Hydrogen Fuel Applications Report

San Bernardino County Transportation Authority Zero-Emission Multiple Unit Project

November 6, 2020

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1 Introduction

1.1 Purpose

The purpose of this report is to provide the Federal Railroad Administration (FRA) with relevant information about hydrogen and how hydrogen is used safely in both transportation and industrial applications. The report also provides additional information on both hydrogen fuel cell and hydrogen-hybrid vehicles in anticipation of the FRA's engagement on the San Bernardino County Transportation Authority (SBCTA) Zero Emission Multiple Unit (ZEMU) Project. This report could also serve as a reference document to provide further information to key stakeholders and the public.

1.2 Hydrogen Characteristics and Properties

Hydrogen (H_2) is the most common element in the universe and a common element here on Earth, where it primarily occurs in compounds such as water (H_2O) and hydrocarbons such as natural gas or petroleum. Pure hydrogen is not abundantly found on Earth; therefore, compounds must be split in order to obtain pure hydrogen. Hydrogen is very light, and its buoyance means it rises and will eventually escape from Earth's atmosphere. Table 1 summarizes some key characteristics of hydrogen.

Table 1: Hydrogen Characteristics

Characteristic	Value	Source
Formula	H_2	National Institute of Standards & Technology (NIST)
Molecular weight	2.02	Hydrogen Tools
Atomic weight	1.008	NIST
Specific gravity (air=1)	0.0696	Hydrogen Tools
Density at NTP (gas)	0.005229 lb/ft^3 (0.08375 kg/m^3)	Hydrogen Tools
Higher Heating Value at 32° F and 1 atm	61,127 Btu/lb (142.18 MJ/kg) 343 Btu/ft^3	Argonne National Lab - GREET
Lower Heating Value at 32° F and 1 atm	51,682 Btu/lb (120.21 MJ/kg) 290 Btu/ft^3	Argonne National Lab - GREET
Boiling point (1 atm)	-423.2 °F (-252.9 °C)	Hydrogen Tools
Flame temperature	3713 °F (2045 °C)	Hydrogen Tools
Flammable range in air	4 to 75 vol.%	Hydrogen Tools
Diffusion of coefficient	0.61 cm^2/s	Hydrogen Tools

Hydrogen is an energy carrier (or vector) rather than an energy source, similar to electricity. As an energy carrier, it can be produced from many different sources enabling a zero-emission energy supply chain. At ambient temperature and pressure, hydrogen is a colorless, odorless gas and the lightest gas. It has the largest energy density by mass of any fuel (~120MJ/kg low heating value, 142 MJ/kg high heating value). It has a low volumetric energy density, which requires compression or liquification to enable storage densities that allow practical ranges for vehicle applications. Other storage options are currently in the research and development phase, such as lightweight composite tanks with high pressure ratings (10,000 psi) for compressed hydrogen and improved insulated-pressure vessels for liquid hydrogen.[1] Figure 1 illustrates the volumetric and gravimetric energy density of various fuels on a lower heating value basis. One gallon of diesel has an energy content of ~145MJ,

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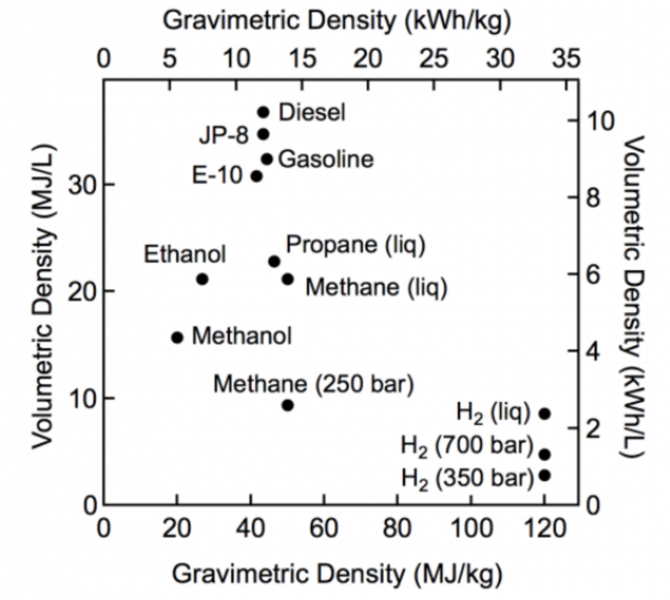
[1] U.S. DOE Hydrogen Storage Research and Development Activities

therefore one gallon of diesel has approximately the same energy content as one kilogram of hydrogen on a high heating value basis. In addition to the energy densities, the mass and volume requirements of the tank system and the efficiency of the powertrain should be considered to obtain a more precise comparison between the fuel options. Figure 2 illustrates the energy density by mass and volume of various fuels, hydrogen, and batteries, including typical container/tank systems, adjusted with representative powertrain efficiencies. Diesel has the highest energy density while batteries have the lowest, hence the requirement for relatively frequent charging of battery-powered vehicles and weight and volume implications on vehicles. To achieve practical ranges with hydrogen technology, additional volume on the vehicle is required when compared to diesel (total mass is often similar when the mass of the powertrain components is considered, not illustrated in Figure 2).

Figure 1: Lower Heating Value Energy Density of Various Fuels (DOE, 2020)[2]



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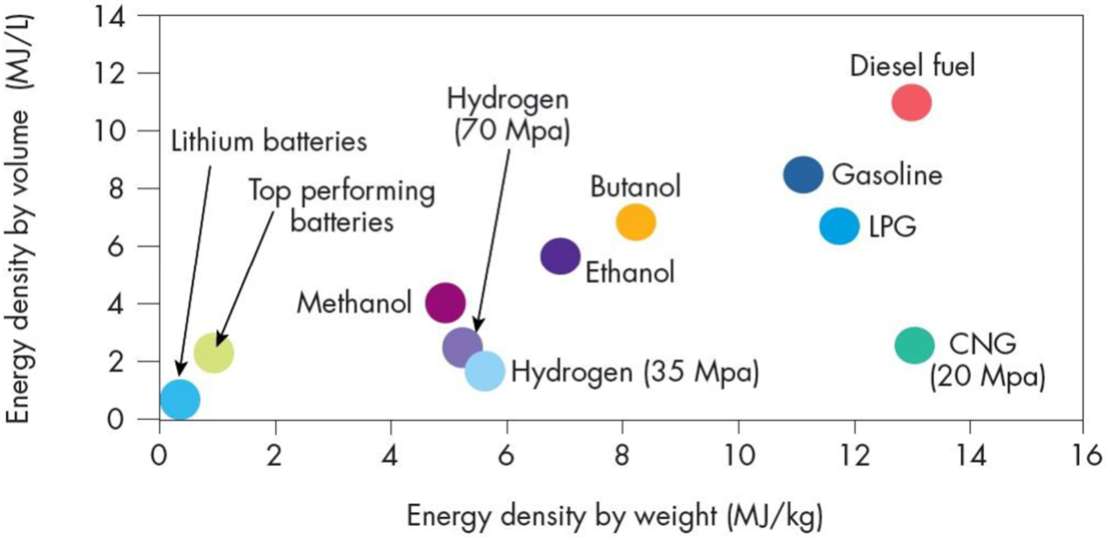
[2] U.S. Department of Energy. (accessed 2020) Hydrogen and Fuel Cell Technologies Office: Hydrogen Storage. Available at https://www.energy.gov/eere/fuelcells/hydrogen-storage

Figure 2: Energy Density of Various Fuels and Energy Carriers Adjusted by Weight and Volume of Typical Tank Systems and Accounting for Representative Powertrain Efficiencies in Vehicles (IEA, 2009)[3]



Hydrogen is not a greenhouse gas itself and its combustion with air results in water and small amounts of NOx, but the latter can be avoided if hydrogen is used in a fuel cell. Hydrogen is an attractive option for an alternative fuel because it:

- does not contain any carbon;
- can be produced from many feedstocks enabling zero-emissions from well-to-wheel;
- can be used in fuel cells, therefore avoiding all harmful emissions;
- has a relatively high energy density; and
- can function as large-scale energy storage.

1.3 Hydrogen Fuel Cell System

Fuel cells are electrochemical devices where a fuel, in this case hydrogen, is combined with oxygen from the air to produce electricity, heat, and water (predominantly in vapor form). Several different types of fuel cell technologies exist and can provide power in a range of applications, such as utility power stations and material handling equipment. The most popular hydrogen fuel cell (HFC) option for vehicles and in some stationary power applications is the proton exchange membrane also known as the polymer electrolyte membrane (PEM).[4] PEM fuel cells are being employed in almost all vehicle applications, such as cars, buses, forklifts, and trains. Their high efficiency, low operating temperature, start-up capabilities, and relatively long operating lifetime make them the preferred option. An illustration of the operation of a PEM fuel cell is provided in Figure 3.

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[3] International Energy Agency (IEA). (2009). Transport, Energy and CO2: Moving Toward Sustainability. France: Paris.

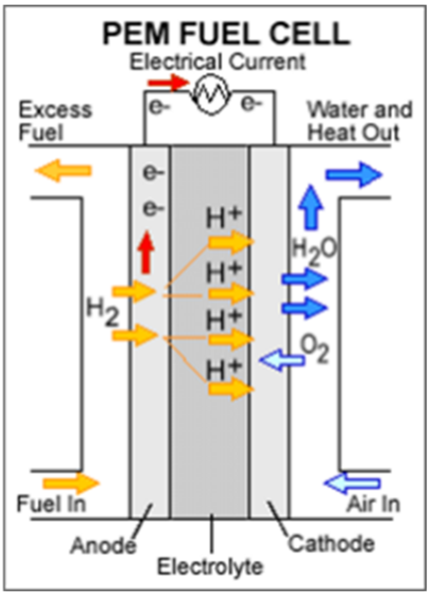
[4] Department of Energy, 2016.

