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Safety Review of the Hydrogen Components of a Reference Design of the Wind-H2-Green Steel/Ammonia Project

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ABSTRACT

The Department of Energy Hydrogen Fuel Cell Technology Office and Wind Energy Technologies Office's Wind-H_2-Green Steel/Ammonia project is an initiative to demonstrate the feasibility and efficacy of GW-scale integrated energy systems. The team designed reference facilities that utilize wind- and solar-produced hydrogen for industrial steel and ammonia production. This novel concept warranted review of safety codes and standards as they apply to the designs and the identification of codes and standards gaps. This report reviews hydrogen production and storage codes and standards using reference design specifications from a Minnesota steel plant. Requirements, recommendations, and exclusions for the system were identified. Observed gaps included non-specific salt cavern storage requirements, electrolyzer capacity beyond regulated ranges, and lack of requirements for iron reduction via hydrogen. This report will aide future project design efforts and may provide a basis for safety reviews in new designs for industrial facilities with hydrogen production integration.

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ACRONYMS AND TERMS

Acronym/Term	Definition
ANSI	American National Standards Institute
API	American Petroleum Institute
ASME	American Society of Mechanical Engineers
CFR	Code of Federal Regulations
CGA	Compressed Gas Association
CSA	Canadian Standards Association
FM	Factory Mutual Insurance Company
GW	Gigawatts
HVAC	heating, ventilation, and air conditioning
IEC	International Electrotechnical Commission
ID	inner diameter
ISO	International Organization for Standardization
NFPA	National Fire Protection Association
PEM	proton exchange membrane
psig	pounds per square inch (gauge pressure)
scf	standard cubic feet
UL	Underwriters' Laboratories

1. INTRODUCTION

The Department of Energy Hydrogen Fuel Cell Technology Office and Wind Energy Technologies Office's Wind-H2-Green Steel/Ammonia project is an initiative to demonstrate the feasibility and efficacy of at-scale integrated systems. These off-grid systems incorporate renewable electricity generation via wind and solar, energy storage via batteries and hydrogen, and the industrial end-use of hydrogen for ammonia and steel production. The integrated and co-located nature of the system allows for low-carbon production of ammonia and steel while driving down production costs. An example schematic of this type of system is shown below in Figure 1-1. The graphic shows how the electricity generated from the wind turbines or solar panels is used to power the electrolyzer and generate hydrogen. The hydrogen is compressed and sent to storage, both long-term, large-scale storage in an underground geologic cavern, and shorter-term, smaller-scale storage aboveground and onsite at the steel manufacturing plant. The hydrogen stored in both types of storage can then be fed into the steel manufacturing plant on demand.

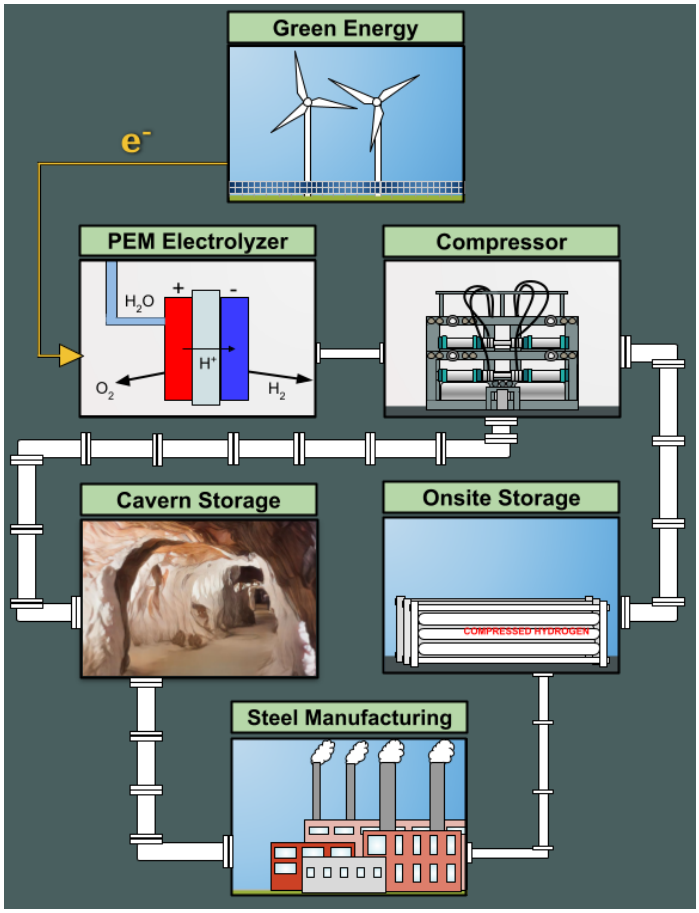
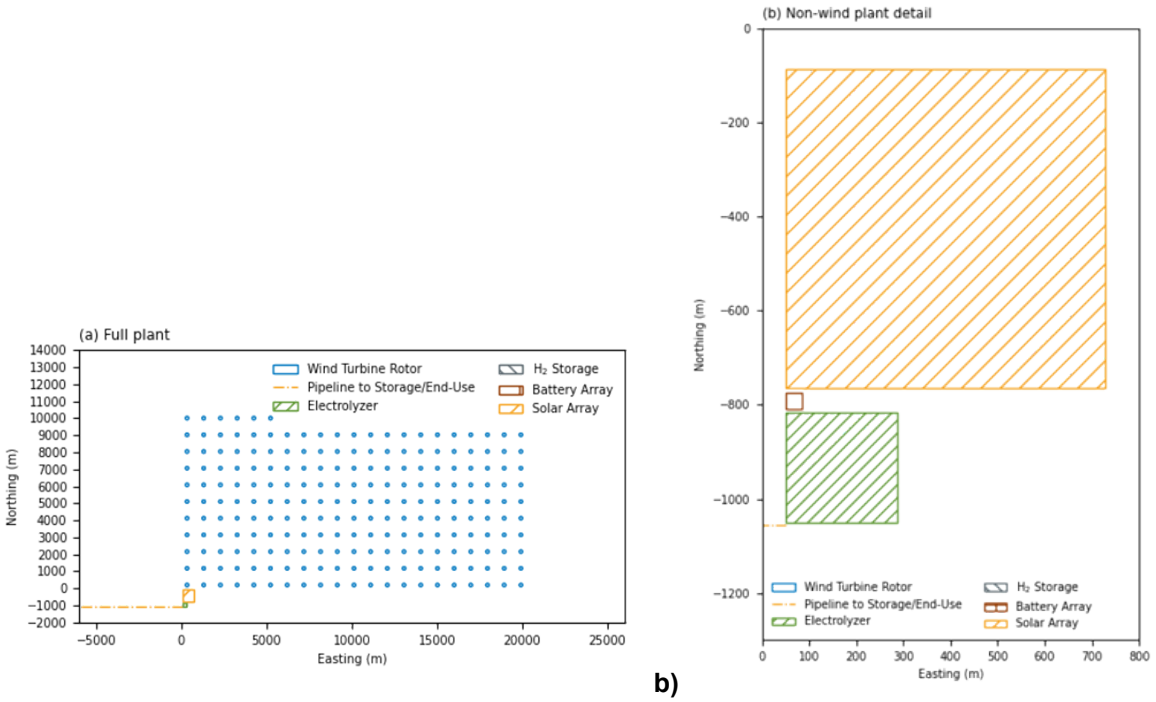


Figure 1-1. Overview of hydrogen pathway through a generic wind/solar-hydrogen-steel system.

The design team generated an engineering design for a wind/solar-hydrogen-steel system located in Minnesota. A generic, unoptimized layout is shown below in Figure 1-2.



a) b)

Figure 1-2. Unoptimized layout of integrated wind/solar-hydrogen-steel/ammonia system, where a) shows the full plant layout and b) shows an expanded view of the solar array, battery array, and electrolyzer array.

The system consists of arrays of wind turbines and solar panels for generation of electricity, an array of batteries for energy storage if needed between the generation of electricity and the use of electricity for hydrogen generation, and an array of electrolyzers for generating hydrogen as an input for both ammonia and steel production. The system also includes a pipeline used to transport the hydrogen to large-scale underground storage and the point of use. In this report, the point of use is assumed to be a steel manufacturing plant, although the considerations used in this report could be extended to other end-uses such as an ammonia production plant or facilities hosting other industrial processes involving hydrogen.

The setup was optimized for a steel manufacturing plant located in Minnesota using GreenHEART software developed by the National Renewable Energy Laboratory. The configuration can be found in GitHub [1]. The design was optimized by "parameters such as electrolyzer costs, natural gas costs, and location, and utilize state-of-the-art projections for future technology and grid costs [2]." However, further constraints or revisions to the design may be necessary to ensure compliance with regulatory guidance. The team then reviewed safety codes and standards relevant to the hydrogen generation and storage components of the preliminary reference design. A similar method was conducted by Glover et al. [3] for hydrogen blends in natural gas pipelines. Although the hydrogen storage, which is planned to be located underground in a lined rock cavern is not shown in the Figure 1-2 layout, it was still considered in this review since it is planned to be part of the system in the future. Note that this review highlights safety recommendations for aspects of the codes and standards that impact facility design choices; it may not cover all

regulations that must be followed by this type of facility. Additionally, the wind turbines, solar array, and batteries were not included in this hydrogen-specific review.

