem from undefined global fill-time expectations and a lack of hydrogen embrittlement data focused specifically on compressors.

Mr. Walti shared that Haskel believes there may be opportunities to reduce hydrogen compressor unit costs by studying hydrogen's embrittlement effect on compression-style units. He noted that the current hydrogen embrittlement process is based on operations at constant elevated pressure; however, compressor units only experience these high pressure levels for a short time at the peak of their working cycle. He remarked that, as a result, Haskel theorizes that hydrogen embrittlement testing specifically for compressors will provide new data, allowing the use of stronger standardized materials for all of its customers.

Mr. Walti also stated that the overall costs for automotive hydrogen refueling will be reduced once global low-, medium-, and high-usage standards for pump flow are achieved. He said that creating guidelines for standard flow will allow all of the compressor companies to work toward their strengths, find their niche, and produce competitive products in volume.

**John Siefert** (Hydro-Pac): Mr. Siefert explained that Hydro-Pac manufactures high-pressure hydrogen compressors based on oil-free non-lubricated pistons, variable speed drives, and water-cooled cylinders. He asserted that the industry is faced with a lack of material data that designers can use, the material recommendations from system developers, the high cost of electric and hydraulic components, and the location of the control box. He noted that the key pathways to reducing the cost of hydrogen compression include the development of a standardized system configuration and fueling strategy using simple and proven designs, and the adoption of economical hydrogen compatible materials. He said that the standardized configuration would be best served by having fewer compressors and stages for a narrow range of supply and discharge pressures at standardized throughput rates.

## Compression Panel Discussion

The discussion following the compression presentations focused on codes and standards, material compatibility and durability, and the trade-offs between on-site compression and storage. It was noted that the two compressors most commonly employed for hydrogen compression at the forecourt are diaphragm and piston compressors. A participant explained that diaphragm compressors have a higher throughput but are also more expensive. Participants discussed how both can benefit from materials research and decreased compression ratio.

The panel stated that most of the standards are designed for long-term, high-pressure testing environments instead of actual operating environments. For example, it was noted that the CSA 4.8 document is not specific enough for hydrogen applications, and that it does not address the materials issues or the nickel content in steel. Participants also stated that low-nickel alloys could be used up to 7,000 psi (~480 bar), but at 700-bar and higher applications, 316 stainless steel is used. Participants acknowledged that this is a significant cost consideration.

Another material issue discussed was the durability of the compressor seals. Panelists noted that the current seals fail after 2,000–8,000 hours of operation, depending on the technology and operating environment, and that the failures are mainly due to thermal degradation of the seals, not the high pressure. A participant stated that the current polymer seals degrade in operation above 200°F, and that seals that can withstand 300°–400°F are needed. It was noted that low-temperature operation is not an issue because the seals will generally warm within a few strokes of the compressor.

The discussion also identified a trade-off between reliability and capital cost. A panelist remarked that a 20%–30% increase in capital cost can significantly improve reliability by moving from two compression stages to three and reducing the compression ratio at each stage. A participant pointed out that lowering the compression ratio consistently increases the reliability by lowering the operating temperature of each stage and the differential pressures. A panelist detailed a possible solution to lowering the compression ratio without additional compression stages—compressing a 200–300 pounds per square inch gauge (psig) hydrogen source to 3,000 psig banks at night with a variable speed drive compressor, and then using the same compressor to pump the 3,000 psig hydrogen pumped at night during the day. See Figure 1 for a concept sketch.

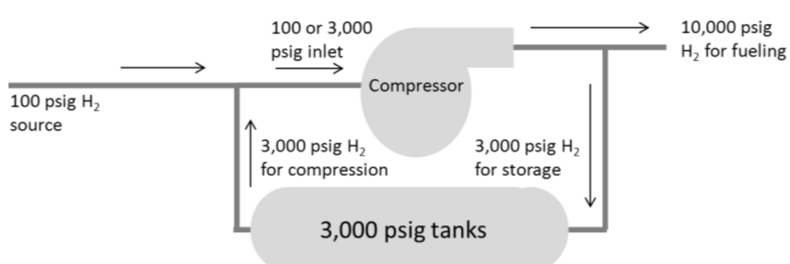


**Figure 1. A possible solution to lowering the compression ratio**

It was noted that this concept does require additional storage rather than higher compressor throughput and compression ratios, which can be challenging in urban settings. A panelist noted that rooftop and underground storage could address the concern over the limited footprint.