The process of obtaining electricity in a PEM fuel cell can be explained in three stages:[5]

1. Hydrogen enters the cell at the anode side where the hydrogen molecule is split into atoms.
2. An anode catalyst separates the electrons from the atom creating hydrogen ions. These hydrogen ions pass to the cathode, whereas the electrons must move across an electric circuit to arrive at the cathode.
3. Oxygen is directed to the cathode, where it combines with the hydrogen ions and electrons to form water, which then leaves the cell.

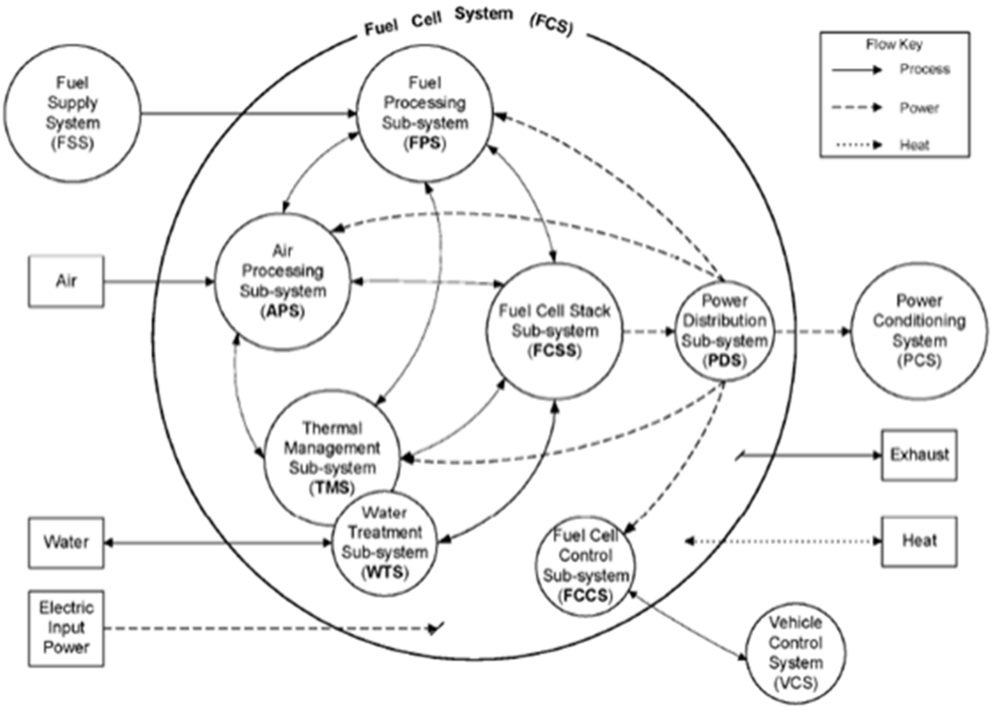
Individual cells do not produce sufficient power for most applications, including vehicles, so several cells are combined into a stack. One or several fuel cell stacks are combined with hydrogen, air, and thermal management components, referred to as balance-of-plant, to create a fuel cell system (FCS). The generic components of an FCS are illustrated in Figure 4. For heavy-duty vehicle applications, typical power output levels are 30kW, 50kW, 80kW, 100kW, and 200kW. If more power is required, several FCSs are combined.

Figure 3: Diagram of a Proton Exchange Membrane (PEM) Fuel Cell



Source: Department of Energy, 2011

Figure 4: General Schematic of a Fuel Cell System



Source: Society of Automotive Engineers International, 2011.

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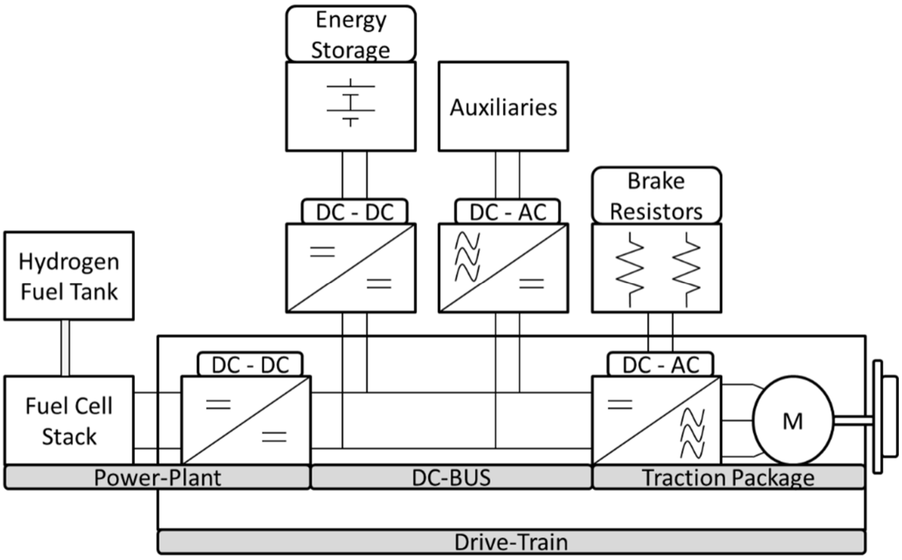
[5] Schlapbach, 2009.

1.4 Hydrogen Fuel Cell - Battery Hybrid System

In a hydrogen fuel cell hybrid powertrain, at least two power sources are combined, e.g. an FCS and battery. This provides operational benefits such as reduced energy consumption, potential for increased peak power and the option to reduce FCS size. In a hybrid configuration the primary power plant (e.g. a FCS) provides the average power often with an added power margin due to redundancy and reliability considerations. The batteries allow the vehicle to meet the peak power demand during acceleration and can provide power to operate onboard heating, ventilation and cooling systems if the primary power plant is not available. Batteries can also enable energy recapture through regenerative braking to reduce overall energy consumption. Figure 5 illustrates a hybrid powertrain configuration.

Figure 5: Illustration of a Hybrid Powertrain



Source: Andreas Hoffrichter, 2013

Batteries and the FCS are sized according to the anticipated duty cycle. A ‘mild’ hybrid is where the average power is relatively close to peak power and a small battery system is installed. A ‘heavy’ hybrid is where the peak power is significantly higher than the average power and a large battery system is installed. In hydrogen fuel cell hybrids, it is often economical to downsize the FCS due to the comparatively high cost per power unit. Batteries provide the peak power demands for a short period, while the hydrogen FCS provide the base load power over the duty cycle. The FCS is typically sized to be larger than average power requirements for redundancy and reliability considerations. Adding a battery allows for less drastic cycling of the FCS, thus increasing its lifetime. The majority of hydrogen fuel cell vehicles have a hybrid powertrain.

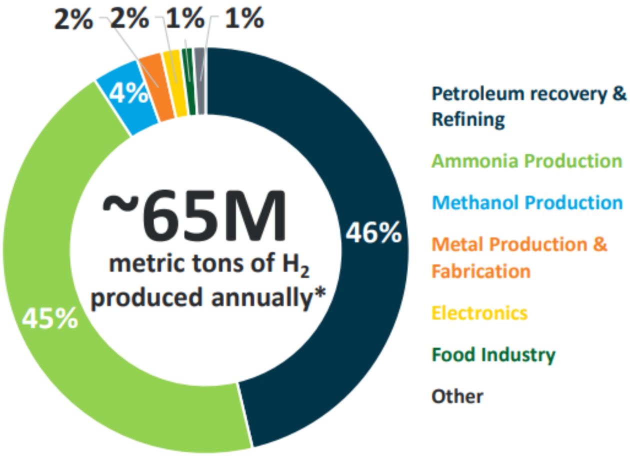
Hybrids can also be designed with ‘plug-in’ capability, which allows the charging of the battery from wayside source. Such an arrangement can be implemented to enable battery charging at maintenance facilities overnight, or during operations at stops or terminus stations depending on dwell and turnaround times.

1.5 Industry Trends for Hydrogen

Hydrogen is widely used in the industrial sector for refining petroleum, treating metals, producing fertilizer and processing foods. Figure 6 provides a breakdown of the volume of global annual hydrogen use in these sectors. For these applications, 98% of the hydrogen produced is derived from fossil fuels such as through natural gas reforming and coal gasification and only 2% is derived from electrolysis.[6]

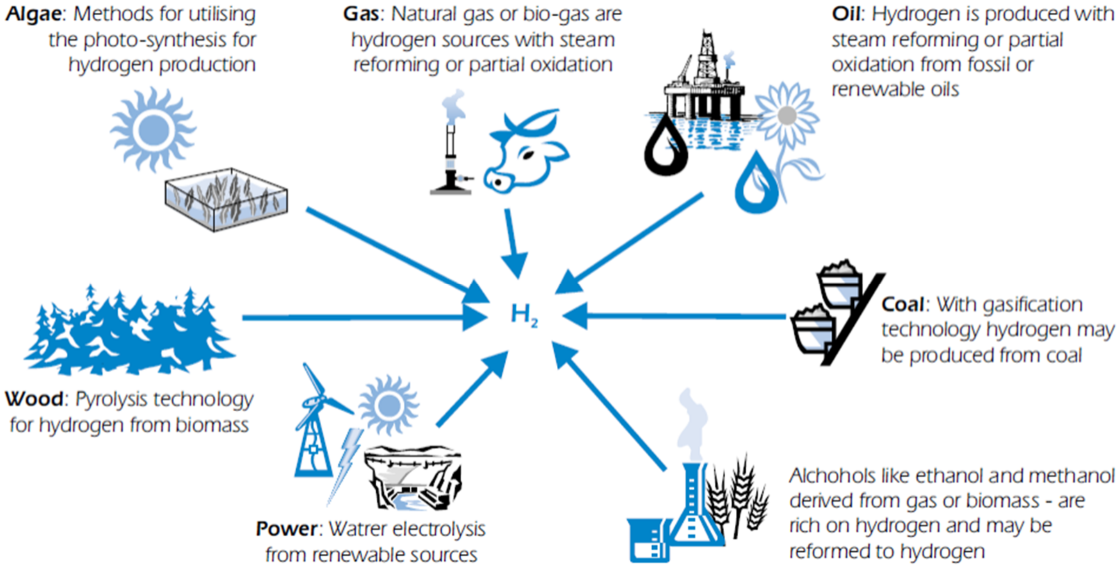
However, hydrogen is more amenable to decarbonization the industrial process than fossil fuels because it can be produced through more sustainable means such as electrolysis. Figure 7 provides some examples of feedstock for hydrogen production.