2. PRELIMINARY DESIGN REVIEW

The methods and cited sections of the codes are generalizable for systems consisting of the same components but with varying sizes. However, the specific parameters discussed in this safety review are based on the Minnesota reference design [1].

It should be noted that while the reference design is nominally located in Minnesota, each state will have its own codes and local code enforcement will have to approve of each site. Whether or not the state where a facility is located has adopted NFPA 2 will need to be confirmed. The aim of this report is to highlight specifically what codes and standards will apply to the use of hydrogen. Beyond what is mentioned here, all state building, fuel, load, and fire codes will need to be followed. It should also be noted that direct reduced iron (DRI) will also have its own set of safety codes.

2.1. Hydrogen Storage Siting Requirements

Hydrogen storage siting requirements are mainly regulated by the National Fire Protection Association (NFPA) Hydrogen Technologies Code, or NFPA 2 [4]. While NFPA 2 is not a mandatory regulation, it is one that can be adopted as a requirement by individual jurisdictions. The 2023 version of NFPA 2 is referenced in this report. There are existing regulations for required minimum distances, or setbacks, between the equipment that makes up hydrogen storage systems and certain exposures. Examples of these exposures are shown in Table 2-1.

Table 2-1. Exposures by group taken from NFPA 2 Chapter 7 [4].

Exposure Group	Relevant Exposures
1	• Lot lines • Air intakes (HVAC, compressors, other) • Operable openings in buildings and structures • Ignition sources such as open flames and welding
2	• Exposed persons other than those servicing the system • Parked cars
3	• 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 buildings in building and structures • Encroachment by overhead utilities (horizontal distance from the vertical plane below the nearest overhead electrical wire of building service)

Exposure Group	Relevant Exposures
	• Piping containing other hazardous materials • Flammable gas metering and regulating stations such as natural gas or propane

There are three main variations of storage categories used to determine siting requirements in NFPA 2. First, the allowed locations and setback distances for a system vary based on whether the storage is located indoors or outdoors. Second, siting requirements vary based on the quantity of stored hydrogen. If the individual storage containers in the facility are not manifolded together and are each less than 5000 scf[1], they are considered to each be a distinct non-bulk hydrogen system. If the storage containers are manifolded together and the collective stored volume is greater than 5000 scf, or if individual storage containers contain more than 5000 scf, the system is considered to be a bulk system. Third, the applicability of the setback distances depends on whether the storage system is located aboveground or belowground. For non-bulk storage, there is no mention of whether the setback distances apply to storage located aboveground, belowground, or both. For bulk storage, the setback distances are explicitly applicable to aboveground storage; there is no siting guidance provided for belowground storage.

Within each system categorization based on the three factors discussed above, setback distances are determined based on different system parameters. For example, non-bulk outdoor storage setback distances depend on stored volume, while bulk outdoor storage setback distances depend on system pressure and pipe inner diameter.

Siting requirements for the wind-hydrogen-steel/ammonia plant can be determined based on the current design and using assumptions based on engineering judgment. The current design specifies that the hydrogen will be generated at the electrolyzer array and transported to storage via a transport pipeline. The storage will be geologic, in an underground lined rock cavern. The hydrogen from the underground storage will be extracted as needed for use in the steel or ammonia plant. While there may also be a transport pipeline to bring hydrogen onsite to the point of use directly as it is being generated, this potential design choice was not included in the current design. A schematic of the flow of hydrogen through the entire facility is provided in Figure 2-1.

[1] Standard Cubic Foot (scf) of Gas: "An amount of gas that occupies one cubic foot at an absolute pressure of 14.7 psi (101 kPa) and a temperature of 70°F (21°C)" [4].

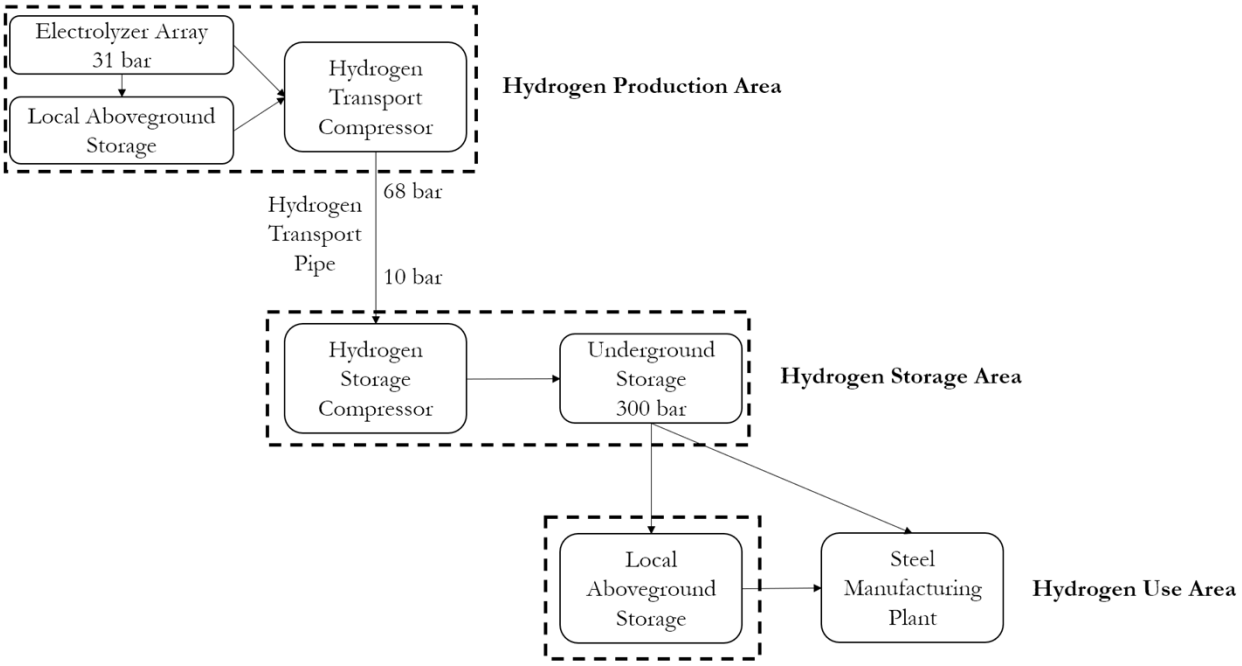


Figure 2-1. Schematic of hydrogen flow from electrolyzers to storage and end-use. Each defined system is distinguished by a dashed-line box.

In Figure 2-1, each dashed-line box represents a distinct system within the facility that was defined by the safety team to determine siting requirements. Each system is characterized by its specified or assumed storage. For the electrolyzer area, no storage is specified in the current design, but the safety team assumed there would be some local aboveground storage as backup. The underground geologic storage area is categorized as its own system. Like the electrolyzer area, it is assumed that the hydrogen use area would also have some local aboveground storage available. The building in which the steel manufacturing takes place is not assumed to have any indoor storage, which is why it is not considered in this analysis to be part of the hydrogen storage system. Each system is connected by a hydrogen transport pipe, which is considered to transport but not store hydrogen. Additionally, while the distances traveled by the pipeline are not yet determined in the current design, they are interpreted as being sufficiently long so that the entire facility is not considered one entire system.

All local storage is assumed to be located aboveground, and the large-scale storage underground will be in geologic storage, not in buried tanks.

2.1.1. Aboveground Storage

All aboveground storage in the system is assumed to be outdoors. Since storage volumes are not yet determined in the design, the local storage in the electrolyzer area is assumed to store a bulk quantity (over 5,000 scf) and the local storage in the hydrogen use area is assumed to store a non-bulk quantity (under 5,000 scf) for demonstrative purposes of determining siting requirements.

The setback distances for aboveground outdoor bulk storage in the electrolyzer area can be determined by the pipe diameter, pressure, and exposure group as shown in Table 2-2; these distances are taken from Table 7.3.2.3.1.2(B)(a) ("Minimum Distance (D) from Outdoor Bulk Hydrogen Compressed Gas Systems to Exposures – Typical Maximum Pipe Size") in NFPA 2 [4].

Table 2-2. Setback distances in meters (feet) for aboveground, outdoor, bulk storage. Taken from NFPA 2 Table 7.3.2.3.1.2(B)(a).

	Pressure Range (psig)	>15 to ≤250	>250 to ≤3000	>3000 to ≤7500	>7500 to ≤15000
	Pipe ID (mm)*	**52.5**	**18.97**	**7.31**	**7.16**
Exposure Group	1	5 (16)	6 (20)	4 (13)	5 (16)
	2	5 (16)	6 (20)	3 (10)	4 (13)
	3	4 (13)	5 (16)	3 (10)	4 (13)

*Typical maximum pipe inner diameter corresponding to pressure range

The current reference design specifies an electrolyzer outlet pressure of 31 bar (450 psig). This pressure is assumed to be the storage pressure in the electrolyzer area. Since the pipe sizing is still undetermined, the typical maximum pipe size for this pressure is assumed – therefore, the setback distances for the pressure range of 250 to 3000 psig and the system pipe diameter of 18.97 mm are used. Thus, the entire electrolyzer area should have a buffer distance of at least 6 m (20 ft) from Group 1 and 2 exposures and at least 5 m (16 ft) from Group 3 exposures. Note that the electrolyzer area is treated as a single storage system and that the setback distances are from the overall boundary of the system rather than between each component in the system (i.e., between each storage tank in the electrolyzer system).

