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Liquid Hydrogen Technologies

2022 Workshop Summary Report

Hydrogen & Fuel Cell Technologies Office

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Preface

Prepared by: U.S. Department of Energy/Office of Energy Efficiency and Renewable Energy/Hydrogen and Fuel Cell Technologies Office in coordination with the National Aeronautics and Space Administration.

Acknowledgments

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- Ned Stetson – U.S. Department of Energy, Hydrogen and Fuel Cell Technologies Office
- Michael Meyer –National Aeronautics and Space Administration
- Oriane Farges – Air Liquide
- Raja Amirthalingam – Plug Power
- Amgad Elgowainy – Argonne National Laboratory
- Jacob Leachman – Washington State University
- Jo-Tsu Liao – Shell International Exploration and Production
- Andy Jacobson – CB&I Storage Solutions
- Ian Neeser – Chart Industries
- Rajesh Ahluwalia – Argonne National Laboratory
- Gladys Anyenya – Wabtec Corporation
- Ravi Subramanian – Gardner Cryogenics Department of Air Products & Chemicals
- Angela Krenn – National Aeronautics and Space Administration
- Aaron Harris – The Hydrogen Safety Panel
- Joe Ronevich – Sandia National Laboratories

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<u>Organizing Team</u>: Ned Stetson, HFTO; Michael Meyer, NASA; Mark Richards, HFTO; Neha Rustagi, HFTO; Jeffrey Feller, NASA; Adam Swanger, NASA; Peter Bradley, NIST; Asha-Dee Celestine, HFTO.

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Nomenclature or List of Acronyms

AIAA	American Institute of Aeronautics and Astronautics
AIChE	American Institute of Chemical Engineers
ANL	Argonne National Laboratory
ANSI	American National Standards Institute
ASME	American Society of Mechanical Engineers
BEV	Battery electric vehicle
BIL	Bipartisan Infrastructure Law
CAPEX	Capital expenditure
DOE	U.S. Department of Energy
EERE	Office of Energy Efficiency and Renewable Energy
EU	European Union
FCEV	Fuel cell electric vehicle
GREET	The Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies Model
HD	Heavy-duty
HDSAM	Hydrogen Delivery Scenario Analysis Model
HFTO	Hydrogen and Fuel Cell Technologies Office
IRAS	Integrated refrigeration and storage
ISO	International Organization for Standardization
LNG	Liquefied natural gas
MD	Medium-duty
MLVI	Multilayer vacuum insulation
MRHT	Maximum rated holding time
NASA	National Aeronautics and Space Administration
NER	Normal evaporation rate
NFPA	National Fire Protection Association
NIST	National Institute of Standards and Technology
OPEX	Operational expenses
OSHA	Occupational Safety and Health Administration
PPE	Personal protective equipment
R&D	Research and development

RD&D	Research, development, and demonstration
SCS	Safety codes and standards
SEC	Specific energy consumption
SOA	State-of-the-art
STMD	Space Technology Mission Directorate
TDT	Technical Discipline Team
tpd	Tonnes per day

Executive Summary

On February 22-23, 2022, the U.S. Department of Energy's (DOE's) Hydrogen and Fuel Cell Technologies Office (HFTO), within the Office of Energy Efficiency and Renewable Energy (EERE), and the National Aeronautics and Space Administration (NASA) Cryogenics Technical Discipline Team jointly held a virtual workshop focused on liquid hydrogen technologies. The primary workshop objective was to address development needs for low-cost, energy-efficient, scalable, and safe liquid hydrogen generation, dispensing, and end use. The workshop included discussion of state-of-the-art technologies, research, development, and demonstration (RD&D) gaps, innovative concepts, safety, and analysis activities.

In total, 625 attendees participated in the two-day workshop, with presentations, panel discussions, and breakout sessions on each day. The first day was focused on liquefaction and began with opening remarks from HFTO and NASA, followed by presentations on the current state-of-the-art (SOA) for hydrogen liquefaction (Air Liquide), lessons learned for liquid hydrogen (Plug Power), innovative approaches to improving scalability and efficiency (Argonne National Laboratory (ANL), Washington State University), and liquid hydrogen in emerging large-scale markets (Shell). Following the presentations on day one, speakers participated in a panel discussion and Q&A session. Attendees then split into three breakout sessions: Hydrogen Liquefaction, Liquid Hydrogen Delivery and Distribution, and Emerging Applications of Liquid Hydrogen.

The second day was focused on liquid hydrogen storage and handling, and featured presentations on the current status of technologies for bulk liquid hydrogen storage (CB&I Storage Solutions, Chart Industries), liquid hydrogen for medium- and heavy-duty vehicles (ANL, Wabtec Corporation), liquid hydrogen transfer and delivery practices (Air Products, NASA-Kennedy Space Center), safety requirements (Hydrogen Safety Panel), and materials performance at liquid hydrogen temperatures (Sandia National Laboratories). Day two's breakout sessions were split into Liquid Hydrogen Handling and Liquid Hydrogen Storage groups. Following breakout sessions on each day, moderators delivered a brief report-out on the key discussion areas covered in their breakout sessions.

Key outcomes of the workshop were open and productive discussions by participants from NASA, DOE, industry, and academia about the SOA of current technologies, research and development (R&D) needs, and outlining the gaps in codes and standards for safe use. This also included discussion of how federal funding can be used to boost component development for the liquid hydrogen ecosystem, and how standards could be further developed and created to be consistent internationally, as well as domestically.

Key recommendations included increased R&D efforts to improve hydrogen liquefaction technologies, as well as storage and component materials and designs. Updated codes and standards associated with liquid hydrogen delivery, handling, and storage was also highlighted as an urgent focus area. Continued collaboration between DOE and NASA, as well as other federal and state entities, was highly recommended.

The following high-level summary provides some background related to liquid hydrogen technologies, including manufacturers' and end-users' perspectives, summaries of discussions, feedback, and conclusions from the workshop. This report, along with the detailed agenda and presentation materials can be found at: https://www.energy.gov/eere/fuelcells/liquid-hydrogen-technologies-workshop. Information and outcomes from other HFTO hosted workshops can also be found on the HFTO website at https://www.energy.gov/eere/fuelcells/workshop-and-meeting-proceedings.

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1 Introduction

As part of the U.S. Department of Energy (DOE) Hydrogen Program, a primary objective of the Office of Energy Efficiency and Renewable Energy's (EERE's) Hydrogen and Fuel Cell Technologies Office (HFTO) is advancing the current state of hydrogen-based technologies. The National Aeronautics and Space Administration (NASA) has extensive experience with liquid hydrogen. Among other activities, HFTO plans and supports workshops that bring together members of the research community from academia, industry, and government to identify and discuss key aspects of individual components within the overall vision for wide-scale use of hydrogen-based technologies, a concept referred to as H2@Scale. One such aspect of the larger system is storage, both prior to the end use and as an intermediate means of transport to an ultimate destination. In order to address the current status of liquid hydrogen technologies, identify barriers to further development and strategies for overcoming them, and guide directions and targets for future work, HFTO and NASA jointly hosted the Liquid Hydrogen Technologies Virtual Workshop on February 22-23, 2022. The workshop included plenary sessions, expert panel presentations, and breakout sessions. This report summarizes the outcomes and achievements of the workshop that will provide guidance to HFTO and NASA in development of future activities on liquid hydrogen.

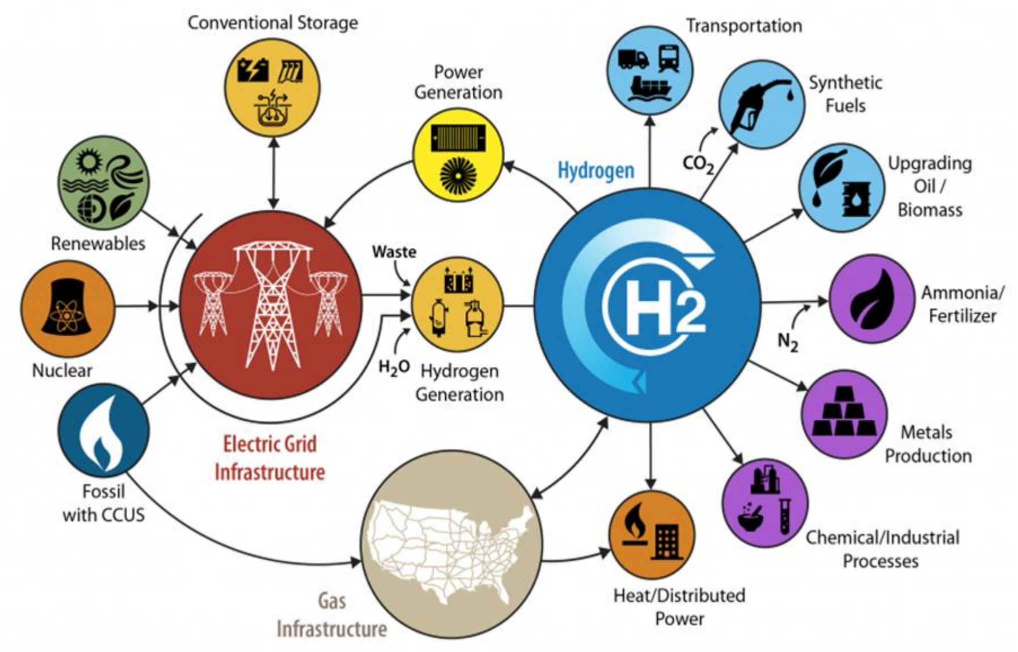

Figure 1. H2@Scale vision to enable decarbonization across multiple sectors of the economy.

1.1 Background on Liquid Hydrogen

Liquefied hydrogen has a much higher density than compressed gaseous hydrogen; 71 kg/m^3 for liquid hydrogen versus 18 kg/m^3 at 250 bar and 40 kg/m^3 at 700 bar for gaseous hydrogen. This increased density facilitates greater storage capacity within a given volume, allowing for longer driving ranges and larger payloads. The higher density of liquid hydrogen storage also means that refueling rates are faster compared to compressed hydrogen gas. Also, the lower storage pressures mean very strong and/or heavy tanks, typically used for compressed storage, are not required. Potential applications of liquid hydrogen include its use onboard heavy-duty vehicles and marine vessels, at vehicle fueling stations, and within the aerospace industry.

For decades, NASA has relied on hydrogen as rocket fuel and has developed extensive experience in safe and effective handling of liquid hydrogen. However, the hardware and processes for liquid hydrogen has not changed much since the 1960's. Inefficiencies have led to major losses of liquid hydrogen purchased during the space shuttle program. Liquid hydrogen is a cryogen that poses technical challenges because of its liquefaction and storage at very low temperatures. Typically, hydrogen is transported and delivered as a liquid when high-volume transport is needed in the absence of pipelines. To liquefy hydrogen, gaseous hydrogen must be cooled to cryogenic temperatures of 20 K (-253°C) or below through a complex, multistep process. Using today's technology, liquefaction consumes an equivalent of more than 30% of the energy content of the liquefied hydrogen and is expensive.