## Compression Breakout Session – Issues and Suggested Activities

The key activities identified by the three groups during the breakout session to lower the cost of hydrogen compression are summarized in Table 1. The additional activity areas identified by each group, but not identified as key activities through voting, appear after the table.

**Table 1. Compression breakout session results**

| | 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. |

The following are other activities to reduce the cost of compression identified by the breakout groups:

- Develop packaged compressor designs to decrease footprint at the forecourt.
- Optimize station designs and delivery pressures to decrease the compression ratio required of the compressors.
- Develop high-reliability, oil-free designs to provide assurance of hydrogen quality.
- Explore advanced compression designs that can address reliability and efficiency, such as ionic compression and electrochemical hydrogen compression.
- Determine the performance of polymer seals under hydrogen saturation and decompression.
- Analyze and mitigate the effects of compressor start/stop cycles caused by underutilization.
- Analyze refueling site economics at the top level to optimize station storage versus compression for cost and reliability. Arrive at a standardized station design to increase component volume and lower costs.

# Storage

## Storage Presentations

**Zhili Feng** (Oak Ridge National Laboratory): Mr. Feng stated that off-board bulk stationary storage of hydrogen is a critical element in the overall hydrogen production and delivery infrastructure. He asserted that stationary storage is needed at locations such as fueling stations, renewable energy hydrogen production sites, central production plants, and terminals. He also noted that the hydrogen pressure and capacity of the stationary storage vessels are expected to vary considerably, depending on the intended usage, location, and other economic and logistics considerations.

Among the various hydrogen storage technologies, Mr. Feng stated, compressed gaseous hydrogen (CGH2) storage in a stationary pressure vessel is the most widely used technology. He detailed the two long-standing challenges that have limited widespread deployment of CGH2 pressure vessels: cost and safety. He acknowledged that today's industry-standard pressure vessels, which are based on steel vessel technology, are expensive, and he asserted that a significant reduction of vessel cost is essential. Moreover, Mr. Feng noted, as stationary storage vessels must endure cyclic mechanical and thermal loadings associated with charging/discharging, hydrogen embrittlement in structural steels—especially the accelerated crack growth due to cyclic fatigue—must be mitigated to ensure vessel safety.

Mr. Feng described how Oak Ridge National Laboratory (ORNL) is working with industry partners to develop and demonstrate a novel, low-cost, high-pressure steel/concrete composite vessel (SCCV) for stationary storage of CGH2. He remarked that the SCCV technology uses commodity materials including structural steels and concrete to achieve cost, durability, and safety requirements. He also noted that the hydrogen embrittlement of high-strength, low-alloy steels—a major safety and durability issue—is mitigated through the use of a unique layered steel shell structure. He stated that detailed manufacturing cost analysis suggests that SCCV can meet the technical and cost targets set forth by FCTO for Fiscal Year (FY) 2015 and FY 2020 relevant to hydrogen production and delivery infrastructure. He contended that further vessel cost reduction is possible through the use of advanced vessel manufacturing technologies and high-strength steels. He said that ORNL is currently designing and constructing for technology demonstration a small but representative mock-up SCCV (1/4–1/5 size), capturing all of the major features of SCCV design and manufacturability with today's manufacturing technologies and code/standard requirements.

**Don Baldwin** (Hexagon Lincoln): Mr. Baldwin stated that successful commercialization of hydrogen FCEVs depends on the development of a hydrogen delivery infrastructure that provides the same level of safety, ease, and functionality as the existing gasoline delivery infrastructure. He reported that compressed hydrogen is typically currently shipped in steel tube trailers at pressures of up to 3,000 psi (about 200 bar). However, he noted, the low hydrogen-carrying capacity of these tube trailers results in high delivery costs.

