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Report on General Hydrogen Safety

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CONTENTS

LIST OF FIGURES

1. BACKGROUND

Hydrogen is an important resource for many different industries throughout the world, including refining, manufacturing, and as a direct energy source. Hydrogen production, through methods such as steam methane reforming, has been developed over several decades. There is a large global demand for hydrogen from these industries and safe production and distribution are paramount for hydrogen systems. Codes and standards have been developed to reduce the risk associated with hydrogen accidents to the public. These codes and standards are similar to those in other industries in which there is inherent risk to the public, such as gasoline and natural gas production and distribution. Although there will always be a risk to the public in these types of fuels, the codes and standards are developed to reduce the likelihood of an accident occurring and reduce the severity of impact, should one occur.

This report reviews the current state of hydrogen in the United States and outlines the codes and standards that ensure safe operation of hydrogen systems. The total hydrogen demand and use in different industries is identified. Additionally, the current landscape of hydrogen production and fueling stations in the United States is outlined. The safety of hydrogen systems is discussed through an overview of the purpose, methods, and content included in codes and standards. As outlined in this safety overview, the risk to the public in operation of hydrogen generation facilities and fueling stations is reduced through implementation of appropriate measures. Codes, such as NFPA 2, ensure that the risk associated with a hydrogen system is no greater than the risk presented by gasoline refueling stations.

2. HYDROGEN BACKGROUND

Hydrogen is the lightest molecule in the universe and is a gas at ambient conditions. Because it is 14 times lighter than air, it rises at almost 20 m/s (44 mph) and disperses rapidly. For application in outside environments, the buoyancy constitutes a built-in safety advantage because the fuel will not pool near potentially sensitive targets. Hydrogen gas is non-toxic and non-poisonous, although it can be an asphyxiant at high concentrations. Hydrogen is flammable and explosive over a wide range of concentrations and has a low ignition energy. [1].

It should be noted that hydrogen has been used for industrial purposes for over 50 years. The codes, standards and design practices have been developed to enable safe use of this fuel source. There are over 70 million metric tons of hydrogen produced globally every year for use in many different industries. As with any fuel, hydrogen must be used with care in systems designed around its properties because it can be hazardous if handled improperly. The hazards for hydrogen are different than that of gasoline due to its unique properties. For example, when there is a gasoline leak, a pool may form on the ground that can be ignited. Also, the leaked fuel can spill into gutters or drains. However, hydrogen is lighter than air and readily disperses. Therefore, a hydrogen leak may result in a hydrogen-air mixture ignition which would resemble a torch that is forced in one direction by the pressure. However, built-in safety systems are implemented to avoid leaks, thus avoiding the opportunity for fuel to ignite [2].

As noted, hydrogen has been used in a variety of industries for over 50 years. These applications include:

- Petroleum refining
- Glass purification
- Semiconductor manufacturing
- Aerospace applications
- Fertilizer production
- Welding, annealing and heat-treating metals
- Pharmaceuticals
- As a coolant in power plant generators
- For hydrogenation of unsaturated fatty acids in vegetable oil.

In addition to these traditional uses of hydrogen, newer applications include forklifts, cars, and trucks powered by hydrogen fuel cells. There are several large companies and government agencies that utilize fuel cell forklifts, such as Walmart, Whole Foods, Bridgestone Firestone, Coca Cola, and Amazon. In most of these applications, the hydrogen is stored outside and the dispensers for refueling the forklifts are located indoors. Also, hydrogen fuel cells are used in stationary applications to provide uninterruptible power supply for hospitals and data centers, backup power for regional emergency shelters, and power for telecommunications in remote locations [3].

3. HYDROGEN PRODUCTION AND REFUELING

3.1. Steam Methane Reforming

Hydrogen must be separated from other elements in the molecules where it occurs in production. Although there are many different sources and methods for production, the most common is steam methane reforming (SMR). Industrial reforming technology was established in 1936 in Billingham, UK [4]. In this process, hydrogen atoms are separated from carbon atoms in methane using high-temperature steam as a catalyst. Through the reaction, hydrogen, carbon, monoxide, and a relatively small amount of carbon dioxide are produced. Natural gas is the main source of methane in this process [5]. Currently, close to 80% of hydrogen is produced through SMR. The worldwide demand for hydrogen in 2020 was 90 Mt, with more than 70 Mt used as pure hydrogen [6].