Once hydrogen is liquefied it can be stored at the liquefaction plant in large insulated tanks, known as dewars. Some amount of the stored liquid hydrogen will typically be lost through evaporation, or “boil-off”, especially when using small tanks with large surface-to-volume ratios. Boil-off losses due to heat transfer from the environment are a major concern for long-term storage and can be as much as 5% per day. Mitigation of these losses requires specialized tank designs, incorporating heat exchangers and insulation systems, which can all add to the total system cost. Research to improve liquefaction technology, liquid hydrogen storage, as well as improved economies of scale, could help lower the energy required and the total cost.

Previously, HFTO in collaboration with NASA, hosted the virtual Advances in Liquid Hydrogen Storage Workshop on August 18, 2021. This workshop covered DOE’s liquid hydrogen related initiatives and outlook, and introduced recent advancements in large-scale liquid hydrogen storage technologies and projects at NASA, including integration of active refrigeration systems, high performance insulation, and the construction of a next-generation 1.25 million gallon liquid hydrogen storage sphere at the Kennedy Space Center. Attendees included U.S. and international stakeholders from industry, academia, and government agencies.

2 Presentations

The Liquid Hydrogen Technologies workshop began with opening remarks and an overview of the DOE Hydrogen Program from Ned Stetson, Hydrogen Technologies Program Manager, HFTO. He discussed the Program's goals and priorities on low-cost, efficient, and safe hydrogen production, delivery, and storage. He also outlined the Hydrogen Energy Earthshot Initiative and discussed the hydrogen provisions in the Bipartisan Infrastructure Law (BIL) that includes $9.5B for clean hydrogen technologies and the development of a National Hydrogen Strategy and Roadmap. He concluded with the top areas to identify needs for technology development and key concerns to discuss, which included hydrogen liquefaction, large-scale markets, applications for liquid hydrogen, and infrastructure for liquid hydrogen storage and handling.

Michael Meyer, NASA Cryogenics Technical Discipline Team Leader, gave an overview of NASA's organizational structure and shared their current developments and applications for liquid hydrogen. He began by outlining the cryogenic activity areas at NASA and the overall scope of the cryogenics technical discipline team (TDT), which includes thermal conditioning for sensors, instruments, and high efficiency electronic motors; in-space propellant storage and utilization; launch vehicle propellant; and ground testing and operations. He mentioned that hydrogen has been used for decades by NASA, and that liquid hydrogen in aeronautics even predates NASA, such as at the NACA Lewis Field (now NASA-Glenn Research Center). Currently, NASA is developing launch and ground testing systems employing new liquid hydrogen storage vessels, including a liquid hydrogen storage sphere with 4,732 m^3 (1.25M gallons) capacity. The space launch system requires 1,770 m^3 of liquid hydrogen and 995 m^3 of liquid oxygen, and the first launch is set to take place in the Spring of 2022. He discussed how the crewed Mars mission orbital mechanics generally require a 2-3 year roundtrip, which involves a very large amount of propulsive energy that will need a reactor, liquid hydrogen pump, hydrogen heat exchanger, converging expanding nozzle to generate thrust, liquid hydrogen storage, large habitat for crew, and in-space assembly. He finished with presenting some of NASA's strategic/key facilities and assets in cryogenics that encompass a wide range of sizes, types, and capabilities.

The following sections summarize the presentation highlights and Q&A discussion from the workshop sessions. Speaker bios and copies of their presentations can be found on the Workshop Proceedings webpage: https://www.energy.gov/eere/fuelcells/liquid-hydrogen-technologies-workshop

An overview of the presentation speakers and topics is presented in Table 1.

Table 1. Workshop speakers, affiliations, and presentation titles.

Day One		
Speaker	**Affiliation**	**Presentation Title**
Oriane Farges	Air Liquide	State-of-the-Art of Hydrogen Liquefaction
Raja Amirthalingam	Plug Power	Experiences and Lessons Learned with Liquid Hydrogen
Amgad Elgowainy	Argonne National Laboratory	Opportunities and Challenges of Liquid Hydrogen Supply Chain
Jacob Leachman	Washington State University	Hydrogen: Novel Liquefiers for Novel Molecules
Jo-Tsu Liao	Shell International	Liquid Hydrogen in Emerging Large-Scale Markets
Day Two		
Andy Jacobson	CB&I Storage Solutions	Liquid Hydrogen Storage Technologies

Ian Neeser	Chart Industries	Liquid Hydrogen Bulk Storage Introduction
Rajesh Ahluwalia	Argonne National Laboratory	Onboard Liquid Hydrogen Storage for Long Haul Trucks
Gladys Anyenya	Wabtec Corporation	Liquid Hydrogen for Medium- and Heavy-Duty Vehicles - Wabtec Overview
Ravi Subramanian	Gardner Cryogenics Department of Air Products	Current Practices to Transfer and Deliver Liquid Hydrogen
Angela Krenn	NASA- Kennedy Space Center	NASA Perspectives on Transfer and Delivery of Liquid Hydrogen
Aaron Harris	Hydrogen Safety Panel	Safety Requirements for Liquid Hydrogen Fueling
Joe Ronevich	Sandia National Laboratories	Materials Performance at Liquid Hydrogen Temperatures

2.1 Liquefaction: Current Status and RD&D Needs

2.1.1 Current State-of-the-Art of Hydrogen Liquefaction

Oriane Farges, Air Liquide
Air Liquide is a world leader in gases, technologies, and services for industry and healthcare. Oriane Farges began by highlighting important properties of hydrogen, including flame visibility and temperature, flammability ranges, and explosive limits, as a reminder of the importance of safety. Personal protective equipment (PPE) and hydrogen detection are important for any hydrogen use case. Air Liquide is involved in all parts of the hydrogen value chain, from production to transportation and fueling stations, with liquefaction falling within condition and storage stage.

Air Liquide has many developments in deep cryogenics (approximately -253°C and below) that are on the colder spectrum, which include helium and hydrogen. For deep cryogenics of hydrogen and helium, Air Liquide has over 20 operating units in the world, with a few more under construction. They develop proprietary purification and liquefaction processes that include solutions for efficient liquid hydrogen boil-off management, and in house proprietary equipment like hydrogen turbines. They also design and manufacture their own cold boxes. Their expertise in cryogenics stems from their ability to design and manufacture their own projects and plants.

For Air Liquide's hydrogen liquefaction plants, the state-of-the-art is currently in the medium range capacity of 30-50 tonnes per day (tpd). Depending on the size, smaller to medium capacity (1-50 tpd) liquefaction plants tend to be more CAPEX oriented, whereas larger plants (> 50 tpd) are more OPEX oriented. Overall efficiency of the hydrogen liquefaction is also affected by plant capacity, with 1-10 tpd capacity liquefaction plants having a >12 kWh/kg efficiency, while plants with capacity greater than 100 tpd have about 6-7 kWh/kg efficiency. Therefore, the technology and components for hydrogen liquefaction can vary depending on the size of the plant. Hydrogen liquefaction plants have a precooling and cold purification process before the liquefaction process. According to Oriane Farges, one of the bottlenecks for expansion of hydrogen liquefaction plants capacity is machinery, which includes compressors. It also requires improvement of insulation technology, and improvements in energy efficiency and recovery.

During the Q&A session, Oriane Farges was asked to discuss the overall efficiency for liquefaction, which she explained is heavily affected by the hydrogen refrigeration cycle. When it comes to scaling down for hydrogen liquefaction, she stated that it is quite developed, and that scaling up is more of a concern. Overall, efficiency is still better for larger plants (6-7 kWh/kg) than for smaller plants (12-15 kWh/kg).

Q&A

Question: What steps are most important to focus on for improving overall efficiency for liquefaction of liquid hydrogen?
Answer: I would say that over 60% of the efficiency is in the hydrogen refrigeration cycle, so this should be the focus.

Question: Looking at scaling up (1000 tpd) and scaling down, what would be the potential of scaling down?
Answer: For scaling down, it is not much of a concern. We already have standard units of 1-2 tpd that are using the helium cycle. Scale down is not a concern. What we are trying to focus on is in scaling up.

Question: How does the efficiency of smaller plants compare to larger plants?
Answer: Typically, for plants of < 5 tpd, the efficiency is 12-15 kWh/kg. For plants with > 100 tpd, it's 6-7 kWh/kg.

2.1.2 Experiences and Lessons Learned with Liquid Hydrogen

Raja Amirthalingam, Plug Power
Plug Power, where Dr. Amirthalingam is a Principal R&D Engineer, is involved in liquid hydrogen handling from production to storage, pumping, and distribution. Important aspects for liquid hydrogen production are selection of precooling and refrigeration cycles, hydrogen purification, catalyst loading in heat exchangers, and vendor selection. For precooling, having impurities can lead to many problems, so it is important to have proper tracing of impurities in transfer lines. Plug Power also stressed the importance of having a good relationship with vendors to improve the development of cost-effective equipment for liquefaction.

Considerations for liquid hydrogen storage include the type of vessel (vertical or horizontal cylindrical tanks, or spheres) and insulating materials (multilayer vacuum jacketed or glass beads), and materials of construction (316L vs 304L steel). Glass beads can be used for cylindrical tanks, which can improve performance by ~40%, but this might not be significant when storing liquid hydrogen for the long term. For continuous use of liquid hydrogen, most of the system losses are outside the tank and can occur due to normal evaporation rate (NER), during pumping operations, with transfer line heat loss, or through blowdown losses. Pump cooling losses are also relevant, and it is necessary to understand when and why these occur as this may happen with valve losses associated with cooling or leaking. Plug Power also focuses on the development of manufacturing liquid hydrogen transportation tanks with emphasis on improving payload, NER, and maximum rated holding time (MRHT).

The Q&A portion of Raja Amirthalingam's talk was quite extensive. Some of the questions were geared towards losses and knowing where most losses occur in the liquid hydrogen value chain. To this, Dr. Amirthalingam responded that major losses are mostly on the transfer lines and pump. Methods to eliminate these losses are still under development, but one major objective is to potentially sub-cool liquid hydrogen. The process of purging lines is done by using nitrogen. Other points discussed were that the driver for increasing to 700 bar is mainly for use in larger vehicles, and that ASME codes are used for all of Plug Power's stationary tanks and equipment. Boil-off is mitigated through recovery, and one of Dr. Amirthalingam's major recommendations was that DOE could focus on liquid hydrogen equipment, which would include cryogenic pumps.

Q&A

Question: What would be the system loss for the whole system?
Answer: In weight percent, I'm not so sure. You waste liquid hydrogen when you don't have a methodology to recirculate it back, which you could save. Though, if you don't have a recirculation method at the end-user site the losses could be as much as 30%.

Question: Are most of the losses for you, and your end users, on the transfers and outside the storage tank?

Answer: Yes. It's all over the lines to the pumps, also in the transfer lines. It's mostly on the transfer lines and the pump.

Question: Are you investigating how to improve the transfers to eliminate the losses?
Answer: There's a lot of R&D work being done by Plug Power to reduce the losses. One of the major objectives is to sub-cool the liquid hydrogen. How to sub-cool it is the real problem. Plug Power has research facilities, including one in Rochester, to try to develop new techniques and test them onsite and in real fueling stations.

