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

FUEL CELL TECHNOLOGIES OFFICE

2014 Hydrogen Transmission and Distribution Workshop Summary Report

July 2014

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(Photos from top to bottom)

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2014 Hydrogen Transmission and Distribution Workshop

Summary Report

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Proceedings from the Hydrogen Transmission and Distribution Workshop

National Renewable Energy Laboratory
February 25–26, 2014

July 2014

Sponsored by:

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy
FUEL CELL TECHNOLOGIES OFFICE

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NOTICE

2014 Hydrogen Transmission and Distribution Workshop

Workshop held February 25–26, 2014
National Renewable Energy Laboratory, Golden, Colorado

Sponsored by:

U.S. Department of Energy (DOE) – Fuel Cell Technologies Office (FCTO)

Hosted by:

National Renewable Energy Laboratory (NREL)

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Executive Summary

Objective and Approach

The Hydrogen Transmission and Distribution Workshop was designed to discuss and share information on the research, development, and demonstration (RD&D) needs and challenges for low-cost, effective hydrogen transmission and distribution from centralized production facilities to the point of use (e.g., retail light-duty vehicle stations and other applications).

The workshop drew on experts from the industrial gas and energy industries, national laboratories, academia, and the National Institute of Standards and Technology to provide content and discussion, organized into two broad topics over the course of two days: pipelines and over-road distribution. These two topics were further divided into breakout sessions on compression and materials for the pipeline topic, and on gaseous distribution and liquid and hybrid distribution for the over-road topic. All presentations from the workshop can be found at http://energy.gov/eere/fuelcells/workshop-and-meeting-proceedings.

Pipeline Transport and Distribution

More than 1,200 miles of steel hydrogen pipeline are in use in the United States today. These pipelines operate at constant line pressures between 30 and 80 bar.[1] In a high-volume market scenario, such as today's natural gas market, pipelines become a cost-effective way to move large quantities of gas. Costly centrifugal compressors, chosen for their high throughput at relatively low output pressures, are used to maintain the line pressure in this scenario. Currently, redundant compressors are often installed due to the poor reliability of these machines and the high availability requirements for the application. These redundant machines add significantly to the cost.

Gaps in the standards for hydrogen pipelines also lead to increased costs and suboptimal pipeline design. The 2011 edition of The Hydrogen Piping and Pipelines Standard (American Society of Mechanical Engineers [ASME] B31.12) does not have defined pressure limits for transmission and distribution pipelines and does not include the use of fiber-reinforced polymer (FRP) pipelines. The challenges in this distribution pathway can be broken into the two main areas addressed by the breakout groups: those relating to compression and those relating to the pipeline material and construction.

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[1] U.S. DRIVE Partnership Hydrogen Delivery Technical Team, Hydrogen Delivery Technical Team Roadmap, May 2013

Compression

The primary needs identified by the Pipeline Compression group include the development of a system-level pipeline network modeling and optimization tool for pipeline design and operations. This tool would be used to perform the technoeconomic analysis needed to determine the optimal operating pressure for transmission and distribution lines as well as the size and distribution of lines required to meet the modeled market demand. Also identified was the need for the development of integrated systems for purification, cooling, and compression of hydrogen gas and investigation of novel compressor drive systems in order to reduce the cost and improve the reliability of pipeline compression. The development of a compressor capable of line packing was also identified as a long-term research and development (R&D) need to support a mature market where demand can be predicted.

Materials

In pipeline materials, the primary needs identified include research into the microstructures of pipeline steels, weld qualification, and the demonstration of FRP pipelines. Research is needed to define the relationship between the microstructure of different steels and the resistance to hydrogen-induced fatigue crack growth. This work is particularly relevant at and around pipeline welds where there are changes in the microstructure of the weld fusion and heat-affected zones. Such a model, validated with targeted testing, could accelerate progress in identifying and creating optimal steels for hydrogen pipelines. Another key area identified is the development of methods and procedures for qualifying welds and heat-treating processes for pipelines used in hydrogen service. A third need is for the demonstration of FRP pipelines as an alternative to traditional welded steel pipelines. FRP pipelines are an attractive alternative to steel pipelines because their materials of construction are not subject to hydrogen embrittlement, and because labor costs on installation are lower due to the fact that FRP can be spooled in lengths of up to a half-mile. However, the industry has little experience with the use of FRP in hydrogen service, and challenges remain regarding the joint technology. Validation of FRP pipeline in real service conditions is necessary to accelerate adoption of this technology.

Over-Road Transport and Distribution

Over-road transport and distribution of hydrogen via gaseous tube trailer or liquid tanker is the most commonly used method. Hydrogen tube trailers are currently limited by the U.S. Department of Transportation to pressures of 250 bar except by special permit. The pressure limitation results in payloads between 250 and 550 kilograms (kg). Cryogenic liquid tankers can carry payloads of up to 4,000 kg at nearly atmospheric pressure; however, boil-off can occur during transport. The challenges and needs relevant to over-road transport were captured within the two main areas of the breakout sessions: high-pressure gaseous transport and other over-road transport, which includes liquid and alternative delivery methods.

Gaseous Tube Trailer

The Gaseous Tube Trailer group identified that lower costs can be achieved through higher payloads and pressures. Increased payload reduces the number of trips the truck operator must make, reducing the cost and energy per kilogram of hydrogen. High delivery pressures can help achieve this goal and also reduce the compression required at the station, which is the dominant cost driver at the forecourt. To achieve the higher payload and delivery pressure, the following needs were identified: permitting for high-pressure trailers, polymer degradation, trailer light-weighting, and the development of a high-pressure test facility. Permitting of high-pressure tube trailers could be addressed through stakeholder engagement by the U.S. Department of Energy (DOE) and other federal and state agencies. The Super Truck activities of the DOE Vehicle Technologies Office can be leveraged for the light-weighting of hydrogen tube trailers along with the use of composite tubes. Of particular R&D interest to the light-weighting discussion is the understanding of polymer degradation mechanisms under high-pressure hydrogen cycles. Testing is needed to understand the life cycle of composite vessels used onboard tube trailers in order to optimize preventative maintenance and inspection and recertification schedules. A technoeconomic analysis of various supply chain and ownership models was identified as important to further progress in this area.

Other Over-Road Delivery

Stringent setback distances for liquid hydrogen storage were noted as a barrier to the use of liquid delivery. In order to reduce the setback distances, both at the terminal and at the station, data are needed on the risk associated with liquid hydrogen releases in order to inform codes and standards. The energy required for the liquefaction of hydrogen adds significant cost and greenhouse gas emissions to the liquid delivery pathway. The group identified the need for lower-cost, high-efficiency liquefaction technologies that could be applied to existing plants as well as new ones. Additionally, the group noted the need for small-scale, modular liquefaction machines that could have low capital cost and, unlike fixed liquefaction assets today, be re-deployed as the market for hydrogen vehicles matures and expands.

While gaseous tube trailers are a mature technology, potential cost and efficiency improvements could be obtained through the discovery and qualification of low-cost, lightweight structural alloys for construction.

Workshop Objectives and Organization

The Hydrogen Transmission and Distribution Workshop was designed to discuss and share information on the research, development, and demonstration (RD&D) needs to enable low-cost, effective hydrogen transmission and distribution from centralized production facilities to the point of use (e.g., retail light-duty vehicle stations and other applications).

The workshop drew upon 30 experts from the industrial gas and energy industries, national laboratories, academia, and the National Institute of Standards and Technology (NIST) to provide input and discussion, organized into two broad topics over the course of two days.

The workshop started with a basic safety briefing and notice that there would be no discussion of current or future funding opportunity announcements (FOAs) at the meeting, followed by an introductory session that included an overview of the Fuel Cell Technologies Office (FCTO) portfolio and hydrogen delivery activities.

Following this, the panel and breakout sessions began. All participants and panelists were asked both in panel presentations and the breakout sessions to focus their attention on two areas:

1. Technical challenges (internal and external) to achieving the U.S. Department of Energy’s (DOE’s) goal of reducing hydrogen delivery from the point of production to the point of use in consumer vehicles to <$3/gallon of gasoline equivalent (gge) by 2015, and to <$2/gge by 2020 (delivery only, all costs in $2007[2]).
    a. Internal challenges – Issues over which developers/industry have some degree of influence.
    b. External challenges – Issues over which developers/industry of transmission and distribution technologies have little or no influence.
2. Suggestions for additional RD&D needs that will help overcome those challenges in the near term (2014–2016), mid term (2017–2020), and long term 2020+.

Panel sessions included a series of short presentations on the relevant challenges to meeting DOE targets. After each panel session, a pair of parallel breakout sessions occurred, during which participants were asked to identify and vote on the highest-priority challenges and RD&D activities to address them. Raw details of the voting are presented in Appendix D: Voting Results.

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[2] Target includes the costs required to capitalize, build, and operate a fueling station that are directly attributable to non-production operations, namely gas compression, on-site gas storage, and dispensing.

Introductory Session

The workshop began with a welcome and round of introductions led by **Mr. Chris Ainscough** of the National Renewable Energy Laboratory (NREL) (on detail to DOE). His comments were followed by **Ms. Jennifer Kurtz,** manager of NREL's hydrogen analysis group, who gave an overview of NREL's hydrogen activities and the DOE facilities located at NREL for performing hydrogen research and development (R&D).

Dr. Sara Dillich then gave a summary overview of the DOE FCTO Hydrogen Delivery portfolio and the goals of the workshop. The ultimate FCTO goal is to produce and deliver hydrogen at <$4/gge, untaxed (U.S. Department of Energy, Fuel Cell Technologies Office, 2012).