Mr. Baldwin explained that recent development of more-efficient rolling stock for compressed gas hauling has been driven by increasing demand for natural gas. He said that manufacturers of lightweight composite over-wrapped pressure vessels have started to offer module and semitrailer systems. He mentioned that because of the increased capacity per trailer, the acquisition cost of these new systems is similar to the acquisition cost of standard steel tube trailers for large gas consumers. He also noted that because of the increased capacity and low rolling mass, these new systems offer significant reductions in operating expenses. He reported that this improved performance offers the same benefits for the transportation of compressed hydrogen gas.

Mr. Baldwin stated that configuration of an optimal mix of hauling equipment for a given user or project must consider multiple operating parameters in addition to the volumetric and mass properties of available systems. For example, he noted that factors such as trip distances, travel times, load/unload times, labor costs, maintenance costs, and fuel costs must all be considered. Using volumetric and mass properties for available systems at 200–250 bar, and also for achievable systems operating at 350 and 540 bar, Mr. Baldwin stated that capital expenditures are calculated for the various module/trailer options in a given use scenario, considering transportation pressures of 250, 350, and 540 bar. He reported that capital expenditures increase exponentially at daily hydrogen delivery demands below 2,000 kg per day for equipment at 540 bar. He noted that at higher hydrogen demands, the penalty for acquiring the next truck/trailer is less severe, bringing down the capital expenditure.

**Nitin Natesan** (Linde LLC): Mr. Natesan noted that advances have been made in compression and dispensing technology to commercially demonstrate fast-fueling, high-throughput, and peak back-to-back filling. He asserted that taking the next step in station forecourt advancement to meet the projected demand of vehicles will require further looking at items specifically limiting these three aspects as well as issues limiting the station deployment targets, which translate to higher station deployment cost. He said that storage technologies are critical to evaluate in this perspective.

Mr. Natesan remarked that with both gaseous and liquid storage, current codes and standards place hard limits on the quantity of hydrogen that can be stored on a station forecourt (area utilization). He said that these limits disqualify many potential commercial retail sites from being considered, thereby delaying station deployment. He predicted that research in technological areas of storage such as cost-effective underground options, high-pressure associated instrumentation, improved cycle life for high-pressure gaseous storage, and improved “usable quantity” will play a large part in driving down station forecourt costs. He stated that there should also be a hard look at codes and standards, an informed reduction of required setback distances, and harmonization of international standards to support increased station roll-out.

**Angela Das** (Powertech Labs): Ms. Das noted that Powertech is recognized worldwide as an authority on high-pressure hydrogen storage systems, and that the company has the most comprehensive high-pressure test facilities for prototype and certification testing of hydrogen tanks, components, and complete vehicle fuel systems. She also reported that Powertech has developed containerized and portable hydrogen fueling station designs that it assembles for various energy storage and vehicle infrastructure markets. She remarked that Powertech not only tests hydrogen storage tank designs for various clients, but also uses various carbon fiber tank types as part of its everyday test facilities and purchases various tank types for use in its hydrogen fueling station designs.

Ms. Das stated that because existing carbon fiber tank designs have been used by both the hydrogen industry and the compressed natural gas industry over the last 20 years, it has been demonstrated that they are safe for vehicle and ground storage service conditions. Indeed, she noted, going to the higher storage pressures associated with compressed hydrogen makes the storage tanks inherently safer. She pronounced, however, that there is a need to reduce the cost of these storage vessels to improve the economics of developing a hydrogen infrastructure.

Ms. Das reported that the single biggest factor in the cost of a hydrogen station is the cost of the carbon fiber used in storage vessels. She said that there should be research into the use of improved production processes to reduce the base cost of carbon fiber, or at least improve the batch quality of carbon fiber so that less is required to achieve the same performance. She also asserted that the service conditions associated with ground storage at a hydrogen fueling station should be more closely defined for the purpose of reducing the testing and performance requirements for high-pressure storage vessels. She recommended that long-term stress rupture tests involving environmental and fatigue conditions should be conducted on thin-wall Type 4 cylinders for the purpose of extending the lifetime of pressure vessels in ground storage service. Finally, she stated that non-destructive inspection techniques should be developed for the in-situ examination of composite structures as a tool to confirm life extension.