In the United States, 10 million metric tons of hydrogen are produced annually, with the majority of production from SMR. Large production facilities are located in nearly every state with around 1,600 miles of hydrogen pipeline for transportation [7]. Figure 1 shows the hydrogen production facilities located in the United states. As shown, there are a substantial number of hydrogen generation facilities located in the Midwest.

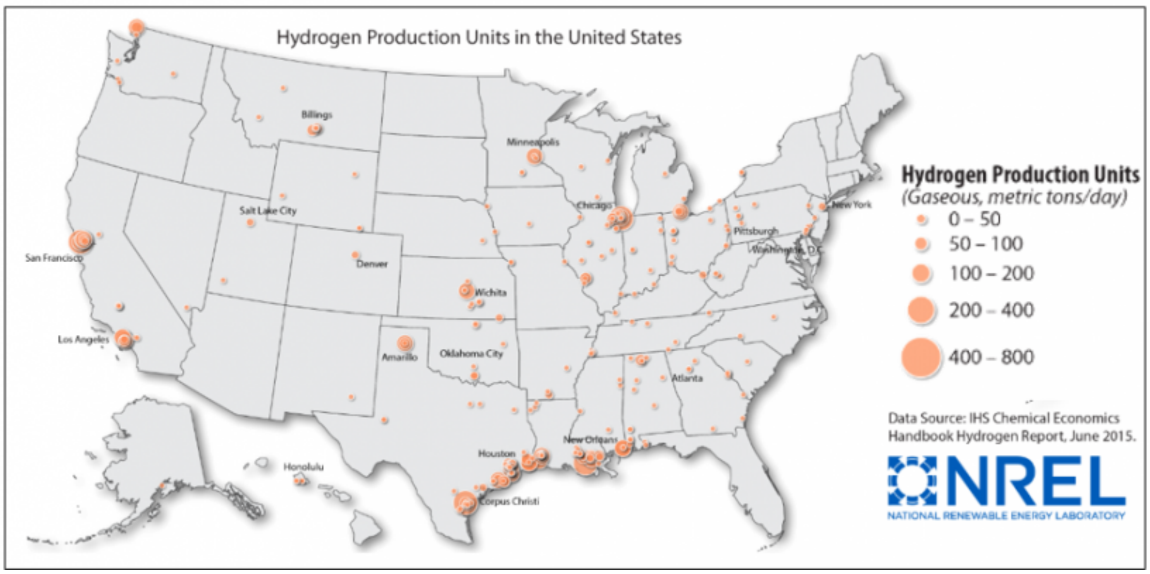

Figure 1: Hydrogen Production in the United States [7]

3.2. Hydrogen Refueling

To support the increased production of fuel cell electric vehicles, hydrogen fueling stations have been developed in select markets. There are several manufacturers offering production fuel cell electric vehicles in select markets, including Honda, Hyundai, and Toyota. This has been most prevalent in California, where hydrogen fuel is being offered at existing gasoline stations in northern California near San Francisco and southern California near Los Angeles and San Diego [8]. Figure 2 shows a map of current hydrogen fueling stations in California. As shown, most stations are clustered in urban areas, with stations in destination locations like Santa Barbara, Napa and Truckee. Additionally, there is a station in Coalinga so a driver can refuel on a trip from San Francisco to Las Angeles [9].