Dr. Dillich's presentation addressed the primary delivery pathways, pipelines, and over-road delivery methods, as well as their status and progress relative to the DOE targets. It identified critical challenges in the areas of compression, dispensing, storage, pipelines, tube trailers, and liquid delivery, with the common themes of capital cost and durability. Dr. Dillich also highlighted recent technical accomplishments, such as a 30% reduction in forecourt storage capital cost through work at Oak Ridge National Laboratory (ORNL), and reviewed the objectives of the meeting.

The keynote speaker of the workshop was **Dr. Amgad Elgowainy** of Argonne National Laboratory, who presented the "Techno-economic Analysis of Traditional Hydrogen Transmission and Distribution Options."

Dr. Elgowainy provided an overview of the traditional transmission and distribution options in both gaseous and liquid forms using both pipelines and trailer carriers. He indicated that the costs of pipeline transmission and distribution could be in the range of $1–$2.5/kilogram (kg) with the key factors influencing these costs being market demand, labor cost, and regional variation in the right-of-way cost. He discussed the opportunity to reduce cost through the use of fiber-reinforced polymer (FRP) pipelines.

He posed a series of questions to the audience involving the economic justification for pipelines, the premium they cost over natural gas lines, the potential of FRP, compression, the effects of line packing[3] and stress cycling, leakage losses, and geologic storage.

Dr. Elgowainy presented analysis that estimates the costs of liquid transmission and distribution to range from $2–$2.5/kg[4] depending on the scale of the market. Currently, liquid distribution is

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[3] Line packing is storing inventory in the pipeline in advance of high-use times by increasing the pipeline pressure. It is a common practice on natural gas pipelines today.

[4] One kilogram of hydrogen is approximately equal to one gallon of gasoline on an energy basis.

range-limited because there are only eight liquefaction plants in North America, mostly east of the Mississippi River. In addition, there is an energy penalty in liquefying hydrogen. These plants currently emit approximately 5 kg of carbon dioxide (CO_2) per gge of hydrogen. If that hydrogen is produced with steam methane reforming (SMR) from natural gas, the production of greenhouse gas (GHG) emissions is 11–12 kg CO_2equivalent/gge of hydrogen. The electricity used by current liquefaction plants in the United States and Canada contributes another 5 kg CO_2e/gge of hydrogen. Although well-to-wheels (WTW) emissions of gasoline internal combustion engine vehicles (ICEVs) is only 11 kg CO_2e/gallon, the per-mile WTW GHG emissions of hydrogen fuel cell electric vehicles (FCEVs), even with the liquefaction electricity use, is lower compared to gasoline ICEVs. This is attributed to the high efficiency of FCEVs, which achieve approximately double the fuel economy of gasoline ICEVs (U.S. Department of Energy, Fuel Cell Technologies Office, 2014).

Dr. Elgowainy posed additional questions to the audience about the size of the fleet that could be supported by excess liquefaction capacity in the United States, demand levels required for investment and liquid delivery, boil-off losses during delivery, and the potential for improvement of the liquefaction process.

He also addressed tube trailer delivery of gaseous hydrogen, for which the estimated cost is $2/kg for capacities of 30–100 metric tons per day. Cost components include the loading terminal ($0.6–$1/kg) and the trailers ($1–$1.5/kg 100 miles of delivery distance).

Finally, he asked the audience questions regarding tube trailer loading terminals and trailer design. Tube trailer design and operation are not well understood and questions abound related to compression technology, the role liquid pumping could play, demand-level justifications for investment, frequency of use required to make this delivery method practical (on both the high and low ends), optimum trailer design, types of tubes used (type III or type IV), and optimum return pressure.

Pipelines

The panel and breakout sessions on pipeline hydrogen transmission and distribution focused on two aspects of pipeline transmission: materials and compressors. The Materials breakout session included discussion on both traditional steel pipelines and FRP pipelines. The Compression session addressed issues and challenges related to pipeline compression technologies. These topics are different from forecourt compression issues, which were established as out of scope for this discussion.

Pipelines Panel Presentations

Dr. Andrew Slifka discussed NIST's work on hydrogen embrittlement and crack propagation in pipeline steels. He noted that balance is needed between cost reduction in pipelines and safety.

While the two are not mutually exclusive, both can be attained. One of the challenges is to identify the roles of strength, microstructure, and pressure in hydrogen fatigue. The exact physics of degradation mechanisms in pipeline steels are not understood and seem to vary with stress intensity factors (ΔK). For example, it is unknown if there is hydrogen pressure beyond which embrittlement does not increase, analogous to a fatigue limit exhibited by some ferrous materials. Dr. Slifka also identified the lack of test facilities as a barrier.

Pipeline steels are sold by the ton and largely cost the same regardless of the grade. American Society of Mechanical Engineers (ASME) B31.12 currently recommends the use of American Petroleum Institute (API) X52 steel because of its long history of safe operation. However, NIST testing shows little fatigue difference between X52 and higher-strength X70 steels in the base metal, but there is a question about what happens in weld fusion and heat-affected zones. There is no discussion of girth welds in the relevant codes today. A combination of testing and fundamental modeling could be used to expand the materials considered in the code. Testing of baseline materials could serve as a modeling starting point for looking at new alloys or microstructures to achieve the desired material performance.

Dr. Brian Somerday of Sandia National Laboratories (SNL) presented SNL's work on hydrogen embrittlement. He noted that no hydrogen-embrittlement-related failures have occurred in existing steel hydrogen pipelines operated at static (time invariant) pressure. However, if pipelines are used in a distribution setting rather than from a dedicated producer to a dedicated consumer, they will likely be subject to line packing (storing capacity in the pipeline by increasing the pressure), which will induce stress cycles. SNL has shown that the microstructure of the steel used and stress orientation results in differing fatigue properties.

The challenge in a cyclic stress operating scenario is to reduce cost while maintaining safety. The two major components of cost related to the pipeline itself are the steel and the installation cost, which includes fabrication of the girth welds in the field. The cost of steel pipelines may be reduced by using thinner wall sections of higher-strength steels. To support this, additional data is needed on the performance of high-strength steels in hydrogen service. Additional cost reduction may be found through the use of new weld technologies to reduce labor costs. Analysis of new weld technologies and reliability would need to be proven.

The next speaker, **Mr. George Rawls** of Savannah River National Laboratory (SRNL), described work on FRP pipelines in hydrogen service. The possible advantages of FRP over steel in hydrogen service include a lack of susceptibility to embrittlement and cost savings on installation. Typical steel pipes are welded together from short sections, whereas FRP can be coiled and installed in sections up to a half-mile in length. This can result in significant labor savings on joining the pipe. Diameters for coilable FRP are currently limited to 6-inch outside diameter.

Challenges with FRP include the fact that FRP has not been demonstrated in hydrogen service, it is not yet included in ASME B31.12 code, and more robust joining technologies are needed. Currently, FRP relies on O-ring-based mechanical joints, which may introduce a leak point and require maintenance. It would be beneficial to develop a bonded, maintenance-free joint for FRP based on existing technologies. Inclusion of FRP in the codes is being addressed by work at both SRNL and ORNL on FRP in hydrogen service for burst and fatigue testing and permeation losses, which was submitted to the ASME B31.12 committee in September 2013 for consideration of inclusion in the code.

The final speaker in this session was **Dr. Hooshang Heshmat** from Mohawk Innovative Technology Inc. (MiTi). Dr. Heshmet spoke about his company's development of a high-speed, high-volume, low-pressure hydrogen pipeline compressor. He identified the remaining challenges as systems integration, full-scale demonstration, and field validation of the technology.

In order to demonstrate this compression technology at full scale, a pipeline application with approximately 500 metric tons per day would be required, which is a challenge with the current size of the hydrogen market. MiTi is therefore developing miniaturized versions of its compressor that operate at lower power levels and flows. Yet there is still a need for a full-scale test facility to validate the compressor, as well as a need for further development of manufacturing processes to produce miniaturized parts at volume.

Pipelines Panel Discussion

The pipeline panel discussion focused on the trade-offs between higher-pressure operation versus the pipeline material and compression costs. In particular, the operating pressure at which hydrogen pipelines would operate in order to serve a mature FCEV market is unknown. In order to lower the cost of pipelines while increasing pressure, a more thorough understanding of hydrogen embrittlement effects is needed. Further increasing the operating pressure of the pipeline would also increase drag in return, increasing the operating costs.

The participants questioned how leak detection would be handled in a hydrogen pipeline. The small size of the molecule and high purity requirements makes this particularly challenging for hydrogen pipelines.

Pipelines Breakout Discussions

There were two parallel pipelines breakout session tracks: one on compression technologies, and one on pipeline materials, including both steels and FRP pipelines.

Compression

The Compression breakout session focused on challenges and RD&D needs related to compression for hydrogen transmission and distribution.

Challenges

The top internal challenges identified by the attendees are shown in Table 1.

Table 1. Pipeline Compression Challenges

1. Compressor maintenance/reliability challenges
    a. Maintenance scheduling
    b. Robust, low-maintenance compressors
    c. Design for maintenance
    d. Reliability
2. Improved compressor design for high-pressure compression
    a. High efficiency
    b. Low-capital-cost compressors
    c. High throughput
3. Optimal hydrogen pressure management
    a. Determine optimal hydrogen pipeline network pressures

Discussion during the compression challenges section of the breakout session centered on issues identified in Table 1; specifically, on how to move from separate compressor units with separate stages to a packaged “black box” machine with high reliability (no need for redundancy), high throughput, high efficiency, and low cost (both capital and operating, which relate to reliability and efficiency).

Specific discussion on maintenance issues touched on condition-based maintenance, which is the art and science of predicting maintenance needs based on the operating history of the machine. Participants discussed standardized parts, maintenance intervals, procedures, and design for maintenance.

Also identified was a lack of modeling and understanding about optimization and operation of such large-scale systems. For example, the optimal transmission and distribution pressure to the forecourt to reduce the overall cost—not just for the pipeline operator, but for the distribution system as a whole—is not well understood.