Figure 6: Global Annual Hydrogen Production/Demand



Source: Department of Energy, 2017

Figure 7: Illustration of Feedstocks for Hydrogen Production



Source: International Energy Agency, 2006

Globally and nationally there has been significant investment in scaling up water electrolysis deployment. Since the early 2000s more than 200 electrolyzer projects have been implemented worldwide.

Hydrogen fuel cell application has also seen a continuous growth in the market, particularly in the logistics and transportation industries. As of 2020 more than 35,000 HFC forklifts were

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[6] Rissman, J. How Hydrogen Could Become a $130 Billion US Industry by 2050. Forbes, 2019.

operating across the U.S., highlighting the growing shift in transforming warehousing and distribution centers. Fuel cell vehicles are also available to consumers, manufactured by Toyota, Honda, and Hyundai. In 2020, it was estimated that there were more than 8,800 fuel cell vehicles on the road in the U.S. Increasingly, the number of hydrogen fuel-cell buses in operation are also on the rise. There are over 60 HFC buses on the road in the U.S. most of which are operating in California.[7] SunLine Transit Agency in California's Coachella Valley has been running hydrogen fuel-cell buses for over 15 years. Nearby in Santa Ana, California, the Orange County Transportation Authority (OCTA) debuted its hydrogen fueling facility in early 2020.

Currently, fuel cells have provided more than 500 MW of stationary power for use in energy systems and power generation in buildings, telecommunication sites, and more.[6] The continued investment in research and development are catapulting hydrogen as a safe and reliable energy carrier in a myriad of applications worldwide.

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[7] U.S. Department of Energy Hydrogen Online Conference. October 8, 2020

2 Transportation Applications

2.1 Introduction

There has been an increase in the use of hydrogen as a safe and efficient alternative fuel/energy carrier in transportation applications. Most hydrogen-fueled vehicles in operation today are automobiles, transit buses, and material handling equipment powered by a hydrogen fuel cell system. Development of fuel cell rail vehicles has been slower to progress due to barriers in commercialization implementation and operating cost and limits in range. However, recent technology advancements have meant hydrogen and fuel cells have become a feasible alternative to diesel for rail applications.

There are many examples of hydrogen vehicles operating safely and efficiently around the world. The following sections provide an overview of local and international examples of various vehicle types that are either in demonstration or operation.

2.2 Railway

There has been increased interest and investment to further expand the use of hydrogen fuel cells in the railway industry. Currently, there are a limited number of alternative self-powered propulsion options for railways, and the majority of commuter or freight trains still operate with diesel power, particularly in the U.S. However, with the desire to improve air quality and reduce greenhouse gas emissions around the world, and with the rising price of diesel, there is a clear emerging trend for regional self-powered trains in Europe and Asia to be powered by alternative technologies like hydrogen fuel cells. Most hydrogen fuel cell rail vehicles developed to date are hybrids. The addition of a battery enables downsizing of the FCS and provides peak power for acceleration, allows for energy recapture through regenerative braking and can provide ancillary power if the FCS is not operating. The following sections highlight some of the recent successful hydrogen fuel cell rail vehicle projects currently operating throughout the world.

2.2.1 Coradia iLint – Germany Example

Alstom, a major rail vehicle manufacturer, has deployed two regional fuel cell trains in northern Germany. These trains have been in regular passenger service since September 2018. The two multiple units have covered over 180,000km to date and are soon to be supplemented by 12 additional trains, with a second order placed for an additional 27 trains for operation elsewhere on the German network. The iLINT is depicted in Figure 8.

Figure 8: Coradia iLINT

Source: Alstom, 2018

The iLINT design is based on a modified diesel multiple unit where the diesel engine and transmission are replaced by a PEM hydrogen fuel cell system, batteries, power electronics and traction motors. This design is similar to what is to be expected on the San Bernardino County Transportation Authority's Zero Emission Multiple Unit Project. Underfloor Lithium Nickel Manganese Cobalt Oxide (NMC) battery packs work in partnership with the FCSs on the roof to boost power during acceleration and store braking energy, with overall performance improved compared to the diesel multiple units operated on the route. The operating range between refueling is approximately 620 miles in the current service, and the maximum operating speed is 90mph.

Approximately 200kg to 260kg of hydrogen are stored at 350bar onboard the train, enabling daily refueling. The hydrogen for the two in-service trains is supplied as a liquid by truck, then gasified before dispensing. A temporary, mobile refueling arrangement is employed as it allowed travel with the train to different test locations during development. Liquid hydrogen delivery was selected to minimize delivery frequency. A permanent refueling station to serve the full fleet of 14 trains is currently under construction. In that phase, hydrogen will be delivered as a compressed gas in a tube trailer, followed by construction of an on-site electrolyzer to produce hydrogen utilizing locally generated electricity from wind power.

Alstom successful completed 530 days of trial operations for two of its vehicles this year to demonstrate that hydrogen can be used safely as a method of propulsion for passenger rail vehicles. [8]

2.2.2 BNSF Hydrogen Locomotive – US Example

Between 2005 and 2011, Vehicle Projects developed, designed, constructed, and tested a hydrogen-hybrid switcher locomotive in collaboration with BNSF and the U.S. Army Corps of Engineers. The intent was to demonstrate, as a proof-of-concept, technology feasibility in rail operations and as back-up power supply for military bases or in natural disaster situations.

The locomotive was converted from a low-emissions diesel hybrid switcher (also known as Green Goat) and powered by two PEM fuel cell systems from Ballard, providing 250kW, and lead-acid batteries to achieve peak power of 1.5MW. The observed mean power requirement was 67kW. Approximately 60kg of hydrogen were stored at 350bar. The vehicle was tested in the Los Angeles rail yards in Commerce and Hobart for three months. After the railway trials the locomotive was transferred to a military base to demonstrate the back-up power capability. After successful demonstration of proof-of-concept, it was decided to upgrade the locomotive to a road-switcher, doubling the fuel cell power to 500kW.

The project was discontinued due to difficulties regarding the timeframe for project completion, associated funding, combined with an issue that developed in one of the original fuel cell system. An additional factor in abandoning the project was the significant reduction in diesel fuel cost and the increasing interest in natural gas options. At the time, the technology was not deemed to be cost-effective for freight operations due to the significant capital and infrastructure requirements for a fleet of hydrogen locomotives. In the freight rail industry fuel is among the top three operating expenses, so it is critical that alternative fuels minimize costs and reduce emissions. Ultimately, the project demonstrated that hydrogen could be a viable fuel for freight switcher locomotives if overall costs become financially feasible for operators. The vehicle and supporting facility were under operation for six months in demonstration mode. During operation, the project developed a safety information handout for train crews and to educate the local fire department and other first responders.[9]

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[8] Alstom, Successful Year and Half of Trial Operation of the World's First Two Hydrogen Trains, May 2020.

[9] Gladstein Neandross & Associates, BNSF Railway, 2020.

Figure 9: BNSF Hydrogen Hybrid Switch Locomotive

Source: Ballard

2.2.3 Doha Msheireb Tram – Qatar with California Manufacturing Example

A new tram line launched in December of 2019 in the city of Doha, Qatar's capital, where the service is operated by a fleet of three hydrogen hybrid vehicles. The vehicles were supplied by TIG/m, a California based railway vehicle manufacturer. The propulsion system is battery-dominant due to the duty cycles, employing lithium-iron phosphate batteries and fuel cells. The trams do not require an overhead contact system, which minimizes infrastructure needs and aesthetic impacts. The vehicles can operate for 20 hours before recharging is required. As of February 2020, the developer estimates that vehicles have carried over 40,000 riders along the 2km route through downtown Doha.

2.2.4 HydroFlex – UK Example

HydroFlex is the United Kingdom's first full-scale, hydrogen-powered passenger train. It is a bi-mode fuel cell train where the existing electric powertrain has been modified to enable power provision from wayside infrastructure or the on-board hydrogen fuel cell hybrid system. The bi-mode (or dual-mode) enables it to run on both electrified and non-electrified lines. The new design enables power provision from overhead lines wherever available, and swapping over to hydrogen elsewhere.