There are several caveats to note in the case that these assumptions deviate from future selections or edits to the current design. In this example, it was assumed that hydrogen storage at 68 bar (990 psig) is present in the system, so this pressure was used to determine the setback distances. In reality, there may be different pressures present in different parts of the system. In this case, NFPA 2 defines the system pressure as the "maximum operating pressure of the storage array with content greater than 5000 scf (141.6 Nm^3), irrespective of those portions of the system elevated to a higher pressure." For example, if the hydrogen is actually stored at 350 bar (5080 psig) and the storage array contains over 5000 scf of hydrogen, then 5080 psig and 7.31 mm would be the pressure and typical diameter used to determine setback distances. However, if less than 5000 scf of hydrogen is stored at 350 bar (5080 psig) and the rest of the hydrogen in the system (over 5000 scf) is at a pressure of 68 bar (990 psig), then the system pressure would be defined as 68 bar (990 psig).

Besides the system pressure, the pipe diameter was also an assumption that may change as the facility design evolves. If the pipe diameter in the system differs from the maximum typical pipe size, then Table 7.3.2.3.1.2(B)(b) and Table 7.3.2.3.1.2(B)(c) can be used to determine siting requirements, since they provide setback distances for combinations of different pipe diameters with each system pressure range. Table 7.3.2.3.1.2(B)(b) provides setback distances for systems with a pipe inner diameter between 0.2 and 2.1 inches and a

pressure between 15 and 3000 psig while Table 7.3.2.3.1.2(B)(c) covers systems with a pipe inner diameter between 0.2 and 2.1 inches and a pressure between 3000 and 15,000 psig. If the pipe diameter changes within the system, NFPA 2 states, "The internal diameter of the piping system shall be determined by the diameter of the piping serving that portion of a storage array with content greater than 5000 scf (141.6 Nm^3). The piping system used in the application of Table 7.3.2.3.1.2(B)(a), Table 7.3.2.3.1.2(B)(b), or Table 7.3.2.3.1.2(B)(c) shall be determined based on that portion of the system with the greatest maximum internal diameter." Therefore, storage quantities in each system, at each pressure, and with each pipe diameter (in addition to the pressures and pipe diameters themselves) are important parameters that are currently unknown and are needed to confirm the relevant siting requirements for the electrolyzer system.

As mentioned at the beginning of this section, the siting requirements will be discussed for the local storage in the part of the overall facility where the steel or ammonia plant is located under the assumption that the storage is non-bulk for the purpose of demonstrating how to determine non-bulk setback distances. The siting requirements for outdoor, non-bulk hydrogen storage are provided in Table 2-3 below, based on Table 7.2.2.3.2 ("Distance to Exposures for Non-Bulk GH_2") in NFPA 2 [4].

Table 2-3. Setback distances in meters (feet) for outdoor, non-bulk storage. Distances in feet taken from NFPA 2 Table 7.2.2.3.2.

Maximum Amount per Storage Area (ft^3)	Minimum Distance Between Storage Areas	Minimum Distance to Lot Lines of Property That Can Be Built Upon	Minimum Distance to Public Streets, Public Alleys, or Public Ways	Minimum Distance to Buildings on the Same Property		
				Less Than 2-Hour Construction	2-Hour Construction	4-Hour Construction
0–4225	1.5 (5)	1.5 (5)	1.5 (5)	1.5 (5)	0 (0)	0 (0)
4226–21,125	3 (10)	3 (10)	3 (10)	3 (10)	1.5 (5)	0 (0)
21,126–50,700	3 (10)	4.5 (15)	4.5 (15)	6 (20)	1.5 (5)	0 (0)
50,701–84,500	3 (10)	6 (20)	6 (20)	6 (20)	1.5 (5)	0 (0)
84,501–200,000	6 (20)	7.6 (25)	7.6 (25)	6 (20)	1.5 (5)	0 (0)

NFPA 2 Table 7.2.2.3.2 applies to non-bulk systems, which are defined as systems with a capacity below 5000 scf. However, the table contains storage quantity levels which are above 5000 scf, which is only relevant for the storage or use of gas cylinders or systems where no one cylinder or system exceeds 5000 scf.

Since the local onsite storage at the ammonia or steel plant is not part of the current design, the storage quantity is unknown. For now, it is assumed that the storage in the hydrogen use area is kept in individual non-bulk containers that are not manifolded together, each with a storage quantity within the range of 0-4225 ft^3. Thus, there should be at least 1.5 m

(5 ft) between each storage area within the ammonia/steel plant site, as well as between each storage container and the lot lines and between each container and public streets, alleys, and ways. Additionally, it is assumed that the steel production process would be located inside a building. If the building is constructed with materials that have less than two hours of fire protection, the perimeter of the storage array should be at least 1.5 m (5 ft) away. If the building materials have a two-hour fire rating or higher, there is no required distance for the storage array. In this early phase of the design process, the conservative assumption can be made that buildings in the vicinity have less than two hours of fire protection; therefore, a 1.5 m (5 ft) setback distance between the storage array and the steel manufacturing building is required. The same setback distances apply for any other buildings in the area.

Hydrogen, ammonia, and processed iron powder, pellets or brickettes will all require a Hazardous H Occupancy if they are stored within a building. The hydrogen and ammonia will also be classified according to NFPA 497 and any airborne dust from the DRI according to NFPA 499.

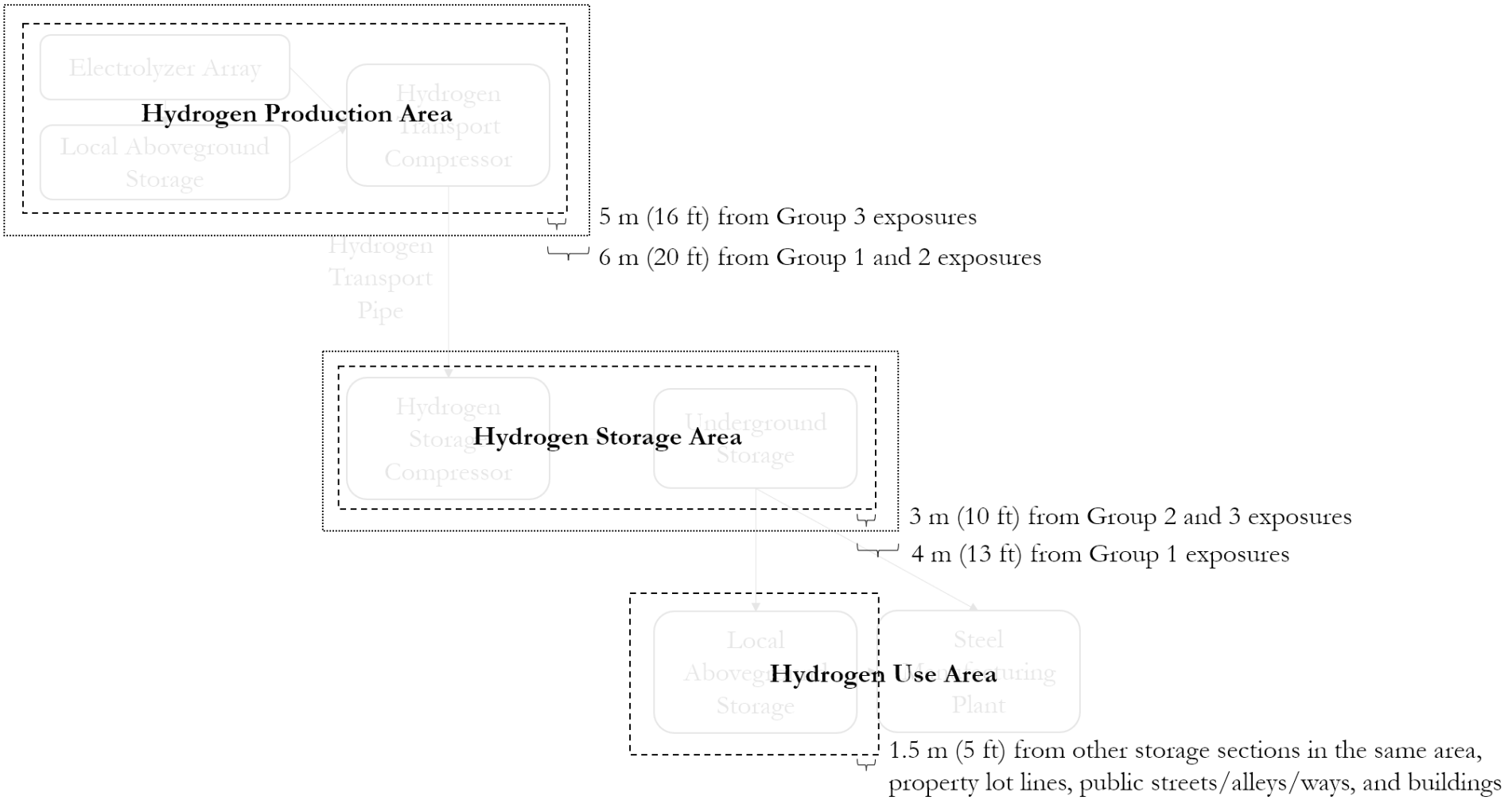


Figure 2-2. Graphic showing recommended setback distance buffers around each hydrogen storage section. Distances are not to scale.