The lack of third-party standardized testing was also mentioned. The participants suggested the need for standard performance and reliability tests that generate comparable metrics for different devices. The compression efficiency in kilowatt-hour/kilogram of hydrogen was given as an example of an appropriate, comparable metric.

External Challenges

External challenges identified include market barriers for stations such as footprint, the high risk of investing capital, and the lack of adequate measurement technology/sites to evaluate compression technologies. While the station issues are not, on their face, specifically related to pipelines, a robust network of stations is a requirement prior to investment in extensive pipeline infrastructure, and it is therefore relevant.

RD&D Activities

Near-Term Needs (2014–2016)

Needed near-term R&D activities reported by the group are summarized in Table 2. The top identified R&D activity is to develop a system-level modeling and optimization tool that will allow for analysis and simulation of a distribution pipeline network in a variety of rollout scenarios. This tool should allow the optimization of the distribution network as a whole in order to address Challenge 3 from Table 1.

Table 2. Pipeline Compression Near-Term RD&D Activities (2014–2016)

1. Pressure management models and algorithms for optimal storage, pressure, and distribution *(Challenge 3)*
2. Integrated systems for purification, cooling, and compression *(Challenge 2)*
3. Novel non-mechanical or non-electrical compression systems *(Challenge 1)*
4. Standardized validation facility and procedure with highly instrumented systems for simulation

Long-Term Needs (2017–2020+)

The long-term R&D activities identified also centered on system-level analysis and optimization. These activities are summarized in Table 3.

Table 3. Pipeline Compression Long-Term RD&D Activities (2017–2020+)

1. Design of compressors with line packing capability *(Challenge 2)*
2. Development of pipeline network modeling tools that would support an understanding of the impacts on the electric grid and potential for support of demand response, energy storage, hydrogen grid-based load shedding, and multiple energy services *(Challenge 3)*

Other Activities Identified

Also discussed was the possibility to work with the DOE Advanced Manufacturing Office to investigate the use of additive manufacturing techniques for high-quality, low-volume compressor parts. This could address the need to deploy advanced technologies without high capital investment, another theme of the discussion.

Materials

The Pipeline Materials breakout session participants were asked the same set of questions and followed the same process as the Pipeline Compression session. The session focused on challenges and RD&D needs related to hydrogen pipeline materials, both steel and FRP.

Challenges

The top challenges identified by participants during the Materials breakout session are shown in Table 4.

Table 4. Pipeline Materials Challenges

1. Identification of hydrogen fatigue properties with respect to the microstructure
2. Investigate the potential for non-metallic materials for joint sealing applications
3. FRP hydrogen pipeline demonstration at scale
4. Develop lower-cost joining technologies (welding and FRP)
5. Codes and standards adoption

Participants discussed how to reduce pipeline cost and avoid overdesign while preventing safety risks. FRP pipelines cost more in raw materials in terms of dollars per mile, but they generally result in much lower labor costs due to the lack of welding and longer pipe runs available with coiled pipe. Welds and joints are a source of defects and a large component of labor. Defects are susceptible to additional embrittlement from hydrogen.

The discussion on codes and standards issues included many different viewpoints on the challenges and potential solutions. Challenges include providing enough data to prove that robust safety factors can still be achieved with thinner-wall pipeline to convincing designers to adopt the new standards, rather than more conservative internal design practices. As one possible solution, participants described a code that is prescriptive enough to be enforceable, but flexible enough to be effective.

External Challenges

Participants identified few external challenges, most of which can be classified as education of the public and code officials and recruitment of younger researchers to the field.

RD&D Activities

Near-Term Needs (2014–2016)

Near-term RD&D activities identified by participants are shown in Table 5.

Table 5. Pipeline Materials Near-Term RD&D Activities (2014–2016)

1. Identification of material microstructure, composition, and properties that effect hydrogen embrittlement resistance *(Challenge 1)*
2. Fatigue testing for the development of physical models that relate material microstructure, composition, and properties to measured behavior *(Challenge 1)*
3. Demonstrate FRP at pilot scale to increase confidence in the product installation and use *(Challenge 3)*
4. Development of efficient inspection and monitoring techniques *(Challenge 5)*
5. Develop a technical basis for factors of safety and provide data to codes and standards organizations *(Challenge 5)*

Participants identified the need for research activities that characterize the classes of steel microstructures as they relate to hydrogen embrittlement and fatigue properties and define the role of fatigue crack initiation. Closer collaboration between NIST and SNL was recommended in order to accelerate the research timeline.

In order to address Challenge 2, the participants suggested evaluating existing materials and developing new materials if necessary for effective sealing of polyethylene pipelines carrying hydrogen. Identification and/or development of joints that can join the liner as well as the reinforcement structural layer around the pipeline were also suggested.

Participants identified the need for a large-scale demonstration of FRP hydrogen pipeline to accelerate adoption. Demonstration would include tests of a variety of soil types and moisture and mineral contents. Outcomes from the demonstration would include the dissemination of data on stress rupture and/or fatigue failure. Participants also felt that a demonstration could have a multiplier effect to attract attention to the viability of the FRP solution.

Regarding Challenge 5 from Table 4 (codes and standards issues), participants suggested finding a basis for rational factors of safety and feeding outcomes of the models from Challenge 1 (hydrogen fatigue properties with respect to the microstructure) activities to code organizations.

Long-Term Needs (2017–2020+)

Breakout session participants identified the development of a physics-based predictive fatigue crack growth (FCG) model, informed by fatigue testing, as a long-term need, as shown in Table 6.

An innovative idea suggested by participants is a machine that could manufacture FRP in place on the trench. The idea is that the machine would receive batch shipments of fiberglass, polymer, and other raw materials, and would extrude the FRP in situ. This could dramatically reduce FRP installation costs and eliminate many of the challenges with FRP today, such as the practical diameter limit on coilable pipe currently being 6.5 inches, and joining technologies (in situ manufactured pipe could have far fewer joints).

Table 6. Pipeline Materials Long-Term RD&D Needs (2017–2020+)
1. Develop physics-based predictive models that relate FCG performance to material properties and microstructure *(Challenge 1)* 2. Develop in situ pipeline manufacturing technology

Pipelines Final Discussion

Participants in the two parallel Pipeline breakout sessions discussed many similar themes, with the cost of pipeline installation being the most prominent. The Materials group desired to address this challenge by using physics-based modeling to determine the best properties of steel microstructure for reducing hydrogen embrittlement issues. The group noted that this could lead to less conservative (but still safe) hydrogen pipeline materials and designs. There is also some promise seen in FRP pipeline as a means to reduce labor, provided reliable, low-cost sealing methods can be developed. Both of these innovations would also require buy-in from code officials and industrial pipeline companies.

The Compression group also recognized the need for modeling activities. That group suggested the need for tools to model pipeline network rollout scenarios, with multiple sources and sinks to determine the optimum pressures, flow rates, line sizes, lengths, and other parameters to achieve a global optimum cost without pushing problems onto the station operators. RD&D need outputs from the breakout sessions are grouped according to the barriers from the delivery chapter of the Multi-Year Research, Development, and Demonstration Plan (MYRD&D), as seen in Table 7. The compression needs map to MYRD&D Barriers A, B and D, relating to infrastructure analysis, hydrogen compression, and the costs of pipelines, respectively. Among these, the development of pressure management algorithms and optimization models may provide significant value for reducing the cost of pipeline-delivered hydrogen. Such modeling and optimization tools should be designed to consider the system from production to end use, and to identify optimal delivery pressures and methods. Such a tool can help provide a systems approach to guide development work, rather than optimizing one component at a time, ultimately resulting in lower costs.

Pipeline materials needs map to Barriers D and K. Among these, the RD&D need that may have the largest impact on the cost of delivered pipeline hydrogen in the long term may be the need to gain confidence in FRP in hydrogen service. Because the installation labor costs of coilable FRP can be much lower than those of welded pipe, the ability to impact hydrogen cost is potentially greater than for steel pipelines. The primary challenges to FRP adoption for hydrogen service appear to be threefold: (1) development of joining technologies that are robust, cost effective, and maintenance free; (2) adoption of FRP into the ASME B31.12 hydrogen pipeline code; and (3) acceptance by the pipeline industry of FRP for hydrogen.

When considering steel pipelines, which are a proven incumbent technology, the development of a physics-based model of the effects of hydrogen on FCG to provide predictive capabilities for FCG resistance, with inputs of metal phase composition, microstructure, loading, and physical environment, could accelerate the development of improved pipeline materials. If validated against fatigue data, the tool could lead to more rapid progress developing robust materials than physical testing alone, which is expensive and time consuming.

Table 7. Classification of Pipeline RD&D Needs into Program Technical Barriers

Barrier	RD&D Activity: Compression	RD&D Activity: Materials
A. Lack of Hydrogen/Carrier and Infrastructure Options Analysis	• Pressure management models and algorithms for optimal storage, pressure, and distribution • Understanding of impacts on the electric grid and potential for support to demand response, energy storage, hydrogen grid-based load shedding, and multiple energy services	
B. Reliability and Costs of Gaseous Hydrogen Compression	• Development of integrated systems for cooling and compression • Investigation of novel compressor drive systems • Line-packing compressor	
D. High As-Installed Cost of Pipelines	• Development of in situ pipeline production	• Gain confidence with FRP in hydrogen service • Define material features of interest • Understanding of FCG in pipeline steel through development of a predictive, physics-based model • Gain confidence in FRP in hydrogen service through a demonstration in a relevant environment • Development of efficient inspection and monitoring techniques
K. Safety, Codes and Standards, Permitting		• Develop a basis for factors of safety and feed outcomes of the models to code organizations

Over-Road

The Over-Road Hydrogen Transmission and Distribution panel and breakout sessions focused on two broad methods of transmission and distribution: gaseous and liquid. The Liquid Delivery breakout session included discussion of traditional cryogenic liquid delivery, liquid carriers, and hybrid approaches. The DOE targets presented to the breakout groups at the beginning of their work were the same as previously discussed in this report.