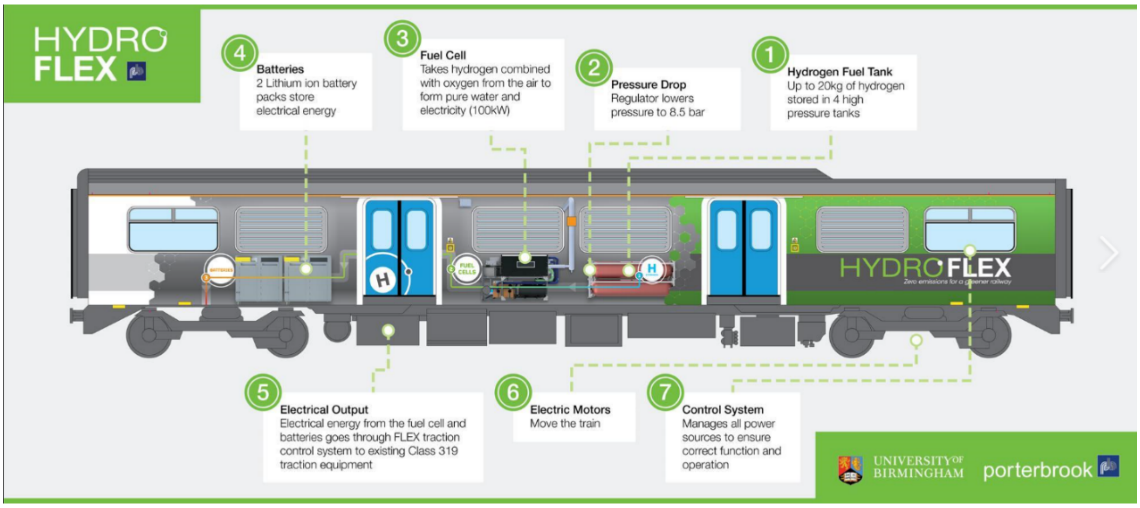
The University of Birmingham has developed the bi-mode powertrain and is supporting the introduction of these units, with a demonstrator that began running in summer 2019. The fuel cell system for the prototype was supplied by Ballard and the lithium-based traction batteries were provided by Denchi Power. The traction power available when running on electricity provided through the overhead contact system is 1000kW with a top speed of 100mph. When running on non-electrified lines, the traction power is lower, but appropriate for regional and branch line operation.

The demonstrator train has four hydrogen tanks, a fuel cell system and lithium ion batteries installed in one of the converted passenger cars of the four-car multiple unit. The intent is to advance the design with the objective to mount the powertrain equipment in locations that do not impact passenger seating capacity, such as under the floor and on the roof.

Figure 10: HydroFlex Vehicle

Source: Porterbrook Leasing, 2018

Figure 11: HydroFlex Schematic Design



Source: Global Railway Review, June 2019

2.2.5 CRRC Hydrogen Fuel Cell Tram – China Example

The China Railway Rolling Stock Corporation (CRRC) is the world's largest railway vehicle manufacturer and produced the first multi-car hydrogen-powered tram globally, which began operation in the City of Tangshan in 2017. The design is based on the Skoda ForCity 15T, and the fuel cell system is provided by Ballard. Ballard's fuel cell systems have undergone rail specific testing to determine how the FCS will perform in rail operating conditions and allow for mitigation of any hazards. The testing included vibration and shock, noise, dust ingress, fire suppression etc.

The fuel cell system has been combined with batteries and supercapacitors that enable the trams to operate without overhead wires. This has been particularly beneficial for congested city centers where overheard wires are difficult or not feasible to implement. The trams have a range of 40km on a single 12kg hydrogen fill-up. CRRC has also produced a fleet of eight hydrogen fuel cell-powered trams for a new light rail line in the city of Foshan. The trams will operate the 17km line at speeds of up to 70km/h. A similar fleet of 7 trams are already in service on a partly electrified 9km line in Qingdao.[10]

Figure 12: CRRC Trams Operating in Tangshan

Source: China Railway Rolling Corporation, 2017

2.3 Heavy Duty Vehicles

Hydrogen-powered, heavy-duty vehicles have been deployed in larger numbers than trains and are on a faster track to widespread commercialization, particularly buses. Heavy-duty trucks are still in the early stages of deployment but have demonstrated successful operating capabilities. Several local and global bus applications have demonstrated the safe and efficient usage of hydrogen fuel cells. There are strict safety protocols in place to govern the operation and fueling of hydrogen vehicles to limit the risk for leaks and potential ignition. Buses are equipped with hydrogen detectors to detect if a leak has occurred. If a leak has occurred, vehicle operators can activate an emergency button to immediately switch off the fuel cell system. Collision sensors are also available to activate a safe shutdown sequence that locks the hydrogen storage tanks and isolates high-voltage components from the system.[11] Periodic

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[10] Metro Report International. Qingdao Opens Fuel Cell Tram Route, 2016.

[11] Sustainable Bus, 2019.

inspection and leak testing for equipment is required to maintain safe usage. Training staff is also a critical safety component. Relevant personnel such as bus operators, maintenance technicians, fueling personnel, station maintenance staff, and first responders must receive training on the properties and hazards of hydrogen.

2.3.1 SunLine Transit Agency – California Example

SunLine Transit Agency is a local agency in Coachella Valley, California, that has been operating hydrogen fuel cell buses for over 20 years. SunLine produces its own hydrogen and has invested in hydrogen fueling infrastructure to serve its growing fleet and reduce the cost of hydrogen.[12] SunLine has been producing hydrogen onsite since 2000 and has demonstrated successful production of hydrogen using both onsite electrolysis as well as a natural gas reformer. Sunline has also demonstrated successful onsite production of hydrogen using solar power. More recently, SunLine completed a new Nel proton exchange membrane (PEM) electrolyzer to increase hydrogen production capacity and meet the demand of over 32 fuel cell buses. Sunline has plans to increase their fleet capacity further to 67 fuel cell buses.[13] Current onsite storage is approximately 900 kg of hydrogen in nine ASME tubes and a tube trailer with another 16 ASME tubes. Hydrogen is dispensed into the vehicles at a pressure of up to 350 bar (~5000 psi).[14] Public hydrogen fueling is also available at both 350 bar and 700 bar. The agency has progressed from hydrogen FCS pilot projects to the proliferation of this technology into their regular operating fleet, aided by the availability of a relatively “off the shelf” hydrogen-battery hybrid 40-foot bus by various manufacturers including New Flyer and American-made El Dorado National bus. Sunline has plans to fully transition its entire fleet to zero emissions by 2035.

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[12] Mott MacDonald. ZEMU Concept Feasibility Study, 2019.

[13] Mass Transit. SunLine’s Fleet will be emission free by 2035, 2020.

[14] National Renewable Energy Laboratory. Sunline Transit Agency Advanced Technology Fuel Cell Bus Evaluation: Second Results Report, 2011.

Figure 13: SunLine Transit's Hydrogen Fuel Cell Bus

Source: SunLine Transit

2.3.2 Orange County Transportation Authority – California Example

The Orange County Transportation Authority (OCTA) is another California agency that has deployed a hydrogen fuel cell bus fleet. The agency was previously operating compressed natural gas (CNG) buses, but in early 2020, OCTA debuted their hydrogen fueling station to fuel their hydrogen bus fleet. OCTA has liquid hydrogen delivered to its facility in Santa Ana, California, then vaporize the hydrogen to a high-pressure gas, which is then pumped into the buses, a similar process to the one employed in the iLINT train in Germany. Their facility currently operates 10 fuel cell buses but is sized to operate 50 buses in the future.

As a part of their transition from CNG to hydrogen, OCTA was also required to complete upgrades to the maintenance facility. This included minor upgrades to the heating, ventilation, and air conditioning (HVAC) system and hydrogen and flame detection.

2.3.3 Wrightbus – UK Example

Transport for London has been operating hydrogen fuel cell buses since 2010. Currently, the agency has 10 single-decker hydrogen fuel cell buses in its fleet. Due to the successful use of hydrogen fuel cell buses, there are now plans to acquire 20 new double-decker hydrogen buses.[15] These are expected to be in operation in late 2020 and will mark the world's first ever hydrogen-powered double-decker buses.

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[15] Transport for London. Bus Fleet Audit March 2019.

2.3.4 Toyota/Kenworth HFC Truck – California Example

Toyota, Kenworth, and Shell have partnered to develop a prototype fuel cell semi (truck) designed to carry containers from California coastal ports to the inland distribution centers. The two fuel cell stacks are based on those in Toyota's Mirai car (just over 200kW in total) and are combined with a 12kWh battery to give the truck 670 horsepower and 1,325 foot-pounds of torque. This enables the truck to easily out-accelerate a conventional diesel semi, albeit with a much lower range of 300 miles for the second-generation truck (first generation shown in Figure 14), but sufficient for the anticipated duty cycle.

Toyota has previously been reluctant to apply their advanced fuel cell and hydrogen tank technology to applications other than personal vehicles. However, this development suggests that they are now ready to engage with applications in the heavy-duty transport market. Toyota is now prepared to have 10 trucks of the second generation be built after having the first generation do 10,000 miles of real-world service. In Japan, the company is partnering with JR East railway to develop a hydrogen fuel cell multiple unit train.

Figure 14: First generation Toyota Fuel Cell Semi Truck

Source: Toyota, 2018

2.3.5 Nikola Hydrogen Trucks

Figure 15: Nikola Hydrogen Fuel-Cell Truck on Display

Source: Nikola Motor Company, 2020

Nikola Motors is an American truck startup company that researches, develops, and deploys semi and pickup trucks powered by alternatives fuels. The company is developing a hydrogen fuel cell powered semi (truck), with a number of prototype vehicles already in operation. The truck incorporates a 320kWh battery and 300kW fuel cell to generate 1,000 horsepower and 2,000 foot-pounds of torque, which enables the truck to comfortably out-accelerate conventional diesel semis. Each truck carries 100kg of hydrogen – sufficient to provide a range of 1,200 miles. Anheuser-Busch, a brewing company, has ordered 800 trucks for operation in the U.S.

Nikola plans to initially have 56 refueling stations in operation by 2019, with the intention to expand this to 700 by 2028. Nikola is partnering with NEL, one of the world's main electrolyzer manufacturers to deliver this network; the operating costs are expected to be considerably lower than for comparable diesel trucks.