2.1.2. Underground Geologic Storage

While the scope of NFPA 2 does not explicitly exclude underground geologic storage, there is no mention of requirements specific to geologic storage in the document; only underground storage requirements are written for buried tanks. For siting requirements in particular, indoor storage requirements are implicitly written for aboveground storage, while the distinction of aboveground or belowground storage is not specified for outdoor systems. While NFPA 2 does specify setback distances for outdoor storage and the underground lined rock cavern is characterized as outdoor storage for the purposes of this report, it is not clear how to apply the setback distances to the rock caverns. Further consideration of the underground geologic and large-scale nature of the storage in comparison to the aboveground outdoor storage for which NFPA 2 siting analyses were conducted is recommended, and the use of NFPA 2 setback distances should not be interpreted as a definitive suggestion. This study interprets the system to be the area above the underground cavern, as well as any associated equipment located aboveground such as the wellhead and the storage compressor, and setback distances would be applied to these. The current design specifies an underground hydrogen storage pressure of 300 bar (4351 psig), based on work done by Papadias and Ahluwalia [5]. Using this value as the storage pressure and the corresponding typical maximum pipe diameter of 7.31 mm from NFPA 2 Table 7.3.2.3.1.2(B)(a) leads to setback distances of 4 m (13 ft) from Group 1 exposures and 3 m (10 ft) from Group 2 and 3 exposures. The underground hydrogen storage quantity of 5198 metric tonnes (6.2×10^7 scf) is well over the 5000 scf requirement for the selected 300 bar (4351 psig) operating pressure to apply. NFPA2 does not have an explicit exclusion of underground geologic storage, however, that does not necessarily mean that these setback distances are safe or recommended by the standard for this application.

As discussed in the previous paragraph, while the setback distances from NFPA 2 may or may not apply to this underground geologic storage system based on the way the standard is currently written, the setback distances are not necessarily appropriate in this context. The risk-informed setback distances in NFPA 2 are based on the potential human harm that could occur from the ignition of a steady-state hydrogen plume exiting a leak point [4]. Immediate ignition would result in a jet flame while delayed ignition would result in an explosive event. The setback distance determinations were based on the probability of fatality of an individual from heat flux exposure, given an assumed exposure time of 30 seconds during which the person can move away from the fire, as well as the probability of fatality from an individual sustaining head trauma from an overpressure event. The heat flux scenario considers short-term consequences while the overpressure scenario considers an instantaneous event, both of which could occur for both small and large quantities of stored hydrogen. However, underground geologic storage is different from existing aboveground storage facilities, namely because its purpose is to store large quantities of hydrogen. Larger stored quantities could potentially lead to longer-lasting leaks and higher consequences [6]. Thus, considering storage quantities and potential long-term consequences in setback determinations could improve the safety of underground geologic hydrogen storage; this gap is currently not addressed in existing codes.

The Pipeline and Hazardous Materials Safety Administration (PHMSA) standard, 49 CFR 192.12 ("Underground natural gas storage facilities") contains requirements that apply to the underground geologic storage component of the current design. Depending on the type of geologic formation used, standards by the American Petroleum Institute such as Recommended Practice 1170, "Design and Operation of Solution-mined Salt Caverns Used for Natural Gas Storage," [7] and Recommended Practice 1171, "Functional Integrity of Natural Gas Storage in Depleted Hydrocarbon Reservoirs and Aquifer Reservoirs" [8] apply. However, the siting guidance in these standards is more relevant to the geochemical and geomechanical properties of the cavern or reservoir itself rather than to setback distances in relation to infrastructure and the public; the safety aspect is mostly focused on well siting and drilling rather than operations. Therefore, suggested setback distances between the underground hydrogen storage and exposures are still an important missing piece to this safety evaluation of the current design. General gaps and applicability of existing codes and standards to underground geologic hydrogen storage are further discussed in [9].

2.2. Pipeline Requirements

Pipelines are defined by the PHMSA regulation 49 CFR 192 ("Transportation of Natural and Other Gas by Pipeline: Minimum Federal Safety Standards") and the American Society of Mechanical Engineers standard ASME B31.12 ("Hydrogen Piping and Pipelines") as "all part of those physical facilities through which gas moves in transportation," which indicates that all facility piping between the point of hydrogen generation and , as well as the associated valves, fittings, instrumentation, and other related equipment, should adhere to the guidance in this standard [10], [11]. 49 CFR 192 "prescribes minimum safety requirements for pipeline facilities and the transportation of gas" [10] All relevant requirements from this standard should be complied with when operating the pipeline system. One hydrogen-specific aspect of 49 CFR 192 is that, for these pipelines, odorant is not necessary since the hydrogen is "intended for use as a feedstock in a manufacturing process." Since the hydrogen is planned for use as a feedstock in the steel production processes, the addition of odorant to the hydrogen pipelines is not necessary. However, if the facility design changes in the future to include using some of the hydrogen for electricity production, an odorant may be required for that particular pipeline.

ASME B31.8, in contrast, provides guidance on the design, construction, and siting characterization for transmission pipelines. The standard distinguishes between industrial piping, which is defined as "piping for liquid and gaseous hydrogen and joints connecting piping to equipment," and pipelines [11]; this report assumes three distinct systems separated by piping in the current design, which lends itself to being defined as piping. Industrial piping is covered in ASME B31.3.

The pipelines in the design were assumed to be built from scratch rather than reused or repurposed from existing infrastructure. Therefore, the two main areas where design choices impact the pipeline regulations in ASME B31.8 are materials and location classification.

It should also be noted that states might also have more restrictive requirements.

2.2.1. Pipeline Materials

While pipelines between facilities are most likely to be constructed from carbon steel, we will discuss the several options listed in ASME B31.12 for materials that can be used for hydrogen pipelines based on the properties of hydrogen. These materials are listed in Table 2-4 and are sorted into materials that are recommended, materials that are not recommended, and materials that are prohibited.

Table 2-4. Materials that are allowed, not recommended, and prohibited for hydrogen service in pipelines and piping systems.

Recommended for Hydrogen Service	Not Recommended for Hydrogen Service	Prohibited for Hydrogen Service
• Carbon steel and low and intermediate alloy steels • High alloy stainless steels • Aluminum and aluminum alloys • Copper and copper alloys	• Nickel • Nickel-based alloys	• Irons • Lead, tin, lead-tin alloys

ASME B31.12 includes potential considerations or aspects of concern for pipeline materials. For example, some of the materials may experience corrosion or heat-related chemical reactions when exposed to specific environments or especially high temperatures; however, many of these conditions are outside of the bounds of normal pipeline operations even under extreme climate conditions. Nickel and nickel-based alloys are not recommended for hydrogen service due to hydrogen embrittlement concerns; however, the material is not explicitly prohibited by ASME B31.12. Irons including cast, ductile, malleable, and high silicon (14.5%) irons are prohibited "due to their lack of ductility and their sensitivity to thermal and mechanical shock." No explanation is provided for the prohibition of lead, tin, and lead-tin alloys in hydrogen service. It is recommended that a material be selected from the list of "allowed materials" based on other factors besides safety – for example, availability or financial feasibility considerations can help narrow down the list and select a pipeline material.

2.2.2. Pipeline Location Classification

Another topic addressed in ASME B31.12 is pipeline location classification. The location classification for a section of pipeline is required to determine system parameters such as the maximum allowable operating pressure (MAOP) for the pipeline, the design factor for steel pipe construction, and the maximum allowed spacing between valves. To determine the location classifications along a pipeline, the zone of interest is created by a boundary 1/8 of a mile to either side of the pipeline. Then, the pipeline is segmented into 1-mile sections such that the number of buildings within each area created by segment and 1/8-mile boundary is maximized. The number of buildings present within each segment is used to determine the class for that segment. It is assumed that the overall facility in the current reference design, as well as the pipelines between each system in the facility, will be in rural, sparsely populated areas. Thus, the team assumed that the entirety of each of the two

pipelines would be characterized as Location Class 1 based on Section PL-3.2.2 in ASME B31.12 [11]. Since the hydrogen production and storage is assumed to be co-located for now, it is likely that the pipeline would be short and that each pipeline in its entirety would be considered a single section. For the purpose of this report, the pipelines are also assumed to have a design factor of less than or equal to 0.72 and to have been tested to 1.1 times the MAOP, which would lead to an overall location classification of Class 1, Division 2.

As previously mentioned, the location classification is used to determine various requirements for the pipeline. Table PL-3.6.1-1 in ASME B31.12 provides the MAOP for the pipeline depending on the location class and the number of buildings. This MAOP also depends on whether a prescriptive design method (Option A) or a performance-based method (Option B) is used for designing the pipeline. If the prescriptive method is used, the MAOP would no greater than 50% of the maximum operating stress (S_m). If the performance-based method is used, the MAOP would be no greater than 72% of the maximum operating stress. Possibly, a performance-based approach to safety would be used in this design due to its novel nature. Therefore, the MAOP of no greater than 72% of S_m would apply. "Original" design in Table PL-3.6.1-1 was assumed since a new pipeline would be built for this system rather than reservicing a previous natural gas or other pipeline being for hydrogen.