Question: How do you purge the lines? How do you purge the systems you use on a medium like helium?
Answer: Normally, in operations when the system is commissioned, the media used for purging would be nitrogen.

Question: What's the driver for moving from 350 bar to 700 bar?
Answer: Mainly for larger vehicles, like trucks. More hydrogen needs to be loaded, so it requires 700 bar for filling.

Question: For your tanks and equipment, what codes do you use? Is it ASME for all stationary systems?
Answer: It is ASME. Yes, you're right.

Question: For the ortho to para conversion, I am assuming you're using a paramagnetic ion catalyst. Do you see any potential for improvements for catalysts?
Answer: Currently, there is really only one method used for ortho to para conversion, but what we can optimize is the location of the catalyst. That catalyst is either in the heat exchanger or in a separate vessel. There are a lot of simulations that show the advantages to have it in the heat exchanger. It could also be indirectly used to optimize the utilization of liquid hydrogen itself, so we have a lot of research into those aspects.

Question: What's the typical time of transfer of hydrogen from the delivery trailer to the local hydrogen storage tank?
Answer: It depends on the pressure. How much pressure is in the tank and in the downstream tank, which you can adjust, but usually it takes a couple hours.

Question: What sort of guidance can you provide on improvements to the liquid hydrogen pumps and the transfers?
Answer: Essentially, it is pump manufacturing, and it's a major topic these days. There are a lot of manufacturers coming up with good ideas that are being tested. However, the major issue is that in the middle of construction how do you measure the system? You also want to do what you can to reduce the friction losses. I feel like the progress that's going on with different vendors will result in good pumps.

Question: For insulation in liquid hydrogen tanks, a lot of the standard dewars use multilayer vacuum insulation (MLVI), whereas circular (larger) tanks use materials like glass beads, perlite, etc. Can you elaborate more on insulation, and at which point would it make sense to switch from MLVI to glass beads, or other types of materials?
Answer: Boil-off losses are common, so whatever MLVI you use, you can increase layers to improve it. But the major issue is holding the vacuum, so that's an issue to consider when choosing a material for insulation. For glass beads, according to vendors, losses are reduced by 40%. So, if you want to store hydrogen for a long time, 40% savings is big. However, when there's continuous use of the tank for fueling, the losses in the transfer lines are huge compared to those from tank, so the 40% improvement becomes insignificant. Still, glass beads are new, so we're still investigating.

Question: Do you do any boil-off recovery?
Answer: Yes, for our production plants, all the boil-off is recovered and goes back to the liquefaction plant.

Question: How about in customer sites (e.g., fueling stations)?
Answer: In liquid hydrogen stations, our work is still ongoing, but we're ultimately focusing on methods to sub-cool it.

Question: For fueling vehicles (e.g., forklift and trucks), what are the nozzle standards that you use?
Answer: I don't have the info for that.

Question: Any recommendations on what areas of focus for DOE to improve both technologies and processes?
Answer: Developing a good liquid hydrogen pump. Any energy spent on developing pumps and compressors is good. For low-flow pumps and compressors, leakage and loss are still issues. Also, low-suction pressure compressors are still developing, so funding this technology would significantly reduce the overall system cost. Also, insulation. I see people talking about using prefabricated panels to reduce losses. So, I wonder if the development of these panels is being supported, so we can use and test them to see the value of their application.

2.1.3 Innovative Approaches to Improve Scalability and Efficiency

Amgad Elgowainy, Argonne National Laboratory
Argonne National Laboratory (ANL) is a science and engineering national research laboratory that is operated by The University of Chicago and DOE. Dr. Amgad Elgowainy leads the Electrification and Infrastructure Group at ANL. As part of the work he leads at ANL, his team works with modeling software for analysis on improving the scalability and efficiency of hydrogen production and delivery, specifically looking into the techno-economics and environmental implications of hydrogen. The analytical tools used are developed by ANL and include the hydrogen delivery scenario analysis model (HDSAM) and the greenhouse gasses, regulated emissions, and energy use in technologies model (GREET).

HDSAM uses data to deliver pathways, component technologies, and costs of interest to government agencies and industry stakeholders. Using HDSAM, Amgad Elgowainy went through the cost contributions that would affect hydrogen liquefaction, which includes cost contributions of pipeline delivery, tube-trailer delivery, and liquid hydrogen delivery. The cost of hydrogen delivery and refueling for light-duty fuel cell electric vehicles (FCEVs) was shown to be strongly driven by onboard requirements. Overall, compression and pumping dominated refueling cost for high pressure tanks. The environmental implication from GREET considers hydrogen production mainly from natural gas steam reformation and gives carbon dioxide (CO_2) emissions from Class 6 MD trucks, and Class 8 day-cab and Class 8 sleeper-cab HD trucks. For liquefaction, the life-cycle criteria of air pollutant emissions can be significant.

From HDSAM and GREET, some of the information includes liquefier CAPEX and specific energy consumption (SEC), which suggest that SEC can potentially be as low as 6 kWh/kg. However, to get to those low values of SEC, having a substantial amount of gaseous hydrogen delivered (~120 tpd) and amounts of liquefying hydrogen (~130 tpd) is important. Similarly, greenhouse emissions could be lower at higher amounts of hydrogen delivery and hydrogen liquefaction.

Dr. Elgowainy was asked questions regarding hydrogen pipelines being built without midline compression or pumping, which he responded to by stating that pumping might increase offload times with additional energy for boil-off and reliquefaction. When it came to discuss which of the four areas could be the most optimal to improve efficiency, Dr. Elgowainy answered that this area is regarding fundamental research, which is often done in academia instead of at the national lab level.

Q&A

Question: Can gaseous hydrogen transmission pipelines be built without midline compression? Or liquid hydrogen lines without pumping?
Answer: Pumping might increase offload times with additional energy for boil-off gas re-liquefaction.

Question: You mentioned three new concepts and four areas where the efficiency could be improved. Where would you invest?
Answer: It needs to be fundamental research, which is not funded by industry, answering questions such as, “can we sieve hydrogen through a nanotube?” and “can we make a diode that functions at cold temperatures?”

Jacob Leachman, Washington State University
Dr. Jacob Leachman is an associate professor at Washington State University where his group is a major player in developing novel liquefiers for hydrogen applications. They look at how to improve hydrogen liquefaction efficiencies by understanding how to use the fundamentals of hydrogen and refrigeration. The fundamentals of hydrogen include the novel hydrogen physics of quantum swelling and nuclear spin isomers and understanding ideal-gas property effects. Hydrogen liquefier efficiencies could be improved by looking at the fundamentals of refrigeration and understanding how it could be changed. For refrigeration, there are only four ways to change its thermodynamic cycle to optimize hydrogen liquefaction, this includes changing the input exergy, heat transfer through entropy, work transfer (enthalpy), and output exergy. Changing the input of liquefaction consists of increasing the exergy of the hydrogen flowing into the cycle via electrochemical compression, radiative cooling, or ortho-para separation. To improve entropy, new materials are being developed to allow for changes in entropy at constant temperature, while the ways to change enthalpy are done via work transfer usually mechanical or electrical work. Finally, output changes could consist of cold hydrogen with 0% ortho conversion at 1.5 atm.

Some of the emerging concepts Washington State University is working on include quantum plumbing, ortho-para catalyzed hydrogen regeneration, and cryogenic hydrogen diodes. For quantum plumbing, orthohydrogen preferentially absorbs on surfaces and can be separated creating opportunities for quantum sieving or tunneling assisted catalysis. Ortho-para hydrogen conversion could counteract stack by-pass by creating localized exotherms. Also, sound speed differences between ortho and para could promote para-migration towards cold. Lastly, cryogenic hydrogen diodes could be used and tuned to 15 meV, which turns ortho-para conversion heat into useful electricity and reduces the amount of heat lift required from any cycle. Overall, hydrogen has unique quantum opportunities for liquefiers. Several quantum concepts have the potential to advance nearly all liquid hydrogen cycles, but more fundamental researcher is still needed.

During the Q&A, Dr. Leachman was asked about liquefiers, operational challenges of scaling up, and at what point could the fundamental research in hydrogen and refrigeration be near commercialization. For determining the advantages of smaller vs. larger liquefiers, he stated that it is on a case-by-case basis. Operational challenges are usually regarding transfer losses and boil-off with large tanks, which might be mitigated by swapping tanks instead of re-filling them.

Q&A

Question: What is the advantage of having a larger number of smaller liquefiers as opposed to less large ones?
Answer 1: Renewable energy is inherently distributed, and liquefiers should match that distributed model.
Answer 2: We’ll need to figure out cryo-compressors which will be necessary for pipelines, more of which would be needed for fewer liquefiers.

Question: What are the operational challenges with scale-up, infrastructure, hazards, and safety management?
Answer 1: Operational issues include achieving transfers quickly, minimizing losses.
Answer 2: Regarding transfer losses, there are large boil-offs with large tanks. What if you swap tankers instead of re-filling tanks?

Question: What is the time to reach pre-commercial scale?
Answer: It’s challenging to determine due to paperwork and studies. Having the right team in the right place is important. Fundamental programs are needed rather than applied programs.

2.1.4 Liquid Hydrogen in Emerging Large-Scale Markets

Jo-Tsu Liao, Shell International
Jo-Tsu Liao is a Senior Engineer at Shell International, Inc. Shell has had a lot of experience in the development of hydrogen in large-scale markets. Shell works on developing and integrating technologies of the liquid hydrogen value chain to address the cost and scale challenges associated with hydrogen production, storage, transportation, distribution, and energy system integration. Shell's viewpoint on the emergence of international distribution is that they are driven by cost differential for clean hydrogen production, which includes renewable resources, existing infrastructure, natural gas and carbon storage availability, and land-use constraints. In the European Union (EU), Korea, Japan, and parts of China, the demand for hydrogen may be met more effectively by importing rather than local production. This shows how vital an expanding network of hydrogen trade routes, plans, and agreements could be. For emerging demands for hydrogen, it is expected to reach $50B by 2027, and the global hydrogen-powered transport market is expected to grow from $2B in 2020 to $20B in 2025.

For liquid hydrogen projects, Shell aims to further develop an integrated supply chain. They have the first demonstration of a commercial scale hydrogen storage tank design for international trade applications with the objective to develop a first-of-its-kind affordable large-scale liquid hydrogen storage tank for international import and export applications. The project aims to design a large-scale tank that can be used in ranges between 20,000 m^3 and 100,000 m^3. Some of the key success criteria of the design are boil-off rates of 0.01-0.1% per day, CAPEX below 150% of comparable LNG storage vessels, and meeting the requirements of safety and integrity regulatory bodies. Their end-of-project deliverables are to complete an affordable large-scale (100,000 m^3) liquid hydrogen storage tank design, build liquid hydrogen-based cryogenic testing apparatus to measure insulation thermal properties down to 20 K, and provide a technology demonstration through construction, start-up, and testing of a prototype vessel, which would ultimately advance liquid hydrogen storage tank technology.

Q&A

Question: Regarding transportation growth, what markets will be in the breakdown?
Answer: For all growth between now and 2027, the heavy-duty (HD) trucking sector is being considered. Marine is also there, but there is slower growth and it's not foreseen by 2027.