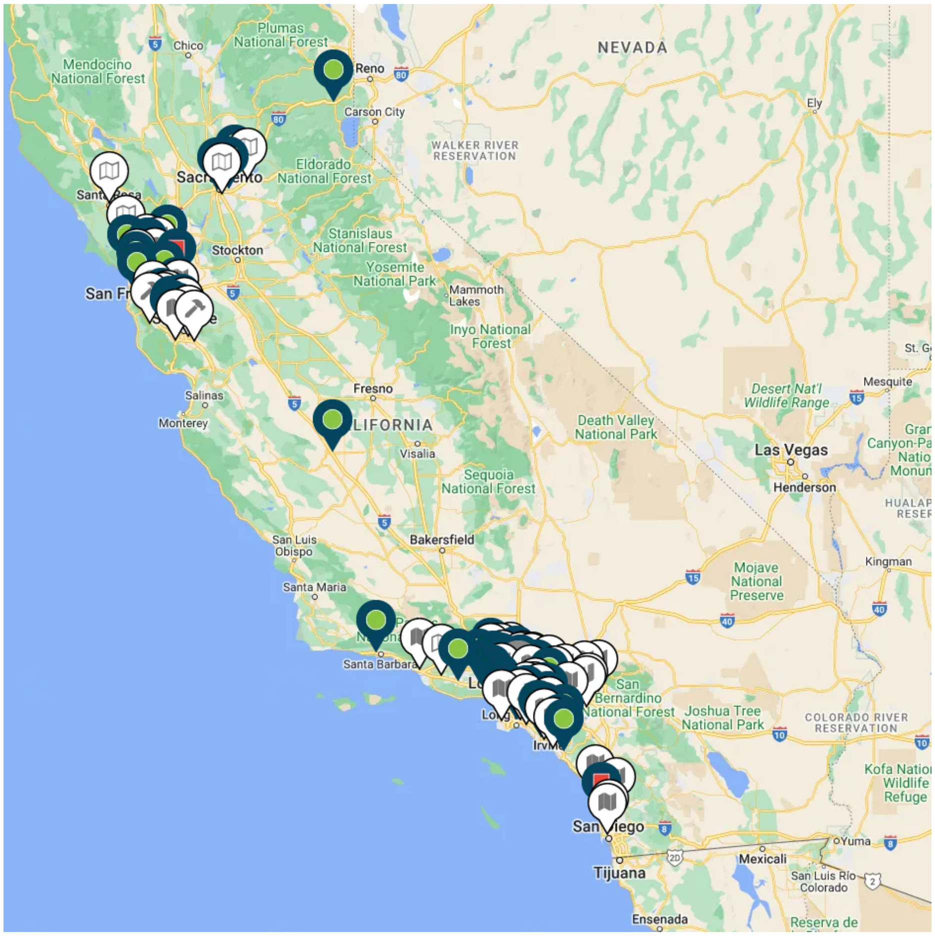

Figure 2: Hydrogen Fuel Station Map in California [9]

3.3. General Safety

In safety analysis, the system pressure of a flammable gas determines the extent of damage if a leak event occurs. For systems with high pressure, a leak event may result in negative consequences (e.g., dispersion, overpressure, etc.) with large zones of influence. Utilization of high pressure is necessary to compress these flammable gases for ease of storage and transportation. However, with the steam methane reforming (SMR) method of hydrogen production, the system is relatively low-pressure. The BayoTech SMR hydrogen generation facility operates at pressures less than 200 psi. For comparison, a liquid propane tank for home use is typically pressurized between 100-200 psi. Therefore, if a leak event occurs within the system, the extent of dispersion is relatively low. Additionally, there are interlocks and sensors within the system that are meant to detect and isolate a leak should one occur. These interlocks would stop production and minimize the impact of a leak.

Another aspect that may affect the extent of damage of an aspect is the quantity of on-site storage of a flammable gas. Flammable gases are compressed prior to being stored to minimize the volume of the stored fuel. When compressed, the pressure increases which could potentially increase the zone of influence should a leak occur. When there is more storage at a facility, there is more energy available for detonation which would impact the extent of damage. For hydrogen refueling facilities without onsite production, there must be a considerable storage system on-site to meet customer demand over a given time period. However, with onsite production, the need for high storage capacity is greatly reduced. BayoTech will utilize a buffer storage system of roughly 1 day of production from the onsite system. This greatly reduces the on-site presence of high-pressure hydrogen when compared to facilities without onsite production.

4. HYDROGEN SYSTEM SAFETY

As noted in by National Renewable Energy Laboratory (NREL) [10], there are range of applicable codes and standards relevant to hydrogen fuel dispensing facilities. These include the International Code Council (ICC), National Fire Protection Association (NFPA), American Society of Mechanical Engineers (ASME), and the Compressed Gas Association (CGA). Although there are many different codes, the objectives of the safety requirements are:

1. To reduce the probability of a release of hydrogen
2. To reduce the probability of an accident if there were a release
3. To reduce the severity of an accident if one were to occur.