The location class and selected design method also help determine the basic design factor (F) for the pipeline, based on Table PL-3.7.1-1 and PL-3.7.1-2. These tables would be used to determine the design factor for classes other than Class 1, Division 2, but, since it was earlier stated that a design factor of less than or equal to 0.72 was assumed, these tables were not needed for this review. The location class and selected design method can also be used to determine the required design factors for steel pipe construction in the case of any exceptions, such as the presence of road or railroad crossings, parallel encroachment of pipelines, fabricated assemblies, pipelines on bridges, pressure or flow control and metering facilities, or compressor station piping, based on Table PL-3.7.1-6 and PL-3.7.1-7. For now, it is assumed that none of these scenarios occur over the length of the pipeline, especially since it is transporting hydrogen between co-located systems.

Finally, the location class specified in ASME B31.12 can be used to determine the maximum allowed spacing between valves, based on section PL-3.15.1. For a Class 1 pipeline, valves should be at most 32 km (20 mi) apart. Since the pipeline is expected to be relatively short, valves may be installed wherever needed, which should sufficiently comply with this requirement from ASME B31.12.

2.3. Fire Safety Guidance

Failures in hydrogen systems can result in the leakage and accumulation of gaseous hydrogen above the flammable concentration limits. If this hydrogen encounters an ignition source, it could result in a fire or explosion. While measures like sensors, pressure relief devices, and automatic shutoff valves are effective for identifying leaks and preventing further damage, it is also important for stakeholders to address fire hazards in their hydrogen systems.

Hydrogen fires share commonalities with hydrocarbon fires. Both require an oxidizer, such as oxygen, for combustion to occur [12]. Pure hydrogen is not combustible, but hydrogen leaked from a system into the surrounding atmosphere poses a risk of combustion at certain concentrations. According to Keçebaş and Kayfeci, the lower flammability limit of gaseous hydrogen in air is 4 vol% and the upper flammability limit is 75 vol% [13]. The same source states that the lower explosive limit for hydrogen is 15 vol% and the upper explosive limit is 59 vol% [13] although it must be emphasized that hydrogen explosion effects are a complex combination of concentration and the surrounding environment. While hydrogen fires burn at temperature typically higher than hydrocarbons, they produce significantly less radiant heat, reducing the risk of secondary ignitions [12].

NFPA 2 is highly applicable for fire safety recommendations for hydrogen storage in the current design. NFPA 2 dedicates Chapter 4 to general hydrogen fire safety, stating recommendations that provide a reasonable level of safety, property protection, and public welfare from hydrogen fires and explosions [4]. Section 4.6 of NFPA 2 describes requirements for the Emergency Plan when dealing with gaseous hydrogen storage that exceeds the maximum allowable quantity per control area, such as the onsite storage modeled in the green steel system [4]. Section 4.12 of NFPA 2 gives safety recommendations for controlling ignition sources such as open flames, high-temperature devices, energy-consuming equipment, and smoking [4]. Section 4.14 provides information on how to protect hydrogen systems from vehicular damage, stating specific requirements for the construction and placement of guard posts around hydrogen storage systems [4]. Section 4.15 of NFPA 2 gives recommendations for the construction materials for hydrogen systems and their related structures. This section refers to noncombustible materials, which must meet the requirements of ASTM E136 (“Combustibility of Materials”) [14] or ASTM E2652 (“Combustibility of Building Materials”) [15], and limited-combustible materials, which must meet the requirements of ASTM E84 (“Standard Test Method for Surface Burning Characteristics of Building Materials”) [16], ANSI/UL 723 (“Test for Surface Burning Characteristics of Building Materials”) [17], ASTM E2965 (“Standard Test Method for Determination of Low Levels of Heat Release Rate for Materials and Products Using an Oxygen Consumption Calorimeter”) [18], and NFPA 259 (“Standard Test Method for Potential Heat of Building Materials”) [19]. Section 4.15.2 of NFPA 2 provides specific requirements a material must meet to be considered a limited-combustible material.

NFPA 2 Chapter 6 contains general hydrogen guidance, including discussion of additional fire safety requirements like sprinkler systems [4]. An indoor sprinkler system may be required based on state building codes in regard to general fires; however, extinguishing a hydrogen fire could allow for an unignited plume to accumulate and combust in an even higher-consequence delayed ignition event. Using a sprinkler system could thus potentially increase the risk in a facility during a hydrogen leak, although it could also help disperse leaking hydrogen to below its flammable limit. It is suggested that a site-specific evaluation could help identify whether sprinklers would increase or reduce risk, and whether asking an authority having jurisdiction for an exemption is necessary.

NFPA 2 also has some requirements for ventilation and venting as fire prevention measures. It requires a minimum ventilation rate of 1 scf/min/ft^2, but considerations such as the stored volume of hydrogen in the electrolyzer area, the operating pressure, parts of

the facility in which hydrogen accumulation can occur, credible leak rates and durations, controls, and risk mitigation actions should be taken into account to determine an appropriate ventilation rate, in case the prescribed ventilation rate is not sufficient for a specific system. CSA/ANSI B22734 ("Hydrogen generators using water electrolysis – Industrial, commercial, and residential applications") provides required dilution concentrations [20], but, again, more specific details about a site must be used to determine appropriate and safe ventilation and venting rates and locations. API RP 521 ("Pressure-relieving and Depressuring Systems") is another reference that can be used to incorporate safe venting from a building producing or using large quantities of hydrogen; it contains requirements and guidance for calculating potential radiant heat exposure from a jet fire at a vent outlet [21].

NFPA 72 ("National Fire Alarm and Signaling Code") provides important information to stakeholders about the application installation, location, inspection, testing, and maintenance of fire alarm and signaling systems [22]. NFPA 72 does not directly address hydrogen systems, but it is an important document that applies to any network of fire alarm systems present in the current reference design. Chapter 7 discusses how to properly document every aspect of fire signaling systems, addressing design, installation, maintenance, and testing documentation. Chapter 10 gives detailed safety recommendations for the equipment, power supplies, and parameters associated with fire alarm systems. Chapter 21 is dedicated to emergency control function interfaces, which are devices that respond to fire sensors and initiate other fire suppression mechanisms [22]. An emergency control function interface should be included in the facility's fire signaling system, controlling HVAC systems, closing doors, and venting smoke in the event of a fire.

2.4. Electrical Requirements

There are many points in the current reference design where there is a risk of electrical components encountering hydrogen gas. The electrolyzer is the largest electrical component in the system, but most electrolyzers tend to not have electrical classifications. Like any other unclassified electrical equipment, the electrolyzer should be shut off if leaking hydrogen is detected in the electrolyzer area of the facility.

The pipelines, compressors, storage compressors, and hydrogen detection systems are also electricity sources within the system. For electrical safety recommendations, NFPA 2 refers to NFPA 70, the National Electric Code. NFPA 70 Article 500 outlines electrical classifications for locations containing electrical equipment that could be exposed to flammable gases or combustible dust or fibers [23]. The code separates these electrical classifications into three classes with two divisions each. Class I signifies a risk of exposure to flammable gases, such as hydrogen. Class II and Class III indicate conditions of exposure to flammable dust and fibers, respectively. The divisions within the classes represent where the combustible hazard is located. Division I locations have a high risk of exposure to flammable gases under normal operating conditions [23]. Division II locations contain flammable gases within closed systems, where exposure is possible in the event of mechanical failure or leakage, characterized as an abnormal condition [23]. Most of the reference design systems would be categorized as a Class I Division II areas based on these conditions, with the immediate area around hydrogen vent stacks and pressure relief

devices categorized as Class I Division I. Distances for these classification boundaries can vary depending on operating conditions and location, with different codes recommending different distances. NFPA 2 gives electrical classification distances in Table 7.3.2.3.1.7.1. This table states that a Class I Division I zone is designated from 0 ft to 3 ft from any point in a system where hydrogen is vented, measured spherically [4]. From 3 ft to 15 ft from a hydrogen vent is the Class I Division II zone, also measured spherically [4]. Storage equipment excluding the piping system downstream of the source valve also holds a Class I Division II designation with a 15 ft zone [4]. Article 501 of NFPA 70 dives further into Class I Locations, providing guidance for wiring and equipment design and installation [23]. NFPA 70 characterizes hydrogen as a group B gas based on its flammability characteristics. All electrical components that are in a Class I Division I or II hydrogen atmosphere should be rated for Group B and meet industry standards such as the UL 60079 series [24]. For general electrical safety recommendations, stakeholders should refer to NFPA 70 for electrical design recommendations [23], 70E for installation recommendations [25], and 70B for electrical maintenance requirements [26]. NFPA 497 [27] provides more detailed information on how to identify ignitability hazards in Class I chemical process locations.

2.5. Gaps in Current Safety Codes and Standards

2.5.1. Underground Hydrogen Storage

As discussed in Section 2.1.2, there is no current centralized guidance regarding siting or other requirements for underground geologic hydrogen storage. As they are currently written, NFPA 2 setback distances could be applied to a system or section of a system containing underground storage. However, because the methodology used to determine those setback distances was not necessarily based on additional hazards potentially posed by much larger quantities than what is currently stored aboveground, the setback distances may not accurately mitigate risk to people and infrastructure. Other codes and standards for underground geologic storage of natural gas, such as API RP 1170 (“Design and Operation of Solution-mined Salt Caverns Used for Natural Gas Storage”) and API RP 1171 (“Functional Integrity of Natural Gas Storage in Depleted Hydrocarbon Reservoirs and Aquifer Reservoirs”), do exist and are sufficiently broad so they can be used as a basis for designing and operating underground hydrogen storage facilities [9]. However, the scope of these documents does not include some crucial aspects of facility design, including siting requirements specific to this application. Therefore, re-evaluation of the recommendations provided in this report regarding the underground hydrogen storage section should be conducted in future work as the regulatory landscape continues to expand.