Question: What kind of fuel for maritime, ammonia?
Answer: They are watching that market, but safety is a concern.

Question: What is the cost analysis of ammonia to convert to hydrogen?
Answer: If the requirement doesn't require pure hydrogen and direct injection, then it could be less cost prohibitive. Pure hydrogen will come with a cost.

2.1.5 Hydrogen Liquefaction Panel Discussion and Q&A

Speakers from the first day's Liquefaction session participated in a panel discussion and Q&A, answering questions posed by the session moderator and workshop attendees.

Question: How to address intermittency issues with renewables?
Answer 1: We need energy storage for hydrogen, ammonia, or others.
Answer 2: The sizing of storage, downstream electrolyzers to buffer perturbations are possible solutions.
Answer 3: These can be addressed by using electrolyzers and hydrogen storage at night.

Question: What affects ortho-para conversion other than temperature equilibrium?
Answer: There is a small difference, but negligible, in the noise of the fuel cell. There may be optical methods (basic physics). It's a fundamental science challenge.

Question: When converting ortho to para, does it convert back to normal hydrogen?
Answer: The para form needs a catalyst for the conversion to ortho.

Question: Will a tank with recently converted gas continuously cool?
Answer: Continuous cooling will depend on temperature.

Question: What about room temperature?
Answer: The exo/endotherm for room temperature is very small.

Question: Can we use isobaric hydrogen to reduce losses?
Answer: Thin film polymers don't break in liquid nitrogen; maybe fuel bladders with hydrogen. NASA is funding research on this. Novel insulation barriers could also be used.

Question: What scale is needed to get cost value for centralized at-scale production?
Answer: As scale increases, the cost decreases. We'll need to optimize SEC. A small farm is easy to convert to liquid hydrogen, but a larger size is better.

Question: How small can a liquefier go?
Answer: Perhaps down to 1 tpd.
Answer: A liquefier can be as small as 0.25 kg/day. There's a valley between large and small liquefaction systems. Currently, small-scale refrigerators have poor efficiency and high costs.

2.2 Liquid Hydrogen Storage and Handling Infrastructure: Current Status and RD&D Needs

2.2.1 Current Status of Technologies Used for Bulk Storage of Liquid Hydrogen

Andy Jacobson, CB&I Storage Solutions
CB&I Storage Solutions is a large engineering, procurement, and construction company, specializing in projects for oil, gas, and now, hydrogen. Andy Jacobson discussed the recent liquid hydrogen storage technology development being done by CB&I, which includes a liquid hydrogen storage vessel at Kennedy Space Center with a capacity of 1.25 million gallons (4,732 m^3). Currently, CB&I is employing two new storage technologies developed by NASA that provide large-scale liquid hydrogen storage and control capability. CB&I is using new technology for insulation of the liquid hydrogen storage vessels, which includes glass bubble thermal insulation (evacuated). An integrated refrigeration and storage (IRAS) system will also be employed to cool the storage gas/liquid and prevent boil-off. The IRAS heat exchanger was developed by NASA and it provides active thermal control by taking up heat through an internal heat exchanger. The refrigerant for this process is helium, which will be fed through 43 meters of stainless steel coils located at the 25% and 75% level fills.

The glass bubble insulation system has been analyzed by filling the annular space of the vessel with 3M K1 glass bubbles. It is predicted that the glass bubbles will show 40-100% better performance compared to perlite with respect to insulation. Field testing with a 190 m^3 vacuum-jacketed liquid hydrogen sphere at Stennis Space Center gave an average boil-off reduction of 46% over three thermal cycles in six years. For advancing the state-of-the-art, which is currently at around 40,000 m^3, the basic design and constructability study continues to provide boil-off gas handling solutions, send out systems such as truck loading, and invites discussion with CB&I on the needs for larger capacity to determine the best overall storage solution.

Ian Neeser, Chart Industries
Chart Industries is a global manufacturer of cryogenic equipment for liquid hydrogen production, delivery, and storage. Ian Neeser joined Chart Industries in 2013 where he is currently a new product development engineer.

His responsibilities include the design and testing of liquid hydrogen storage systems for new markets. Mr. Neeser's talk focused on Chart's liquid hydrogen storage tanks and trailers.

Chart's liquid hydrogen tanks are double walled with a stainless steel inner wall and carbon steel outer wall which provides excellent ductility at low temperatures. These tanks have capacities exceeding 100,000 gallons with approximately 7% vapor space. The material selection, welding, and forming processes used during tank fabrication are all employed to mitigate hydrogen embrittlement. The inner vessel support system is thermally optimized to achieve negligible thermal stresses between the inner and outer vessels. Both an evacuated annular space and radiation shielding are used for heat leak mitigation. Mr. Neeser also described the basic pressure transfer offload steps which include hose purging, a pressure ramp, dispensing and sustaining pressure, fill termination, and finally, hose purging/emptying. Helium is the best option for a purge gas, but it is very expensive, so nitrogen is typically used to purge large vessels. Hydrogen can also be used to cycle purge the hoses.

Mr. Neeser provided more details about Chart's liquid hydrogen tanks during the Q&A session following his talk. In response to a question on slosh baffle design, Mr. Neeser described slosh baffles as stainless steel plates with a few flow orifices welded to the inside of the inner vessel, designed to dissipate the bulk kinetic energy of the transported liquid (e.g., during acceleration/braking). While it is a good idea to have them, the reactive forces in liquid hydrogen tanks are typically lower than other cryogens and slosh baffles may not be necessary.

Q&A

Question: Can you share more details on the 10,000 lb limit for on-site storage (without triggering additional Occupational Safety and Health Administration (OSHA) requirements)? This applies to gaseous storage, also?
Answer: The 10,000 lb limit applies to OSHA Process Safety Management (PSM). PSM has a bunch of additional regulatory requirements; over 10,000 lbs on-site storage OSHA 29 CFR 1910.119 requires a Process Safety Management (PSM) program. I am not as familiar with the OSHA specifics on that, but to my knowledge, if your designed maximum payload is under 10,000 lbs, the required reporting levels are significantly reduced/eliminated.

Question: Is aluminum an acceptable alternative to 304/316 stainless steel?
Answer: As far as I know, aluminum is not an acceptable alternative to stainless steel, mainly because of its relatively low melting temperature. If the tank were in a fire, it would be more likely to have loss of containment, thus adding more fuel to the fire.

Question: With hydrogen permeation through steel, do you foresee any problem with lamination on the outer carbon steel plate?
Answer: I do not foresee/have not heard of any issues with delamination of the carbon steel.

Question: What about slosh baffles?
Answer: For slosh baffles on mobile units, in my opinion, it is still a good idea to have them. However, due to the significantly low density of hydrogen liquid, you'll find that the reactive forces are much lower than other cryogens.

Question: Please explain slosh baffle design.
Answer: It is basically a stainless steel plate with a few flow orifices welded to the inside of the inner vessel - designed to dissipate the bulk kinetic energy of the transported liquid (e.g., during acceleration/braking).

Question: Does Chart offer a liquid nitrogen-cooled shield for liquid hydrogen tanks like helium tankers employ?
Answer: Chart does indeed offer liquid hydrogen tanks with a sacrificial liquid nitrogen shield.

Question: What is the thermal induced stress on the internal shell supporting brackets given the temperature differential between the inner and outer shells?
Answer: We design our inner support systems very carefully to achieve negligible thermal stresses between the inner and outer vessels. That is, we calculate the expected shrink and design the support system geometry to "take up slack" in certain places when the inner tank goes from ambient temperature (during fabrication) to cryogenic temperatures (in service).

2.2.2 Potential Benefits and Challenges to Liquid Hydrogen for MD/HD vehicles

Rajesh Ahluwalia, Argonne National Laboratory
Dr. Rajesh Ahluwalia is a Senior Engineer and the manager of the Hydrogen and Fuel Cell Systems Section at Argonne National Laboratory. His DOE-sponsored analysis projects focus on fuel cells, hydrogen storage and transmission, and hydrogen production. Dr. Ahluwalia's talk covered the design and analysis of an onboard liquid hydrogen storage system for heavy-duty trucks.

The onboard liquid hydrogen storage system was designed for Class 8 trucks including semi-trailers, refuse trucks, and drayage trucks. Specific metrics included a range of 750 miles, system capacity of more than 60 kg of hydrogen, gravimetric capacity of 15 wt%, and a volumetric capacity exceeding 35 g/L. Ideal refueling and discharge rates were also stipulated along with an overall system cost of $8-9/kWh. Once a duty cycle for semi-trailer long haul trucks was established, refueling and packaging options were then evaluated. Based on these considerations, three storage system designs were analyzed: 1) system with an onboard pump and a low pressure offboard refueling pump; 2) system with an onboard pump and a medium pressure offboard refueling pump; and 3) system without an onboard pump but with a medium pressure offboard refueling pump. Structural analyses of the tank liner and liner support were also performed.

Dr. Ahluwalia presented the performance results of each system and compared them to the goals of the project. The inclusion of the onboard pump increased the usable hydrogen capacity by 19%. The best performing system was the system with the onboard pump coupled with a low pressure offboard refueling pump. The gravimetric capacity and volumetric capacity were 17.7 wt% and 37.1 g/L, respectively. The amount of hydrogen stored onboard was 94.6 kg and the range between refueling was estimated at 621 miles. The maximum usable hydrogen was approximately 82 kg for a two-tank system when ullage and heel were considered.

One question raised during the Q&A focused on thermally induced stresses on the brackets due to the difference in temperature between the inner and outer shell. Dr. Ahluwalia stated that heat leakage was a main concern since the brackets provided a heat leak path. However, their analysis kept the total heat gain to 1 W/m^2, which is a challenging condition. In their analysis, ANL did not consider the brackets to be a thermal cycling concern because the onboard tanks would be relatively low-pressure systems.

Q&A
Question: What is the thermal induced stress on the brackets, given the delta T (change in temperature) between the inner and outer shells?
Answer: There are two concerns when using brackets, the first is heat leakage. ANL tried to keep the total heat gain to 1 W/m^2 which is challenging, and the brackets provide a heat leak path. ANL does not consider these brackets to be a thermal cycling concern because these tanks are relatively low-pressure systems. Though thermal cycling may not be important for on-design conditions, it may need to be considered for off-design conditions such as letting the tank heat up.

Question: Can you restate the capacity for liquid hydrogen on Class 8 trucks?
Answer: ANL looked at three systems and the total amount of hydrogen storage was between 85.2 kg and 94.6 kg, however not all is usable because of ullage and heel. The maximum usable liquid hydrogen was about 82 kg for a two-tank system.

Question: What is the status of onboard cryopumps?
Answer: These are needed, critical developments. Critical design specifications are delta P (change in pressure) of 4-5 bar and a maximum flow rate of 17 kg/hr.

Dr. Gladys Anyenya, Wabtec Corporation
Wabtec Corporation is a provider of freight and transit rail technologies and services. Dr Gladys Anyenya is the engineering lead for fuel cell development at Wabtec where she is responsible for the design and development of fuel cell systems for locomotive and mining applications. Dr. Anyenya's talk focused on potential adoption of liquid hydrogen for rail and freight applications.