## Storage Panel Discussion

A major point of discussion centered on the fact that station footprint is a significant constraint to forecourt storage due to the urban settings of initial deployments. It was noted that setback distances for both liquid and gaseous storage from any wall opening (e.g., gas station window or door) are approximately twice as conservative as European standards. A participant also pointed out that siting of early stations at existing gasoline stations is restrictive due to the lack of real estate available at these locations. Panelists noted that the on-site storage footprint could be reduced through underground storage installations, but they also acknowledged that current codes and standards do not address this option and that it does not eliminate the setback distance requirement of 75 feet between a liquid tank and a wall opening. It was mentioned that methods and data to determine the minimum setback distance and other risk mitigation strategies are needed to address installation in cramped urban environments.

Panelists and participants also discussed how the cost of on-site storage could be reduced through the use of high-pressure composite storage either through the swap and drop of high-pressure tube trailers, which would help to push compression cost upstream where the volume cost reductions are greater, or the use of installed on-site composite storage. It was noted that increasing the lifetime of carbon fiber tanks can reduce the cost of use. A panelist explained that the current 15-year lifetime of the tanks is based on the fatigue life of glass fiber because the fatigue design life for carbon fiber has not been determined. Participants felt that this is a conservative estimate and that work should be performed to determine the fatigue design life of carbon fiber vessels in forecourt applications. In addition, participants noted that non-destructive tests (such as acoustic emission defined by ASME Section 10 for steel vessels) need to be developed for the recertification of carbon fiber composite tanks.

## Storage Breakout Session – Issues and Suggested Activities

The key activities identified by the three groups during the breakout session to lower the cost of hydrogen storage are summarized in Table 2. The additional activity areas identified by each group, but not identified as key activities through voting, appear after the table.

**Table 2. Storage breakout session results**

| | 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). |

The following are other activities to reduce the cost of hydrogen storage identified by the breakout groups:

- Develop inspection criteria for welds in high-pressure applications to lower the cost of tank fabrication.
- Verify that leaching of composite tanks is not an issue to allow for industry adoption of high-pressure carbon fiber storage tanks.
- Research the viability of small-scale geologic storage at the forecourt.

# Other Forecourt Issues

## Other Forecourt Issues Presentations

**Amgad Elgowainy** (Argonne National Laboratory): Mr. Elgowainy noted that refueling station components are sized to satisfy vehicles' demand during peak hours, and that several combinations of compression capacity and buffer storage volume can satisfy the peak demand. He stated that the optimum configuration (for minimum hydrogen refueling cost) is determined by the cost and economies of scale of compressors and storage systems. He explained that this optimum configuration varies according to the refueling hourly demand profile and the hydrogen delivery method (e.g., tube trailers, liquid trucks, or another method), but that it could be constrained by scaling of technology, land area, power requirement, and other actions.

Mr. Elgowainy remarked that a more uniform demand profile can reduce the size of the compressor and require a smaller buffer storage system, lowering the station cost. He stated that this advantage becomes more pronounced at larger stations with higher daily demand. He explained that for large stations where peak demands are high, power consumption and the cost of upgrading the power supply can become significant. He said that while the station-levelized cost decreases with increasing capacity, it imposes a larger land area requirement, which may be constrained.

**Aaron Harris** (Sandia National Laboratories): Mr. Harris remarked that while CSD equipment takes up considerable space, even more is needed to accommodate the separation distances required by code to mitigate the hazards of hydrogen release, fire, detonation. He reported that setting up a barrier wall can reduce the separation distance by half. He also noted that the National Fire Protection Association has setback requirements for numerous safeguards that include air intake openings, parked vehicles, and public sidewalks, among other considerations.

Mr. Harris stated that the increase in temperature of the gas in the fuel tank, due to the heat of compression during refueling at 700 bar, may be mitigated through precooling of the hydrogen before the dispenser. He explained that for a given pressure and dispensing rate the degree of precooling can be optimized to prevent overheating, exceeding pressure limits, and overfilling. He noted that besides the added system complexity, the cooling system incurs capital cost ($20,000–$80,000) and consumes power (18–45 kilowatts).