2.4 Light Duty Vehicles – Passenger Vehicles and Material Handling Equipment

Hydrogen-powered passenger vehicles and material handling equipment such as forklifts are commercially available in several countries, including the United States, Japan, South Korea, and Germany. Hydrogen forklifts have experienced the highest adoption on the market thus far, where more than 35,000 are being used in warehouses of major distributors such as Amazon and Walmart. Plug Power is a company that has ben designing and manufacturing hydrogen fuel cell systems for applications in material handling, e-mobility, and stationary power. The company was launched in 1997 and indoor forklifts were their first viable market. Plug Power has provided material handling equipment to companies such as Whole Foods, Home Depot, FedEx, and Carrefour. It is expected that over the next five years this market will continue to grow and will also see an emergence of medium and large-sized hydrogen-powered cars.[16]

Three models of fuel cell electric vehicles are already available to the public in California (Toyota Mirai, Honda Clarity, and Hyundai ix35/Tuscon) with 10 additional models slated for release by the end of 2020. Toyota will be releasing a second generation Mirai in 2020 that offers a 30 percent increase in range through a more efficient fuel cell system and additional hydrogen capacity. Generally, a passenger car's hydrogen propulsion system is similar to that of railway vehicle and heavy-duty applications differences between the two include onboard hydrogen storage capacity or pressure and the sizing and design of the fuel cell stacks. Passenger cars tend to employ 700 bar (10,150 psi) pressure tanks compared to 350 bar (5075 psi) in heavy-duty applications such as buses. The pressure difference enables more hydrogen storage in the same available volume, which is more limited in a car than in a bus. As of 2017,

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[16] Hydrogen Council. Hydrogen Scaling Up: A Sustainable Pathway for the Global Energy Transition, 2017.

fuel cell electric vehicles have had more than 20 million kilometers or 12.4 million miles of real-world driving experience and satisfy all relevant safety certifications and regulations.[9]

2.5 Hydrogen Storage and Refueling

To support operations of hydrogen vehicles, a storage and refueling facility is required. Often operators will also consider whether onsite production is feasible to lower operating costs by reducing their price per kilogram of hydrogen. A key safety consideration for production and storage/refueling sites is proper ventilation, detection, parts, and installation of parts. Hydrogen can present different risks and hazards than diesel should a leak occur. Facilities should be designed to ensure adequate ventilation, have hydrogen and flame detection and emergency response procedures in the event of a leak. Another key consideration is reducing as much as possible the risk of ignition in the event of a leak by ensuring mechanical and electrical equipment within the facility is classified for hydrogen use (i.e. spark proof). Dispensing of hydrogen as a fuel can present similar risks as any application handling hydrogen. Regular inspection of the component parts, emergency off switches, and leak checks immediately prior to refueling are all key considerations. Leak check detection is often automated as part of the standard installation of hydrogen sensors at refueling equipment.

Hydrogen storage and refueling sites have established codes, standards and safety protocols based on hydrogen's widespread usage in industrial practices for 50 years. Today, there are more than 40 public hydrogen refueling stations located in the U.S., with the majority in California. These refueling stations provide examples of the safe handling of hydrogen related to a transportation application.

The Center for Hydrogen Safety and their Hydrogen Safety Panel are a resource for collaboration on new hydrogen projects. They provide information online related to codes, standards, training resources and lessons learned to assist in the design and development of new storage and fueling stations. They also provide links to papers and references to other recently completed studies for risk and hazard assessments for design of fueling and storage sites including Sandia National Laboratories Hydrogen Risk Assessment Model (HyRAM) software program.

2.6 Hydrogen Delivery

Hydrogen is delivered from its production site location to the point of end-use, such as a dispenser at a refueling station. It can often be more economical to generate hydrogen onsite as it reduces transportation costs, but when this is not an option, hydrogen can be easily and safely transported. Infrastructure needed for delivering hydrogen can include pipelines, tanker trucks, storage facilities, compressors, chillers and dispensers. Hydrogen is regularly transported as either a gas or liquid:

- Gaseous hydrogen is typically delivered through pipelines or trucks. Most existing hydrogen pipelines in operation today are installed at oil refineries and have been used safely for decades. Key safety considerations for gaseous hydrogen transport include maintaining proper pressure in storage, control of ignition sources, embrittlement of pipes, leak detection and isolation, and appropriate ventilation.
- Liquid hydrogen is delivered via super insulated, cryogenic tanker trucks. Gaseous hydrogen is liquefied by cooling it to cryogenic temperatures. Hazards associated with handling liquid hydrogen are similar to those of gaseous hydrogen with added hazards resulting from the low pressure and cold temperature. Liquid hydrogen is less frequently used given the increased costs and energy required to produce liquid hydrogen, as well as the potential for boil-off during delivery.

Liquid delivery however is becoming more common given the increased energy storage density in a liquid format. Over long distances, hydrogen transport by truck in liquid format is more economical that in gaseous form as a liquid tanker can hold a larger quantity then a gaseous tube trailer.[17] Steel tube trailers have a carrying capacity of approximately 280 kg of hydrogen due to the heavy weight of steel tubes. Composite storage vessels have recently been developed that can deliver 560-720 kg of hydrogen per trail. LH2 tanker trucks can have a capacity of up to 4,000 kg of hydrogen.[18] Delivery frequencies can be dramatically reduced for a liquid versus a gas, which can make it a more attractive option for transit operators. As the technology develops, it is expected that liquid production and delivery will become more efficient and cost effective. The U.S. Department of Energy has complete analyses on the relative benefits of various hydrogen storage and transportation technologies and this information can be applied to new projects looking to assess the relative cost versus benefits of potential options.

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[17] Department of Energy, Office of Energy Efficiency and Renewable Energy. Liquid Hydrogen Delivery, 2020.

[18] US Drive. Hydrogen Delivery Technical Team Roadmap. June 2013.

3 Industrial Applications

3.1 Introduction

In the U.S. almost all the hydrogen produced is consumed by industrial applications, such as in oil refineries, producing fertilizer, and in processing foods. The longstanding presence of hydrogen in industrial processes have demonstrated safe production, handling, and storage in daily operations for over five decades. Hydrogen fuel cells have also been making a breakthrough in power generation systems for buildings and back-up power systems for major companies around the globe, including in back-up power supply for communication towers employed by the U.S. railway industry. The following sections summarize how these industries have been using hydrogen, safely and efficiently, in their operations.

3.2 Hydrogenation in Industrial Applications

The largest users of hydrogen are the petroleum-chemical and fertilizer production industry. Hydrogenation is the main process used in industrial applications to solidify, preserve or purify many products, raw materials or ingredients. The petroleum industry uses hydrogenation to remove sulfur and heavy refinery products from natural gas and crude oil. This creates lighter petroleum products such as diesel, gasoline, and other products. Ammonia used in fertilizers is produced by combining nitrogen and hydrogen under pressure and temperature using a metal catalyst.

In food processing, the most commonly hydrogenated product is vegetable oil. Hydrogen is used to convert unsaturated fats into saturated oils and fat, such as those found in peanut butter and margarine. Hydrogen gas is added to a heated pressure vessel that contains liquid vegetable oil and other chemicals, creating a hydrogenation reaction. The oil mixture is then cooled to allow it to solidify. The pharmaceutical industry uses hydrogen to manufacture vitamins, hydrogen peroxide and other pharmaceuticals.

Many of the industries that use hydrogen produce it on-site or have it delivered by pipelines as a gas. In the U.S., there are 1,600 miles of hydrogen pipelines in operation and these have been used to safely transmit hydrogen for decades. Therefore, hydrogen safety requirements for industrial uses are relatively well established. The National Fire Protection Association (NFPA) and the Compressed Gas Association (CGA) have published safety standards that address the storage, use, and handling of hydrogen in industrial applications that date back to the first edition of NFPA 567 (later renumbered as NFPA 50A) (National Fire Protection Association 1963) circa 1960. The safety measures are similar to those discussed in earlier sections of this report.

3.3 Electricity and Power Generation

Hydrogen fuel cells can produce electricity through the chemical reaction that results when combining hydrogen and oxygen atoms. Large fuel cells can be used to provide electricity for back-up generators, telecommunication sites, or to buildings off the power grids. These fuel cell systems are usually paired with a battery and include compressed hydrogen storage.[19] Hydrogen production and delivery for these uses is similar for other applications of hydrogen, in that hydrogen can either be delivered or produced on-site. In 2019, there were 80 fuel cell power plants operating in the U.S. Major companies such as Microsoft, Adobe, Apple, Union

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[19] Department of Energy. Early Markets Fuel Cells for Backup Power, 2014.

Pacific, and AT&T have been increasingly investing in hydrogen fuel cells for primary and backup power.[20] Hospitals require constant power for their daily operations 24/7 and fuel cells have been increasingly considered and implemented as more efficient form of backup power to meet their needs.[21]

3.4 NASA Applications

The National Aeronautics and Space Administration (NASA) has been using hydrogen since the agency was founded in 1958. Initially, NASA started to use hydrogen as rocket fuel to propel its space shuttles. Additionally, the agency has now transitioned to using hydrogen in other applications, such as using hydrogen fuel cells as a method of generating electricity onboard space stations, and to create water and breathable oxygen for crew members while in space.

For years, NASA was the largest consumer of liquid hydrogen in the United States.[22] Liquid hydrogen was used with oxygen as a propellant for various Apollo missions and was transported in large quantities and stored in liquid storage tanks at their launch facilities. Today, the majority of hydrogen purchased by NASA is in liquid form as liquid hydrogen offers volumetric and purity benefits. More energy can be stored in a smaller volume of hydrogen when compared to gas and freezing hydrogen into liquid form removes most contaminants. Another benefit is that liquid hydrogen is stored at lower pressures, therefore high-pressure tanks are not required during transportation and storage, which can also reduce the need for certain additional safety considerations related to high pressure.