Wabtec has the first 100% battery-electric locomotive worldwide, with a capacity of 7 MWh, and fuel and emissions savings of 30%. Wabtec's roadmap to carbon-zero locomotives entails moving from diesel-electric (biodiesel and renewable diesel) locomotives to battery-electric and then to hydrogen fuel cell locomotives by 2030. Locomotives have aggressive duty cycles (3,500-4,000 MWh/yr, 80% daily uptime and 3,300 kW rated power at 17% usage). They also operate in extreme environmental conditions with temperatures ranging from -40 to over 120 F, at altitudes up to 10,000 ft.

The volume of liquid hydrogen required for locomotives is approximately three times that of diesel for the same range. Liquefied natural gas (LNG) would be a precursor to full adoption of liquid hydrogen on rails. The lessons learned in LNG tender development are critical to subsequent hydrogen tender designs. However, several barriers to hydrogen adoption for rail must first be addressed. These include onboard hydrogen storage limitations for long ranges, refueling time and establishing refueling stations along the rail network, rail's aggressive duty cycle, and hydrogen system safety uncertainty.

During the Q&A, Dr. Anyenya addressed issues of where the liquid hydrogen would be stored, on the locomotive or in a tender. The choice would depend on the locomotive's application. For applications where the power requirements are low, e.g., shunter applications, smaller fuel cells could be used on the locomotive allowing for hydrogen storage on the locomotive itself. Line haul applications, however, would need larger fuel cells and excess hydrogen storage and, therefore, a tender would be necessary. Ideal solutions would be to vaporize the hydrogen before transferring it to the locomotive. Typical flow rates for a 4 MW fuel cell locomotive would be 250 kg/hr or higher.

Q&A

Question: How likely is it that most of the liquid hydrogen is stored on the locomotive and not in a tender if we have conformable tanks available?
Answer: It will depend on the application of the locomotive. For example, shunter applications may be able to store most of the hydrogen on the locomotive since they have relatively low power requirements. The lower power requirements allow for downsizing the fuel cell which frees up more volume for hydrogen storage on the locomotive itself. However, for line haul applications the fuel cell will need to be larger (~6,000 hp) which means there won't be excess volume for hydrogen storage, and a tender will be necessary.

Question: Thoughts about the use of ammonia as an alternative fuel?
Answer: Ammonia may alleviate some of the challenges hydrogen presents. Ammonia is already transported via rail today, so safety codes and standards are already in place, along with ammonia carrier cars. However, we would still need to develop the ammonia reformer and transport hoses over the car/locomotive coupler.

Comment: The large variation in environment conditions (-40F to 120F, 0 to 10,000 ft altitude) for rail applications has a lot in common with environment variation for aviation applications.

Comment: On the LNG tender car project mentioned in her talk, the natural gas is vaporized and fed to the engine.

Question: Do you propose transferring the liquid hydrogen from the tender car to the locomotive? Assuming that the fuel cell is on the locomotive.
Answer: The ideal solution is to vaporize the hydrogen before transferring it over the coupler to the locomotive.

Question: What are typical flow rates of hydrogen to power these operations (kg per hour)?
Answer: For example, a 4000 kW fuel cell locomotive would require about 250 kg/hr at rated power.

2.2.3 Current Practices to Transfer and Deliver Liquid Hydrogen

Ravi Subramanian, Air Products
Gardner Cryogenics Department of Air Products manufactures cryogenic tanks for the transportation and storage of liquid hydrogen and liquid helium. Ravi Subramanian currently has commercial and technology responsibility within Gardner Cryogenics department to develop and implement strategy for the equipment and energy businesses within the helium and hydrogen markets. His talk addressed liquid hydrogen storage and delivery options provided by Gardner.

Three main options for liquid hydrogen delivery are via semi-trailers, portable tanks, and International Organization for Standardization (ISO) Swap Body tank containers. Liquid hydrogen can be stored on site in horizontal, liquid nitrogen-shielded tanks for long duration storage (up to 33,000 gallons) or in containerized dewars (11,000 gallons). Other storage options include portable tanks (10,000 gallons) and semi-trailers (up to 18,100 gallons). Each tank uses a combination of vacuum technology, multi-layer insulation and thermal shielding to minimize boil-off. Thermal shielding technology offers longer hold times enabling international transportation of liquid hydrogen.

Angela Krenn, NASA
NASA owns the world's largest liquid hydrogen storage tanks at 3200 m^3 (850,000 gallons) useable volume each. In 2019, construction began on an additional tank with storage capacity of 4732 m^3 (1.25 million gallons) of liquid hydrogen. Angela Krenn is the Principal Technologist for thermal management systems in NASA's Space Technology Mission Directorate (STMD). Her talk covered standard practices for liquid hydrogen tank loading and maintenance.

The liquid hydrogen storage tank at Kennedy Space Center was built in the 1960's. It is evacuated and insulated with perlite. Delivery and transfer steps include liquid hydrogen tanker offload from supplier, system leak check and sampling, and finally liquid hydrogen loading to the launch pad. All steps in the process follow the standard practices as established in OSHA 1910.119, NFPA 497 and AIAA/ANSI G-095A-2017.

Leak checks are common during tanker offload and are usually resolved by cinching the transfer hose. Flow operations during the transfer of liquid hydrogen from the main storage tank to the launch pad are performed remotely from a control room and the launch pad is fully evacuated during the liquid hydrogen transfer.

The topic of liquid hydrogen purity was raised during the Q&A session. Purity is always verified before offloading from the tanker trucks and monitored at several points in the system. Additionally, filters are used to maintain the desired purity level and the storage tank is sampled annually. Ms. Krenn advised those considering the safety of large-scale liquid hydrogen storage to dedicate time to training their staff on the safety protocols and guidelines on safely handling liquid hydrogen.

Q&A

Question: How do you verify that there is less than 1% oxygen in your line after a purge?
Answer: Several ports in the system allow us to measure oxygen levels at various points. We also use hand-held meters.

Question: During filling, do you experience any pressure drops?

Answer: We typically don't see drops in pressure during filling since we have vaporizers to help control the pressure.

Question: Are you concerned about the purity of liquid hydrogen?
Answer: Yes, NASA is very sensitive to purity. We would always double-check tanker truck manifests to verify the source before offloading. We would also sample our storage tanks annually. We also used filters to maintain the desired purity level.

Question: Is NASA involved with HySTRA?
Answer: Angela is not directly involved. Adam Swanger would be better prepared to answer this question.

Question: For others considering the safety of large-scale storage, what tips can NASA share?
Answer: Most importantly, take the time to train your staff on the safety protocols. There are established guidelines on how to safely handle liquid hydrogen. So long as staff are trained on those guidelines, large quantities of liquid hydrogen can be safely stored.

Question: That photo contained a hydrogen vapor cloud? What was the justification to allow this as part of the risk analysis?
Answer: The photo shows water vapor, evidence of hydrogen venting, not hydrogen itself. Several things made this venting allowable, from a safety perspective. Venting occurred significantly above operator head level. Hydrogen is light and very unlikely to migrate downward to operator level. Operators had hydrogen meters on hand and regularly checked for hydrogen in the immediate area. Pre-planned procedures were in place to stop flow in the event of hydrogen detected in the immediate area.

2.2.4 Safety Requirements for Liquid Hydrogen Handling and Refueling

Aaron Harris, Hydrogen Safety Panel
The Hydrogen Safety Panel's main goal is to promote the safe handling and end use of hydrogen systems. Aaron Harris serves on the Hydrogen Safety Panel and is also the Director of Operations and Technology for Air Liquide Hydrogen Energy. The Hydrogen Safety Panel operates under the Center for Hydrogen Safety and provides reviews and identifies major gaps in the "safe operation, handling and use of hydrogen and hydrogen systems across all installations and applications". Mr. Harris' discussion focused on challenges associated with safe liquid hydrogen handling and storage and the necessary safety codes and standards which must be implemented.

Early standards for liquid hydrogen handling were developed in the 1960's for space applications. Regulations, codes and standards for liquid hydrogen transfer to vehicles to this date, however, do not exist. Also, inconsistencies between OSHA and NFPA requirements which necessitate site-specific understanding is a challenge. However, before updated standards can be developed, the community needs to understand if, and what, standards are actually needed. Input from equipment manufacturers will also be important.

Several questions were raised during the Q&A session regarding NFPA 2, the Hydrogen Technologies Code. This code provides safety provisions "for the generation, installation, storage, piping, use, and handling of hydrogen in compressed gas form or cryogenic liquid form." NFPA documents are model code and must be adopted by a state fire agency or delegated by the state to the municipal or county level fire authority. The model code may be heavily edited in that adoption process, for example, the New York City Fire Code. Current concerns within the hydrogen community are focused on how to make NFPA 2 more efficient and better aligned with related ISO and OSHA standards. Mr. Harris believes that there is potential for future alignment and current developments are moving in that direction. However, globally harmonized standards will be difficult to develop due to each nation's different risk tolerance. Instead, harmonizing across market segments may be possible.

Q&A

Question: How do we get NFPA 2 to address large volume liquid hydrogen storage?
Answer: What we're concerned about is how to make the standard efficient. There's still a problem with OSHA approving existing liquid hydrogen storage, so not sure how quickly NFPA. How necessary is NFPA 2 guidance if you may have to evaluate on case-by-case basis?

Question: How much of NFPA 2 is aligned to what is going on in ISO/TC197?
Answer: A lot of potential for future alignment, for future capital-intensive alignment. It's headed towards alignment.

Question: Any existing standards for liquefiers?
Answer: Yes, they are common. In terms of materials requirements – those might be design specific. Not going to see development of that in the near-term.

Question: Is it unrealistic to bring all codes/standards under one comprehensive umbrella?
Answer: It depends on the vision at the end of the day. We're not going to have globally harmonized standards because of different risk tolerances of each nation. For example, that difference underpins why there are different safe distances, etc. It is possible to re-evaluate national templates from mid-2000s to better align codes development and standards development organizations to define ownership.
DOE can monitor those affected by hydrogen and the application. A process of harmonizing across market segments could be possible.

Question: Is it possible to have a universal guideline?
Answer: Not alone in thinking that, but not likely because humans don't behave the same in all applications.

Question: How does the safety panel work? And how do people access resources from the panel?
Answer: The Hydrogen Safety Panel operates under the Center for Hydrogen Safety. Panel members are from academia, industry, and consultants who have been selected to participate. The Panel provides reviews and identifies major gaps in the application side of safety. It's not involved in R&D of behaviors of materials. The Panel can contract to review DOE and CEC projects, as well as individual industrial projects.

Question: Does NFPA 2 enumerate the various jurisdictions' documents that need to be addressed, and does it supersede all prior NFPA codes (NFPA 55 and NFPA 50A and 50B) in relation to compliance?
Answer: Regarding NFPA 2 superseding other code document: NFPA documents are model code and must be adopted by a state fire agency or delegated by the state to the municipal or county level fire authority. The model code may be heavily edited in that adoption process, example: New York City Fire Code. There is an open discussion between NFPA 2 and NFPA 55 as each are the primary code for various installations depending on the location and installation date.