2.5.2. Electrolyzer Capacity

Chapter 13 of NFPA 2 gives recommendations for three types of hydrogen generation systems, including water electrolyzers. NFPA 2 applies to stationary hydrogen generation systems that have a rated capacity to generate between 36 g/hr (1.3 oz/hr) and 100 kg/hr (220 lb/hr); electrolyzers with higher ratings are not currently covered by NFPA 2. The electrolyzer stack in the facility discussed in this report that will be used the direct reduction of iron will be stationary, but its production rate will likely exceed 100 kg/hr, rendering NFPA 2 nonapplicable to the facility’s hydrogen production area. CSA/ANSI

B22734 ("Hydrogen generators using water electrolysis – Industrial, commercial, and residential applications") should be referenced in place of NFPA 2 for electrolyzer safety recommendations [20]. CSA/ANSI B22734 covers requirements for the design, construction, and performance of industrial, commercial, and residential water electrolyzers and does not exclude generators based on production rate [20]. As electrolyzer technology progresses and larger hydrogen production systems are built, hydrogen codes and standards will grow to include electrolyzers with production capacities above 100 kg/hr.

Both oxygen and hydrogen safety must be accounted for since both are produced during electrolysis. Besides leaks to the outside of the equipment, leaks across the electrolyzer membrane could lead to combustion events. Standards such as NFPA 53 ("Recommended Practice on Materials, Equipment, and Systems Used in Oxygen-Enriched Atmospheres") [28] and 29 CFR 1910.104 ("Oxygen") [29] can be used as references for oxygen-specific considerations at the location of the electrolyzers. Some of these requirements may depend on the electrolyzer capacity and rate of oxygen production.

Besides the specifications described above, the existing regulatory landscape lacks comprehensive prescriptive requirements. Therefore, using site-specific risk-based protocols and best practices is currently recommended for designing and maintaining a safe facility.

2.5.3. Hydrogen-Fueled Direct Reduction of Iron

The processes that occur inside of the steel plant are an important aspect of the hydrogen use area in the current design. Hydrogen is utilized in steel production as a reducing agent, removing oxygen from iron ore to make sponge iron, which is then melted and turned into steel. The most common iron reducing agent is carbon monoxide, which emits carbon dioxide as a byproduct of reduction. Hydrogen reduction emits water as a byproduct, decreasing the effect of steel manufacturing on the environment.

From the onsite hydrogen storage system to the hydrogen end-use of iron, there are piping systems, gaseous detection systems, valves, and pressure relief devices. Standards like ASME B31.12 and CGA S-1.3 refer to relevant safety recommendations for these common components [11] [30]. There are no design, safety, or construction recommendations for the components involved in the direct reduction process, such as the shaft furnace or electric arc furnace. Many of the standards associated with iron reduction are not safety-related but instead provide specific testing and material analysis procedures. For example, ASTM E382 provides recommendations for the crushing strength of iron ore pellets for the direct-reduced iron process [31]. Another relevant standard is API RP 941, which discusses process operating limits for carbon and low-alloy steels for hydrogen service at elevated temperatures [32]. This standard informs stakeholders of the high-temperature hydrogen attack phenomenon and gives strategies and operating limits that protect steel components which interact with hydrogen at temperatures greater than 400°F (204°C). The direct reduction of iron occurs at temperatures above 1,000°F, so this document can provide useful material integrity recommendations. Standards like these are important to stakeholders interested in the direct reduction process, but they do not provide comprehensive recommendations for component design or safety. Codes and standards

like NFPA 2, ASME B31.12, and CGA S-1.3 can assist with safe design and installation, but stakeholders must refer to sources outside of codes and standards to safely design, construct, and install hydrogen-based direct-reduced iron shaft furnaces and electric arc furnaces.

It should also be considered that DRI is flammable when in contact with water. This might cause conflict with state fire codes that require a sprinkler fire suppression system to be used with hydrogen. A possible gap in NFPA 2 might be to include an alternative to the standards when hydrogen is being used to produce DRI.

3. CONCLUSIONS

This document provides an overview of sections of codes and standards applicable to hydrogen production and storage, specific to the current reference station design for the steel plant in Minnesota, as part of the Wind-H2-Green Steel/Ammonia project. A review of codes and standards relevant to hydrogen use was completed using the specifications of the design. Requirements, recommendations, and exclusions with regards to the system are reported.

First, the entire facility was split into three sections using each pipeline as the start or end to each section. Broadly, these sections were defined as the area containing the electrolyzer, the area containing the large-scale underground geologic hydrogen storage, and the area in which hydrogen is used in the steel manufacturing process. Each section was considered a separate hydrogen storage facility for the purposes of determining storage siting requirements. Relevant siting requirements were identified in NFPA 2, which provides guidance for setback distances between hydrogen storage systems and different exposures. A summary of recommended setback distances is provided in Figure B-1 and in the Appendix. The guidance can be tailored to any changes that may be made to the design in the future, using the setback distance tables provided in Section 7.3 of NFPA 2.

Regulations were also reviewed for the pipelines between each area of the system. The main standard used for pipeline recommendations was ASME B31.12; the guidelines include recommended materials for pipeline construction, as well as pipeline location classification and design limits such as the MAOP and the design factor. A flow chart summarizing how the relevant pipeline requirements were chosen is provided in Figure C-2 in the Appendix.

Fire safety recommendations from NFPA 2 and NFPA 72 were reviewed for applicability to the proposed system design. NFPA 2 fire safety guidance focuses on gaseous hydrogen storage Emergency Plans, controlling ignition sources, and the proper construction materials for protecting against hydrogen fires. NFPA 2 references several documents from ASTM and ANSI that cover material requirements. NFPA 72's guidance centers around general fire signaling systems, and how these devices should be installed, tested, and maintained. Stakeholders should use NFPA 2 and 72 together to understand how to prevent and address hydrogen fires during the design and operation phases of a project.

Electrical components pose a risk of ignition when installed near hydrogen systems. NFPA 70 Articles 500 and 501 were reviewed for important information on electrically classified locations. Class I Division I locations have a high likelihood of being exposed to hydrogen gas during normal operating conditions, while Class I Division II locations have a lower likelihood of exposure since hydrogen gas would be present during abnormal conditions. Based on NPFA 70's descriptions, the current reference design would have a Class I Division II classification at all points in the system due to the possibility of hydrogen leakage. Areas that intentionally vent hydrogen, such as those around vent stacks and pressure relief devices, would be classified as Class I Division I.

Several gaps in existing codes and standards were identified. First, the current codes and standards that were reviewed in this task were found to provide inadequate or incomplete guidance for underground geologic storage of hydrogen. While some of the regulations

have wording that does not explicitly exclude this application, the quantitative recommendations in NFPA 2 such as setback distances were determined using assumptions that did consider the unique risks of storing large quantities of hydrogen or storing hydrogen underground in a non-tank containment system. Other existing regulations such as 49 CFR 192.12 are well established in the underground natural gas storage regulatory landscape and can be applied as the basis for design, operation, and maintenance of the underground hydrogen storage system. However, many of these requirements are generic and lack key quantitative recommendations for safe design such as setback distances from exposures around the system. Second, the electrolyzer capacity in the current reference design was determined to be outside the scope of NFPA 2; CSA/ANSI B22734 was recommended as a relevant supplement for electrolyzer regulations. Finally, design, safety, and construction guidance that goes beyond common hydrogen systems is needed for components involved in the direct reduction process, such as the shaft furnace or electric arc furnace.

This report will aid in the next steps of facility design, where more detailed safety requirements will be needed. The process could be expanded to include a system where the renewable electricity, or even the hydrogen, is produced offshore, and how that aspect might affect the safety analysis. It could also be a guide for the first steps of considering safety recommendations for others designing industrial facilities that incorporate large-scale hydrogen production.

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[18] ANSI/UL 723, "Test for Surface Burning Characteristics of Building Materials." American National Standards Institute.

[19] ASTM E2965, "Standard Test Method for Determination of Low Levels of Heat Release Rate for Materials and Products Using an Oxygen Consumption Calorimeter." American Society for Testing and Materials.

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[22] NFPA 70, “National Electrical Code.” National Fire Protection Association.
[23] UL 60079 Series, “Explosive Atmospheres.” Underwriters’ Laboratories.
[23] NFPA 70E, “Standard for Electrical Safety in the Workplace.” National Fire Protection Association.
[24] NFPA 70B, “Standard for Electrical Equipment Maintenance.” National Fire Protection Association.
[26] 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.” National Fire Protection Association.
[28] “Recommended Practice on Materials, Equipment, and Systems Used in Oxygen-Enriched Atmospheres.” National Fire Protection Association.
[37] 29 CFR 1910 Subpart H, “Hazardous Materials.” Occupational Health and Safety Administration.
[26] CGA S-1.3, “Pressure Relief Device Standards -- Containers for Compressed Gases.” Compressed Gas Association.
[29] ASTM E382, “Standard Test Method for Determination of Crushing Strength of Iron Ore Pellets.” American Society for Testing and Materials.
[30] API RP 941, “Steels for Hydrogen Service at Elevated Temperatures.” American Petroleum Institute.
[29] API 618, “Reciprocating Compressors.” American Petroleum Institute.
[30] ASME B31.12, “Process Piping.” American Society of Mechanical Engineers.
[33] ASME B31.8, “Gas Transmission and Distribution Pipelines.” American Society of Mechanical Engineers.
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[36] CGA H-7, “Standard Procedures for Hydrogen Supply Systems.” Compressed Gas Association.
[39] CSA C22.2 No.152-M1984, “Combustible Gas Detectors.” Canadian Standards Association.
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[41] IEC 60079-10-1, “Explosive Atmospheres.” International Electrotechnical Commission.
[42] ISO 15848, “Industrial Valves.” International Organization for Standardization.
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[46] UL 2017, “General-Purpose Signaling Devices and Systems.” Underwriters’ Laboratories.
[47] UL 2075, “Gas and Vapor Detectors and Sensors.” Underwriters’ Laboratories.