Over-Road Panel Presentations

Mr. Don Baldwin of Hexagon Lincoln discussed his company's work on bulk gaseous delivery tube trailers that are operated as a virtual pipeline for the natural gas industry. Similar infrastructure would be needed for a high-volume hydrogen market, including the large terminal facilities where trailers fill and then drive to stations and large-volume dedicated customers.

Mr. Baldwin noted that the 700-bar operating pressure is challenging and, though necessary to achieve a driving range similar to gasoline vehicles today, may not be optimal. He identified the need for reduced delivery pressure requirements and component research to meet operating conditions. He also suggested leveraging the experience of the natural gas industry and aligning the certification/qualification requirements with real-world experience. For example, a system approach to vehicle impact and fire protection can be used to optimize overall cost and safety.

Reduction in the cost of trailers was also identified by Mr. Baldwin as a challenge. Lower-cost carbon fiber is needed to reduce costs, and a reduction in the excise tax on trailers, currently at 30%, is a problem for both hydrogen and natural gas delivery. Also, the patchwork of state regulations causes confusion and redundant effort to comply with all the states in which operators wish to do business. He also noted that in contrast with hydrogen, natural gas usage in vehicles is starting with urban fleets, heavy-duty fleets, private light-duty fleets, and finally personal light-duty consumer vehicles. Mr. Baldwin suggested that a similar market development path may be appropriate for hydrogen vehicles.

Dr. Jacob Leachman of Washington State University spoke about cryo-compressed hydrogen. The storage density (of the fluid alone) for cryo-compressed hydrogen at 440 bar and 30 K is higher than that of liquid hydrogen at its normal boiling point (90 grams/liter [g/L] versus 71 g/L). Vehicle filling can be much faster with cryo-compressed hydrogen than with gaseous, and much of the energy that is spent to liquefy the hydrogen can be recovered through autogenous pressurization of the tank.

Dr. Leachman listed the major challenges facing cryo-compressed hydrogen, which include the development of a low-cost cryo-compression pump, cost reduction of tanks, a lack of appropriate commercial metering technologies, component safety, and the need to accelerate technology advancement. He identified opportunities for cost reduction and design improvements such as cryo packaging as a replacement of the traditional vacuum jacket. He further identified other research and testing activities for cost reduction, including accelerated testing, fatigue, impact thermal testing, and Failure Modes and Effects Analysis (FMEA).

Dr. Satish Tamhankar of Linde discussed terminal operation for liquid trucks and tube trailers. Dr. Tamhankar broke the challenges into four broad areas: gaseous hydrogen, liquid hydrogen, green hydrogen, and regulations on new delivery and storage equipment. For gaseous hydrogen, Dr. Tamhankar identified the logistics of maneuvering the trailers, including speed of delivery, demand profile planning, and the amount of space they take up at a retail station, as a challenge. Similar issues are relevant for liquid delivery, with the added challenges of line purging and cooling as well as the large incremental investment that is required to add more liquefaction capacity. He also noted that currently there is more liquefaction capacity in the United States than needed, which results in a lack of investment in this area. The main challenge with green hydrogen is that there is no way for a producer to receive a price premium for its production. Given that renewable hydrogen is generally more expensive than nonrenewable hydrogen, there is no financial incentive to produce it. Finally, Dr. Tamhankar discussed the challenges of meeting regulations for new equipment.

Dr. Tamhankar suggested focusing on new delivery methods and lightweight, high-pressure tubes (gaseous, short distance delivery) and cryogenic trailers (liquid, medium-to-long distance). Although the payload of liquid delivery is much higher, there is a place in the market for both technologies, depending on the time to fill, capacity, time to off-load, demand, and distance travelled. A possible short-term option to alleviate the space and unloading time issues is to deliver filled tubes in an International Standards Organization (ISO) shipping container to a site and retrieve an empty container for later refilling. There is an opportunity to go to higher pressures than 500 bar to eliminate compression stages at the forecourt. He noted the overarching need to conduct technoeconomic analysis of the preferred options, pilot relevant technologies, and then commercialize the technologies.

Dr. Tamhankar also mentioned a need for interagency cooperation between DOE, the U.S. Department of Transportation (DOT), and ASME on new equipment approvals. Given the current lack of market value for green hydrogen, he suggested that investment support could be within the role of government.

Mr. Al Burgunder of Praxair presented an overview of the 250-ton-per-day liquefaction capacity in the United States, including the diversity of feedstocks (chlor-alkali, SMR, and petrochemicals) and major markets (manufacturing, space programs, and metropolitan areas). Safety needs to be industry’s top priority due to the extreme temperatures, pressures, and flammability issues of handling a cryogenic fuel gas. Purity is a challenge, due to the low boiling temperature of hydrogen. All contaminants will condense out before hydrogen and can foul the liquefaction equipment; therefore, purity must be maintained throughout the supply chain.

Another challenge is the high liquefaction energy of approximately 13 kilowatt-hours/kg. The European Union (EU) IdealHy project performed analysis to show it is possible to reduce energy costs of liquefaction by approximately 45% through a series of process improvements in the pre-cooling, pre-compression, cryo-cooling, expansion, and power recovery steps of a liquefaction plant (Fuel Cells and Hydrogen Joint Undertaking, 2012). At this time, there are no public plans to commercialize that technology, due to the lack of market demand. Mr. Burgunder also discussed the lack of value placed by the market on green hydrogen. However, it is important to maintain a diversity of hydrogen sources to compensate for supply disruptions from any single source.

Over-Road Panel Discussion

Panelists stated that supplying liquid hydrogen for a large-scale rollout of hydrogen-powered vehicles is a challenge due to the high incremental cost of additional liquefaction capital and the energy penalty. The emissions associated with liquid hydrogen are an issue due to the high energy requirements of the liquefaction process. The discussion then moved to the possibility of smaller plants or co-location with green hydrogen sources. Several panelists noted that there is no market premium for it now, and although several producers use renewable hydropower to make hydrogen, they cannot sell it for more than hydrogen from SMR. Panelists also remarked that the availability of renewable hydrogen tends to be location specific.

A question was asked if the materials challenge for composite vessel fabrication is greater for the steel polar bosses of the tanks or for the polymer composites. Experts in the audience indicated that the challenges are greater for the polymer composites.

The group also discussed codes and standards, specifically National Fire Protection Association (NFPA) 55; setback distances (particularly for liquid storage); and DOT approval. A participant expressed concern that moving to higher-pressure tube trailers is very expensive and time intensive because of DOT regulations. It was also noted that Linde has a 500-bar trailer certified for use in Europe, but that it was currently cost prohibitive to have the trailer certified in the United States.

Over-Road Breakout Discussions

The breakout discussions on over-road hydrogen transmission and distribution were split into two parallel tracks: one on gaseous approaches and one on liquid and hybrid approaches. Each breakout group was given the same tasks as described in the pipelines breakout discussion.

Gaseous Transmission and Distribution

The Gaseous Transmission and Distribution session focused on challenges and RD&D needs related to delivery via high-pressure gas tube trailers over-road.

Challenges

The top challenges identified by the breakout session participants are shown in Table 8. The discussion can be broadly grouped into the following categories: technoeconomic; materials; safety; regulations, codes, and standards; and new ideas.

Table 8. Gaseous Transmission and Distribution Internal Challenges

1. Lack of understanding of degradation mechanisms
2. High cost of materials
3. Cost of new infrastructure vs. demand for hydrogen
4. Need for advanced tube trailer design
5. Improved process for standards and regulations development

Much of the technoeconomic discussion in the breakout session was centered on the high cost of tube trailers and the relatively small payload they carry (300 kg of hydrogen) compared to liquid (4,500 kg of hydrogen) (Al Burgunder, Praxair).

There are two methods of increasing trailer payload: (1) increase the pressure or (2) increase the volume of the tubes. Both approaches have been explored with high-volume trailers from Hexagon Lincoln and higher-pressure trailers from most of the companies in the over-road distribution business. Participants then discussed the need for a 700–1,000-bar trailer; however, they noted that the lack of compatible trailer hardware at that pressure level is a challenge.

Participants also discussed changing the ownership model for a tube-trailer delivery situation. For example, participants suggested that the economics of owning and operating a hydrogen station could be improved if the hydrogen storage was owned by the gas supplier and leased by the station owner, similar to how propane tanks are leased to homeowners today. Participants discussed this concept in the general context of understanding the business case for station owners and why station owners would want to put hydrogen at their station and where they would get the capital to do so.

The participants noted that this kind of communication and coordination is currently missing between possible partners in the market. The lack of communication results in incomplete data and therefore inaccurate analysis with which to make decisions. Areas of incomplete understanding include intercity right-of-way costs, costs of building a hydrogen infrastructure on existing infrastructure, energy and costs related to compressed and refined hydrogen, and regional feedstock issues (where the molecules come from).

Several attendees mentioned the high cost of trailer materials as a challenge. This applies both to carbon fiber and steels used to make the tubes. An additional materials challenge is the light-weighting of both the tubes and the trailer rolling stock. This could allow increased payload while staying under DOT weight limits. This might be low-hanging fruit that could be addressed through collaboration with the DOE Vehicle Technologies Office’s (VTO’s) Super Truck Program.

Any new material development or light-weighting would need to consider the effects of hydrogen on those materials. Challenges posed by the attendees include the lack of coupon-level testing of materials, understanding of materials’ behavior (especially composites) in high-pressure hydrogen, and understanding of chemical degradation (embrittlement is largely a physical phenomenon). Developing a gaseous sorbent material that could allow delivery without the high pressures currently required would be beneficial.