NASA purchases their hydrogen from various suppliers including Air Products, Praxair and Air Liquide. Their requirements are unique in that they need large quantities at a time (estimated to be 6 truckloads or roughly 20 tons of hydrogen per delivery). Accepting large quantities at one time helps to reduce energy loses as vehicles and transfer equipment is cooled for a single transfer, rather than multiple smaller deliveries. This also helps to reduce boil-off losses, which when handling large quantities can have an impact to overall costs.

Boil-off during transfer and storage has presented such a challenge for NASA that they have focused their efforts on developing better technologies for the storage of cryogenics. It was estimated that roughly half of the liquid hydrogen purchased to fuel one of their space shuttle's three main engines was lost due to boil-off evaporation during storage and transfer operations. As a result of their research and findings, NASA has retrofitted their largest storage facility at the Kennedy Space Center to reduce boil-off (see Figure 16 below). The previous storage tank (roughly 850,000 gallons), which was well designed per standards in 1965, was using outdated technology. The tanks have been retrofit with an Integrated Refrigeration and Storage System, which actively removes heat from the liquids within the storage tanks and dramatically reduces losses due to evaporation.

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[20] Fuel Cell & Hydrogen Energy Association. Fuel Cell-Powered Data Centers, 2018.

[21] Fuel Cell & Hydrogen Energy Association. Fuel Cells and Hospital Applications, 2010.

[22] National Aeronautics and Space Administration, Space Applications of Hydrogen and Fuel Cells, 2017

Figure 16. Newly Refurbished Liquid Hydrogen Storage Tank at Launch Pad 39B at NASA's Kennedy Space Center

Source: National Aeronautics and Space Administration (NASA), 2017

In addition to research and development on transportation and handling of hydrogen, NASA is also focused on development at the components and sub-components level, looking at material compatibility as well as evaluating durability of materials. Studies at their White Sands facility also focus on explosion and leak testing under various scenarios. NASA publishes information on past incidents and lessons learned, which are made publicly available on the US DOE's H2 Tools website. Relevant examples can also be referred to at the end of this report.

Finally, NASA offers various hydrogen specific training programs targeted to both engineers and designers, as well as handlers and technicians. Their focus on hazard and risk analyses of hydrogen has made them a leader in the U.S. hydrogen industry.

4 Hydrogen Safety Considerations

The properties of hydrogen are different to commonly used liquid fuels, such as gasoline or diesel. Some of these properties make it safer than conventional fuels, such as being non-toxic and not resulting in toxic emission if combusted in air (i.e., no toxic smoke). The low radiant heat of burning hydrogen can also be an advantage as fewer areas are directly impacted. Additionally, hydrogen is the lightest element, significantly lighter than air, leading to relatively quick dissipation in case of release.

However, some of the properties require additional engineering controls for its safe use. The wider range of flammable concentrations in air and relatively low ignition energy result in easier ignition compared to conventional fuels. Adequate ventilation and leak detection are essential in a safe hydrogen system design. Flame detectors are required as hydrogen burns nearly invisibly. In addition, some materials including certain metals can become brittle when exposed to hydrogen for long periods of time. Appropriate material selection for hydrogen pipes and storage tanks is necessary. Hydrogen can also leak into adjacent pipes, so hydrogen pipes should be installed above others to prevent this from occurring. Similar to natural gas, hydrogen is colorless and odorless making it difficult for humans to detect. It is possible to add an odorant, as the industry does for natural gas, however the odorant tends to damage fuel cells. Instead, hydrogen sensors have been used by the hydrogen industry for decades with success.

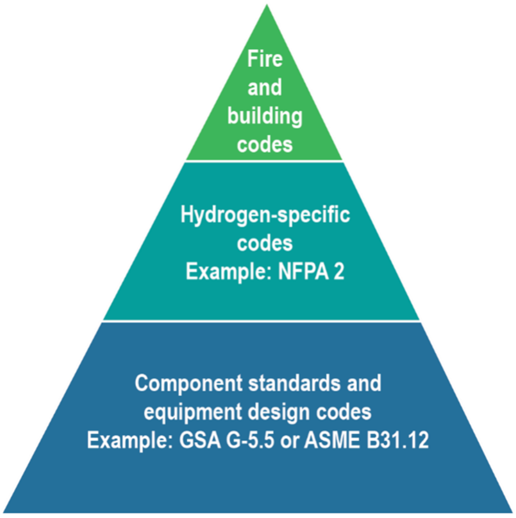
Hydrogen gas is typically stored and dispensed at very high pressures, which poses its own hazards. Careful design, certification, operation and inspections of vessels and dispensers used for hydrogen systems must be implemented for safe use. Various organizations and agencies offer guidance and standards for safe hydrogen operations, such as the Society of Automotive Engineers (SAE) and the U.S. Department of Energy. In addition, non-profit hydrogen advocacy groups, such as the Center for Hydrogen Safety (CHS) and California Fuel Cell Partnership (CaFCP) can provide guidance and oversight to projects during design development based on their experience on past projects in the U.S. and internationally.

4.1 Codes and Standards

There are codes and standards that control the use of hydrogen technologies in a way similar to other commonly used fuels. It should be noted that the use of hydrogen as a fuel for propulsion is a relatively new technology and therefore codes and standards are continuing to be developed and refined as the technology and nature of the projects advance. Codes and Standards are better established for stationary applications of hydrogen (i.e. storage) given hydrogen has been used in industrial applications for longer.

Figure 17 shows a hierarchy of current codes and standards applied to most hydrogen projects to date. The top of the pyramid consists of building and fire codes that are directly adopted by jurisdictions and are therefore the law in the jurisdiction in which they are adopted. Any code or standard referenced in the body of a building or fire code adopted by a jurisdiction becomes a legally enforceable document in that jurisdiction. These reference documents must be written in an enforceable format to be referenced in building or fire codes. The second level of the pyramid illustrates documents related to hydrogen technologies. Key documents at this second level include the NFPA 2 Hydrogen Technologies Code and the NFPA 853 Standard for Fuel Cell Energy Systems. These documents contain references to component standards, which comprise the bottom level of the pyramid. These component standards must also be written in legally enforceable text to be referenced by these second-level codes and standards. Examples of these documents include the CGA S series of documents for pressure relief devices and the American Society of Mechanical Engineers (ASME) B31.12 standard for piping. Together these documents address key aspects of system design, construction, operation, and maintenance.[23]

Figure 17: Hierarchy of Codes and Standards for Hydrogen



Source: National Renewable Energy Laboratory

4.2 Material Compatibility

Appropriate material selection and material compatibility is a critical aspect for safe hydrogen infrastructure development. Material selection is an important consideration given the properties of hydrogen can embrittle metals and can also permeate through its storage containers. For example, high-strength steel is subject to embrittlement while many other forms of steel and aluminum are unlikely to be affected given typical operating conditions. Sandia National Laboratories has addressed this risk by completing studies into the impacts of hydrogen on specific materials in order to provide guidance on material compatibility for hydrogen infrastructure. This information is published online.[24] Further analyses will be required for material selection for both transportation applications as well as stationary storage and refueling facilities as the technology develops and is more widely applied in the industry.

4.3 Hydrogen Safety Training

Education on the safe handling of hydrogen and appropriate training for personnel working with or around hydrogen infrastructure is important for risk and hazard mitigation. Development of safety and emergency procedures and training programs should take place for any new hydrogen project. The California Fuel Cell Partnership and Center for Hydrogen Safety provide reference information for training programs online for safe hydrogen handling. Existing transportation applications such as SunLine Transit have also developed extensive training programs for their vehicle operations and refueling which they made publicly available as reference information.

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[23] Burgess, R., Buttner C., & Rivkin C. National Renewable Energy Laboratory. Hydrogen Technologies Safety Guide, 2015.

[24] https://granta-mi.sandia.gov/mi-viewer/index.aspx

4.4 Safety Incidents

The Hydrogen Safety Panel established by the Center for Hydrogen Safety compiled safety incidents in a database to track incidents related to hydrogen and has categorized them according to materials, equipment, and activities. Incidents that are relevant to transportation applications include pressure relief devices, hydrogen cylinders, piping, industrial trucks, and fueling stations. Appendix A summarizes the incidents and describes what occurred.

5 Conclusion

This report is meant to provide the FRA with examples and information of the safe use of hydrogen and fuel cells in various transportation and industrial applications. This reference material will support the SBCTA Zero Emissions Multiple Unit Project as it progresses through the design and environmental processes and approval processes with the FRA. Community outreach is essential to educate the public and stakeholders on the safe uses of hydrogen so this document could support those efforts as well. The project is expected to be operational by 2024.