APPENDIX A. SUMMARY OF RELEVANT CODES AND STANDARDS

Table A-1. Summary of regulations relevant to Wind-H2-Green Steel/Ammonia plant design.

Short Name	Full Name	Scope or Relevance to Reference Design	Citation
*ANSI/UL 723	Test for Surface Burning Characteristics of Building Materials	Building materials in a potentially flammable environment	[17]
API RP 521	Pressure-relieving and Depressuring Systems	Venting guidance	[21]
API RP 618	Reciprocating Compressors	Hydrogen compressors	[33]
API RP 941	Steels for Hydrogen Service at Elevated Temperatures	Direct reduction of iron process	[32]
*API RP 1170	Design and Operation of Solution-mined Salt Caverns Used for Natural Gas Storage	Underground geologic storage	[7]
*API RP 1171	Functional Integrity of Natural Gas Storage in Depleted Hydrocarbon Reservoirs and Aquifer Reservoirs	Underground geologic storage	[8]
*ASME B31.12	Hydrogen Piping and Pipelines	Hydrogen piping, pipelines	[11]
ASME B31.3	Process Piping	General process piping	[34]
ASME B31.8	Gas Transmission and Distribution Piping Systems	Hydrogen transmission and distribution	[35]
ASME BPVC	ASME Boiler and Pressure Vessel Code Section VIII: Rules for Construction of Pressure Vessels	Hydrogen storage vessels	[36]
	ASME Boiler and Pressure Vessel Code Section XIII: Overpressure Protection	Hydrogen storage, pressure safety devices	[36]
ASTM E136	Combustibility of Materials	Building materials in a potentially flammable environment	[14]
ASTM E382	Standard Test Method for Determination of Crushing Strength of Iron Ore Pellets	Direct reduction of iron process	[31]
ASTM 2652	Combustibility of Building Materials	Building materials in a potentially flammable environment	[15]
ASTM E2965	Standard Test Method for Determination of Low Levels of Heat Release Rate for Materials and Products Using an Oxygen Consumption Calorimeter	Building materials in a potentially flammable environment	[18]
CGA G-5.4	Standard for Hydrogen Piping Systems at User Locations	Hydrogen supply piping	[37]
CGA G-5.5	Standard for Hydrogen Vent Systems	Venting hydrogen	[38]
CGA G-5.6	Hydrogen Pipeline Systems	Hydrogen pipelines	[39]
CGA H-5	Standard for Bulk Hydrogen Supply Systems	Hydrogen supply systems	[40]
CGA H-7	Standard Procedures for Hydrogen Supply Systems	Personnel interacting with hydrogen supply systems	[41]
CGA S-1.3	Pressure Relief Device Standards – Containers for Compressed Gases	Pressure relief devices for hydrogen storage	[30]
29 CFR 1910 Subpart H	Hazardous Materials	Worker safety around hydrogen	[29]

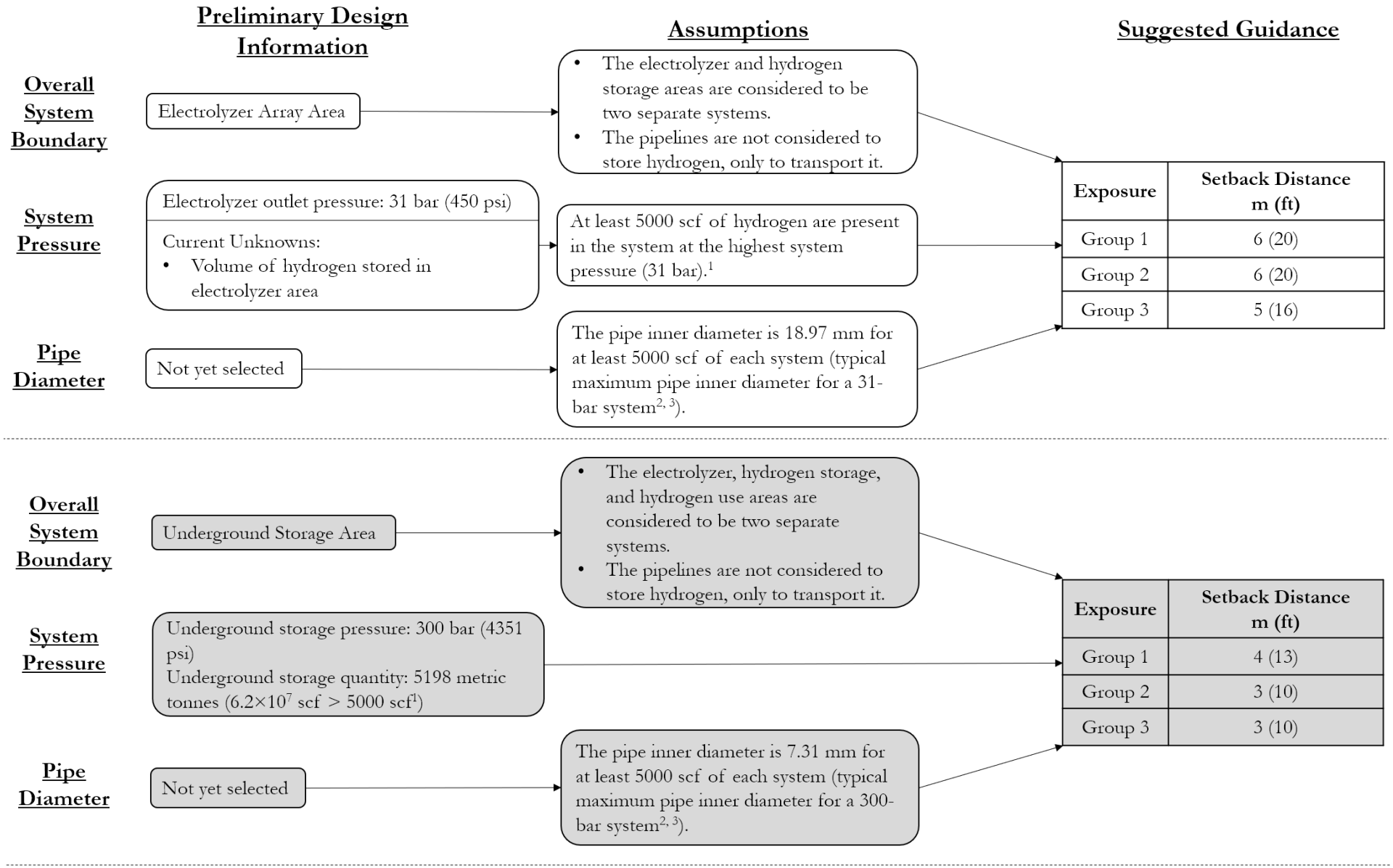
Short Name	Full Name	Scope or Relevance to Reference Design	Citation
49 CFR 105-110 and 190-192	Hazardous Materials and Oil Transportation, Pipeline Safety	Hydrogen pipelines	[10]
*CSA/ANSI B22734	Hydrogen Generators Using Water Electrolysis	PEM Electrolyzer	[20]
CSA C22.2 No.152-M1984	Combustible Gas Detectors	Hydrogen detection	[42]
FM 6310/6320	Combustible Gas Detectors	Hydrogen detection	[43]
*IEC 60079-10-1	Explosive Atmospheres	Classification of hydrogen areas	[44]
ISO 15848	Industrial Valves	Valves for hydrogen systems	[45]
ISO 26142	Hydrogen Detection Apparatus	Hydrogen detection	[46]
*NFPA 2	Hydrogen Technologies Code	Hydrogen storage, piping, compressors, detection	[4]
NFPA 53	Recommended Practice on Materials, Equipment, and Systems Used in Oxygen-Enriched Atmospheres	Oxygen safety	[28]
*NFPA 70	National Electric Code	Electrical classifications for locations with hydrogen	[23]
NFPA 70B	Standard for Electrical Equipment Maintenance	Electrical classification	[26]
NFPA 70E	Standard for Electrical Safety in the Workplace	Electrical classification	[25]
*NFPA 72	National Fire Alarm and Signaling Code	Hydrogen fire signaling systems	[22]
*NFPA 259	Standard Test Method for Potential Heat of Building Materials	Building materials in a potentially flammable environment	[19]
*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	Electrical classification	[27]
NFPA 715	Standard for the Installation of Fuel Gases Detection and Warning Equipment	Hydrogen detection	[47]
UL 864	Standard for Control Units and Accessories for Fire Alarm Systems	Hydrogen detection control units	[48]
UL 2017	General-Purpose Signaling Devices and Systems	Hydrogen detection	[49]
UL 2075	Gas and Vapor Detectors and Sensors	Hydrogen detection	[50]
*UL 60079 series	Explosive Atmospheres	Equipment requirements where explosive fuels are present	[24]