There are requirements that address all of the different system components in a refueling facility. For example, there are requirements related to components, materials, and piping that are meant to prevent unintended hydrogen releases. Additionally, the codes outline system separation distance requirements to reduce the probability and severity of accidents [10].

4.1. NFPA 2

NFPA has developed several codes that address fire risk in a range of different systems. NFPA 2, Hydrogen Technologies Code, is an all-encompassing document that establishes the necessary requirements for hydrogen technologies to address the increased use of hydrogen as a fuel source [11]. These codes are developed through a consensus process for standards development that is approved by the American National Standards Institute. Generally, this process achieves consensus between volunteers representing varied viewpoints and interest from different industries to address fire and safety issues.

In 2006, the Technical committee on Hydrogen Technology was formed to develop a set of standards that address all aspects of hydrogen storage, use, and handling. To do this, the committee utilized existing codes and standards as a basis and addressed technical gaps that existed relating to hydrogen. Relevant standards that were drawn upon during the formation of NFPA 2 include NFPA 52: Vehicular Natural Gas Fuel Systems Code, NFPA 55: Compressed Gases and Cryogenic Fluids Code, NFPA 853: Standard for the Installation of Stationary Fuel Cell Power Systems, and others. Relevant to the BayoTech hydrogen generation and refueling system, NFPA 2 includes chapters that address general fire safety requirements, general hydrogen requirements (alarm, detection, explosion control, etc.), gaseous hydrogen storage, gaseous vehicle fueling facilities, and hydrogen generation systems [11].

There are several requirements listed in NFPA 2 for hydrogen systems that relate to both refueling and hydrogen production. These requirements are meant to ensure safe operation of these systems and similar requirements have been in application for different industries for many years. To illustrate this, requirements 10.2.1.1 and 10.2.1.2 are shown below as they address safety in gaseous hydrogen refueling stations [11]:

- 10.2.1.1: Dispensing facilities shall be certified as meeting the requirements of this code by qualified engineer(s) with expertise and competence in the design, fabrication, and construction of hydrogen containers, piping systems, site fire protection, gaseous detection,

- emergency shutdown provisions, isolation, drainage, site spacing, fire protection equipment, operating procedures, worker protection, and other components of the facility.
- 10.2.1.2: A hazard analysis shall be conducted on every hydrogen fueling system installation by a qualified engineer with proven expertise in hydrogen fueling systems, installations, and hazard analysis techniques.

These are just examples of how the code ensures that safety is achieved in hydrogen refueling systems. They mandate inspections and hazard analysis to ensure that the design and application of a given hydrogen refueling system follows the code and is safe during operation.

Hydrogen production facilities are also addressed in detail in NFPA 2. Items that are addressed include approved equipment, connections, outdoor installations, and much more. To illustrate this, requirement 13.3.2.3.1 is shown below as it addresses safety in hydrogen production through SMR [11]:

- 13.3.2.3.1: The area containing the catalytic reformer system and associated conditioning equipment shall be located such that HVAC air intakes, windows, doors, and other openings into buildings cannot be exposed to the following: 1) Hazardous atmospheres, 2) Toxic gases in excess of applicable OSHA exposure limits.

4.2. Risk Discussion

Set-back distances are included in codes to define how far away a hydrogen system needs to be from its surroundings. In NFPA 2, there are different recommended set-back distances for bulk outdoor compressed hydrogen systems to different exposure groups [11]. Exposure group 1 generally has the largest set-back distances. This group includes lot lines, air intakes, operable openings in buildings and structures, and ignition sources such as open flames and welding. Exposure Group 2 includes exposed persons other than those servicing the system and parked cars. This group generally has smaller set-back distances than Group 1. Exposure Group 3 has the least restrictive set-back distances and includes the following:

- Buildings of non-combustible non-fire-rated construction
- Buildings of combustible construction
- Flammable gas storage systems above or below ground, hazardous materials storage systems above or below ground
- Heavy timber, coal, or other slow-burning combustible solids
- Ordinary combustibles, including fast-burning solids such as ordinary lumber, excelsior, paper, or combustible waste and vegetation other than that found in maintained landscaped areas
- Unopenable openings in building and structures
- Encroachment by overhead utilities (horizontal distance from the vertical plane below the nearest overhead electrical wire of building service)
- Piping containing other hazardous materials
- Flammable gas metering and regulating stations such as natural gas or propane.