Appendix A: Summary of Hydrogen Safety Incidents

Type of Incident	Equipment/Activity Involved	Date	Description
Pressure Relief Device Incidents	Incorrect Relief Valve Set Point Leads to Explosion	Dec 31, 1969	During a standard testing procedure, a 3000-psig relief valve actuated at normal line pressure, releasing gaseous hydrogen. The gaseous hydrogen combined with air, resulting in an explosion which damaged the test facility. The relief valve was improperly set to open at line pressure, and the inspection was inadequate in that it didn't identify this error. A contributing cause was poor design of the venting system, which was installed in a horizontal position, causing inadequate venting and buildup of static electricity.
Hydrogen Cylinder Incidents	Leaking Hydrogen Cylinder	Mar 13, 2012	An alarm sounded at a recently inaugurated hydrogen fueling station in a major metropolitan area. Of the 120 high-pressure hydrogen cylinders located on the roof of the fueling station, one failed in service. Gaseous hydrogen was leaking from a screw fitting of the cylinder, but the hydrogen was not ignited. Three hydrogen gas sensors detected the leakage and triggered an alarm that resulted in an immediate emergency shutdown, isolating the leaking high-pressure cylinder bank from the other three banks and notifying the local fire department. There was no ignition.
Piping Incidents	Laboratory Compression Fitting Installation	Sep 30, 2004	While research staff were working in a laboratory, a staff member opened the primary valve to a 0.2-inch (1500 psi) hydrogen gas line connected to an instrument supply manifold. When the valve was opened, the hydrogen gas line failed at a fitting on the switching manifold, releasing a small amount of hydrogen gas. The staff member closed the valve immediately, then inspected the gas line and found the front ferrule (of the compression-style fitting) to be missing. There were no injuries or damage to equipment. Start-up testing was considered less than adequate because it would have normally caught this type of leakage before introduction of hydrogen. The person installing the compressed gas line into a compression style fitting tee failed to include the front ferrule. Later, when the line was pressurized at 1500 psi, the fitting and line separated. It was learned from the research staff that approximately 1 month earlier, a similar condition (front ferrule missing from a fitting) was found while performing a modification to a similar manifold.
Piping Incidents	Check Valve Shaft Blow-out	Nov 4, 1997	Several workers sustained minor injuries and millions of dollars' worth of equipment was damaged by an explosion after a shaft blew out of a check valve. The valve failure rapidly released a large vapor cloud of hydrogen and hydrocarbon gases, which subsequently ignited. The valve had a shaft or stem piece which penetrated the pressure boundary and ended inside the pressurized portion of the valve. When this penetration happened, an unbalanced axial thrust on the shaft occurred, which would tend to force it, if unconstrained, out of the valve. In this case, the shaft was retained by a dowel pin, which also transmitted torque from the shaft to the disk. The dowel pin was made from hardened steel and may have been subjected to hydrogen embrittlement. The valve repeatedly slammed shut with great force during compressor trips and shutdowns. Such repeated loads may have caused propagation of cracks in the dowel pin. System pressure at the failure point was approximately 300 psig. Most modern valve designs incorporate features that reduce or eliminate the possibility of shaft blow-out. However, certain types of check and butterfly valves can undergo shaft-disk separation and fail catastrophically or "blow-out," causing toxic and/or flammable gas releases, fires, and vapor cloud explosions. Such failures can occur even when the valves are operated within their design limits of pressure and temperature. 10 Several design and operational factors may have contributed to this

Type of Incident	Equipment/Activity Involved	Date	Description
			failure. The valve contains potential internal failure points, such as shaft dowel-pins, keys, or bolts such that shaft-disk separation can occur inside the valve. The dimensions and manufacturing tolerances of critical internal parts (e.g., keys, keyways, pins, and pin holes) as designed or as fabricated cause these parts to carry high loads. Two-piece valve stems ("stub shafts") that penetrate the pressure boundary (resulting in a differential pressure and unbalanced axial thrust as described above), single-diameter valve shafts (i.e., shafts with internal diameters smaller than the diameters of their packing glands), or shafts without thrust-retaining devices (such as split-ring annular thrust retainers) are susceptible to blow-out. These valves are subject to high cyclic loads. Valves used in hydrogen-rich or hydrogen sulfide-containing environments may be more susceptible to blow-out due to hydrogen embrittlement of critical internal components, particularly if these are made from hardened steel (as was the dowel pin in this incident).
Piping Incidents	Hole Rubbed in Hydrogen Piping	Dec 31, 1969	During inspection of a hydrogen make-up compressor, it was discovered that a 1/4-inch stainless steel screw and nut that mounted a temperature gauge to a stainless-steel pipe was resting against the side of a schedule 160 high-pressure hydrogen pipe. Constant vibration of the process equipment had caused the bolt to rub a hole in the high-pressure suction piping, resulting in the release of make-up hydrogen. The pipe was out of sight, and the problem was identified by an employee who heard the whistling sound of escaping hydrogen. The compressor was taken offline and depressurized.
Piping Incidents	Failure of Stainless-Steel Valves due to Hydrogen Embrittlement	Aug 19 1986	Difficulties were experienced with two solenoid-operated globe valves in a charging system. When shut, the valves could not be reopened without securing all charging pumps. During a refueling outage, the two valves were disassembled and examined to determine the cause of the malfunction. It was found that the springs of the disc guide assembly in both valves had undergone complete catastrophic failure. The springs, which initially had 25 coils, were found in sections of 11 only 1-2 coils. Metallurgical analysis of the failed springs attributed the probable cause of failure to hydrogen embrittlement. The springs are made of 17-7 PH stainless steel. Discussion with the valve manufacturer revealed that similar failures occurred on three previous occasions. These spring failures were also attributed to hydrogen embrittlement.
Piping Incidents	Ball Valve Fails to Open Due to Valve Stem Failure	Feb 6, 2008	A safety research laboratory experienced two similar air-actuated ball valve failures in a 6-month period while performing hydrogen release experiments. The hydrogen release system contains several air-actuated ball valves which are sequenced by a programmable logic controller (PLC). During an experimental release sequence, a PLC valve command failed to open the valve even though the PLC signal indicated the valve had opened. On further investigation, the researchers discovered that the valve actuator and valve stem were found to be moving correctly, but the valve was not opening. The system was depressurized and purged with nitrogen, and the valve was removed for inspection. Inspection required dismantling the valve, and in both incidents a sheared valve stem was found. The valve stem failures occurred after 8 to 14 months of continuous hydrogen operation at pressures of 800 to 850 bar (11,603 to 12,328 psi). The two failed hydrogen valves were identical and rated by the valve manufacturer for hydrogen service. 12 The cause of this incident has not been determined, but valve stem material incompatibility with hydrogen (causing a material weakening) is suspected, although it could also have been a design flaw. Review of the valve manufacturer's drawings showed the valve stem material to be 17-4 precipitation hardening stainless steel that has been reported in the literature as having a 90% reduction in fracture toughness in a hydrogen environment. No metallurgical analysis was done on the failed valve stems to confirm the mode of failure. The valves were repaired with new valve stems made from 316 stainless steel,

Type of Incident	Equipment/Activity Involved	Date	Description
			placed back in service, and have operated satisfactorily for 18 months without failure.
Industrial Truck Incidents	Government Warehouse	Jul 21, 2011	A significant hydrogen leak occurred during refueling of the onboard hydrogen storage tank of a fuel cell-powered lift truck while it was completely depowered. The in-tank shutoff solenoid valve had recently been replaced, and this was the initial refueling event after the replacement. The fuel zone access panel was removed to allow constant visual leak checking with Snoop leak-detection fluid. The event occurred during the final pressure testing of the repaired system when an O-ring failed at approximately 4500 psi, releasing the entire contents of the hydrogen tank in about 10 minutes. The dispenser hose/nozzle was immediately disconnected, and the leak location was quickly isolated to the tank/valve interface. A 30-foot boundary around the lift truck was cleared of personnel and equipment. The combustible gas detector mounted on the wall above the hydrogen dispenser did not alarm because a large overhead facility fan was providing ventilation throughout the event. The leaking hydrogen did not ignite, no one was injured, and there was no property damage as a result of this event. The fuel cell systems for the lift trucks were originally built by Company A and placed into service in 2009. Company B assumed the service and support responsibilities in 2011, and then subcontracted the service labor to Company C. The only instructions given to Company C regarding the tank valve and the O-ring were to follow the tank valve manufacturer’s torque specification for ensuring a seal. Shortly after this event occurred, an investigation was undertaken by Company B. Company C reported that the O-ring was clean, lubricated, and tight when installed. However, after removing the failed tank and valve from the lift truck for investigation, it was noted that there was insufficient insertion depth of the in-tank solenoid valve, and the O-ring was not able to provide a sufficient seal due to inadequate compression at the tank/valve interface. This situation was caused by the internal thread of the tank that did not allow full engagement at the specified tank manufacturer’s torque requirement, and this geometric discrepancy was confirmed by comparison with a new tank that had been purchased as a spare. The investigation revealed that the tank threads were modified on other tanks of this same model, but not on the specific tank involved in this event. Thus, the tank would have required substantially more torque than provided to fully compress the O-ring as intended (i.e., much more than the manufacturer’s recommended torque specification).
Industrial Truck Incidents	Ball of Fire from Hydrogen Fuel Cell Forklift	Feb 8, 2011	A fuel cell forklift operator stated that he observed a "ball of fire" coming from the left side of the forklift that seemed to flash and extinguish. Investigators found no external signs of a fire, but the forklift would not start. The fuel cell power pack access panel was removed to enable investigators to search for any internal signs of a fire. Some areas inside the fuel cell stack appeared to have experienced an electrical arc or some type of overheating. All connections were verified to be tight and secure. The internal fuel cell stack circuit board cover was then removed, and the circuit card on top of the stack also showed signs of overheating. After the fuel cell stack circuit board was removed, a broken drill bit was discovered on top of the fuel cell stack plates. Evidently, the drill bit was jostled around when the forklift was operated, causing a spark and fire inside the fuel cell stack that burned the circuit card. It is unclear how the drill bit got where it was on top of the fuel cell stack plates. Records indicated that there had not been any maintenance performed on this fuel cell pack that would require drilling. In addition, an inventory check of technician tools used for fuel cell stack assembly accounted for all drill bits.
Industrial Truck Incidents	Fuel Cell Evaporator Pad Fire	Dec 9, 2010	The evaporator pad in a fuel cell power unit installed in a hydrogen-powered forklift caught fire during operation. The evaporator pad is used for wicking the product water created by the fuel cell. The operator dismounted the forklift, observed flames coming from the fuel cell unit, and