Finally, participants discussed new ideas that do not fit easily into any of the other categories. Specifically, attendees noted that there has been insufficient discussion on rail delivery of hydrogen, either as liquid or gas. It was noted that it might be useful to have hydrogen-compatible motors available to drive pumps and compressors (as is common practice in the natural gas industry).

External Challenges

Safety was an area of robust dialogue. Challenges cited by participants included the lack of scientific understanding of damage accumulation effects, standard accident models, legacy stewardship and maintenance requirements, and predictive failure capabilities on tube trailers (again, especially composites).

The discussion on safety led to a discussion on regulations, codes, and standards. Participants noted that the DOT approval process is expensive and time consuming. DOT participates in the development of the national codes and standards that inform the DOT approval process. Because of this, participants suggested that the DOT approval process could be streamlined when the associated codes and standards have already been met. Attendees also suggested that the codes and standards process is generally too slow to address technical issues.

The patchwork of state regulations, in addition to federal rules on maximum bridge weight, is a challenge because of the complexity of complying with the different rules in each jurisdiction. Because harmonization of these rules is unlikely, attendees suggested developing a single source of information for the different rules. They also noted that a larger outreach effort to local authorities is needed in order to facilitate approval of hydrogen transmission and distribution technologies.

RD&D Activities

Near-Term Needs (2014–2016)

Top near-term RD&D needs from the group are shown in Table 9.

Table 9. Gaseous Transmission and Distribution Near-Term RD&D Activities (2014–2016)

1. Development of a high-pressure test facility—must be coordinated with existing facilities *(Challenge 1)*
2. Understanding of polymer degradation mechanisms related to hydrogen *(Challenge 1)*
3. Develop test procedures and acceptance criteria for polymers in hydrogen environments *(Challenge 1)*
4. Identify and study new lightweight, low-cost materials for tube trailers *(Challenge 2)*
5. Develop models of supply chain/ownership options *(Challenge 3)*
6. Interface with VTO to identify opportunities for lowering vehicle weight *(Challenge 4)*
7. Engineering study of current tube trailers to identify potential for design improvements *(Challenge 4)*

A high-pressure test facility would accelerate progress on many of the safety and materials challenges noted in Table 8. The facility could be tasked with such activities as understanding damage mechanisms and accumulation, characterizing the relationship between trailer pressure and risk, understanding polymer degradation mechanisms (physical and chemical) in hydrogen, developing standard testing procedures, and providing in situ monitoring of test vessels.

Participants found that the key need regarding materials research is to identify and develop new, lighter-weight materials that can help reduce trailer weight and cost. Results from materials research could inform the design of lightweight, high-performance tube trailers, engaging DOT and other stakeholders at the outset of the process. One possible way to accomplish this activity is to develop a tube trailer working group with membership across industry, government (including DOT and DOE), and academia.

Regarding the economics of hydrogen distribution, a model for the various supply chain and business model scenarios that might arise in a hydrogen transmission and distribution system would be beneficial. It should leverage existing models to minimize the global cost of hydrogen distribution, as well as account for sensitivities to the system inputs.

Participants' suggestions related to safety include more regulatory body engagement in developing codes and standards; outreach to national fire associations (including use of the FCEV first responder training facility at Pacific Northwest National Laboratory [PNNL]); development of a database of codes, standards, and regulations across states; and identification of the highest-priority safety issues with trailers in the field.

Long-Term Needs (2017–2020+)

The group did not identify any long-term needs.

Liquid and Hybrid Transmission and Distribution

The Liquid and Hybrid Transmission and Distribution breakout group was tasked with discussing the issues, barriers, and R&D needs associated with liquid delivery, liquid carriers, and cryo-compressed hydrogen.

Challenges

The liquid delivery pathway is attractive because it is a well-developed pathway with mature technologies for delivering hydrogen outside the range of hydrogen pipelines. It is also currently more economical for high-demand markets than gaseous hydrogen delivery via tube trailers because it offers a much higher capacity of delivered hydrogen. However, the high energy requirements of liquefaction as well as boil-off issues are just some of the challenges associated with liquid hydrogen delivery. Liquid organic carriers chemically store hydrogen in a liquid state without the intense energy requirements of liquefaction and have the potential to use existing infrastructure.

Finding a carrier that will dehydrogenate under the appropriate conditions without the formation of harmful/hazardous by-products, and which can be easily regenerated, has proven to be a challenging task. Cryo-compression offers a higher-capacity hydrogen storage option than typical gaseous hydrogen storage without the energy penalties of the ortho-para conversion of hydrogen required for liquefaction. The top internal challenges identified by the group are shown in Table 10.

Table 10. Liquid and Hybrid Transmission and Distribution Internal Challenges

1. Capital expense reduction for smaller plants/smaller-scale, low-cost modular liquefiers
2. Lightweight transportation/materials and processes to increase truck payload
3. Reducing bleed off during filling, transport, offloading/boil-off recovery
4. Liquid carriers R&D: simple chemistry
5. Liquefaction efficiency/refrigeration efficiency

A major internal barrier for the liquid hydrogen pathway is reducing the required capital expense to allow for smaller plants and smaller-scale, low-cost modular liquefiers. According to the group, unless liquefaction and refrigeration efficiencies are improved, liquid hydrogen will likely only be an incremental player in lowering the cost of hydrogen transmission and distribution. Participants highlighted increasing truck payload, possibly through lighter vehicle materials, as well as reducing bleed off during filling, transport, and offloading and boil-off recovery as internal issues that needed to be addressed to allow liquid hydrogen to become a viable pathway for hydrogen transmission and distribution.

The breakout group recognized that simple chemistry is important for liquid carriers to serve as an economically feasible transmission and distribution pathway. The participants noted that a carrier is needed that would allow for easy dehydrogenation by simply adding heat to yield a spent fuel that is safe to handle and easily and cost-effectively regenerated.

External Challenges

The major external issue identified is the need for codes and regulations that are tailored to over-road trucks and relevant to state-of-the-art technology. Participants noted that many of the codes and regulations are outdated, and that with the current set of regulations, the community might not be protecting itself from the "right" things. Furthermore, participants noted that there is a need for DOT regulations that define capacity and standards for variable/smaller deliveries, because none exist for capacities less than 1,000 gallons. Attendees also discussed how education and training is needed for handling liquid hydrogen. Work has been done for gaseous hydrogen, but the participants were not aware of similar studies for liquid hydrogen.

RD&D Activities

Near-Term Needs (2014–2016)

The group identified testing to gather the necessary data for the development of informed codes and standards as the most critical need. The top R&D activities needed in the near term as identified by the group are summarized in Table 11.

Table 11. Liquid and Hybrid Transmission and Distribution Near-Term RD&D Activities (2014–2016)

1. Design/conduct testing and collect data to inform codes/standards in order to reduce setback distances
2. Discover and qualify low-cost, low-temperature, lightweight structural alloys *(Challenge 2)*
3. Design high-efficiency compressors/expanders; improve liquefaction efficiency *(Challenge 5)*
4. Characterize physical effects of cryo-cycling on polymers for composites and extended lifetime *(Challenge 2)*
5. Develop novel/low-cost and volume insulation systems *(Challenges 2 & 3)*
6. Design low-cost, small-scale modular liquefier *(Challenge 1)*

Another critical need that participants identified is the discovery and qualification of low-cost, lightweight alloys. Participants suggested that EU NaturalHy efforts in this area could be leveraged. Research to provide a better understanding of the thermal cycling effects on the fiber-wrapped composite tanks with polymer liners used for storing cryo-compressed hydrogen is needed. The thermal fatigue of the polymer liner needs to be qualified in order to determine tank lifetime and establish appropriate codes and safety factors. Other critical near-term needs that participants identified are designing high-efficiency compressors and expanders and conducting R&D for improved liquefaction efficiency, because the liquid hydrogen transmission and distribution pathway will not be a long-term solution if efficiencies are not improved.

Long-Term Needs (2017–2020+)

Participants acknowledged the development of low-cost, high-pressure cryo-storage tanks as a long-term R&D need.

Table 12. Liquid and Hybrid Transmission and Distribution Long-Term RD&D Activities (2017–2020+)
1. Develop low-cost, high-pressure cryo-storage tank

Over-Road Final Discussion

The parallel sessions on gaseous and liquid transmission and distribution both focused heavily on cost, a component of which is the weight of the trailers carrying the hydrogen. Both mentioned the need to develop lighter-weight trailers that can help increase payload; however, at least one participant felt this might not be a worthwhile effort for cryogenic liquid carriers because the payload is so much higher than for a gas trailer. A scoping study would help to determine potential savings from designing optimized trailers in both cases (see Table 9, activity 7).

Both sessions discussed materials compatibility with hydrogen, with the added complications of high pressure (gaseous), and low temperature (liquid). The Gaseous Transmission and Distribution session participants identified the need for a facility to test materials and systems at relevant scales and environments.

Codes and standards simplification was a common theme in the Liquid and Hybrid Transmission and Distribution session. This applied both to DOT regulations for the carriers and setback distances for liquid storage at the forecourt.

Participants in the Liquid and Hybrid Transmission and Distribution session also focused on efficiency and the capital cost of liquefaction plants. They identified needs such as development of novel insulation systems beyond vacuum jacketing; a modular, small-scale liquefaction machine (transportable, in contrast to a whole plant); and, longer term, development of a low-cost, high-pressure cryogenic vessel (see Table 11).

One topic raised that has received limited attention in the past is the possibility of rail-based hydrogen distribution. Liquid hydrocarbon fuels are moved by rail every day in the United States. It has yet to be studied at what point rail-based distribution would make economic sense.

Table 13 maps MYRD&D barriers to the needs identified in this session. Over-road gaseous hydrogen transmission R&D needs map to Barriers A, E, and K. The two needs identified most likely to result in reduction of over-road gaseous R&D costs are the development of a model to investigate various supply chains and ownership options, and the development of lower-weight gaseous tube trailers.