The setback distances were developed as a function of line size and system pressure. Therefore, they are unique to each facility. These setback distances were developed through a risk analysis of hydrogen systems and provide safe operation of hydrogen facilities when in close proximity to different targets. It should be noted that a risk informed approach to safety, which was used to develop the setback distances, does not completely eliminate the possibility of a severe consequence from a potential accident (e.g., fatality). There is a level of risk that the public, and governing bodies, accept in everyday life. It is reasonable to set a risk-criterion for any application that is a fraction of the sum of the fatality risk resulting from other accidents to which members of the public are generally exposed in everyday life (e.g., fatal automobile accidents). For example, the individual fatality risk from unintentional injuries in the United States is on the order of 3.8×10^{-4}/yr [12].

Another consideration for a risk criterion, specifically for hydrogen refueling, is that the risk should be equal to or less than the risk associated with gasoline stations. An analysis of gas station data over a 5-year period indicated the frequency of a fatality or an injury associated with the operation of a single gasoline station are approximately 2×10^{-5}/yr and 3.3×10^{-4}/yr, respectively. Based on those considerations, the fatality risk guideline of 2×10^{-5}/yr for members of the public was used in development of setback distances for hydrogen applications. This ensures that the hydrogen system is as safe as gasoline refueling stations, which are much more prevalent [12].

4.3. Other Codes and Standards

In hydrogen systems, it is important to show compliance with codes regulating the hydrogen generation, storage, and dispensing unit of the system. Specific to hydrogen generation and refueling, the codes used in the design of the BayoTech system include:

- NFPA 2, Hydrogen Technologies Code – 2020 Edition
- ISO 16110:2007 Hydrogen generators using fuel processing technologies – Part 1: Safety
- NFPA 70, National Electrical Code
- NFPA 79, Electrical Standard for Industrial Machinery, 2018 Edition
- UL 121201 Nonincendive Electrical Equipment for Use in Class I and II, Division 2 and Class III, Divisions 1 and 2 Hazardous (Classified) Locations
- ASME B31.3 (Process Piping)
- ASME Boiler and Pressure Vessel Code

In addition to the hydrogen generation codes, there are many additional design specifications for which the BayoTech system is in compliance:

- SAE J2719, Hydrogen Fuel Quality for Fuel Cell Vehicles – March 2020
- ASTM International Designation D1193-06, Standard Specification for Reagent Water, Reapproved 2018
- NFPA 86, Standard for Ovens and Furnaces, 2019 Standard
- NFPA 497, Recommended Practice for the Classification of Flammable Liquids, Gases, or Vapors and of Hazardous (Classified) Locations for Electrical Installations in Chemical Process Areas
- NACE MR0103-2015/ISO 17945-2015, Petroleum, petrochemical, and natural gas industries - Metallic materials resistant to sulfide stress cracking in corrosive petroleum refining environments
- NEMA, National Electrical Manufacturer's Association
- API 520 Part I, 10th Edition & API 520 Part II, 7th Edition, Sizing, Selection, and Installation of Pressure-Relieving Devices in Refineries, October 2020
- API Standard 521, 7th Edition, Pressure-relieving and Depressuriing Systems, June 2020

- CSA/ANSI FC5, Hydrogen Generators Using Fuel Processing Technologies - Part 1: Safety, March 2021
- PIP Process Industry Practices, Latest Editions

4.4. Natural Gas Comparison

Natural gas is another flammable fuel source that is used in many applications throughout the world. Although the physical properties of hydrogen and natural gas differ, similar safety concerns exist between the two in the event of a leak and subsequent consequence. Both gases are flammable and may present a risk to public safety in terms of injury or death. However, through adherence to codes and standards, the risk associated with production and transportation of these gases has been reduced. To illustrate the prevalence of natural gas within the united states, and the public's acceptance of its inherent risks, Figure 3 shows a map of compressor stations and pipelines throughout the United States. As shown, these systems are located throughout the country in every state within the continental United States [13].