Type of Incident	Equipment/Activity Involved	Date	Description
			called for help. The facility fire brigade used a fire extinguisher to put out the fire. The upper left corner of the fuel cell evaporator pad was burned entirely; the plastic bracket that holds the evaporator pad in place was distorted; there was some discoloration of the radiator. No injuries were sustained by the operator and no damage was sustained by the forklift. The fuel cell unit continued to run during the incident, as did the onboard data acquisition device. Hydrogen concentrations from an array of six hydrogen sensors around the unit during low and high duty cycles measured at less than 0.2%. The root cause of the fire that burned the evaporator pad and distorted the plastic evaporator pad bracket remains unknown.
Fueling Station Incidents	Fueling Hose Fails	Jun 11, 2007	The evaporator pad in a fuel cell power unit installed in a hydrogen-powered forklift caught fire during operation. The evaporator pad is used for wicking the product water created by the fuel cell. The operator dismounted the forklift, observed flames coming from the fuel cell unit, and called for help. The facility fire brigade used a fire extinguisher to put out the fire. The upper left corner of the fuel cell evaporator pad was burned entirely; the plastic bracket that holds the evaporator pad in place was distorted; there was some discoloration of the radiator. No injuries were sustained by the operator and no damage was sustained by the forklift. The fuel cell unit continued to run during the incident, as did the onboard data acquisition device. Hydrogen concentrations from an array of six hydrogen sensors around the unit during low and high duty cycles measured at less than 0.2%. The root cause of the fire that burned the evaporator pad and distorted the plastic evaporator pad bracket remains unknown.
Fueling Station Incidents	Fitting Failures for Fueling Equipment	Sep 19, 2007	Two fitting failures occurred in the filling systems of the fueling equipment. Both fittings were installed in the system thermal chamber experiencing ambient temperatures of -40 °C (-40 °F) to 50 °C (122 °F). They were connected in high-pressure lines used for 70-MPa hydrogen fueling. The first fitting, a 0.25-inch national pipe tapered (NPT) hose connection, was in service for approximately 1 year with no signs of leakage. The failure was noticed when the system was pressurized during a filling sequence. The failure was discovered by an audible hissing noise during leak checking. The system was depressurized and the fitting removed and replaced. The system was re-pressurized with no further leakage. When technicians attempted to reconnect a second fitting for a double-ferrule high-pressure connection, it would not re-seal. The nut would not spin freely on the tubing and had created gouge marks. The fitting was replaced and no further leakage occurred. 33 For the use of mechanical fittings in hydrogen service, administrative controls should be in place, as in this case, to ensure that leak testing is conducted on a regular basis. It should never be assumed that every fitting is tight. Additional discussion of best practices for fittings and joints can be found in the Hydrogen Safety Best Practices Manual.
Fueling Station Incidents	Leak on Liquid Hydrogen Tank at Fueling Station	Dec 19, 2004	A valve packing started to leak during cold ambient temperatures. A technician was dispatched. He first reduced the pressure to minimize the release and then re-tightened the packing to stop the leak. The fueling station staff included inspection on monthly preventive maintenance plan and evaluated alternate materials for better cold-weather performance.
Fueling Station Incidents	Leak on Compressor	Oct 05, 2009	A vehicle fill depleted the high-pressure hydrogen inventory. The compressor turned on to refill the storage by compressing 60 psig gas from a liquid hydrogen tank up to the 5500 psig storage pressure. After running about 2 hours, a crankshaft bearing started to fail. This allowed greater movement of the shaft, which led to a shaft seal leaking hydrogen. The compressor shut down on low suction pressure and then the system was shut down using the e-stop by the emergency responders. 34 A gas detector was added in close proximity to the compressor shaft and a vibration switch is under consideration. Additional predictive measures are

Type of Incident	Equipment/Activity Involved	Date	Description
			being considered to predict bearing failure. In addition, the manufacturer has been contacted and the bearing design is being analyzed to see if it can be improved.
Fueling Station Incidents	Hydrogen Delivery Truck Causes Hydrogen Leak at Fill Station	Aug 25, 2008	A hydrogen leak occurred at a hydrogen fill station when a vendor's hydrogen fill truck trailer pulled away after filling and caught an improperly stored hydrogen fill line. The driver of the hydrogen truck trailer did not properly stow the hydrogen fill line after filling and failed to verify that the hydrogen fill line was clear of the trailer prior to departure. As the driver pulled away from the fill station, the hydrogen fill line caught on the trailer and subsequently pulled on the hydrogen fill station's ground storage tubes' distribution manifold. The force of this pull bent the hydrogen distribution manifold and hydrogen began leaking from a threaded connection and from the hydrogen fill line. The truck trailer driver reported hearing a "pop and hissing sound," stopped the truck movement, and then promptly left the truck to report the incident at approximately 6:45 p.m. The local fire department was contacted, and the building was evacuated. The fire department arrived by 8:00 p.m., along with the hydrogen vendor's service technician, to isolate the hydrogen leak. The hydrogen leak at the plant's hydrogen ground storage system was stopped by closing the individual valves on each hydrogen storage tube, thereby isolating the distribution manifold. At 10:00 p.m., the all clear was given. Hydrogen operations were restored to the plant the next day by removing the damaged hydrogen ground storage unit and replacing it with a hydrogen tube trailer with concrete barriers installed to provide protection. The hydrogen leak from this event caused no hydrogen fire/explosion or personnel injuries.
Fueling Station Incidents	Pressure Relief Device Fails	May 04, 2012	A pressure relief valve failed on a high-pressure storage tube at a hydrogen fueling station, causing the release of approximately 300 kilograms of hydrogen gas. The gas ignited at the exit of the vent pipe and burned for 2-1/2 hours until technicians were permitted by the local fire department to enter the station and stop the flow of gas. During this incident, the fire department evacuated nearby businesses and an elementary school, closed adjacent streets, and ordered a high school to shelter in place. There were no injuries and very little property damage. The corrugated roof on an adjacent canopy over a fueling dispenser was slightly singed by the escaping hydrogen flame, causing less than $300 in damage. The station's operating systems worked as they were designed to function in an emergency. All equipment and fuel supplies were completely isolated, and all storage vessels were well within acceptable and safe pressure and temperature limits prior to and throughout the incident. 36 After a thorough analysis of the incident was conducted, corrective actions were taken to replace pressure relief valves, heighten vent stacks, modify response procedures, and improve communication protocols with first responders. A considerable amount of time was taken to review the station design, evaluate emergency action plans and procedures, meet with the public, train first responders, and conduct follow-up drills with employees and first responders. The station reopened 9 months after the incident and has been fully operational since that time. Three root-causes were noted during the investigation: (1) the use of incompatible materials in the manufacturing of the PRD valve, (2) improper assembly resulting in over-torqueing of the inner assembly, and (3) over-hardening of the inner assembly materials by the valve manufacturer.
Fueling Station Incidents	Fueling Station High Pressure Storage Leak	Jun 10, 2019	A hydrogen leak originating from a tank within a high-pressure storage unit serving a hydrogen vehicle fueling station resulted in fire and explosion. Emergency responders arrived on scene within 7 minutes and contained the fire within 3 hours. No damage was reported to the separate forecourt hydrogen dispenser or to other major station components within the station backcourt compound. No personnel injuries resulted directly from the fire and explosion, but a nearby vehicle airbag was triggered due

Type of Incident	Equipment/Activity Involved	Date	Description
			to the explosion pressure, with minor injuries to the vehicle occupants. Immediately after the explosion, all potentially affected hydrogen stations were idled until the root cause was determined. The root cause of the incident was subsequently identified as an assembly error of a specific plug in a hydrogen tank in the high-pressure storage unit. The inner bolts of the plug had not been adequately torqued. This led to a hydrogen leak, creating a mixture of hydrogen and air that ignited. The source of ignition has not been positively identified. An inspection and integrity verification program for the high-pressure storage units with similar plugs was implemented, including check and re-torque of tank plugs. Additional measures implemented include revised assembly, verification, and documentation of procedures as well as increased automated leak detection frequency. Dependent on site, additional ignition control measures are considered, including loose gravel removal/smooth surface around the high-pressure storage unit, additional backcourt compound ventilation, and higher extent use of explosion-proof components.
Fueling Station Incidents	Fueling Station High Pressure Storage Leak	Jun 1, 2019	On Saturday, June 1 Santa Clara Fire Department extinguished a fire at Air Products and Chemicals, Inc. in Santa Clara. At approximately 4:30 p.m. firefighters from the Santa Clara Fire Department responded to reports of an explosion and fire at a chemical, gas storage and transportation facility near the 1500 block of Norman Avenue. When crews arrived on scene at Air Products and Chemicals, Inc., they located multiple hydrogen tanker trucks on fire in the facility yard. Businesses in a two-block radius were evacuated or advised to shelter in place for approximately two hours. The fire was reported extinguished as of 5:40 p.m. Additional air sampling and thermal imaging was conducted to ensure air quality, and that the hydrogen, which is not visible when burning in the daytime, did not pose a threat. Early interviews with Air Products and Chemicals, Inc. employees indicated that a hydrogen tanker truck was being fueled and a leak occurred, When the shutdown of the tanker truck that was being fueled occurred, an explosion resulted. The explosion damaged the emergency shutoff panel and valve near the tanker. Workers were able to shut off two valves but couldn’t shut off the valve near the original tanker truck. The tanker caught on fire, which spread to other tankers nearby. Only some tankers in the fueling area were affected and the fire didn’t spread beyond that area. No civilians or firefighters reported injuries at the incident. The exact cause of the explosion and subsequent fire is under investigation.

Source: Center for Hydrogen Safety, Hydrogen Safety Panel. Hydrogen Incident Examples, 2020

Source: Santa Clara Weekly, “Hydrogen Gas Explosion and Fire at Air Products and Chemicals Inc.” June 4, 2020.

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