**Kevin Harrison** (National Renewable Energy Laboratory): Mr. Harrison stated that the safety and reliability data from CSD operations during DOE's Hydrogen Fuel Cell Electric Vehicle Learning Demonstration was reported, collected at the National Renewable Energy Laboratory (NREL), and bundled to avoid attribution. He said that the failure events included data error, electrical short, excessive noise, metal fatigue, and hydrogen leak, among other factors. He reported that the most common cause of failure events were hydrogen compressors, representing 47% of the total, and that dispenser events represented 22% of the total.

Among compressor failures, Mr. Harrison reported that metal fatigue was identified as the most common mode, representing 26% of the events and 36% of the lost hours of productivity. He noted that the next most common causes for shutdown were excessive noise, hydrogen leak, and low pressure.

Analyzing hydrogen leaks in the plant, Mr. Harrison explained that the most common source of leaks was the compressor (47%), followed by leaks at the fittings (18%) and dispenser (16%). He noted that a process hazard analysis showed that all of the events could be classified at either “low” or “routine” risk levels, yet they led to a significant amount of lost labor hours. Additional information can be found at http://www.nrel.gov/hydrogen/cdp_topic.html.

**John Daly** (GE Measurement and Controls Solutions): Mr. Daly noted that GE manufactures coriolis meters for hydrogen dispensers. He explained that these devices measure mass flow with accuracy of 4.5% (of range) and repeatability to within 3.75%, as well as operate over a wide range of flow (1,000:1). He stated that current designs can measure up to 10 kg per minute of hydrogen. He said that improving the accuracy to 1%–2% and the repeatability to 1% is desirable for hydrogen fueling application. Mr. Daly also acknowledged that the development of metering devices is constrained by a lack of facilities where these devices can be tested with large volumes of high-pressure hydrogen. He asserted that the expansion of a hydrogen infrastructure and the consequent demand for metering devices will help bring down the cost of these meters by way of high-volume manufacturing.

## Other Forecourt Issues Panel Discussion

Participants agreed that the general trend for meters is to move to smaller meters. They acknowledged that one of the limitations is the pressure drop across the meter, which is variable with the temperature conditions but considerably higher for smaller meters. It was noted that the coriolis meter shows the greatest promise to meet the 2% accuracy specification at the 700 bar delivery conditions.

A participant pointed out that a contributing factor to the dispenser cost is the requirement to meet the NFPA-2 and NFPA-52 defined Class-1 Div-1explosion-proof component standards. A panelist remarked that this is perhaps too strict a requirement and it is expected that revisions to NFPA-2 will change the classification to allow intrinsically safe components, which will help drive the dispenser costs down.

The failure and reliability data presented from NREL sparked a discussion on the need to update and specify the types of data that need to be collected at newly deployed stations in order to track the stations’ performance and reliability. It was noted that failure events resulting from compressor metal fatigue  was predominately based on diaphragm compressors, and that they may be another area for investigation into reliability improvements.

## Other Forecourt Issues Breakout Session – Issues and Suggested Activities

The key activities identified by the three groups during the breakout session to lower the cost of hydrogen attributable to other forecourt issues are summarized in Table 3. The additional activity areas identified by each group, but not identified as key activities through voting, appear after the table.

**Table 3. Other forecourt issues breakout session results**

| | 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. |

The following are other activities to reduce the cost of hydrogen CSD at the forecourt identified by the breakout groups:

- Perform analysis to evaluate the cost benefits of the higher-reliability liquid pumps over gaseous compressors.
- Optimize refueling protocols (e.g., SAE J2601, mass capacitance (MC) method) to lower cost. Determine the station capital and operating and maintenance costs of precooling requirements and communication fills and suggest optimal protocols.
- Develop low-cost, high-efficiency precoolers to meet the SAE J2601 protocol.
- Develop lower-cost refueling nozzles to address dispenser cost.
- Research and develop high-pressure fitting technologies for >900-bar applications to lower capital costs and maintenance costs.
- Educate authorities having jurisdiction to reduce station deployment times.