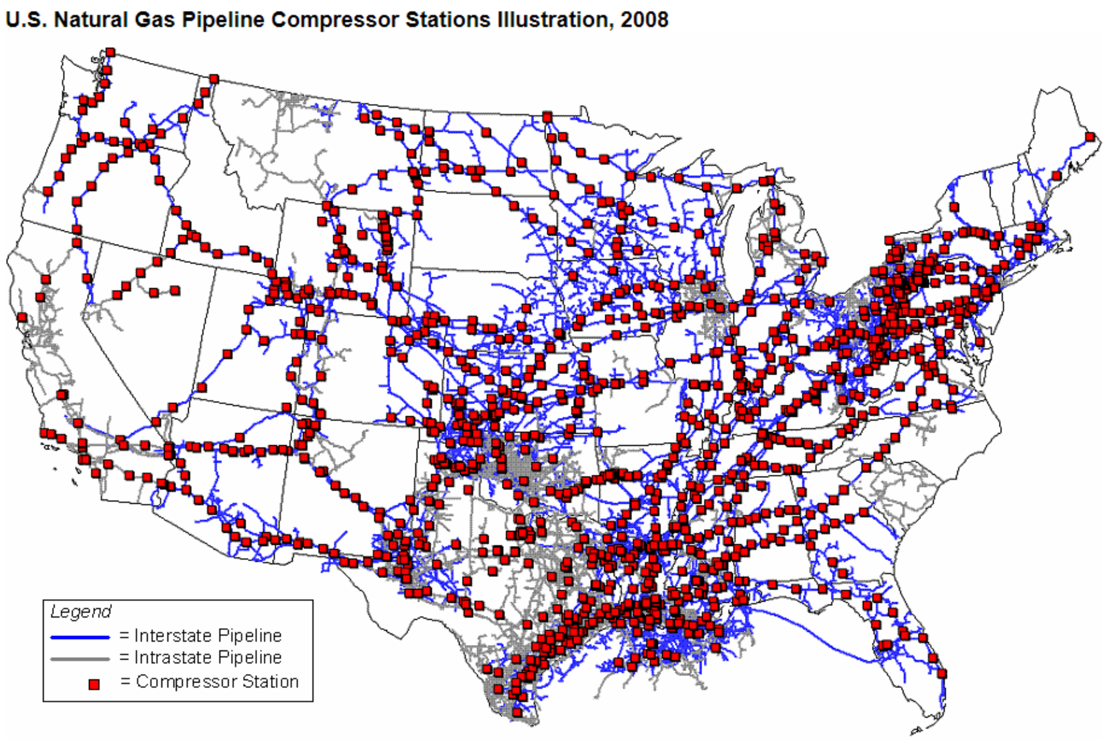

Figure 3: U.S. Natural Gas Pipeline and Compressor Stations [13]

5. CONCLUSION

Hydrogen has been produced and used in different industries for several decades all around the world. Not only is it prevalent in refining and manufacturing industries, but also for use as an alternative fuel source. Currently, hydrogen is used in fuel cell electric vehicles, such as forklifts and cars, as well as stationary applications to provide an uninterruptible power supply. To support the increasing demand of hydrogen as a fuel, the appropriate infrastructure is growing across the country. There are hydrogen production facilities located throughout the country and fueling stations in localized markets like California. However, as with any energy source, it is important to ensure that operation of hydrogen infrastructure systems is safe to the public. There are many codes and standards that have been developed to reduce the risk of public harm from a hydrogen generation system or fueling station. It is important to note that similar codes are used for different fuel sources, such as natural gas and gasoline. Although the risk of a severe accident is not 0 in any of these applications, society and governing officials accept a reasonable level of risk with these types of facilities. Specific to hydrogen, the codes and standards were developed so that the risk associated with a hydrogen system is the same or lower than that of a gasoline refueling station. This ensures that undue risk is not being undertaken by the public when in close proximity to a hydrogen generation facility or hydrogen fueling system.

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