Question: Is it possible or realistic to try and bring all the hydrogen-related codes & standards under one, comprehensive umbrella? At least a go-to place that summarizes them all for more streamlined, practical use.
Answer: There is a searchable database of hydrogen codes & standards here: https://h2tools.org/codes-standards. For comprehensive "umbrella" guidance - I recommend starting at https://h2tools.org/. One of the unique aspects of the U.S. is our permitting process. There are 17,000 independent fire jurisdictions in the U.S. Most other countries have federal fire codes with very little local variation. I recommend "Reaching the U.S. Fire Service with Hydrogen Safety Information: A Roadmap" - NFPA report 2009 - https://www.nfpa.org/News-and-Research/Data-research-and-tools/Emergency-Responders/Archived-reports---Emergency-responders.

Question: Any thoughts about aircraft fueling in 3500 kg liquid hydrogen amounts per flight (737, about three hours of flight)?
Answer: Regarding aircraft fueling, if you want to develop a standard around aircraft fueling, the process could be similar. You would want to first develop the target fueling performance, duration, acceptable boil-off loss,

one-way or two-way transfer, active or passive process controls, etc. Then you would develop a consensus process through demonstration.

2.2.5 Materials Performance at Liquid Hydrogen Temperatures

Joe Ronevich, Sandia National Laboratories
Dr. Joe Ronevich is a Principal Member of the Technical Staff at Sandia National Laboratories and works in the Hydrogen Effects on Materials Laboratory. In his talk, he discussed the effects of liquid hydrogen and cryogenic temperatures on component material properties.

Hydrogen embrittlement occurs in materials under the influence of stress while in a hydrogen environment. The embrittlement process entails hydrogen first dissociating on the metal surface then dissolving into the metal lattice and diffusing into regions of tensile stress. While hydrogen embrittlement is a concern in all environments, higher pressures and cycling rates tend to result in faster material degradation.

Conventional cryogenic materials used for liquid hydrogen applications include 3XX series austenitic stainless steel and aluminum alloys. The 3XX stainless steels possess high toughness, high ductility, and good performance in hydrogen environments. The aluminum alloys exhibit low sensitivity to hydrogen and no ductile to brittle transition temperatures. Aluminum alloys are good options when weight reduction is critical. Alloys, however, require high toughness at cryogenic temperatures (20 K).

While hydrogen diffusion into these materials is important, diffusion kinetics at 20 K tend to be slow as cryogenic temperatures greatly limit hydrogen diffusion. The hydrogen effect at 20 K is no different than the impact of helium at the same temperature. At low temperatures, however, ductility is significantly affected by the presence of hydrogen, and this can lead to material cracking. Dr. Ronevich identified the need to characterize material behavior after long term exposure to hydrogen at cryogenic temperatures and examine material response during slow rate fracture testing as there are notable gaps in the scientific literature.

During the Q&A session, Dr. Ronevich also discussed hydrogen pre-charging which refers to placing the specimen in the presence of hydrogen for a span of time at high temperature and pressure and increased stress levels. This is done to encourage hydrogen to charge into the material and pre-charged specimens can then be used to study the long-term effects of hydrogen. Novel materials for hydrogen applications were also discussed. These include aluminum alloys, Nitronic alloys, titanium alloys, and composites but their adoption would depend on cost and available markets.

Q&A

Question: What is H-precharged?
Answer 1: It is difficult to get hydrogen to go into stainless steel at room temperature. So, they will heat up the material in a pressure vessel with hydrogen and then pre-expose it to hydrogen to pre-load the hydrogen content, which can then be used to study long term effects.
Answer 2: Precharging refers to placing the specimen in the presence of hydrogen for a span of time (higher temperature, high pressure, increased stress levels) to encourage hydrogen to charge into the material.

Question: Under what conditions is hydrogen embrittlement a concern?
Answer: Higher pressure, higher cycles will tend to cause faster degradation. But it is a concern for really all environments.

Question: Do you have opinions on novel materials for liquid hydrogen storage?
Answer: Historically, 300 series stainless steel was the predominant alloy because it has worked (good for stationary applications). Aluminum alloys, Nitronic alloys, and composites have potential, but it’s not clear if there is a market there (will depend on costs).

Question: The cost of titanium is competitive, what is your opinion?

Answer: We exposed titanium to hydrogen and stress… it turned to powder (because it hydrided), but the behavior will depend on the alloy.

3 Breakout Sessions

On each day, attendees were divided into breakout sessions following the speaker presentations. The topics for Day One were hydrogen liquefaction, liquid hydrogen delivery and distribution, and emerging applications of liquid hydrogen. On Day Two, attendees were split into four groups, two each in the topic areas of liquid hydrogen handling and liquid hydrogen storage, to better facilitate discussions. Breakout sessions were 40 minutes long on both days. A summary of the breakout session topics, as well as the moderator(s) and scribes for each session are shown in Table 2.

Table 2. Breakout session topics, moderators, and scribes.

Day One		
Session Topic	**Moderator**	**Scribes**
Hydrogen Liquefaction	Robert Johnson	Angela Macedo Andrade Martin Sulic
Liquid Hydrogen Delivery and Distribution	Mark Richards	Christine Watson Tomas Green
Emerging Applications of Liquid Hydrogen	Neha Rustagi	Nikkia McDonald Anne Marie Esposito
Day Two		
Session Topic	**Moderators**	**Scribes**
Liquid Hydrogen Handling #1	Mark Richards Asha-Dee Celestine	Christine Watson Eric Heyboer
Liquid Hydrogen Handling #2	Adam Swanger Marika Wieliczko	Anne Marie Esposito Tomas Green
Liquid Hydrogen Storage #1	Neha Rustagi Zenia Garcia	Nikkia McDonald Martin Sulic
Liquid Hydrogen Storage #2	Brandon Marsell Robert Johnson	McKenzie Hubert Zac Taie

3.1 Hydrogen Liquefaction

With the guidance of the moderator, attendees were asked to consider four main topics of hydrogen liquefaction, which included limitations of conventional liquefaction pathways, novel approaches to liquefaction and associated technology readiness, liquefaction needs for different scales, and safety codes and standards.

1. *Limitations of conventional liquefaction pathways.*

Generally, there is still a lot of R&D needed to bring costs down in all aspects of the liquefaction cycle. Also, considering and developing fundamental approaches to improve liquefaction are needed. Glass beads might be considered viable solutions for insulation; however, funding is still needed to explore them as an option. Managing boil-off is another limiting factor, which NASA tries to mitigate by changing the position of the heat exchanger to the liquid portion of the tank and then using internal coils to cool. The set-up is different for larger tanks that only have a coolant loop. Still, funding would be needed for a portable refrigerator to cool down the tank to liquid hydrogen temperatures.

2. *Novel approaches to liquefaction and associated technology readiness.*

Some novel approaches for liquefaction include using mixed refrigerants, magnetic refrigeration, along with the use of glass beads for insulation. For glass beads, there is potential benefits for liquid hydrogen storage and for improving insulation. Recently, glass beads have been used with a vacuum, and have been used at smaller scales. NASA has used them for 50,000 gallons of liquid hydrogen, but if they would be used for larger capacity it will be difficult to pull the vacuum required for that application.

Variability with using renewable power is an issue, adding an energy storage buffer (e.g., fuel cells) to generate electricity is still considered an option for future applications that need development.

3. *Liquefaction needs for different scales.*

For liquefaction needs at different scales, typically, the smaller scales are less efficient because there is higher cost/kg for liquefaction and storage. However, small scale is still necessary for some applications, especially when considering end-user needs to determine the best system. Therefore, the scales needed for liquefaction should be determined on a case-by-case basis.

Other considerations for different scales are the capacities of different types of tanks, and the differences and advantages of horizontal vs. spherical tanks. Generally, spherical tanks have better surface area to volume at larger sizes, but if you are considering a smaller sized tank then a horizontal tank would be a better option. There are issues with transportation if the tank is too big, especially with larger spherical tanks. This is one of the reasons spherical tanks are typically manufactured in the field.

When considering energy efficiency and power requirements of liquefaction, the power needed for hydrogen liquefaction is 9-12 kWh/day, but with new technological developments it can be brought down to 6-7 kWh/day. Some of these developments include using different refrigerant cycles and cooling methods to help improve energy efficiency. Hydrogen liquefaction of 6-7 tpd is reasonable, but if you want to go smaller then it will be more expensive. Therefore, it comes down to considering the tradeoff between CAPEX and OPEX. When considering what are the liquefaction capacities needed to displace current fuels like diesel, there are currently no targets or scales at those capacities.

4. *Safety codes and standards for hydrogen liquefaction.*

Liquefaction of hydrogen is not new, NASA has been working with it for decades, so there are safety codes and standards (SCS) that have been developed. However, there are still some gaps and obstacles where SCS need to catch up. This is especially true for sub-cooled liquids where there has been limited development. A possible solution would be getting in contact with others that are handling sub-cooled liquids (e.g., SpaceX) that might have information on the SCS used for sub-cooled liquids and explosive mixtures. In addition, sub-cooling below atmospheric pressure (~1/10 to 1/25 psi) requires safety for operating at those pressures, and for pressurizing the tank to then feed the liquid to the vehicle. Currently, there are limited or no codes available for sub-cooled liquids.

3.2 Liquid Hydrogen Delivery and Distribution

With the guidance of the moderator, attendees were asked to consider three main discussion topics related to liquid hydrogen delivery and distribution.

1. *Limitations of current delivery and distribution pathways.*

The group discussed the status of filtration for distribution, where potential contaminants come from, and how they are dealt with. Because hydrogen must be pure to liquefy, the operation of liquefaction itself implies purification. Contaminants can be introduced from components used during handling of the liquefied hydrogen. NASA uses MIL-PRF-27201 which is the military specification for liquid hydrogen. This specification requires filter use and limits the number of producers, because most producers do not use filters to avoid added pressure and keep the temperature low. Particulate matter can be introduced throughout the systems and valves. The military specification does not provide any added benefit since the filtering only occurs once and not later when particulates may be introduced. In any case, most products are not going to the military.

Some groups, such as mining and aviation, require higher volumes, e.g., large equipment require 1000 kg/day, 500-700 kg at a time, and quick distribution. Achieving an efficient and fast fill is important. Cryogenic storage onboard vehicles is challenging too, e.g., if you need > 50 kg/min fueling of vehicles with cryogenic storage. Gas is very challenging to store on vehicles, and the transfer rate using gas is too low for some vehicles. Some, such as vehicles used in mining, may need to transfer fuel in ~20 minutes. Rail and ferries also have large liquid hydrogen requirements but may not have the same time constraints. HD vehicles could use gaseous or liquid hydrogen onboard, but higher capacities make more sense to have liquid, as this helps with transfer rate.

For aircraft, turn-around time for a plane is a major constraint. This would require a volume of around 40,000 L to refuel a smaller plane in 15-20 minutes, and >160,000 L for a larger plane in 30-40 minutes. High transfer rates can be managed well using bayonet connectors, which allow up to 100 kg/min depending on the pressure differential. With 2,000 kg of hydrogen at the gate, you can refuel in 20 minutes. But a major challenge is still getting the fuel to the gate.