Because the finances of the various players in a hydrogen R&D market are so important to the development and viability of the market, it is necessary to understand which technology factors influence the finances. A model should be developed that can inform optimum and efficient transfer of value along the supply chain to understand and identify where efficiency can be improved in order to achieve overall cost savings, while maintaining economic value for all participants.

Regarding gaseous tube trailers, the majority of the weight of a full trailer is the trailer itself. Therefore, any reduction in the trailer weight or increase in the trailer pressure that can be realized safely can result in an increase in the payload of hydrogen the trailer can carry. The benefit of light-weighting liquid trailers is not as great due to the much higher relative mass of hydrogen to trailer weight in liquid trailers. Any activity to address this RD&D need should include stakeholders such as VTO, DOT, industrial gas companies, and tank and trailer manufacturers in order to streamline the development and approval process.

Liquid R&D needs map to Barriers H and K. The key activity identified was to work with safety codes and standards organizations to reduce setback distances for liquid storage systems. For near-term rollout of liquid-based systems, reduction of setbacks could potentially open up a large portion of existing gasoline stations to the addition of liquid hydrogen systems. While the concept of modular liquefaction systems is novel, the United States is not yet at the point where hydrogen for vehicle fuel will stress the installed liquefaction capacity in operation; therefore, this is considered a long-term activity.

Table 13. Classification of Over-Road RD&D Needs into Program Technical Barriers

Barrier	RD&D Need: Gaseous	RD&D Need: Liquid
A. Lack of Hydrogen/Carrier and Infrastructure Options Analysis	• Model of various supply chain/ownership options	
E. Gaseous Hydrogen Storage and Tube Trailer Delivery Costs	• Understanding of polymer degradation mechanisms related to hydrogen • Develop test procedures for polymers with acceptance criteria • Identify and study new lightweight, low-cost materials for tube trailers • Identify opportunities for lowering vehicle weight • Engineering study of current tube trailers to identify potential for design improvements	
H. High Cost and Low Energy Efficiency of Hydrogen Liquefaction		• Discover and qualify low-cost, lightweight structural alloys (low temperature effects) • Design high-efficiency compressors/expanders; improve liquefaction efficiency • Understand physical effects of cryo-cycling on polymers for composites and extended lifetime • Develop novel/low-cost and volume insulation systems • R&D for low-cost, small-scale modular liquefier • Develop low-cost, high-pressure cryo-storage tank
K. Safety, Codes and Standards, Permitting	• Assign national laboratories to specific codes and standards as subject matter experts • Improved efficiency for standards and regulations development (external challenge)	• Design/conduct testing and collect data to inform codes/standards → reduce setback distances

Conclusions and Next Steps

Discussions over the two-day workshop covered many aspects of distributing hydrogen, from its point of production to its point of use. The Pipeline discussions featured issues with material testing, optimization, and compatibility. The Over-Road sessions looked at the need to lightweight hydrogen trailers and increase the efficiency while reducing the capital cost of liquefaction. Interfacing with codes, standards, and regulating organizations was a pervasive theme throughout the workshop.

Regarding pipelines, cost reduction of well-proven technologies such as steel pipelines is a clear need. This must be balanced with maintaining the long-term safety of the pipelines. Hydrogen pipelines today are typically operated at a fixed pressure and are not subject to many stress cycles. Pipelines in a hydrogen distribution network will be subject to line packing, which will greatly increase the number and severity of stress cycles.

The major challenge to developing pipeline materials that are robust in hydrogen service is understanding how FCG is influenced by material characteristics, microstructure, strength, and weld issues. Welding is one of the larger cost components of installing a pipeline that can be influenced by the R&D community. There is a need for better understanding of FCG mechanisms in the fusion and heat-affected zones of welds, and knowing that, there is a need for the development of better, lower-cost welding technologies.

FRP offers some promise in addressing this issue, but its application to hydrogen service is untested in the field (in contrast to steel pipelines, which have operated for many years without incident). While FRP is not currently addressed by ASME codes, work to enable its inclusion is underway. Builders can deploy FRP in coilable lengths of up to a half-mile. This dramatically reduces the labor associated with joining, although it limits diameters to 6 inches. However, the currently available joining technologies rely on O-rings that may be a source of failure or maintenance. The participants identified the need to develop new joining technologies and deploy a large-scale demonstration of FRP in hydrogen service to build confidence with wary code officials and pipeline designers.

Participants shared the novel idea of developing a machine that could manufacture FRP in situ alongside the trench. The vision is for delivery of polymer, glass fiber, and other raw materials to a machine that would continuously extrude and test the FRP as it creeps alongside the trench. This approach could result in lower installation and joining costs and could support pipelines of larger diameters than currently available coilable pipe (6 inches) because the pipe would not have to be coiled on a truck. Such a development could be supported by the shale gas boom for natural gas pipelines.

Much of the focus in the Over-Road sessions related to developing lighter-weight materials and trailers with which to carry hydrogen. Each kilogram of trailer weight removed is potentially another kilogram of hydrogen that could be carried, generating additional revenue. Crosscutting work with VTO was mentioned as a possible path to address this need. This work would likely start with a scoping study to determine just how much benefit could be gained by light-weighting both liquid and gaseous trailers.

Materials compatibility with hydrogen at high pressures (gaseous) and at cryogenic temperatures (liquid) was mentioned in both the Gaseous Transmission and Distribution and Liquid and Hybrid Transmission and Distribution sessions and is a shared need with the Pipeline groups. Participants in both the Over-Road and Pipeline breakout sessions also noted that the availability of facilities to test materials and systems at relevant conditions is an issue.

Another overarching theme that emerged from the workshop is the need for more analysis capabilities. In the case of pipeline materials, participants discussed a physics-based model that could reasonably predict the effects of hydrogen on FCG in materials without the need for exhaustive and expensive tests. Another modeling need that participants identified is a pressure trade study to determine the optimum delivery pressure for hydrogen to the forecourt to minimize the cost to the system as a whole. This applies to both pipe and road-based transmission and distribution. Participants stressed the importance of addressing transmission and delivery issues with a systems approach that accounts for the inputs, outputs, and stakeholders of the system, and develops optimal solutions that reduce overall cost.

The needs identified across the sessions of this workshop can be placed into four broad categories: (1) materials compatibility; (2) testing and validation; (3) analysis; and (4) codes, standards, and regulations development and engagement. Although the specific characteristics of each of these needs may vary slightly for each application, these are unifying themes across the transmission and distribution pathways.

Appendix A: Abbreviations and Acronyms

Acronym	Definition	Page
API	American Petroleum Institute	4
ASME	American Society of Mechanical Engineers	4
CNJV	Corporate Allocation Services - Navarro Joint Venture	
CO_2	carbon dioxide	3
CSA	Canadian Standards Association	39
DOE	U.S. Department of Energy	1
DOT	U.S. Department of Transportation	14
EU	European Union	15
FCEV	fuel cell electric vehicle	3
FCG	fatigue crack growth	9
FCTO	Fuel Cell Technologies Office	1
FMEA	failure modes and effects analysis	14
FOA	funding opportunity announcement	1
FRP	fiber-reinforced polymer	2
g	gram	13
gge	gallon of gasoline equivalent	1
GHG	greenhouse gas	3
GVW	gross vehicle weight	40
ICEV	internal combustion engine vehicle	3
ISO	International Standards Organization	14
kg	kilogram	2
L	liter	13

Acronym	Definition	Page
MiTi	Mohawk Innovative Technology Inc.	5
MYRD&D	Multi-Year Research, Development, and Demonstration Plan	10
NFPA	National Fire Protection Association	15
NIST	National Institute of Standards and Technology	1
NREL	National Renewable Energy Laboratory	2
ORNL	Oak Ridge National Laboratory	2
PNNL	Pacific Northwest National Laboratory	18
R&D	research and development	2
RD&D	research, development, and deployment	1
SMR	steam methane reforming	3
SNL	Sandia National Laboratories	4
SRNL	Savannah River National Laboratory	4
VTO	Vehicle Technologies Office	17
WTW	well-to-wheels	3

Appendix B: References

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Appendix C: Agenda

Tuesday, February 25, 2014		Room
8:30 am	Check in and security processing	San Juan A/B
9:00 am	Welcome and Introductions, **Chris Ainscough**, DOE/NREL	San Juan A/B
9:20 am	Overview of DOE Delivery Work, **Sara Dillich**, DOE	San Juan A/B
9:50 am	Technoeconomic Analysis, **Amgad Elgowainy**, Argonne National Laboratory.	San Juan A/B
10:50 am	Break	
Pipelines Session - Technical Challenges and RD&D Needs		
11:00 am	Panel Presentations and Discussion Hydrogen Embrittlement in Pipeline Steels, **Andrew Slifka**, National Institute of Standards and Technology Hydrogen Pipeline Materials Compatibility, **Brian Somerday,** Sandia National Laboratories Fiber Reinforced Pipeline Fatigue Testing, **George Rawls,** Savannah River National Laboratory Pipeline Hydrogen Compression **Hooshang Heshmat**, Mohawk Innovative Technology Inc.	San Juan A/B
12:30 pm	Lunch	San Juan A-C
1:15 pm	Breakout Discussions	Breakout 1 – Compression San Juan C Breakout 2 – Materials San Juan A/B
3:15 pm	Break	
3:30 pm	Breakout Reporting	San Juan A/B
4:00 pm	Full group discussion	San Juan A/B
5:00 pm	Adjourn	