# Conclusion and Next Steps

Speakers and participants at the workshop identified the challenges at hydrogen fueling stations that contribute to the delivery cost of hydrogen. These stakeholders recognized a number of issues that affect both compression and storage, including (1) the lack of standardized components that can be produced in large numbers and supplied to multiple purchasers and (2) codes and standards that either must be updated for these applications or are too conservative compared to other nations. It is anticipated that costs will come down with increasing demand for hydrogen through a combination of high-volume production by manufacturers and increased competition between manufacturers.

The high cost of compressors in service may be attributable to the existence of custom specifications for materials of construction, capacity, pressure, and other attributes for each unit. Another potential cost driver is the frequent maintenance required in light of compressors' frequent start-ups and shutdowns due to a lack of consistent hydrogen demand. Volume production of standardized units is expected to reduce the cost of compressors. The compressors also represent the majority of service calls, which even for minor issues do incur labor costs. For compressor R&D, participants suggested developing improved and/or standardized metals and seals that can withstand higher (>200°F) temperatures.

Similar to compressors, a major cost barrier with storage vessels is the unique specification of each order, which precludes volume production by manufacturers. A new tank made of a concrete/steel composite holds great promise in meeting cost targets. Conservative codes and standards for setback distances add to the cost of the station. R&D recommendations include improving the quality and reducing the cost of carbon fibers, as well as developing non-destructive testing techniques that can be used to recertify tanks for additional life.

Participants recommended data collection and R&D to find the optimal design and operating points based on trade-off studies (e.g., compression vs. storage capacities and precooling needs) as well as to improve demand predictions in the near- , mid-, and long-terms. Technology advances in compressor designs to improve efficiency will lower both energy consumption and cost, while newer materials can increase the life of the components and reduce plant costs.

A request for information (RFI) has been issued along with the publication of this report for open feedback on the issues identified here. These proceedings along with the results from the RFI will be used to inform DOE FCTO on potential future work in the area of hydrogen delivery.

# Appendix A: Abbreviations and Acronyms

| | |
|---|---|
| ANL | Argonne National Laboratory |
| CGH2 | compressed gaseous hydrogen |
| CSD | compression, storage, and dispensing |
| DOE | U.S. Department of Energy |
| EHC | electrochemical hydrogen compressor |
| FCTO | Fuel Cell Technologies Office |
| FCEV | fuel cell electric vehicle |
| FY | fiscal year |
| HAZOP | hazard and operability |
| kg | kilogram |
| NREL | National Renewable Energy Laboratory |
| OEM | original equipment manufacturer |
| ORNL | Oak Ridge National Laboratory |
| PEM | polymer electrolyte membrane |
| psi | pounds per square inch |
| psig | pounds per square inch gauge |
| R&D | research and development |
| RD&D | research, development and demonstration |
| SCCV | steel/concrete composite vessel |
| SIL | safety integrity level |
| ZEV | zero emission vehicle |

# Appendix B: Index

# Appendix C: Workshop Agenda

## ***Compression, Storage and Dispensing Workshop***

*APS Auditorium Building*
*Argonne National Laboratory*
*Argonne, IL*

### Agenda

**Wednesday, March 20, 2013**

| Time | Location | Item | Speaker/Panelists |
|---|---|---|---|
| 09:50 – 10:30 AM | Lobby | Registration | |
| 10:30 – 10:55 AM | E1100 | Welcome and Logistics | Ed Daniels, ANL<br>Shabbir Ahmed, ANL |
| 10:55 – 11:30 AM | E1100 | Introduction Workshop Objectives | Sunita Satyapal, DOE - FCTO<br>Erika Sutherland, DOE - FCTO |
| 11:30 – 11:50 AM | E1100 | Deployments – Issues & Barriers | Bill Elrick, CA FCP |
| 11:50 – 1:00 PM | Cafeteria | Lunch (Bus to Building 213) | |
| 1:00 – 2:15 PM | E1100 | Compression Panel<br>Presentations and Q&A | John Cornish, EPC<br>Matt Weaver, PDC<br>Ludwig Lipp, Fuel Cell Energy<br>Greg Walti, Haskel<br>John Siefert, Hydropac |
| 2:15 – 2:30 PM | | Break | |
| 2:30 – 4:00 PM | Gallery<br>E1100 | Compression Breakout Session | |
| 4:00 – 4:10 PM | E1100 | Reconvene | |
| 4:10 – 4:40 PM | E1100 | Compression Breakout Summary and General Discussion | |
| 4:40PM | | Adjourn | |