2. *Novel approaches to delivery and distribution and associated technology readiness.*

The group discussed an alternative approach of using swappable tanks, similar to exchangeable propane tanks. A well-designed, standard tank would be key. Leaving the entire trailer at the station or swapping the entire tank could be ideal for trains, and heavy-duty end uses that have very large scales. Loading a stationary tank could take more time in some cases than refueling a tank. There are challenges in standardization for loading bays and connections. Those with LNG experience face similar problems. For marine and heavy-haul truck applications, it is not the same as "cold diesel" fuel, because flammability, safety, and other risks are different. The idea of swapping containers instead of refueling infrastructure has some merit. ASTM did some work on this. Dry disconnects can seal system so that lines do not have to be purged each time. Universal Hydrogen makes modular tanks that are loaded and unloaded off an aircraft.

3. *Safety codes and standards for liquid hydrogen delivery and distribution.*

Liquid hydrogen tanks are close to being standardized in the joint SAE Aerospace Standards & EU activity. Regarding the liquid hydrogen nozzle, Walther Praezision worked together with BMW to create a hose and nozzle for liquid hydrogen fueling. This was about to be standardized at SAE J2600 when BMW dropped the program for gaseous hydrogen. This means that much of the work is either very mature and/or existing hardware is possible. There is a new forum called H2-Aero Team that is working with SA Aerospace on standardizing processes for Europeans, and people were encouraged to join future seminars and learn more. The question of managing transfer operation with respect to PPE standards remains.

3.3 Emerging Applications of Liquid Hydrogen

With the guidance of the moderator, attendees were asked to consider five main discussion topics with regards to emerging applications of liquid hydrogen.

1. *Emerging applications for hydrogen that are likely to require delivery in liquid form.*

The aviation sector is one of the key areas that will likely require liquid hydrogen delivery as it can provide the power-to-weight densities that are needed. Liquid hydrogen will enable both short and medium haul flights. There is also the possibility of using liquid hydrogen for ultra-long-haul flights due to the lighter weight of the fuel, but larger aircrafts will be required to make this possible. Options include superconducting propulsion, fuel cells and combustion, with combustion as the first technology expected to be implemented between 2030 and 2035.

Other emerging applications include fuel cell buses, trucks, and farm equipment which would entail high usage. The maritime sector is also poised to adopt liquid hydrogen which can be used to power long range ships and passenger ferries. Liquid hydrogen can also be used for grid balancing and for backup power applications.

2. *Associated regions of emerging applications.*

Liquid hydrogen adoption in the aviation industry is being led by teams in the U.K. and Europe. Rollout of liquid hydrogen fueled buses, trucks, farm equipment, etc. is focused within the U.S., while Norway is leading the way in the application of liquid hydrogen for passenger ferries.

3. *Timelines and scale requirements for adoption in emerging applications.*

Liquid hydrogen fueled trucks are already in development and the first trucks should be ready this year, 2022. Maritime deployment is expected in two to three years, while the timeline for full deployment in the aviation sector is a bit later, 2040's to 2060's. In terms of scale, a fleet of 200-300 buses would need 5-7 tonnes of hydrogen per day. Trucks, on the other hand will need approximately 100 kg hydrogen per truck. Currently, small passenger ferries need 3 tonnes every two weeks. Larger ferries, however, will need 10-16 tpd. An international airport may need the hydrogen equivalent of 20 million liters per day of kerosene (~6000 tpd hydrogen) to function fully. And it is estimated that 650 tonnes will be needed for grid backup.

4. *Cost and technical barriers to use of liquid hydrogen in emerging applications*.

Cost barriers to the adoption of liquid hydrogen in emerging applications include the uncertainties associated with required CAPEX and insuring assets for the liquid hydrogen infrastructure. The lack of research facilities that can handle liquid hydrogen is a critical technical barrier. Insufficient equipment and liquefaction suppliers were also identified as technical barriers. On the personnel side, there is a pressing need for training and maintenance personnel competent in the handling of liquid hydrogen. Finally, managing the expectations of the customer when comparing liquid hydrogen and gasoline is another hurdle which must be surmounted.

5. *Safety codes and standards concerns for emerging applications.*

Traditionally, safety codes and standards have focused on compressed gaseous hydrogen and not liquid hydrogen. Increased understanding and risk management of leaks, fire mitigation, and overall response strategies as they relate to liquid hydrogen are needed. Materials compatibility with hydrogen is also a major concern with the adoption of liquid hydrogen in new applications.

3.4 Liquid Hydrogen Handling

With the guidance of the moderator, attendees in each of the Liquid Hydrogen Handling breakout sessions were asked to consider four main discussion topics.

1. *Limitations of refueling and handling infrastructure and associated needs.*

A standardized fueling nozzle has not been defined. ISO is looking at this issue for liquid hydrogen trucks, in partnership with Daimler. This body of work is circulating among the various ISO committees. It will take some time to define an international standard. Also, tank swapping is an option being explored since it makes the nozzle question a moot point. There isn't much in the way of pump transfer but using pumps may avoid changing pressure and temperature. Time is money and customers often have only a limited window to offload, so replacing the whole tank may be quicker. This approach only makes sense if the quantities involved warrant it.

Pumps are not robust enough in performance to warrant the expense and losses. Pumps aren't needed for off-loading right now, as current delivery structure is sufficient. Pumps on trucks are not very common. It's most common to have liquid hydrogen pumps on the ground. If you have a large bunkering vessel with a suction device, and you had multiple trailers to offload, that might be a scenario worth exploring. This is entirely dependent on the application though. It is cost effective to move liquid hydrogen since it is so light.

It would be nice to have a forum on liquid hydrogen boil-off. There isn't much of a consensus on this topic, although lots of research is currently being done. Solutions for LNG are out there (such as sub-cooling), so what about liquid hydrogen? Boil-off is highly dependent on the application. The time that the liquid hydrogen needs to be stored in the tank is a critical consideration. The use-case makes a difference, as well as adding to the cost and complexity.

The Canadian military is looking at procuring electric vehicles, either battery electric vehicles (BEVs) or fuel cell electric vehicles (FCEVs). Currently, it is not clear which single option would maximize their investment. They are interested to know whether liquid and gaseous hydrogen are competing concepts or if both will be used and, if so, where. DOE hosted a workshop on bulk storage where it was stated that all options are being considered. Onboard liquid hydrogen storage is being investigated for medium- and heavy-duty vehicle applications. Customers that are using and producing hydrogen are looking at when liquid hydrogen makes more sense and where geologic storage of gaseous hydrogen is not a viable option. Liquid hydrogen is more attractive especially when considering bulk storage.

Personal vehicles may be the most complicated application area because liquid hydrogen storage is not viable onboard. It is more likely that high-pressure gas will be used in those applications. However, fleet vehicles and trains could see onboard liquid hydrogen storage. Vehicles with long duty cycles and regular use have less boil-off concerns. From a safety perspective, liquid hydrogen storage can be argued to be intrinsically safer than high pressure gaseous storage, as it is more predictable than gasoline, and will not lead to long burns but will dissipate quickly.

2. *Novel approaches to liquid hydrogen handling*

Maritime applications offer unique challenges. Huge quantities of liquid hydrogen need to be transferred in a short time.

3. *Training requirements for liquid hydrogen handling*

A training standard for truck drivers transporting LNG is in development in Europe. The same standards are needed for liquid hydrogen. Training for liquid hydrogen has been limited, due to niche market applications for liquid hydrogen. Apprenticeships can provide an avenue. Academia has not typically provided good training. Training requirements come from industry, but still require Operation Qualifications. It would be beneficial to have more universal training requirements. ASP/AIChE may offer a training course and could provide universal requirements. Considerations for workforce training must include those outside of academia as well.

4. *Safety codes and standards for liquid hydrogen handling*

It may help to consider who the "authority having jurisdiction" is for a project and focus on the codes and standards that apply there. Much of the work taking place is to ensure the requirements are consistent between the documents, which requires consensus.

ISO has focused on compressed hydrogen in the past year. There is interest in creating international standards specifically for liquid hydrogen. DOE has done some work with gaseous hydrogen to gauge the impact of various leak scenarios. NFPA ended up reducing their setbacks as a result. Efforts are underway to develop a similar standard for liquid hydrogen.

For truck refueling, the hardware currently available cannot adequately support current needs. Unique nozzle designs are employed based on the application. This will take years to sort out. PPE is not a huge concern for gaseous fueling. An untrained member of the public would not need to be concerned about PPE. There is a need for a consistent message across the industry making it clear when PPE is needed, such as with handling liquid hydrogen, though.

What are the standards in terms of servicing hydrogen vehicles? Most garages are not equipped and oftentimes you need highly trained technicians to safely maintain a hydrogen vehicle. This was a gap identified when LNG vehicles that were taken to traditional automotive maintenance shops.

3.5 Liquid Hydrogen Storage

With the guidance of the moderator, attendees in each of the Liquid Hydrogen Storage breakout sessions were asked to consider five main discussion topics.

1. *Limitations of current liquid hydrogen storage technologies (key drivers of cost, barriers to flexibility, efficiency, performance, reliability).*

Several limitations of current storage technologies were highlighted during the breakout session, first of which was supply chain constraints. The lack of a high volume, reliable supply of cryogenic components and equipment, coupled with limited manufacturing capability, is a challenge. Additionally, current component technologies such as seals and actuators fall short in terms of performance and scale. Safety considerations for above ground storage, such as footprint, setback distances, and downstream entrainment mitigation, also present additional limitations. More work is needed in vent stack designs for enclosed areas. Furthermore, the current weight of liquid hydrogen storage vessels is a barrier, especially in transportation and aviation applications.

2. *Limitations of current boil-off mitigation approaches and barriers to implementation of new approaches.*

One limitation to current boil-off mitigation approaches is the lack of integration between boil-off and end uses. Participants believed that an optimized mitigation strategy would involve using the boil-off to feed ancillary hydrogen demands.

3. *Novel approaches to liquid hydrogen storage and associated technology readiness*

The cryogenic flux capacitor, a semi-solid liquid hydrogen storage system developed by NASA, was hailed as a novel approach to liquid hydrogen storage that is ready to be commercialized. Other approaches discussed included high density gas storage and compressed cryogenic hydrogen storage. Cryogenic composite tanks which would be used mainly for space and aircraft applications were suggested as novel tank options. Similarly, vapor-cooled shielding tanks, which can take boil-off vapors and circulate them around thin polymer films, were also mentioned. The polymer films in these tanks are lightweight and their sizes and geometries can be customized. The technology is reported to enable 20-liter liquid hydrogen fills in 5-10 minutes. Another novel approach discussed was the use of portable liquid hydrogen tank cartridges in lieu of large-scale liquid hydrogen transfers.

4. *Materials needs, design attributes, requirements & gaps*

An urgent need within the liquid hydrogen storage field is for materials which do not experience hydrogen embrittlement. More test data is needed to understand hydrogen effects on alternative materials such as ceramic matrix composites, carbon fiber composites and high entropy alloys. Developing techniques to reduce the cost of these novel materials is also important.