Wednesday, February 26, 2014

Over-road Transmission and Distribution Technical Challenges and RD&D Needs

8:00 am	Assemble	San Juan A/B
8:10 am	Panel Presentations and Discussion Fiber Bulk Gaseous Carriers, **Don Baldwin**, Hexagon Lincoln Cryocompressed Hydrogen Storage and Liquid Transmission and Distribution, **Jacob Leachman**, Washington State University Terminal Operations for Tube Trailer and Liquid Tanker Filling, **Satish Tamhankar**, Linde Liquefaction, **Al Burgunder**, Praxair	San Juan A/B
9:40 am	Break	
9:50 am	Breakout Discussions	Breakout 1 – Gaseous A/B San Juan Breakout 2 – Liquid Carriers, Cryo-compressed, liquid. C San Juan
11:50 pm	Lunch	
12:30 pm	Breakout Reporting	San Juan A/B
1:00 pm	Full Group Discussion	San Juan A/B
2:00 pm	Adjourn	

Appendix D: Voting Results

Table 14. Pipeline Compression Internal/External Challenges Brainstorming and Voting

Internal

- Increased fuel density (1)
- How to fill multiple trailers. One compressor vs. multiple compressors (1)

Compressors

- Robust, low-maintenance machine (7) (1)
- Design for maintenance (1) (1)
- High-efficiency compressors and need to lower Opex (5)
- Lower capital costs (1)
- Contamination-free compressors (3)
- High-reliability compressors (3)
- High-pressure, high-throughput hydrogen compression in a single step (2)
- Facility requirements, validation of multistage compressors, technology comparison (1)
- Qualify lower-cost structural materials to relevant P&T in distribution (1)
- Geologic storage purification w/compression (1)
- Ability to work with negative pressure at inlet (suction)
- Hydrogen property prediction above 600 K & material compatibility

Models

- Simulation of an evolving network of compressors, trucks, pipelines, storage, etc. (2) (2)
- Compression – Better utilize tube trailer inventory through better pressure management tools (3) (1)
    - Timing: Short-mid range
- Determine optimal hydrogen pipeline network pressure—match operating pressure with throughput and compression needs of end users (long-term challenge) (2)

External

- Lack of adequate data and measurement technology for evaluation (1) (1)
- Market barriers for stations—overcome by moving costs and equipment upstream (3)
    - Footprint
    - High risk capital

Table 15. Pipeline Compression RD&D Activities Brainstorming and Voting

Near-Term (2014–2016)

- Develop pressure management algorithms for optimal storage, pressure, and distribution (6) (2)
- Purification, cooling, and compression in a single integrated system (6) (1)
- Develop and validate oil-free, contaminant-free, high-efficiency, high-flow compressor system (2) (1)
- Highly instrumented validation facility to simulate field conditions compressors will see (2) (1)
- Reduce cost of compressor. Investigate three-dimensional printing for manufacturing compressor components (2)
- Oil-free seals for reciprocating compressors (2)
- Develop contaminant-free high-power drive system (1)
- Standardized validation facility and procedure (setpoints, etc.)

Long-Term (2017–2020+)

- Develop pipeline network modeling tools (1) (2)
- Novel, non-mechanical compression systems (3) (1)
- Understand impacts of electric grid and potential for support: (3) (1)
  - Demand response
  - Energy storage
- Compressor design that can do line packing (3) (1)
  - Develop pipeline network modeling tools (1) (2)
  - Use of off-peak power for compression. Intermittent storage (1) (1)
- In situ FRP pipeline production at diameters greater than 6” (3)
- Step-out technology for low Capex and Opex (1)
- Non-electric, waste-energy-driven compressors (1)
- Compact thermal management technology and materials (1)
- Waste (heat) energy recovery (1)
- Hydrogen-grid-based load shedding
- Pressure optimizer across system
- Analyze line packing as a means of reducing overall system costs

Table 16. Pipeline Materials Internal/External Challenges Brainstorming and Voting

- Develop/modify weld technologies to reduce labor costs (5) (2)
- Sealing technology (4) (2)
- Make a case for the installation of FRP demonstration (2) (2)
- Understanding the effect of microstructure on fatigue (1) (2)
- Ignorance of structure-property relationships in hydrogen (5) (1)
- Reliable methods for measuring fatigue properties of welds in the hydrogen gas (2) (1)
- Tackle codes and standards permitting requirements to reduce pipeline thickness (avoid overdesign), reducing material and labor costs (2) (1)
- Identify advanced techniques to study fatigue crack growth behavior (2) (1)
- Get more grads and young engineers on the problem (1) (1)
- Leak detection (post commissioning) (1) (1)
- Determine relationship between steel metallurgy characteristics and measure fatigue properties in hydrogen gas (1) (1)
- Understanding of non-metallic material behavior under high pressure (>1,500 psi); Hydrogen embrittlement mechanisms (1)
- An engineering standard for pipeline materials intended for hydrogen service (5)
- Need a big demonstration program (national) (4)
- Understand type of contaminants from the pipeline material (4)
- Pipeline inspection methods versus failure modes (4)
- Develop high-strength steels that are hydrogen resistive (3)
    - A lot can be learned from other industries, such as Navy shipyards
- Reduction of labor (welding, inspection) (3)
- Find out other hydrogen markets that, when lumped together, can produce demand that justifies pipeline investment (3)
- Develop data from R&D to support the development of less conservative design rules and requirements (3)
- Review pipe production capabilities in support of less conservative rules (2)
- Influence of microstructure on mechanical properties (2)
- Improving joining methods, both to improve quality and reduce cost (2)
- Understand time scale of material failure in real environment (2)
- Reduce the cost of welding by developing or improving welding technologies (2)
- Lack of understanding of material received when one purchases "API" steel (2)
- Hydrogen quality for pipelines (2)
- Influencing pipeline companies and codes to reduce the material (steel) thickness via higher strength and full use of design factors (2)
- Acceptance of FRP for hydrogen pipelines (1)
- Manufacturing technologies to produce better couplings and fittings for non-metallic pipes (1)

Pipeline Materials Internal/External Challenges Brainstorming and Voting

- Education of public and politicians (1)
- Model and predict fatigue crack growth behavior (1)
- Labor cost for pipelines. Specifically joining and inspection, both metals and FRP (1)
- Define the pipeline set pressure, perhaps “2,400 psi.” Currently undefined (1)
- Alternative materials (1)
- Understand the effects of microstructure on fatigue crack growth behavior in air and hydrogen environments (1)
- Convince pipeline designers that less conservative designs are safe (1)
- Identify list of public misconceptions; e.g., fracking
- Ensuring communication through all aspects of the community
- Atmospheric influences on materials
- FRP composite pipes joining
- Model the fatigue crack growth behavior
- Need/desire for vaulting
- Reduce labor cost. Qualify FRPs

Table 17. Pipeline Materials RD&D Activities Brainstorming and Voting

- Develop hydrogen-induced-crack-resistant steels (high strength) to reduce wall thickness and to reduce cost, including welding cost (5) (1)
- Measure fatigue crack growth of commercial steels and steels with systematically varying features in hydrogen gas (3) (1)
- Define the relevant class of microstructures (near term) (6)
- Use advanced techniques to study fatigue behavior (1)
- Structure-property relationships in hydrogen (near term): (1)
    - Hydrogen diffusion in model materials
    - Fatigue crack growth (or other testing) of model materials
- Physics-based model of H_2 effect on base/weld/heat-affected zone (long term) (4)
- Develop material specifications that improve microstructure (3)
- Define role of fatigue crack initiation (S-N curves) (2)
- Creation of models to predict macroscopic response as a function of microstructural hydrogen interactions (long term) (2)
- Model the fatigue properties with respect to microstructures (2)
- Develop accelerated test method (1)
- Research and development on welds and base metals, including microstructure (1)
    - Data → models to reduce testing requirements
- Measure fatigue properties of representative microstructures (1)
- Collect (sample) data from hydrogen pipeline materials currently in use (1)
- Develop a physics-based model to qualify new materials (1)

Pipeline Materials RD&D Activities Brainstorming and Voting

- Effects of microstructure on fatigue cracking of carbon and low-alloy steels
- Comprehensive test program to address fatigue with respect to microstructure
- More data with round-robin comparisons
- Examine (several) individual steels with different structures
- Generate properties database for hydrogen service
- Model and predict the relationship between fatigue properties and microstructure
- Better (tighter) material specifications

Understanding non-metallic material with respect to joint sealing

- Non-metallics: Qualification of non-polyethylene, non-metallics for hydrogen. Qualification of non-metallics in air, ground water/earth, sunlight, and impurities in pipeline hydrogen (2) (1)
- Test unique joints in non-metallic materials (2)
- Spoolable joint R&D (1)
- Select the most likely materials in the short and long terms and test them
- Identify material property issues for non-metallic material
- Compile material list (non-metallic) for joint sealing and identify testing needed

Make the case for FRP adoption/demonstration

- Design and construct FRP demonstration (6) (4)
- Lease section of FRP pipeline and use with hydrogen (2)
- Long-term durability testing of FRP materials in realistic environments (2)
- Show performance in operating installation

Develop lower-cost joining technologies

- Develop welding practices to reduce residual stress and friction stir welding (1) (1)
- Establish reliable methods for measuring fatigue properties of steel welds in hydrogen gas (6)
- Welding is a significant portion of pipeline costs. New inspection techniques needed (4)
- Better inspection and monitoring technologies (1)
- Joining: Alternatives to epoxy bounding and fusing. How do you bond/splice the reinforcement layers (1)
- Develop measurement and modeling of welds and heat-affected zones
- Select joint options and request quotes

Pipeline Materials RD&D Activities Brainstorming and Voting

Resolve the code situation

- Develop methods/procedures for qualifying welds/steel heats for hydrogen pipeline service (7) (2)
- D-FMEA failure mode/effect detection/prevention (2) (2)
- Work with end users to provide models in a form they will use. Educate them on the amount of research that supports models/mitigates risk (3) (1)
- Conduct an accelerated demonstration project on steel and FRP to prove design criteria are safe (X70, 3,000 psi, pressure cycles, minimal design factors, etc.) (2)
- More data with round-robin comparisons
- Relevant data to justify reduction in safety factors. Tort reform to limit liabilities from an incident
- U.S. Department of Transportation adoption of B31.12 code