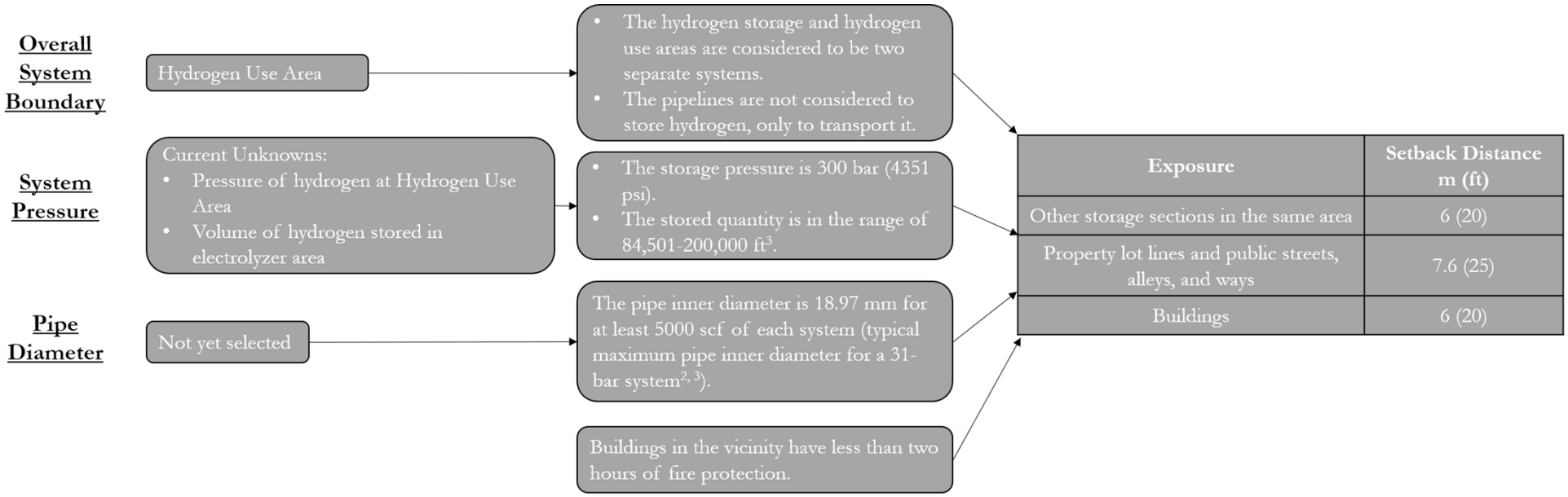
*Mentioned or discussed in this report

APPENDIX B. SUPPLEMENTARY MATERIAL FOR SITING REQUIREMENTS

Table B-2. Summary of parameters used to determine siting requirements based on storage category from NFPA 2 [4].

Non-Bulk vs. Bulk	Indoor vs. Outdoor	Aboveground vs. Belowground	Applicability	Parameters Used to Determine Allowed Locations	Parameters Used to Determine Setback Distances	Section in NFPA 2
Non-Bulk	Indoor	Implied aboveground	"Hydrogen systems of less than 5000 scf (141.6 Nm^3) and greater than the MAQ"	All applicable systems have the same allowed locations.	All applicable systems have the same setback distance.	7.2.2.2.2.1
Non-Bulk	Outdoor	Not specified	Storage quantities up to 5,000 scf	Not specified	Maximum stored volume per storage area	Table 7.2.2.3.2
Bulk	Indoor	Implied aboveground	Storage quantities greater than 5000 scf	Stored volume of hydrogen	Not specified	Table 7.3.2.2.1
Bulk	Outdoor	Not specified	Storage quantities greater than 5,000 (implied)	Not specified	System pressure and internal pipe diameter	Table 7.3.2.3.1.2(B)(a), 7.3.2.3.1.2(B)(b), 7.3.2.3.1.2(B)(c)


Preliminary Design Information
Assumptions
Suggested Guidance
Overall System Boundary
Electrolyzer Array Area
The electrolyzer and hydrogen storage areas are considered to be two separate systems.
The pipelines are not considered to store hydrogen, only to transport it.
System Pressure
Electrolyzer outlet pressure: 31 bar (450 psi)
Current Unknowns:
Volume of hydrogen stored in electrolyzer area
At least 5000 scf of hydrogen are present in the system at the highest system pressure (31 bar).[1]
Pipe Diameter
Not yet selected
The pipe inner diameter is 18.97 mm for at least 5000 scf of each system (typical maximum pipe inner diameter for a 31-bar system[2, 3]).
Exposure
Setback Distance m (ft)
Group 1
6 (20)
Group 2
6 (20)
Group 3
5 (16)
Overall System Boundary
Underground Storage Area
The electrolyzer, hydrogen storage, and hydrogen use areas are considered to be two separate systems.
The pipelines are not considered to store hydrogen, only to transport it.
System Pressure
Underground storage pressure: 300 bar (4351 psi)
Underground storage quantity: 5198 metric tonnes (6.2×10^7 scf > 5000 scf[1])
Pipe Diameter
Not yet selected
The pipe inner diameter is 7.31 mm for at least 5000 scf of each system (typical maximum pipe inner diameter for a 300-bar system[2, 3]).
Exposure
Setback Distance m (ft)
Group 1
4 (13)
Group 2
3 (10)
Group 3
3 (10)



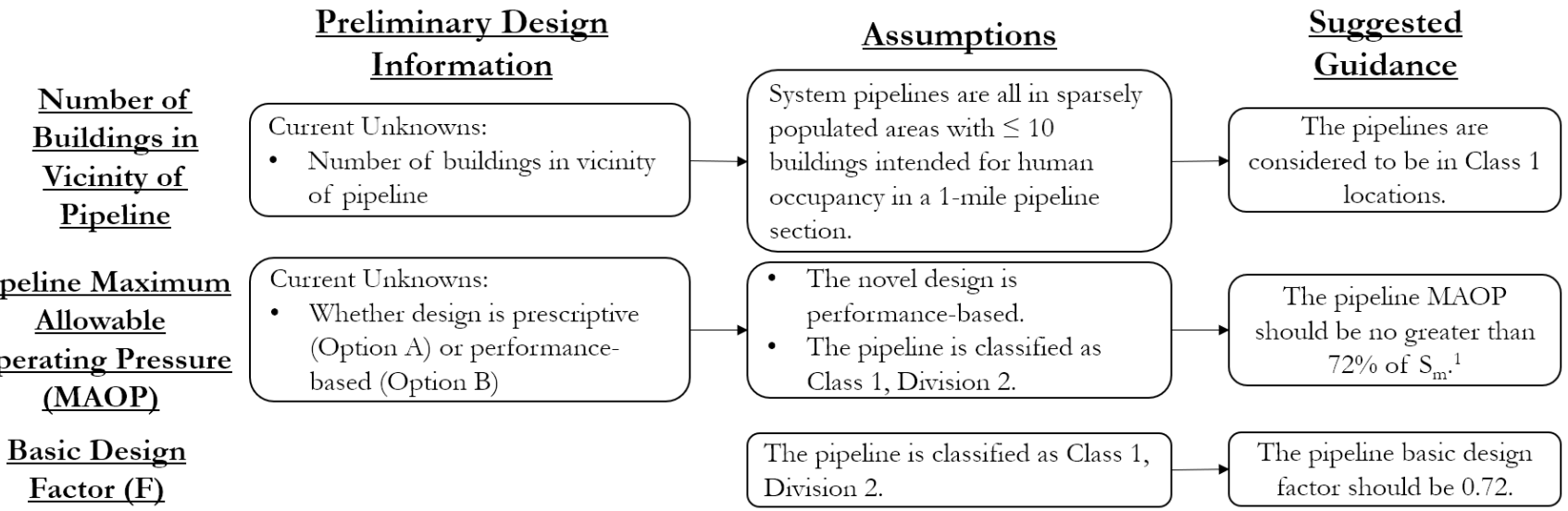
[1] NFPA 2 Section 7.3.2.3.1.2(B)(5) states, "The system pressure shall be determined by the maximum operating pressure of the storage array with content greater than 5000 scf (141.6 Nm^3), irrespective of those portions of the system elevated to a higher pressure."

[2] Section 7.3.2.3.1.2(B)(4) states, "The internal diameter of the piping system shall be determined by the diameter of the piping serving that portion of a storage array with content greater than 5000 scf (141.6 Nm^3).

[3] Typical maximum pipe inner diameter by pressure range found in NFPA Table 7.3.2.3.1.2(B)(a).

Figure B-1. Flowchart showing decision-making pathway for recommendations for hydrogen storage siting requirements, using NFPA 2 as guidance [4].

APPENDIX C. SUPPLEMENTARY MATERIAL FOR PIPELINE REQUIREMENTS



[1] Maximum allowable operating stress, calculated as the product of minimum yield strength and material performance factor H_f. H_f can be found in in various appendices and tables in ASME B31.12 and accounts for the effects that hydrogen gas may have on the mechanical properties of pipeline carbon steels.

Figure C-2. Flowchart showing decision-making pathway for recommendations for pipeline requirements, using ASME B31.12 as guidance [11].

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