Nitronic materials, for example, have been developed, but the demand to drive down cost does not exist as the incumbent 304/316 stainless steel alloys are viewed as "good enough". Similarly, carbon fiber composite transfer lines could potentially minimize boil-off due to the lower capacity of the carbon fibers. However, costs and scale up mechanisms are unknown. High entropy alloys possess high ductility at very low temperatures and have the potential to replace 304/316 as lower cost alternatives but need to be further evaluated.

The choice of material and design attributes would depend greatly on temperature and pressure while in use as these conditions influence hydrogen uptake. Thermal stresses at cryogenic temperatures present the biggest challenge, but pressure build up is also very important. The use of additive manufacturing for the design of insulation and cooling components would benefit this work as well.

5. *Safety codes and standards* - *what are the gaps and obstacles?*

The existence of multiple, and sometime conflicting, sources of requirements, codes, and standards was identified as a major obstacle in the implementation of liquid hydrogen storage projects. New players in the field are uncertain as to what is needed to ensure compliance. Also, the current codes and standards do not sufficiently address the current state-of-the-art for liquid hydrogen storage in terms of quantity/scale and the necessary safeguards. A need also exists for a harmonization of safety factors between transportation and aviation (e.g., through the H2-Aero effort).

3.6 Breakout Session Report-out

Following the breakout sessions on each day, the attendees were reconvened in the main session and moderators gave a brief summary of the key discussion topics from their groups. A summary of the report-out slides is shown in Table 3.

Table 3. Summary of report slides produced by breakout session moderators.

Hydrogen Liquefaction	
Limitations of conventional pathways	• R&D to lower costs in all aspects of the liquefaction cycle • Fundamental approach needed
Liquefaction needs	• Smaller, less efficient scale is still vital • Scale and end use are important to determine the best system (case by case)
Novel approaches	• Use of mixed refrigerant or magnetic refrigeration
Safety codes and standards	• The codes need to catch-up especially for sub-cooled hydrogen
Liquid Hydrogen Delivery and Distribution	
Limitations of current pathways	• Speed and volume of transfer: speed of gravity feed insufficient • Better pumps needed for large-scale, end-use applications • Very large-scale on-board storage (mining, off-road) needed
Novel approaches	• Swapping tanks/trailers instead of refilling tanks for large-scale end use, such as rail • Need improved design of liquid hydrogen tanks
Safety codes and standards concerns	• Standardization of loading bays & connections • PPE related to refueling infrastructure & interchangeability
Emerging Applications of Liquid Hydrogen	

Emerging applications of liquid hydrogen, regions, and timelines	• Range extenders for traditional and short-range aviation, United Kingdom, 2030-2035 for traditional engines, 2040 for fuel cells • Trucks, bus fleets, transportation clusters – fast fill time (6-15 minutes), 2022, 5-7 tpd per bus depot of 200-300 buses • Grid balancing or resiliency in the event of grid outage requires hundreds of thousands of gallons • Pickup trucks and farm equipment, United States • Passenger ferries and long-range ships, Norway, 2024-2025, 1 tonne per week for small ferries, 10-16 tpd for larger ferries
Barriers to adoption	• Lack of research facilities that can handle cryogenic hydrogen • Materials compatibility with hydrogen • Uncertainty of market mitigates capital investments • Nozzle freeze-lock – influences time and reliability • Supply chain buildout for insulation – could benefit from standardization • Available supply of liquefaction • Available staff, skillsets for operation and maintenance of liquid hydrogen
Safety codes and standards concerns	• Fire mitigation/response – understanding of relative risk of liquid releases vs. gaseous releases, understanding of available mitigation options (e.g., improved ventilation, mitigation of ignition source) • Understanding and management of risk of leaks
Liquid Hydrogen Handling	
Limitations of current technologies	• Use of helium as the purging gas • Transfer termination has not been updated since the 1950's • A lot of codes and standards issues, makes it difficult to demonstrate liquid hydrogen storage • Availability of dispensing components for liquid hydrogen that are easy to use without PPE
Refueling and handling needs	• Standardized nozzle/receptacles for liquid hydrogen beyond the traditional bayonet/pressure driven transfers • Pumps at particular flow thresholds • Need for liquid hydrogen underground storage, buried tanks or vaults • Universal set of training requirement useful for vehicle maintenance personnel, modeled after gaseous hydrogen and LNG • Operational qualifications for hydrogen, carryover from natural gas
Novel approaches	• Innovative materials for storage including Al, Ti, polymers
Safety codes and standards concerns	• Standardized set of rules to follow needed to allow rapid permitting • Rationalize liquid hydrogen setback distances • End-use codes and standards e.g., for aircraft fueling
Liquid Hydrogen Storage	
Limitations of current technologies	• Venting boil-off in enclosed spaces • Mitigation of entrainment downstream of vent stacks • Industry's current manufacturing capability for onboard tanks e.g., HD vehicles and aviation • Weight of liquid hydrogen storage for aviation and associated supply chain • Lack of commercial size performance data on integrated refrigeration and storage systems technologies, misalignment in obtaining the necessary data, and what is needed from the engineering perspective

Materials and design needs	• New materials: fiber reinforced polymer composites, ceramic matrix composites, high entropy alloys to replace 304/316 (higher ductility at cryogenic temperatures) • Cost and scalability of polymer tanks • Characterization data made available to general population • Government-funded research and demos of new materials
Novel approaches	• Integration of boil-off with end uses; ideally boil-off would be optimized to feed ancillary demands for hydrogen • Use of boil-off to cool specific high heat load areas of the tank structure has been successful in the past • Vapor cooled shielding tanks; use polymer films to make vapor shielded vessels • Use of additive manufacturing for insulation and cooling • Portable liquid hydrogen tank cartridges instead of large-scale transfers, e.g., for ferries • High density gas storage – denser than liquid • Nanoparticles, nano material storage research • Cryogenic and ambient options • NASA's 'hydrogen flux capacitor' • Carbon fiber inner vessel for cryo-compressed gas storage
Safety codes and standards concerns	• Harmonization of safety factors between transportation and aviation • Requirements scattered across multiple sources, sometimes conflicting direction/requirements • Setback distance requirements particularly for above ground storage • Safety codes and standards are lagging current state-of-the-art on quantity/bulk storage sizes/safeguards • Sub-cooled liquid hydrogen storage/sub-atmospheric safeguards/safety systems • Higher pressure liquid hydrogen vessels may not be covered by ASME code

4 Conclusions and Recommendations

Closing remarks were given by Ned Stetson, HFTO. He thanked presenters, attendees, organizers, moderators, and scribes for their valuable contributions. Attendees gave positive feedback on the workshop and were appreciative of the opportunity to participate in the informative and engaging event. Participants were also invited to engage in other upcoming workshops.

The workshop achieved its objective to address development needs for low-cost, energy-efficient, scalable, and safe liquid hydrogen generation, dispensing, and end use. Discussions focused on state-of-the-art technologies, research, development, and demonstration (RD&D) gaps, innovative concepts, safety, and analysis activities. There was a high level of engagement from external stakeholders, confirming their interest in liquid hydrogen as an important part of the future energy economy. The workshop was a valuable opportunity for DOE to include them in helping to shape future pathways to achieve common goals. The breakout sessions were invaluable, and the presentations on relevant topic areas set the stage for productive exchange, as many questions and discussions arose from the content of these presentations. Topics that elicited the most discourse were the need for greater liquefaction capacity to meet the needs for heavy-duty transportation applications, managing fast and efficient refueling, the design of suitable and innovative storage vessels for large-scale applications, and liquid hydrogen transfer protocols. The need for regular review of, and updates to regulations, safety codes, and standards related to liquid hydrogen delivery, handling, and storage, was a recurrent theme throughout the workshop. Together, the presentations and breakout discussions will allow DOE to better understand the various challenges and opportunities for liquid hydrogen in meeting future energy storage and refueling demand.

Key recommendations for DOE include: 1) increase research and development efforts to enhance the efficiency and cost of hydrogen liquefaction; 2) further focus research and development of improved storage tank designs and materials for above ground and subsurface storage of liquid hydrogen; 3) review and support updates to regulations, safety codes, and standards related to liquid hydrogen delivery, handling and storage; 4) make federal funding available to boost component development for the liquid hydrogen ecosystem; and 5) continued collaboration between DOE and NASA, as well as other federal and state entities. These activities will provide the strong foundational support system on a federal level that will allow liquid hydrogen to become a major player in the future energy market and fulfill DOE’s mission to ensure America’s energy and environmental security.

References

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2. https://www.nasa.gov/content/space-applications-of-hydrogen-and-fuel-cells
3. https://www.energy.gov/eere/fuelcells/liquid-hydrogen-delivery
4. https://www.energy.gov/eere/fuelcells/advances-liquid-hydrogen-storage-workshop

Appendix

This appendix provides a summary of the workshop agenda.

Day One - Liquefaction: Current Status and RD&D Needs

11:00 am Opening remarks

- DOE Hydrogen Program Perspectives (Ned Stetson, U.S. Department of Energy)
- NASA Perspectives (Michael Meyer, National Aeronautics and Space Administration)

11:20 am Current State-of-the-Art of Hydrogen Liquefaction (Oriane Farges, Air Liquide)

11:40 am Experiences and Lessons Learned with Liquid Hydrogen (Raja Amirthalingam, Plug Power)

12:00 pm Innovative Approaches to Improve Scalability and Efficiency

- Amgad Elgowainy (Argonne National Laboratory)
- Jacob Leachman (Washington State University)

12:40 pm *Break*

1:00 pm Liquid Hydrogen in Emerging Large-Scale Markets (Jo-Tsu Liao, Shell)

1:20 pm Panel Discussion and Q&A with Speakers

1:40 pm Breakout Sessions

- Hydrogen Liquefaction
- Liquid Hydrogen Delivery and Distribution
- Emerging Applications of Liquid Hydrogen

2:20 pm *Break*

2:35 pm Breakout Session Report Out

2:55 pm Day One Closing Remarks

Day Two - Liquid Hydrogen Storage and Handling Infrastructure: Current Status and RD&D Needs

11:00 am Introduction to Day Two

11:05 am Current Status of Technologies Used for Bulk Storage of Liquid Hydrogen

- Andy Jacobson (CB&I Storage Solutions)
- Ian Neeser (Chart Industries)

11:45 am Potential Benefits and Challenges to Liquid Hydrogen for MD/HD vehicles

- Rajesh Ahluwalia (Argonne National Laboratory)
- Gladys Anyenya (Wabtec Corporation)

12:25 pm Current Practices to Transfer and Deliver Liquid Hydrogen

- Ravi Subramanian (Gardner Cryogenic Department of Air Products)
- Angela Krenn (NASA-Kennedy Space Center)

1:05 pm *Break*

1:25 pm Safety Requirements for Liquid Hydrogen Handling and Refueling (Aaron Harris, Hydrogen Safety Panel)

1:45 pm Materials Performance at Cryogenic Temperatures (Joe Ronevich, Sandia National Laboratories)

2:05 pm Breakout Sessions

- Liquid Hydrogen Handling
- Liquid Hydrogen Storage

2:45 pm *Break*

3:05 pm Breakout Session Report Out

3:25 pm Workshop Concluding Remarks

For more information, visit:
https://www.energy.gov/eere/fuelcells/liquid-hydrogen-technologies-workshop

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