Table 18. Gaseous Transmission and Distribution Internal/External Challenges Brainstorming and Voting

Codes and Standards **(9)**

- Support of development of 700-bar hardware, product standards, and product testing (internal)
- Codes and standards: Accelerate the process, identify specific issues, and conduct research to address
- Outreach to local authorities to streamline acceptance (e.g., hydrogen behavior on industrial scale in tunnels and bridges)

Regulatory (external) **(4)** **(1)**

- Improve the DOT permit process to facilitate direct acceptance of national codes and standards
- Understand inter-city right-of-way costs and challenges, building on existing infrastructure
- DOT acceptance of 15,000 psi hydrogen tube trailers
- Renewable feed stocks—credits now available in the West (internal)
- Federal mandate to convert water treatment facilities to anaerobic digester for source of “green” CH_4

Compression Hardware (internal) **(7)**

- R&D—hydrogen-compatible electric motors to drive pumps and compressors and reduce the cost
- Energy cost to compress/liquefy hydrogen

Legacy and Maintenance **(1)**

- Legacy and maintenance requirements

Speed of Product Dev. **(2)**

- Transition R&D to product dev. such as hydrogen compressors, etc. **(1)**

Gaseous Transmission and Distribution Internal/External Challenges Brainstorming and Voting

Degradation Mechanisms (11) (4)

- Develop new materials for bulk gaseous carrier (1)
- Model the damage behavior of tube trailers (1)
- Study the damage mechanisms of tube trailers (1)
- No fundamental understanding of potential chemical degradation of polymers due to hydrogen
- Improve understanding of polymer behavior in high-pressure hydrogen. Define the pressure level where this is an issue
- Coupon-level testing of materials in a high-pressure environment (e.g., polymer test method development)
- Understand damage accumulation and failure prediction of composites

Cost of Materials (8) (2)

- Lightweight, low-cost, hydrogen-compatible material for storing hydrogen is not available
- Cost of materials of manufacture
- Lower-cost carbon fiber
- Capex of tube trailers too high

Capital Availability (6) (2)

- Catch-22 situation around supply and demand is a barrier to realization
- Assumptions about who owns equipment; i.e., cascade at hydrogen station
- Make capital available
- Business model for station ownership
- Incomplete data and lack of intimacy from technoeconomic analysis limits use for decision making

Trailer Design and Specs (8) (1)

- Limited max. capacity – highway vehicle weight limit
- Lightweight trailers (materials)
- Light-weighting of tube trailers
- Better understanding of the potential benefits and challenges with GH_2 rail delivery
- Design and build the “cool”-looking delivery vehicle of the future!
- Truck delivery at 700–800 bar—material cost, weight, technology (1)

Safety (external) (5) (1)

- Idiot’s guide—blast radius of hydrogen. Public will ask!
- Define a standard set of accidents for over-road vehicles and pipelines transporting hydrogen
- Safety issues related to storing and delivering hydrogen

Table 19. Gaseous Transmission and Distribution RD&D Activities Brainstorming and Voting

Degradation Mechanisms

- Hydrogen pressure vessel test facility for fatigue, degradation, coordinated with CSA, UL, etc. (5) (2)
- Understand polymer degradation mechanisms related to hydrogen (5) (2)
- Development of cost-effective filtration systems (new ideas) for contaminant-free hydrogen gas (1) (1)
- Material testing of non-metallic materials (academic and literature search) (coordinated through the Society of Automotive Engineers and ASME)—environment exposure, permeability, hydrogen exposure, explosive decompression, etc. (1) (1)
- Develop a test procedure for testing polymers in high-pressure hydrogen with acceptance criteria (1) (1)
- Use advanced techniques to study damage mechanism (1)
- Apply computational materials science/theoretical chemistry to understand potential hydrogen-related degradation in polymers (3)
- In situ monitoring of pressure vessel condition/damage—“dashboard warning light” (3)
- Model and predict damage mechanisms (1)
- Understand the damage mechanisms (1)
- Characterize risk versus pressure based on material degradation

Cost of Materials

- Promote interaction between academic studies and industry to more effectively identify pathways for lower-cost carbon fiber (4)
- Outreach, material testing (government funded)—dangerous testing at national laboratories, relatively safe testing at universities (4)
- Identify and study new lightweight, low-cost materials (3)
- Material and manufacturing technology to reduce the cost (2)

Capital Availability/Systems Thinking

- Model of various supply chain ownership options to understand decision making and financial risk (3) (1)
- R&D into innovative manufacturing processes for system components for hydrogen development (3) (1)
- Make available technoeconomic “tools” that allow users to evaluate input assumption sensitivity (1)
- Optimize cost model to minimize absolute cost of system

Trailer Design and Specs

- Interface with the DOE Vehicle Technologies Office to identify opportunities for lowering weight of tube trailers (5)
- Lightweight trailer engineering study (3)

- Apply automotive light-weighting strategies to trailer light-weighting (2)
- DOE pay for fleet of tube trailers to be deployed in different climatic regions to validate technology and identify areas for further development (1)
- Lightweight “supertrailer” group
- Nationalize GVW and trailer configurations for fuel gases

Safety/Codes and Standards

- Assign specific codes and standards issues to a national laboratory to become the expert for that code (e.g., NREL → NFPA 2 expert) (1) (1)
- Develop consensus industry safety requirements for H_2 transport and pipelines (2)
- Leverage existing quantitative risk assessment models to understand risks associated with high-pressure hydrogen delivery (2)
- Development of a “toolkit” for local authorities would provide information on necessary requirements and calculations (2)
- Outreach to national fire marshal organizations and national building inspection organizations on the status of codes and standards. Reach out to state factory mutual offices in targeted states—CA, HI, MI, CT, MA, NY, NJ, PA, GA, FL, and TX (2)
- Ramp up PNNL first responder training (1)
- Identify where cost can be reduced without compromising safety (1)
- Database of local/state/national/international codes/standards regulations (1)
- Include regulator involvement in codes and standards process (1)
- Develop inspection monitoring technology for tube trailers

Table 20. Liquid and Hybrid Transmission and Distribution Internal/External Challenges Brainstorming and Voting

Internal

- Smaller-scale modular liquefiers (6) (2)
- Materials and process to increase truck payload (3)
- Liquid carriers research and development (6) (1)
- Boil-off recovery (6)
- Low-cost, small-scale, modular liquefier (1)
- Liquefaction efficiency (1)
- Refrigeration efficiency (5)
- Need lightweight transportation (4)
- Find synergies to harness cold capacity (4)
- High-density storage without going to liquid hydrogen temperature or high pressure (3)
- Rail car distribution infrastructure for large plants (2)
- Reducing bleed off during filling, transport, off-loading (1)
- How can hydrogen be effectively made green? (1)
- Excess liquid production capacity (1)
- Liquid carriers simple chemistry
- Capex reduction for smaller plants

External

- Education/training to safely handle liquid hydrogen (5)
- More flexible, easier-to-understand/implement codes and regulations for over-road trucks (1)
- Variable delivery DOT capacity and standards for small deliveries

Table 21. Liquid and Hybrid Transmission and Distribution RD&D Activities Brainstorming and Voting

Near-Term (2014–2016)

- Design/conduct testing and collect data to inform codes/standards. Reduce setback distances (6) (3)
- Discover and qualify low-cost, lightweight, structural alloys (low temperature effects) (6) (2)
- Design high-efficiency compressors/expanders. Improve liquefaction efficiency (4) (2)
- Understand physical effects of cryo-cycling on polymers (for composites) and extend lifetime (4) (1)
- Develop novel, low-cost, and volume insulation systems (3) (1)
- Develop cost-effective method for boil-off recovery (7)
- Heat exchanger designs for loading and off-loading cryogenic. Compressed gas/liquid (6)
- Develop low-cost, high-pressure cryo-storage tank (4)
- High entropy—change cryogenic materials for refrigerators (3)
- Computational screening of liquid carrier candidate molecules (3)
- Develop low-cost materials of construction for liquid hydrogen plants (2)
- Get DOT to work with code bodies to review liquid hydrogen regulations (1)
- Develop low-cost cryo-compressor to recover boil-off losses

Long-Term (2017–2020+)

- Develop liquid carrier chemistry of viable logistics (1)
- Develop large-scale cold sink for use in large-scale cooling applications

Appendix E: Participant List

Participants (Name – Organization)	
Andrew Bermingham – Montreux Energy	Christopher Moen – SNL
Nico Bouwkamp – California Fuel Cell Partnership	Scott Morgan – Energetics
Al Burgunder – Praxair	Bob Oesterreich – Air Liquide
Bill Collins – Consultant	George Parks – Phillips66 (Consultant)
Sara Dillich – DOE FCTO	Steven Pawel – ORNL
Huyen Dinh – NREL	David Peterson – DOE FCTO
Elizabeth Drexler – NIST	Katie Randolph – DOE FCTO
Amgad Elgowainy – Argonne National Laboratory	George Rawls – SRNL
Mitch Ewan – Hawaii Natural Energy Institute	Robert Remick – Consultant
James Fekete – NIST	Gita Sheth – ASME
Zhili Feng – ORNL	Andrew Slifka – NIST
Louis Hayden – ASME Consultant	Brian Somerday – SNL
Hooshang Heshmat – MiTi	Erika Sutherland – DOE FCTO
Charles James – DOE FCTO	Amit Talapatra – Energetics
Jacob Leachman – Washington State University	Satish Tamhankar – Linde LLC
Peter Liaw – University of Tennessee	Dylan Waugh – Energetics
Marc Melaina – NREL	Brian Weeks – Gas Technology Institute

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July 2014