**Thursday, March 21, 2013**

| Time | Location | Item | Speaker/Panelists |
|---|---|---|---|
| 8:00 – 8:30 AM | Gallery | Coffee & Snacks | |
| 8:30 – 9:35 AM | E1100 | Storage Panel<br>Presentations and Q&A | Zhili Feng, ORNL<br>Don Baldwin, Lincoln<br>Nitin Natesan, Linde<br>Angela Das, Powertech |
| 9:35 – 9:45 AM | | Break | |
| 9:45 – 11:15 AM | Gallery<br>E1100 | Storage Breakout Session | |
| 11:15 – 11:20 AM | E1100 | Reconvene | |
| 11:20 – 11:50 AM | E1100 | Storage Breakout Summary and General Discussion | |
| 11:50 – 1:00 PM | Cafeteria | Lunch (Bus to Building 213) | |
| 1:00 – 2:30 PM | E1100 | Forecourt Issues Panel:<br>- Storage Volume vs. Compressor Capacity<br>- Station Foot Print<br>- Component Safety and Reliability Data<br>- Hydrogen Metering<br>Presentations and Q&A | Amgad Elgowainy, ANL<br>Aaron Harris, SNL<br>Kevin Harrison, NREL<br>John Daly, GE |
| 2:30 – 2:40 PM | | Break | |
| 2:40 – 4:10 PM | Gallery<br>E1100 | Forecourt Issues Breakout Session | |
| 4:10 – 4:20 PM | E1100 | Reconvene | |
| 4:20 – 4:50 PM | E1100 | Forecourt Issues Summary and General Discussion | |
| 4:50 – 5:10 | E1100 | Workshop Summary, Wrap-up and Next Steps | |
| 5:10 PM | | Adjourn | |

# Appendix D: Workshop Participant List

| Last name | First name | Affiliation |
|---|---|---|
| Ahmed | Shabbir | Argonne National Laboratory |
| Babick | Kristine | Energetics Incorporated |
| Baldwin | Don | Hexagon Lincoln |
| Benjamin | Tom | Argonne National Laboratory |
| Boyd | Robert | Boyd Hydrogen LLC |
| Brown | Daryl | Pacific Northwest National Laboratory |
| Burgunder | Albert | Praxair, Inc. |
| Cornish | John | EPC |
| Daly | John | GE Measurement and Controls Solutions |
| Daniels | Ed | Argonne National Laboratory |
| Das | Angela | Powertech Labs |
| Elgowainy | Amgad | Argonne National Laboratory |
| Elrick II | William | California Fuel Cell Partnership |
| Feng | Zhili | Oak Ridge National Laboratory |
| Gordon | Bryan | Nuvera Fuel Cells |
| Harris | Aaron | Sandia National Laboratories |
| Harrison | Kevin | National Renewable Energy Laboratory |
| Lipp | Ludwig | FuelCell Energy, Inc. |
| McMichael | Dennis | Praxair, Inc. |
| Mintz | Marianne | Argonne National Laboratory |
| Morgan | Scott | Energetics Incorporated |
| Natesan | Nitin | Linde LLC |
| Osborne | David | Air Liquide |
| Parks | George | FuelScience LLC |
| Patil | Pinakin | FuelCell Energy, Inc. |
| Poppe | Daniel | Hydrogen Frontier, Inc. |
| Ratkowski | Timothy | Pressure Products Industries, Milton Roy |
| Remick | Robert | Consultant |
| Sarkar | Dipankar | South Coast Air Quality Management District |
| Satyapal | Sunita | U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Fuel Cell Technologies Office |
| Siefert | John | Hydro-Pac, Inc. |
| Sutherland | Erika | U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Fuel Cell Technologies Office |
| Taylor | Jeff | Praxair, Inc. |
| Walti | Greg | Haskel International |
| Waugh | Dylan | Energetics Incorporated |
| Weaver | Matt | PDC Machines, Inc. |